A Water and Sediment Budget for the Lower Mississippi-Atchafalaya River in Flood Years 2008-2010: Implications for Sediment Discharge to the Oceans and Coastal Restoration in Louisiana

A report to the Louisiana Coastal Area (LCA)
Science and Technology Program

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Executive Summary

The challenges of studying the Mississippi River are due to its complex sediment-water dynamics and the multiple (and often competing) uses of its resources. Flood control and navigation are primary factors that control how the river is managed. A third factor is the use of the river resources, namely water and sediment, for nourishing the degrading coastal wetlands of the states of Louisiana and Mississippi. As such, these factors must be fully considered and coordinated while developing techniques to harness the sediment resources of the River for coastal restoration. This study utilizes data from USGS/USACE monitoring stations and site-specific studies to develop a detailed suspended sediment budget for the lowermost Mississippi and Atchafalaya River systems for the flood years of 2008, 2009, and 2010. The following conclusions can be drawn from the sediment budget analysis:

1. The Mississippi River reach below Old River Control (ORC) is a highly efficient trap for sand. The single largest removal of sand from suspended transport is interpreted to be primarily associated with the loss of stream power caused by the withdrawal of water at ORC, which leads to channel aggradation in the ORC to St. Francisville reach. This has long-term implications for navigation in this reach. A second zone of downstream-increasing channel aggradation was identified by comparing the 1993 and 2004 USACE channel navigation surveys. This aggradation is found below Belle Chasse, LA, and is likely linked to the progressive loss of stream power caused by the natural and man-made water exits and passes above the Head of Passes deepwater exits. Bed aggradation is already impacting navigation in the anchorages adjacent to the West Bay diversion and will likely impact anchorages further upstream in the future. Due to the storage and exits, only 2-7% (1.8 to 6.8 of 97.3 million tons) of the sand in suspension at ORC reaches Head of Passes as suspended load.

2. Approximately 47-67% of fine (<62.5 microns) sediment in suspension at ORC leaves the channel above Head of Passes. This is a result of the loss through channel exits mentioned above and by overbank flow into the batture at higher discharges. Overbank flow mainly takes place upriver of Baton Rouge, where batture area increases because flood control levees are farther from the river channel. This is a mechanism for sand loss as well as fines, in addition to those outlined in #1. While the loss of fines has no known impact on navigation, it does impact the water:sediment ratio of river water passed through present and future river sediment diversions.

3. Approximately 30% of the fines and 49% of the sand in suspension in the upper Atchafalaya station at Simmesport, LA is trapped in the basin upriver of the exits into Atchafalaya Bay. The widening of the guide levees away from the channel in the lower Atchafalaya Basin allows for significant overbank sediment storage during floods. This accretion in the lower basin has been measured directly by previous studies. Any additional (sand) storage through channel aggradation, and its implications for navigation, cannot be resolved from the dataset.

4. The division of suspended sediment at ORC differs from the 70:30 water split of Mississippi+Red River discharge due to the distinct Red River suspended sediment load. Sand is apportioned between the lower Mississippi and Atchafalaya pathways at an 83:17 ratio, and fines at a 60:40 ratio. This difference in water and sediment division ratios needs to be a consideration

for any future alteration of the Congressionally-mandated ORC split for the purposes of aiding coastal restoration in southern Louisiana. These results indicate that increasing the volume of water passing down the Mississippi pathway will be more advantageous for bringing fines to the proposed diversions in the river below New Orleans.

5. Total (fines + sand) suspended sediment loads can increase by a factor of four on timescales of a few days in the Baton Rouge to Head of Passes reach (and decrease at a similar rate) during rising discharge conditions. These "spikes" in suspended load are caused by a sediment pulse in the early phase of overbank flooding in the reaches of the river above ORC (basin hysteresis), and the remobilization of fines stored for several months on the bed in low river discharge conditions below Baton Rouge. With additional daily monitoring of turbidity at all existing USGS/USACE monitoring stations, water and sediment diversions could be operated to maximize suspended sediment capture and minimize freshwater capture.

6. It is clear from the channel aggradation response to large water withdrawal observed at ORC and at the exits below Belle Chasse, as well as from the results of a recent study for the LCA Program of channel aggradation associated with the 2011 opening of the Bonnet Carre Spillway, that large (>1% of total water discharge) water diversions have a significant downstream impact on suspended sand transport capacity. Future modeling should be concentrated on testing multi-diversion operation scenarios and their potential impact on navigation downstream. In the immediate vicinity of a diversion, this sand storage could be viewed as beneficial—developing a repository for sand that could be utilized by dredging and pipeline conveyance through the diversion (augmented diversions) or to other nearby land-building projects.

7. Significant land-building is not taking place in the Barataria and Breton Sound basins downriver of Pt. a la Hache, LA in spite of receiving significant sediment from multiple exits (26% of the fines and 8% of the suspended sand available at ORC or 34% and 25% available at Belle Chasse). One possibility to explain this is that subsidence-induced relative sea level rise is offsetting this large sediment contribution, which would have significant implications for locating any future land-building projects south of this reach. Another possibility is that the trapping efficiency of these basins is relatively low (i.e., sediment is dispersed far field).

8. Water:suspended sediment ratios of individual water exits downriver of Belle Chasse indicates that there is a progressive downstream reduction in the efficiency of these channels in passing sediment per unit water discharge. This is likely a response to the progressive loss of sand by channel bed aggradation, and to a reduction in hydraulic head in the tidal and estuarine reach. Again, this favors the location of diversions further upriver and above existing water exits, where stream power is higher and additional sediment is available in suspended transport for diversion.

9. A comparison in this report of the impact of bedload processes for transporting sand suggests that the downstream variability in bedload rates and in exchange rates of sand between bed and water column creates a complex and interactive set of processes that hinders our ability to predict whether (and on what timescale) observed bed sequestration will have any effect on dredging rates required at Southwest Pass and other areas near Head of Passes. Some sand is sourced from upstream (washload and traction load) and some is sourced locally on the bed and transported downstream in the lower water column (bed material suspended load) over reach-

scale distances (e.g., miles) during floods. What is required to make these predictions is the development of a multi-dimensional numerical model(s) that accurately simulate these phenomena. The goal is to develop the ability to simulate individual sand particle trajectories downchannel to arrive at estimations of annual downstream transport rates by the various mechanisms. This should be a major goal of the LCA Mississippi River Hydrodynamic and Delta Management Feasibility Study.

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1. Introduction

Recent attempts to quantify the riverine sediment supply to the world ocean (Walling et al. 2003; Vörösmarty et al. 2004; Syvitski et al. 2005) have highlighted the degree to which river loads have been altered by human activities in drainage basins in the past 1 to 2 centuries (e.g., land use changes, damming, artificial levees and other river control works, etc.). As we enter the "Anthropocene" era (Meybeck and Vörösmarty, 2005) of increasing human populations and global climate change that may alter precipitation patterns, these factors, coupled with the opposing effects on sediment discharges of many existing human alterations (for instance, dams trap sediment while deforestation increases denudation) complicate predictions of the future sediment supply of individual river systems. It was also recognized by Meade (1996) that quantifying the sediment supply to the world ocean by rivers can be misleading because, until recently, very few were monitored in their tidal and/or estuarine reaches due to limitations in time-series measurement instrumentation. River "end member stations" often are found 100's of km upstream of the mouth in large rivers (e.g., Amazon, 398 miles; Mississippi, 306 miles; Ganges, 242 miles; Brahmaputra, 216 miles; Meade, 1996).

Draining approximately 41% of the conterminous U.S., the Mississippi River has the seventh largest water discharge and suspended load of world rivers (Milliman and Meade, 1983; Meade, 1996). Sediment budgets from the upper basin to the "end member station" were first constructed (Meade and Parker, 1985; Meade et al. 1990; Meade, 1995) using monitoring data from gauging stations operated by the U.S. Geological Survey (USGS) and the U.S. Army Corps of Engineers (USACE). More recent budgets (Horowitz, 2010; Meade and Moody, 2010) have utilized ongoing data collections at these stations to examine declining suspended sediment loads attributed to damming and other river control works, and the multi-annual effect of major floods (such as 1993) on sediment loads. All of these budgets include monitoring station data downstream only to an "end member station"—either Tarbert Landing (306 river miles above the Head of Passes mouth of the Mississippi) or St. Francisville (RM 266) (Fig. 1a). Locations of the monitoring stations and other land marks along the length of the river will be identified by distance (river miles RM) above the Head of Passes (HOP, RM 0; Fig. 1a). The Mississippi River sediment and water budgets through the LDE reach below these stations remains poorly quantified and is the focus of the present study.

The Mississippi divides into two distributaries immediately upstream of the Tarbert Landing monitoring station at the Old River Control structures. The Old River outflow channel merges further downstream with the Red River near Simmesport, LA to form the Atchafalaya River (Fig. 1a). These two distributary channels then pass through the subaerial LDE, which extends downstream through a lowland floodplain/alluvial valley and across the Holocene-age deltaic plain (Saucier, 1994). Prior to reaching the Gulf of Mexico, the Mississippi-Atchafalaya River is modified by a network of natural and artificial water diversions, and is constrained by flood, storm, and navigation control structures, which complicate tracing water and sediment discharges through the LDE. These structures have also been cited as overarching factors in the rapid (wetland) land loss in the lower deltaic plain of coastal Louisiana (10-12 miles^2/y; Barras et al. 2003), both through a levee-induced reduction in overbank riverine sediment supply (Baumann et al., 1984; Walker et al., 1987; Boesch et al., 1994; Penland and Ramsey, 1990), and by serving as pathways for tropical storm surge inundation (Barras, 2006; NAS, 2008). The continuing threat to these deltaic wetlands, compounded by accelerating sea level rise (Blum and Roberts, 2009), has led to a host of planning efforts in recent years to examine methods to stem this loss and restore coastal Louisiana (e.g., Coast2050 [http://www.coast2050.gov], the

Louisiana Coastal Area Ecosystem Restoration [http://lca.gov/] plan, and post-Hurricane Katrina, the State of Louisiana [http://www.lacpra.org] and U.S. Army Corps of Engineers [http://lacpr.usace.army.mil/] master plan documents). An understanding of the Mississippi-Atchafalaya water and sediment budget through the LDE reach is critical to the planning for engineered diversions and other mechanisms for re-introducing riverine sediments into the Louisiana coastal zone, and serves as the major motivation for the present study. The primary objective is to utilize monitoring station data and project-specific studies to examine suspended sediment fluxes and water discharge through the Mississippi-Atchafalaya LDE reach, including those portions of the fluxes passing through natural and artificial diversions prior to both distributary channels reaching the Gulf of Mexico. This budget will be utilized to examine the 1) interannual sediment storage or supply either in the channel or by overbank flow, 2) impact of tidal and estuarine processes on this budget, and 3) suitability of various reaches as sites for future river diversions.

2. Study Area and Background

Water movement through the Mississippi-Atchafalaya LDE reach is coordinated and funded by the USACE through the basin-wide Mississippi River and Tributaries (MR&T) Project that was initated to minimize the impact of large floods following the catastrophic 1927 Mississippi flood. The flood control network is designed to handle a maximum Mississippi + Red River discharge of 3.03 million cubic feet per second (cfs) at the latitude of Red River Landing, LA (RM302). This flood control involves three elements within the study area, namely 1) earthen guide levees along the Mississippi and Atchafalaya channels, 2) floodways and spillways to divert floodwaters out of the Mississippi channel above New Orleans, LA, and 3) channel improvements and bank stabilization.

Earthen levees line the entire Mississippi channel on both banks from the upper limit of the study area (Natchez, MS; RM363) except where constrained by natural bluffs. Downriver, these levees extend to RM11 at Venice, LA on the west bank, and to RM45 at Bohemia, LA on the east bank (Fig.1b). Levee heights decrease downstream, reflecting a decreased river stage range between high and low discharge: historic stage extremes recorded by USACE at Red River Landing, LA are 3.0 and 59.4 ft above National Geodetic Vertical Datum (NGVD) and at Venice are -0.7 and 9.2 ft NGVD. Downriver of Baton Rouge, LA (RM231) levees are generally within 0.5 miles of the channel, creating only narrow belts of vegetated land inside the levees (known as batture) that is flooded in high discharges. Upriver of Baton Rouge, flood protection levees do not closely follow the highly meandering river channel, creating areas in tight bends where the levee is set back 6-13 miles from the channel; this allows for significant overbank water storage in floods. However, lateral channel migration is constrained throughout the Mississippi channel in the study area through the use of concrete mats that line the channel shallows and bankline stone (rip-rap) revetments. In the Atchafalaya River, the flood control levees that form the Atchafalaya Basin are set back from the channel to create an 18- to 30-mile wide flood basin. However, the upper basin (including the stations at Simmesport at RM5 and Melville at RM30) has a second set of lower earthen levees that constrain the channel to a width of less than three miles. These secondary levees begin to increase in distance from the channel at about Krotz Springs, LA (RM42) and disappear below RM57 (Morgan City is at RM120). Bankline stabilization is limited to the same upper basin reach as the secondary levees, (except opposite Morgan City), where it takes the form of revetments (no mats) that are generally found on one side of the channel only, and alternate downstream between reaches sensitive to lateral channel migration.

Operation of the flood control system is coordinated by a series of discharge limits gauged at Red River Landing, LA. Regardless of water discharge, the three spillway structures at Old River Control (RM 316-312) are federally mandated to remove a volume of Mississippi water, that, when added to the Red River contribution, allows 30% of the combined discharge to pass down the Atchafalaya pathway. This contribution is adjusted on a daily basis. When discharge at Red River Landing (e.g., below Old River Control) reaches 1.25 million cfs, additional water up to 250,000 cfs is passed through the Bonnet Carre Spillway above New Orleans (Fig. 1a) into Lake Pontchartrain. Discharges above 1.5 million cfs cannot be passed through Bonnet Carre and are accommodated through the Morganza Spillway and West Atchafalaya Floodway upriver of Baton Rouge, and pass into the Atchafalaya Basin.

The Mississippi hydrograph exhibits a large seasonal and interannual variability, with high discharge of >1 million cfs below Old River Control occurring between January and May, and typically with several individual peaks of 1- to 2-week duration. The Atchafalaya hydrograph closely mirrors the Mississippi's given that 60-93% of the water discharge originates in the Mississippi rather than the Red River (Mossa, 1996). Mean Mississippi discharges during the high-water months were about three times the discharge during the low water months (Meade, 1995). Within the lowland reach, the timing of the sediment discharge has been described as preceding the water discharge maxima due to hysteresis, with more pronounced offset in large flood years (Mossa, 1996). Tides penetrate approximately 125 miles into the Mississippi River during low discharge (Sept-Nov) and as little as 35 miles during high discharge. Currents (2.6 to 5.3 feet/sec) in the tidal reach are dominated by the river outflow throughout the year; tidal currents are generally too weak to reverse the flow. A salt wedge is present throughout the discharge cycle, and is confined at higher discharges to the Southwest (SW) Pass channel (Fig. 1b; 14m depth) rather than the shallower Mississippi passes to the east (e.g., South Pass, Pass a Loutre). At discharges below about 300,000 cfs, the saltwater wedge emerges into the main channel above the Head of Passes (HOP; Soileau, 1989). The thalweg of the Mississippi River channel exceeds the depth of the surface of the Gulf of Mexico, allowing for upstream migration of the salt front for ca. 125 miles above HOP, constrained and controlled primarily by the volume of water discharge, although flow duration, wind velocity and direction, tides and water temperature are all contributing factors (Soileau et al., 1989; Galler and Allison, 2008). No salt wedge penetration has been observed upriver of the main Atchafalaya entrance into Atchafalaya Bay (Galler and Allison, 2008). Significant low discharge sediment trapping of fines occurs on the channel bed in both the freshwater tidal reach of the Mississippi and associated with areas mantled by the salt wedge and driven by estuarine circulation (Demas and Curwick, 1988; Galler and Allison, 2008; Allison and Meselhe, 2010).

3. Methods

Evidence of an ongoing decline in suspended sediment load supplied from the upper basin (Moody and Meade, 2010; Horowitz, 2010), in part led to the present study being focused on creating water and sediment budgets only for flood years (FY) 2008-2010 to minimize this systemic source of variability (although some comparison with historic data is presented as well). A flood year begins on October 1st, as this is typically close to minimum water discharge in the Mississippi River. Hence, the study period extends from October 1, 2007 to September 30, 2010.

Given the station-to-station variability in how monitoring is conducted, it was not possible to utilize a standardized methodology for calculating water and suspended sediment loads for FY 08-10. Stations are divided into two types: USGS/USACE monitoring stations where a year or more of continuous data are available about water or suspended sediment discharge, and project studies, which were conducted to address a specific scientific or management issue, or which relate to a specific exit point (natural or man-made) from the river. Most of the latter results tend to extend only over a short time interval or over a few separated dates within the FY08-10 period of the budget calculations. Detailed information about the data processing for each station, including daily numbers presented as figures and as electronic files, is outlined in Appendix A. However, a general workflow was followed to arrive at these numbers. The first step for all stations was to calculate daily water discharge (cms). This calculation was straightforward for USGS/USACE stations making daily measurements using horizontal acoustic doppler current profiler (H-ADCP) technology (Belle Chasse, Wax Lake, Morgan City), or where the channel is well-contained within the levees leading to a high-quality gauge height:discharge water rating curve (e.g., Baton Rouge, for instance). H-ADCP results typically only extend across ½ to ⅓rd of the total channel width and are extrapolated to the full cross-section (by USGS/USACE) using regular boat-based ADCP measurements that are bank-to-bank. A further reason for concentrating only on FY08-10 was that the tidally influenced daily measurement stations only have been outfitted with H-ADCP technology in recent years. At two additional monitoring stations (Melville and Natchez), stage is gauged, but discharge is not measured directly: at these stations, stage:discharge rating curves from the nearest discharge measuring stations were utilized (see Appendix A). Water discharge at project study stations was either measured directly (by boat-based ADCP or fixed H-ADCP) or water discharge was obtained from a nearby USGS/USACE monitoring station (see Appendix A).

Suspended sediment discharge at USGS/USACE monitoring stations typically is carried out using boat-deployed D96 or D99 (hereafter referred to as D90 series), depth-integrative, isokinetic water samplers (Edwards and Glysson, 1988) along a cross-section with 3-7 vertical profiles. The heavier sampler (D96 is 60 kg, D99 is 125 kg) is utilized at higher discharges to minimize wire angle produced by higher stream velocities in the lower Mississippi-Atchafalaya (Beverage, 1987). The USGS strategy in the lowermost Mississippi is to collect samples 12-15 times/y across the entire flood year but with denser sampling during periods of peak discharge. Depth-integrative samplers collect a single sample per vertical cast that provides a depth averaged sediment concentration (mg/l): this sample is sieved in the laboratory to determine the concentrations of individual size fractions. For the present study, the size fractions were grouped only into a sand and mud fraction (e.g., larger and smaller than 62.5 μm fraction). Results from multiple verticals collected sequentially along the monitoring station transect are averaged to arrive at a mean cross-sectional and depth integrative concentration (Edwards and Glysson, 1988). Over the three flood-year study period, this yielded 36-45 individual data points that were then utilized to construct a suspended sediment rating curve applying the water discharge calculated for that point on that day. Separate curves were calculated for total (sand + mud) and sand load. Curve fitting software was used to test many individual best fit regression curves to these data points. Only a limited number of curve types gave the best fit (see Appendix A) likely because of the hysteresis loop of sediment data in rivers—typically either exponential rise to maximum, power law, or logarithmic curves.

Two monitoring stations (Baton Rouge and Belle Chasse) and several project study sites used optical backscatterance sensors (OBS) to obtain daily-averaged turbidity (NTU) measurements. These turbidities were calibrated to total (mud+sand) suspended sediment concentration using a ratings curve developed from the isokinetic boat data for available days (see Appendix A) in FY2008-2010. Other project study sites were sampled using point-integrative isokinetic suspended sediment samplers (P-61 at 100 lb or P-63 at 200 lb). Where multiple depths were measured in a vertical, these values were averaged to be comparable with depth-integrative sampler results from the monitoring stations. The cross-sectional averaged concentrations (mg/l) were then fit to a sediment rating curve with boat-measured ADCP water discharges in the same way as the monitoring station data (see Appendix A). Sample comparisons between the heavier P-63 with D90 results agreed well since both were deployed to a maximum of 0.9 total water depth; when the P-61 was utilized (e.g., Natchez, MS), suspended loads were significantly lower—likely because of an increase in wire angle which reduced true depth (Beverage, 1987). Where suspended sediment measurements were not available at project study sites, local water discharges were combined with concentrations for that day at the nearest USGS/USACE monitoring station to estimate loads.

For the Mississippi reach below the lowest monitoring station (Belle Chasse), channel sediment storage was calculated by a different method. The two most recent USACE decadal navigation surveys from January-March 1992 and August 2003 were utilized to calculate shoaling over specific bank-to-bank reaches extending from RK121 (Belle Chasse) to RK4.2. Volumes were corrected to sediment loads (MT/y) using methods outlined in Appendix A.

4. Results

4.1 Channel Monitoring Stations

Annual water discharge in three flood years (FY08-10) ranged from 169.3 to 214.5 x 10^{11} ft^3/y (Fig. 3, Table 1) at the Tarbert Landing station below Old River Control (ORC), with maximum daily discharges of 1.46 (FY08), 1.28 (FY09), and 1.02 (FY10) million cfs. FY10 had an unusual hydrograph of five individual freshets (see Appendix A for individual station water discharge records), including record high levels in October 2010, which led to the largest annual flow volume for the three years despite the smallest maximum discharge. Maximum discharges in FY08 took place during an opening (April 12-May 7, 2008) of the Bonnet Carre Spillway above New Orleans triggered by a discharge at the Red River Landing stage gauge near Tarbert Landing of 1.25 million cfs. This was the 9th occasion that the Bonnet Carre structure had been opened since 1930. Annual water discharge at Tarbert Landing in 1950-2007 ranged from 220-665 cubic km (Meade and Moody, 2010), and all three years of the present study were above the median: 4^{th}, 8^{th} and 24^{th} highest of the 60-year time span (adding these years after the published study).

Averaged over the three flood years (Fig. 2), water discharge trends downriver exhibited a significant variability—particularly in the Mississippi channel. Water discharge at Natchez, when corrected for the water loss through ORC (59.0 x 10^{11} ft^3/y) was 5.3 x 10^{11} ft^3/y lower than Tarbert Landing, implying an additional source(s) of water in the Natchez to Tarbert Landing reach. At stations below Tarbert Landing on the Mississippi this trend was reversed, with discharge decreasing by about 8.9 x 10^{11} ft^3/y between Tarbert Landing and Belle Chasse. A calculated 2.5 x 10^{11} ft^3/y of this loss was through Bonnet Carre (open and closed), and through the freshwater diversion structures at Davis Pond and Caernarvon (Fig. 1). No water discharge data are presented for the St. Francisville station because overbank flow complicates rating the local stage measurement (see Appendix A; sediment data are calculated based on Baton Rouge water). In the Atchafalaya channel, 24.7 x 10^{11} ft^3/y of Red River water (Fig. 2) are needed to account for the measured three-year average water discharge at Simmesport, given the Mississippi contribution through ORC. This number is a 29.5% Red + Mississippi water contribution, very close to the federally mandated 30% Red + Mississippi discharge. Below Simmesport, water discharge was unchanged at Melville, and is relatively unchanged (+0.4 x 10^{11} ft^3/y) in the combined Wax Lake and Morgan City outflow (84.1 x 10^{11} ft^3/y; Fig. 2).

Figure 4 displays a downriver budgeting of mud (< 62.5 µm) and sand (>62.5 µm) suspended sediment recorded at the USGS/USACE monitoring sites averaged over the FY08-10 period. Table 1 and Figures 5 and 6 display the annual values used to calculate these three year site averages. The values in Figure 4 are not presented with error bars (representing variability between the individual years) as that would inflate the apparent measurement error. As Table 1 and Figure 4 and 5 show, year-to-year increases or decreases in suspended sediment load at a station are mimicked at all the stations. Total suspended discharge at Tarbert Landing in FY08-10 ranged from 152-197 million short tons (MT): Meade and Moody (2010) reported a 20-year averaged (1987-2006) annual total suspended load at Tarbert Landing of 127 MT. Atchafalaya total sediment discharge at Simmesport was 68-88 MT/y in FY08-10, compared to a 1987-2006 average (Meade and Moody, 2010) of 63 MT/y. St. Francisville in FY08-10 ranged from 84-115 MT/y, compared to a 1993-2007 average of 93 MT/y calculated by Horowitz (2010). Data at all three stations suggests flood years 2008 and 2010 were above average (following the trends for water discharge noted above) for total suspended sediment discharge and 2009 was near, to slightly above average.

The historical sediment discharge records at Tarbert Landing, St. Francisville, and Simmesport examined by Horowitz (2010) and Meade and Moody (2010) indicate progressively declining sediment loads since the 1950's. They attribute that decline to the integrative effects of catchment dams, soil erosion control, river training and bank revetment structures, and a supply limitation caused by large floods such as 1993. Figure 7 are plots of isokinetic, boat-collected discharge data from 1978 to 2010 relative to the ratings curve data utilized to collect sediment loads (total and sand) in FY08-10 at the two stations (Belle Chasse and Morgan City) furthest downstream in the Mississippi and Atchafalaya. Total sediment loads relative to water discharge were significantly higher in 1978-1987 at both stations. The decrease in sand loads displayed by FY08-10 data was confined to lower discharges (<530,000 cfs in the Mississippi and 140,000 cfs in the Atchafalaya) and was more pronounced at Belle Chasse. These data suggest that the declining sediment loads observed by previous investigators propagate into the lowermost Mississippi-Atchafalaya as well.

The suspended sediment budget (mud and sand) for FY08-10 in Figure 4 displays large downstream fluctuations in sediment load in both the Mississippi and Atchafalaya. Data for Natchez, Mississippi is not shown because of the sampler bias (see Appendix A) associated with the use of a lighter sampler and a maximum sampling depth of 0.84 total water depth (other stations were 0.9). There was a large decrease in sand load (59.3 MT) in the Mississippi between Tarbert Landing and St. Francisville. Sand discharge increased by 11 MT/y at Baton Rouge and declined by a similar amount at Belle Chasse. Mud (<62.5 µm) discharge declined from Tarbert Landing to Baton Rouge and increased slightly (6.1 MT/y) at Belle Chasse. Both sand and mud load decreased in the Atchafalaya between Simmesport and Melville, with mud loss three times that of sand. Sand loads continued to decrease in the combined Morgan City and Wax Lake outlet stations to Atchafalaya Bay, but mud load increased by 16.6 MT/y. The lowermost river pathways, taken as Tarbert Landing to Belle Chasse (Mississippi) and Simmesport to Morgan City+Wax Lake, displayed a net basin storage (Fig. 4) of 75.3 and 25.4 MT/y, respectively. Of that total, 80% was sand in the Mississippi reach and 30% in the Atchafalaya reach. This loss is that fraction recorded at Tarbert Landing and Simmesport that does not reach below the lowermost monitoring stations (net annual basin storage). In the Atchafalaya, the lowermost stations are immediately adjacent to the coast (Atchafalaya Bay), while Belle Chasse is located at RM75 above Head of Passes (HOP; RM0).

An operational definition used by the USGS and USACE in Louisiana of when the lower Mississippi River is in "flood" (high discharge) is 700,000 cfs, while "low" flows are those below about 535,000 cfs. To examine the effects of sediment throughput between stations with the water discharge hydrograph, Figure 8 is a plot of the annual suspended sediment load (mud and sand) carried at water discharges above and below these values. The discharge interval between "low" and "high" is considered a "transitional" (rising or falling phase) hydrograph. Atchafalaya low, transitional, and high values at Simmesport and Melville are reduced to account for the FY08-10 water fraction carried by Simmesport versus Tarbert Landing (42.9% annual water discharge; Fig. 2) so "low" is <230,000 cfs and "high" is >300,500 cfs. Values are reduced proportionally again to account for the flow division between Morgan City (54.2% of water) and Wax Lake (45.8%). The results show that the suspended sediment load (sand and mud corrected to tons/d), increased from low to high discharge at all eight stations. In the four Mississippi stations, daily mud loads increased by a factor of 1.5 (Baton Rouge) to 3.0 (St. Francisville) between low and high discharge. Sand loads were greater in high discharge by a factor of 2.5 at Tarbert Landing, increasing progressively downstream to 18.5 at Belle Chasse.

In the Atchafalaya stations, daily mud loads increased by a factor of 2.1 (Simmesport) to 3.7 (Morgan City) between low and high discharge: sand loads were greater in high discharge by a factor of 8.4 at Simmesport, increasing progressively downstream to 53.6 at Wax Lake and 81.4 at Morgan City.

4.2 Water and Sediment Loss in the Belle Chasse to Head of Passes Mississippi River Reach

Three-year means of annual water losses from the Mississippi River channel below the Baton Rouge and Belle Chasse monitoring stations are quantified in Figure 9 and Table 2 and individual year water losses are shown in Figure 10. These water discharges are quantified from individual ratings curves for each channel exit developed from measurements taken during project studies in FY08-10 (see Appendix A). Several other smaller types of water losses are not included in this assessment. Water siphons utilized for small freshwater diversions are present at Naomi (RM64) and West Point a la Hache (RM49). They are not included because 1) of their small maximum discharge (2,000 cfs), 2) they only operate at higher discharges, and 3) operational record keeping is non-continuous. Navigational locks at Ostrica (RM24.8), Empire (RM29), Intracoastal Waterway-Algiers (RM88), Intracoastal Waterway-Harvey (RM98) and New Orleans Industrial Canal (RM93) are also not included because of their 1) small maximum discharge, and 2) the difficulty in quantifying the number of opening cycles and volume of water exchanged in each cycle. An older freshwater diversion is also present at Bayou Lamoque (RM33.6) that consists of two structures with four box culverts each, and a rated discharge of 1,000 cfs for each culvert. However, this structure is operated locally, with limited record keeping and measurements conducted by the authors (Allison and Vosburg) during the Gulf

Horizon Oil Spill in 2010 when the structure was opened by the State to full capacity showed discharges less than half the rated maximum.

Approximately 50% of the average annual water loss in Figure 9 between Baton Rouge and Belle Chasse (4.9×10^{11} ft^3/y) can be accounted for by the Bonnet Carre (open in 2008 only), Davis Pond and Caernarvon diversions. Below Belle Chasse, water loss through *measured* natural and artificial exits above HOP totaled 83.6×10^{11} ft^3/y, or 44.8% of flow. An independent measurement of *total* water loss in the reach can be arrived at by summing the total flows of the three river mouth passes (e.g., Southwest, South, Pass a Loutre) which were measured individually and a ratings curve constructed relative to Belle Chasse (see Appendix A). These measurements were used for the values in Figure 9 and total 89.3×10^{11} ft^3/y, or 48% of Belle Chasse. These calculations also indicate Southwest Pass carried 64% of the total water discharge below HOP.

Suspended sediment loss (total and sand) is shown in Figure 11 and individual flood years are shown (as mud and sand) in Figures 12 and 13. Only 4.6% of the average annual suspended sand loss between Baton Rouge and Belle Chasse (11.1 MT/y) can be accounted for by the Bonnet Carre (open in 2008 only), Davis Pond, and Caernarvon diversions. Given that mud load increased between Baton Rouge and Belle Chasse, the three diversions discharged only 0.3 MT/y out of the total increase of 6.4 MT/y of mud load between stations. Below Belle Chasse, sediment loss in Figure 11 through measured natural and artificial exits above HOP totaled 32.7 MT/y (33%), including 4.9 MT/y (26%) of sand (see Appendix A for methods of calculating sand loss through each exit).

4.3 Channel Storage in the Belle Chasse to Head of Passes Mississippi River Reach

Suspended sediment load loss or gain calculated for specific river reaches (Fig. 4) does not encompass the lowermost Mississippi region from Belle Chasse (RM75) to HOP. For this reach, channel sediment storage was calculated by a different method; utilizing USACE navigational surveys from 1992 and 2003, and deriving MT/y from shoaling displayed in specific river reaches. No more recent mapping was available to do a comparison during the FY08-10 period of examination for other stations. . Hence, any intercomparison of these data with the monitoring station results presented in the following sections has the caveats that the channel storage quantities reflect an accretion that is 1) over an earlier period than the station data and 2) encompasses an entire decade (including a 1997 Bonnet Carre opening). The channel storage was divided into eight reaches (density assumptions and results shown in Appendix A and plotted in Fig. 14), and are combined into three individual reaches in Figure 11 and 13. The storage in Figure 11 was 9.3 MT/y integrated over the entire Belle Chasse to RM2.6 reach. Figure 14 demonstrates a downriver trend of channel bed storage of sediment three-fold increasing when plotted in terms of tons per river mile (RM).

5. Discussion

5.1 Lower Mississippi-Atchafalaya Basin Storage in the Monitored Reach

The suspended sediment load calculations for the monitored reach of the lower Mississippi (Tarbert Landing to Belle Chasse) and Atchafalaya (Simmesport to Morgan City/Wax Lake) were potentially impacted by variability in annual water discharge (Fig. 2, Table 1). Such variability in the water discharge influences the sediment ratings curves. In the Atchafalaya, calculated annual water discharge averaged over FY08-10 varied by only 0.5 x 10^{11} ft^3/y (<0.5%)

over the study reach, and was an increase that may reflect input from rainfall in the Atchafalaya Basin. In the Mississippi, there was a progressive water loss between Tarbert Landing and Belle Chasse (corrected for diversion loss) of 6.4 x 10^{11} ft^3/y. An undetermined amount of loss likely occurred due to withdrawal of drinking water by cities (New Orleans and smaller communities downstream of Baton Rouge, which utilizes groundwater from wells). This loss may be balanced in part by wastewater discharge returned to the river. Losses above this amount would be through industial uses, as well as evaporative flux and discharge to groundwater. While this water loss likely had some impact on sediment transport capacity, the water loss is smaller than the individual loss from five of the channel exits below Belle Chasse (Fig. 9).

In the Tarbert Landing to Belle Chasse reach of the lower Mississippi, there is a net annual loss from suspended sediment load of 75.3 MT/y, or 43% of the total (Fig. 4). Two possibilities exist to explain this basin storage: channel aggradation or loss to overbank flow. A study of channel aggradation and deepening of the Mississippi River reach between Arkansas City, Arkansas (RM570) and ORC for the period 1949-1989 is summarized in Biedenharn et al. (2000) and Harmar et al. (2005). These studies utilized water surface slope (from stage gauges) and decadal USACE channel bathymetry surveys to discover that a major increase in stream power took place post-1949 associated with channel straightening, bank stabilization, and channel narrowing produced by lateral channel dyke-field construction. Water surface slope increased throughout the reach (Biedenharn et al. 2000) and Harmar et al. (2005) conclude that the reach upstream of Vicksburg, MS (RM436) responded by rapid channel deepening (downcutting). From Vicksburg to the ORCS, the longitudinal bed profile downcut slightly pre-1975 but in 1975-1989 began aggrading (Biedenharn et al. 2000). As these results measure aggradation only extending to the ORCS, they do not encompass our study reach immediately below the structures—direct comparison is hindered by the sampler bias in the results from Natchez, MS station (see Appendix A). Another factor which favors channel aggradation in this reach is the "backwater effect" (Parker, 2004; Chaudry, 2008), whereby stream power is reduced as a river approaches its receiving basin and transitions from gravity (slope)-driven to mixed gravity and pressure-driven transport. Nittrouer et al. (2011a) demonstrate in the lower Mississippi this backwater transition is found at lower discharges in the reach from HOP to about RM404—a divergence between water surface and bed slopes begins immediately above Natchez (RM363). The large storage loss observed in the present study between Tarbert Landing and St. Francisville coincides with the expected transition zone, and the predominance of sand storage suggests a hypothesis that fines stored at lower discharges were preferentially remobilized by the gravity-driven high flow events (Horowitz, 2010).

A detailed stage and bathymetric survey examination has not been conducted to date for the ORCS to Baton Rouge reach, or for post-1989. However, Galler et al. (2003) analyzed the Baton Rouge to HOP reach decadal bathymetric surveys from 1893-1992 and found net channel aggradation from Baton Rouge to RM109, with a switch to deepening to HOP. The change was mainly in the period 1921-1948 and was ascribed to the channel adjustment associated with the construction of federal guide levees in 1928-1930. They report the reach has been relatively stable post-1948 in contrast to the present evidence of aggradation below Belle Chasse (Fig. 14).

A final factor favoring channel aggradation in the Tarbert to St. Francisville reach is the loss in stream power below the ORCS caused by the exit of water into the Atchafalaya Basin. The stream power reduction can be observed in the rapid drop in river surface slope passing the ORCS. Utilizing an average stage over FY08-10 for each station, the reach from Natchez to Knox Landing (RM364) immediately above ORC has an average slope of 0.623 ft/mile, from

Knox Landing to Red River Landing below ORC (RM303) the slope is 0.660 ft/mile, while that from Red River Landing to Baton Rouge is 0.533. It should be noted that the overall trend of sand loss from transport is interrupted in the St. Francisville to Baton Rouge reach (Fig. 4). A possible explanation for this is anthropogenic: maintenance dredging in the channel at Baton Rouge Harbor (RM235.2) and Baton Rouge Front (RM233.0). A total of 1.80 million yd^3/y were dredged from the channel margin in FY08-10 and dumped by hopper dredge into the channel thalweg immediately upriver and adjacent to the Baton Rouge monitoring station (RM229.9) (E. Creef, pers. comm.).

Overbank flooding into the vegetated batture region inside the guide levees cannot be ruled out as an additional source of loss from suspended load in the lower Mississippi reach. Evidence of this is the difficulty of calculating daily water discharge at St. Francisville from the nearby stage gauge at Bayou Sara (outlined in Appendix A), which stems from the overbank flow at this site at discharges above 750,000 cfs. Although the extent of this overbank batture region is still constricted relative to the pre-levee floodplain (average width 3 miles; Biedenharn and Thorne, 1994), the region above Baton Rouge is of much greater extent than further downriver, where guide levees are within 0.5 miles of the river. This mechanism may also explain the storage of mud observed from Tarbert Landing to Baton Rouge (Fig. 4).

In the Simmesport to Morgan City/Wax Lake reach of the lower Atchafalaya, there was also a net annual loss from suspended load of 25.4 MT/y or 32% of the total (Fig. 4). Unlike the lower Mississippi, the majority of the loss was mud (30% sand). The reduction in stream power approaching the Gulf of Mexico associated with the backwater effect, outlined for the lower Mississippi, may play a role in the Atchafalaya as well. However, the 97% duration stage:discharge relationship at Morgan City was calculated for the four low discharges in FY08-

10: a 57,987 cfs discharge corresponded to a stage of 2.53 ± 1.02 ft. An analysis of stages at Simmesport and Melville during the 97% duration stage in 1980-2010 (not shown), exhibited an interannual variability in stage height that can be attributed to seasonal hysteresis (Simons et al., 1973) since this duration occurred in July-December in various years. More significantly, these interannual trends were mirrored at Simmesport and Melville, suggesting limited channel deepening or aggradation at either site has altered the water surface slope at a given discharge relative to Morgan City through time.

A more likely explanation is overbank storage. Atchafalaya basin width ranges from 18-30 miles in the lower basin (Krotz Springs to Morgan City/Wax Lake) to less than 3 miles in the upper basin, allowing for more significant overbank storage. It is unclear whether the secondary levees in the upper basin constrain overbank flooding at the highest discharges, or whether water exits through small, controlled and uncontrolled canals and bayous into the wider basin floodplain. The overbank storage mechanism would tend to support a less sand-dominated removal from suspended transport. Hupp et al. (2008) utilized feldspar marker horizons to document 0.08 to 1.7 inches/y sediment accumulation rates in the Atchafalaya Basin floodplain in an area between Melville and Morgan City in 2000-2003, with 5 to 44% of the storage composed of sand. Lacustrine deltas progradation into the lake reaches of the basin is also well documented as a process that stores Atchafalaya sediment (Tye and Coleman, 1989), particularly sand. Although many of these lakes are now infilled, which has been cited as a reason for bypassing to Atchafalaya Bay and subaerial bay head delta emergence after 1973 (Rouse et al. 1978), lake delta expansion may still be actively storing sediment to some extent. Bank stabilization also is more limited than in the Mississippi in the upper basin (revetments on one bank alternating downstream and no concrete mats). The absence of stabilization is may allow for significant lateral channel migration that may serve as an additional source of suspended sediment in the lower Atchafalaya Basin (as observed between Melville and Morgan City/Wax Lake; Fig. 4).

5.2 Importance of Bed Material Load Transport

The calculated sediment loads in this study do not directly measure bed material (bedload) load, as isokinetic sampling is typically conducted only to 0.9 of total water depth: suspended load is extrapolated for the 0.9-1.0 water depth interval. As discussing in detail by Gomez (1991), the near-bed division between what is in suspension versus bed material (traction and saltation) load is unresolved. For the purposes of this study, an estimate of the relative importance that fraction of bed material load that is involved in translation of channel floor sand dunes (i.e., bedform transport) can be calculated using results obtained for the New Orleans to HOP reach in Nittrouer et al. (2008) and Allison and Meselhe (2010). These studies utilized repeat multibeam bathymetric mapping of bank-to-bank dune translations to derive “bedform” transport rates. The resulting exponential relationship (r^2=0.98) of bedform transport rates with water discharge is:

$$y = 146.3\, e^{1.77E\text{-}4 * x} \qquad (1)$$

where y = bedform transport rate in metric tons/d

x = water discharge (cfs).

An estimate for the bedform (sand) transport rate for the Belle Chasse station can be calculated from daily water discharge and Eq. 1—Belle Chasse is the only station that falls within the study reach of the bedform transport studies and limited spatial variability in these rates has been detected in this reach. Annual bedform transport rates were 2.5 MT, 1.7 MT and 2.4 MT in FY08, 09, and 10, respectively. No sand was observed in suspension (using the sediment ratings curve) at Belle Chasse at water discharges below about 375,000 cfs. These conditions existed on an average of 82 days/y over FY08-10. Bedform transport continued even at these low discharges (100% of total sand transport; Nittrouer et al., 2008), but averaged only 0.07 MT/y over this period (3% of the average annual bedform transport total). At a moderate discharge of 535,000 cfs, sand transport as bedform load was 7.8% (2,356 tons/d) of suspended sand transport: that value rose to 12.5% (24,225 tons/d) at a flood of 1,000,000 cfs. Averaged over FY08-10, sand transport through bedform translation was 2.2 MT/y and suspended sand transport (Table 1) was 19.7 MT/y at Belle Chasse.

We conclude that bedform sand transport was of sufficient magnitude to partly (<11% of the 9.3 MT/y; Fig. 11) account for interannual channel bed storage measured in the Belle Chasse to HOP reach. This interannual channel storage is assumed to be primarily sand given the results of recent bed surveys (Allison and Meselhe, 2010; Nittrouer et al., 2011). While these results cannot be extrapolated upriver to examine its impact on the sand storage in the Tarbert Landing to Baton Rouge reach, the close coupling of bedform transport rates with stream power (e.g., exponential relationship with water discharge; Richards, 1982) suggest this transport mechanism is closely linked with changes in the water surface slope related to backwater flow and to the loss of water at ORCS.

5.3 Impact of Hysteresis on Sediment Load Calculations

Sediment rating curves utilize a best fit regression to develop a water discharge:sediment load relationship. As such, variability about this best fit curve is assumed to represent sampling and analytical error. In reality, rivers are known to experience hysteresis "loops" that have been attributed to channel bed scour and injection into the suspended load of stored bed sediment throughout the catchment reach (Walling, 1977; Wood, 1977; Meade et al. 1990). In the lower Mississippi, Mossa (1996) has described the suspended sediment load maxima as preceding the water discharge maxima. However, most of the station data utilized in that examination was based on low temporal resolution sampling (biweekly to monthly boat-based sampling). In the lowermost Mississippi and Atchafalaya, this hysteresis is also magnified by low discharge bed storage of fines in the tidal and estuarine reach that are remobilized on the rising limb (Demas and Curwick, 1988; Galler and Allison, 2008; Allison and Meselhe, 2010). The impact of these processes complicates assigning error estimates to the water discharge:sediment load relationship, making it difficult to separate sample/analytical error from real variability in suspended load.

To evaluate the impact of basin and local remobilization on the daily suspended sediment loads derived for the monitoring stations in the present study (Fig. 4), we calculated suspended sediment loads for three stations (e.g., Baton Rouge, Belle Chasse and RM24) on the lower Mississippi where optical backscatterance sensors (OBS) were installed to measure turbidity (NTU) for a significant fraction of FY08-10. Methods for calibrating these sensors are reported in Appendix A and the results are plotted in Figure 15. This calibrated load represents a total suspended load and cannot be divided into sand and mud fractions. These records demonstrate that most peaks in water discharge were accompanied by a rising-limb maximum in total sediment discharge of less than one week duration, with suspended loads falling prior to peak water discharge. An exception to this trend was observed in late June-early July in both 2009 and 2010 (Fig. 15 arrows); this coincided in both years with late, snowmelt-related increases in water discharge from the Missouri River branch of the Mississippi, which is known to be the predominant sediment source tributary (Meade and Moody, 2010). When compared to ratings curve results, the OBS total suspended load at Baton Rouge was 220.4 MT integrated over 727 days, while the ratings curve for those days was 210.0 MT. At Belle Chasse over 391 days, the OBS was 128.7 MT and the ratings curve 132.1 MT. These daily results demonstrate that the rating curve method utilized for all the stations in the present study is an accurate method for deriving total suspended discharges when averaged over annual timescales. However, hysteresis was clearly a major factor when examining sediment discharges over shorter time intervals, and the water:sediment discharge relationship is more complicated than reported in previous studies (e.g., Mossa 1996). By seasonally altering the timing of maximum sediment discharge relative to the water discharge peak, this phenomenon has major implications for the supply of sediment to the Gulf of Mexico (see below) and operation strategies for existing and future river diversions in the lowermost Mississippi to optimize sediment delivery to wetlands. Brief (~1 week) openings during the rising limb of spikes and when the late Missouri input arrives in the lowermost river would be optimal for minimizing freshwater inputs. These could be timed by installing a network of OBS sensors at all the main monitoring stations to track the sediment pulses prior to their arrival in the planned diversion area below New Orleans.

5.4 Mississippi-Atchafalaya Sediment Discharge to the Gulf of Mexico

While the Morgan City and Wax Lake monitoring stations are within the tidal reach of the Atchafalaya River and relatively close to the outlet to the Gulf of Mexico (e.g., Atchafalaya

Bay), the lowermost station on the Mississippi at Belle Chasse is 75 miles upstream of the entrance (HOP; Fig. 1b) to the deep-water passes to the Gulf of Mexico. Our quantification of water and sediment loss through the natural passes and man-made exits, and the channel aggradation in the Belle Chasse to HOP reach, has a major impact on the water and sediment loads exiting to the deeper Gulf. Water loss through the exits above HOP amounted to 44.8% of the annual water discharge reaching Belle Chasse. With the addition of loss to channel aggradation, sediment loss above HOP amounted to 42.0 MT/y, or 43% of the total suspended load passing Belle Chasse. Given that recent surveys have indicated bottom morphology in the Belle Chasse-to-HOP reach is lateral sand bars, relict fluvio-deltaic outcrops, and limited recent fines in the shallows that are seasonally deposited and reworked (Allison and Meselhe, 2010; Nittrouer et al., 2011b), we conclude that most of the sediment loss to channel aggradation was sand. This is as much as 14.2 MT/y of sand loss through a combination of channel storage and exits—equivalent to 74% of the sand load passing Belle Chasse (Fig. 11). This quantity would be reduced if significant mud was disseminated in the sand-rich channel deposits, but recent bed sampling confined to the bar surfaces in the reach below Belle Chasse indicates near surface sands are less than 10% mud at high and low discharge (Allison and Meselhe, 2010). A more likely possibility would be if bed material transport plays a significant role in supplying the sand for channel aggradation (Section 5.2).

Several methods were pursued to validate the quantities of water and suspended sediment loss below Belle Chasse. The OBS record at RM24 (Fig. 1b) was converted to an annual total suspended load (see Appendix A for methods) using Belle Chasse minus Bohemia water discharge (Fig. 9). The results in Table 1 averaged 95.1 MT/y, which agrees well with the 97.0 MT/y of Belle Chasse minus Bohemia in Fig. 11.

Other independent calculations of in-channel water and sediment discharge were less in agreement with the budgets shown in Figures 11-13. Boat measurements were made at RM2.6 and RM5.2/9.5 (Fig. 1b; Table 1) by the authors (Pratt) in FY08-10. Details of these methods can be found in Appendix A, but the water ratings curve developed for RM2.6 averages 97.8 x 10^{11} ft^3/y, compared with 102.9 x 10^{11} ft^3/y for Belle Chasse minus measured exits above HOP (Fig. 9). The three-year averaged annual water discharge at RM5.2/9.5 was 120.1 x 10^{11} ft^3/y compared with 136.3 x 10^{11} ft^3/y for Belle Chasse minus measured exits above RM5.2/9.5. Water discharge measurements and independent ratings curves for the three pass entrances below HOP (used to calculate values in Fig. 9) totaled 89.3 x 10^{11} ft^3/y, while the Belle Chasse minus measured exits above HOP was 102.9 x 10^{11} ft^3/y. These three underestimations of the water discharge are the primary cause for reduced sediment loads calculated by ratings curves (Table 1) for these cross-sections. An additional source may be the use of a lighter (P-61) sampler that produced larger wire angles. For instance, the three-year averaged annual sediment discharge at RM5.2/9.5 was 33.7 MT/y (2.6 MT/y of sand), compared with 61.2 MT/y (15.2 MT/y of sand) for Belle Chasse minus measured exits above RM5.2/9.5.

ADCP measurement error (which typically averages 1-2% of cross-sectional discharge; Edwards and Glysson, 1988) cannot explain this apparent water deficit. While factors such as loss to groundwater/evaporation, limited number of data points, and underestimation of the water loss through the poorly constrained exits at Bohemia, Ostrica, and Ft. St. Philip may have played a role, we believe tidal and estuarine processes were the most significant variable. Diurnal tidal modulation of water velocity produces a variation in ADCP cross-sectional discharge measurements made over different phases of the tide; and this becomes a more important process approaching the Gulf and at lower discharges (Meade, 1972; Galler and Allison, 2008). Even more important to discharge measurements made at low flows and utilized to construct the water and sediment ratings curves for RM2.6 and RM5.2/9.5, a persistent salt wedge is present in the main channel above HOP at discharges below about 300,000 cfs (Soileau et al. 1989) and is typically confined to the reach below Baptiste Collette except in extreme low water periods. Below the pycnocline, water is moving upstream and the density interface itself serves to degrade ADCP measurement quality of this deep layer. Further, the estuarine circulation processes trap and store fine-grained sediments on the channel floor under the wedge and, through flocculation, reduce turbidities in the saline layer (Galler and Allison, 2008). The latter will also impact sediment load ratings curves. Given that the passes in the wedge-influenced reach (e.g., Cubit's Gap, Grand Pass, etc.) have entrance channels perched above the main channel floor, the salt wedge is not present in these channels. We conclude the methods followed to produce the budgets in Figure 11-13 are the most reliable, although they are likely impacted by the tidal modulation, suggesting the need for a more comprehensive monitoring of water and sediment flow through these exits by future studies to refine the budget.

While stage measurements to follow water surface slopes described in Section 5.1 are difficult to examine in the reach below Belle Chasse because of a limited number of gauges that record in sufficiently rapid frequency to remove diurnal tidal-induced stage variation, and an overall limited stage range, we can infer that a reduction in stream power, and sediment transport capacity, takes place associated with the water exits. Stream power is potential energy reduction per unit river length (Lane, 1955; Knighton, 1998; Biedenharn et al. 2000):

$$\Omega = \gamma QS \qquad (2)$$

where Ω = stream power per unit channel length,

γ = specific water weight

Q = discharge

S = channel slope

Since specific weight is relatively constant, Ω is proportional to QS. While Nittrouer et al. (2011a) demonstrated that there is an increase in slope in this backwater reach associated with high water discharges, it can be anticipated that this increase in slope power is reduced by the removal of discharge through the exits above HOP. This mechanism is the most likely explanation for the observed progressive downstream increase in channel storage (Fig. 14). The potential increase in shoaling and its implications for navigation of deep draft vessels must be considered for future sediment (land building) diversions for coastal restoration in the adjacent interdistributary basins (Breton Sound, Barataria Basin; Fig. 1b). A secondary factor could be the ongoing relative sea level rise (RSLR) in south Louisiana, which represents a combination of land subsidence in conjunction with sea level rise (Blum and Roberts, 2009 and references therein). The potential role of this factor in channel storage (by the creation of accommodation space) is not definable at present due to a limited understanding of regional trends in subsidence. However, we believe that this factor is secondary given that present RSLR estimates for the area by Blum and Roberts are $\leq$ 0.6 inches/y. In comparison, the 1992 to 2003 volumes of sediment storage in the reach below Belle Chasse, when converted to an average vertical accretion over the study areas (miles^2), ranged from 1.7 to 5.3 inches/y for the reaches in Figure 14. If subsidence impacts the sand storage, it would *increase* the mass stored in the channel that we have calculated, since the creation and filling of accommodation space would not be marked by a shoaling in elevation.

A summation of the channel/overbank storage of Mississippi + Red suspended sediment in the Atchafalaya and Mississippi pathways (Fig. 4, 11, 17 and 18) indicate as much as 44% of the annual total suspended sediment load (110.0 of 251.8 MT/y) and 80% (76.3 of 94.8 MT/y) of the sand load was sequestered between Old River Control and Mississippi-Atchafalaya exits to the Gulf of Mexico in FY08-10. An additional 34% (32.7 MT/y) of the suspended sediment (25% of the sand) available at Belle Chasse exited through man-made and natural passes below Belle Chasse in the Mississippi and did not directly debouch into the deep water Gulf of Mexico (Fig. 11). Together, channel/overbank storage and exit loss calculated by the two methods mean that only 19% of the annual total suspended sediment load (33.3 of 173.0 MT/y) and 2% (1.8 of 78.8 MT/y) of the sand load at Tarbert Landing reached the deep water Gulf via the main pathway in FY2008-10. These figures are equivalent to (or exceed) the fraction of sediment load stored in the lowland reach of other large rivers whose sediment budget has been quantified. In the Amazon, a quantification of coastal and marine depocenters, led Nittrouer et al. (1995) and Mertes et al. (1996) to conclude that about 1/3rd of the total suspended load of this relatively unaltered river was stored in the lowland reach, primarily by overbank sedimentation. A similar fraction has been attributed to lowland overbank storage in more heavily altered (e.g., artificial levees) Ganges-Brahmaputra delta (Allison et al., 1998; Goodbred and Kuehl, 1999; Kuehl et al. 2005). The lower Mississippi-Atchafalaya storage is unusual for two reasons. The storage and overbank aspects of the sediment budget were quantified from direct measurement of changing water and suspended sediment loads at multiple stations along the river. The density of monitoring stations in most large rivers is insufficient to allow for this type of analysis.

Secondly, this storage is taking place in a system that has been highly altered for flood control, and stands in the future, to be further altered by artificial river diversions that will magnify a process (e.g., crevasse splay deposition) that, along with overbank flow, plays a primary role in sequestering sediment in lowland fluvial reach landward of the global ocean.

5.5 Implications for Siting, Design and Operation of River Sediment Diversions

The sediment budget results suggest several criteria should be followed with respect to future river sediment diversions to build land in splay deposits lateral to the main Mississippi channel to combat coastal wetland loss in coastal Louisiana (this section stresses the Mississippi pathway as the site of most of the conceptual planning for medium-to-large sediment diversions). With respect to location of a diversion(s), there is limited information yield in the present study about where in a reach a diversion would be most efficient at capturing suspended sediment load. On a broader scale, the results suggest that ***the reach immediately downriver of Belle Chasse (RM75) would be most suitable to maximize suspended sediment:water ratio***. Upriver of Belle Chasse, it is mainly an issue with increasing infrastructure, but with increasing distance downstream of Belle Chasse, two mechanisms are reducing the available suspended load for diversions. The first is the loss of water and sediments associated with the multiple man-made and natural exits into Barataria Basin and Breton Sound (Fig. 11, 17 and 18). In total, this mechanism removes 34% of the suspended fines and 25% of the suspended sand available at Belle Chasse. However, less than 1% of this loss takes place above the locks at Ostrica (RM24), and the loss becomes progressively more important downriver to Head of Passes.

The second process reducing available suspended sediment is the channel storage of sand below Belle Chasse that is interpreted to be associated with the loss in stream power engendered by these exits. This process removes an additional 47% of the sand (0% mud) in the Belle

Chasse to Head of Passes reach (75 river miles). This process is somewhat more important in the reach above Ostrica, suggesting that the natural loss in hydraulic head approaching the Gulf is a complicating factor in the loss of stream power. Even allowing for this, only 11% of the total suspended sand removal to channel aggradation takes place upriver of Ostrica (RM24). It is also evident from the sediment to water ratios of the measured exits that ***channels become less efficient in transporting sediment per unit of water discharge approaching the Gulf***. For instance, Baptiste Collette at RM13 discharges twice the fines (8.2 versus 3.9 x 10^6 tons/y) and 16 times the sand (1.6 versus 0.1 x 10^6 tons/y) of Cubit's Gap at RM3 (Fig. 11), despite carrying similar water (17.4 versus 18.3 x 10^{11} ft^3/y; Fig. 9). This is a response to the progressive loss in stream power.

Not only does the loss of sediment to channel aggradation and through exits suggest the reach above Ostrica is most suitable, but the negative influence of increasing subsidence in the lowermost reach (see Blum and Roberts, 2009 and references therein) can be observed indirectly in the present dataset. In spite of receiving 34% of the fines and 25% of the available sand at Belle Chasse, there is net land loss in both the Breton Sound and Barataria Bight regions (Barras et al., 2003), most recently due to the effects of tropical storms (Barras et al., 2006). We infer a connection between rapid sequestration of this material (as well as dispersal in the case of the fines) and rapid subsidence, to limit any beneficial growth of new land. This suggests that ***directing additional sediment into the lower reaches (below RM24) of these basins through future diversions would have limited benefit on coastal land-building***.

The present study also provides insights into design criteria for diversion structures. We are assuming that future diversions, unlike the West Bay Diversion, will be "controlled", e.g., constructed with fixed, concrete gates or culverts where discharge of water and sediment discharge can be managed. While most of the monitoring station data in the present study area utilizes depth-integrative isokinetic samplers that provide no information about the depth relationship of suspended concentration, some of the project studies utilized point-integrative samplers to examine suspended sediment concentrations at various depths in the water column. These results echo those of Allison and Meselhe (2010) that the upper water column, which would be "skimmed off" in diversions, has a low suspended sediment concentration, particularly with respect to the sand-sized fraction, relative to deeper parts of the water column. This depth relationship is true across the water discharge range. The ***most realistic method for significantly increasing the sediment:water ratio passing through the diversion would be some form of "augmentation"*** which either 1) pumps sediment-rich water from deep in the water column through the structure, or 2) dredges the adjacent river bottom sand and pumps it through pipelines into the diversion. The latter could involve either direct injection into the active flow, or stockpiling of sand in the exit channel while the diversion is closed, to be mobilized when it is opened.

The comparison of daily turbidity data with the ratings curve data at the Baton Rouge and Belle Chasse stations (Fig. 15) shows the temporally variable nature of the fine fraction of suspended sediment concentration, and how relatively unrelated it is to the water discharge cycle. We conclude that, although river diversions can be operated (timing of opening and closing) to maximize sediment capture and minimize freshwater input into the receiving basin, this operation cannot be planned in advance relative to the water discharge. Although mainly occurring during rising limb of water discharge pulses, these concentration "spikes" differ in importance depending on whether it is the first, second, or third water pulse of that flood year, and in the case of the June-July Missouri River spikes (Fig. 15), are not accompanied by rise in water discharge. Hence, maximizing sediment discharge would require daily decision-making criteria be developed in the way the water diversion through ORC is coordinated using the Red River Landing and Simmesport gages. In this case, ***a network of turbidity sensors would be required on the monitoring stations from Tarbert Landing through Belle Chasse*** that could relay information in real time to managers, who could then identify sediment spikes when they entered the upper reaches of the ORC to Gulf reach, and could track them downriver and coordinate structure operation.

5.6 Implications for River Dredging and Navigation

The observed channel shoaling in the Belle Chasse to HOP reach (Fig. 14) and the shoaling inferred from the large decrease in suspended sand in the Tarbert Landing to St. Francisville reach (Fig. 4) have both been interpretated as a river response to water removal at the natural and man-made exits from the Mississippi pathway channel. As such, these have a potential impact on navigation of deep draft navigation in the channel mainstem (e.g., above HOP). While the storage values calculated do not provide information about where in the channel cross-section this storage is concentrated, it can be inferred to be concentrated on the lateral sand bars that line the river—thalweg areas tend to be exposed relict fluvio-deltaic strata (Allison and Meselhe, 2010; Nittrouer et al., 2011b). As such, this would suggest that the threatened reaches (e.g., Tarbert to St. Francisville and Belle Chasse to HOP) would experience a greater risk to vessels by shoaling in the anchorages, rather than restriction of the deepwater navigation channel.

An allied question is the potential impact of channel storage on the sand supply to Southwest Pass. This can be posed as "if there is more storage upstream, will the amount of dredging required at Southwest Pass be reduced"? To address this question, we compared the calculated sand supply reaching the deepwater passes to dredge statistics for the FY2008-2010 period. In

2008-2010, dredge removal of sediment from the distributary mouth bar at Southwest Pass ranged from 13.3 to 29.3 million yd^3. An additional 4.1 (2008) and 6.0 (2010) million yd^3 were dredged from the Hopper Dredge Disposal Area at HOP (S. Ayres, pers. comm.). Dredging statistics (only available for 2010) indicate an additional 5.2 million yd^3 was removed from the Southwest and South Pass navigation channels. While these statistics are calculated by calendar year, dredging at the Southwest Pass bar begins in late October to mid-January timed with the increasing discharge and shoaling, and, hence is generally comparable to flood year (FY). On average, we estimate in FY2008-2010 that 32.2 million yd^3/y or 36.9 MT/y were removed from HOP and further downstream (utilizing a volume conversion of 85 lbs/ft^3). This is far in excess of the calculated suspended sand discharge arriving at the deepwater passes: 1.8-5.4 MT/y (Fig. 18). There are multiple potential causes for this difference including:

a) Volume to mass conversions may be too high given that the dredged material may be water-rich.

b) The sand:mud ratio of the dredged material is undefined and there could be considerable fines in the dredged material.

c) Dredging could include non-recent sediment (e.g., relict units that underlie the sand in active transport).

d) Additional alongshore and offshore sources for sand into the deepwater pass entrances.

It is also clear that the bedload sand component (calculated as 2.2 MT/y at Belle Chasse) is an additional mechanism for delivering sand to the deepwater passes from upstream. Our inability to "close" the total (suspended + bedload) sand budget is evidence of our poor understanding of this reach. This is mainly due to the absence of daily suspended sediment data at any station below Belle Chasse and the complicating effects of tides and estuarine processes in this reach.

6. Recommendations for Future Monitoring and Observational Studies of Water and Sediment Load in the Mississippi-Atchafalaya River in Louisiana

The results of the present examination of the suspended sediment budget have suggested several avenues for future research to improve our understanding of these processes and to monitor future changes in the sediment budget due to fluctuations in climate in the drainage basin or human alterations to the sediment supply (e.g., future diversions, etc.). The recommendations are:

a) Daily turbidity sensors emplaced at all the main Mississippi pathway stations (e.g., Tarbert Landing, St. Francisville, Baton Rouge, Belle Chasse) can be calibrated to yield total daily suspended sediment discharges for these stations using boat-based data already collected by the USGS and USACE. Installation of these relatively low-cost sensors would permit a better understanding of the hysteresis effects on suspended loads relative to the lowland reach and would provide a future network to operate controlled diversions to maximize sediment capture relative to water capture. Boat-based measurements of bedload discharge at these stations would also allow for quantification of this poorly studied portion of the sand budget—estimates in the present study were only possible at the Belle Chasse site with existing observational data.

b) A boat-based observational campaign to the Mississippi reach immediately below ORC is necessary to establish how much of the enormous loss of suspended sediment (particularly sand) observed between Tarbert Landing and St. Francisville is due to channel storage (as opposed to overbank flow) and results from the loss of stream power associated with water diversion at ORC. This shoaling has navigational implications and effects the use of the Tarbert/Red River

Landing gages to modulate flow through ORC and the timing of opening of flood control structures further downstream (e.g., Morganza and Bonnet Carre Spillways).

c) The navigational survey analysis (1993 and 2004) of the Belle Chasse to HOP reach that was used to calculate sand storage in the channel should be extended further upriver to ORC to quantify this decadal-averaged storage over the entire reach. When the next USACE decadal survey is conducted, this dataset should be included to examine if this storage has changed in magnitude or spatial pattern.

d) Installation of a water and sediment discharge measuring station below Belle Chasse would allow for much better quantification of suspended sediment loss through the exits above HOP and the sediment arriving at the deepwater passes (which has navigational implications). A boat-based observational campaign—at the station and in the entrances of the exits after its installation—would be necessary to calibrate such a station. The ideal location would be in the RM2.6 to HOP reach below all the water exits. While in section 5.5 we suggest the reach below Ostrica (RM24) is not suitable for siting diversions, a better understanding of the sediment dynamics in this complicated tidal and estuarine reach will be necessary to develop multi-dimensional numerical models that can be utilized to predict the effects in this reach (e.g., accelerated shoaling) that may result from future installation of water and sediment diversions above Ostrica for coastal restoration.

e) The 2011 flood year was a very large one, requiring the operation of Bonnet Carre Spillway at full capacity and partial opening of the Morganza Spillway. The present sediment budget analysis should be extended through the 2011 flood year when data from the USGS/USACE stations becomes available. This will allow the effects of a very large flood on the sediment budget to be quantified.

7. Concluding Remarks

The lowermost Mississippi and Atchafalaya system is generally thought to be an efficient conveyor for throughput of basin sediment to the Gulf of Mexico. Guide levees have cut off overbank flooding to much of the pre-levee lowland floodplain and deltaic plain areas. Bank stabilization practices throughout the channel length (including upriver of the study reach) limit lateral channel migration that remobilizes alluvial deposits. In spite of these control practices, the results of the present study indicate that the lowland zone in the Mississippi-Atchafalaya was as effective at trapping fluvial sediment in FY08-10 as other large major rivers, such as the Amazon and Ganges-Brahmaputra. When configured in terms of basins and mechanisms of loss (Fig. 16-18), it is evident that as much as 22% of the annual mud (<62.5 μm) suspended sediment load and 80% of the sand load of the Mississippi + Red Rivers was sequestered between Old River Control and the Mississippi (deepwater) and Atchafalaya exits to the Gulf of Mexico in FY08-10. This reduction in available suspended sediment is a significant consideration for coastal restoration planning in the Mississippi delta to use diversions from the channel to create land-building splay deposits in the adjacent interdistributary basins—particularly the removal of the sand from suspension that is vital to establishing marsh platform substrates in our estimation. Much of the planning to date has relied on suspended sediment availability estimates taken from long-term stations upstream such as Tarbert Landing.

Another serious implication of the present study for channel diversions is the linkage between water exits and downstream aggradation of the river channel. There was a progressive increase in channel aggradation rates downstream between 1992 and 2003; sequestering as much as 48% of the suspended sand reaching Belle Chasse, depending on the contribution of bed material load. It is the Belle Chasse to Head of Passes reach that is the focus of diversion planning. The reduction in stream power is attributed to multiple natural pass and man-made exits 1) above Tarbert Landing (ORC), 2) between Baton Rouge and Belle Chasse (Bonnet Carre, Davis Pond, and Caernarvon), and 3) below Belle Chasse that, in addition to being linked to channel bed aggradation. The exits below ORC collectively removed 44% of the water and 26% of the available suspended mud and 8% of the sand from the Mississippi pathway in FY08-10 (Fig. 16-18). These large sediment inputs into the lower parts of the shallow Breton Sound and Barataria interdistibutary basins are inefficient at land-building—based upon land-loss studies of these regions conducted by other investigators. These results suggest the need to 1) locate diversions above the rapidly subsiding thick Holocene section near the river mouth and 2) limit diversion water discharge in order to reduce potential channel aggradation that imperils navigation by deep-draft vessels. The latter limitation could be minimized by operating diversions at maximum during the sediment-rich rising limb of discharge and minimizing loss in stream power during the flood maximum which is most efficient at bed material transport and remobilizing suspended sediments deposited during the low discharge phase.

8. References

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Table 1. Water and sediment discharge in FY2008-2010 for USGS/USACE monitoring stations in the lower Mississippi and Atchafalaya Rivers.

STATION	Annual Water Discharge in cubic km/y (in 10^{11} ft^3/y)			Total Sediment Discharge in 10^6 metric tons/y (in 10^6 short tons/y)			Sand Discharge in 10^6 metric tons/y (in 10^6 short tons/y)		
	FY2008	FY2009	FY2010	FY2008	FY2009	FY2010	FY2008	FY2009	FY2010
Natchez	712 (252)	608 (215)	792 (280)	undefined	undefined	undefined	undefined	undefined	undefined
Tarbert Landing	570 (201)	479 (169)	607 (215)	155 (171)	137 (152)	178 (197)	73.5 (81.0)	62.2 (68.6)	78.9 (86.9)
St. Francisville	No data	No data	No data	91.0 (100)	75.8 (83.5)	104 (115)	17.6 (19.4)	14.4 (15.8)	21.0 (23.2)
Baton Rouge	548 (193)	471 (166)	605 (214)	93.3 (103)	81.0 (89.3)	103 (114)	31.8 (35.1)	20.1 (22.2)	31.6 (34.8)
Belle Chasse	523 (185)	465 (164)	592 (209)	88.7 (97.8)	72.7 (80.1)	103 (114)	18.6 (20.5)	12.7 (14.0)	22.1 (24.4)
Simmesport	244 (86.2)	206 (72.7)	260 (92.0)	72.8(80.3)	61.7 (68.0)	80.0 (88.2)	16.8 (18.5)	10.8 (11.9)	15.9 (17.5)
Melville	243 (86.0)	206 (72.8)	261 (92.1)	39.0 (43.0)	30.8 (34.0)	42.9 (47.3)	13.6 (15.0)	8.4 (9.3)	12.7 (14.0)
Morgan City	133 (47.1)	113 (40.0)	140 (49.4)	30.9 (34.1)	22.7 (25.1)	30.1 (33.2)	7.3 (8.0)	3.8 (4.2)	5.0 (5.5)
Wax Lake	108 (38.0)	95 (33.5)	126 (44.4)	20.1 (22.1)	16.9 (18.6)	24.6 (27.1)	2.3 (2.6)	1.4 (1.5)	2.5 (2.7)
RK39	520 (184)	463 (164)	588 (208)	88.0 (97.1)	73.8 (81.4)	97.0 (107)	No data	No data	No data
RK8.4/15.3	133 (119)	304 (107)	378 (133)	31.2 (34.4)	23.9 (26.3)	36.8 (40.6)	4.1 (4.5)	2.3 (2.5)	2.9 (3.2)
RK4.2	275 (97.1)	244 (86.1)	312 (110)	31.8 (35.0)	24.7 (27.2)	37.6 (41.5)	2.3 (2.5)	1.2 (1.3)	1.4 (1.5)

Table 2. Water and sediment discharge in FY2008-2010 for channel diversions and passes in the lower Mississippi River.

STATION	Annual Water Discharge in cubic km/y (in 10^{10} ft^3/y)			Total Sediment Discharge in 10^5 metric tons/y (in 10^5 short tons/y)			Sand Discharge in 10^5 metric tons/y (in 10^5 short tons/y)		
	FY2008	FY2009	FY2010	FY2008	FY2009	FY2010	FY2008	FY2009	FY2010
Old River Control	187 (662)	141 (498)	172 (607)	403 (444)	285 (314)	352 (388)	64.3 (70.9)	32.8 (36.1)	43.4 (47.9)
Bonnet Carre	5.7 (20.3)	0.2 (0.7)	0	9.4 (10.4)	0.4 (0.4)	0	0.6 (0.7)	0.2 (0.2)	0
Davis Pond	2.5 (8.9)	2.9 (10.4)	3.5 (12.3)	4.4 (4.8)	4.6 (5.0)	5.7 (6.2)	0.9 (1.1)	0.8 (0.9)	1.0 (1.0)
Caernarvon	2.3 (8.0)	1.4 (4.8)	2.7 (9.4)	4.0 (4.4)	1.9 (2.1)	4.4 (4.8)	0.9 (1.0)	0.3 (0.3)	0.8 (0.9)
Bohemia	1.7 (5.9)	0.9 (3.3)	0.9 (3.3)	3.7 (4.1)	2.0 (2.3)	2.0 (2.2)	1.1 (1.3)	0.6 (0.7)	0.6 (0.7)
Ostrica	9.9 (35.0)	4.5 (16.0)	10.7 (37.8)	21.0 (23.2)	9.8 (10.8)	21.8 (24.1)	6.2 (6.8)	2.9 (3.2)	6.0 (6.7)
Ft. St. Philip	29.9 (106)	24.7 (87.2)	37.8 (134)	56.3 (62.0)	42.9 (47.3)	68.5 (75.6)	13.5 (14.9)	8.9 (9.8)	15.4 (17.0)
Baptiste Collette	48.9 (173)	42.9 (152)	56.0 (198)	88.4 (97.4)	76.0 (83.8)	103 (114)	18.6 (20.5)	10.3 (11.3)	15.6 (17.2)
Grand Pass	51.7 (183)	46.4 (164)	58.0 (205)	51.6 (56.8)	39.3 (43.3)	60.2 (66.3)	7.9 (8.7)	4.6 (5.1)	7.1 (7.9)
West Bay	32.3 (120)	28.5 (95.1)	36.8 (130)	32.7 (36.0)	24.1 (26.6)	39.0 (43.0)	3.8 (4.2)	2.1 (2.3)	2.6 (2.9)
Small Cuts	10.4 (36.9)	10.3 (36.2)	10.6 (37.4)	10.1 (11.2)	8.7 (9.6)	11.9 (13.1)	1.1 (1.3)	0.6 (0.7)	1.1 (1.3)
Cubit's Gap	51.2 (181)	43.6 (154)	60.3 (213)	38.6 (42.5)	26.3 (29.3)	44.5 (49.0)	1.6 (1.8)	0.9 (1.0)	1.1 (1.2)
Southwest Pass	161 (570)	137 (484)	190 (671)	212 (234)	160 (177)	251 (276)	16.5 (18.2)	8.9 (9.8)	10.1 (11.1)
South Pass	47.0 (166)	42.0 (148)	52.9 (187)	46.9 (51.7)	37.9 (41.8)	55.0 (60.7)	3.2 (3.5)	1.7 (1.9)	2.0 (2.2)
Pass a Loutre	42.5 (150)	39.3 (139)	46.2 (163)	47.8 (52.7)	39.1 (43.1)	55.9 (61.7)	3.1 (3.4)	1.7 (1.9)	2.0 (2.2)

10. Figure Captions

Figure 1. (a) Map of the lower Mississippi and Atchafalaya Rivers and the location of monitoring stations discussed in the present study. Three diversion locations discussed in the text are also shown at Bonnet Carre (BC), Davis Pond (DP) and Caernarvon (CA). (b) NASA Space Shuttle visual band photograph of the lowermost Mississippi River taken on May 19, 2009 and showing the location of natural and man-made exits for water and sediment exits from the channel. Also shown are location of four river cross-sections discussed in the text at river kilometer (RM) 24, 9.5, 5.2 and 2.6.

Figure 2. Average annual water discharge (in 10^{11} ft^3/y) for the three flood years (2008-2010) discussed in the present study for U.S. Geological Survey and U.S. Army Corps of Engineers monitoring stations in the lower Mississippi and Atchafalaya Rivers. Input from the Red River is calculated indirectly (Simmesport water minus water discharge through the Old River Structures). Integrated water loss for the three diversion channel exits between Baton Rouge and Belle Chasse are also shown.

Figure 3. Annual water discharge (in 10^{11} ft^3/y) values for each of the three flood years (2008-2010) in Figure 2.

Figure 4. Average annual total sediment discharge (in 10^6 short tons/y) for the three flood years (2008-2010) discussed in the present study for U.S. Geological Survey and U.S. Army Corps of Engineers monitoring stations in the lower Mississippi and Atchafalaya Rivers. Input from the Red River is calculated indirectly (Simmesport minus sediment discharge through the Old River Structures). Integrated sediment loss for the three diversion channel exits between Baton Rouge and Belle Chasse are also shown. Arrows within boxes (white down = loss from suspended load, black up = addition to sediment load) indicate changes in suspended sediment load (in 10^6 tons/y) between stations separated into sand (>62.5 µm) and mud (<62.5 µm) fractions. Net basin sediment storages for the lowermost Mississippi (load differential between Tarbert Landing and Belle Chasse) and Atchafalaya (load differential between Simmesport and Morgan City+Wax Lake) are also shown.

Figure 5. Annual total mud discharge (in 10^6 short tons/y) for each the three flood years (2008-2010) shown in Figure 4.

Figure 6. Annual total sand discharge (in 10^6 short tons/y) for each the three flood years (2008-2010) shown in Figure 4.

Figure 7. Depth-integrated isokinetic sampler, boat-based measurements of suspended sediment load (total in upper plots, sand load in lower) collected by the U.S. Geological Survey at two lowermost stations in the Mississippi (Belle Chasse) and Atchafalaya (Morgan City) rivers. The 2008-2010 data points are those utilized to calculate the suspended loads reported in the present study. These are compared with data collected at the same site in previous decades (1978-87 and 1988-97) using the same methodology.

Figure 8. Mud (<62.5 µm; upper plots) and sand (lower plots) suspended sediment loads at four Mississippi (left plots) and four Atchafalaya (right plots) monitoring stations in flood years 2008-2010 for low, transitional and high water discharge phases of the hydrograph. Figures are calculated in tons/d utilizing mean (and standard deviation error bars) values for all days over the three years that were within the flow range. Flow divisions are discussed in the text.

Figure 9. Average annual water discharge (in 10^{11} ft^3/y) for the three flood years (2008-2010) discussed in the present study for natural and man-made water exits from the Mississippi River below Baton Rouge, Louisiana. Locations of these exits are shown in Figure 1.

Figure 10. Annual water discharge (in 10^{11} ft^3/y) for each the three flood years (2008-2010) shown in Figure 9.

Figure 11. Average annual suspended sediment discharge (total suspended load at left, sand load at right (in 10^6 short tons/y) for the three flood years (2008-2010) discussed in the present study for natural and man-made water exits from the Mississippi River below Baton Rouge, Louisiana. Also shown are annual channel storage rates (in 10^6 short tons/y) for three sub-reaches (A-C) of the channel between Belle Chasse and river mile (RM) 2.6. Rates were calculated bathymetric changes derived from decadal navigational surveys as described in the text.

Figure 12. Annual suspended mud discharge (in 10^6 short tons/y) for each of the three flood years (2008-2010) shown in Figure 11.

Figure 13. Annual suspended sand discharge (in 10^6 short tons/y) for each of the three flood years (2008-2010) shown in Figure 11.

Figure 14. Annual channel storage rates (in 10^6 short tons/y) divided into eight sub-reaches of the Mississippi River channel between Belle Chasse and river mile (RM) 2.6. Rates were calculated bathymetric changes derived from decadal navigational surveys as described in the text. Also plotted are the sub-reach locations of major water and sediment exits from the river included in the present study.

Figure 15. Total suspended sediment load in the Mississippi River at Baton Rouge (upper plot) and Belle Chasse, Louisiana (lower plot) for flood years 2008-2010 as measured by a) boat-based isokinetic sampler, b) optical backscatterance (turbidity) sensor, and c) calculated ratings curve from the isokinetic measurements and daily water discharges. The optical backscatterance sensor (OBS) records on the Belle Chasse plot include one sensor at the Belle Chasse site and another at river mile 24 (location on Fig. 1b). Arrows indicate late June-early July increases in sediment load interpreted in the text as being due to an increased Missouri River tributary contribution.

Figure 16. Percentages of total latitudinal water flow at Old River (Tarbert Landing + Simmesport stations) averaged over flood years 2008-2010 and apportioned into each storage component and water exit (in terms of basin it enters) from the channel. Positive values reflect additions to the water budget. Water exiting the deepwater passes was calculated using the

collective loss from the passes and storage (32.1%), and using a ratings curve derived from the USACE measurements at each of the deepwater pass entrances (45.8%).

Figure 17. Percentages of mud in suspension relative to the total flux at the latitude of Old River (Tarbert Landing + Simmesport stations) averaged over flood years 2008-2010 and apportioned into each sediment storage component and water exit (in terms of basin it enters) from the channel. Mud in suspension exiting the deepwater passes was calculated using the collective loss from the passes and storage (31.8%), and using a sediment ratings curve derived from the water USACE measurements at each of the deepwater pass entrances combined with sediment loads calculated at RM 2.6 (19.9%).

Figure 18. Percentages of sand in suspension relative to the total flux at the latitude of Old River (Tarbert Landing + Simmesport stations) averaged over flood years 2008-2010 and apportioned into each sediment storage component and water exit (in terms of basin it enters) from the channel. Sand in suspension exiting the deepwater passes was calculated using the collective loss from the passes and storage (5.7%), and using a sediment ratings curve derived from the water USACE measurements at each of the deepwater pass entrances combined with sediment loads calculated at RM 2.6 (1.9%).

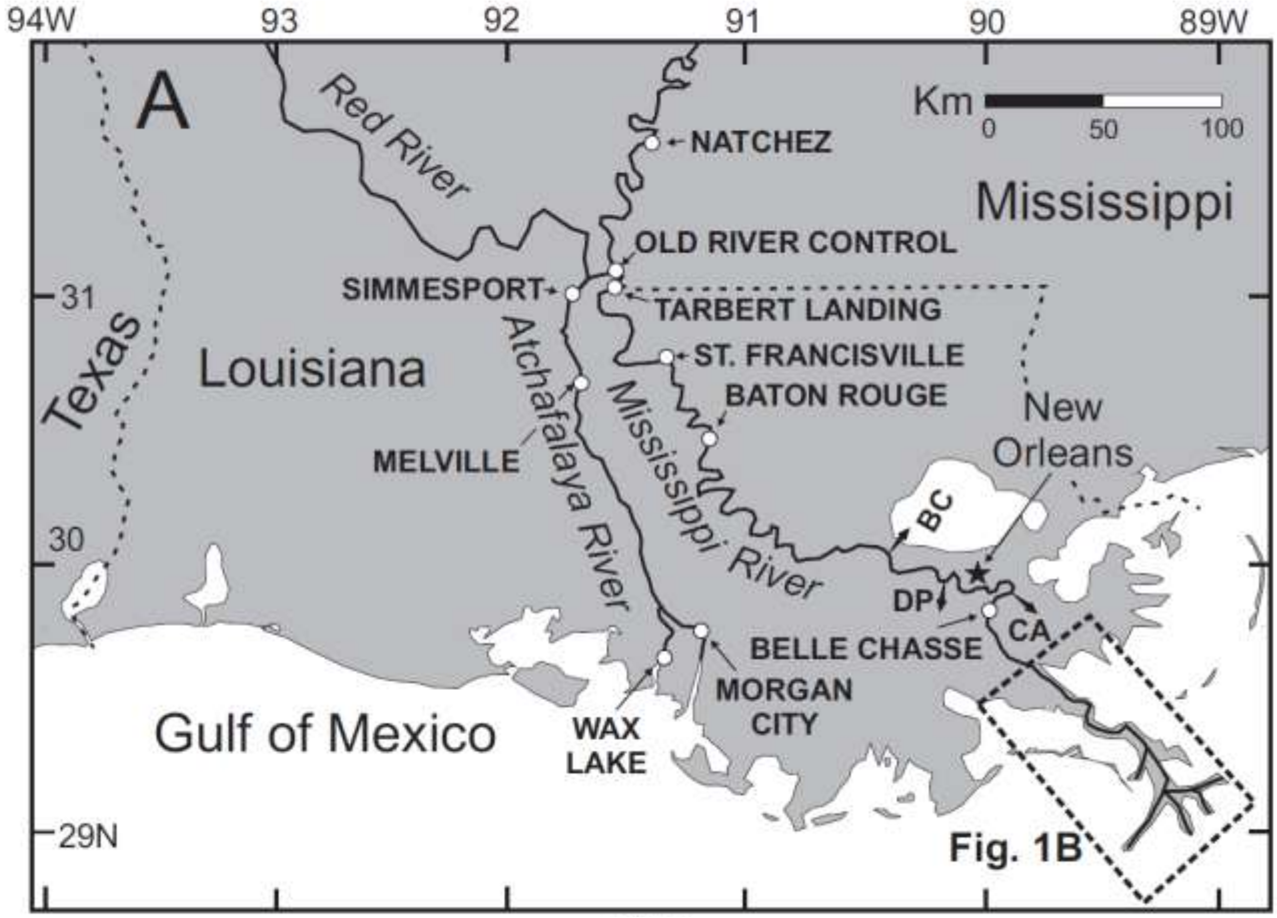
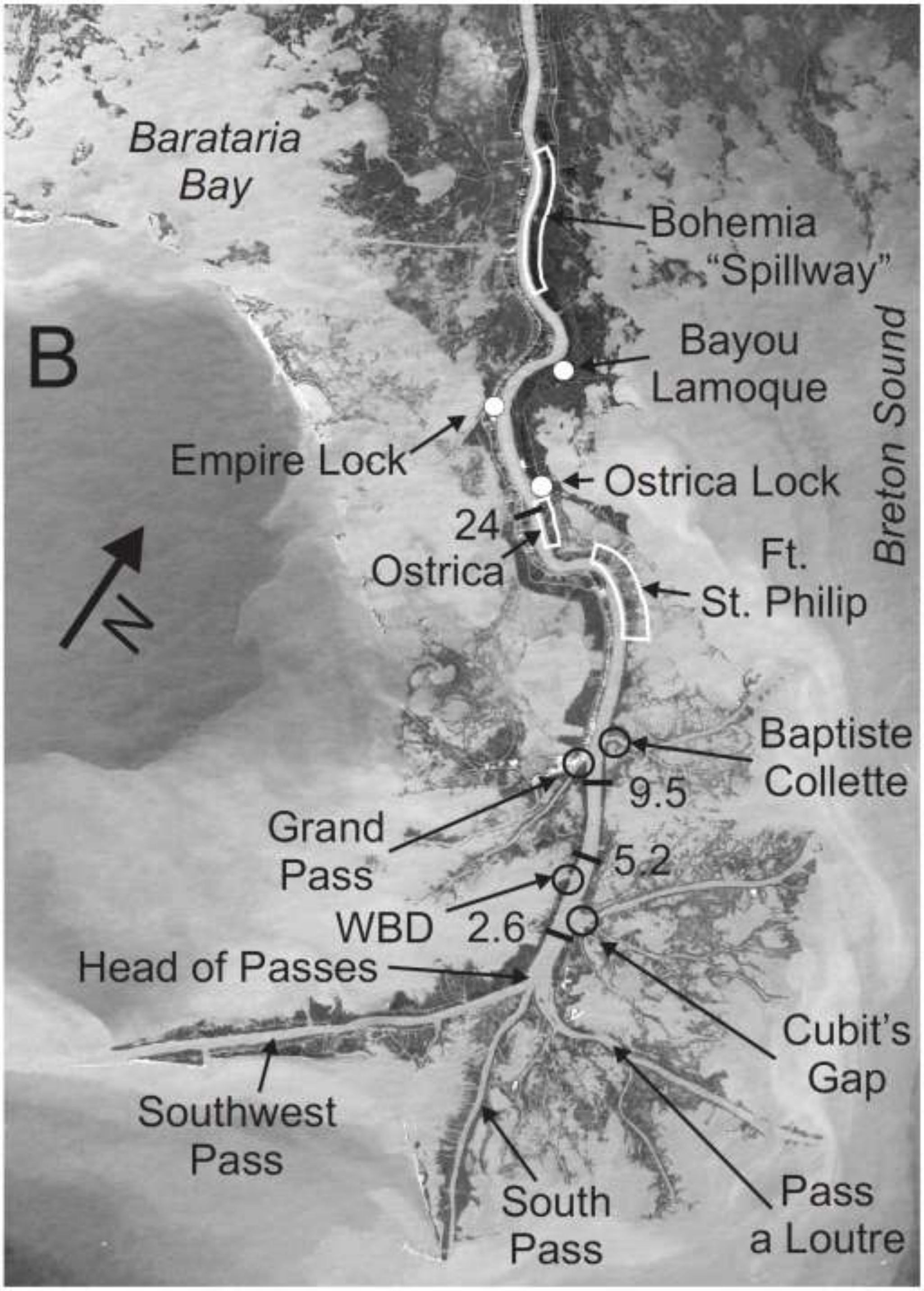

94W
93
92
91
90
89W
A
Km
0
50
100
Red River
NATCHEZ
Mississippi
OLD RIVER CONTROL
SIMMESPORT
TARBERT LANDING
31
Texas
Louisiana
Atchafalaya River
ST. FRANCISVILLE
BATON ROUGE
New
Orleans
MELVILLE
Mississippi River
BC
30
DP
CA
BELLE CHASSE
MORGAN
CITY
Gulf of Mexico
WAX
LAKE
29N
Fig. 1B

Figure 1A.



Barataria
Bay
Bohemia
"Spillway"
B
Bayou
Lamoque
Breton Sound
Empire Lock
Ostrica Lock
24
Ostrica
Ft.
St. Philip
N
Baptiste
Collette
9.5
Grand
Pass
5.2
WBD
2.6
Head of Passes
Cubit's
Gap
Southwest
Pass
South
Pass
Pass
a Loutre

Figure 1B.

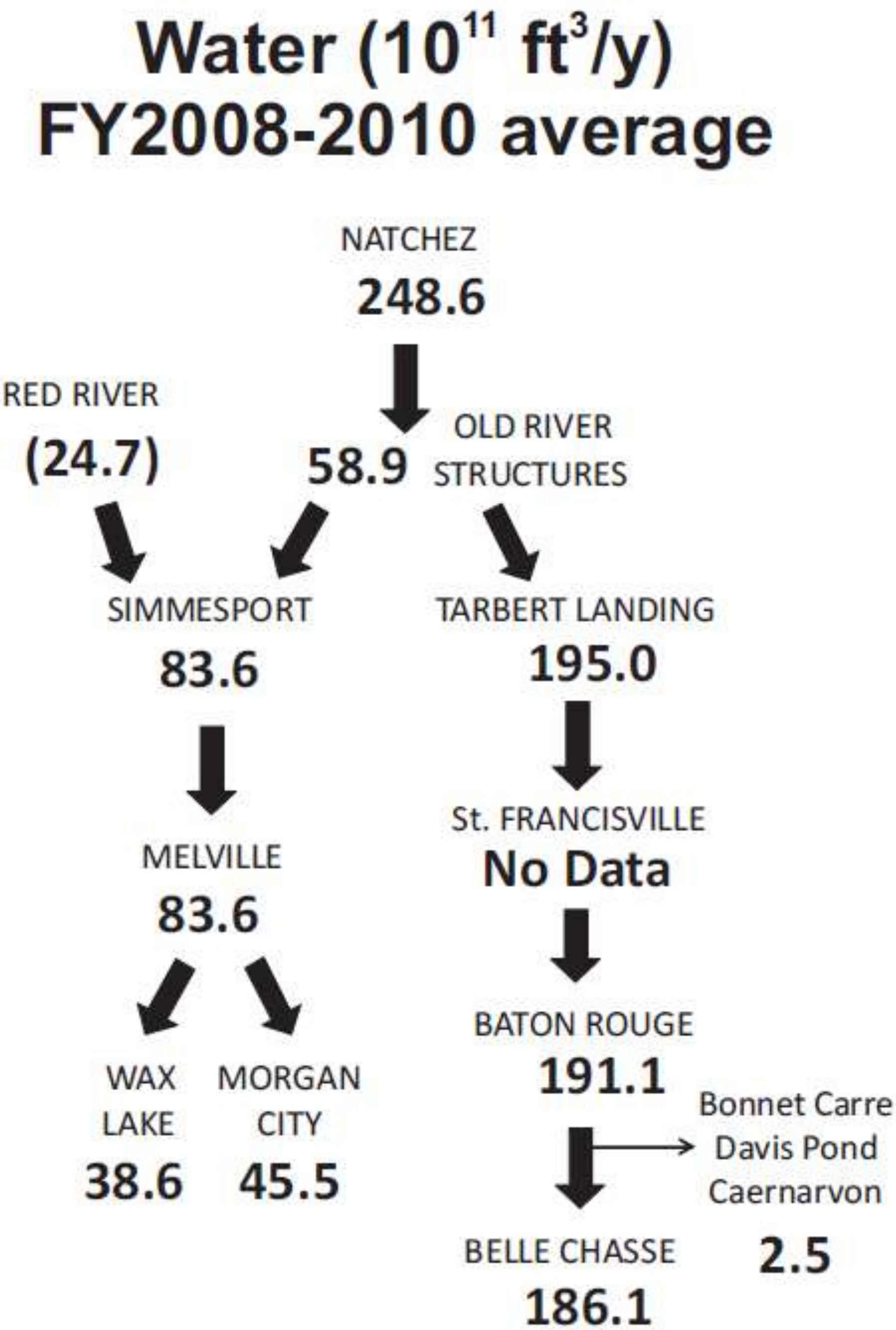

Water (10^{11} ft^3/y)
FY2008-2010 average
NATCHEZ
248.6
RED RIVER
(24.7)
58.9
OLD RIVER
STRUCTURES
SIMMESPORT
83.6
TARBERT LANDING
195.0
MELVILLE
83.6
St. FRANCISVILLE
No Data
BATON ROUGE
191.1
WAX
LAKE
38.6
MORGAN
CITY
45.5
Bonnet Carre
Davis Pond
Caernarvon
2.5
BELLE CHASSE
186.1

Figure 2.

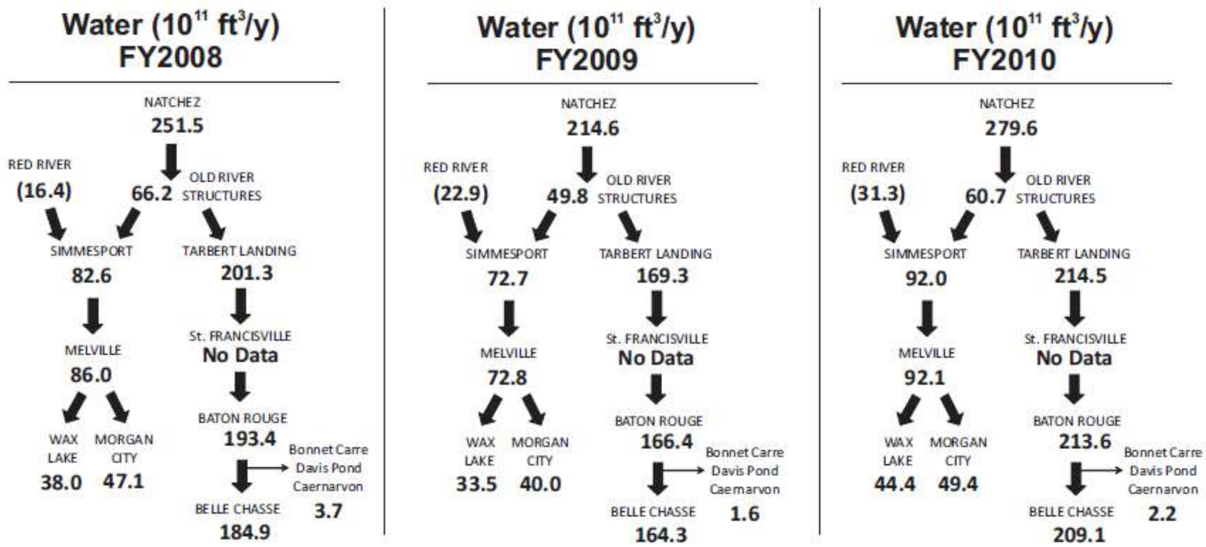

Water (10^{11} ft^3/y)
FY2008
NATCHEZ
251.5
RED RIVER
(16.4)
66.2
OLD RIVER
STRUCTURES
SIMMESPORT
82.6
TARBERT LANDING
201.3
MELVILLE
86.0
St. FRANCISVILLE
No Data
BATON ROUGE
193.4
WAX LAKE
38.0
MORGAN CITY
47.1
Bonnet Carre
Davis Pond
Caernarvon
3.7
BELLE CHASSE
184.9
Water (10^{11} ft^3/y)
FY2009
NATCHEZ
214.6
RED RIVER
(22.9)
49.8
OLD RIVER
STRUCTURES
SIMMESPORT
72.7
TARBERT LANDING
169.3
MELVILLE
72.8
St. FRANCISVILLE
No Data
BATON ROUGE
166.4
WAX LAKE
33.5
MORGAN CITY
40.0
Bonnet Carre
Davis Pond
Caernarvon
1.6
BELLE CHASSE
164.3
Water (10^{11} ft^3/y)
FY2010
NATCHEZ
279.6
RED RIVER
(31.3)
60.7
OLD RIVER
STRUCTURES
SIMMESPORT
92.0
TARBERT LANDING
214.5
MELVILLE
92.1
St. FRANCISVILLE
No Data
BATON ROUGE
213.6
WAX LAKE
44.4
MORGAN CITY
49.4
Bonnet Carre
Davis Pond
Caernarvon
2.2
BELLE CHASSE
209.1

Figure 3.

Figure 4

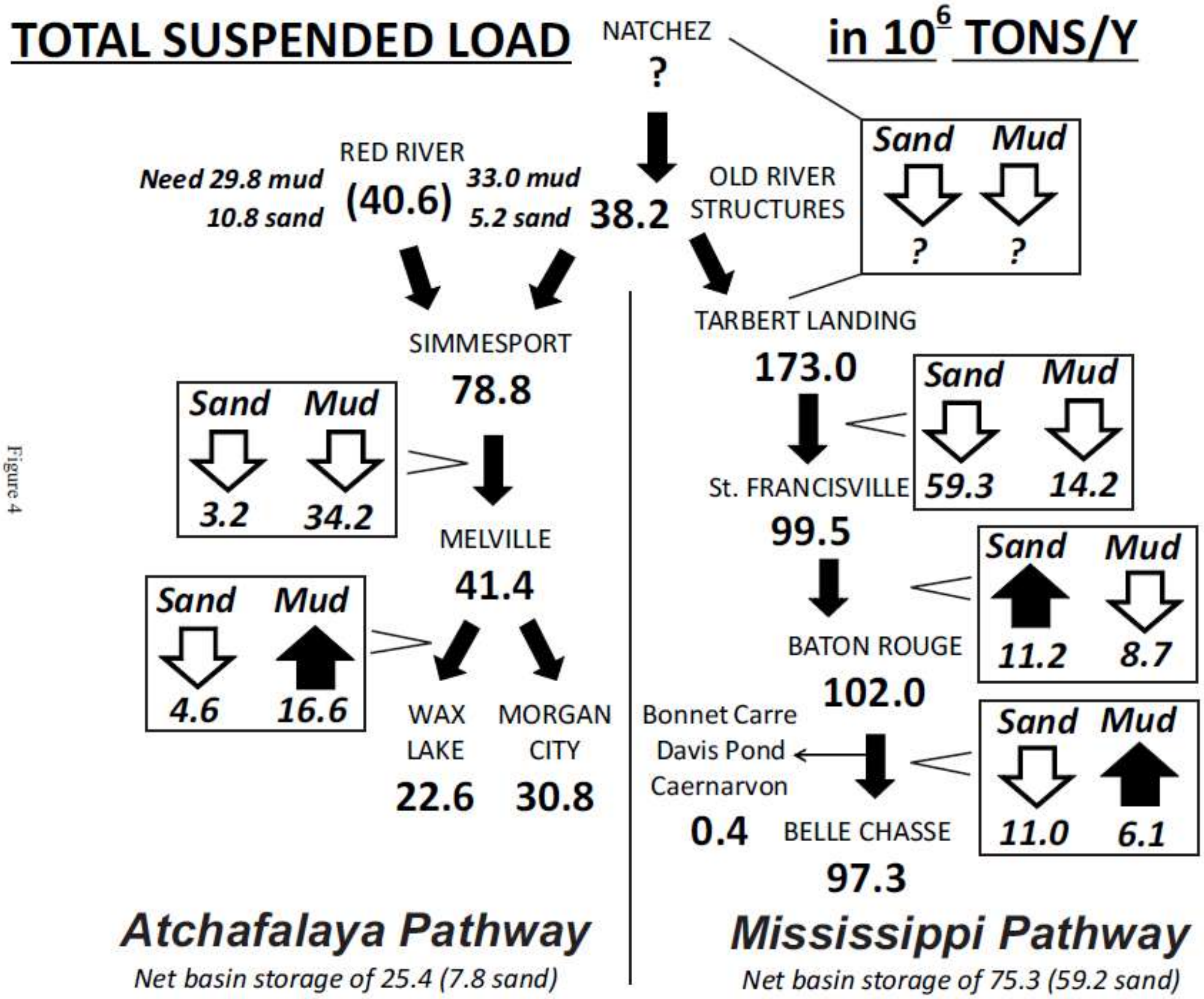
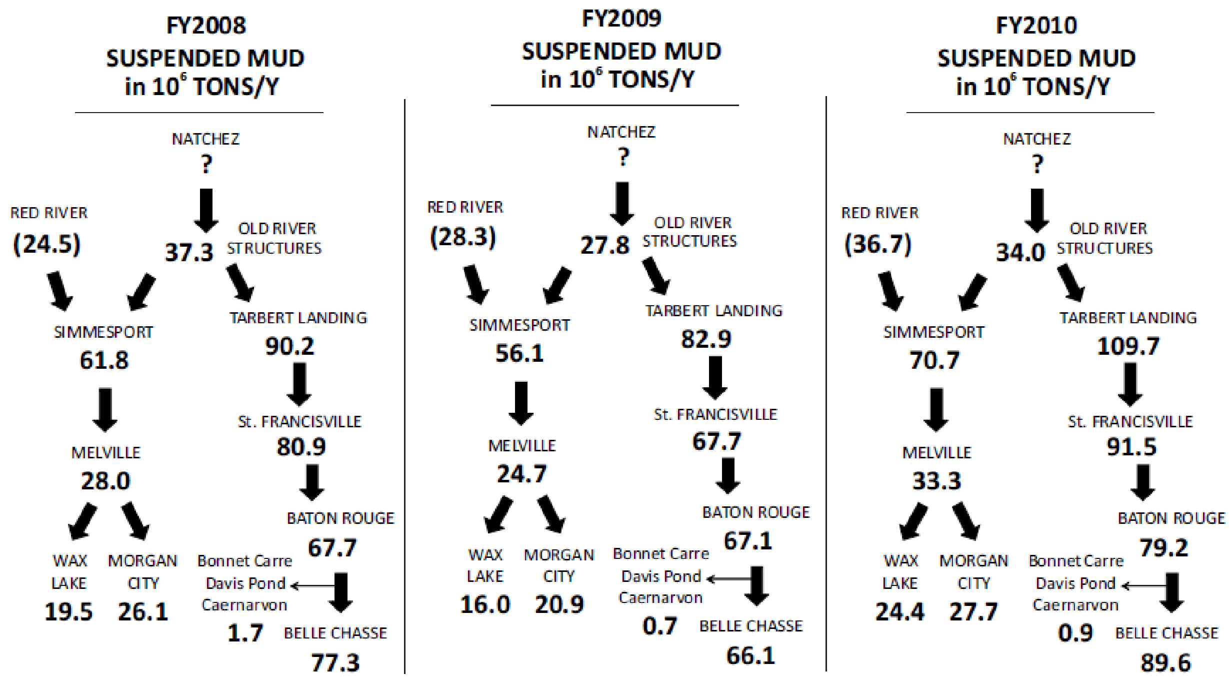
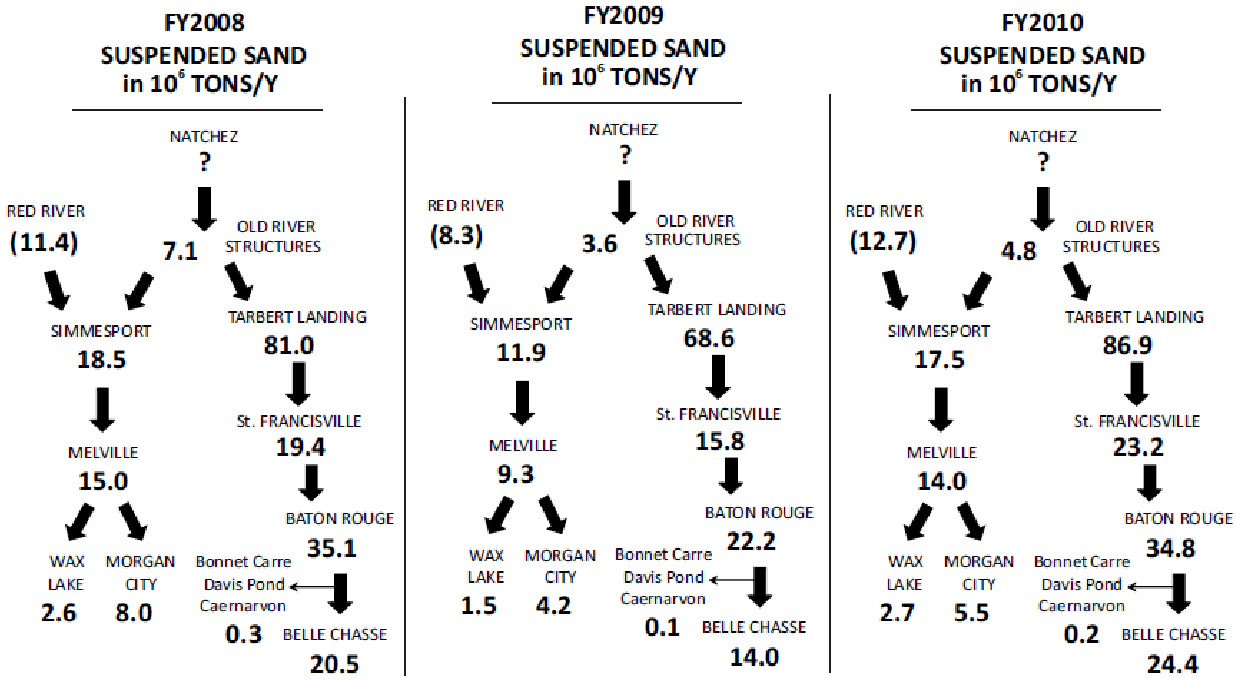


Figure 4.



FY2008
SUSPENDED MUD
in 10^6 TONS/Y
NATCHEZ
?
RED RIVER
(24.5)
37.3
OLD RIVER STRUCTURES
SIMMESPORT
61.8
TARBERT LANDING
90.2
St. FRANCISVILLE
80.9
MELVILLE
28.0
BATON ROUGE
67.7
WAX LAKE
19.5
MORGAN CITY
26.1
Bonnet Carre
Davis Pond
Caernarvon
1.7
BELLE CHASSE
77.3
FY2009
SUSPENDED MUD
in 10^6 TONS/Y
NATCHEZ
?
RED RIVER
(28.3)
27.8
OLD RIVER STRUCTURES
SIMMESPORT
56.1
TARBERT LANDING
82.9
St. FRANCISVILLE
67.7
MELVILLE
24.7
BATON ROUGE
67.1
WAX LAKE
16.0
MORGAN CITY
20.9
Bonnet Carre
Davis Pond
Caernarvon
0.7
BELLE CHASSE
66.1
FY2010
SUSPENDED MUD
in 10^6 TONS/Y
NATCHEZ
?
RED RIVER
(36.7)
34.0
OLD RIVER STRUCTURES
SIMMESPORT
70.7
TARBERT LANDING
109.7
St. FRANCISVILLE
91.5
MELVILLE
33.3
BATON ROUGE
79.2
WAX LAKE
24.4
MORGAN CITY
27.7
Bonnet Carre
Davis Pond
Caernarvon
0.9
BELLE CHASSE
89.6

Figure 5.



FY2008
SUSPENDED SAND
in 10^6 TONS/Y
NATCHEZ
?
RED RIVER
(11.4)
7.1
OLD RIVER
STRUCTURES
SIMMESPORT
18.5
TARBERT LANDING
81.0
St. FRANCISVILLE
19.4
MELVILLE
15.0
BATON ROUGE
35.1
WAX
LAKE
2.6
MORGAN
CITY
8.0
Bonnet Carre
Davis Pond
Caernarvon
0.3
BELLE CHASSE
20.5
FY2009
SUSPENDED SAND
in 10^6 TONS/Y
NATCHEZ
?
RED RIVER
(8.3)
3.6
OLD RIVER
STRUCTURES
SIMMESPORT
11.9
TARBERT LANDING
68.6
St. FRANCISVILLE
15.8
MELVILLE
9.3
BATON ROUGE
22.2
WAX
LAKE
1.5
MORGAN
CITY
4.2
Bonnet Carre
Davis Pond
Caernarvon
0.1
BELLE CHASSE
14.0
FY2010
SUSPENDED SAND
in 10^6 TONS/Y
NATCHEZ
?
RED RIVER
(12.7)
4.8
OLD RIVER
STRUCTURES
SIMMESPORT
17.5
TARBERT LANDING
86.9
St. FRANCISVILLE
23.2
MELVILLE
14.0
BATON ROUGE
34.8
WAX
LAKE
2.7
MORGAN
CITY
5.5
Bonnet Carre
Davis Pond
Caernarvon
0.2
BELLE CHASSE
24.4

Figure 6.

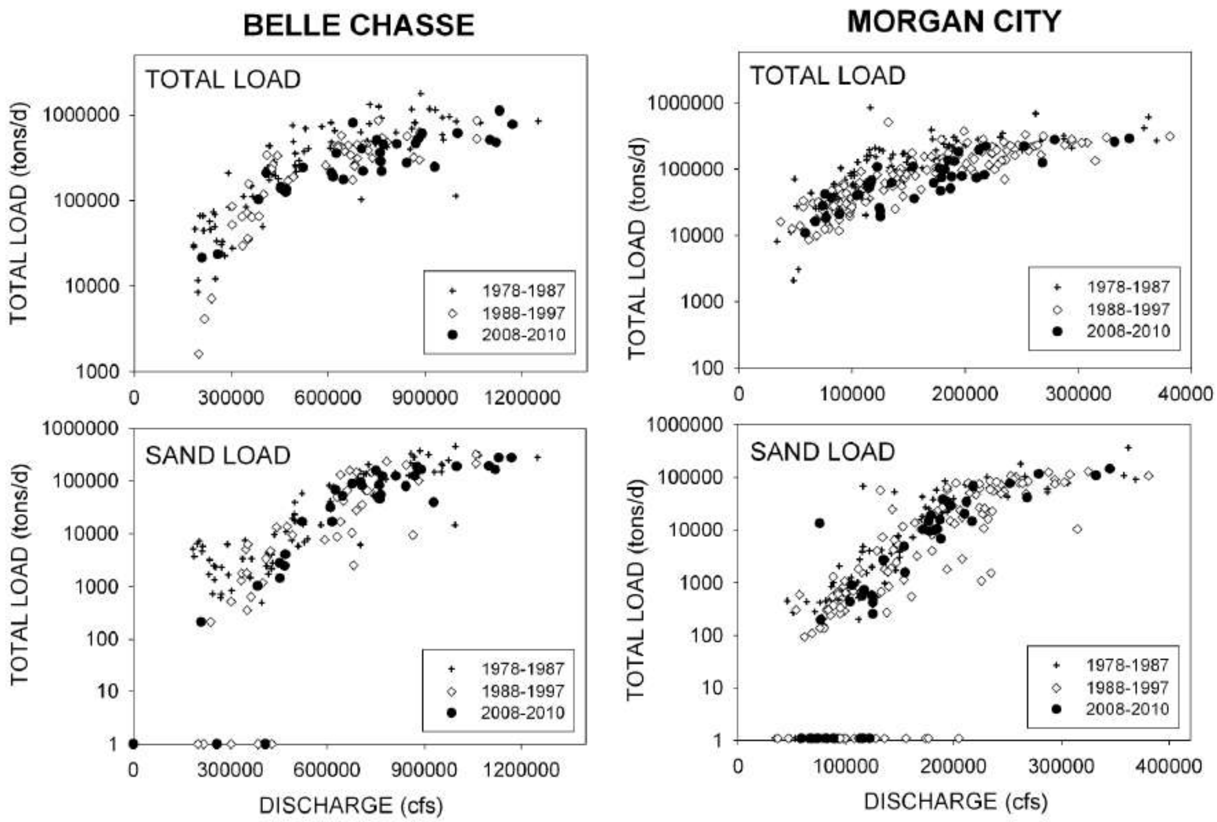
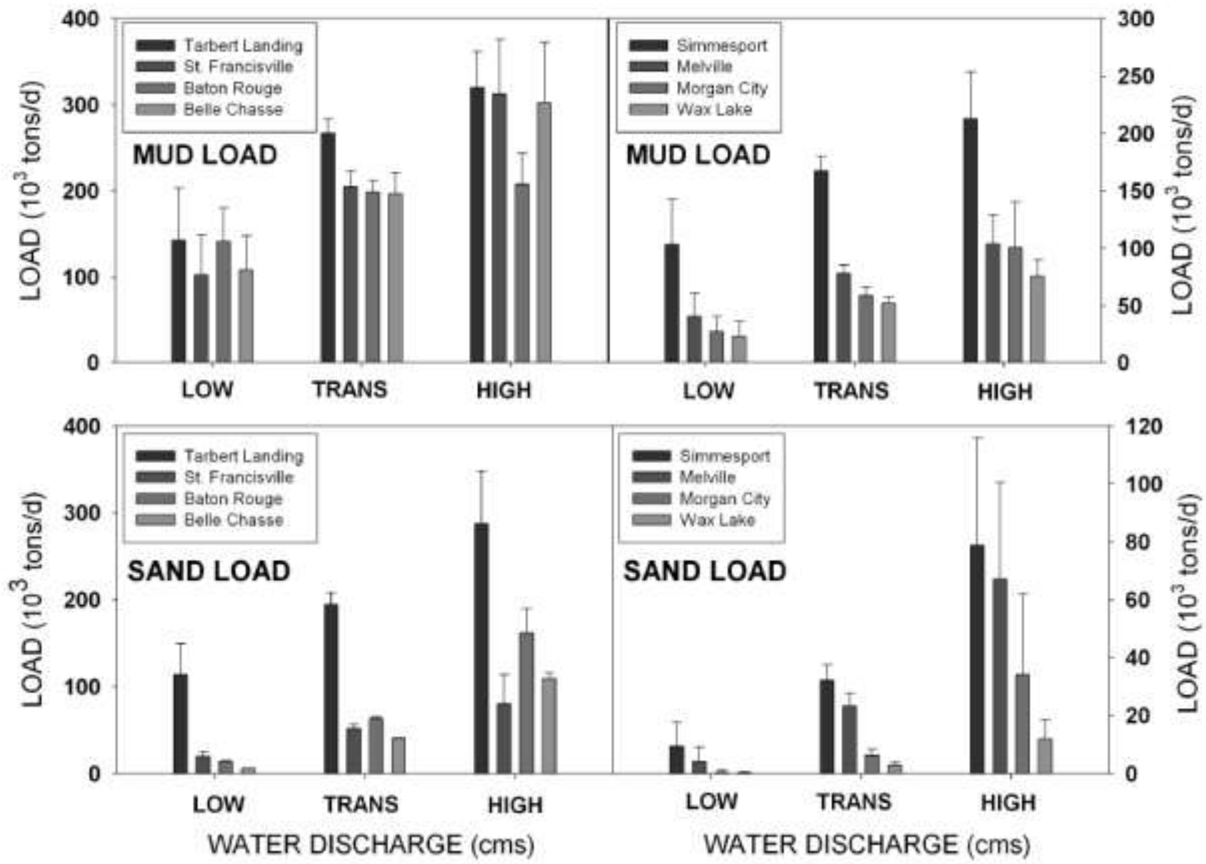

BELLE CHASSE
MORGAN CITY
TOTAL LOAD
SAND LOAD
TOTAL LOAD (tons/d)
DISCHARGE (cfs)
1978-1987
1988-1997
2008-2010
1000000
100000
10000
1000
100
10
1
0
300000
600000
900000
1200000
200000
300000
400000

Figure 7.



400
300
200
100
0
LOAD (10^3 tons/d)
Tarbert Landing
St. Francisville
Baton Rouge
Belle Chasse
MUD LOAD
LOW
TRANS
HIGH
Simmesport
Melville
Morgan City
Wax Lake
MUD LOAD
300
250
200
150
100
50
0
LOAD (10^3 tons/d)
SAND LOAD
120
100
80
60
40
20
WATER DISCHARGE (cms)

Figure 8.

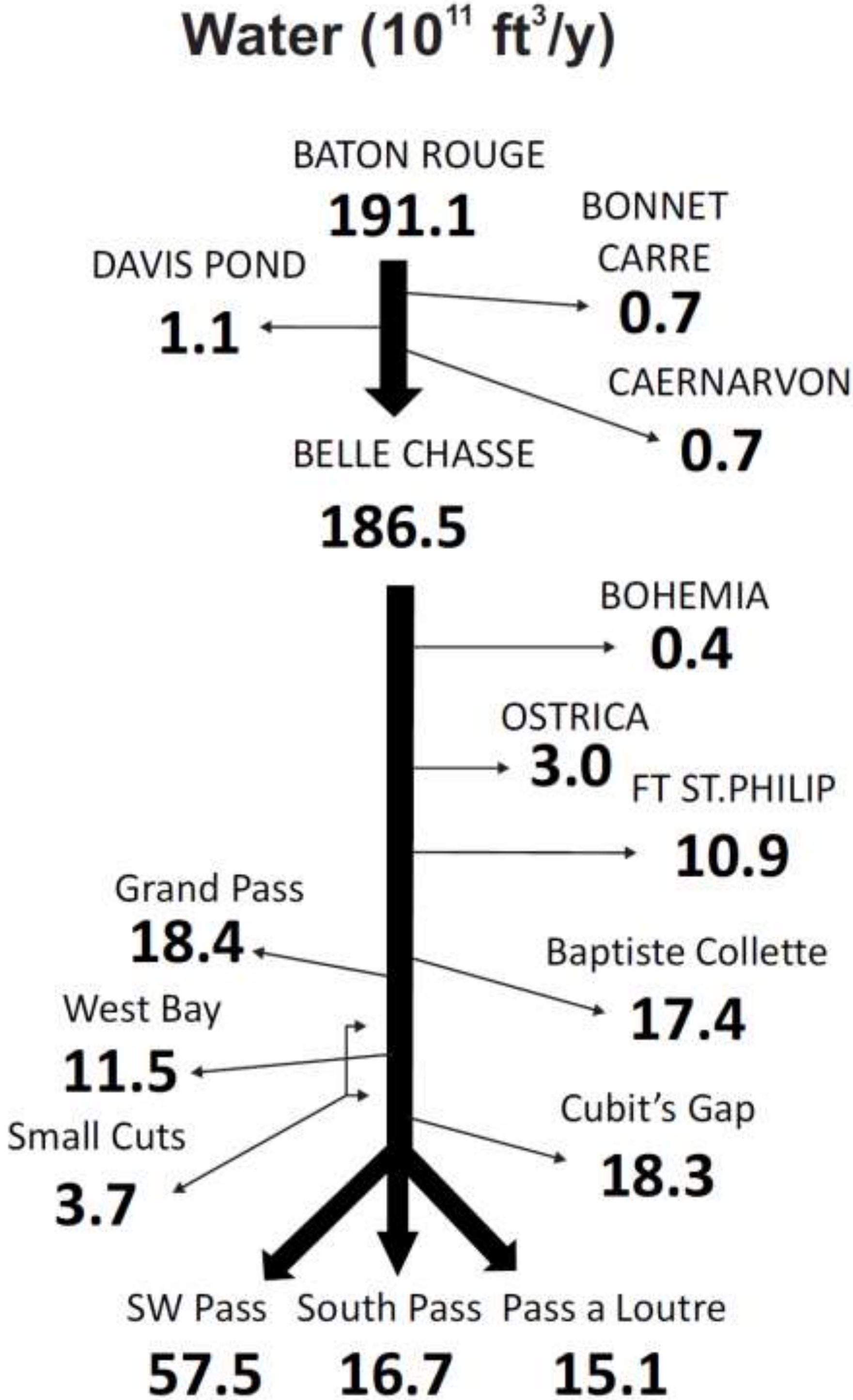
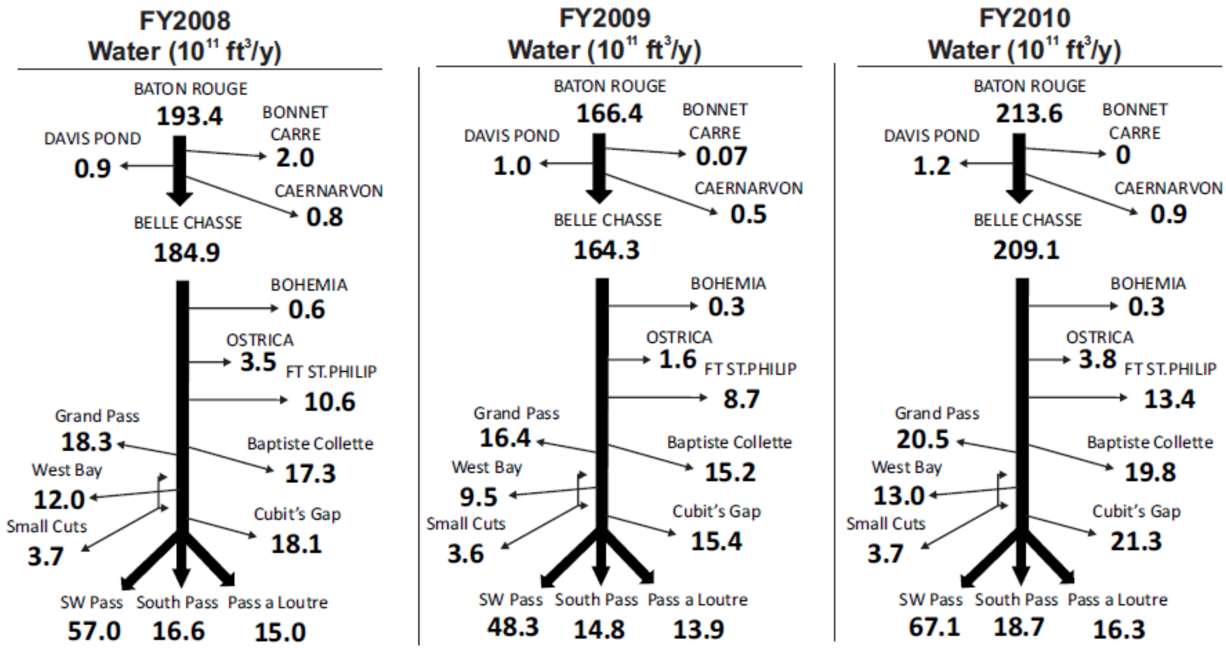
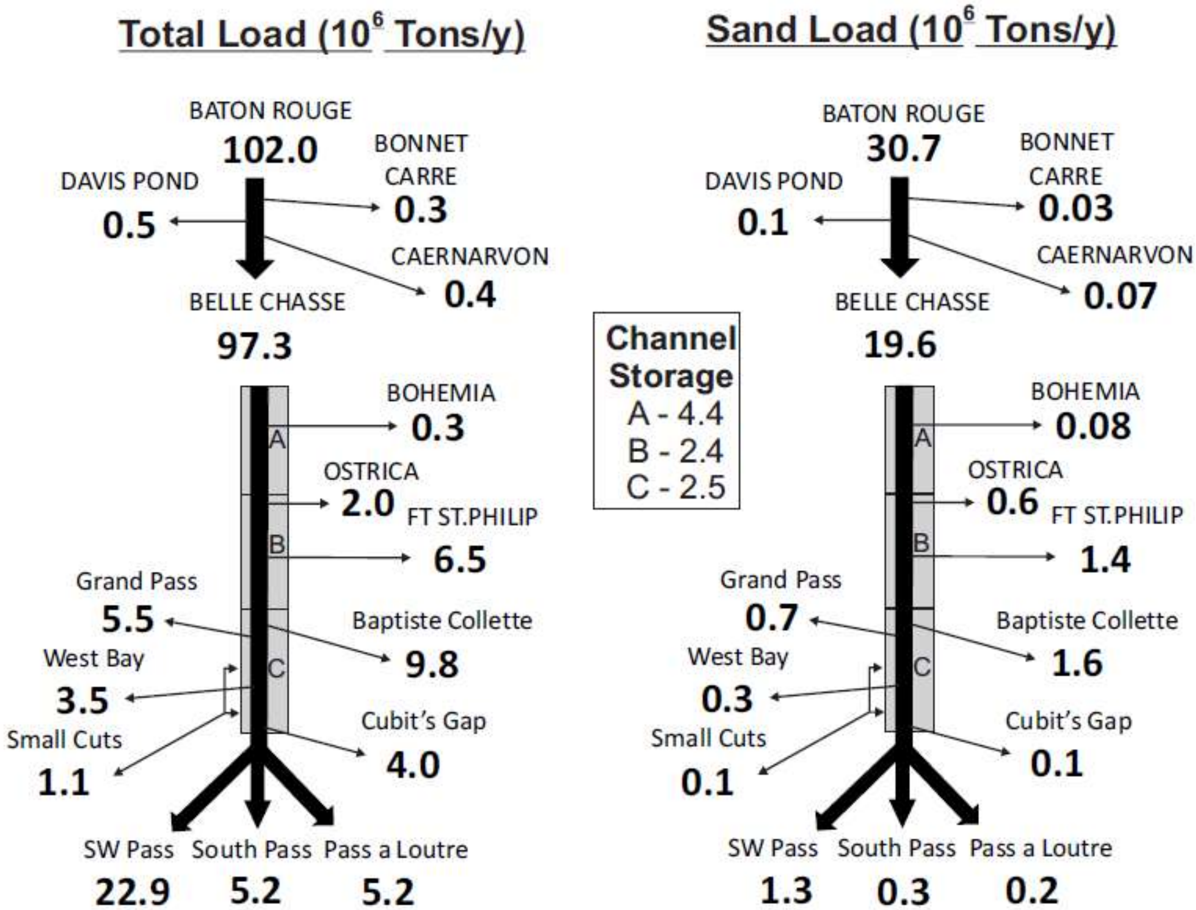

Water (10^11 ft^3/y)
BATON ROUGE
191.1
BONNET
CARRE
0.7
DAVIS POND
1.1
CAERNARVON
0.7
BELLE CHASSE
186.5
BOHEMIA
0.4
OSTRICA
3.0
FT ST.PHILIP
10.9
Grand Pass
18.4
Baptiste Collette
17.4
West Bay
11.5
Small Cuts
3.7
Cubit's Gap
18.3
SW Pass
57.5
South Pass
16.7
Pass a Loutre
15.1

Figure 9.



FY2008
Water (10^{11} ft^3/y)
BATON ROUGE
193.4
BONNET CARRE
2.0
DAVIS POND
0.9
CAERNARVON
0.8
BELLE CHASSE
184.9
BOHEMIA
0.6
OSTRICA
3.5
FT ST.PHILIP
10.6
Grand Pass
18.3
Baptiste Collette
17.3
West Bay
12.0
Small Cuts
3.7
Cubit's Gap
18.1
SW Pass
57.0
South Pass
16.6
Pass a Loutre
15.0
FY2009
Water (10^{11} ft^3/y)
BATON ROUGE
166.4
BONNET CARRE
0.07
DAVIS POND
1.0
CAERNARVON
0.5
BELLE CHASSE
164.3
BOHEMIA
0.3
OSTRICA
1.6
FT ST.PHILIP
8.7
Grand Pass
16.4
Baptiste Collette
15.2
West Bay
9.5
Small Cuts
3.6
Cubit's Gap
15.4
SW Pass
48.3
South Pass
14.8
Pass a Loutre
13.9
FY2010
Water (10^{11} ft^3/y)
BATON ROUGE
213.6
BONNET CARRE
0
DAVIS POND
1.2
CAERNARVON
0.9
BELLE CHASSE
209.1
BOHEMIA
0.3
OSTRICA
3.8
FT ST.PHILIP
13.4
Grand Pass
20.5
Baptiste Collette
19.8
West Bay
13.0
Small Cuts
3.7
Cubit's Gap
21.3
SW Pass
67.1
South Pass
18.7
Pass a Loutre
16.3

Figure 10.



Total Load (10^6 Tons/y)
BATON ROUGE
102.0
BONNET CARRE
0.3
DAVIS POND
0.5
CAERNARVON
0.4
BELLE CHASSE
97.3
BOHEMIA
0.3
A
OSTRICA
2.0
FT ST.PHILIP
6.5
B
Grand Pass
5.5
Baptiste Collette
9.8
West Bay
3.5
C
Small Cuts
1.1
Cubit's Gap
4.0
SW Pass
22.9
South Pass
5.2
Pass a Loutre
5.2
Channel Storage
A - 4.4
B - 2.4
C - 2.5
Sand Load (10^6 Tons/y)
BATON ROUGE
30.7
BONNET CARRE
0.03
DAVIS POND
0.1
CAERNARVON
0.07
BELLE CHASSE
19.6
BOHEMIA
0.08
A
OSTRICA
0.6
FT ST.PHILIP
1.4
B
Grand Pass
0.7
Baptiste Collette
1.6
West Bay
0.3
C
Small Cuts
0.1
Cubit's Gap
0.1
SW Pass
1.3
South Pass
0.3
Pass a Loutre
0.2

Figure 11.

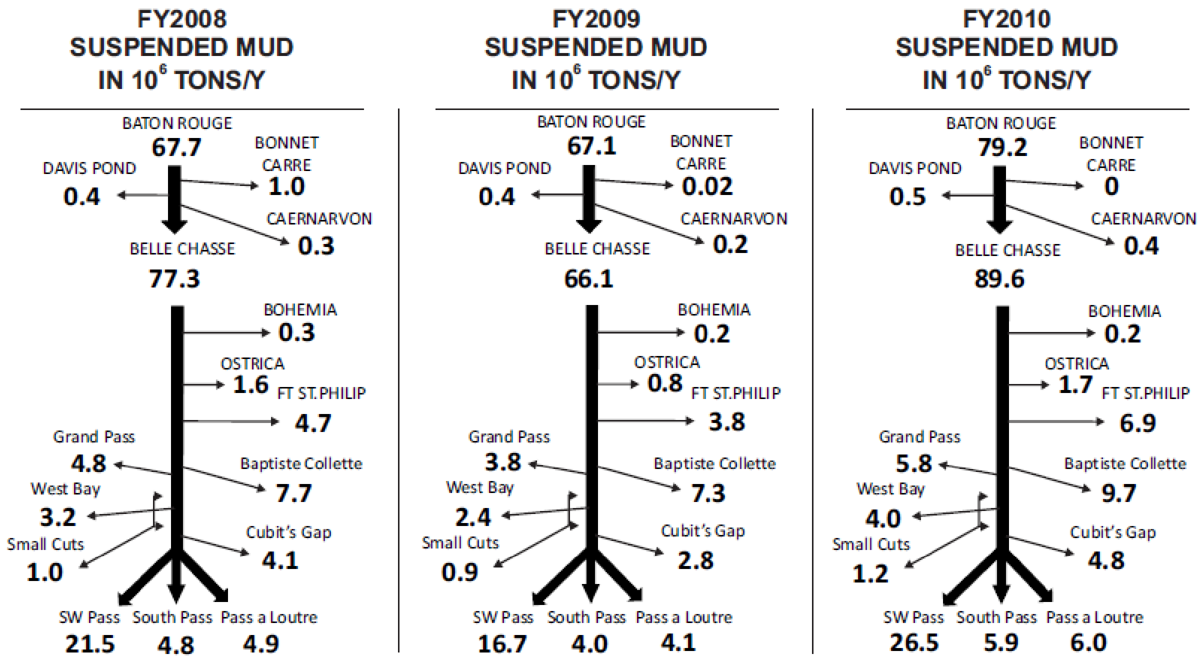

FY2008
SUSPENDED MUD
IN 10^6 TONS/Y
BATON ROUGE
67.7
BONNET
CARRE
1.0
DAVIS POND
0.4
CAERNARVON
0.3
BELLE CHASSE
77.3
BOHEMIA
0.3
OSTRICA
1.6
FT ST.PHILIP
4.7
Grand Pass
4.8
Baptiste Collette
7.7
West Bay
3.2
Small Cuts
1.0
Cubit's Gap
4.1
SW Pass
21.5
South Pass
4.8
Pass a Loutre
4.9
FY2009
SUSPENDED MUD
IN 10^6 TONS/Y
BATON ROUGE
67.1
BONNET
CARRE
0.02
DAVIS POND
0.4
CAERNARVON
0.2
BELLE CHASSE
66.1
BOHEMIA
0.2
OSTRICA
0.8
FT ST.PHILIP
3.8
Grand Pass
3.8
Baptiste Collette
7.3
West Bay
2.4
Small Cuts
0.9
Cubit's Gap
2.8
SW Pass
16.7
South Pass
4.0
Pass a Loutre
4.1
FY2010
SUSPENDED MUD
IN 10^6 TONS/Y
BATON ROUGE
79.2
BONNET
CARRE
0
DAVIS POND
0.5
CAERNARVON
0.4
BELLE CHASSE
89.6
BOHEMIA
0.2
OSTRICA
1.7
FT ST.PHILIP
6.9
Grand Pass
5.8
Baptiste Collette
9.7
West Bay
4.0
Small Cuts
1.2
Cubit's Gap
4.8
SW Pass
26.5
South Pass
5.9
Pass a Loutre
6.0

Figure 12.

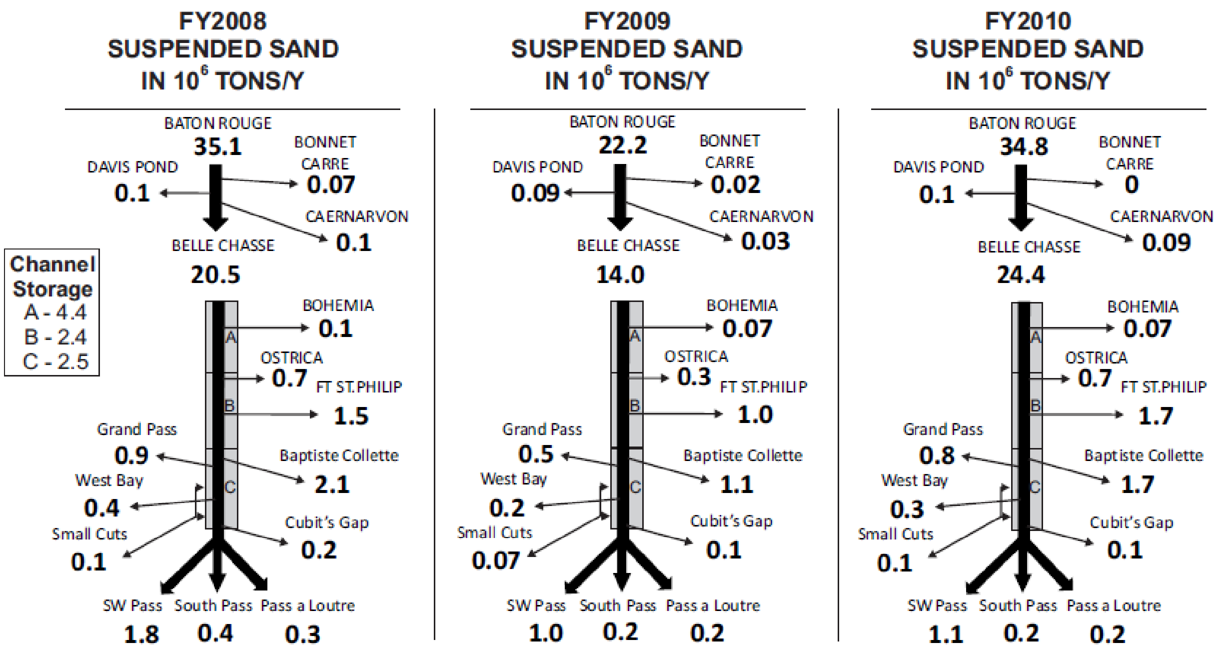
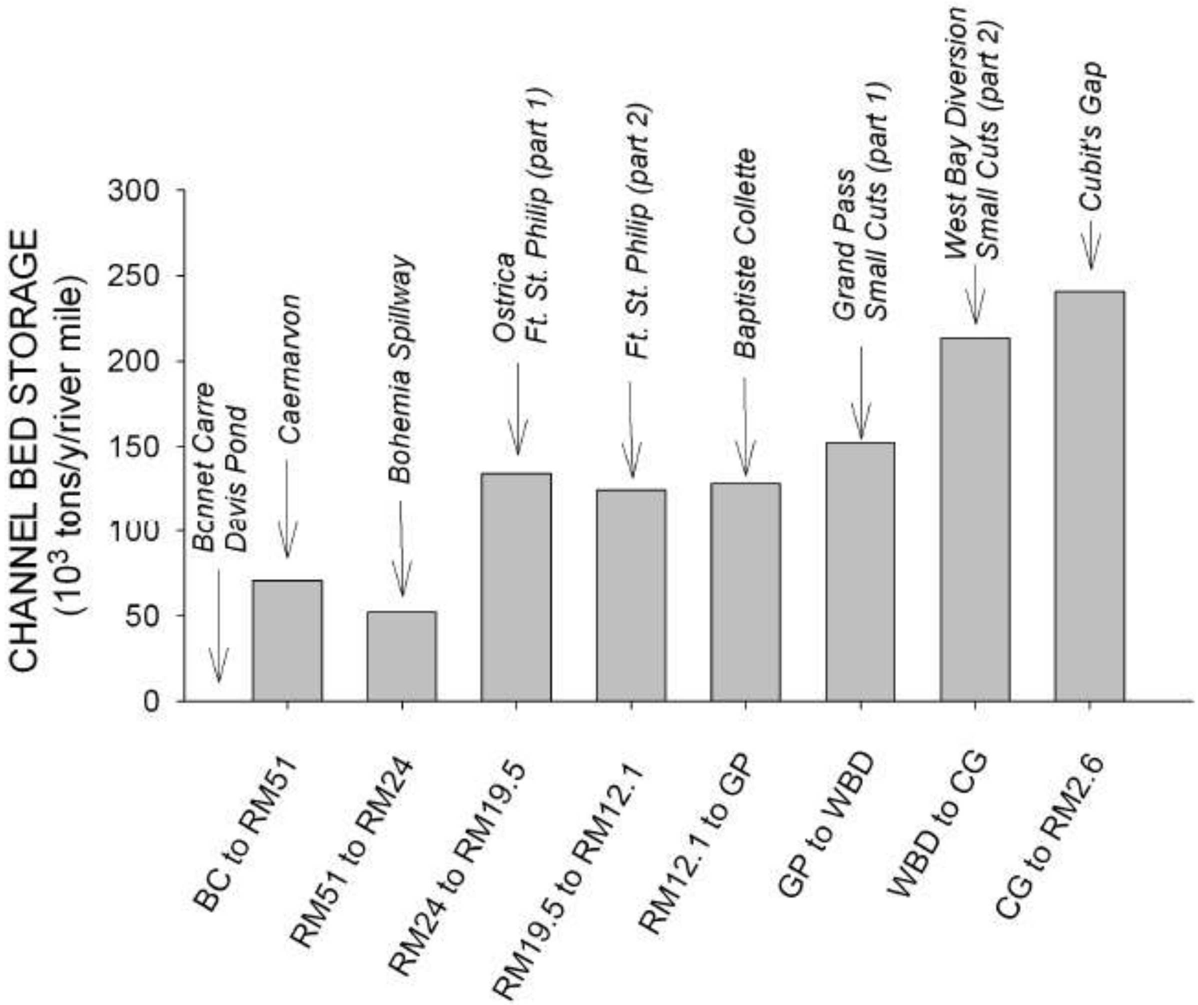
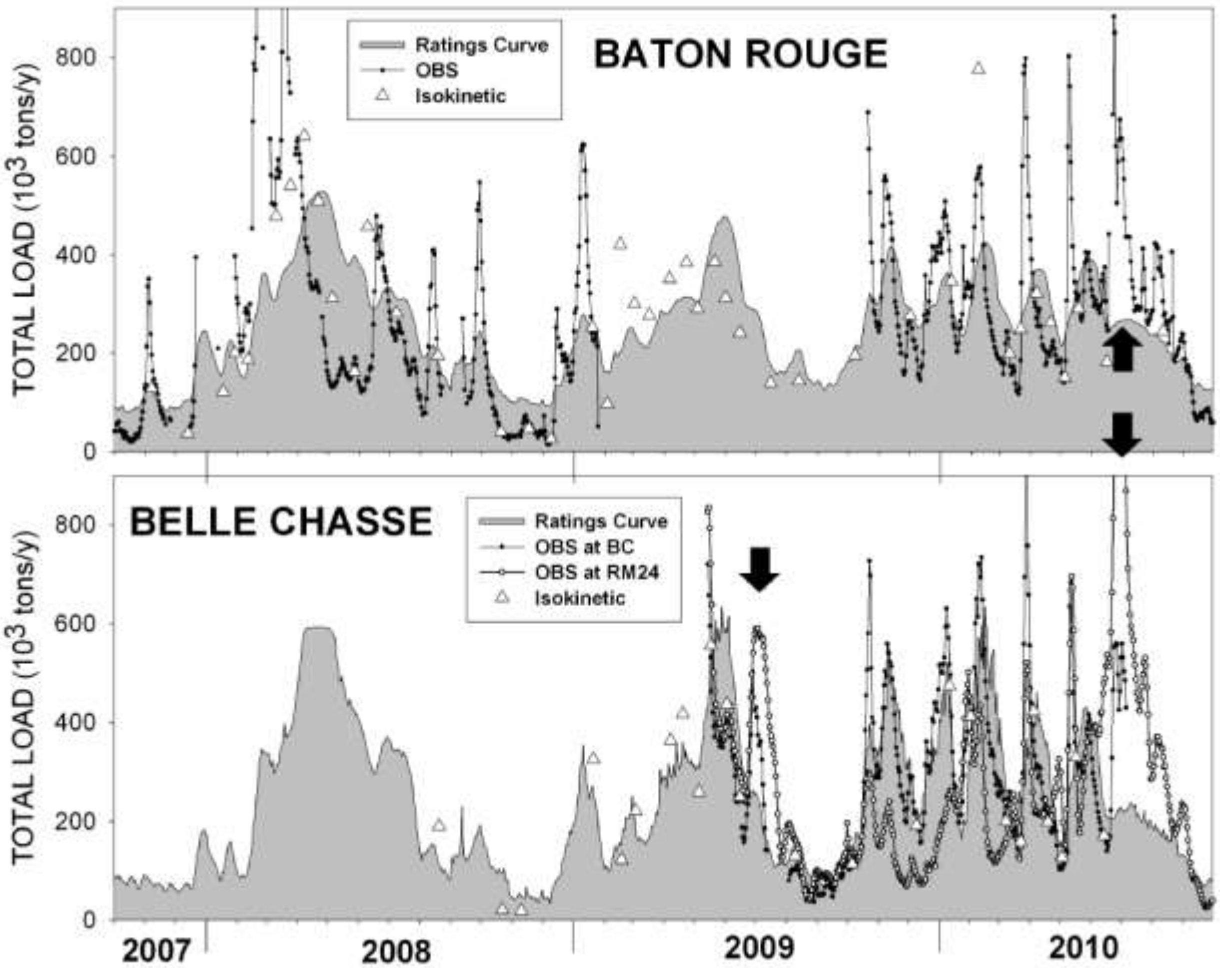

FY2008
SUSPENDED SAND
IN 10⁶ TONS/Y
BATON ROUGE
35.1
BONNET CARRE
0.07
DAVIS POND
0.1
CAERNARVON
0.1
BELLE CHASSE
20.5
Channel Storage
A - 4.4
B - 2.4
C - 2.5
BOHEMIA
0.1
OSTRICA
0.7
FT ST.PHILIP
1.5
Grand Pass
0.9
Baptiste Collette
2.1
West Bay
0.4
Small Cuts
0.1
Cubit's Gap
0.2
SW Pass
1.8
South Pass
0.4
Pass a Loutre
0.3
FY2009
SUSPENDED SAND
IN 10⁶ TONS/Y
BATON ROUGE
22.2
BONNET CARRE
0.02
DAVIS POND
0.09
CAERNARVON
0.03
BELLE CHASSE
14.0
BOHEMIA
0.07
OSTRICA
0.3
FT ST.PHILIP
1.0
Grand Pass
0.5
Baptiste Collette
1.1
West Bay
0.2
Small Cuts
0.07
Cubit's Gap
0.1
SW Pass
1.0
South Pass
0.2
Pass a Loutre
0.2
FY2010
SUSPENDED SAND
IN 10⁶ TONS/Y
BATON ROUGE
34.8
BONNET CARRE
0
DAVIS POND
0.1
CAERNARVON
0.09
BELLE CHASSE
24.4
BOHEMIA
0.07
OSTRICA
0.7
FT ST.PHILIP
1.7
Grand Pass
0.8
Baptiste Collette
1.7
West Bay
0.3
Small Cuts
0.1
Cubit's Gap
0.1
SW Pass
1.1
South Pass
0.2
Pass a Loutre
0.2

Figure 13.



CHANNEL BED STORAGE
(10³ tons/y/river mile)
300
250
200
150
100
50
0
Bcnnet Carre
Davis Pond
Caernarvon
Bohemia Spillway
Ostrica
Ft. St. Philip (part 1)
Ft. St. Philip (part 2)
Baptiste Collette
Grand Pass
Small Cuts (part 1)
West Bay Diversion
Small Cuts (part 2)
Cubit's Gap
BC to RM51
RM51 to RM24
RM24 to RM19.5
RM19.5 to RM12.1
RM12.1 to GP
GP to WBD
WBD to CG
CG to RM2.6

Figure 14.



BATON ROUGE
Ratings Curve
OBS
Isokinetic
TOTAL LOAD (10^3 tons/y)
800
600
400
200
0
BELLE CHASSE
Ratings Curve
OBS at BC
OBS at RM24
Isokinetic
TOTAL LOAD (10^3 tons/y)
800
600
400
200
0
2007
2008
2009
2010

Figure 15.

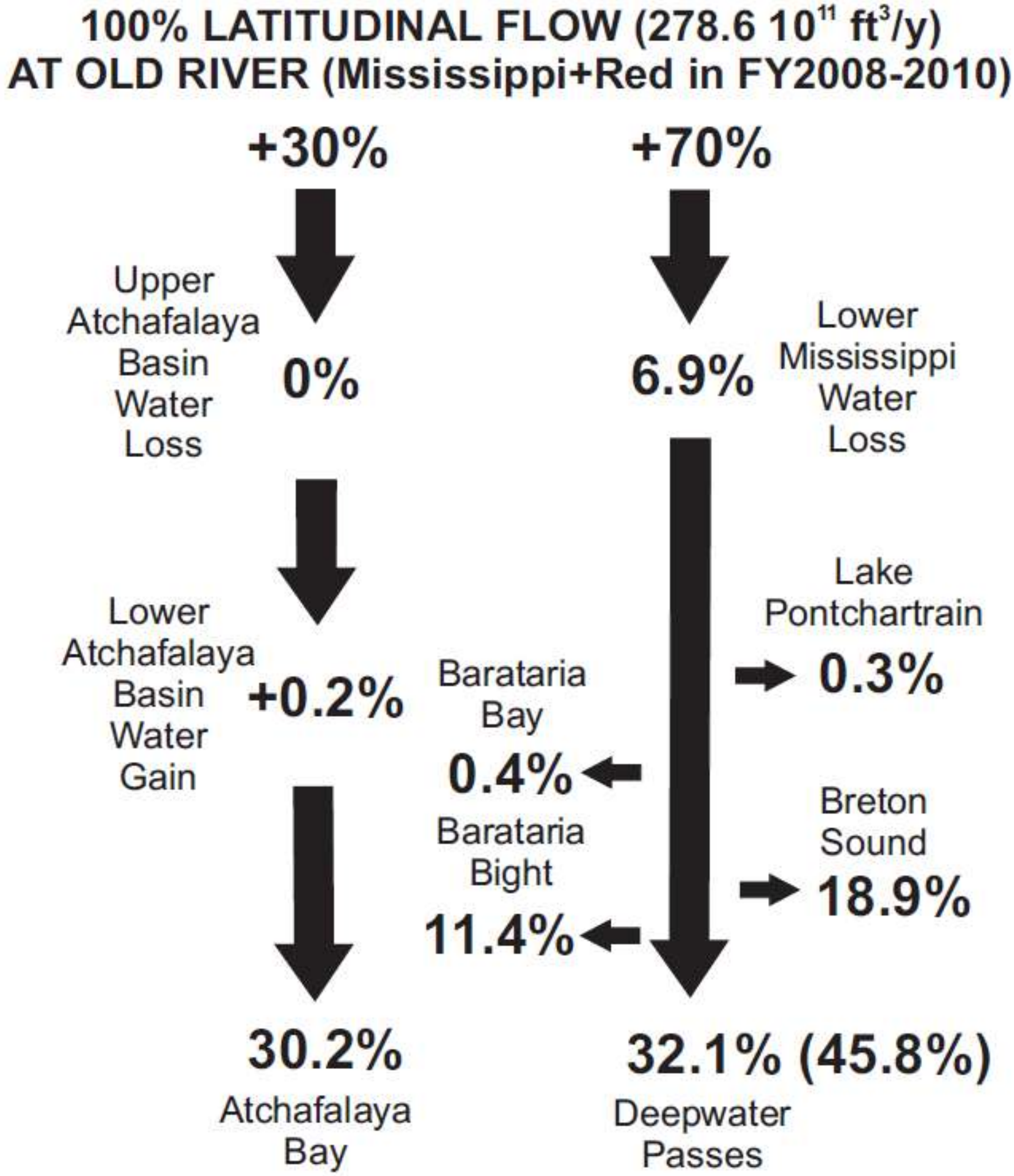

100% LATITUDINAL FLOW (278.6 10¹¹ ft³/y)
AT OLD RIVER (Mississippi+Red in FY2008-2010)
+30%
+70%
Upper Atchafalaya Basin Water Loss
0%
6.9%
Lower Mississippi Water Loss
Lake Pontchartrain
0.3%
Lower Atchafalaya Basin Water Gain
+0.2%
Barataria Bay
0.4%
Breton Sound
18.9%
Barataria Bight
11.4%
30.2%
Atchafalaya Bay
32.1% (45.8%)
Deepwater Passes

Figure 16.

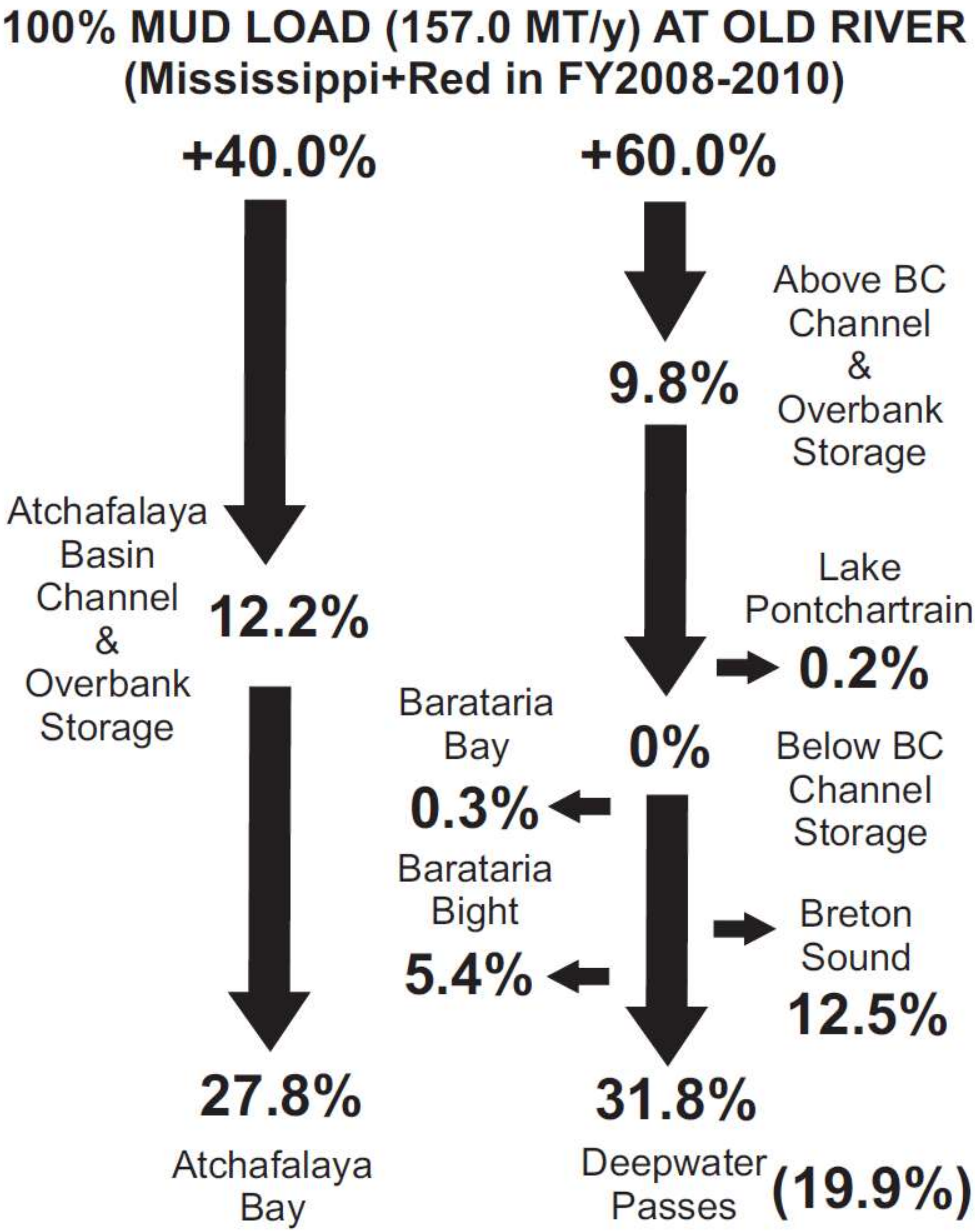

100% MUD LOAD (157.0 MT/y) AT OLD RIVER
(Mississippi+Red in FY2008-2010)
+40.0%
+60.0%
Above BC Channel & Overbank Storage
9.8%
Atchafalaya Basin Channel & Overbank Storage
12.2%
Lake Pontchartrain
0.2%
Barataria Bay
0.3%
0%
Below BC Channel Storage
Barataria Bight
5.4%
Breton Sound
12.5%
27.8%
Atchafalaya Bay
31.8%
Deepwater Passes
(19.9%)

Figure 17.

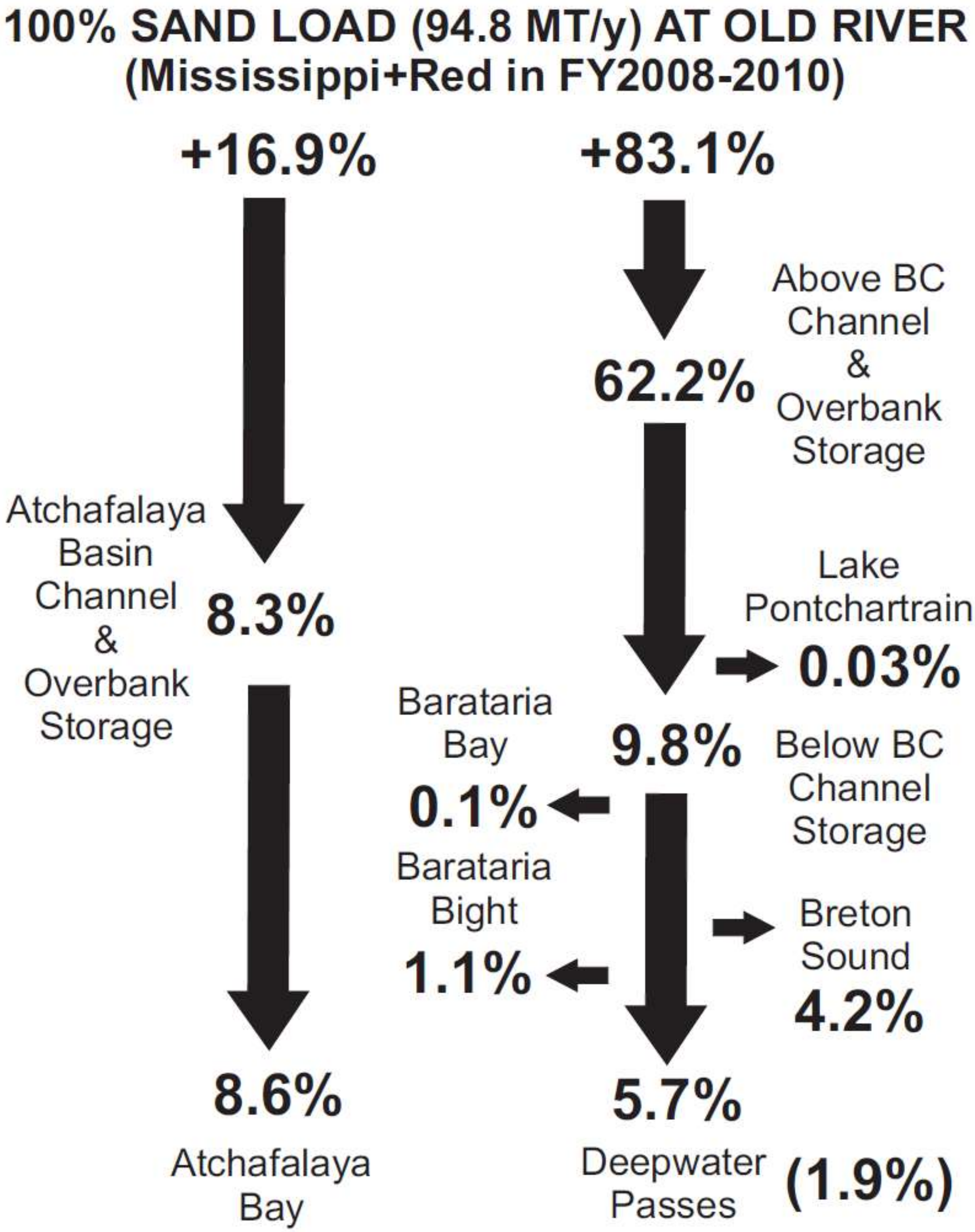

100% SAND LOAD (94.8 MT/y) AT OLD RIVER
(Mississippi+Red in FY2008-2010)
+16.9%
+83.1%
Above BC Channel & Overbank Storage
62.2%
Atchafalaya Basin Channel & Overbank Storage
8.3%
Lake Pontchartrain
0.03%
Barataria Bay
0.1%
9.8%
Below BC Channel Storage
Barataria Bight
1.1%
Breton Sound
4.2%
8.6%
Atchafalaya Bay
5.7%
Deepwater Passes
(1.9%)

Figure 18.

Appendix A: SUPPLEMENTARY DATA

This section includes all data, assumptions and methods utilized to calculate the water and sediment load for each Mississippi-Atchafalaya station whose results are published in the manuscript. They are divided into two types: monitoring stations where a year or more of continuous data is available about water or sediment discharge, and project studies, which were conducted to address a specific scientific or management issue, or which relate to a specific exit point (natural or man-made) from the river. Most of these results tend to extend only over a short period or over a few dates within the flood year (FY) 2008-2010 period (FY= 1 October to 30 September) of the budget calculations. All data records and figures reported herein are in English units (cubic feet per second, short tons per year) following U.S. Army Corps of Engineers and U.S. Geological Survey conventions.

1. MONITORING STATIONS

1.1 Baton Rouge, Louisiana The station at Baton Rouge is operated by the U.S. Geological Survey (USGS 07374000) and is located on the east bank of the Mississippi River channel at latitude 30°26'44.4", longitude 91°11'29.6". Data for this station is available online at:

http://waterdata.usgs.gov/la/nwis/nwisman/?site_no=07374000&agency_cd=USGS

Daily water discharge (Fig 1.1a) is obtained from the online USGS data repository and is calculated by the USGS utilizing boat-based acoustic Doppler current profiler (ADCP) measurements rated to stage recorded at the platform. This has been in operation since March of 2004. Daily data for FY2008-2010 can be found in supplementary file "MonitoringWater&Sediment.xls".

Sediment loads for Baton Rouge are based on USGS boat surveys conducted along a cross-section at the site 12-15 times per year and available online at the aforementioned website. A D96,99 series samplers, hereafter referred to as "D90 depth integrative, isokinetic water samplers" are used to collect mean suspended load water samples from 3-5 vertical points along the cross-section. Water discharge is also measured along the cross-section on each survey using a pole-mounted 600 kHz ADCP and averaging of multiple (4 or more) individual measurements. The moving boat method (Edwards and Glysson, 1988) is used (by the USGS) to sub-section the river cross-sections into units around each vertical sample point, which, when combined with the discharge in these units, is used to calculate total sediment loads (Fig. 1.1a). These unit loads are then combined to arrive at a cross-sectional total load. Water samples collected by the D90 in the laboratory are dried and weighed (to measure total mass per unit volume utilized in the total load measurement) and separated into grain size fractions. This data is also available online and is used in the present calculations of sand (>62.5 µm fraction) versus total sediment load. Boat measured water and sediment data (water discharge, total sediment load, sand load) for USGS sampling dates at Baton Rouge in FY2008-2010 can be found in the supplementary file "MonitoringWater&Sediment.xls".

Daily sediment loads at Baton Rouge were calculated utilizing the isokinetic boat data in FY2008-2010 and a ratings curve methodology. Separate ratings curves were constructed for total sediment load and sand load (Fig. 1.1b). The best fit (r^2=0.59) for the total load was obtained using the following exponential rise to maximum (double, 4 parameter) curve:

Total Load (tons/day) = a * (1-exp(-b*cfs)) + c * (1-exp(-d*cfs))

a = 7.357E+11
b = 3.406E-21
c = 3.402E+6
d = 1.427E-7

The best fit (r^2=0.71) for the sand load was obtained using the following three parameter power law equation:

Sand Load (tons/d) = Y_0 + (a * cfs^b)

Y_0 = -1.552E+4
a = 3.211E-8
b = 2.144

Daily results (total and sand) can be found in the supplementary file "MonitoringWater&Sediment.xls" and are plotted in Figure 1.1a.

An optical backscatterance sensor (OBS) was also located on the station platform at Baton Rouge and provided real-time measurements of turbidity (NTU) in the near surface. This data was available for 724 days during FY2008-2010 and was utilized to provide an independent measurement of total sediment load for these dates that can be compared with the ratings curve-derived load. Daily averages of OBS-derived turbidity were calibrated to the mean cross-sectional sediment concentration (mg/l) measured by the depth-integrative sampler in the boat surveys at the site on days when the surveys were conducted. The resulting linear relationship (r^2= 0.72; Fig. 1.1c) was utilized to yield a daily mean sediment load (in mg/l) for the OBS data that was converted to tons/d (plotted in Fig. 1.1a) using the daily water discharge (cfs). Daily OBS turbidity (NTU) and calculated loads can be found in the supplementary file "MonitoringWater&Sediment.xls".

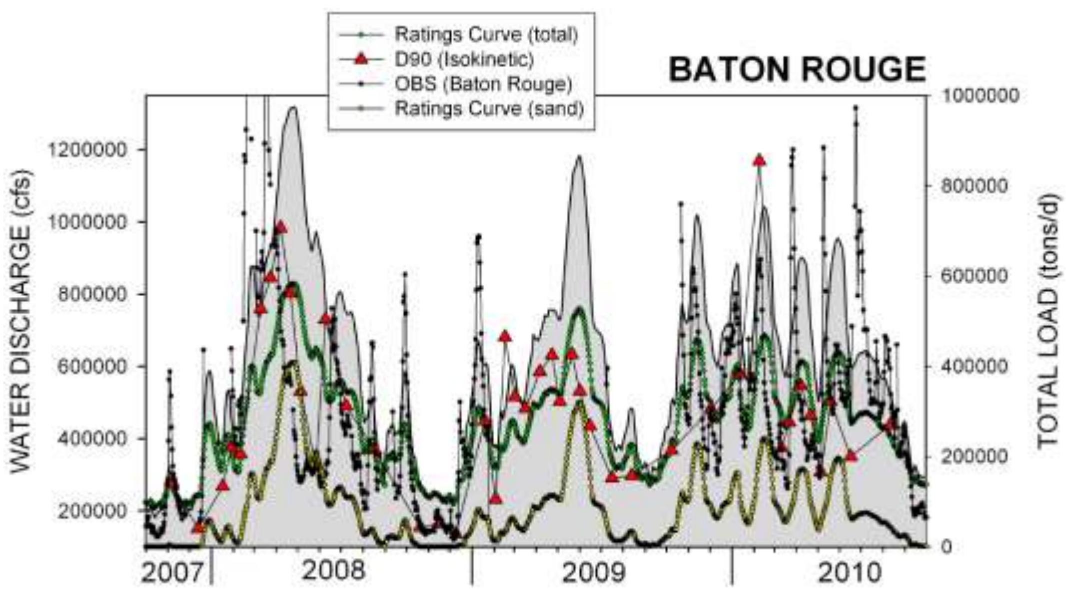


Figure 1.1a. Measured daily water discharge (gray curve), isokinetic total sediment load measured by boat (D90 sampler), total sediment load calculated by both the ratings curve and OBS methods, and sand load calculated by the ratings curve method for Baton Rouge.

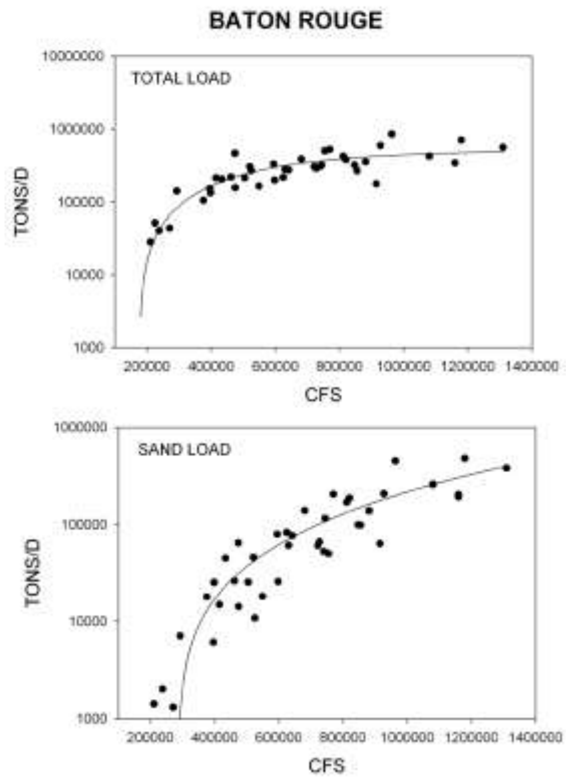


Figure 1.1b. Ratings curve fits for the water versus sediment load (total upper, sand lower) for all boat measurements made at Baton Rouge in FY 2008-2010.

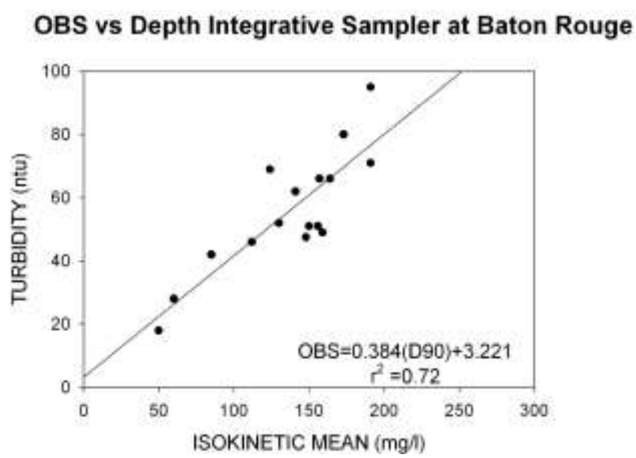


Figure 1.1b. Linear best fit regression line for the turbidity (NTU) sensor at Baton Rouge versus mean sediment concentration in the boat-measured cross-section that day (in mg/l). This records all boat measurements in FY 2008-2010.

1.2 Belle Chasse, Louisiana The station at Belle Chasse is operated by the U.S. Geological Survey (USGS 07374525) and is located on the west bank of the Mississippi River channel at latitude 29°51'25", longitude 89°58'40". Data for this station is available online at:

http://waterdata.usgs.gov/la/nwis/nwisman/?site_no=07374525&agency_cd=USGS

Daily water discharge (Fig 1.2a) is calculated based on USGS averaging of higher frequency data collected with a horizontal acoustic Doppler current profiler (H-ADCP) mounted on the platform. Since this H-ADCP unit has only been in operation beginning October 29, 2008, USGS daily figures are only utilized for FY2009-2010. Water discharge in FY2008 was obtained using a water ratings curve constructed using daily FY 2009-2010 Belle Chasse data compared with the nearest daily stage gage (U.S. Army Corps of Engineers stage gage at river mile 102.8 at latitude 29°56'05", longitude 90°08'10. Data for this gage can be found at:

http://www.mvn.usace.army.mil/cgi-bin/watercontrol.pl?01300

The results of this comparison can be found in Figure 1.2b and 1.2c. Two best fit curves (linear versus five parameter sigmoidal) gave the highest r^2—0.96 and 0.97, respectively. The sigmoidal was utilized to determine FY2008 water discharge due to a slightly higher r^2 and slightly better estimation of the peaks when compared with H-ADCP data from the site (Fig. 1.2c). The sigmoidal relationship was:

cfs = Y_0 + a/(1 + exp(-(STAGE-X_0)/b))^c

a = 1.412E+6
b = 4.078E-1
c = 2.490E-2
X_0 = 1.562E+1
Y_0 = -3.374E+5

Daily data for FY2008-2010 can be found in supplementary file "MonitoringWater&Sediment.xls".

Sediment loads for Belle Chasse are based on USGS boat surveys conducted along a cross-section at the site 12-15 times per year and available online at the aforementioned website. It should be noted that this data began in May 2007 and thus is available throughout the FY 2008-2010 period (Fig. 1.2a). This data was earlier collected by USGS during the period of 1978-1997. The D90 and ADCP measurement methods were identical to those previously outlined for Baton Rouge above. Boat measured water and sediment data (water discharge, total sediment load, sand load) for USGS sampling dates at Belle Chasse in FY2008-2010 can be found in the supplementary file "MonitoringWater&Sediment.xls".

Daily sediment loads at Belle Chasse were calculated utilizing the isokinetic boat data in FY2008-2010 and a ratings curve methodology. Separate ratings curves were constructed for total sediment load and sand load (Fig. 1.2c). The best fit (r^2=0.63) for the total load was obtained using the following three parameter power law equation:

Total Load (tons/d) = Y_0 + (a * cfs^b)

Y_0 = -1.361E+4
a = 2.874E-4
b = 1.553

The best fit (r^2=0.82) for the sand load was obtained using the following exponential rise to maximum (double, 4 parameter) curve:

Sand Load (tons/day) = a * (1-exp(-b*cfs)) + c * (1-exp(-d*cfs))

a = -7.673E+5
b = 1.087E-6
c = 5.087E+11
d = 1.344E-12

Daily results (total and sand) can be found in the supplementary file "MonitoringWater&Sediment.xls" and are plotted in Figure 1.2a.

An optical backscatterance sensor (OBS) was also located on the station platform at Belle Chasse (operated by Fenstermaker, Inc. for the State of Louisiana Office of Coastal Protection and Restoration, OCPR) and provided real-time measurements of turbidity (NTU) in the near surface. This data was available for 418 days during FY2008-2010 and was utilized to provide an independent measurement of total sediment load for these dates that can be compared with the ratings curve-derived load. Daily averages of OBS-derived turbidity were calibrated to the mean cross-sectional sediment concentration (mg/l) measured by the depth-integrative sampler in the boat surveys at the site on days when the surveys were conducted. The resulting linear relationship (r^2= 0.88; Fig. 1.2e) was utilized to yield a daily mean sediment load (in mg/l) for the OBS data that was converted to tons/d (plotted in Fig. 1.2a) using the daily water discharge (cfs). Daily OBS turbidity (NTU) and calculated loads can be found in the supplementary file "MonitoringWater&Sediment.xls".

Additional comparative data for sediment load and discharge are available from project studies conducted by OCPR at Myrtle Grove, Louisiana (river mile 61.6 to 58.0) and at Magnolia, Louisiana (river mile 46.6). Water discharge was collected with a pole-mounted boat ADCP unit (1200 kHz) while total and sand discharge was calculated using verticals collected with a P-63 (208 lb) isokinetic point sampler and fractionated samples in the laboratory. All techniques match the USGS standard methodologies except that point samples from five water depths (0.1, 0.3, 0.5, 0.7, and 0.9 total depth) were integrated to arrive at an equivalent D90 sediment load. Water and sediment discharge results from these surveys are plotted on Figure 1.2a.

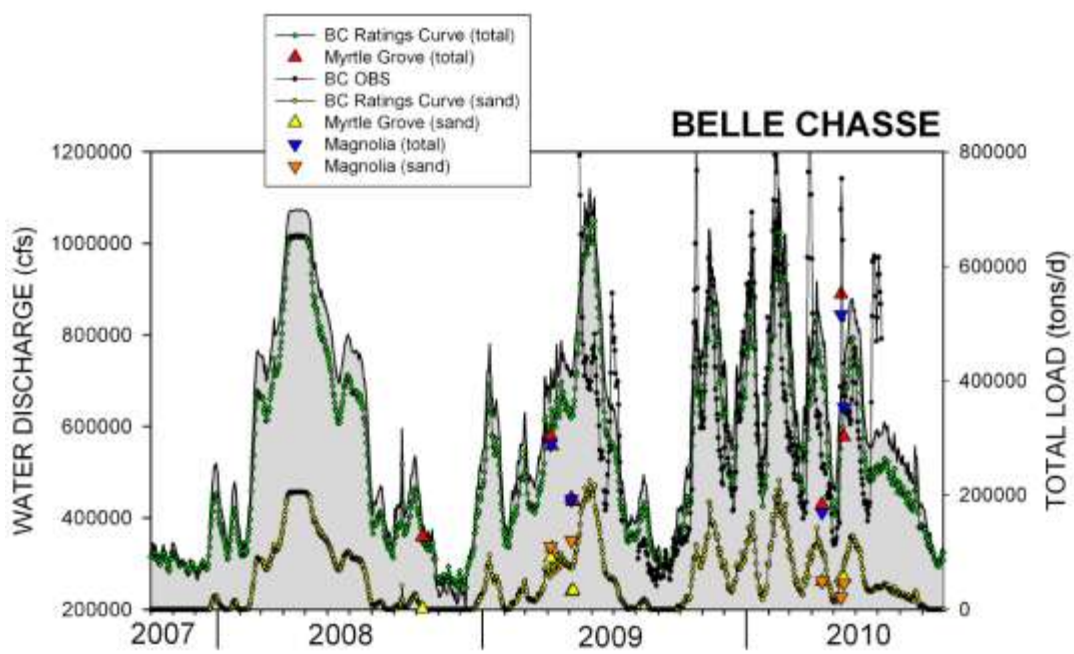


Figure 1.2a. Measured daily water discharge (gray curve), isokinetic total sediment load measured by boat (D90 sampler), total sediment load calculated by both the ratings curve and OBS methods, and sand load calculated by the ratings curve method for Belle Chasse. Also shown are the results of the project studies at Myrtle Grove and Magnolia.

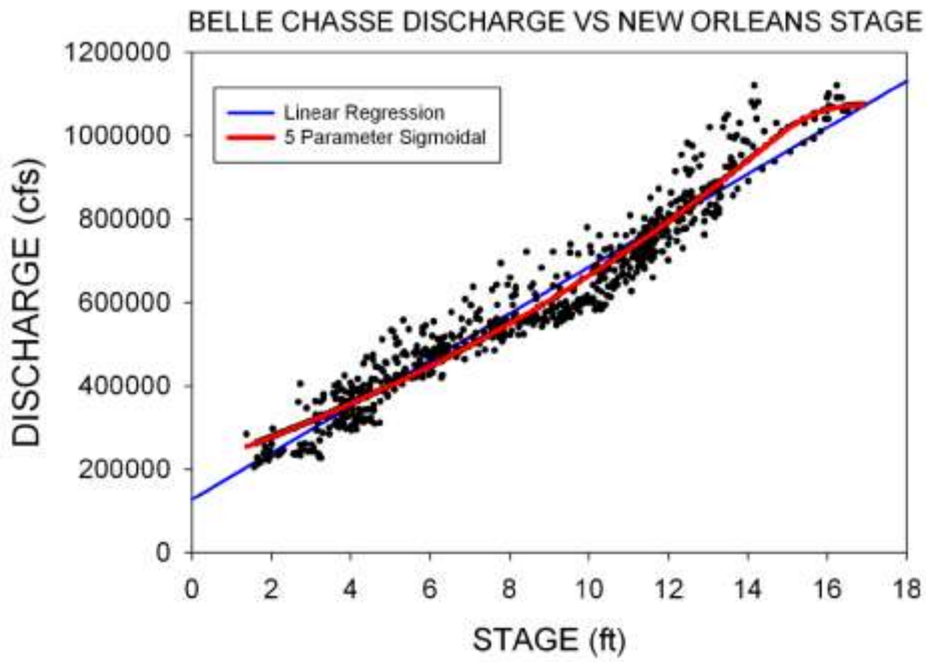


Figure 1.2b. Water ratings curve for Belle Chasse developed using the New Orleans stage gage at river mile 102.6. Two best fit regressions are plotted.

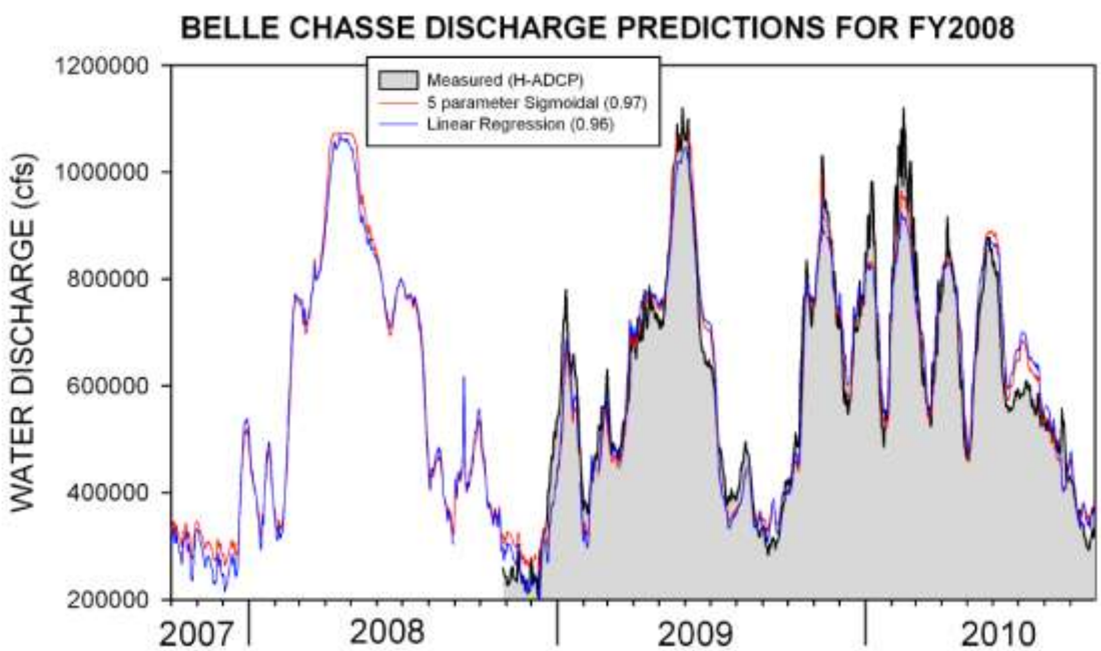


Figure 1.2c. Water discharge at Belle Chasse predicted from the ratings curves shown in Fig. 1.2a plotted against the measured (H-ADCP) values at the site beginning in October 2008.

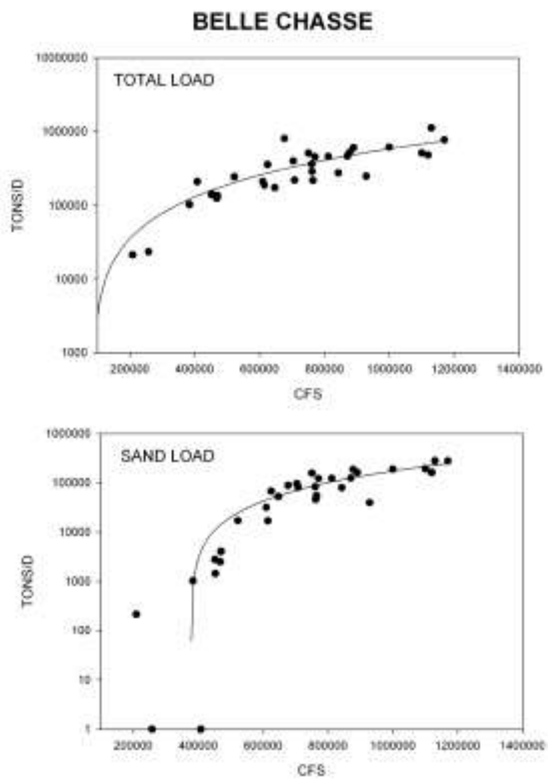


Figure 1.2d. Ratings curve fits for the water versus sediment load (total upper, sand lower) for all boat measurements made at Belle Chasse in FY 2008-2010.

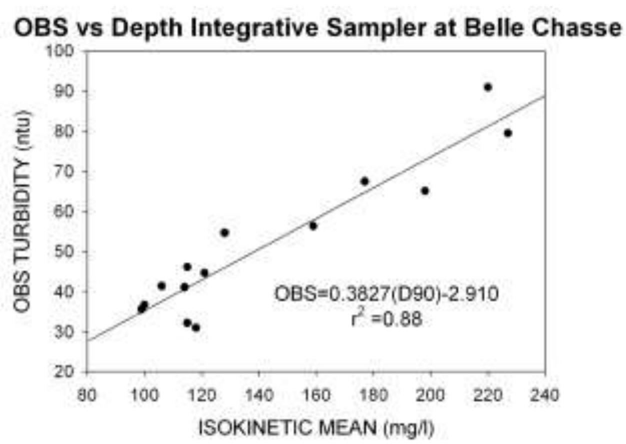


Figure 1.2e. Linear best fit regression line for the turbidity (NTU) sensor at Belle Chasse versus mean sediment concentration in the boat-measured cross-section that day (in mg/l). This records all boat measurements in FY 2008-2010.

1.3 Melville, Louisiana The station at Melville is a site maintained by the U.S. Army Corps of Engineers (USACE) but boat measurements are conducted by the U.S. Geological Survey (USGS 07381495). The site is located on the Texas and Pacific Railroad bridge on the Atchafalaya River channel at latitude 30°41'26", longitude 91°44'10". Data for this station is available online at the USGS at:

http://waterdata.usgs.gov/la/nwis/inventory/?site_no=07381495&agency_cd=USGS&

Stage information is available from the USACE New Orleans District at:

http://www.mvn.usace.army.mil/cgi-bin/watercontrol.pl?03060

Daily water discharge (Fig 1.3a) for FY2008-2010 is calculated using a water ratings curve constructed using daily FY 2009-2010 Simmesport, Louisiana discharge data (see section 1.8) compared to daily stage gage measurements. The results of this comparison can be found in Figure 1.3b Two best fit curves (linear versus five parameter sigmoidal) gave the highest r^2—0.97 and 0.99, respectively. The sigmoidal was utilized to determine water discharge due to its better r2. Given the close relationship of the calculated values with those at Simmesport, days where the stage gage was inoperable (about 2% of the total), the Simmesport value was utilized. The sigmoidal relationship was:

$$cfs = Y_0 + a/(1 + \exp(-(STAGE-X_0)/b))^\wedge c$$

$a = 2.443E+6$
$b = 1.597$
$c = 6.288E-2$
$X_0 = 6.217E1$
$Y_0 = -1.431E5$

Daily data for FY2008-2010 can be found in supplementary file "MonitoringWater&Sediment.xls".

Sediment loads for Melville are based on USGS boat surveys conducted along a cross-section at the site 12-15 times per year and available online at the aforementioned website. The D90 and ADCP measurement methods were identical to those previously outlined for Baton Rouge above. Boat measured water and sediment data (water discharge, total sediment load, sand load) for USGS sampling dates at Melville in FY2008-2010 can be found in the supplementary file "MonitoringWater&Sediment.xls".

Daily sediment loads at Belle Chasse were calculated utilizing the isokinetic boat data in FY2008-2010 and a ratings curve methodology. Separate ratings curves were constructed for total sediment load and sand load (Fig. 1.3c). The best fit (r^2=0.75) for the total load was obtained using the following exponential rise to maximum (double, 4 parameter) curve:

$$\text{Total Load (tons/day)} = a * (1-\exp(-b*cfs)) + c * (1-\exp(-d*cfs))$$

$a = -4.46E+4$
$b = 2.868E-5$
$c = 8.77E+8$
$d = 6.799E-10$

The best fit (r^2=0.81) for the sand load was obtained using the following three parameter power law equation:

$$\text{Sand Load (tons/d)} = Y_0 + (a * cfs^\wedge b)$$

$Y_0 = -1.111E+4$
$a = 4.296E-7$
$b = 2.017$

Daily results (total and sand) can be found in the supplementary file "MonitoringWater&Sediment.xls" and are plotted in Figure 1.3a.

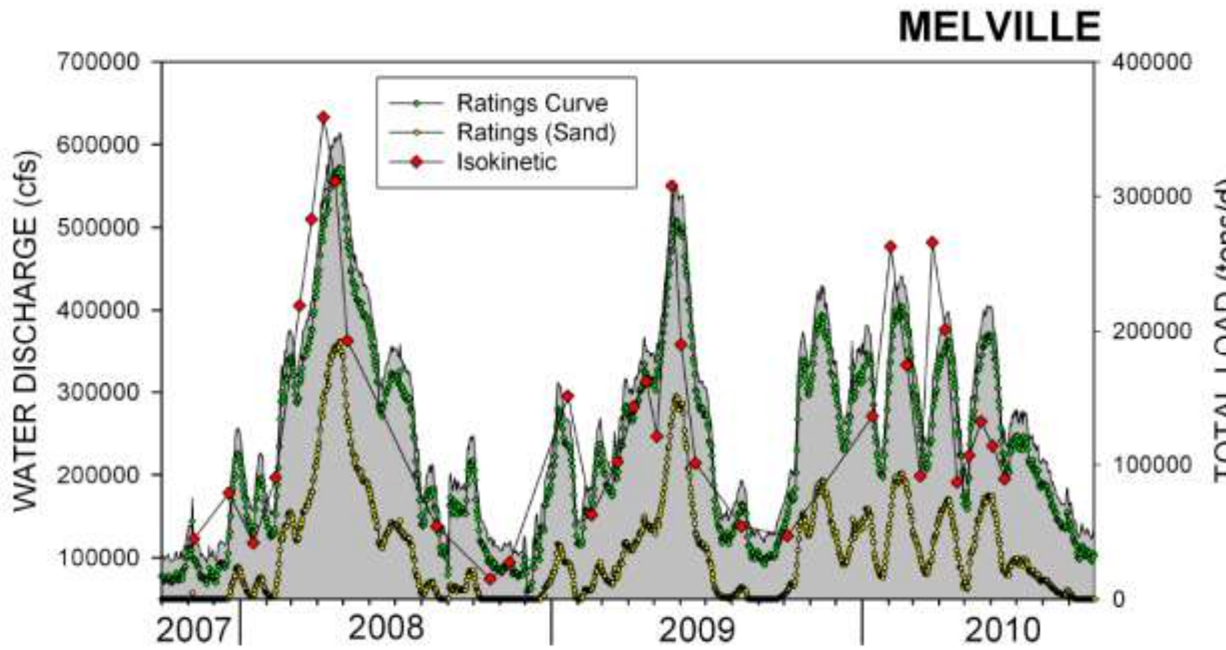


Figure 1.3a. Measured daily water discharge (gray curve), isokinetic total sediment load measured by boat (D90 sampler), total sediment load calculated by ratings curve method, and sand load calculated by the ratings curve method for Melville.

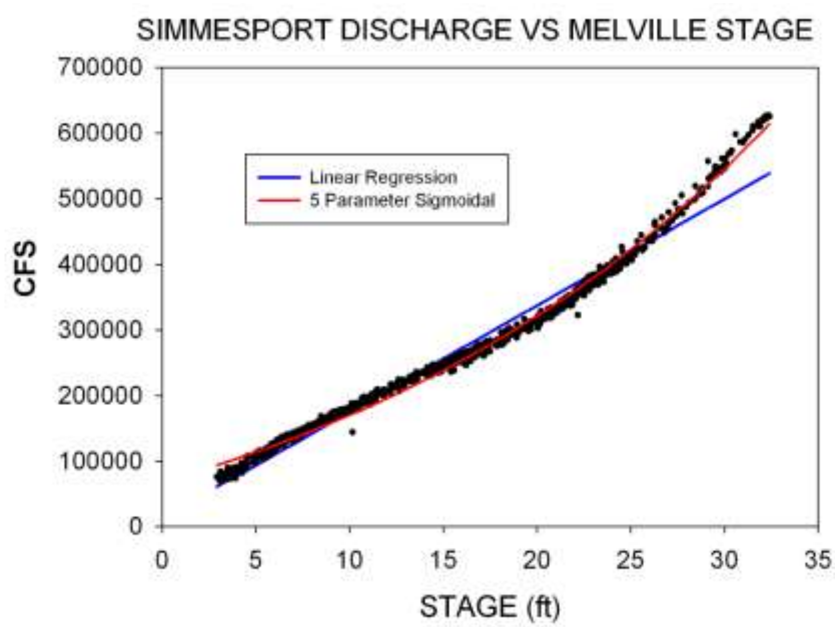


Figure 1.3b. Water ratings curve for Melville developed using the Melville stage gage compared to measured water discharge at Simmesport, Louisiana. Two best fit regressions are plotted.

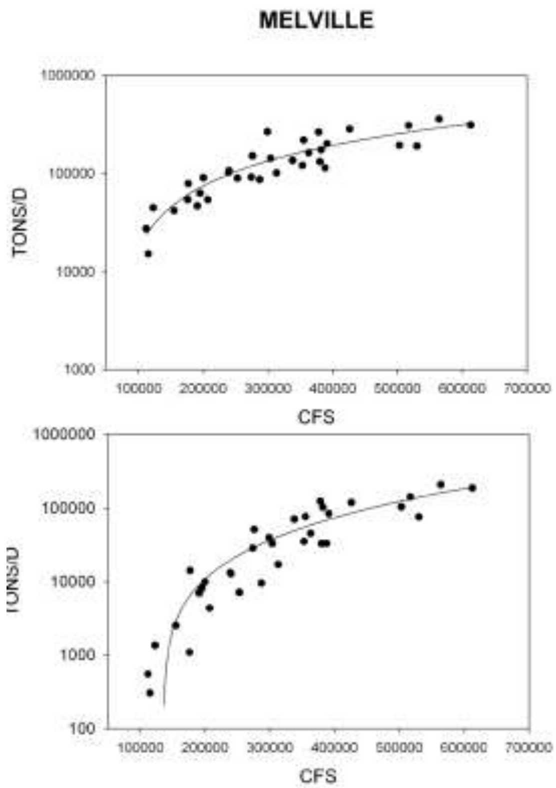


Figure 1.3c. Ratings curve fits for the water versus sediment load (total upper, sand lower) for all boat measurements made at Melville in FY 2008-2010.

1.4 Mississippi Channel at River Mile 24, Louisiana

The station at river mile 24 (immediately below Empire, Louisiana) consists only of an optical backscatterance sensor (OBS) mounted in shallow water on a pier piling. The OBS is part of the same study by Fenstermaker, Inc. for the State of Louisiana Office of Coastal Protection and Restoration, OCPR) as the OBS at Belle Chasse. This sensor provided real-time measurements of turbidity (NTU) in the near surface. This data was available for 561 days during FY2008-2010 and was utilized to provide a measurement of total sediment load for these dates. Given that no boat-based measurements were available to construct a calibration curve at river mile 24 for converting NTU to mg/l, the linear relationship (r^2= 0.88; Fig. 1.2e) for the OBS at Belle Chasse (same model and operator) was utilized.

To convert these data to a daily total sediment load (sand load component is not possible), it is necessary to have a daily estimate of water discharge at the site and then use this value to develop a total sediment ratings curve. Daily water discharge (cfs) was calculated using the value at Belle Chasse minus the loss through the Caernarvon Freshwater Diversion (see Section 2.3). At discharges above 930,000 cfs, an additional 1.4% loss of the calculated total was added to account for loss through the Bohemia Spillway (see Section 2.1). Results are shown in Figure 1.4a). A direct water measurement is available using the USACE stage gage at Empire, Louisiana (river mile 29.5):

http://www.mvn.usace.army.mil/cgi-bin/wcmanual.pl?01440

This record was not used to construct a water ratings curve with the Belle Chasse data due to only about half of the dates was the gauge operating and the relationship, likely due to tidal effects, showed a relatively low best fit linear regression (r^2=0.62, not shown).

Calculated water values were then compared to the total sediment concentrations (mg/l) calculated for the OBS daily values to develop a ratings curve (Fig. 1.4b). The linear ratings curve with the following equation was utilized (r^2=0.43):

Total load (tons/d) =10^((cfs*9.946E-7)+4.778)

A comparison of the OBS daily values and the ratings curve calculated total sediment loads is shown in Figure 1.4a. Daily OBS turbidity (NTU) and calculated loads can be found in the supplementary file "MonitoringWater&Sediment.xls".

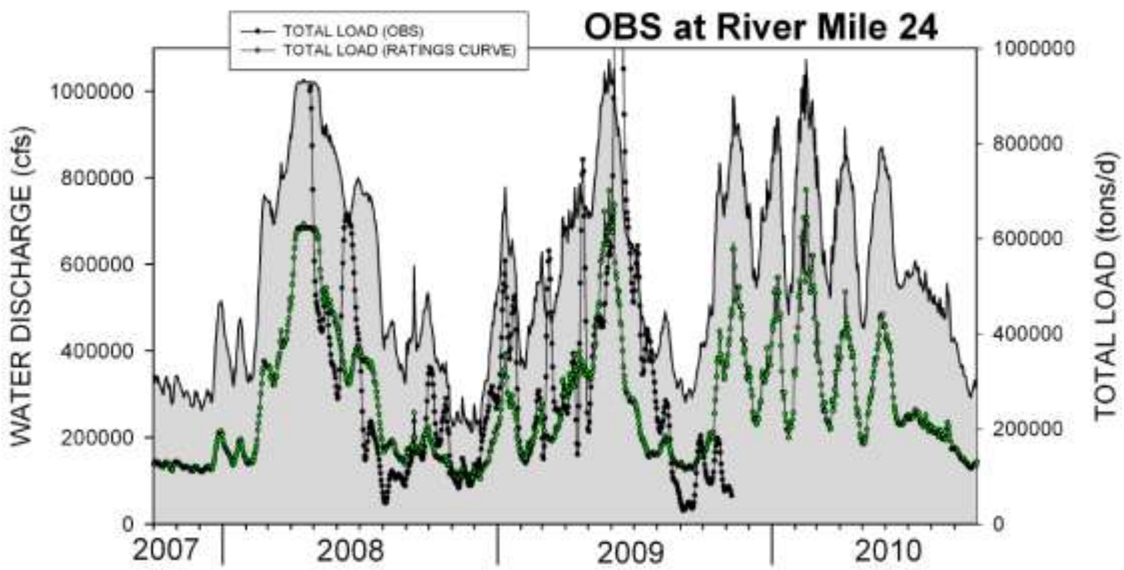


Figure 1.4a. Calculated daily water discharge (gray curve), total sediment load measured by OBS and, total sediment load calculated by ratings curve method for the OBS station at River Mile 24 on the Mississippi.

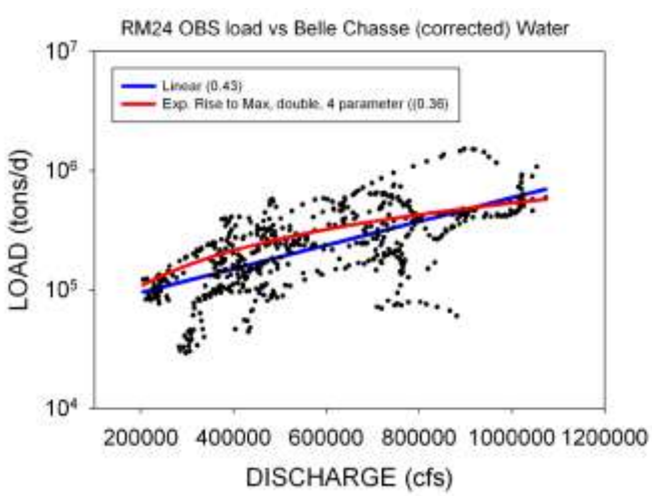


Figure 1.4a. Ratings curve fits for the water versus total sediment load for all OBS daily measurement averages made at River Mile 24 in FY 2008-2010.

1.5 Morgan City, Louisiana The station at Morgan City is operated by the U.S. Geological Survey (USGS 07381600) funded by the U.S Army Corps of Engineers and is located on the east bank of the Atchafalaya River channel at latitude 29°41'33.4", longitude 91°12'42.6". Data for this station is available online at:

http://waterdata.usgs.gov/la/nwis/nwisman/?site_no=07381600&agency_cd=USGS

Daily water discharge (Fig 1.5a) is calculated based on USGS averaging of higher frequency data collected with a horizontal acoustic Doppler current profiler (H-ADCP) mounted on the platform. This has been in operation since October of 1995. Daily data for FY2008-2010 can be found in supplementary file "MonitoringWater&Sediment.xls".

Sediment loads for Morgan City are based on USGS boat surveys conducted along a cross-section at the site 12-15 times per year and available online at the aforementioned website. The D90 and ADCP measurement methods were identical to those previously outlined for Baton Rouge above. Boat measured water and sediment data (water discharge, total sediment load, sand load) for USGS sampling dates at Morgan City in FY2008-2010 can be found in the supplementary file "MonitoringWater&Sediment.xls".

Daily sediment loads at Morgan City were calculated utilizing the isokinetic boat data in FY2008-2010 and a ratings curve methodology. Separate ratings curves were constructed for total sediment load and sand load (Fig. 1.5b). The best fit (r^2=0.76) for the total load was obtained using the following exponential rise to maximum (double, 4 parameter) curve:

Total Load (tons/day) = a * (1-exp(-b*cfs)) + c * (1-exp(-d*cfs))

a = 5.707E+8
b = 3.742E-9
c = -5.799E+5
d = 3.567E-6

The best fit (r^2=0.87) for the sand load was obtained using the following three parameter power law equation:

Sand Load (tons/d) = Y_0 + (a * cfs^b)

Y_0 = -5.106E+3
a = 4.058E-11
b = 2.810

Daily results (total and sand) can be found in the supplementary file "MonitoringWater&Sediment.xls" and are plotted in Figure 1.5a.

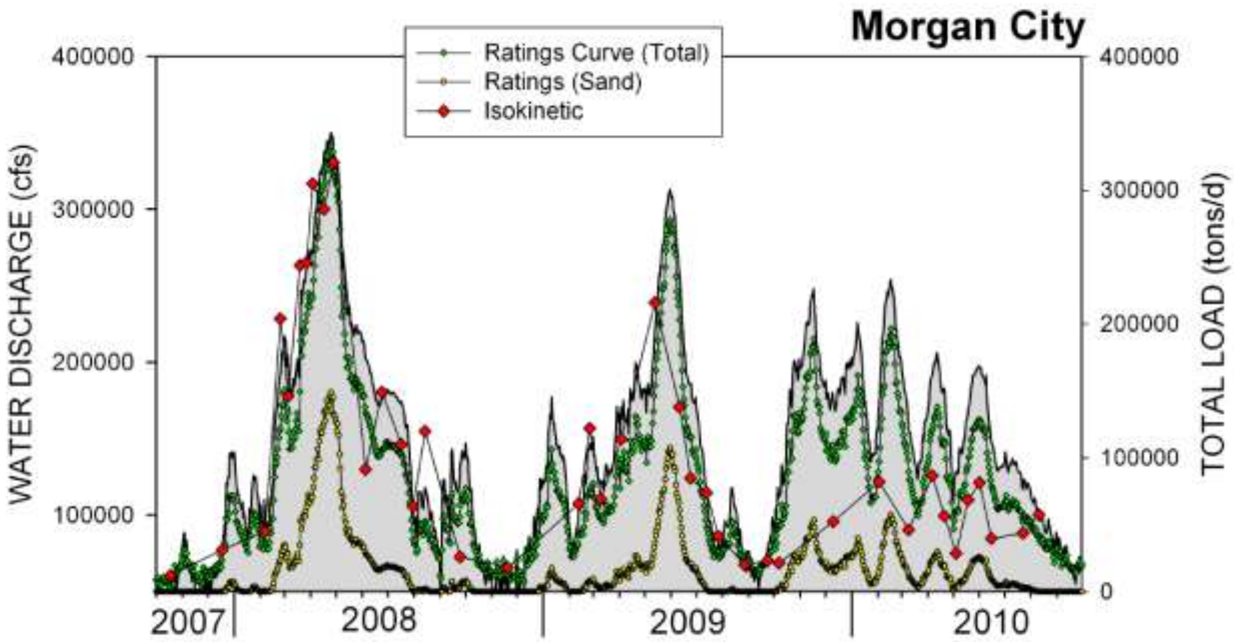


Figure 1.5a. Measured daily water discharge (gray curve), isokinetic total sediment load measured by boat (D90 sampler), total sediment load calculated by ratings curve method, and sand load calculated by the ratings curve method for Morgan City.

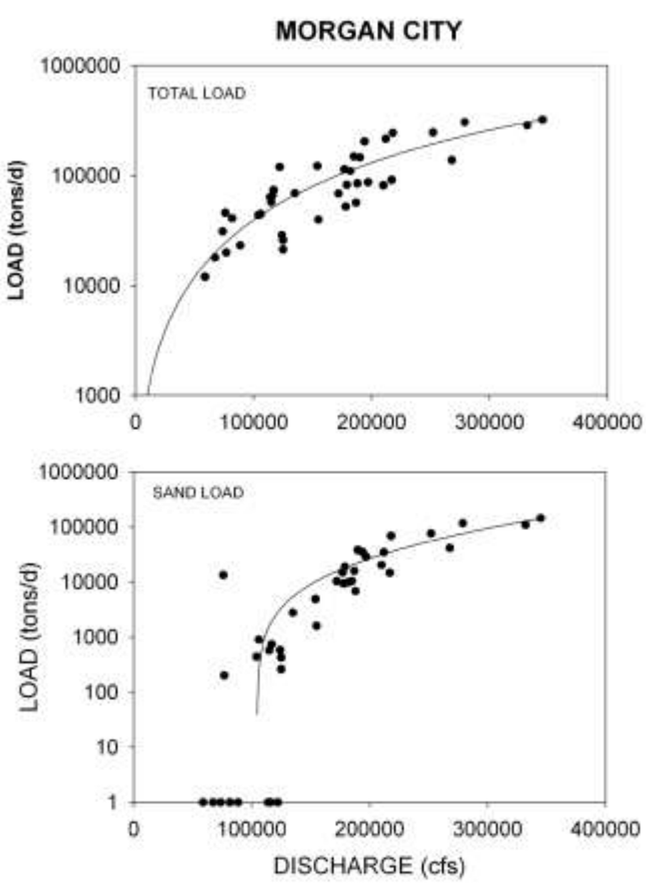


Figure 1.5b. Ratings curve fits for the water versus sediment load (total upper, sand lower) for all boat measurements made at Morgan City in FY 2008-2010.

1.6 Natchez, Mississippi The station at Natchez is operated by the U.S. Army Corps of Engineers, Vicksburg District and is located on the Mississippi River bridge (RM363.3) at latitude 31.544017, longitude -91.433412. Stage data for this station is available online at:

http://www2.mvr.usace.army.mil/WaterControl/stationinfo2.cfm?sid=CE4103F4&fid=NTZM6&dt=S

Daily water discharge (Fig 1.6a) for FY2008-2010 is calculated using a water ratings curve constructed using boat-based ADCP measurements of discharge by the USACE compared to daily stage gage measurements. The results of this comparison can be found in Figure 1.6b. The best fit curve (quadratic) gave an r^2 of 0.98 and was utilized to determine water discharge. The quadratic relationship was:

$$cfs = Y_0 + a(STAGE) + b(STAGE)^2$$

$a = -1.522E4$
$b = 6.873E2$
$Y_0 = 3.859E5$

Daily data for FY2008-2010 can be found in supplementary file "MonitoringWater&Sediment.xls".

Sediment loads for Natchez are based on USACE boat surveys conducted along a cross-section at the site approximately six times per year and made available to the authors through the Vicksburg District. A D96 series, depth-integrative sampler was utilized throughout the discharge cycle—unlike other stations where the heavier D99 is utilized at higher discharges. The D96 was used to collect mean suspended load water samples from 3-5 vertical points along the cross-section. Water discharge is also measured along the cross-section on each survey using a pole-mounted 600 kHz ADCP and averaging of multiple (4 or more) individual measurements. The moving boat method (Edwards and Glysson, 1988) is used (to sub-section the river cross-sections into units around each vertical sample point, which, when combined with the discharge in these units, is used to calculate total sediment loads (Fig. 1.6a). These unit loads are then combined to arrive at a cross-sectional total load. Water samples collected by the D96 in the laboratory are dried and weighed (to measure total mass per unit volume utilized in the total load measurement) and separated into grain size fractions. Boat measured water and sediment data (water discharge, total sediment load) for USACE sampling dates at Natchez in FY2008-2010 can be found in the supplementary file "MonitoringWater&Sediment.xls".

Daily sediment loads at Natchez were calculated utilizing the isokinetic boat data in FY2008-2010 and a ratings curve methodology. The best fit (r^2=0.47) for the total load was obtained obtained using the following three parameter power law equation:

$$\text{Total Load (tons/d)} = Y_0 + (a * cfs^{\wedge}b)$$

$Y_0 = -3.828E4$
$a = 7.525E-2$
$b = 1.123$

Daily results (total) can be found in the supplementary file "MonitoringWater&Sediment.xls" and are plotted in Figure 1.6a.

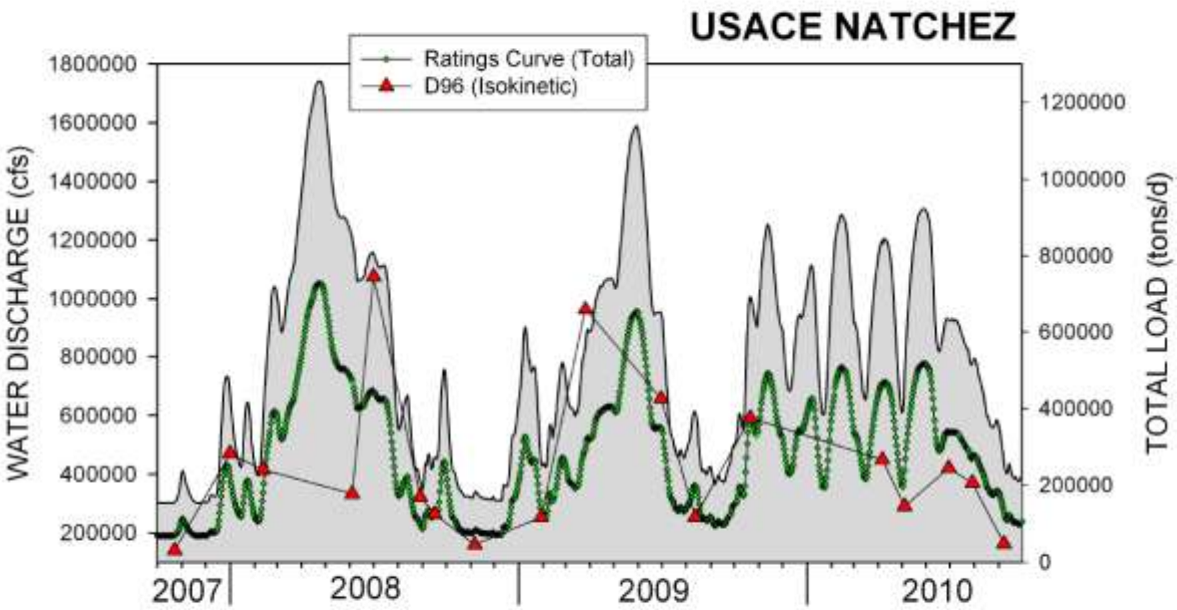


Figure 1.6a. Measured daily water discharge (gray curve), isokinetic total sediment load measured by boat (D96 sampler), total sediment load calculated by the ratings curve method for Natchez.

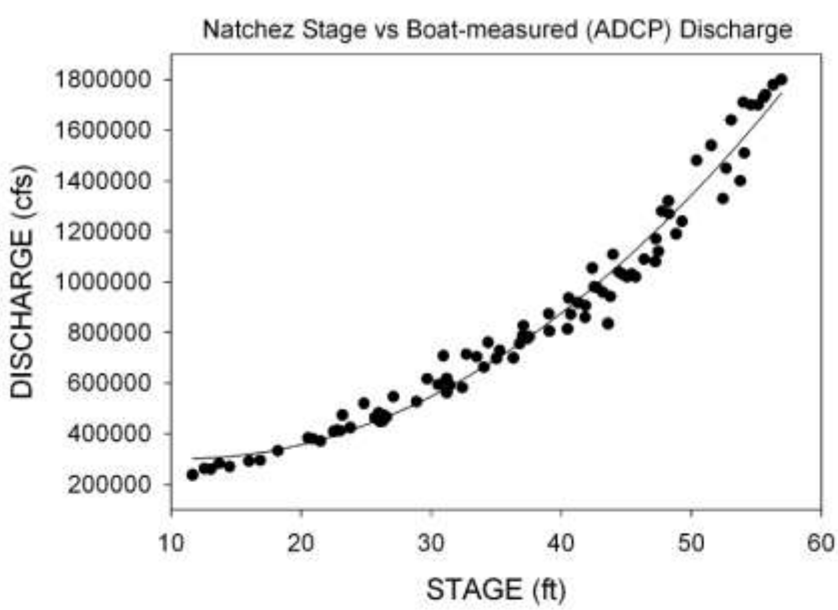


Figure 1.6b. Water ratings curve for Natchez developed using the Natchez stage gage compared to boat-based measured water discharge in FY2008-2010. The quadratic best fit regression is plotted.

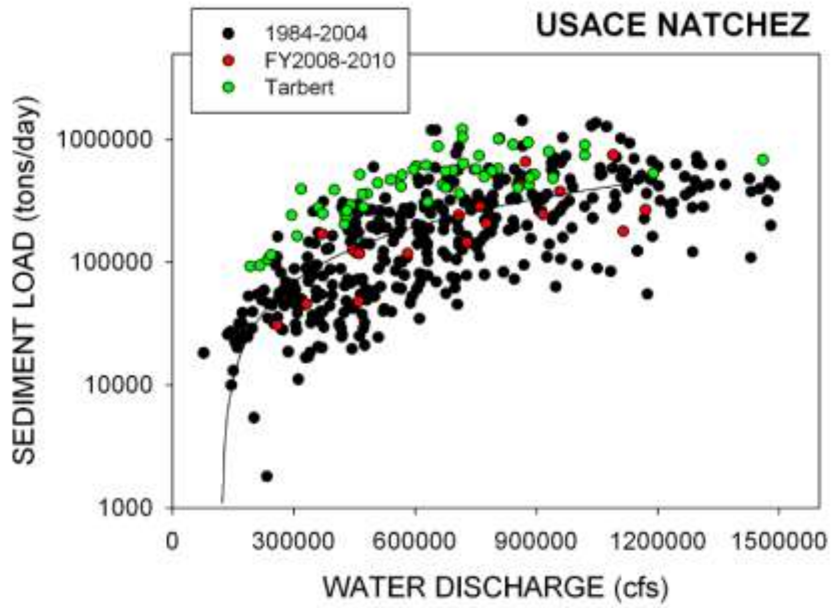


Figure 1.6c. Ratings curve fits for the water versus total sediment load for all boat measurements made at Natchez, MS in FY 2008-2010 with the best fit quadratic regression. Also plotted are the historic sediment loads at Natchez (1984-2004) and the sediment loads calculated for Tarbert Landing, MS (Fig. 1.10a).

The difference in suspended sampling methodology led to a comparison with historic data at Natchez and with the next station downstream at Tarbert Landing, MS (Fig. 1.6c). These results suggested a sampler-caused underestimation of sediment load relative to other monitoring stations utilized in this study. This is likely a function of a) the deepest sample at Natchez is collected at 0.84 total water depth rather than 0.9 at the other stations, and b) the lighter sampler experiences greater wire angles at high discharge (leading to a shallower-than-recorded water depth. Due to these reasons, the Natchez sediment data was not utilized in the main manuscript.

1.7 Old River Control, Louisiana

Old River is the point on the Mississippi where flow is diverted into the Atchafalaya River through three control structures: the Hydroelectric Plant, Low Sill, and Auxiliary structures. The arrangement of these structures and the outflow channel is shown in Figure 1.7a. Water discharge is adjusted daily such that the Atchafalaya River discharges 30% of the combined Mississippi and Red River discharge using flow adjustments of the three structures: generally the Hydro Plant carries the most discharge, except in flood, to generate power.

Combined water discharge is measured daily using H-ADCP at the outflow channel near Knox Landing, Louisiana at latitude 31°04'40", longitude 91°35'50". These data are available from the USACE New Orleans District at:

http://www.mvn.usace.army.mil/cgi-bin/wcmanual.pl?02600

Daily data for FY2008-2010 can be found in supplementary file "MonitoringWater&Sediment.xls" and are shown in Figure 1.7b. Additional daily data is collected at each of the three structures as well: a comparison of these data (not shown) indicates that the combined outflow of these channels is almost identical to that measured at the outflow channel.

Total sediment concentration is measured daily at the turbine/gate point at each of these entrance channels using a single bottle sample that is sieved and dried to arrive at sand load as well as total. These data were converted to sediment loads using the water discharge measured for that day at each of the structures. Sample gaps of 1-10 days in length were filled using the data for the adjacent days.

Sediment loads were calculated for FY 2010 utilizing bottle data in FY2008-2010 and a ratings curve methodology. Daily results (total and sand) can be found in the supplementary file "MonitoringWater&Sediment.xls" and are plotted in Figure 1.7b.

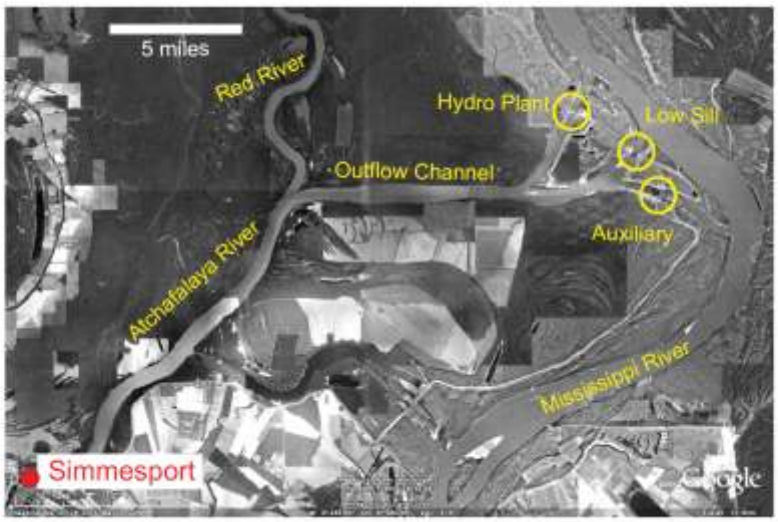


Figure 1.7a. Map of the arrangement of outflow channels between the Mississippi-Atchafalaya-Red River at Old River Control.

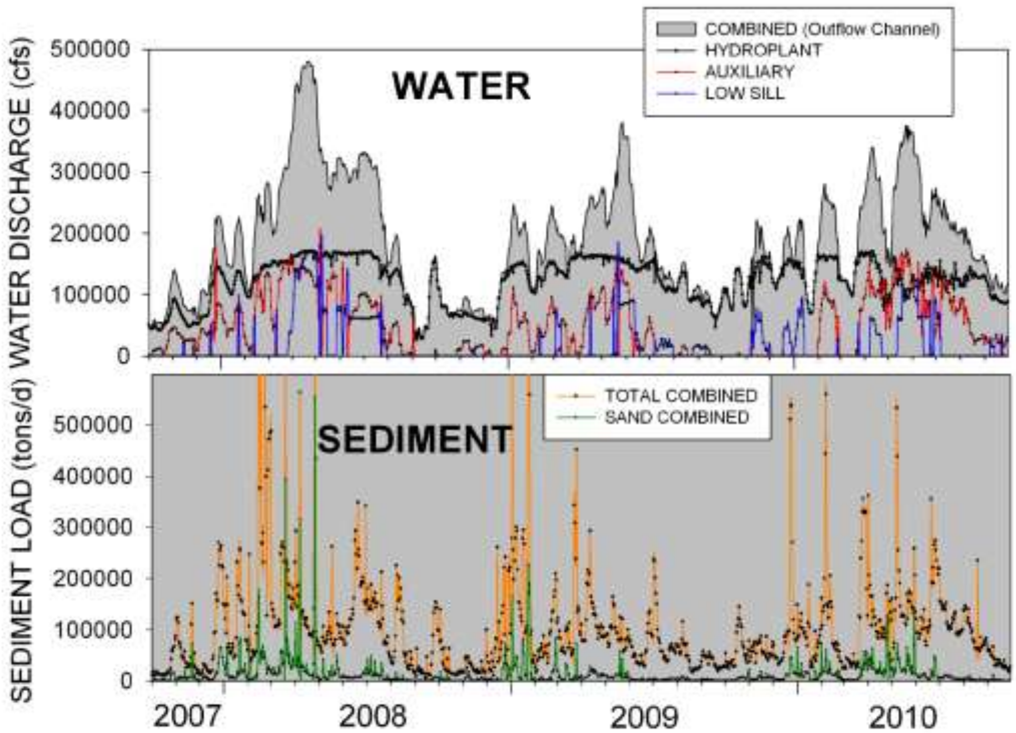


Figure 1.7b. Measured daily water discharge (upper plot) for the three structures and at the combined outflow point at Old River. Lower plot is measured daily (single bottle sample in each channel) combined sediment load at the three structures.

1.8 Simmesport, Louisiana The station at Simmesport is operated by the U.S. Geological Survey (USGS 07381490) funded by the U.S Army Corps of Engineers and is located on the west bank of the Atchafalaya River channel at latitude 30°58'57", longitude 91°47'54". Data for this station is available online at:

http://waterdata.usgs.gov/la/nwis/nwisman/?site_no=07381490&agency_cd=USGS

Daily water discharge (Fig 1.8a) is obtained from the online data repository and is calculated by the USGS utilizing boat-based acoustic Doppler current profiler (ADCP) measurements rated to stage recorded at the platform. Daily data for FY2008-2010 can be found in supplementary file "MonitoringWater&Sediment.xls".

Sediment loads for Morgan City are based on USGS boat surveys conducted along a cross-section at the site 12-15 times per year and available online at the aforementioned website. The D90 and ADCP measurement methods were identical to those previously outlined for Baton Rouge above. Boat measured water and sediment data (water discharge, total sediment load, sand load) for USGS sampling dates at Morgan City in FY2008-2010 can be found in the supplementary file "MonitoringWater&Sediment.xls".

Daily sediment loads at Morgan City were calculated utilizing the isokinetic boat data in FY2008-2010 and a ratings curve methodology. Separate ratings curves were constructed for total sediment load and sand load (Fig. 1.8b). The best fit (r^2=0.87) for the total load was obtained using the following three parameter power law equation:

Total Load (tons/d) = Y_0 + (a * cfs^b) Y_0 = -7.996E+4
a = 2.761E+1
b = 7.447E-1

The best fit (r^2=0.87) for the sand load was obtained using the following three parameter power law equation:

Sand Load (tons/d) = Y_0 + (a * cfs^b) Y_0 = -8.114E3
a = 2.318E-6
b = 1.895

Daily results (total and sand) can be found in the supplementary file "MonitoringWater&Sediment.xls" and are plotted in Figure 1.8a.

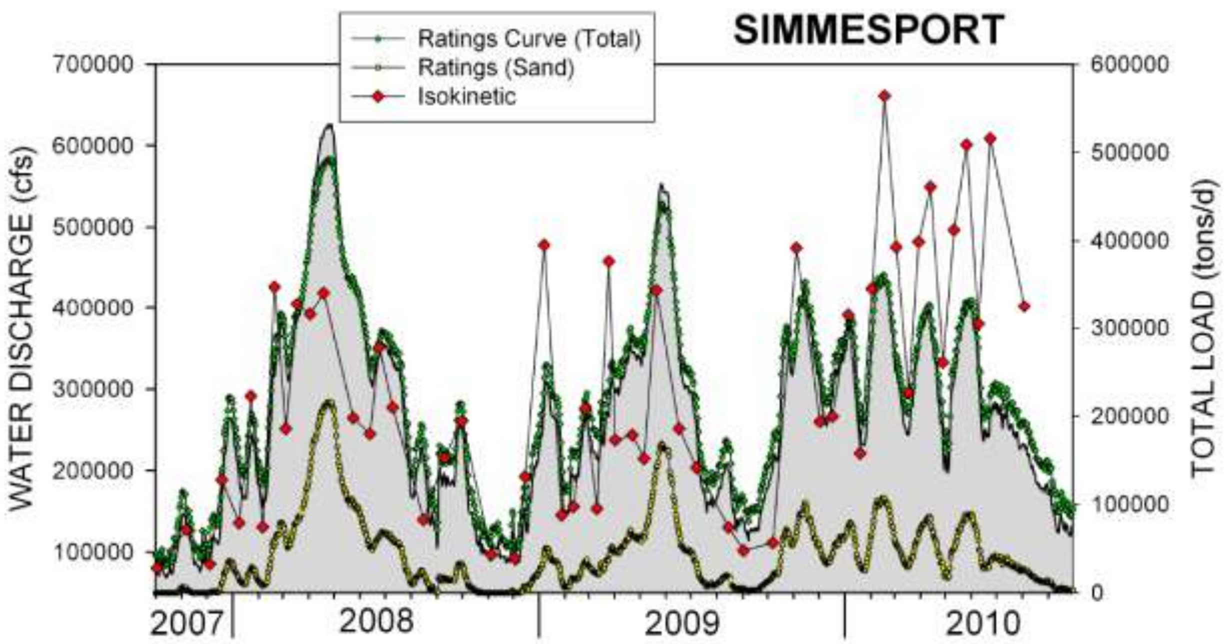


Figure 1.8a. Measured daily water discharge (gray curve), isokinetic total sediment load measured by boat (D90 sampler), total sediment load calculated by ratings curve method, and sand load calculated by the ratings curve method for Simmesport.

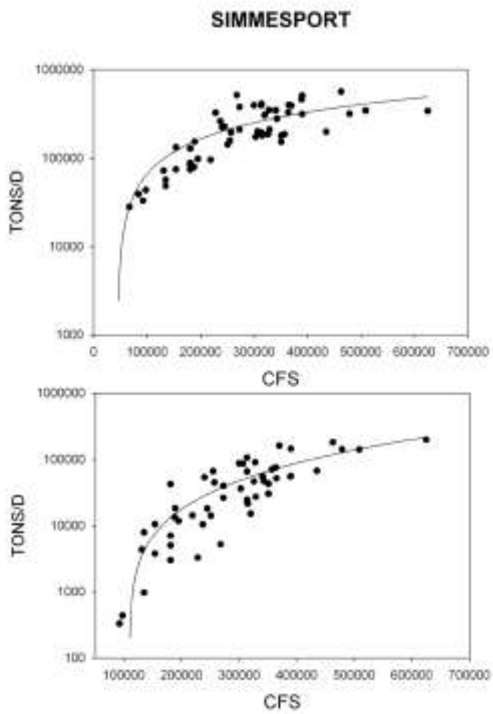


Figure 1.8b. Ratings curve fits for the water versus sediment load (total upper, sand lower) for all boat measurements made at Simmesport in FY 2008-2010.

1.9 St. Francisville, Louisiana The station at St. Francisville is operated by the U.S. Geological Survey (USGS 07373420) and is located on the east bank at latitude 30°45'30", longitude 91°23'45", river mile 266.0. Data for this station is available online at:

http://nwis.waterdata.usgs.gov/la/nwis/nwisman/?site_no=07373420&agency_cd=USGS

Daily water discharge is not measured at this site, only river stage is available at the nearby U.S. Army Corps of Engineers gage at Bayou Sara (river mile 265.4). These data are available online at:

http://www.mvn.usace.army.mil/cgi-bin/wcmanual.pl?01140

The Bayou Sara stage data is compared to boat measured discharge at the St. Francisville site occupied by the U.S. Geological Survey to develop a water ratings curve (Fig. 1.9a). This is a quadratic best fit regression (r^2=0.97) with a relationship of:

Discharge (cfs) = a + (b + stage) + (c * stage^2)

a = 1.251E+5
b = 7.884E+3
c = 2.384E+2

However, when the resulting calculated daily discharge is compared to measured discharge downstream at Baton Rouge (Fig. 1.9b) it is apparent that the ratings curve underestimates the magnitude of discharges above about 750,000 cfs. This suggests the possibility of overbank flow around the channel and over the significant batture width present at the stage gage and boat-measurement sites. Hence, no station water discharge is calculated for this site: water discharges utilized in the main text discussion are those at Baton Rouge (see Section 1.1).

Because the boat-based water discharge measurements made during isokinetic D90 samplings are also likely compromised by overbank flows at discharges about about 750,000 cfs, the sediment ratings curves at this site (Fig. 1.9c) are calculated using only data points below that water discharge. Baton Rouge data for total water discharge are not utilized for those dates because it assumes overbank flow is of the same concentration as that measured in the channel—which may not be the case. Separate ratings curves were constructed for total sediment load and sand load using the (Fig. 1.9c). The best fit (r^2=0.68) for the total load was obtained using the following exponential rise to maximum (single, 3 parameter) curve:

Total Load (tons/day) = Y_0 + a * (1-exp(-b*cfs)) Y_0 = -8.279E+4
a = 3.568E+6
b = 1.749E-7

The best fit (r^2=0.63) for the sand load was obtained using the following exponential rise to maximum (double, 4 parameter) curve:

Sand Load (tons/day) = a * (1-exp(-b*cfs)) + c * (1-exp(-d*cfs)) a = -3.689E4
b = 1.338E-4
c = 3.055E+5
d = 5.976E-7

Daily results (total and sand) can be found in the supplementary file "MonitoringWater&Sediment.xls" and are plotted in Figure 1.9d. Also plotted in the figure are the best fit regression line results for all the data points (including those above 750,000 cfs) shown in Figure 1.9c—the same curve types were utilized.

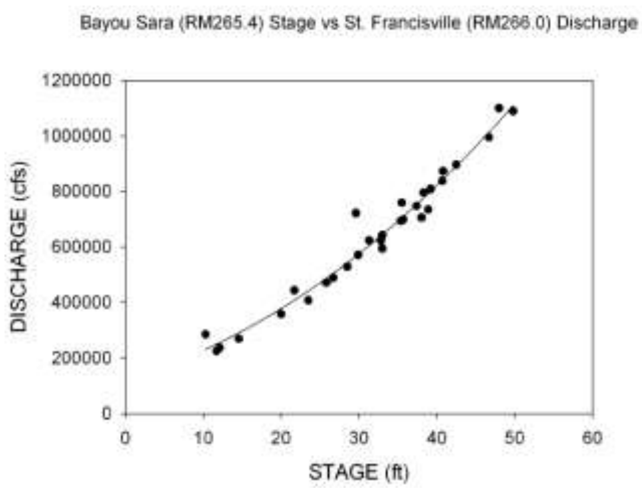


Figure 1.9a. Stage versus water discharge relationship at St. Francisville and the nearby Bayou Sara stage gage for data collected in FY 2008-2010.

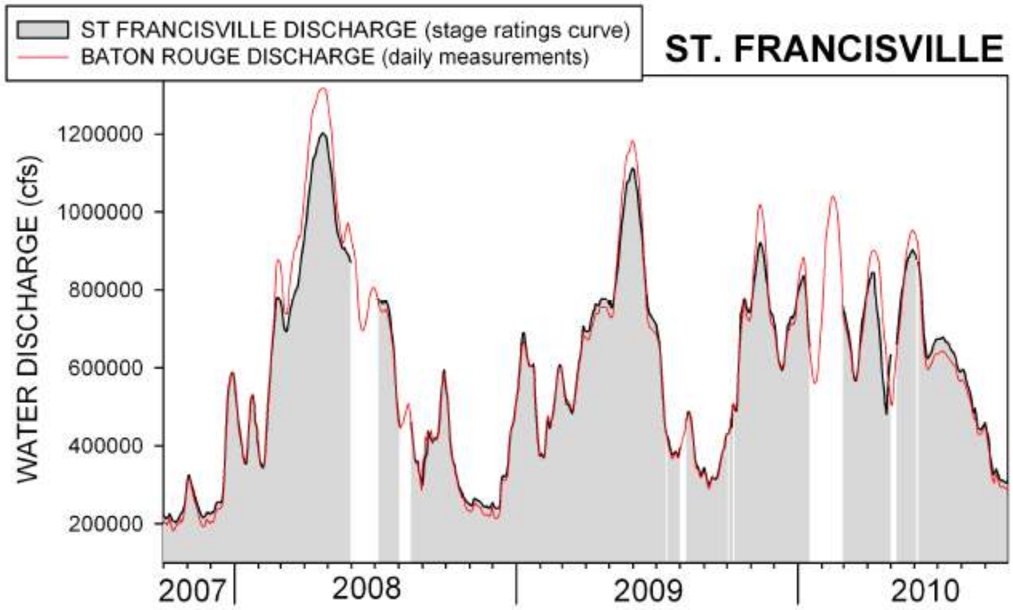


Figure 1.9b. Calculated water discharge (from Fig. 1.9a) plotted against measured water discharge at Baton Rouge (section 1.1), showing the loss of water by overbank flow at St. Francisville above about 750,000 cfs.

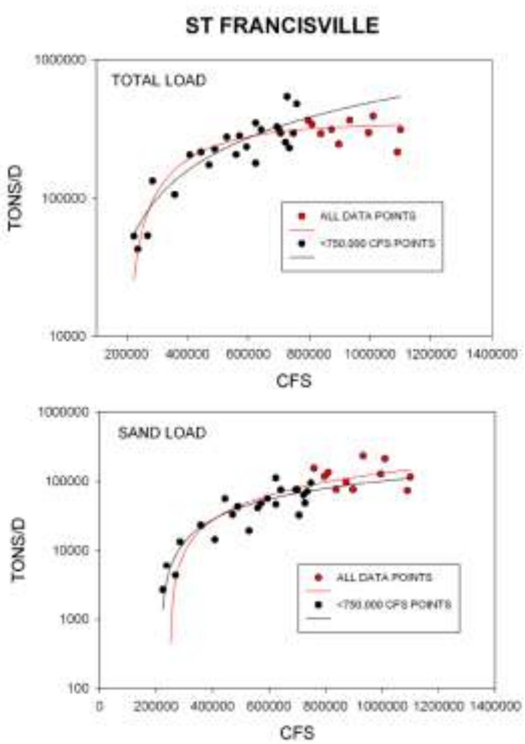


Figure 1.9c. Ratings curve fits for the water versus sediment load (total upper, sand lower) for all boat measurements for discharges below 750,000 cfs (black points and curve) and including those above that discharge (red points and curves) made at St. Francisville in FY 2008-2010.

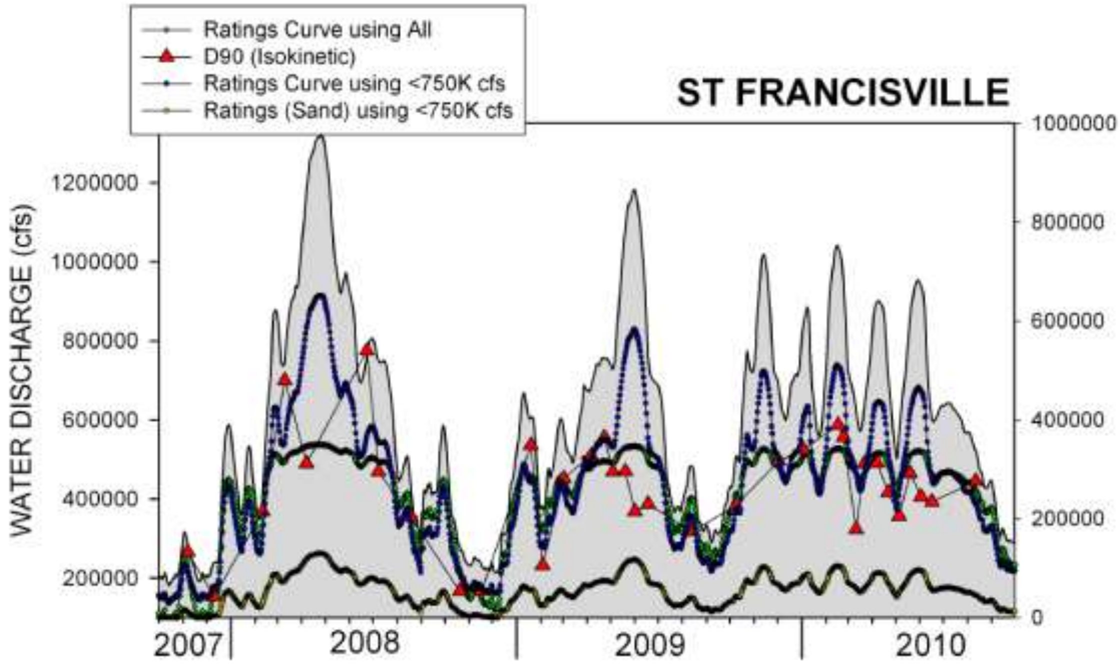


Figure 1.9d. Measured daily water discharge (gray curve, Baton Rouge), isokinetic total sediment load measured by boat (D90 sampler), total sediment load calculated by ratings curve method, and sand load calculated by the ratings curve method for St. Francisville comparing (for total load only) a ratings curve of all points (green) versus only those <750,000 cfs (blue).

<u>1.10 Tarbert Landing, Mississippi</u> The station at Tarbert Landing is a site operated by the U.S. Army Corps of Engineers (USACE). The site is located on the east bank of the Mississippi River at river mile 303.6 (immediately below the Old River Control structures) at latitude 31°00'30", longitude 91°37'25". Data for this station is available online at the USGS at:

http://waterdata.usgs.gov/la/nwis/inventory/?site_no=07295100&agency_cd=USGS&

Stage and daily water discharge information is available from the USACE New Orleans District at:

http://www.mvn.usace.army.mil/cgi-bin/wcmanual.pl?01100

Daily water discharge (Fig 1.10a) is obtained from USACE the online data repository and is calculated by the USACE utilizing boat-based acoustic Doppler current profiler (ADCP) measurements rated to stage recorded at the platform. Daily data for FY2008-2010 can be found in supplementary file "MonitoringWater&Sediment.xls".

Sediment loads for Tarbert Landing are based on USGS boat surveys conducted along a cross-section at the site 12-15 times per year and available online at the aforementioned website. The D90 and ADCP measurement methods were identical to those previously outlined for Baton Rouge above. Boat measured water and sediment data (water discharge, total sediment load, sand load) for USGS sampling dates at Tarbert Landing in FY2008-2010 can be found in the supplementary file "MonitoringWater&Sediment.xls".

Daily sediment loads at Tarbert Landing were calculated utilizing the isokinetic boat data in FY2008-2010 and a ratings curve methodology. Separate ratings curves were constructed for total sediment load and sand load (Fig. 1.10b). The best fit (r^2=0.53) for the total load was obtained using the following 2nd order logarithm curve:

Total Load (tons/day) = $Y_0 + (a * \ln(cfs)) + (b * \ln(cfs)^2)$

Y_0 = -1.863E+3
a = -3.416E+5
b = 2.852E+4

The best fit (r^2=0.62) for the sand load was obtained using the following rise to maximum (double, 4 parameter) curve:

Sand Load (tons/day) = a * (1-exp(-b*cfs)) + c * (1-exp(-d*cfs))

a = -7.869E+4
b = 1.004E-5
c = 9.193E+8
d = 3.809E-10

Daily results (total and sand) can be found in the supplementary file "MonitoringWater&Sediment.xls" and are plotted in Figure 1.10a.

In addition to the sediment loads calculated using the boat and ratings curve method outlined above, a single D90 depth integrated profile of total suspended load (sand load is not separated) is collected by the USGS at Tarbert Landing. This data can be found online at:

http://waterdata.usgs.gov/la/nwis/dv?referred_module=sw&site_no=07295100

This daily measurement is plotted against the ratings curve results in Figure 1.10a and can also be found in the supplementary file "MonitoringWater&Sediment.xls".

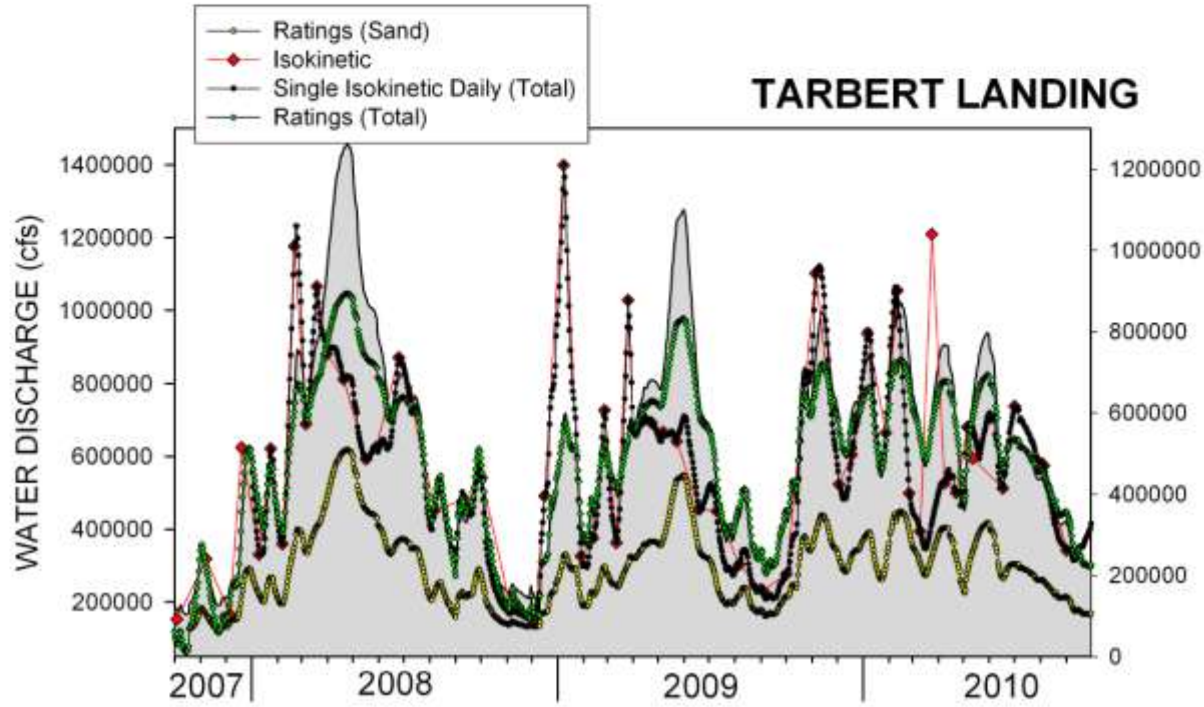


Figure 1.10a. Measured daily water discharge (gray curve), isokinetic total sediment load measured by boat (D90 sampler), total sediment load calculated by ratings curve method, and sand load calculated by the ratings curve method for Tarbert Landing. Also plotted are the daily measurements from the single depth integrated isokinetic profile.

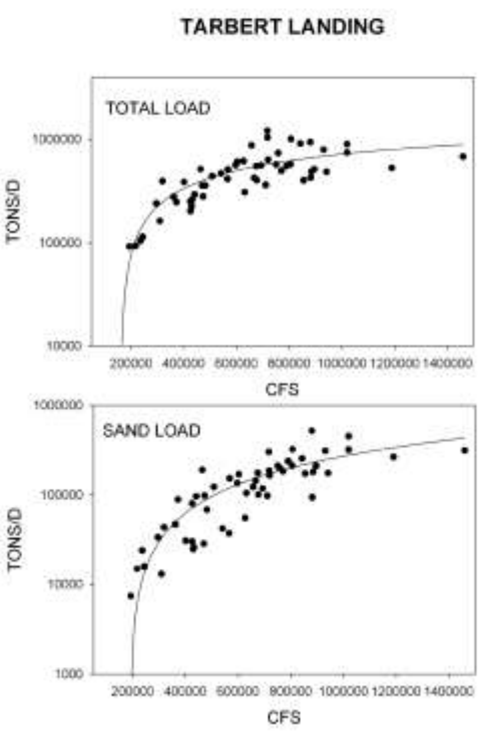


Figure 1.1b. Ratings curve fits for the water versus sediment load (total upper, sand lower) for all boat measurements made at Tarbert Landing in FY 2008-2010.

1.11 Wax Lake Outlet, Louisiana The station at Wax Lake is operated by the U.S. Geological Survey (USGS 07381590) funded by the U.S Army Corps of Engineers and is located on the railroad bridge across the Wax Lake (Atchafalaya) Outlet channel at latitude 29°41'52", longitude 91°22'22". Data for this station is available online at:

http://waterdata.usgs.gov/la/nwis/nwisman/?site_no=07381590&agency_cd=USGS

Daily water discharge (Fig 1.11a) is calculated based on USGS averaging of higher frequency data collected with a horizontal acoustic Doppler current profiler (H-ADCP) mounted on the platform. This has been in operation since March of 1986. Daily data for FY2008-2010 can be found in supplementary file "MonitoringWater&Sediment.xls".

Sediment loads for Wax Lake are based on USGS boat surveys conducted along a cross-section at the site 12-15 times per year and available online at the aforementioned website. The D90 and ADCP measurement methods were identical to those previously outlined for Baton Rouge above. Boat measured water and sediment data (water discharge, total sediment load, sand load) for USGS sampling dates at Wax Lake in FY2008-2010 can be found in the supplementary file "MonitoringWater&Sediment.xls".

Daily sediment loads at Wax Lake were calculated utilizing the isokinetic boat data in FY2008-2010 and a ratings curve methodology. Separate ratings curves were constructed for total sediment load and sand load (Fig. 1.11b). The best fit (r^2=0.53) for the total load was obtained using the following 2nd order logarithm curve:

Total Load (tons/day) = $Y_0 + (a * \ln(cfs)) + (b * (\ln(cfs)^2)$

$Y_0 = -1.863E+3$
a = -3.416E+5
b = 2.8524E+4

The best fit (r^2=0.62) for the sand load was obtained using the following three parameter power law equation:

Sand Load (tons/d) = $Y_0 + (a * cfs\verb|^|b)$

$Y_0 = -1.501E+3$
a = 5.003E-12
b = 2.945

Daily results (total and sand) can be found in the supplementary file "MonitoringWater&Sediment.xls" and are plotted in Figure 1.11a.

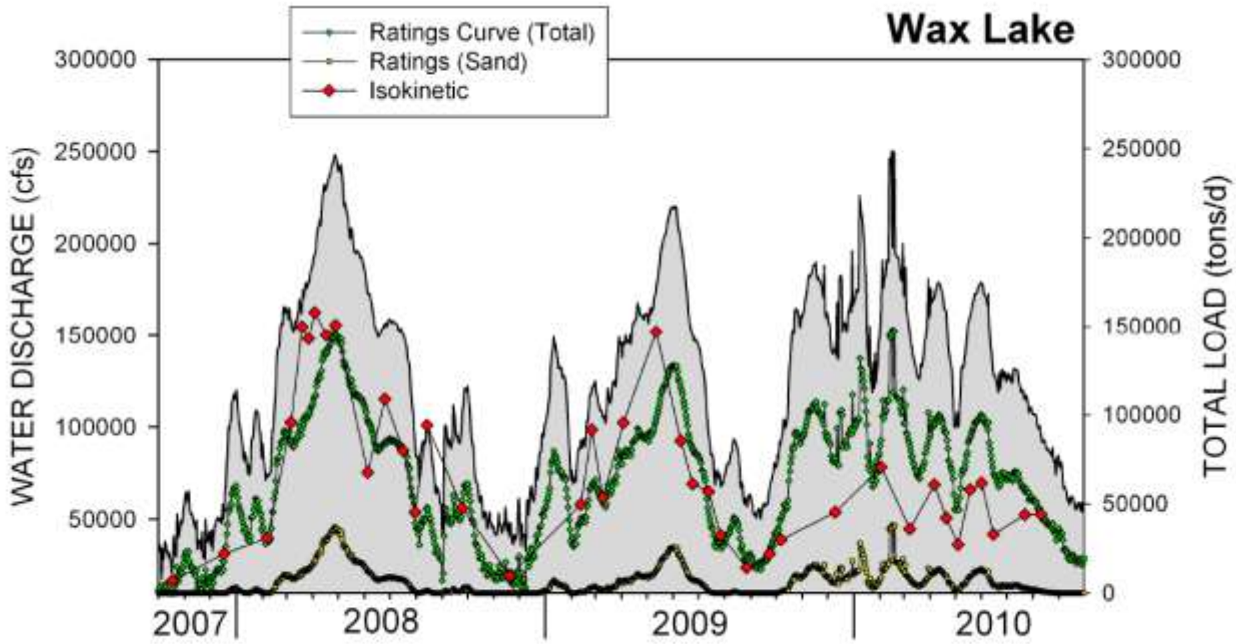


Figure 1.11a. Measured daily water discharge (gray curve), isokinetic total sediment load measured by boat (D90 sampler), total sediment load calculated by ratings curve method, and sand load calculated by the ratings curve method for Wax Lake.

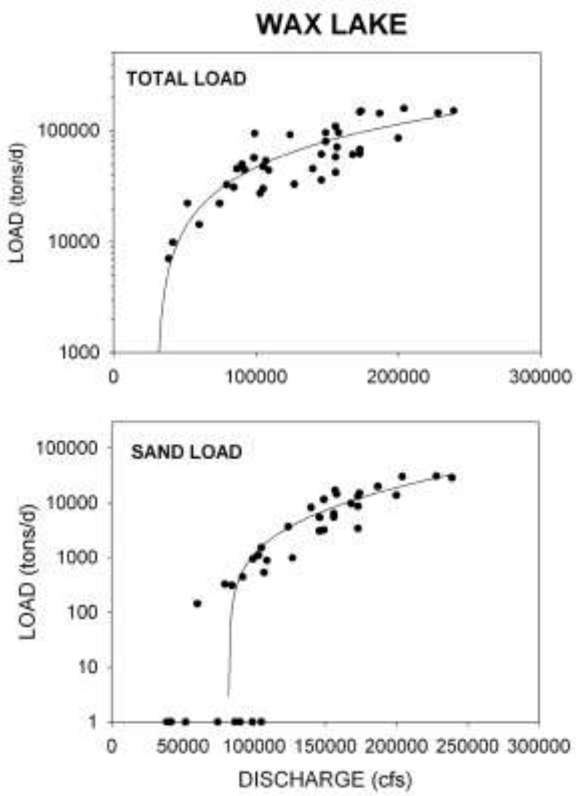


Figure 1.11b. Ratings curve fits for the water versus sediment load (total upper, sand lower) for all boat measurements made at Wax Lake in FY 2008-2010.

2. PROJECT STUDIES

2.1 Bohemia Spillway The Bohemia "Spillway" as it has been called, is along the east bank of the Mississippi River channel in Plaquemines Parish, Louisiana immediately downriver of the Point a la Hache ferry landing. This region (see Figure 2.1a), extending from the downriver limit of the river and hurricane protection levees (river mile 45) on this side of the river, to immediately above the Sixty Mile Point bend (about RM35), has a raised, river-parallel roadbed that is pierced by several culverts and semi-ruinous older diversion structures that are presently unmanaged.

Elevation mapping by the USACE has been utilized by the USACE and the present authors (Meselhe) to estimate loss out of the river through this reach at various discharges with the 1D model HEC-RAS (Fig. 2.1b) . These results suggest overbank flow begins at discharges above about 700,000 cfs and reach as much as 30% of total flow at discharges above one million. An earlier modeling exercise by USACE Mississippi Valley Division prior to 2005 (utilizing the HEC-6T model) assumed no overbank until a discharge of about 930,000 cfs and a constant 4% of river discharge above that. Prior to our efforts in the present study, we are not aware of any field data collection that was conducted to verify these estimates.

On May 12, 2011 the authors (Allison) conducted a boat-based acoustic Doppler current meter (ADCP) survey (RD Instruments 600 kHz unit) of the area of the Spillway during an extreme discharge when the Bonnet Carre Spillway was open. At a transect at RM46.6 upriver of the Spillway and below the Point a la Hache ferry landing, an average of multiple channel transects was 1.155 million cfs. Mid-way down the Spillway at a point (RM41.5) below the most recently emplaced diversion structure at Bohemia and at a point where revetment (rip-rap) was exposed (assuring no downriver loss beyond the measured transect) a discharge of 1.146 million cfs was measured. Below the Spillway at RM35.5 (immediately upriver of Sixty Mile Point), discharge was 1.139 million cfs. All transects were completed within a 1.5 hour period. This data suggests a loss of only 16,000 cfs over the Bohemia reach even at this extreme discharge: even a 4% loss at this discharge using the model parameters would result in 46,200 cfs, and far less than that predicted by the HEC-RAS model runs. Given that this is ostensibly the maximum flow allowed past Bonnet Carre, and these values fall within the 1-2% generally observed for these discharge measurements, we conclude that there is negliglble loss from the river through this pathway. Continued modification of the roadbed in the area to maintain access to the canals out to Breton Sound (see Fig. 2.1a) may be responsible for limiting diversion of river water.

Following the HEC-6T model results, water discharge through Bohemia Spillway was assumed to be 0 at river discharges below 930,000 cfs and 1.4% (16,000/1,155,000) at higher discharges. While not shown in figure form, the daily water results for FY2008-2010 can be found in supplementary file "Diversions&PassesWater&Sediment.xls". In the absence of other data, sediment loads (total and sand) were estimated as 1.4% of USGS Belle Chasse minus the loss at Caernarvon at discharges above 930,000 cfs. Daily results (total and sand) for FY2008-2010 can be found in the supplementary file "Diversions&PassesWater&Sediment.xls".

Figure 2.1a. Google[@] map image of the Mississippi River reach associated with the Bohemia Spillway.

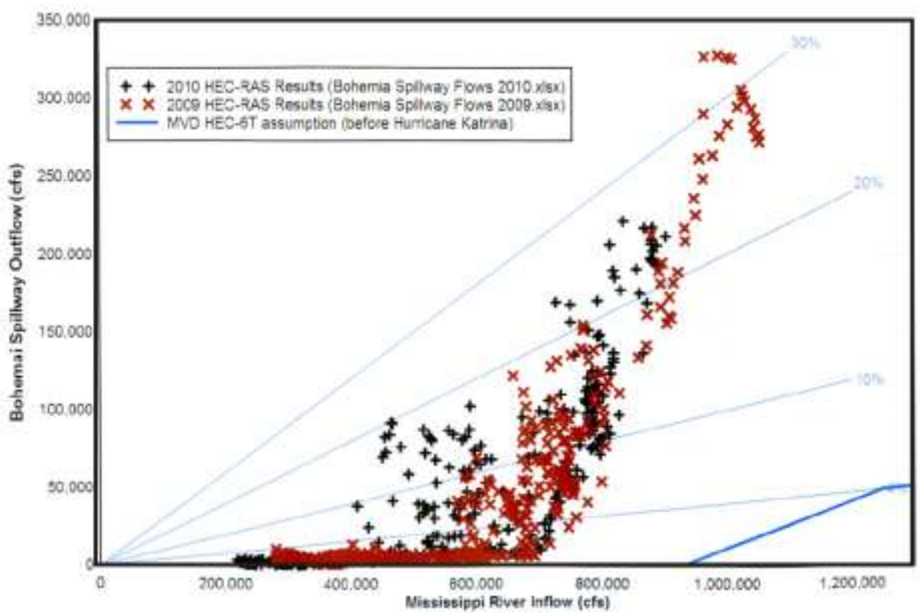


Figure 2.1b. Graph of discharge through the Bohemia Spillway predicted by HEC-RAS and HEC-6T modeling carried out by the authors and the USACE.

2.2 Bonnet Carre Spillway The spillway at Bonnet Carre is a flood protection diversion structure operated by the USACE on the east bank of the Mississippi River between river miles 129 and 127 (above New Orleans). The structure is a 7000 ft long (2134 m) concrete weir with 350 bays, each sealed with 20 timber ''needles" that can be raised by a crane running along the weir top to allow river water to pass into an earthen leveed spillway into Lake Pontchartrain: total capacity is 250,000 cfs (7,079 cms). The spillway's opening is triggered when discharge reaches 1.25 million cfs at the USACE's gage at Red River Landing (available online through the USACE at http://www.mvn.usace.army.mil/eng/edhd/rrl.gif). Opened on nine occasions between 1937 and 2010, detailed monitoring of suspended sediment behavior (in the spillway) was conducted by the USGS and USACE in the last two openings (1997 and 2008; see Allison and Meselhe, 2010 for information on these statistics).

Two methods of water loss from the channel through the Bonnet Carre Spillway took place during the FY2008-2010 period that is the focus of this study. The first is an opening triggered by discharge above 1.25 million cfs that took place from April 12-May 7, 2008. Water statistics provided by the USGS (and discussed in detail in Allison and Meselhe, 2010) show a gradual increase in flow after the first gates were opened on April 12th, reaching a maximum of 169,000 cfs on April 22nd, followed by a gradual decrease in exiting flow until the last gates were closed on May 7th. The second method of water loss is leakage through the pins of the closed structure when stage at Bonnet Carre (available online at through the USACE at http://www.mvn.usace.army.mil/cgi-bin/watercontrol.pl?01280) is above 15.5 ft NGVD. Measurements of leakage made by the USACE New Orleans district at various stages (Fig. 2.2a) demonstrate this effect is non-linear. A best fit (r^2=0.9996) relationship for this water loss was obtained using the following three parameter power law equation:

$$\text{Stage (ft.)} = Y_0 + (a * \text{cfs}^b)$$

$Y_0 = 1.539E+01$
$a = 4.334E-02$
$b = 5.484E-01$

To determine what discharge the stage at Bonnet Carre (where discharge is not measured directly) equates to, a comparison was made of Bonnet Carre stage versus Baton Rouge measured discharge in FY 2008-2010 (Fig. 2.2b). Two best fit curves (linear versus five parameter sigmoidal) gave the highest r^2—0.96 and 0.97, respectively. The sigmoidal was utilized to determine water discharge due to its better r^2. The sigmoidal relationship was:

$$\text{cfs} = Y_0 + a/(1 + \exp(-(\text{STAGE}-X_0)/b))^c$$

$a = 5.5773E+6$
$b = 1.503$
$c = 7.804E-02$
$X_0 = 4.484E1$
$Y_0 = -3.758E5$

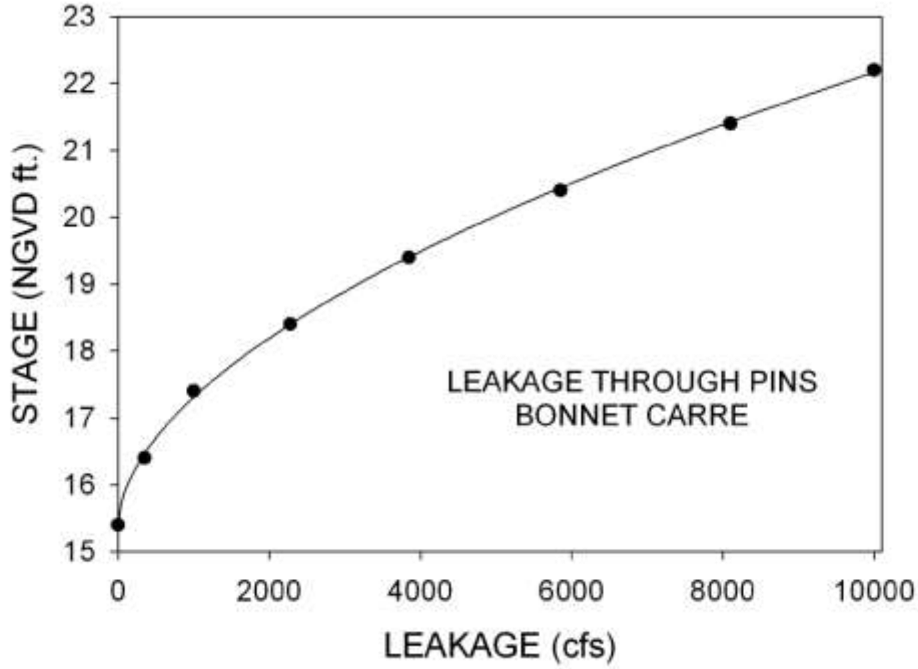


Figure 2.2a. Graph of water leakage relationship through the pins at Bonnet Carre when the structure is closed and the stage at the site exceeds 15.5 ft above NGVD.

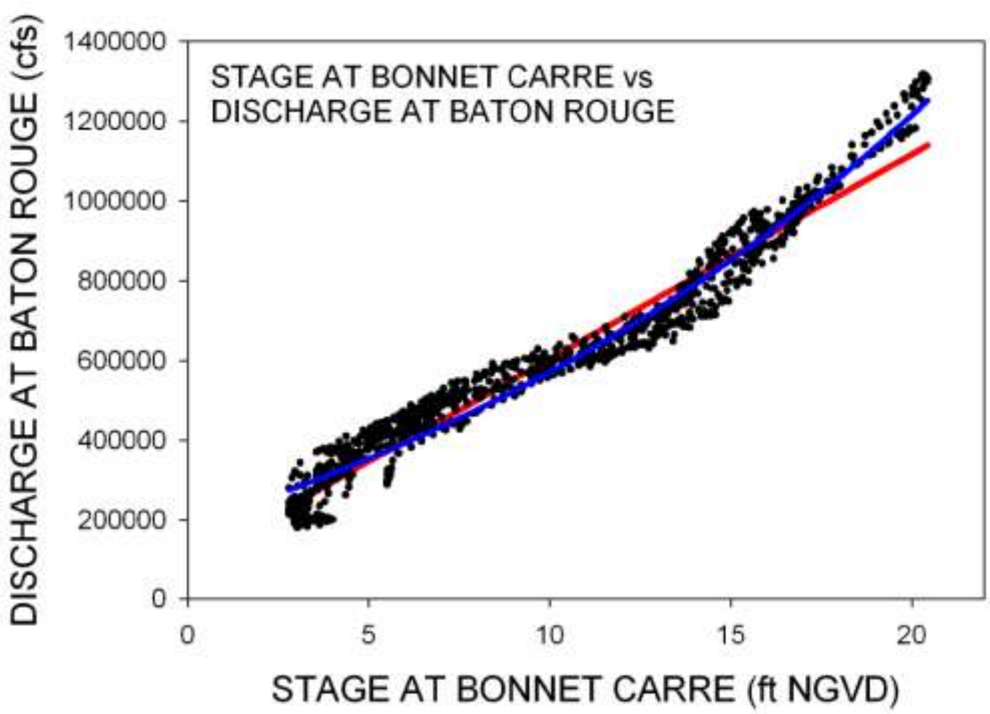


Figure 2.2b. Graph of stage at Bonnet Carre versus discharge at Baton Rouge used to calculate daily loss through pin leakage at the structure. Red line is the best fit linear regression, blue the best fit 5 parameter sigmoidal relationship.

The final water loss values through Bonnet Carre are a summation of the two mechanisms and are shown in Figure 2.2c. This daily data for FY2008-2010 can be found in supplementary file "Diversions&PassesWater&Sediment.xls". In calendar year 2010, the USACE New Orleans district placed covers over the pins to limit leakage, in order to facilitate sand mining in the Spillway. Hence, the estimates shown in Figure 2.2c were not used in FY 2010 water calculations, and total loss was assumed to be zero.

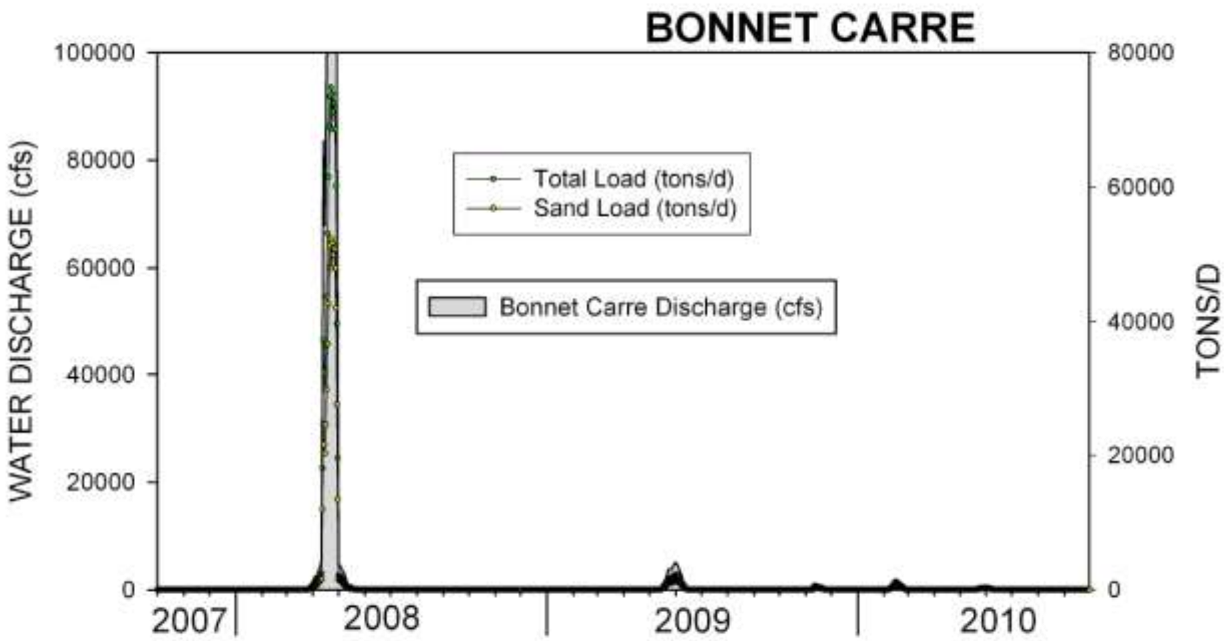


Figure 2.2c. Calculated daily water discharge (gray curve), total sediment load calculated by ratings curve method, and sand load calculated by the ratings curve method for the Bonnet Carre Spillway in FY 2008-2010.

Given that suspended sediment discharges measured during the 2008 opening of Bonnet Carre were in the spillway (at the Airline Highway bridge) and not at the bays, likely there was major sediment deposition in the Spillway (particularly of sand; Allison and Meselhe, 2010) making these numbers unreliable for determining actual total and sand load loss from the river in the event. No measurements are made of suspended load in the pin leakage events. Hence, total and sand load estimate through the structure (Fig. 2.2c) were made using Baton Rouge sediment loads, and a percentage of the daily water discharge at Bonnet Carre relative to Baton Rouge (measured) total water discharge. Daily results (total and sand) can be found in the supplementary file "Diversions&PassesWater&Sediment.xls". In FY 2010, no sediment loss was assumed due to the pin covers at the Spillway.

2.3 Caernarvon Freshwater Diversion The station at Caernarvon diversion is operated by the U.S. Geological Survey (USGS295124089542100) and is located on the east bank of the Mississippi River channel in the outfall channel of the diversion at latitude 29°51'12.8", longitude 89°54'27.7". Water data for this station is available online at:

http://waterdata.usgs.gov/nwis/nwisman/?site_no=295124089542100&agency_cd=USGS

Daily water discharge (Fig 2.3a) is calculated based on USGS averaging of higher frequency data collected with a horizontal acoustic Doppler current profiler (H-ADCP) mounted in the outfall channel. This has been in operation since January of 2001. Daily data for FY2008-2010 can be found in supplementary file "Diversions&PassesWater&Sediment.xls".

While some optical backscatterance sensor turbidity data was available for the outfall channel, it was not utilized for constructing suspended sediment loads through the diversion as it was observed to increase to levels above that in the adjacent river when the structure was first opened. This was interpretated to be due to resuspension of sediments deposited in the outfall channel. Hence, total and sand load estimate through the structure (Fig. 2.3a) were made using sediment loads at the nearby Belle Chasse station (Belle Chasse river mile 73 vs. 81.5), and a percentage of the daily water discharge passing through the structure relative to Belle Chasse (measured) total water discharge. Daily results (total and sand) can be found in the supplementary file "Diversions&PassesWater&Sediment.xls".

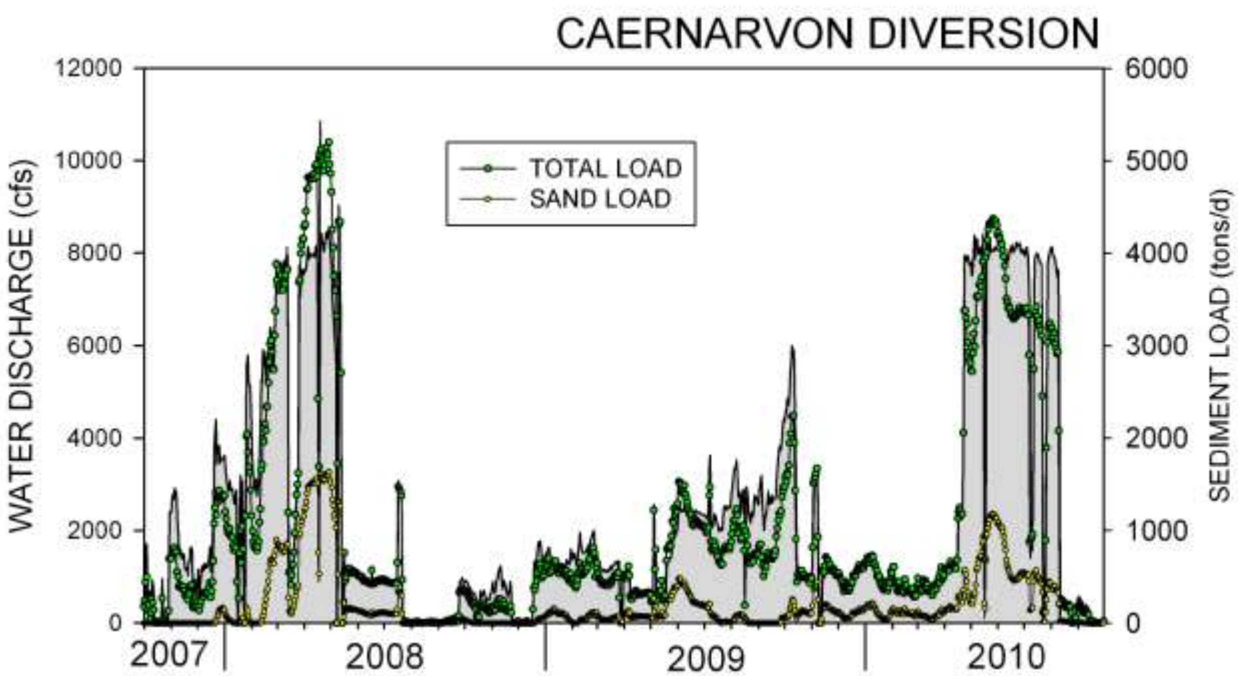


Figure 2.3a. Measured daily water discharge (gray curve) and total and sand suspended sediment load calculated for the Caernarvon Freshwater Diversion in FY 2008-2010.

2.4 Davis Pond Freshwater Diversion The station at the Davis Pond diversion is operated by the U.S. Geological Survey (USGS295501090190400) and is located on the west bank of the Mississippi River channel in the outfall channel of the diversion at latitude 29°55'01", longitude 90°19'04". Water data for this station is available online at:

http://waterdata.usgs.gov/nwis/nwisman/?site_no=295501090190400&agency_cd=USGS

Daily water discharge (Fig 2.4a) is calculated based on USGS averaging of higher frequency data collected with a horizontal acoustic Doppler current profiler (H-ADCP) mounted in the outfall channel. This has been in operation since April of 2002. Daily data for FY2008-2010 can be found in supplementary file "Diversions&PassesWater&Sediment.xls".

Total and sand load estimate through the structure (Fig. 2.4a) were made using sediment loads at the nearby Belle Chasse station (Belle Chasse river mile 73 vs. 111), and a percentage of the daily water discharge passing through the structure relative to Belle Chasse (measured) total water discharge. Daily results (total and sand) can be found in the supplementary file "Diversions&PassesWater&Sediment.xls".

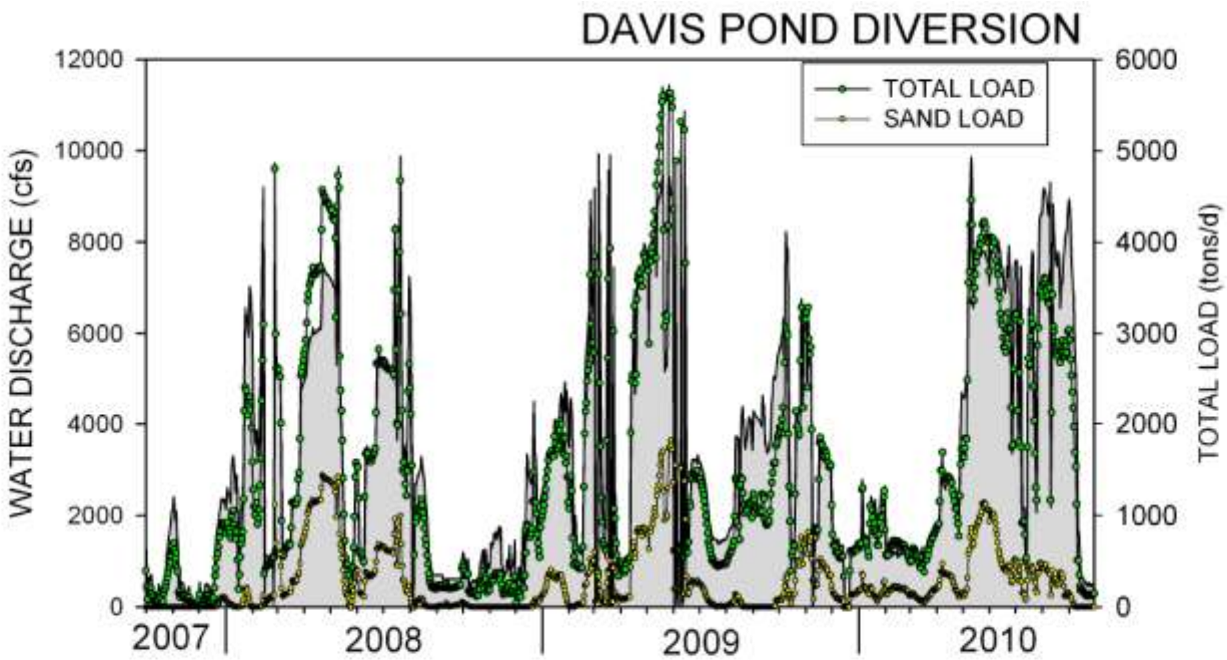


Figure 2.4a. Measured daily water discharge (gray curve) and total and sand suspended sediment load calculated for the Davis Pond Freshwater Diversion in FY 2008-2010.

2.5 Ostrica A series of 5 breaks in the east bank revetment (Fig. 2.5a) are located below the Ostrica Locks (river mile 25.2) and extending to river mile 23. The authors (Allison) carried out an ADCP survey at river mile 22.3 (below these features) on May 12, 2011 approximately 1 hour after the measurements were carried out at the Bohemia Spillway. As noted in section 2.1, the transects below the Spillway at RM35.5 (immediately upriver of Sixty Mile Point) measured a discharge of 1.139 million cfs. Discharge at river mile 22.3 was 1.083 million cfs. This suggests at this near maximum discharge allowed below Bonnet Carre a loss through these structures of about 56,000 cfs or about 5.2% of total latitudinal flow. A second study conducted at low discharge on September 23, 2009 over a three hour period. No loss was measured from multiple crossings (4/transect) conducted at RM26.4 (above) and RM22.7 (below): mean discharge above and below was 369,518 cfs. We are not aware of model simulations of these cuts estimating discharge relative to their elevation, hence, no information is available about what discharge these breaks become active or whether water loss with discharge is non-linear. To estimate water and sediment loss a linear loss of 5.2% of flow is utilized for discharges above 800,000 cfs.

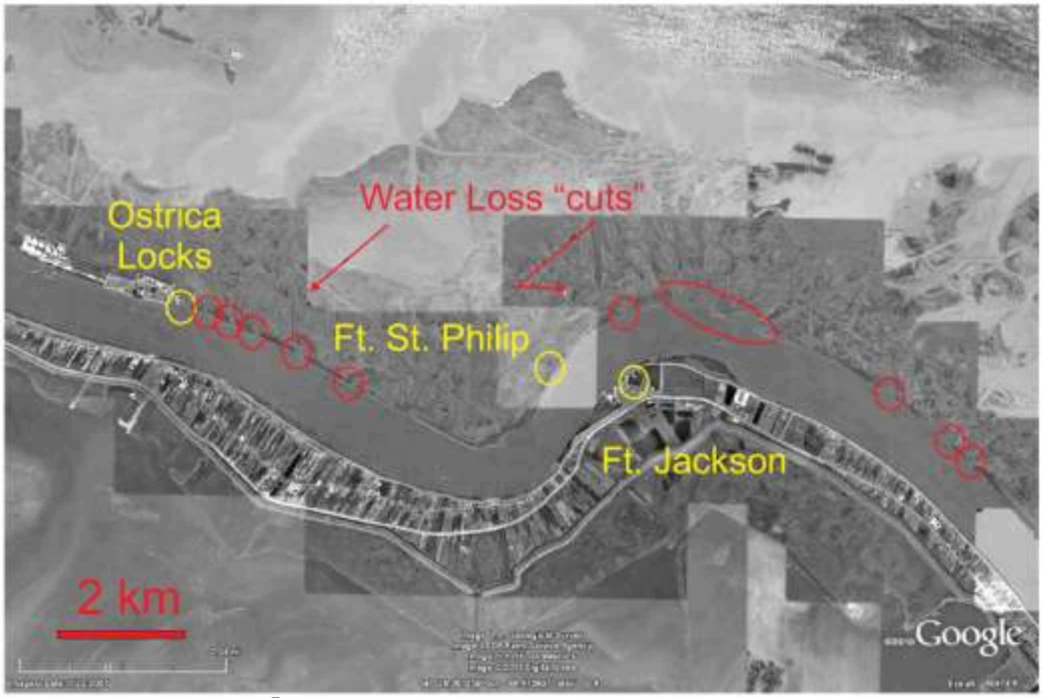


Figure 2.5a. Google[@] map image of the Mississippi River reach associated with the east bank river breaks in the revetment above and below Fort St. Philip.

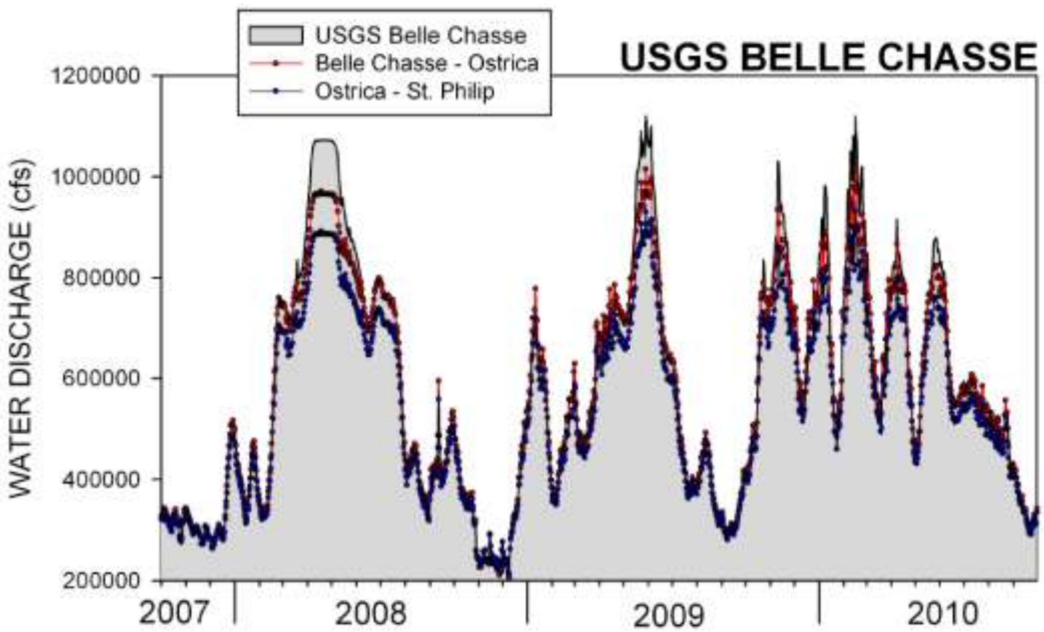


Figure 2.5b. Measured daily water discharge at Belle Chasse (gray curve) and calculated discharges below the revetment breaks at Ostrica and Ft. St. Philip in FY 2008-2010.

The daily water results for FY2008-2010 can be found in Fig. 2.5b and in the supplementary file "Diversions&PassesWater&Sediment.xls". In the absence of other data, sediment loads (total and sand) were estimated as 5.2% of USGS Belle Chasse at discharges above 800,000 cfs. Daily results (total and sand) for FY2008-2010 can be found in the supplementary file "Diversions&PassesWater&Sediment.xls"

2.6 Ft. St. Philip A second area of water loss on the east bank occurs downriver of the bend at Fort Jackson/Fort St. Philip (Fig. 2.5a). A series of breaks in the revetment have been observed by the authors on field surveys extending from between river miles 20.5 and 16. These breaks were surveyed by the authors (Allison) at low discharge on the same day (1-3 hours later) as Ostrica (September 23, 2009). Discharge below the revetment breaks was measured as 358,588 cfs (4 crossings each at RM13 and RM15.3). This is a reduction of 10,930 cfs or 3.0% of total latitudinal flow. The authors (Pratt) carried out additional ADCP survey on March 31, 2011 and April 4, 2011. Discharge above the revetment breaks (measured at RM 22) was 945,000 and 954,000 cfs, respectively on these dates. Loss below the breaks (measured at RM15.3) was 9.5% and 6.7%, respectively. We are not aware of model simulations of these cuts estimating discharge relative to their elevation, hence, we utilize a linear loss of flow applied using these values: best fit linear regressions for these breaks water ratings are slope 0.8868, y-intercept +30659 (r^2=0.99) using Belle Chasse water minus Ostrica loss. The calculated daily water results for FY2008-2010 are plotted in Figure 2.5b and can be found in supplementary file "Diversions&PassesWater&Sediment.xls". Total and sand load estimate through the revetment breaks were made using sediment loads at Belle Chasse station and the percentage of the daily water discharge passing through the structure relative to Belle Chasse (measured) minus Ostrica water discharge. Daily results (total and sand) for FY2008-2010 can be found in the supplementary file "Diversions&PassesWater&Sediment.xls"

2.7 Mississippi Passes above Head of Passes Observational studies of water and sediment dynamics related to the possible closure of the West Bay Diversion associated with shoaling in the main channel were carried out by the USACE (authors Pratt and Little) in 2009-2010. The aspects that are discussed in this report are shown in Fig. 2.7a and involve water and sediment discharge measurements through three (e.g., Baptiste Collette, Grand Pass, Cubit's Gap) major natural crevasses (modified by dredging in some cases), a series of four smaller "cuts" (results combined hereafter), and the artificial West Bay Diversion that was created in November 2003. Three main channel cross-sections where water and sediment discharge data were collected on the same field studies are also discussed: RM9.5 immediately below Grand Pass, RM5.2 immediately above the West Bay Diversion, and RM2.6 below all these passes, but above the channel tri-furcation at Head of Passes (Fig. 2.7a).

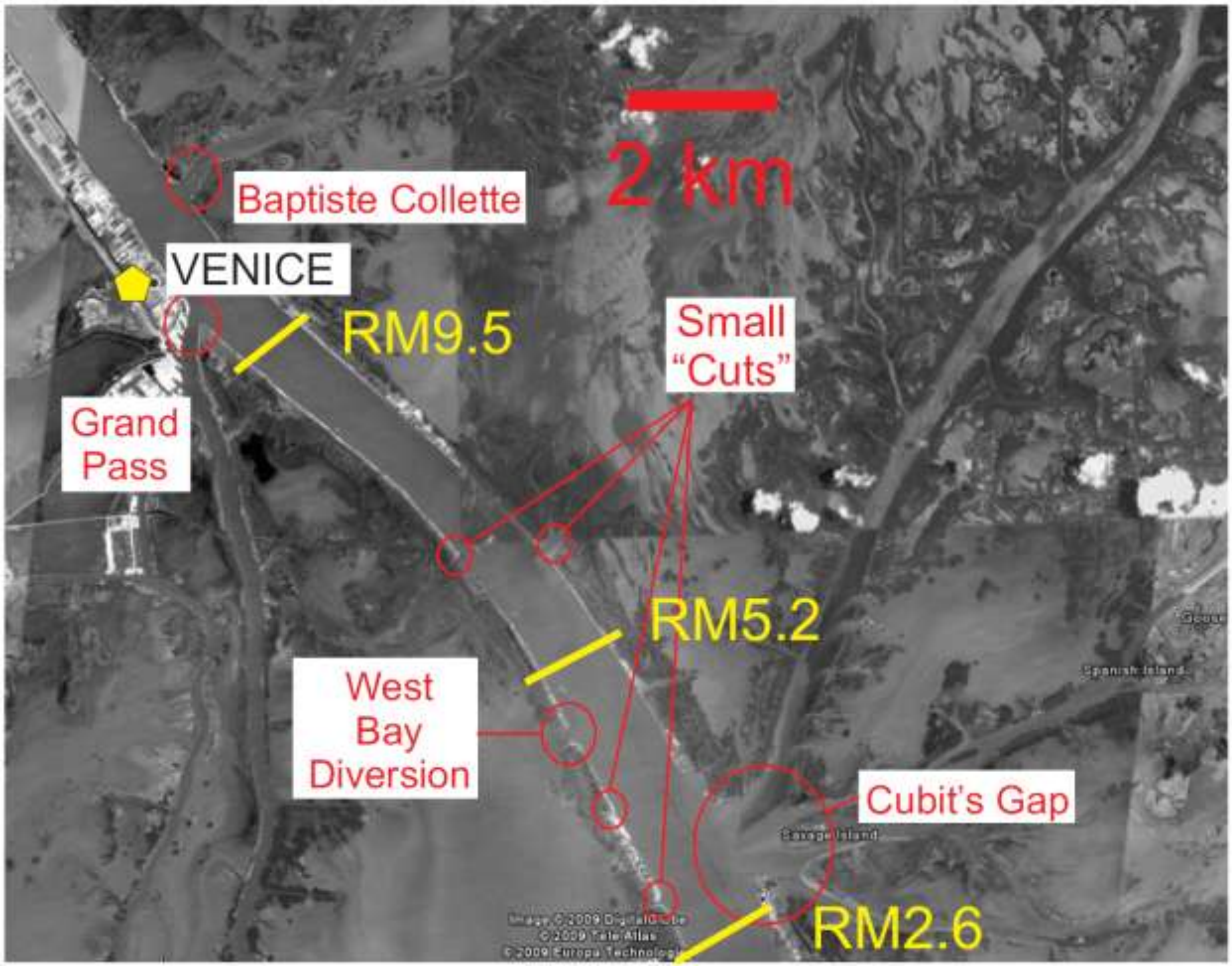


Figure 2.7a. Google@ map image of the Mississippi River reach associated with the Passes immediately upriver of Head of Passes.

Water discharges for the five passes (e.g., Baptiste Collette, Grand Pass, West Bay Diversion, Cubit's Gap and the combined small "cuts") were calculated utilizing ADCP cross-sections collected at the pass exit points on six dates between April 22-23, 2009 and Feb. 10, 2010 by the USACE (Pratt) team. Additional dates in FY2008-2010 were provided by the USACE New Orleans district from the same dataset described below in section 2.8. The resulting water ratings curves relative to daily discharge measured at the Belle Chasse station at RM73 are shown in Fig. 2.7b.

Best fit linear regressions for these passes water ratings are:

Baptiste Collette –	slope 0.1031, y-intercept -5631 (r^2=0.88)
Grand Pass –	slope 0.0915, y-intercept +4288 (r^2=0.92)
West Bay Diversion -	slope 0.0653, y-intercept -2075 (r^2=0.94)
Cubit's Gap-	slope 0.1319, y-intercept -19939 (r^2 =0.94)
Small "cuts"-	slope 0.0025, y-intercept +10196 (r^2 = 0.82)

The resulting daily discharge for FY2008-2010 for these three passes using these relationships and the daily discharge at Belle Chasse are shown in Fig. 2.7c-g). Daily data for FY2008-2010 can be found in supplementary file “Diversions&PassesWater&Sediment.xls”.

Water discharge at the main channel cross-sections was handled using the same datasets as the passes. Data from the RM9.5 and RM5.2 (collected on separate studies) was combined, given that only two small cuts change water discharge in the channel between those two points (see Fig. 2.7a). These linear relationships shown in Figure 2.7b versus Belle Chasse and show the following best fit regression:

RM9.5/5.2 – slope 0.5793, y-intercept +38930 (r^2=0.89)
RM2.6 – slope 0.5362, y-intercept -6233 (r^2=0.92)

The resulting daily discharge for FY2008-2010 for these two channel cross-sections using these relationships and the daily discharge at Belle Chasse are shown in Fig. 2.7h-i). Daily data for FY2008-2010 can be found in supplementary file “Diversions&PassesWater&Sediment.xls”.

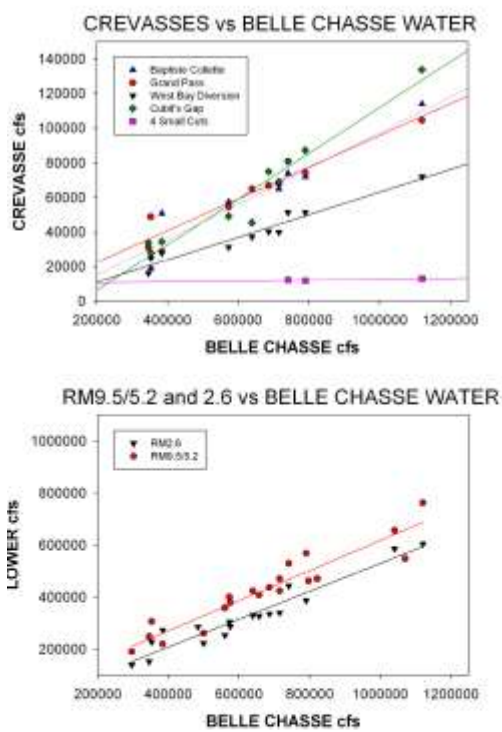


Figure 2.7b. Water ratings curves for discharge in the passes (upper) and main channel cross-sections (lower) in the Venice to Head of Passes reach of the Mississippi River.

Daily sediment loads at the passes and the two main channel cross-sections were calculated utilizing the isokinetic boat data collected in six studies between April 22-23, 2009 and Feb. 10, 2010 (from the Pratt study) and a ratings curve methodology. Separate ratings curves were constructed for total sediment load and sand load (Fig. 2.7j-k). The best fit relationships for the sites are as follows:

Baptiste Collette

The best fit (r^2=0.61) for the total load was obtained using the following exponential rise to maximum (double, 4 parameter) curve:

Total Load (tons/day) = a * (1-exp(-b*cfs)) + c * (1-exp(-d*cfs))	a = 1.735E12 b = 3.224E-13 c = -3.940E3 d = 9.020E-4

The best fit (r^2=0.49) for the sand load was obtained using the following simple exponent, 3 parameter exponential rise to maximum:

Sand Load (tons/d) = Y_0 + (a *(1- cfs^b))	Y_0 = -6.940E3 a = 6.022E7 b = 1.000

While this relationship fit well for lower discharges (see Fig. 2.7j), at gave abnormally high values at discharges above 80,000 cfs. For discharges above 80,000, sand load was calculated as total load * 0.165.

Grand Pass

The best fit (r^2=0.64) for the total load was obtained using the following three parameter power law equation:

Total Load (tons/d) = Y_0 + (a * cfs^b)	Y_0 = -1.694E3 a = 1.495E-6 b = 2.097

The best fit (r^2=0.63) for the sand load was obtained using the following 3 parameter exponential growth:

Sand Load (tons/d) = Y_0 + a * exp(b * cfs)	Y_0 = -3.650E2 a = 3.573E1 b = 5.834E-5

West Bay Diversion

The best fit (r^2=0.64) for the total load was obtained using the following three parameter power law equation:

Total Load (tons/d) = Y_0 + (a * cfs^b)	Y_0 = -2.085E3 a = 1.515E-5 b = 1.935

The best fit (r^2=0.50) for the sand load was obtained using the following single parameter exponential growth:

Sand Load (tons/d) = exp(a * cfs) a = 1.334E-4

Cubit's Gap

The best fit (r^2=0.94) for the total load was obtained using the following three parameter power law equation:

Total Load (tons/d) = Y_0 + (a * cfs^b) Y_0 = -1.434E3
a = 4.702E-7
b = 2.161

The best fit (r^2=0.42) for the sand load was obtained using the following single parameter exponential growth:

Sand Load (tons/d) = exp(a * cfs) a = 6.760E-5

Small "Cuts"

Given that no isokinetic measurements were made at these small features, total and sand discharge was calculated using the sediment load:water discharge relationships for the West Bay diversion corrected using the relative combined daily water discharge at the cuts versus that of West Bay Diversion.

RM9.5/5.2

The best fit (r^2=0.94) for the total load was obtained using the following three parameter power law equation:

Total Load (tons/d) = Y_0 + (a * cfs^b) Y_0 = -1.767E4
a = 7.826E-7
b = 1.989

The best fit for the sand load was obtained using the following single parameter exponential growth:

Sand Load (tons/d) = exp(a * cfs) a = 1.433E-5

Two curves are shown in Fig. 2.7k. While the relationship above described the data shape, it underestimated the values and was corrected to a best fit taking this relationship and multiplying by a factor of 7.

RM2.6

The best fit (r^2=0.87) for the total load was obtained using the following three parameter power law equation:

Total Load (tons/d) = Y_0 + (a * cfs^b)

Y_0 = -1.436E4
a = 3.182E-5
b = 1.729

The best fit (r^2=0.31) for the sand load was obtained using the following single parameter exponential growth:

Sand Load (tons/d) = exp(a * cfs)

a = 1.926E-5

Daily results (total and sand) can be found in the supplementary file "Diversions&PassesWater&Sediment.xls" and are plotted in Figure 2.7c-i.

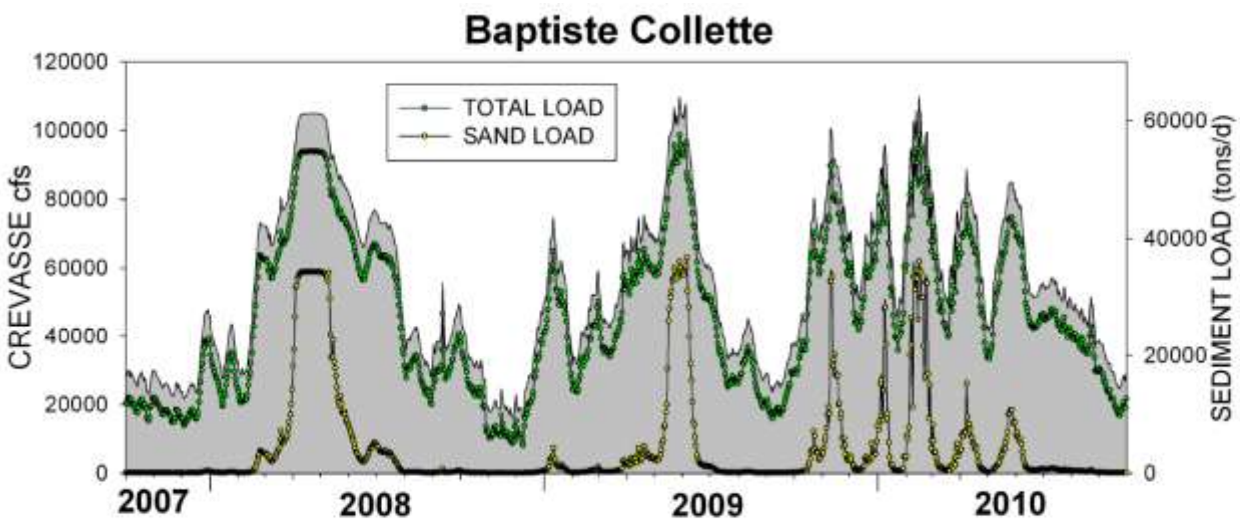


Figure 2.7c. Calculated daily water discharge (gray curve), total sediment load calculated by ratings curve method, and sand load calculated by the ratings curve method for Baptiste Collette in FY 2008-2010.

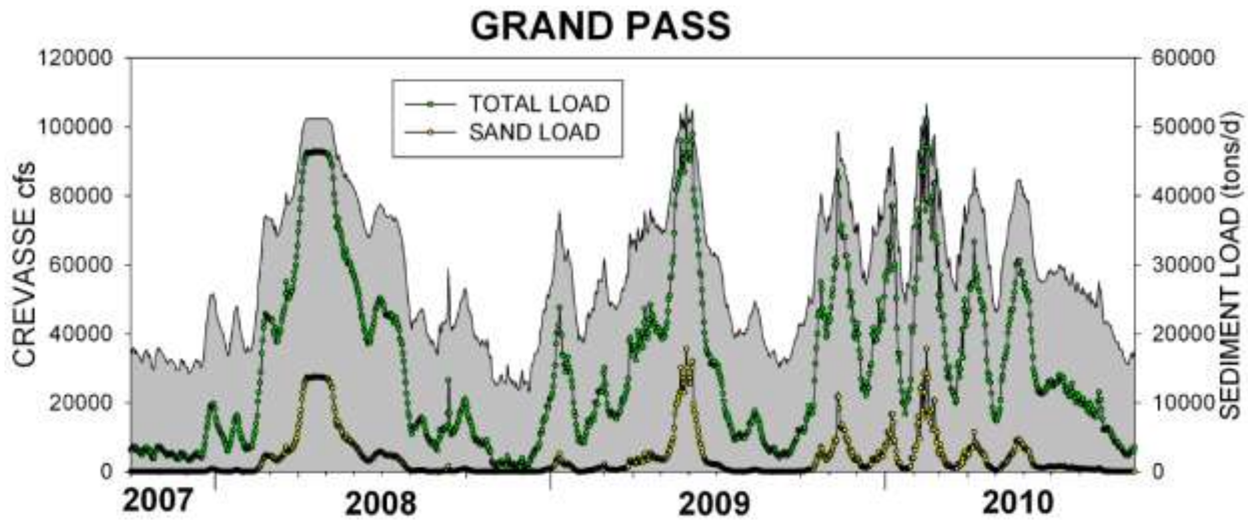


Figure 2.7d. Calculated daily water discharge (gray curve), total sediment load calculated by ratings curve method, and sand load calculated by the ratings curve method for Grand Pass in FY 2008-2010.

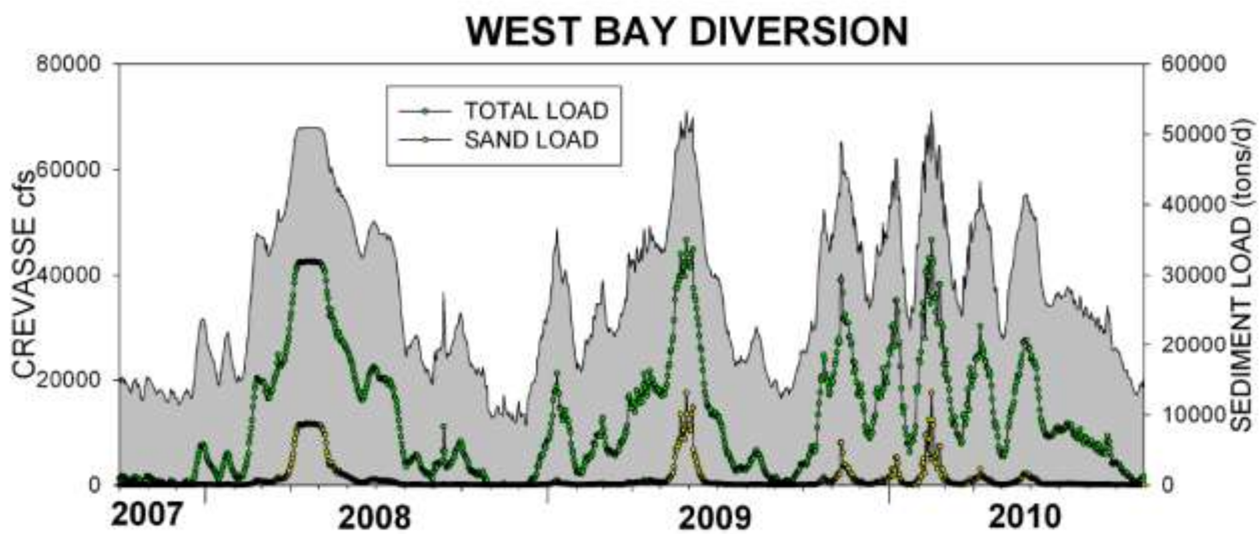


Figure 2.7e. Calculated daily water discharge (gray curve), total sediment load calculated by ratings curve method, and sand load calculated by the ratings curve method for West Bay Diversion in FY 2008-2010.

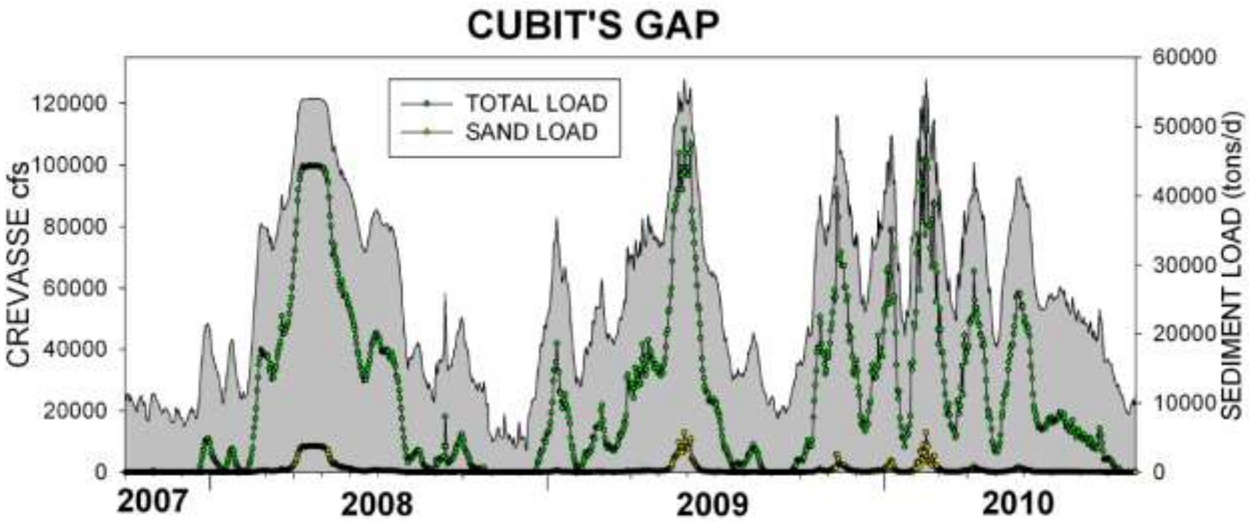


Figure 2.7f. Calculated daily water discharge (gray curve), total sediment load calculated by ratings curve method, and sand load calculated by the ratings curve method for Cubit's Gap in FY 2008-2010.

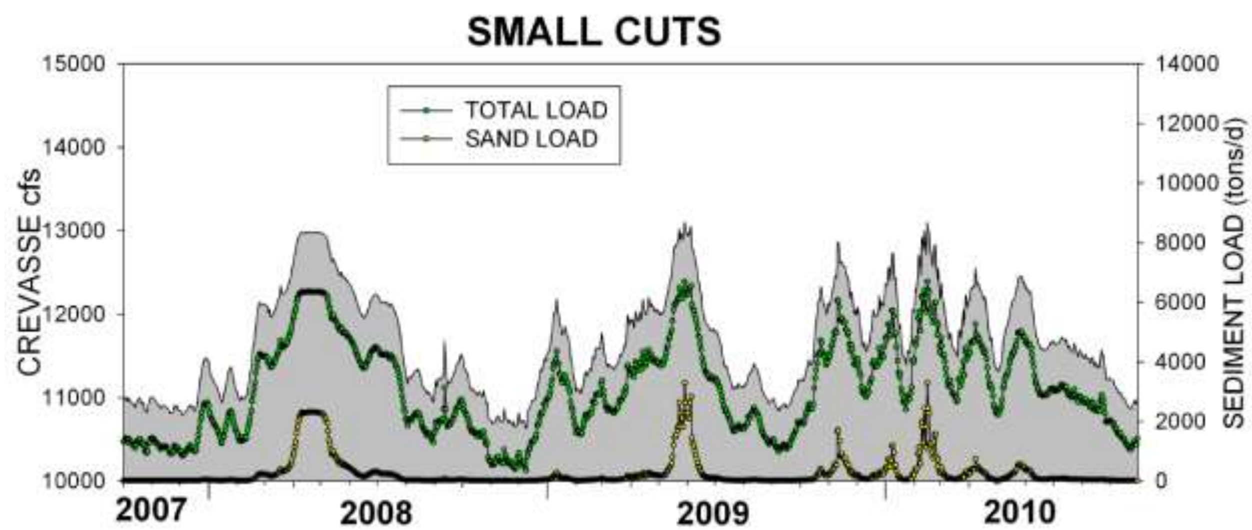


Figure 2.7g. Calculated daily water discharge (gray curve), total sediment load calculated by ratings curve method, and sand load calculated by the ratings curve method for the Small "cuts" in FY 2008-2010.

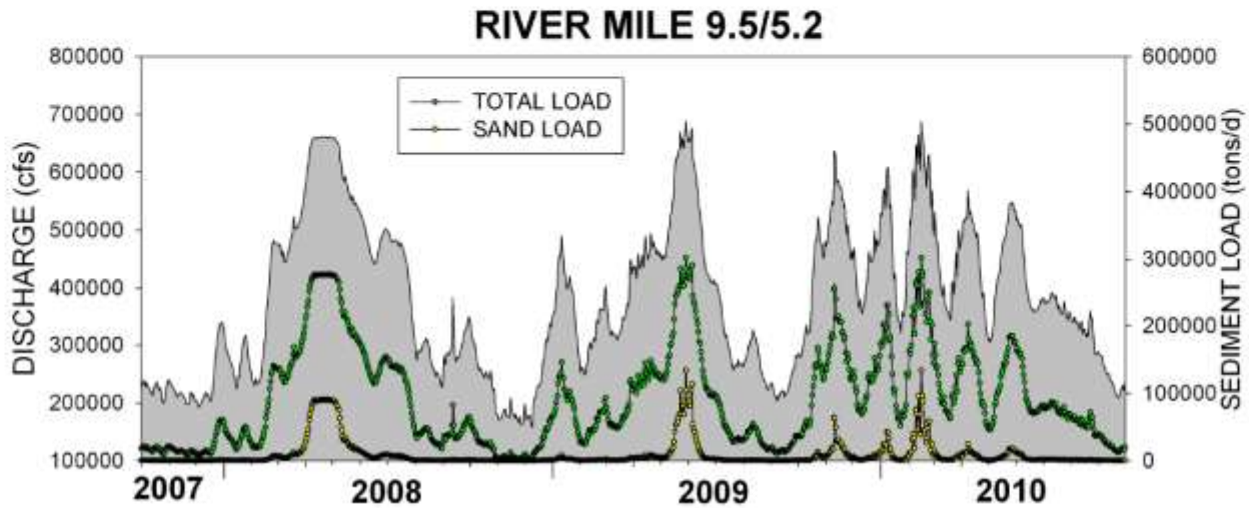


Figure 2.7h. Calculated daily water discharge (gray curve), total sediment load calculated by ratings curve method, and sand load calculated by the ratings curve method for River Mile 9.5/5.2 main channel in FY 2008-2010.

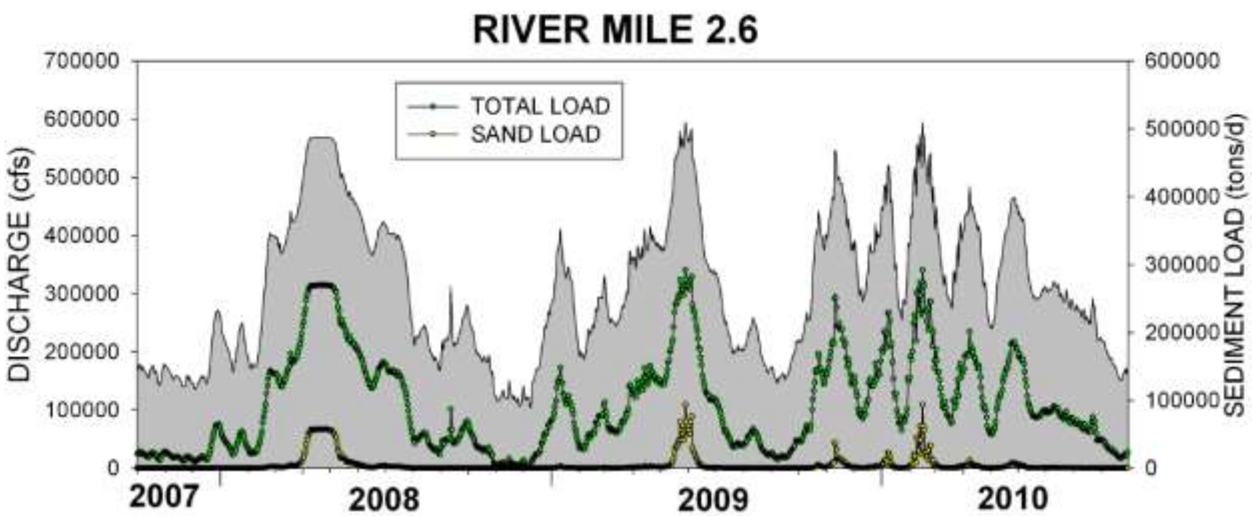


Figure 2.7i. Calculated daily water discharge (gray curve), total sediment load calculated by ratings curve method, and sand load calculated by the ratings curve method for River Mile 2.6 main channel in FY 2008-2010.

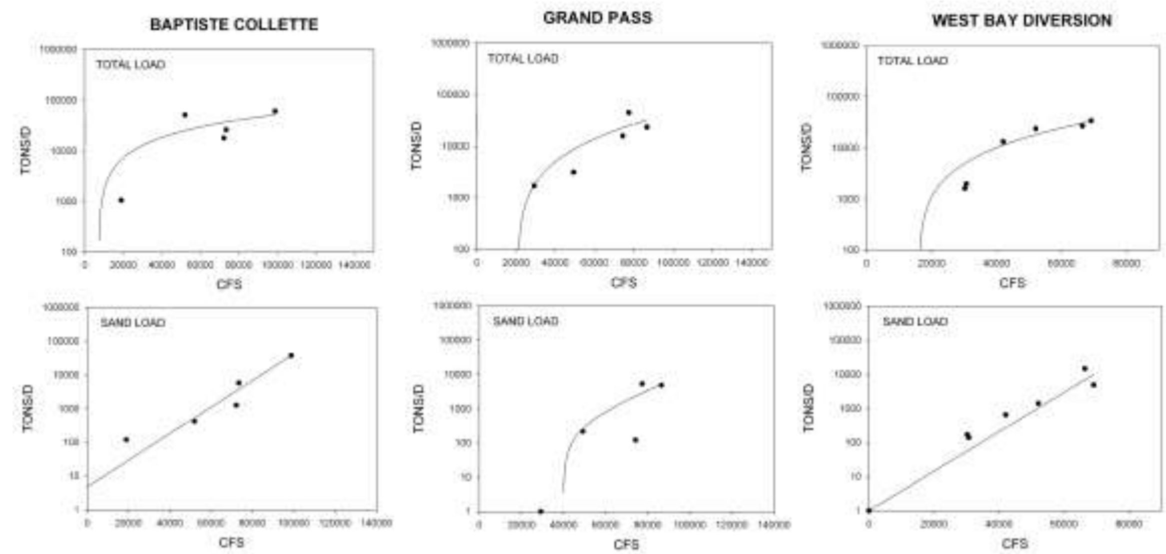


Figure 2.7j. Ratings curve fits for the water versus sediment load (total upper, sand lower) for all boat measurements made at Baptiste Collette, Grand Pass and West Bay Diversion in FY 2008-2010.

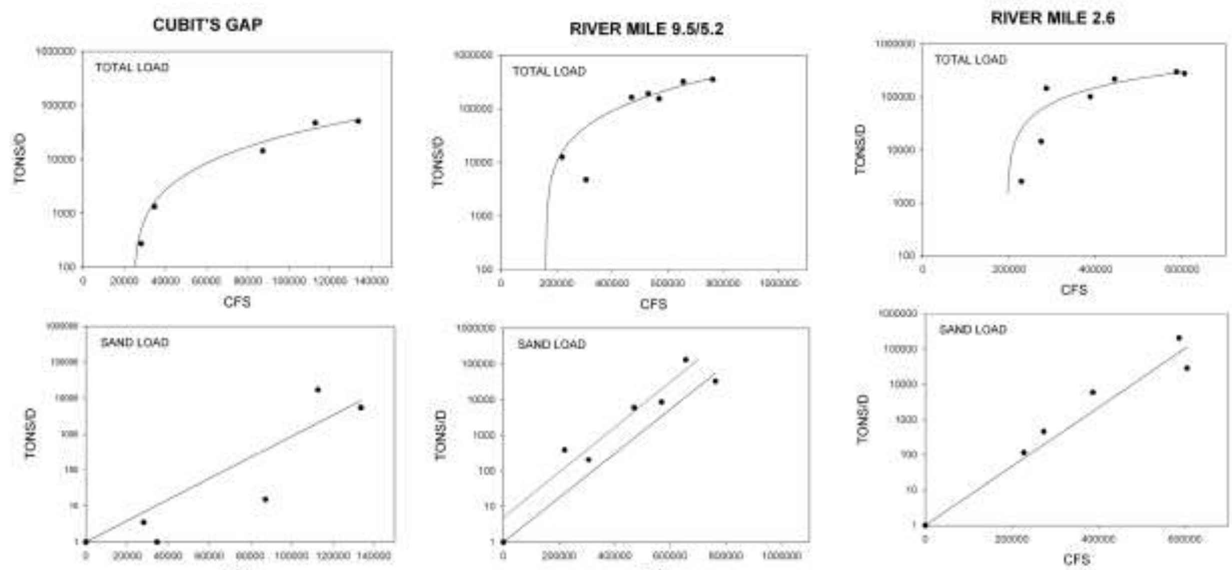


Figure 2.7k. Ratings curve fits for the water versus sediment load (total upper, sand lower) for all boat measurements made at Cubit's Gap, main channel RM9.5/5.2 and main channel RM2.6 in FY 2008-2010.

2.8 Mississippi Passes below Head of Passes Water discharge through the three main passes of the Mississippi River (e.g., Southwest Pass, South Pass, and Pass a Loutre; Fig. 2.8a) was measured by boat-based ADCP (USACE New Orleans District) on 14 occasions between December 19, 2008 and January 24, 2011. This data is plotted in Figure 2.8b against discharge for those dates measured at Belle Chasse to construct a water ratings curve. Best fit linear regressions for these three passes water ratings are:

Southwest Pass –	slope 0.4189, y-intercept -64787 (r^2=0.96)
South Pass –	slope 0.0858, y-intercept +2332 (r^2=0.90)
Pass a Loutre -	slope 0.0543, y-intercept +15700 (r^2=0.74)

The resulting daily discharge for FY2008-2010 for these three passes using these relationships and the daily discharge at Belle Chasse are shown in Fig. 2.8c-e. Daily data for FY2008-2010 can be found in supplementary file "Diversions&PassesWater&Sediment.xls".

The authors are unaware of sediment load measurements made in the pass channels that can be utilized to construct a sediment ratings curve. Direct comparison of the Belle Chasse sediment loads would neglect sediment fractionation taking place in the tidal and estuarine reach, likely leading to significant error. Hence, calculations of sediment load through the passes were developed using the sediment ratings curve at RM2.6 (see Figure 2.7k). These loads were calculated by first calculating the daily total and sand load at RM2.6 (see section 2.7), then fractionating it for each pass using its individual water discharge divided by the total water discharge for the three passes. This methodology yielded sediment numbers when totaled for the three passes that differed slightly from the RM2.6 values—given that they are based on independent)water ratings curves. The resultant total and sand loads for the three passes are shown in Figures 2.8c-e and can be found in the supplementary file "Diversions&PassesWater&Sediment.xls".

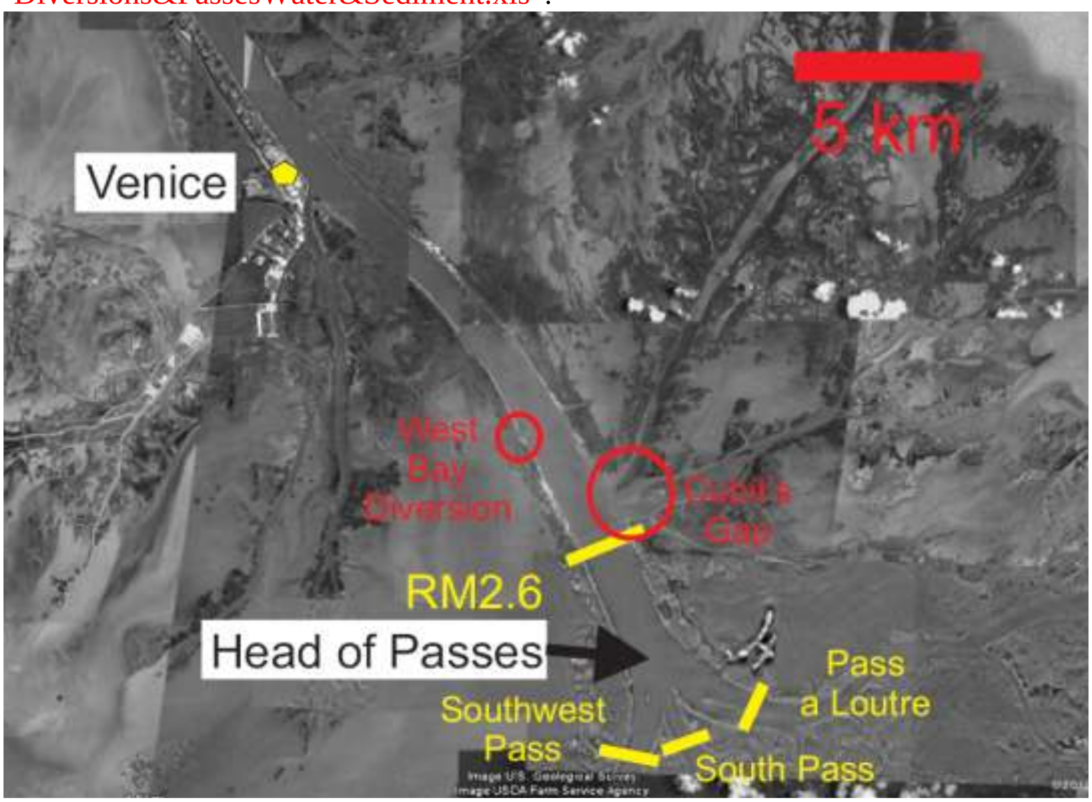


Figure 2.8a. Google® map image of the Mississippi River reach associated with the Passes immediately downriver of Head of Passes.

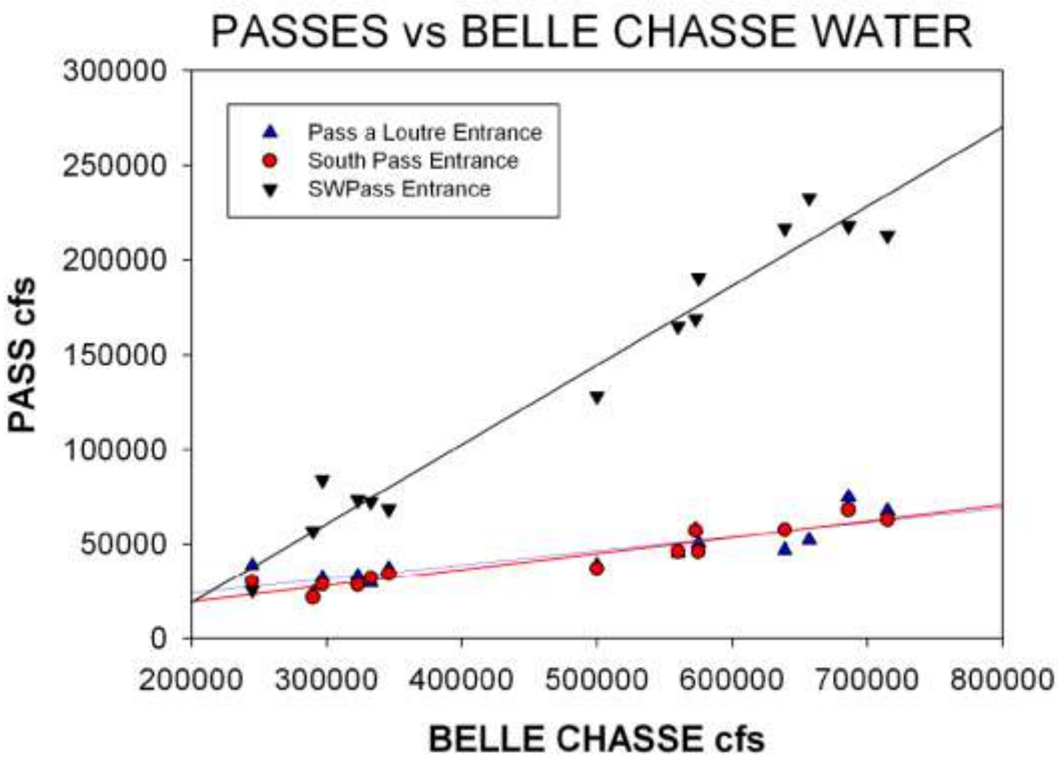


Figure 2.8b. Water ratings curve for the three Mississippi River passes below Head of Passes developed using ADCP transects relative to Belle Chasse discharge for that day.

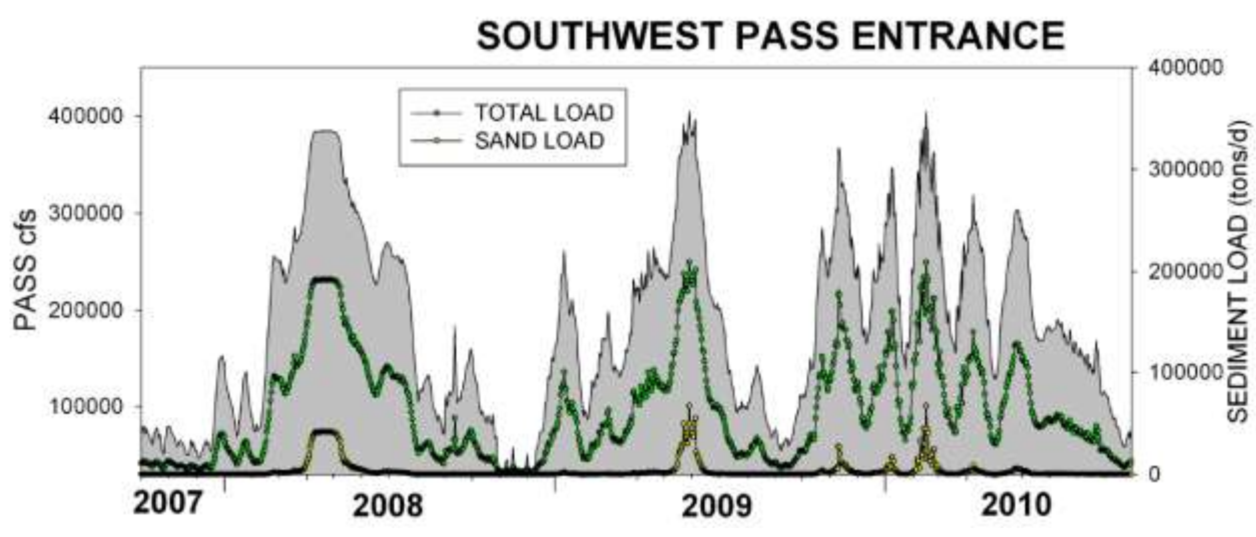


Figure 2.8c. Calculated daily water discharge (gray curve), total sediment load calculated by ratings curve method, and sand load calculated by the RM2.6 ratings curve for Southwest Pass channel in FY 2008-2010.

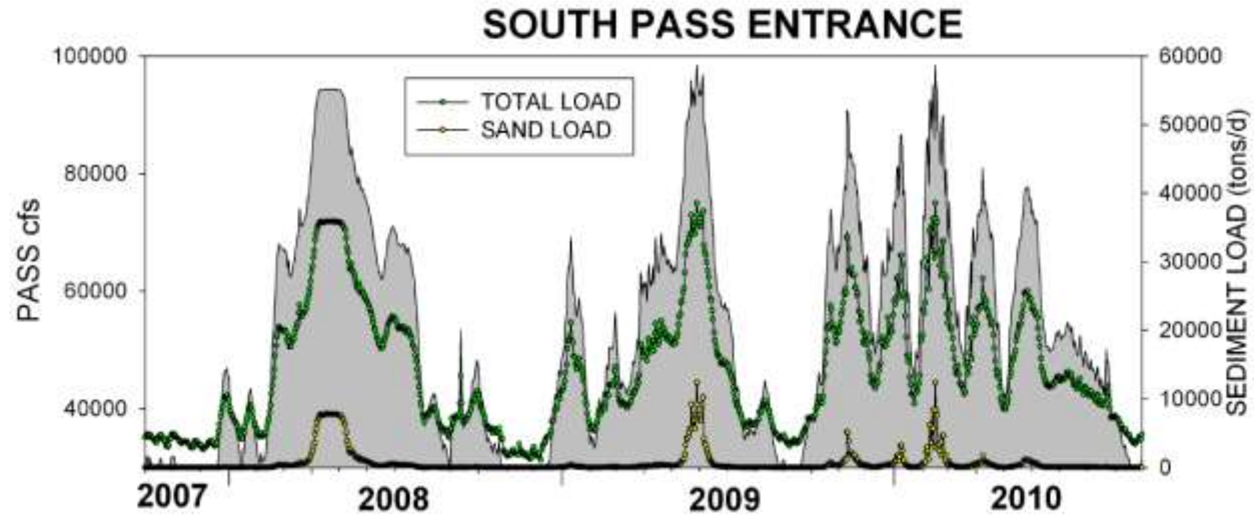


Figure 2.8d.   Calculated daily water discharge (gray curve), total sediment load calculated by ratings curve method, and sand load calculated by the RM2.6 ratings curve for South Pass channel in FY 2008-2010

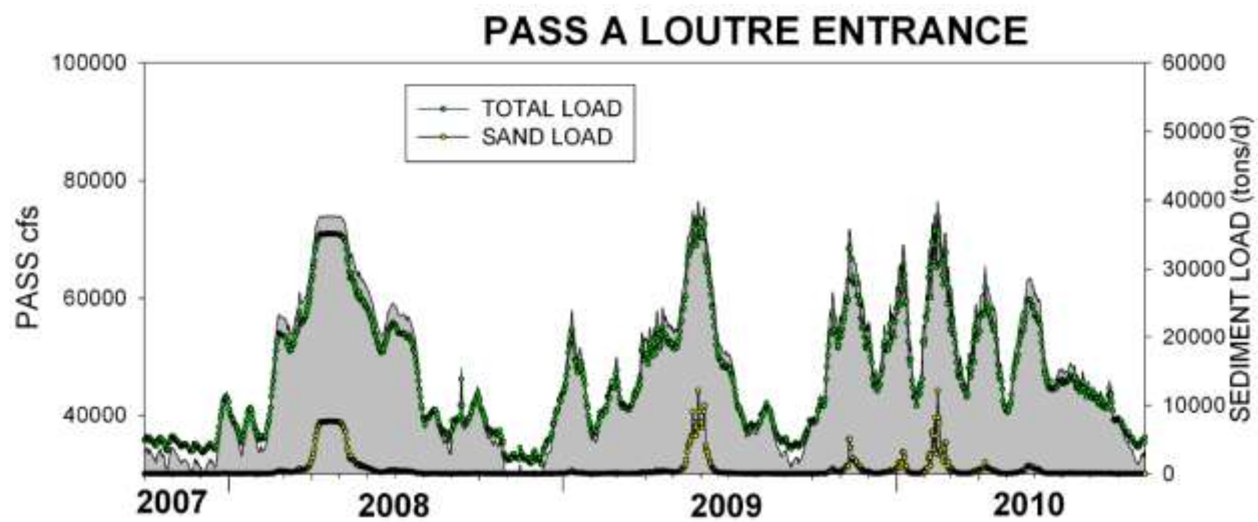


Figure 2.8e.   Calculated daily water discharge (gray curve), total sediment load calculated by ratings curve method, and sand load calculated by the RM2.6 ratings curve for Pass a Loutre channel in FY 2008-2010

2.9 Channel Storage Between RM75 and RM2.6 As part of the West Bay study conducted by the USACE (see section 2.6) an estimate was made of decadal-scale, in-channel sediment storage in the lowermost river—it was this shoaling that was the primary reason the study was conducted. Although not confined to the FY2008-2010 limits of the other datasets utilized in this project, it is the only available estimate of storage. Given the results of bottom sampling carried out at various discharges in this reach by the USACE during this survey, we have also assumed that this storage is primarily sand, and hence will only be treated as a component of the sand budget.

The analysis was carried out utilizing the USACE's decadal navigation surveys of the Mississippi River available at http://www.mvn.usace.army.mil/eng/edsd/index.asp. Surveys done in 1992 (Jan-March) and 2004 (Aug. 2003) were chosen and used elevations relative to NAVD88. TIN were created for each survey and polygons constructed for the region between river mile RM 75 and RM2.6. Volumes were computed for each TIN below a lid elevation of 0 feet NAVD88
for eight subareas:

1. Belle Chasse (RM75) to RM51
2. RM51 to RM24
3. RM24 to RM19.5
4. RM19.5 to RM12.1
5. RM12.1 to Grand Pass
6. RM10.5 (Grand Pass) to West Bay Diversion
7. RM4.7 (West Bay Diversion) to Cubit's Gap
8. RM3.2 (Cubit's Gap) to RM2.6

These volumes were converted to tons using a value of 85 lb/ft^3 and reduced to an annual rate (tons/y) assuming a time difference of 11.5 years between surveys. The results are shown in Table 2.9a.

Table 2.9a. Sediment storage in the Mississippi River channel 1992-2004 between RM75 and 2.6.

River Section	***Area of polygon (10^6 ft^2)***	***Volume Diff. (10^6 ft^3)***	***Deposition Rate (tons/y)***
BC to RM51	327.59	738.6	2,729,586
RM51 to RM24	281.60	454.19	1,678,519
RM24 to RM19.5	68.18	263.01	971,985
RM19.5 to RM12.1	112.34	401.05	1,482,125
RM12.1 to GP	24.64	89.48	330,962
GP to WBD	85.57	384.31	1,420,291
WBD to CG	27.29	139.45	515,364
CG to RM2.6	14.13	62.46	230,840

3. SUPPLEMENTARY REFERENCES CITED

Allison, M. A., and E. A. Meselhe, 2010. The use of large water and sediment diversions in the lower Mississippi River (Louisiana) for coastal restoration, *J. Hydrology*, *387*, 346-360.

Edwards, T. K., Glysson, G. D., 1988. Field methods for measurement of fluvial sediment, US Geological Survey Open-File Report 86-531.