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SEDIMENT TRANSPORT AND CHANNEL MORPHOLOGY DYNAMICS OF HIGHLY
REGULATED ALLUVIAL RIVERS – A CASE STUDY OF THE LOWERMOST
MISSISSIPPI RIVER

A Dissertation

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

in

The School of Renewable Natural Resources

by
Sanjeev Joshi
B.Sc., Institute of Forestry, 2008
M.Sc., Louisiana State University, 2012
August 2017

I dedicate this dissertation to my aunt: Late Mrs. Govindi Bhatta. She always inspired me to be strong amidst struggles, to be optimistic and kind-hearted and to do well in life. Her sheer innocence always inspired me to be kind and try helping the people in need. She may not be around me physically but her lessons and her love, affection and blessings for me will always be in my heart. I further dedicate this dissertation my grandmother: Mrs. Kausalya Devi Joshi, my father: Prof. Dr. Choodamani Joshi and my mother: Mrs. Bishna Joshi. I will always be grateful for the endless love they have showered in me. It's only due to them that I am what I am right now.

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ABSTRACT

The Mississippi River delta is facing severe land loss. An urgent need exists to examine sediment transport and channel morphology dynamics along this highly engineered alluvial river that has shaped and will continue to shape its delta. This dissertation research focuses on investigating channel morphology dynamics and sediment transport in the recent three decades along a 327-km reach (from about 492 to 167 km upstream from the river's outlet in the Gulf of Mexico) of the Lowermost Mississippi River (LmMR). The specific objectives of this research were to: 1) analyze riverbed adjustment, i.e., channel-bed aggradation or channel erosion at seven locations along the 327-km LmMR reach over the last three/four decades; 2) determine suspended sand availability under various discharge regimes at Tarbert Landing (the uppermost location of LmMR) during the period between 1973 and 2013; and 3) quantify bedload at Tarbert Landing, St Francisville and Baton Rouge (three uppermost locations of LmMR) and suspended load at St Francisville and Baton Rouge over the last one to four decades. This research found that the first 20–25 km LmMR reach below its diversion to the Atchafalaya River and the reach from ~ 80 to 140 km experienced significant riverbed aggradation, while the reach in between (i.e. from ~ 25 to 80 km) experienced riverbed degradation over the last three/four decades. The lower 187-km reach (i.e. from 140 to 327 km) showed higher sediment outflow and negligible sediment trapping. Furthermore, the LmMR discharged an average annual sand load (SL_s) of 27 million tons (MT) during 1973 and 2013, at Tarbert Landing, varying largely from 3.4 to 52.3 MT. Also, during the four decades, the LmMR at Tarbert Landing carried about 71% of the total annual sand load in about 120 days each year, when the discharge was ≥ 18000 cubic meters per second (cms). The bedload transport rates along the LmMR gradually increased from Tarbert Landing [83 million tons (MT) during 2004-2015 for grain size of 0.125 mm] to Baton Rouge (at

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CHAPTER 1: INTRODUCTION

Channel morphology dynamics of alluvial rivers is controlled by many factors including geology, climate, human alteration, and topography (Montgomery 1999, Hogan and Luzi 2010). These factors affect the dependent landscape variables within alluvial rivers such as river discharge, river stage and sediment transport (Montgomery and Buffington 1993, Buffington et al. 2003). Therefore, alluvial rivers are shaped by the constant interactions of stage, discharge, and sediment transport. Channel morphology of alluvial rivers affects the river stage, discharge, and sediment transport in the short run, however, is controlled by the interaction of these components in the long run (Church and Ferguson 2015). In addition, these three components play an important role in the formation and development of alluvial river deltas.

River stage can be defined as the elevation of water surface at any arbitrary datum. Similarly, river discharge is the volume of water flowing through a given cross-section of a river per unit of time. These parameters principally determine the width and depth of alluvial river channels (Leopold and Maddock 1953), while sediment forming in the channel can modify channel width and depth (Schumm 1961, 1962). The interaction between river stage and river discharge can affect riverbed dynamics over time (Khabiti et al. 2012), such that continuous change in river stage and river discharge independently and/or in river stage within a given discharge regime can indicate riverbed adjustment, i.e., sediment deposition or channel erosion (Schumm 1963, Leopold and Wolman 1970). Both sediment deposition and channel erosion are the functions of sediment transport in alluvial rivers.

Sediment transport is the movement of sediment particles along alluvial river channels. Sediments carried in rivers are categorized as bedload, suspended load, dissolved load and wash load (Hickin 1995). Bedload and suspended load interact more with river discharge and stage,

while other types of sediment cannot be easily or clearly distinguished from suspended load (Hickin 1995). Hence, bedload and suspended load are the most important components in sediment transport of alluvial rivers. Bedload is formed by bed materials in rivers which move closer to the river bottom by rolling, sliding or saltating (Church 2006, Nittrouer et al. 2008). On the other hand, suspended load is formed by sediment particles in rivers which move with the river flow as suspension, typically between the river bed and water surface (Southard 2006). Suspended load can be further divided into coarser sand particles (with diameter > 0.063 mm) and finer clay/silt particles (with diameter < 0.063 mm) (Mossa 1996, Allison et al 2012). Bedload and suspended load constitute the total sediment supply in rivers (Van Rijn 1984, Church 2006).

Sediment supply contributes significantly to spatiotemporal changes in channel adjustment and morphology of alluvial rivers (Montgomery and Buffington 1997, Parker et al. 2007, Turowski et al. 2010). Many studies on sediment supply of alluvial rivers, however, have ignored the bedload fraction (Holeman 1968, Milliman and Meade 1983, Milliman and Syvitski 1992). Some studies estimated bedload as a fixed fraction of suspended load based on tables proposed by Maddock and Borland (1950) and further expanded by Lane and Borland (1951). However, these reference tables seem to subject bedload analysis to substantial potential bias because both studies did not measure and/or quantify either the suspended load or bedload fraction of any of the river types. The limitations in bedload measurements arise because bed materials are generally intermixed with sand particles in the suspended load due to which bedload and suspended load become inseparable (Gomez 1991, Nittrouer et al. 2008). Hence, the relationship between bedload and suspended load components remain poorly understood in alluvial rivers. The investigation of long-term channel morphological changes, riverbed adjustment patterns,

sediment transport and deposition mechanics, and total sediment supply are especially important for understanding those alluvial rivers that are continuously losing their deltas to bigger water bodies.

The Mississippi River Delta Plain (MRDP) in the southern USA is the prominent example of a river delta experiencing land loss over the last several decades (Gagliano et al. 1981, Meade and Moody 2010, Couvillion et al. 2011). It is associated with the Lowermost Mississippi River (LmMR), the lowermost 500-km reach of the Mississippi River from the Old River Control Structure to the river's Gulf outlet. Several human and natural factors have helped caused the MRDP land loss problem including river engineering (Turner 1997, Meade and Moody 2010), accelerated subsidence (Gagliano et al. 1981, Yuill et al. 2009), disconnection of the river with its floodplains (Xu 2014), coastal land erosion (Reed and Wilson 2004), and relative sea level rise (Georgiou et al. 2005). In addition, reduced riverine sediment supply in the LmMR has caused MRDP land loss (Kesel 1988, Meade and Moody 2010, Thorne et al. 2008).

Sediment load in the LmMR decreased about 3.5 fold [from approximately 400 million tons (MT)/year to 115 MT/year] from the late 1800s (pre-human interference period) to the late 1950s (post-human interference period) at Tarbert Landing [river kilometer (*rk*) 492.8], LmMR's uppermost sediment load recording station which is about 10-15 km below the diversion of the Mississippi River to the Atchafalaya River (Meade and Moody 2010). Previous studies have documented recent multi-decadal trends of suspended sediment load, but only at Tarbert Landing (Kesel 1988, Thorne et al. 2008, Horowitz 2010, Meade and Moody 2010, Rosen and Xu 2014). Furthermore, annual estimates of sediment load at Tarbert Landing have varied from 115 to 150 MT/year during the last three/four decades (Kesel 1988, Thorne et al. 2008, Horowitz 2010, Meade and Moody 2010, Rosen and Xu 2014). However, none of these studies investigated how

this noticeable range of suspended sediment load was transported throughout the 500-km LmMR reach over the same period.

Allison et al. (2012) quantified sediment load at four locations (Tarbert Landing, St Francisville, Baton Rouge and Belle Chase) covering ~ 372 km of the LmMR reach for three years only (2008–2010). They noted that the annual sediment load at Tarbert Landing during 2008-2010 was about 67 MT/year higher than the annual SL at St Francisville (at *rk* 419, LmMR's second recording station ~ 74 km below Tarbert Landing). Allison et al. (2012) proposed two explanations for the loss of sediment load: (1) overbank deposition in unleveed floodplains between Tarbert Landing and St Francisville and (2) riverbed storage. In a follow-up study, Smith and Bentley (2015) examined sediment load in the unleveed floodplains, but found that the sediment load stored in the unleveed floodplains was a negligible portion of the difference reported by Allison et al. (2012) (2 MT/year: 3% of 67 MT/year). Joshi and Xu (2015) noted that Allison et al. (2012) may have overestimated annual sediment load at Tarbert Landing. However, the notable discrepancy between sediment loads at the two upper locations of LmMR in a short duration reflects the need to understand riverbed sediment storage along the reach. This can be achieved by investigating long term riverbed adjustment trends (i.e., channel aggradation or channel erosion) and quantifying the long term sediment transport throughout the LmMR reach.

My dissertation research helps explain the channel morphology and sediment transport dynamics of an alluvial river – the Lowermost Mississippi River. It examines a 327-km reach of the LmMR between Tarbert Landing (*rk* 492.8) and Carrollton, New Orleans (*rk* 165.4) (see Fig. 2.1 in Chapter 2). The research consisted of three interrelated studies and is presented here in Chapters 2, 3 and 4. My first study in Chapter 2 presents the riverbed adjustment trends at seven

locations along the 327-km LmMR reach over the last three to four decades. Chapter 3 helps quantify the availability of suspended sand under various discharge regimes at Tarbert Landing during 1973-2013. Finally, Chapter 4 presents the third study that had the goal of determining long-term bedload transport rates at Tarbert Landing, St Francisville and Baton Rouge (third recording station at *rk* 367.5) and long-term suspended load at St Francisville and Baton Rouge. Chapter 5 provides a basic synopsis of all the findings from the three studies. Chapters 2, 3 and 4 are written as stand-alone manuscripts which have either been published in peer-reviewed journals (Chapters 2 and 3) or are ready for submission (Chapter 4).

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CHAPTER 2: RECENT CHANGES IN CHANNEL MORPHOLOGY OF A HIGHLY ENGINEERED ALLUVIAL RIVER – THE LOWERMOST MISSISSIPPI RIVER

2.1 INTRODUCTION

Alluvial rivers are well-defined by constant interaction of flow, sediment transport and channel morphology dynamics. Bathymetry of alluvial rivers can affect hydrodynamics, hence sediment transport and deposition, which in turn can change geomorphological properties of the river (Bridge 1993, Merwade 2009). Similarly, river stage, river surface slope and discharge are three other important factors affecting riverbed dynamics over time. Therefore, changes in river stage and river surface slope over time with a same discharge regime can indicate riverbed adjustment, i.e., channel bed aggradation or channel erosion (Leopold and Wolman 1957, Leopold and Wolman 1970, Van Rijn 1993). Previous studies have explored river bathymetry (Biedenharn et al. 2000, Harmar et al. 2005, Harmar and Clifford 2006) and river stage and slope in specific discharge regimes (Biedenharn and Watson 1997, Wazkiewicz et al. 2004, Pinter et al. 2006) separately; however, there is still an ambiguity over how these components interact together to affect long term sediment transport and deposition in river systems. Such information can be especially useful for management of regulated rivers that are of great relevance to transportation, flood control and sediment delivery to their deltaic plains.

The Lowermost Mississippi River (LmMR), the lowermost 500-km reach of the Mississippi River which starts from the Old River Control Structure (ORCS) and drains to the northern Gulf of Mexico, is one prominent example of rivers facing significant morphological changes pertaining to artificial interferences along its channel. River engineering since the early 1900s, such as control and diversion structures, training dikes, spillways, levees, meander cutoffs, bank stabilization, and dredging has lead the LmMR channel to be straightened and confined with

reduced sediment supply and floodplain connectivity (Mossa 1996, Kesel 2003, Hudson et al. 2008, Meade and Moody 2010). These channel adjustments have played a significant role in substantial land loss along the delta associated with the LmMR i.e., the Mississippi River Delta Plain (MRDP) from the last several decades (Craig et al. 1979, Gagliano et al. 1981, Meade and Moody 2010, Couvillion et al. 2011). Several MRDP restoration projects focus on diverting LmMR water carrying maximum amount of sediments to coastal marshes for building lands (CPRA 2012, Dean et al. 2013, Peyronnin *et al.* 2013). The United States Army Corps of Engineers (USACE) have constructed the West Bay sediment diversion and have proposed two other sediment diversions in the lowermost river reach (approximately 8 to 165 kilometers upstream of Head of the Passes near the Gulf of Mexico) (CPRA 2012). Sediment loads along the lowermost LmMR reach have been destabilized by frequent channel dredging for navigation and large cargo transportation and have possible chances to disappear into the deep waters of the Gulf of Mexico. Therefore, there is an urgent need to determine potential sediment diversion sites along the upper and middle LmMR reach (approximately 165 to 450 kilometers upstream of Head of the Passes). In-depth knowledge of the morphological changes pertaining to sediment transport and deposition mechanics along upper and middle LmMR reaches can aid determining such sites.

In spite of their significance, the LmMR morphological changes have only been well documented for the uppermost LmMR reach (approximately 365 to 500 kilometers above Head of the Passes) (Harmer et al. 2005, Hudson and Kesel 2000, Knox and Latrubesse 2016) and remain poorly examined for the middle (165 to 365 kilometers above Head of the Passes) and lower LmMR (0 to 165 km above Head of the Passes). Harmer and Clifford (2006) investigated the whole length of the LmMR channel (about 1600-km long from Cairo, Illinois to Head of the

Passes); however, their study focused only on the channel shape. Also, these studies analyzed the LmMR morphological changes using the river's bathymetry measurements over time and ignoring the spatiotemporal trends in river stages and their slopes in specific discharge regimes. Mossa (2013) used both bathymetric and river stage data to analyze hydrological changes in the Lower Old River, the river which connects the Mississippi, Atchafalaya and Red Rivers. However, the bathymetric investigation in this study was not carried out at any site of the LmMR and the river stage analysis only matched for two proximate sites in the uppermost LmMR reach (Tarbert Landing and Red River Landing). Combined analysis of cross-sectional change and river stage and slope change in specific discharge can strengthen our understanding of morphological changes with respect to sediment transport and deposition along the LmMR reach.

Previous studies have recognized several behavioral aspects of sediments and their grain-size fractions in the LmMR, while focus on investigating sediment transport and deposition mechanics along the reach has been relatively lower. Pereira *et al.* (2009) and Nittrouer *et al.* (2012) estimated sediment transport rates at several sites in the upper and middle LmMR, but without clear information about temporal sediment deposition and erosion mechanics along the reach. Allison *et al.* (2012) carried out a sediment budget investigation at four sites of the upper and middle LmMR, but with a short-term data series (2008-2010). Rosen and Xu (2014) and Joshi and Xu (2015) analyzed long-term sediment and sand availability and flow-sediment and flow-sand relationships, respectively, but only for the uppermost location at Tarbert Landing (near ORCS). Furthermore, to the best of my knowledge no peer reviewed literature is available on how long-term changes in the river bathymetry and in river stages and maximum river surface

slopes pertaining to specific flow conditions can synchronously relate to morphological changes along the LmMR reach downstream.

This study attempts to analyze multi-decadal changes in river channel morphology and in river stages and maximum river surface slopes under equal flow conditions at seven locations in the upper and middle LmMR reaches from Tarbert Landing to Carrollton (Figure 2.1). Such an assessment can aid in understanding its routing downstream, differentiating between sediment erosion and deposition mechanics along the reach and further distinguishing potential sediment diversion sites based on maximum sediment availability. The specific objectives of this study include: (1) assessing decadal changes in cross-sectional areas of river bed profiles at six locations covering the upper and middle LmMR reaches; (2) analyzing long-term trends in average annual river stages pertaining to specific flow conditions ranging from low to high at the selected locations; and (3) investigating long-term river surface slope trends (for consecutive sites) pertaining to maximum annual river stages in each aforementioned flow conditions. The primary goal of the study is to determine the long-term riverbed adjustment (i.e. erosion and deposition) at each selected location to elucidate sediment transport and transformation patterns in this large, highly engineered alluvial river. Therefore, the information gained from this study may have implications for riverine sediment management, channel engineering, and coastal land restoration in the world's other sinking deltas fed by alluvial rivers.

2.2 METHODS

2.2.1 Study Site Selection

The area of focus for this study is the Lowermost Mississippi River which stretches from its diversion structure, the Old River Control Structure (ORCS), over 500 km downstream to its outlet of the Gulf of Mexico (Figure 2.1). Over the last four decades (1973-2013), daily

discharge (Q_d) below the ORCS at Tarbert Landing averaged 15027 cubic meter per second (cms), varying from 3143 to 45844 cms (Joshi and Xu 2015). Average Q_d during the high water months in the LmMR is approximately three times more than the average Q_d during the low water months (Meade 1995, Rosen and Xu 2013). In terms of sediment transport, the LmMR at Tarbert Landing discharged an average annual load of 127 megatonnes (MT) of total suspended solids during 1980-2010 (Rosen and Xu 2014), while an average annual load of 27 MT sand particles at this site has been reported for 1973-2013 (Joshi and Xu 2015).

In this study, seven locations along the LmMR over a distance of 327 kilometers were selected for comprehensive assessment of bathymetric and river stage changes. These locations included: Tarbert Landing (TBL) at river kilometer (rk) 492.8, Red River Landing (RRL) at rk 486.5, Bayou Sara (BS) at rk 427, Baton Rouge (BTR) at rk 367.5, College Point (CP) at rk 253.3, Bonnet Carre (BC) at rk 204.2, and Carrollton (CAR) at rk 165.4 (Fig. 1). USACE has daily river stage measurements for at least 20 years at these locations from Red River Landing to Carrollton, however, only few years of river stage measurements are available for the locations below Carrollton. The 160-km reach below Carrollton is the lowermost end of the LmMR which has experienced frequent channel dredging and revetment for large cargo transportation, complicating sediment transport assessment. Hence, this reach was excluded in this study.

2.2.2 Data Collection

For bathymetric analysis, three cross-sectional (CS) measurements conducted by USACE in 1992, 2004 and 2013 were selected each at six of the seven locations (except Red River Landing) described above. USACE used single beam fathometer and multibeam side scan sonar to measure cross-sections while developing hydrographic survey maps for the Mississippi River (during these years) from Black Hawk, Louisiana (rk 521.4, just above the ORCS) to the river's

Gulf Outlet at Head of Passes (rk 0). Each cross-section consisted of riverbed elevation measurements at 30 m intervals across the river. All elevations in the LmMR during 2004 and 2013 were recorded with reference to the North American Vertical Datum of 1988 (NAVD 88), while the elevations in 1992 were recorded with reference to the National Geodetic Vertical Datum of 1929 (NGVD 29). Therefore, the 1992 survey data were converted to NAVD 88 using corresponding reference conversion factors at each location provided by USACE. Red River Landing was excluded because of its close proximity from Tarbert Landing (about 5 km) and used CSs at Tarbert Landing to represent the bathymetric and areal changes near ORCS.

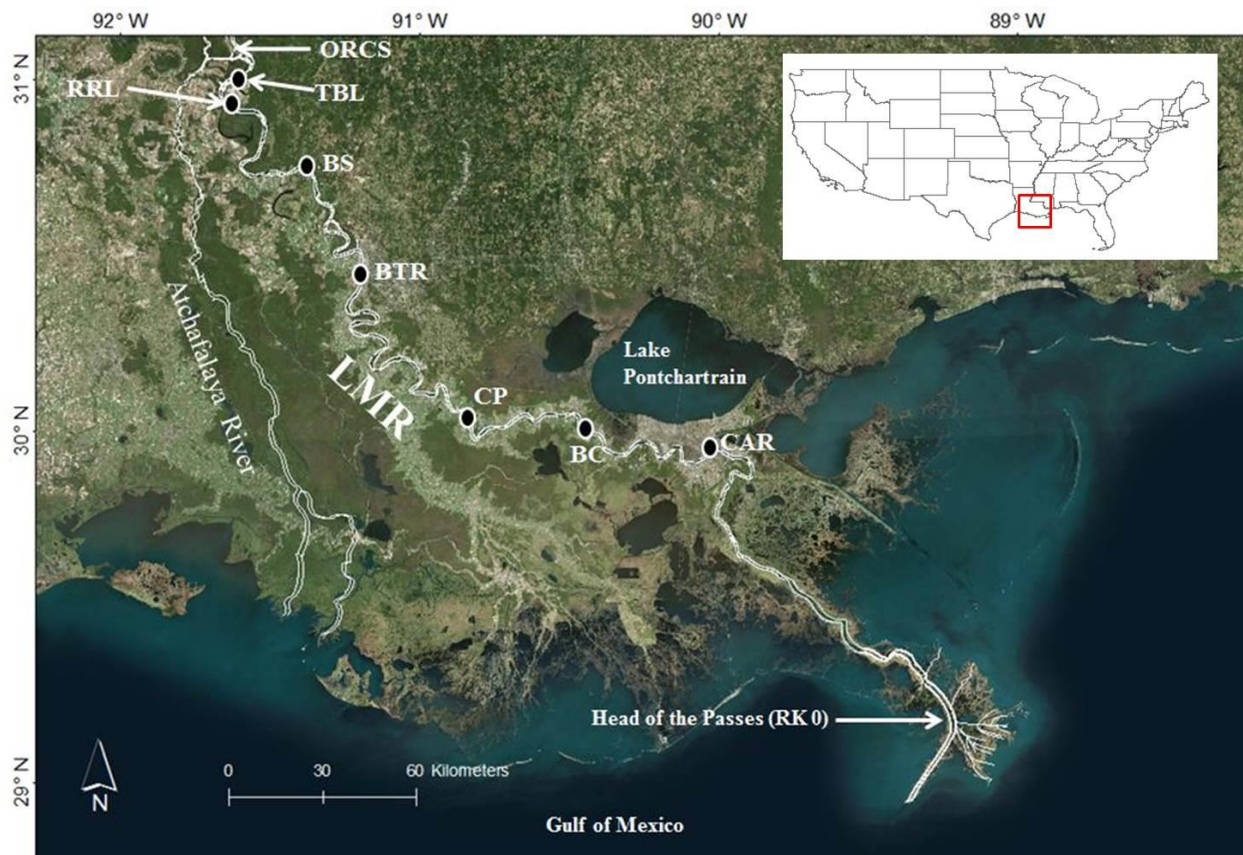


Figure 2.1: Location of seven study sites along the Lowermost Mississippi River (LmMR) from Tarbert Landing [near Old River Control Structure (ORCS)] to Carrollton (New Orleans). Note: All study sites have been systematically annotated from upstream to downstream along the LmMR reach as: TBL – Tarbert Landing [at river kilometers (RK) 492.8]; RRL – Red River Landing (at RK 486.5); BS – Bayou Sara (at RK 427); BTR – Baton Rouge (at RK 367.5); CP – College Point (at RK 253.3); BC – Bonnet Carre (at RK 204.2); and CAR – Carrollton (at RK 165.4). Head of the Passes at RK 0 represents the LmMR’s outlet to the Gulf of Mexico.

For river stage analysis in specific discharge conditions, daily discharge records (Q_d) were collected at Tarbert Landing and daily river stage records (RS_d) at Red River Landing, Bayou Sara, Baton Rouge, College Point, Bonnet Carre and Carrollton for corresponding available periods (Red River Landing and Baton Rouge: 1987-2015; Tarbert Landing, Bayou Sara and College Point: 1973-2015; Bonnet Carre: 1989-2015 and Carrollton: 1986-2015) from USACE. It is noted that during these four decades of Q_d and RS_d records (1973-2015), the LmMR experienced high magnitude spring floods in 1973 and 2011 and a summer flood in 1993.

No long-term discharge measurements are available for the sites downstream of Tarbert Landing. Based on USACE's velocity observations across several river stage ranges (from low to high) at Tarbert Landing (average surface velocity of 2.88 km/hr in a stage of 1.52 m to 8.32 km/hr in a stage of 18.29 m) and Baton Rouge (average surface velocity of 1.92 km/hr in a stage of 0.61 m to 8.8 km/hr in a stage of 12.12 m), it was deduced that the LmMR flows from Tarbert Landing to Carrollton between twenty-four and thirty-six hours. Therefore, discharge measurements at Tarbert Landing were used to analyze corresponding river stages for same days at all other locations downstream of Tarbert Landing.

2.2.3 Bathymetric and Specific River Stage Analyses

The cross-sectional area of a given transverse river bed profile was calculated as the sum of areas of all sub cross-sections between two opposite top bank elevations of the profile (Figure 2.2). The river bed elevations in the profile (depth) multiplied with the distance between their measurement points (breadth = 30 m, see section 2.2.2) gave the areas of all sub cross-sections (Figure 2.2). Also, the two opposite top-bank elevations in each profile were defined by water surface lines marked by USACE (Figure 2.2). In each profile, a few points had variable elevations above mean sea level. Therefore, all elevations were subtracted from a single bench-

mark elevation higher than and nearest to the highest elevation of the profile during 1992, 2004 and 2013 to get a unified reference point for calculating all areas in the profile. Changes in areas of all corresponding cross-sections from 1992 to 2004 and 2004 to 2013 were determined to discern decadal trends of the river channel and bed sediment dynamics. The cross-sections with decreased areas from 1992 to 2013 indicate bed sediment accumulation, while those with increased areas suggest bed erosion. For this analysis, a prerequisite of $\pm 5\%$ change in area was kept as noticeable change. Thus, the sites with a cross-sectional area decrease greater than 5% were identified as noticeable sediment accumulating, and the sites with an area increase greater than 5% were identified as noticeable bed eroding. The sites in between 5% areal decrease and increase were identified as no change. During 1992-2013, LmMR's stage at Red River Landing was lower than the flood stage provided by National Weather Service (14.6 m) for 1992, 1999, 2005, 2006 and 2012. Furthermore, the river stage stayed above 14.6 m for less than 50 days and from 50 to 75 days for 8 years each out of the remaining 17 years. In 2011 only, the river stage stayed above 14.6 m for as much as 87 days. Based on these trends, it was hypothesized that the annual flood cycle in LmMR did not affect the change in cross-sections significantly.

Long term trends in daily river stages of all locations below Tarbert Landing were examined based on the following four selected flows at Tarbert Landing: 10000 Q_d representing for $9000 \leq Q \leq 11000$ cms (29th to 40th percentile of total flow in the Lowermost Mississippi River during 1973-2015), 15000 Q_d for $14000 \leq Q \leq 16000$ cms (53rd to 60th percentile of the total flow), 20000 for $19000 \leq Q \leq 21000$ cms (70th to 77th percentile of the total flow), and 25000 cms for $24000 \leq Q \leq 26000$ cms (85th to 90th percentile of the total flow). These flows covered low to high percentage of the LmMR discharge during 1973 to 2015 and 1986/87/89 to 2015 and their ranges were selected according to $\pm 5-10\%$ bin width criteria given by Turnipseed and Saur

(2010). The percentage occurrence of these flows were calculated for the two periods 1973-2015 and 1986-2015 because river stage data for specific discharge analysis were available from 1973 at Bayou Sara and College Point and from 1986/87/89 at the other sites. Trends in RS_d s over time in the four Q_d types were analyzed by fitting a linear trend-line between RS_d (y) (dependent variable) and date (x) (independent variable). Temporal autocorrelation was checked by the Durbin-Watson test (Durbin and Watson 1950, Durbin and Watson 1951, Durbin and Watson 1971). An autoregressive model with one-day lag in each dependent variable was applied for RS_d s with significant temporal autocorrelation (Farebrother 1980, Kramer 2011). Finally, RS_d trends were determined by following 3-ranges of p -values obtained from the RS_d -date regression model within each flow type at all locations, a criteria used in several studies (Pinter *et al.* 2006, Watson and Biedenharn 2009, Little and Biedenharn 2014):

- 1) No significant trend if $p > 0.1$, which means RS_d s did not change with time.
- 2) Significant trend if $p < 0.01$, which means RS_d s changed with time (RS_d s decreased if mean annual RS_d of starting year $<$ mean annual RS_d of ending year and increased if mean annual RS_d of starting year $>$ mean annual RS_d of ending year).
- 3) Inconclusive trend if $0.01 < p < 0.1$, which means the RS_d trends with time could not be determined clearly.

RS_d trends were also analyzed by comparing the percentage difference between mean annual RS s of starting and ending years in each Q_d type at all locations below Tarbert Landing. For all Q_d types in all locations, mean annual RS had an increasing trend if the percentage difference was more than + 5%, a decreasing trend if the difference was less than -5%, while an insignificant trend if the difference was between +5 and -5% (Error Range = $\pm 5\%$). Finally,

locations with sediment accumulation (increasing trend in *RS*) were distinguished from locations with sediment erosion (decreasing trend in *RS*).



Figure 2.2: Screen-shot kept from the LmMR Hydrographic Survey Book of 2013 (USACE, 2013) showing schematics of three cross-sections at Tarbert Landing. ‘Water Lines’ in red represent the black dashed water surface lines marked by USACE denoting the top bank elevations for both ends of the cross-section. The elevations of the cross-sections measured are shown next to the blue line. All the elevations on the Hydrographic Survey Book are in feet and have been converted to meters for channel analysis in this study.

2.2.4 Slopes of Maximum Annual River Stages of all Discharge Types

River surface slope between two consecutive sites downstream of a river is the difference between maximum annual *RS* in both sites divided by the length of the reach between the sites (Biedenharn *et al.* 2000). This study analyzed the change in slopes of maximum annual *RS*s

between the LmMR sites, i.e., from Red River Landing to Bayou Sara, Bayou Sara to Baton Rouge, Baton Rouge to College Point, College Point to Bonnet Carre, and Bonnet Carre to Carrollton, for all Q_d types. Trends in yearly slope in maximum annual RSs of the four Q_d types was checked by fitting a trend-line between annual slope (y) (dependent variable) and year (x) (independent variable). The criteria used for determining trends in slope were exactly the same as that of specific river stage analysis, i.e. the three ranges of p-values obtained from the annual slope-year model had exactly the same interpretation as those obtained from the daily river stage-date model. Finally, locations downstream from Tarbert Landing were checked with sediment accumulation (decreasing trend in slope) or sediment erosion (increasing trend in slope).

2.3 RESULTS

2.3.1 Channel Morphological Changes

The net and percentage changes in all cross-sections (CS) from 1992 to 2004 and 2004 to 2013 at the six study locations along the LmMR have been shown in cross-sectional plots in Figures 2.3 through 2.8 and documented in Table 2.1. Over these three decades, areas of the first and third cross-sections (CS I and III) at Tarbert Landing observed a continuous decrease of 14 and 12% respectively from 1992 to 2013. However, CS II decreased by 10% during the first decade (1992-2004) and increased by a negligible 2% during the second decade (2004-2013), balancing up to a decrease of 8% during 1992-2013. At Bayou Sara, the next station downstream, areas of CS I and II increased continuously by 8% and 7% respectively from 1992 to 2013. However, CS III at Bayou Sara had a negligible alternate change in area during 1992-2013 (5% increase from 1992 to 2004 and 4% decrease from 2004 to 2013). At Baton Rouge, the next station downstream from Bayou Sara, areas of CS I and II decreased continuously by 14% and 8% respectively from 1992 to 2013. The change in area of CS III at Baton Rouge during

1992-2013 was also continuous, however, negligible (1 and 2% increase during 1992-2004 and 2004-2013 respectively). The areal change (increase or decrease) in all but one CSs at all stations further downstream from Baton Rouge was within the selected error range ($\pm 5\%$) both from 1992 to 2004 and from 2004 to 2013. The only CS with the areal change greater than the error range was CS II at Bonnet Carre from 1992 to 2004 (decrease of 8%) and from 2004 to 2013 (increase of 9%). However, these decadal changes balanced to a negligible areal change (1% decrease) at Bonnet Carre during 1992-2013. For all study locations along the LmMR, Tarbert Landing had the highest change (either increase or decrease) in total cross-sectional areas of selected cross-sections during 1992-2013 (a decrease of 34%), while the cross-sectional change at Carrollton was lowest (an increase of 1%).

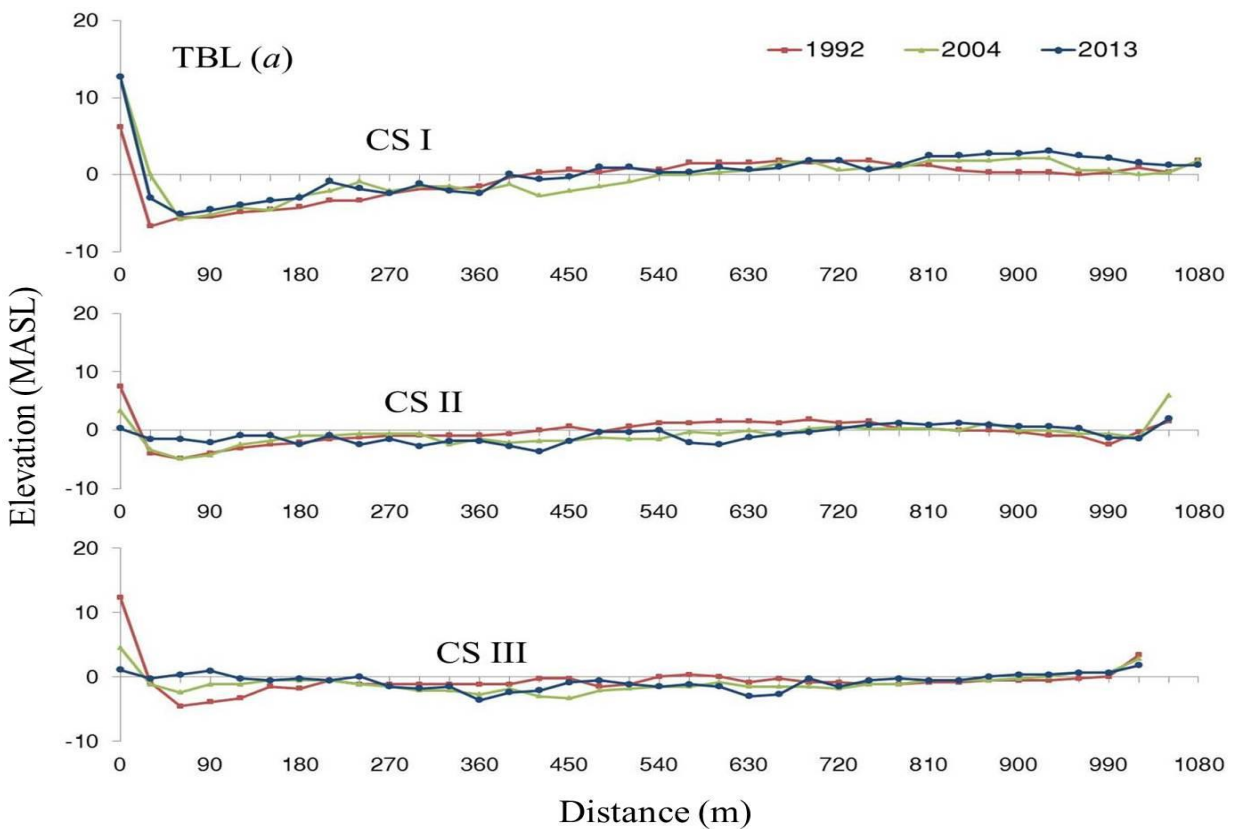


Figure 2.3: Three river channel cross sections (CS) (I, II and III) each at Tarbert Landing (TBL) of the Lowermost Mississippi River in 1992, 2004 and 2013.

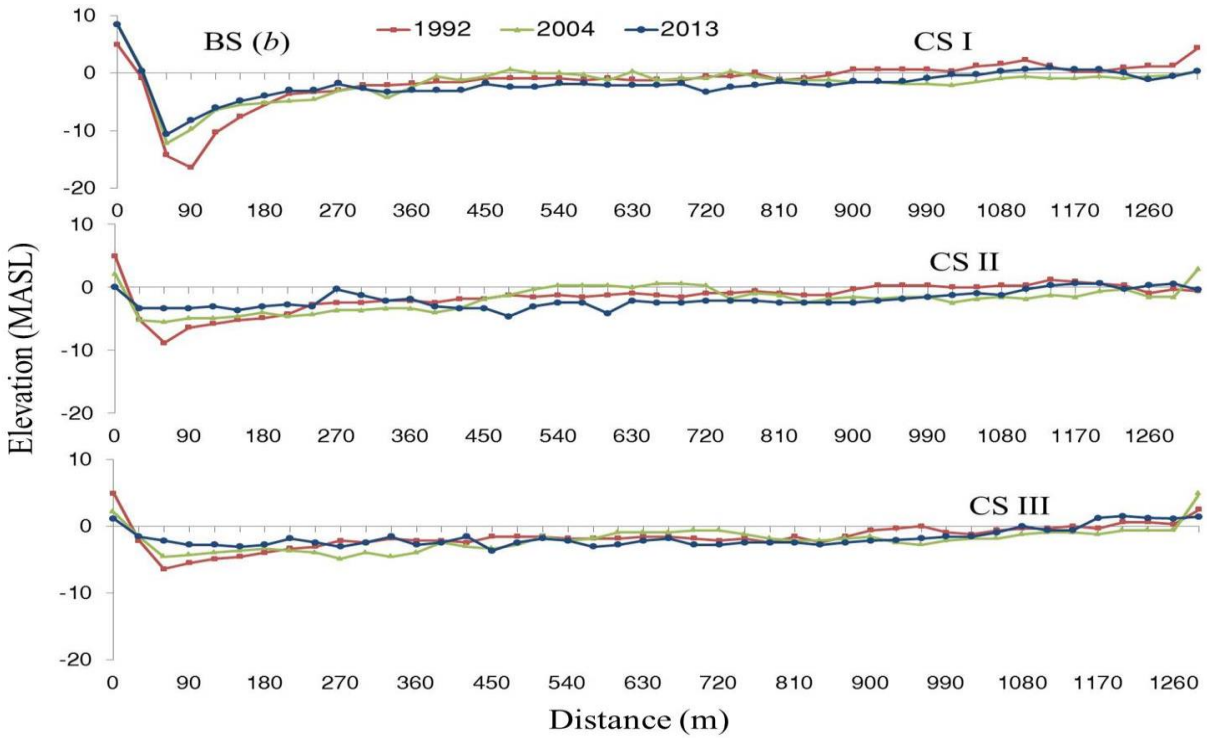


Figure 2.4: Three river channel cross sections (CS) (I, II and III) each at Bayou Sara (BS) of the Lowermost Mississippi River in 1992, 2004 and 2013.

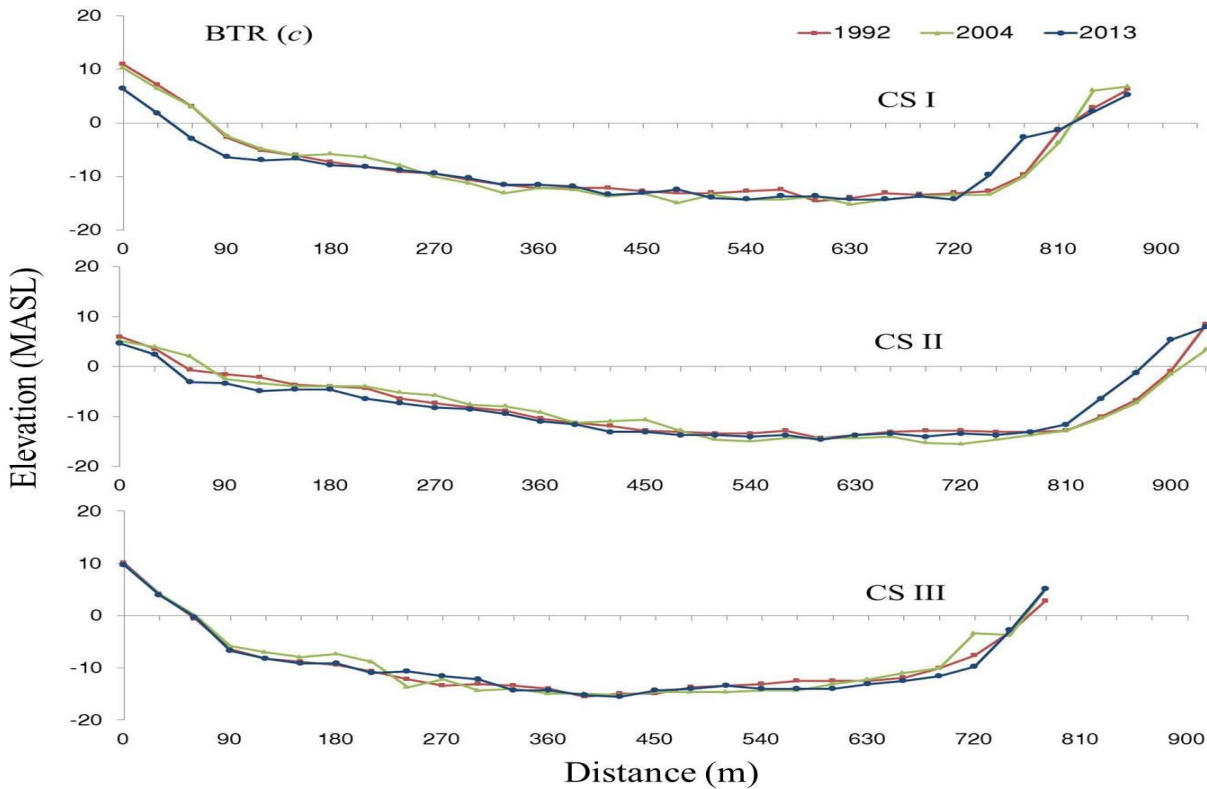


Figure 2.5: Three river channel cross sections (CS) (I, II and III) each at Baton Rouge (BTR) of the Lowermost Mississippi River in 1992, 2004 and 2013.

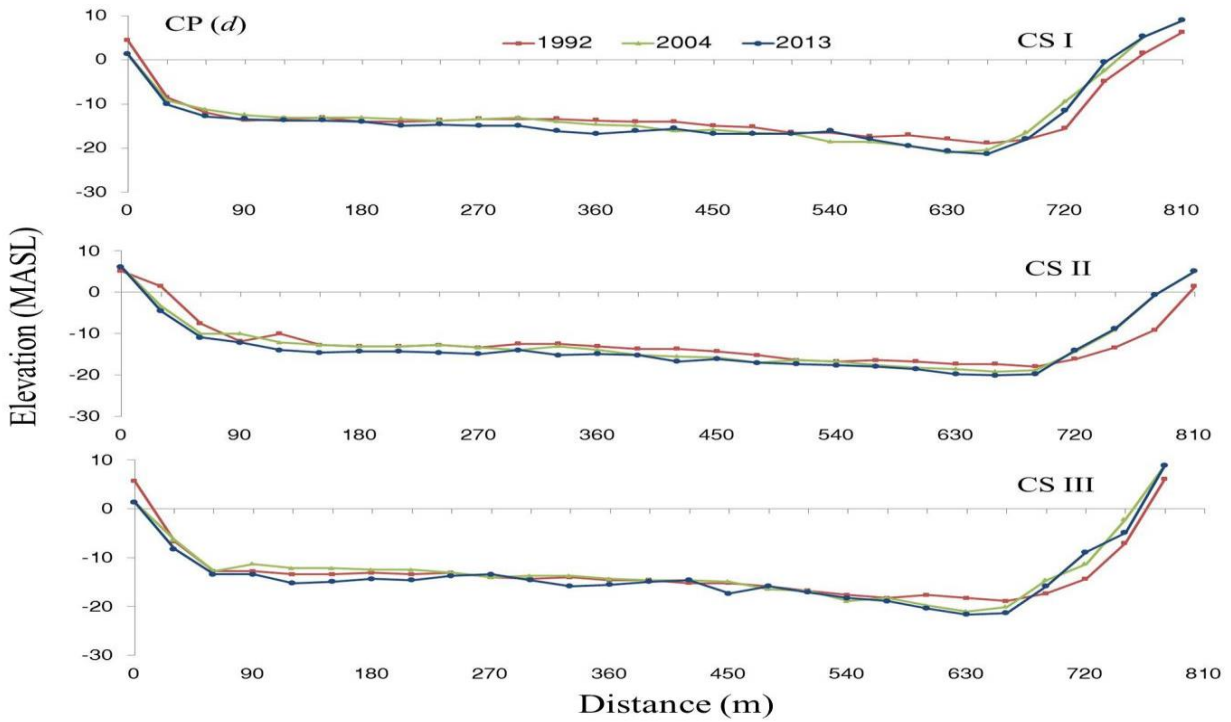


Figure 2.6: Three river channel cross sections (CS) (I, II and III) each at College Point (CP) of the Lowermost Mississippi River in 1992, 2004 and 2013.

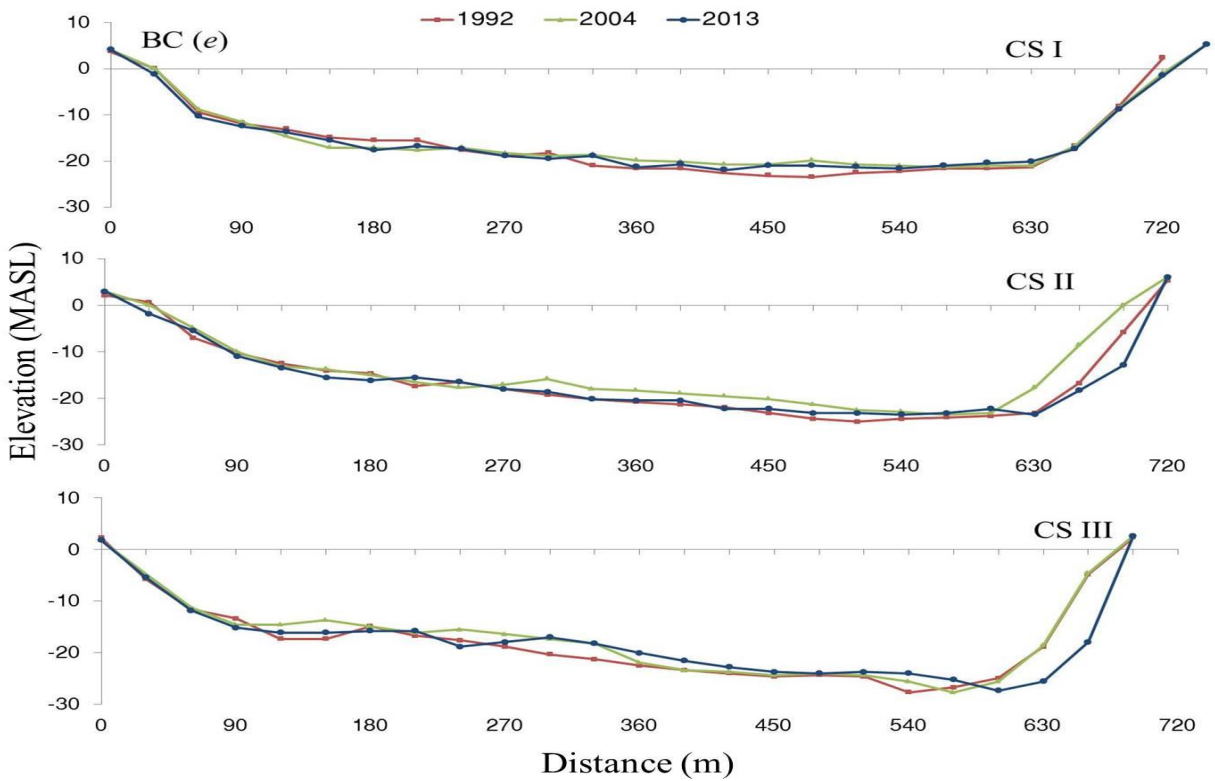


Figure 2.7: Three river channel cross sections (CS) (I, II and III) each at Bonnet Carre (BC) of the Lowermost Mississippi River in 1992, 2004 and 2013.

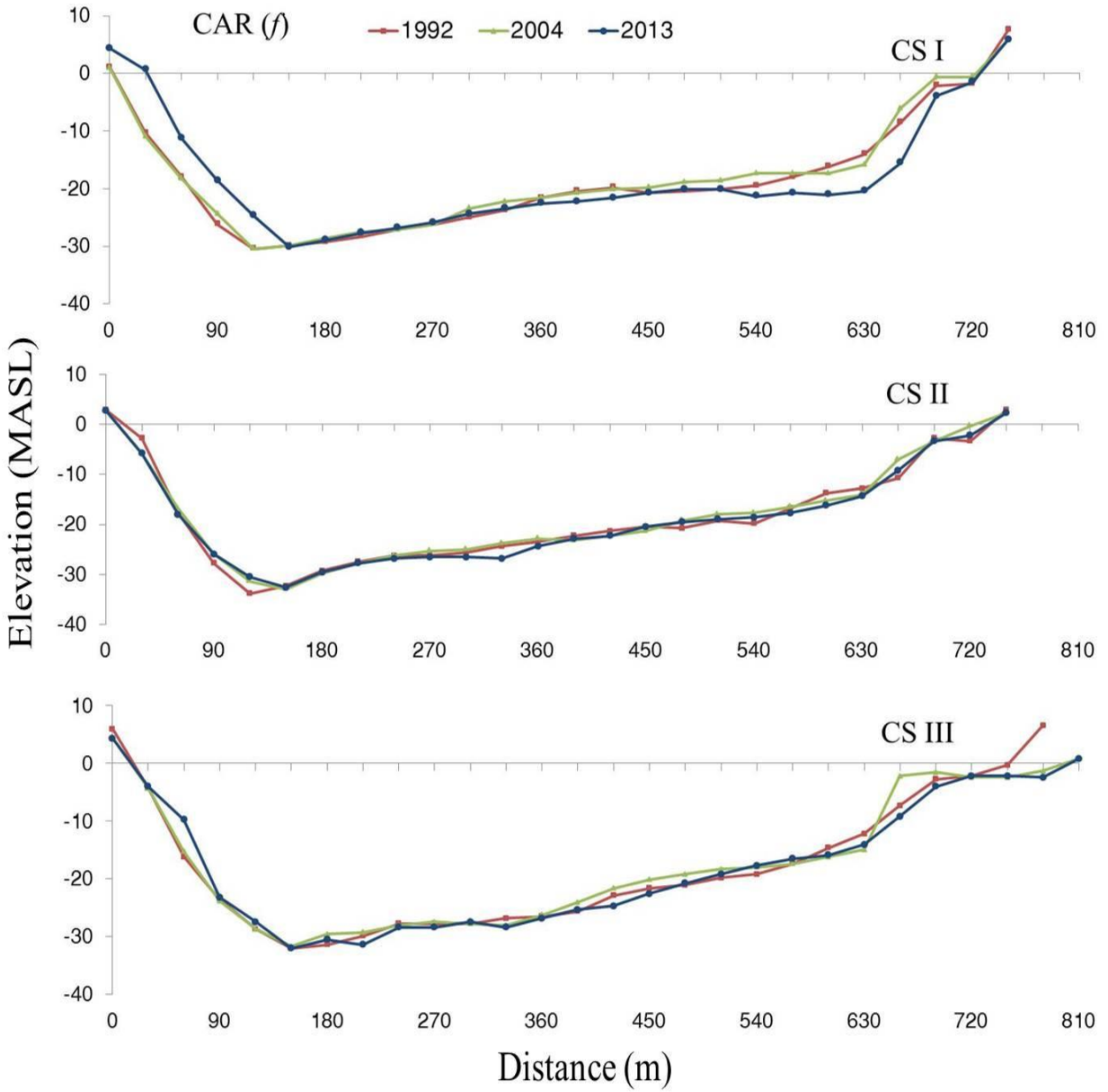


Figure 2.8: Three river channel cross sections (CS) (I, II and III) each at Carrollton (CAR) of the Lowermost Mississippi River in 1992, 2004 and 2013.

Table 2.1: Comparison of net and percentage changes in cross-sectional areas (CSA) at six locations along the LmMR (in the order of distance from upstream to downstream): Tarbert Landing (TBL), Bayou Sara (BS), Baton Rouge (BTR), College Point (CP), Bonnet Carre (BC) and Carrollton (CAR). Note: BE represents bench elevation for each Cross-Section (CS). CSs with “+” sign within parenthesis of their corresponding % CSA change had a clear increase in area, those with “-” sign had a clear decrease in area, while, those with “0” sign had no conclusive change in area (since the areal changes fell within the aforementioned error range of $\pm 5\%$).

Station	CS [BE (m)]	CSA (m ²)			Net-change in CSA (m ²)			% change in CSA			Overall change from 1992–2013
		1992	2004	2013	1992–2004	2004–2013	1992–2013	1992–2004	2004–2013	1992–2013	
TBL	I (4)	5051	4969.2	4402.3	-381.8	-266.9	-648.7	-8 (-)	-6 (-)	-14 (-)	Decrease
	II (6)	6839.4	7190.6	7199.9	-748.7	109.2	-639.5	-10 (-)	2 (0)	-8 (-)	
	III (4)	5076.7	5305.3	4896.6	-328.6	-280.1	-608.7	-6 (-)	-6 (-)	-12 (-)	
BS	I (6)	10028.6	10498.6	10718.1	470	219.5	689.5	6 (+)	2 (+)	8 (+)	Increase
	II (4)	7447.1	7861.4	7923.9	414.2	62.6	476.8	6 (+)	1 (0)	7 (+)	
	III (6)	9968.4	10446.6	10001.3	478.2	-445.3	32.9	5 (+)	-4 (0)	1 (0)	
BTR	I (8)	16296.2	14516.6	14138.6	-1779.6	-378	-2157.6	-11 (-)	-3 (0)	-14 (-)	Decrease
	II (10)	17022.1	17322.9	16210.5	300.8	-1112.4	-811.6	-2 (0)	-6 (-)	-8 (-)	
	III (10)	15660.3	15466.8	15763.6	-193.5	296.8	103.3	1 (0)	2 (0)	3 (0)	
CP	I (10)	18586.3	18513.2	19016.1	-73.2	502.9	429.7	0 (0)	3 (0)	3 (0)	Insignificant
	II (8)	16825.5	16997.4	17692.4	171.9	694.9	866.8	1 (0)	4 (0)	5 (+)	
	III (10)	18506.7	18102.5	18852.4	-404.2	749.8	345.6	-2 (0)	4 (0)	2 (0)	
BC	I (6)	16528.9	16112	16368.1	-417	256.1	-160.9	-3 (0)	2 (0)	1 (0)	Insignificant
	II (8)	17707.2	16322.2	17795.5	-1384.9	1473.3	88.4	-8 (0)	9 (0)	1 (0)	
	III (4)	15373.2	14743.2	15447.3	-630	704.1	74.1	-4 (0)	5 (0)	1 (0)	
CAR	I (8)	19802.9	19428	19674.9	-374.9	246.9	-128	-2 (0)	1 (0)	-1 (0)	Insignificant
	II (4)	17079.5	16896.6	17289.8	-182.9	393.2	210.3	-1 (0)	2 (0)	1 (0)	
	III (8)	20123	19720.6	20132.1	-402.3	411.5	9.2	-1 (0)	2 (0)	1 (0)	

2.3.2 Distribution of River Stages in Specific Discharge Regimes

The four selected discharge regimes represented a substantial range (from low to high) of daily discharge in the LmMR over the last three to four decades. The lowest selected LmMR discharge regime between 9000 and 11000 cms accounted for approximately 71 to 61% of all discharge events during 1986-2015 and approximately 71 to 60% during 1973 to 2015 (Table 2.2). Similarly, the highest selected regime from 24000 to 26000 cms accounted for about 14 to 10% of all discharge events during 1986-2015 and 15 to 11% of all events during 1973-2015 (Table 2.2). Other discharge ranges in between these lowest and highest selected flows varied between 47% (14000 cms) and 23% (21000 cms) during 1986-2015 and 47 to 24% during 1973-2015.

All maximum $RS_{d/s}$ and all but one minimum $RS_{d/s}$ within the four selected discharge ranges increased gradually from lowest (29th percentile) to highest (90th percentile) selected discharge ranges at each location (Figure 2.9). For only a single instance at Red River Landing, minimum river stage in (14000-16000) cm discharge regime (6.19 m) was lower than the minimum river stage in (9000-11000) cms discharge regime (6.90 m) (Figure 2.9). Also, all minimum and maximum river stages in same discharge regimes decreased gradually from upstream (at Red River Landing) to downstream (at Carrollton), except that the minimum discharge at Bayou Sara in 14000-16000 cms (6.80 m) was higher than the minimum river stage at Red River Landing upstream under the similar flow regime (6.19 m) (Figure 2.9). Furthermore, the highest variability observed between intra-discharge maximum and minimum river stage along the LmMR was for 14000-16000 flow range at Red River Landing (6.61 m), while the lowest variability was for 24000-26000 flow range at Carrollton (1.22 m). All other intra-discharge variabilities between maximum and minimum discharge had a low range from 1.26 (for 9000-

11000 cms discharge at Carrollton during 1986-2015) to 3.83 m (for 9000-11000 cms discharge at Bayou Sara during 1986-2015) (Figure 2.9). The intra-discharge variability in river stages generally decreased gradually from upstream to downstream locations (Figure 2.9).

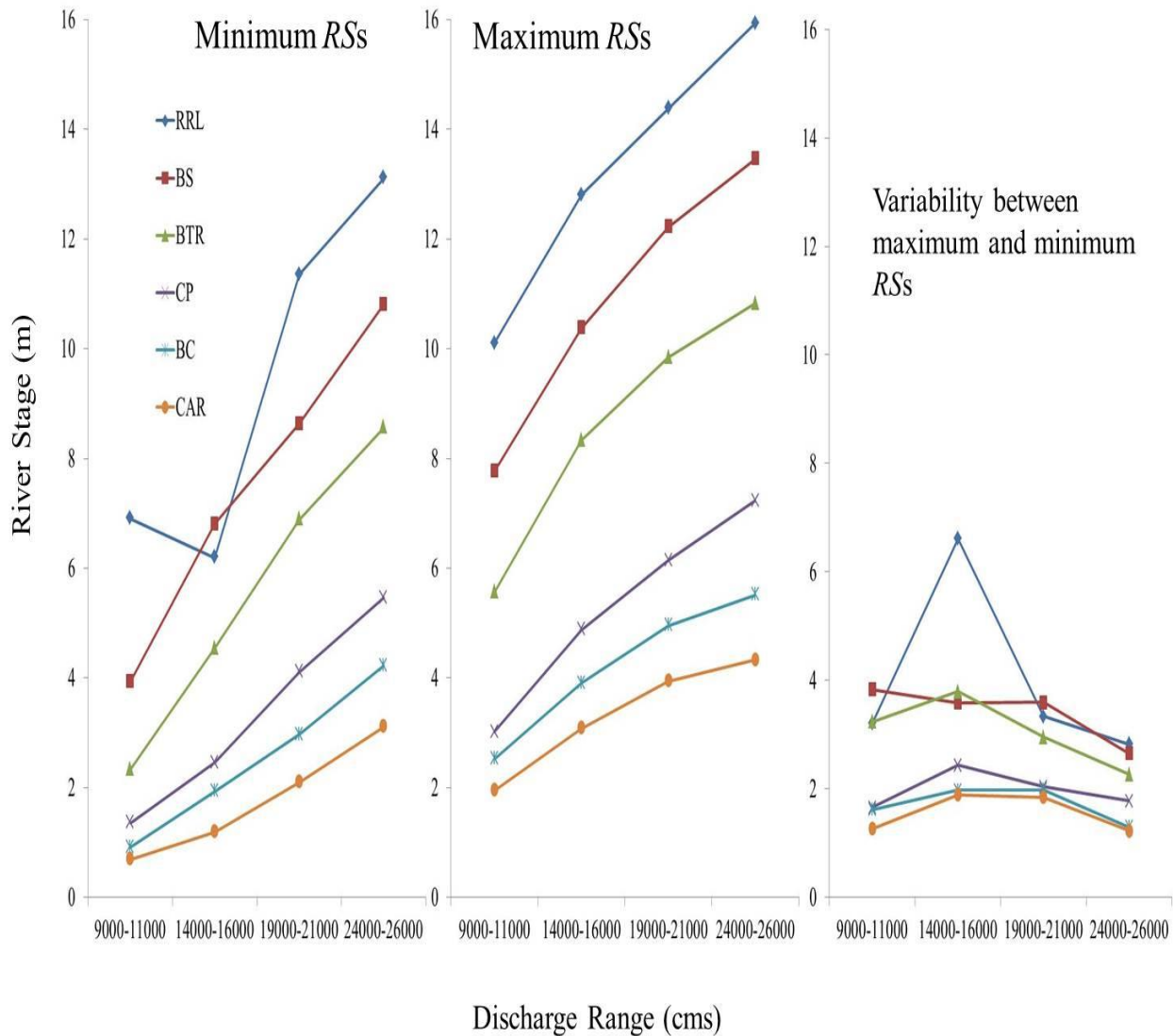


Figure 2.9: Minimum (left) and maximum (middle) river stages and variability between maximum and minimum RS (right) in the four selected discharge regimes at the following locations and their corresponding periods (in parenthesis) of the Lowermost Mississippi River: Red River Landing (RRL) (1987-2015), Bayou Sara (BS) (1973-2015), Baton Rouge (BTR) (1987-2015), College Point (CP) (1973-2015), Bonnet Carre (BC) (1989-2015) and Carrollton (CAR) (1986-2015).

Table 2.2: Percentage occurrence of four discharge regimes at Tarbert Landing in two periods from 1986 to 2015 and 1973 to 2015. These four discharge regimes were further used for specific river stage analysis. Note: The percentage occurrence of discharge regimes was calculated for the given two periods to match the discharge data with corresponding years of river stage data at different locations (i.e., during 1986-2015 at Red River Landing, Baton Rouge, Bonnet Carre and Carrollton and during 1973-2013 at Bayou Sara and College Point).

Discharge Regimes (cms)	% occurrence (1986-2015)	% occurrence (1973-2015)
9000-11000	71.4 - 60.65	70.96 - 60.31
14000-16000	47.4 - 40.83	46.98 - 41.21
19000-21000	29.61 - 23.4	30.1 - 23.65
24000-26000	14.21 - 9.81	15.03 - 10.59

2.3.3 Specific River Stage Changes

From 1987 to 2015, an increasing RS_d and mean annual RS trend was found in all Q_d s at Red River Landing ($p < 0.0001$ and % difference between mean annual RS of 1987 and 2015 = 11.5, 12.2, 12.8 and 10.9 for 10000, 15000, 20000 and 25000 cms Q_d types respectively) and BTR ($p < 0.0001$ and % difference between mean annual RS of 1987 and 2015 = 13.9, 11.2, 13.5 and 15.1 for 10000, 15000, 20000 and 25000 cms Q_d types respectively) (Figures 2.10, 2.12 and 2.16, Table 2.3). However, Bayou Sara (the station in between Red River Landing and Baton Rouge) showed a decreasing trend of RS_d and mean annual RS in two of the four Q_d types (1973-2015) (15000 and 20000 cms Q_d types: $p = 0.0047$ and < 0.0001 and % difference between mean annual RS of 1973 and 2015 = -13.4 and -8.6 respectively) (Figures 2.11 and 2.16, Table 2.3). RS_d and mean annual RS at Bayou Sara had no significant trend in 10000 cms flow ($p = 0.19$ and % difference between mean annual RS of 1973 and 2015 = 2.9) (Figures 2.11 and 2.16, Table 2.3), while, trend could not be concluded for the 25000 cms flow ($p = 0.0123$ and % difference between mean annual RS of 1973 and 2015 = 2.9) (Figures 2.11 and 2.16, Table 2.3).

No clear trend in RS was found for all other sites further downstream from Baton Rouge (Figures 2.13 through 2.16, Table 2.3). RS_d s and mean annual RSs further downstream from Baton Rouge had a decreasing trend only in 1 Q_d type at College Point (1973-2015) (15000 cms

flow: $p < 0.0001$ and % difference between mean annual RS s of 1973 and 2015 = -13.4) (Figures 2.13 and 2.16, Table 2.3), and 2 Q_d types at Bonnet Carre (1989-2015) (10000 and 15000 cms flow: $p = 0.008$ and 0.014 and % difference between mean annual RS s of 1989 and 2015 = -6.8 and -7.3 respectively) (Figures 2.14 and 2.16, Table 3). RS_{dS} and mean annual RS s of all other Q_d types at all other locations had insignificant trends in six instances (25000 cms flow at College Point, 20000 cms flow at Bonnet Carre and all flows at Carrollton) and inconclusive trends in two instances (20000 cms flow at College Point and 25000 cms flow at Bonnet Carre) (Figures 2.13 through 2.16, Table 2.3).

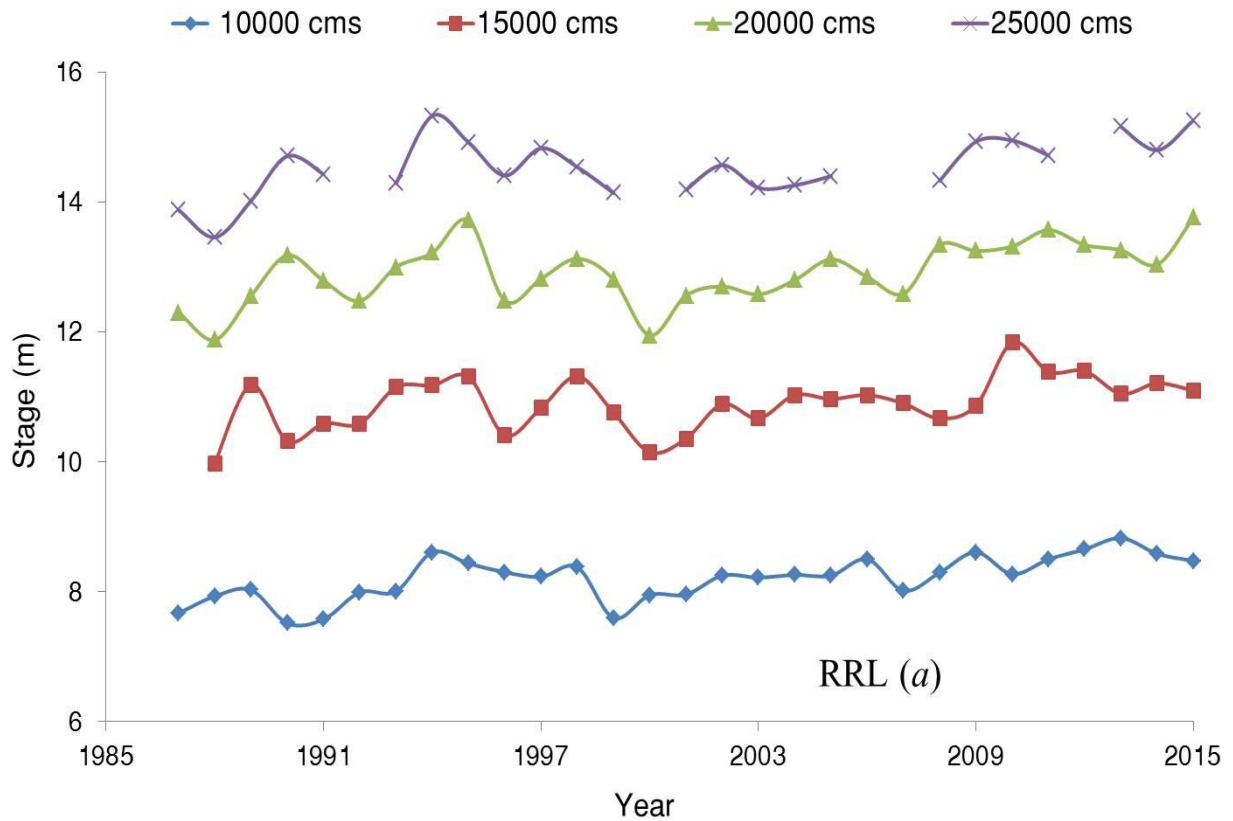


Figure 2.10: Trends in mean annual RS s of four Q_d types at the Red River Landing (RRL) of the Lowermost Mississippi River.

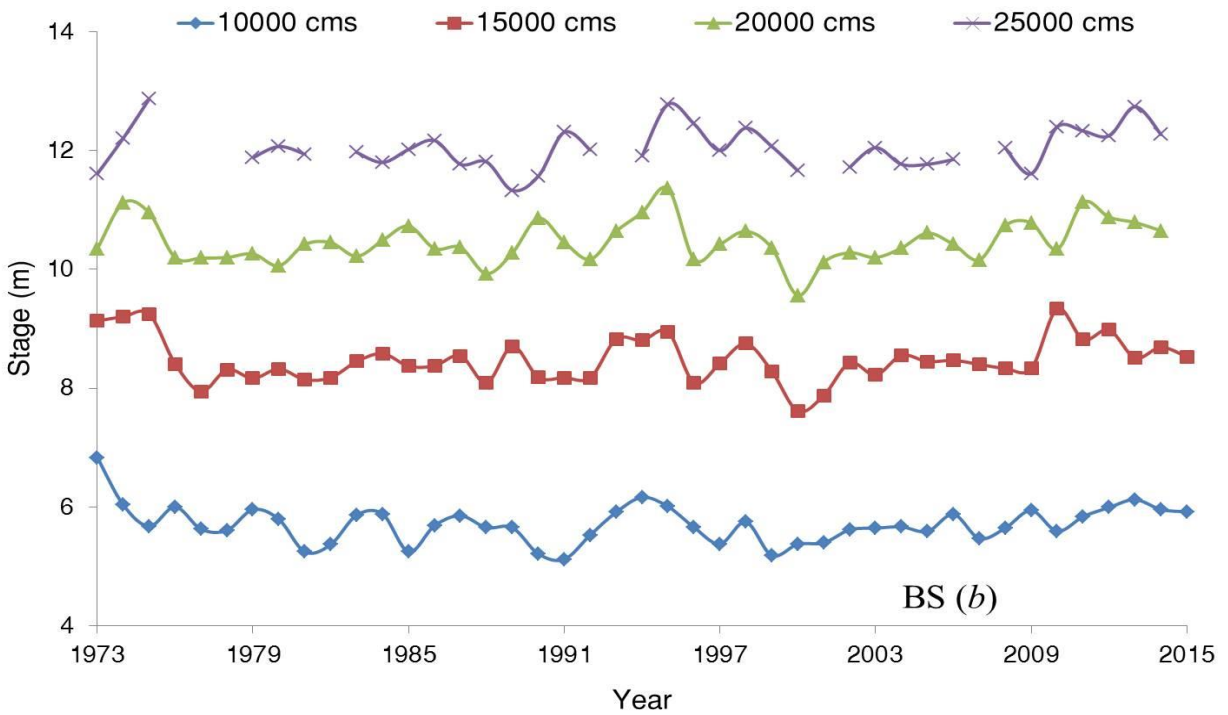


Figure 2.11: Trends in mean annual RSs of four Qd types at Bayou Sara (BS) of the Lowermost Mississippi River.

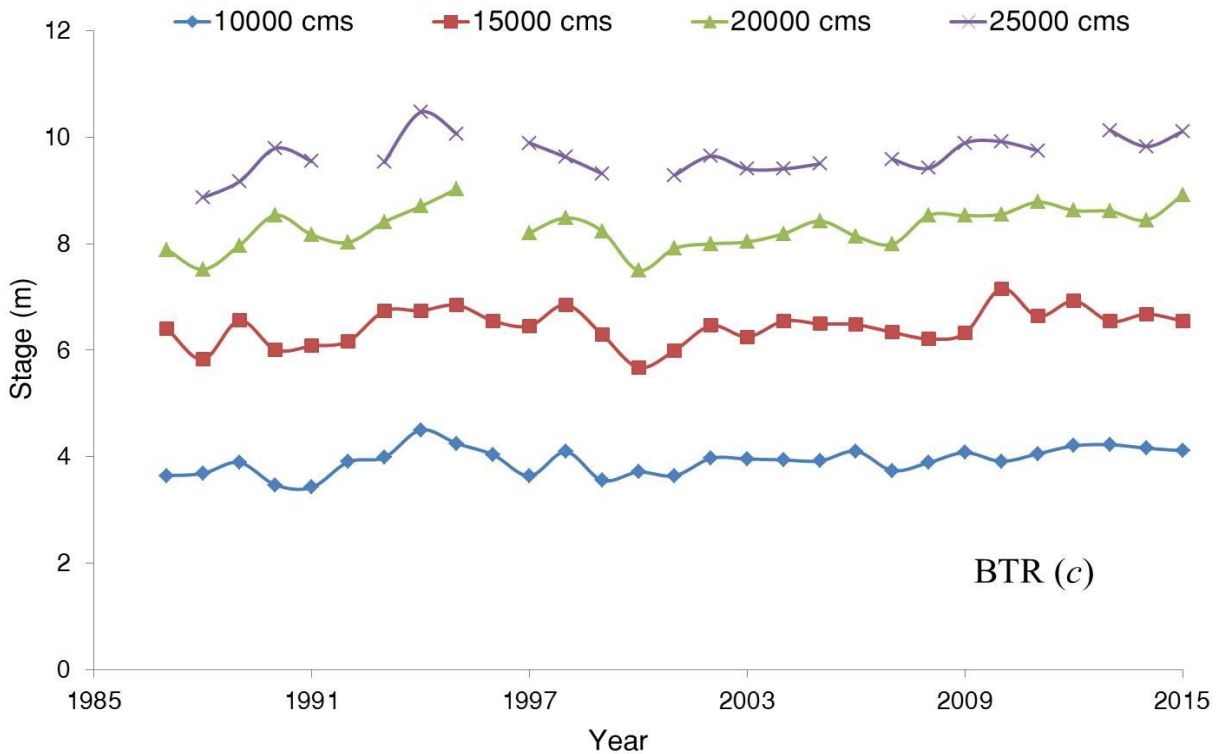


Figure 2.12: Trends in mean annual RSs of four Qd types at Baton Rouge (BTR) of the Lowermost Mississippi River.

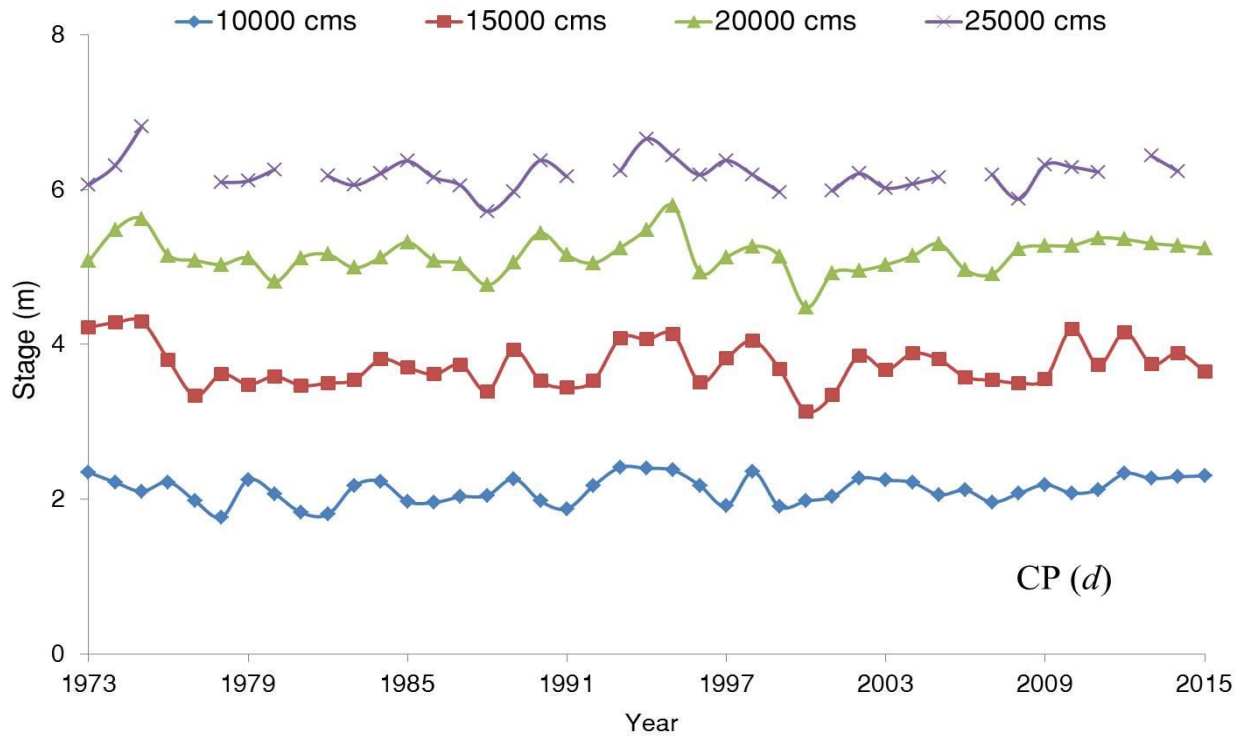


Figure 2.13: Trends in mean annual RSs of four Qd types at College Point (CP) of the Lower Mississippi River.

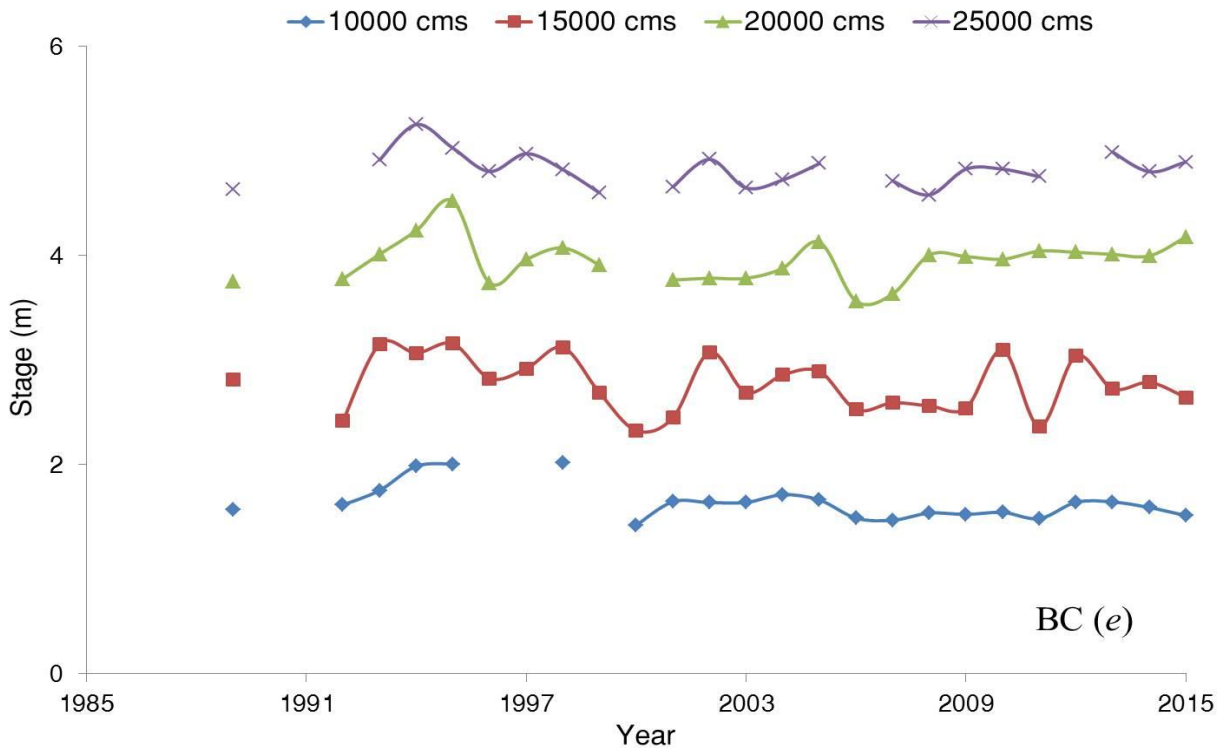


Figure 2.14: Trends in mean annual RSs of four Qd types at Bonnet Carre (BC) of the Lowermost Mississippi River.

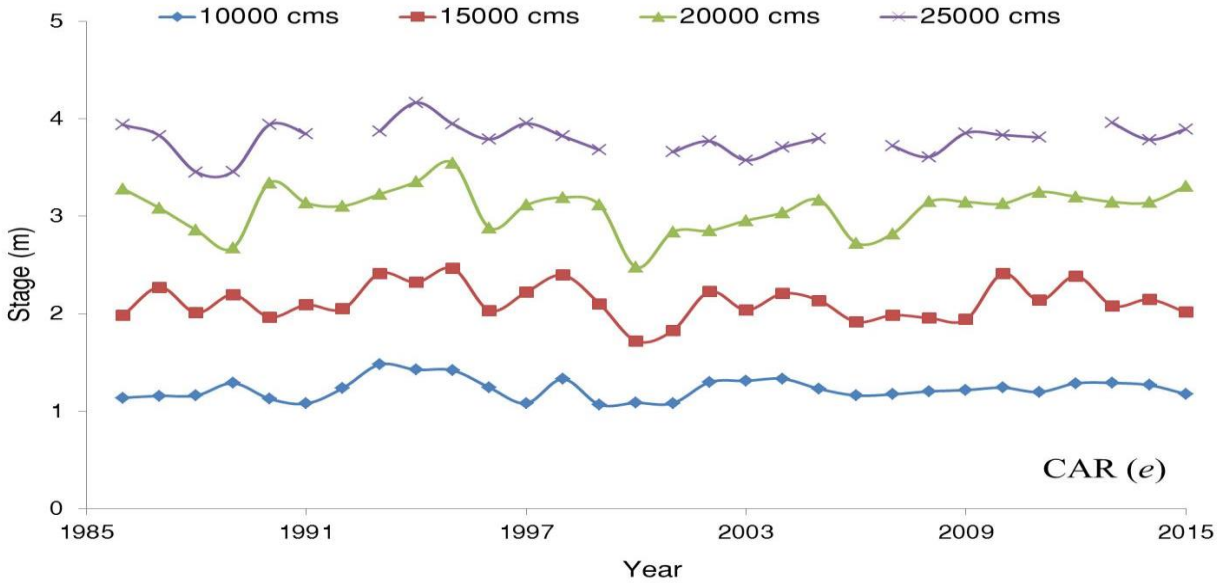


Figure 2.15: Trends in mean annual RSs of four Qd types at Carrollton (CAR) of the Lowermost Mississippi River.

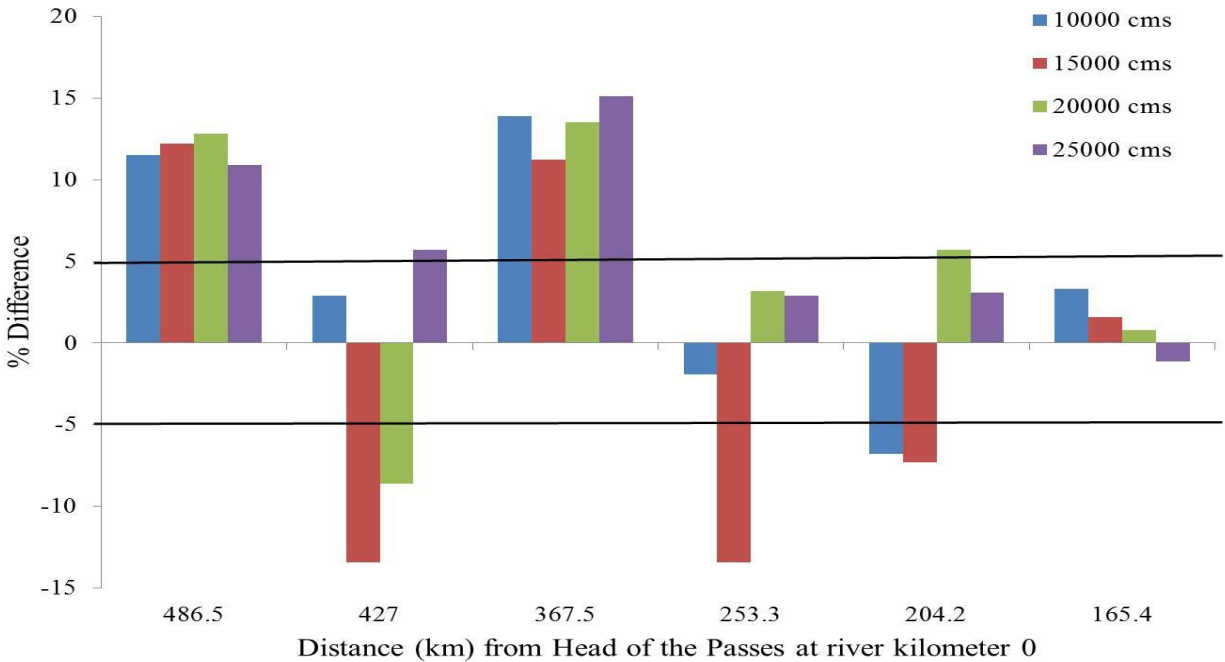


Figure 2.16: Percentage differences between mean annual RSs of starting and ending years in all Q_d types at Red River Landing (RRL) [at river kilometer (rk) 486.5] (1987-2015), Bayou Sara (BS) (at rk 427) (1973-2015), Baton Rouge (BTR) (at rk 367.5) (1987-2015), College Point (CP) (at rk 253.3) (1973-2015), Bonnet Carre (BC) (at rk 204.2) (1989-2015), and Carrollton (CAR) (at rk 165.4) (1986-2015) of the Lowermost Mississippi River. Note: Percentage differences falling within the black horizontal lines in both axes were considered insignificant based on the selected error range of $\pm 5\%$ for significance in average annual RSs of all Q_d s. X-axis distances are from the Head of the Passes (at rk 0) near the LmMR’s Gulf outlet.

Table 2.3: Yearly trends in river stages of four flow types [(a) 10000 cms (flow duration = 65.67%) (35th Percentile); (b) 15000 cms (flow duration = 43.88%) (57th Percentile); (c) 20000 cms (flow duration = 26.35%) (73rd Percentile); and (d) 25000 cms (flow duration = 11.92%) (87th Percentile)] at following six LmMR sites downstream chronologically: Red River Landing (RRL), Bayou Sara (BS), Baton Rouge (BTR), College Point (CP), Bonnet Carre (BC) and Carrollton (CAR). Information on the range of each flow types can be found in section 2.3. Note: River stage trends have been denoted as – SI: Significantly Increasing, SD: Significantly Decreasing, ND: No Difference (insignificant trend), and IC: Inconclusive (trend could not be concluded).

Station	Flow Type	Stage-Time trend line equation	P-value	Stage trend
RRL	10000	$y = 7.06 + 0.00007x$	< 0.0001	SI
	15000	$y = 9.96 + 0.00006x$	< 0.0001	SI
	20000	$y = 11.71 + 0.00008x$	< 0.0001	SI
	25000	$y = 13.65 + 0.00006x$	< 0.0001	SI
BS	10000	$y = 5.75 - 0.000004x$	0.19	ND
	15000	$y = 8.32 + 0.00001x$	0.0047	SD
	20000	$y = 10.24 + 0.00002x$	< 0.0001	SD
	25000	$y = 11.91 - 0.00001x$	0.0123	IC
BTR	10000	$y = 3.33 + 0.00004x$	< 0.0001	SI
	15000	$y = 5.83 + 0.00004x$	< 0.0001	SI
	20000	$y = 7.49 + 0.00004x$	< 0.0001	SI
	25000	$y = 9.06 + 0.00004x$	< 0.0001	SI
CP	10000	$y = 1.98 + 0.00001x$	0.02	IC
	15000	$y = 3.63 + 0.000006x$	< 0.0001	SD
	20000	$y = 5.1 + 0.000006x$	0.08	IC
	25000	$y = 6.25 - 0.000003x$	0.26	ND
BC	10000	$y = 1.73 - 0.000009x$	0.008	SD
	15000	$y = 3.05 - 0.000002x$	0.014	SD
	20000	$y = 3.97 - 0.0000002$	0.96	ND
	25000	$y = 4.924 - 0.000007$	0.097	IC
CAR	10000	$y = 1.20 + 0.00001x$	0.5	ND
	15000	$y = 2.19 - 0.000005x$	0.18	ND
	20000	$y = 3.13 - 0.000001x$	0.8	ND
	25000	$y = 3.88 - 0.000005x$	0.12	ND

2.3.4 River Stage Slope Changes

Significant long-term river surface slope trends between maximum annual RSs of all Q_{as} were observed only at upper consecutive sites of LmMR (Red River Landing-Bayou Sara and

Bayou Sara-Baton Rouge), while, the lower consecutive sites (Baton Rouge-College Point, College Point-Bonnet Carre, Bonnet Carre-Carrollton) all had either insignificant or inconclusive trends (Figure 2.17, Table 2.4). Annual slope from Red River Landing to Bayou Sara had a decreasing trend in 10000 cms flow type ($p = 0.0004$) (Figure 2.17a, Table 2.4), increasing trend in 25000 cms flow type ($p = 0.0072$) (Fig. 2.17d, Table 2.4), while inconclusive and insignificant trends in the 15000 and 20000 cms flow types respectively [$p = 0.02$ (inconclusive) and 0.12 (insignificant)] [Figure 2.17 (b, c), Table 2.4]. Further downstream from Bayou Sara to Baton Rouge, slope had an increasing trend for 10000, 15000, and 20000 cms flow types ($p = 0.0075$, 0.0019, and 0.0037 respectively) [Figure 2.17 (a, b, c), Table 2.4], while the trend could not be concluded for 25000 cms flow type ($p = 0.022$) (Figure 2.17d, Table 2.4). All but one LmMR slope trends in maximum annual river stage of all flow types at all other consecutive reaches downstream from Baton Rouge (Baton Rouge-College Point, College Point-Bonnet Carre, and Bonnet Carre-Carrollton) were insignificant (Figure 2.17, Table 2.4). Only, the slope trend in maximum annual *RS* of 25000 cms flow from College Point to Bonnet Carre could not be concluded ($p = 0.07$) (Figure 2.17d, Table 2.4).

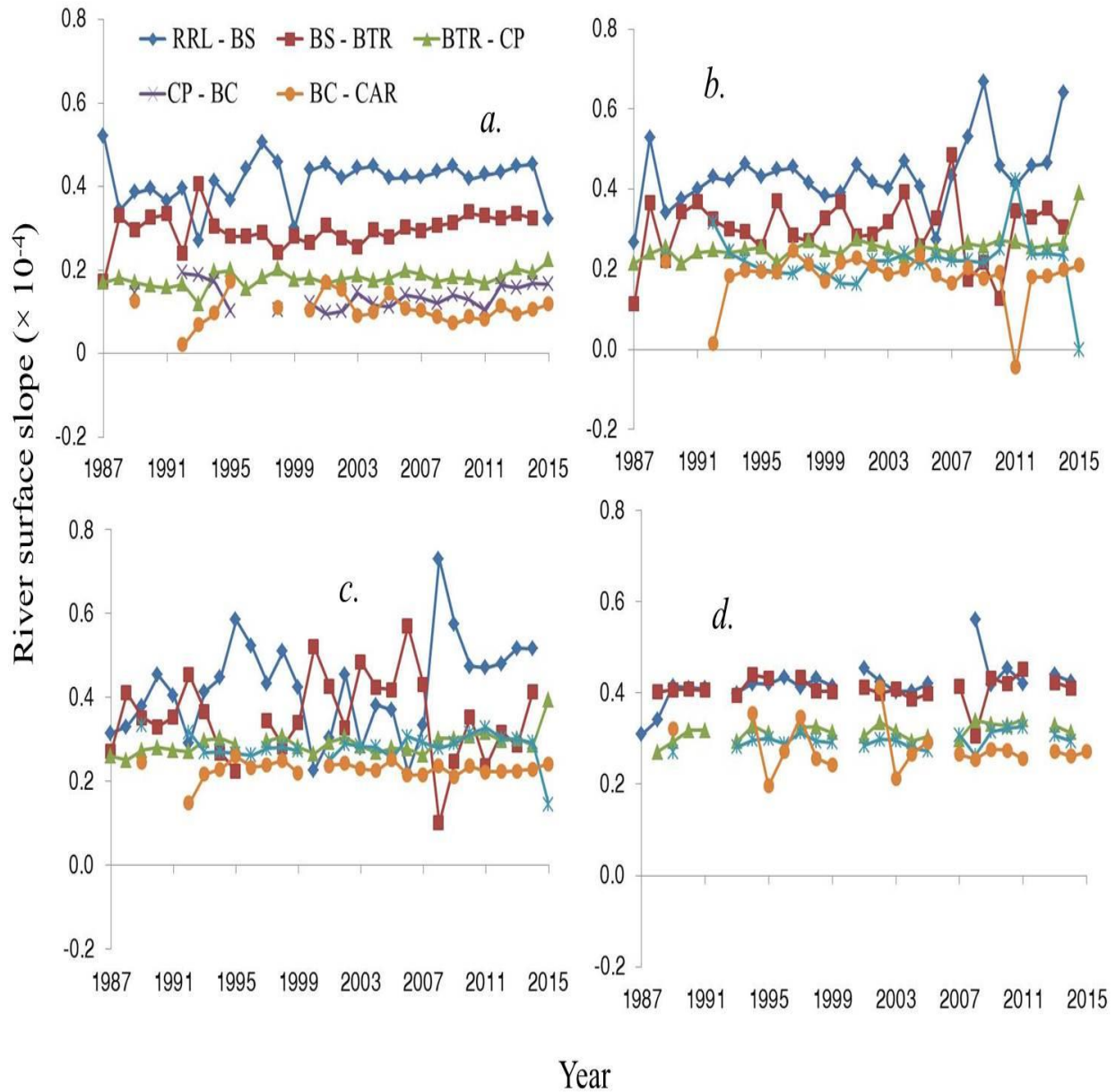


Figure 2.17: Trends in river surface slopes of maximum annual RSs of Qd type = 10000 cms (flow duration = 65.67%) (35th Percentile) (a), 15000 cms (flow duration = 43.88%) (57th Percentile) (b), 20000 cms (flow duration = 26.35%) (73rd Percentile) (c), and 25000 cms (flow duration = 11.92%) (87th Percentile) (d) from Red River Landing to Bayou Sara (RRL – BS), Bayou Sara to Baton Rouge (BS – BTR), Baton Rouge to College Point (BTR – CP), College Point to Bonnet Carre (CP – BC) and Bonnet Carre to Carrollton (BC – CAR) along the Lowermost Mississippi River.

Table 2.4: Yearly trends in river surface slopes of maximum annual *RSs* in four flow types [(a) 10000 cms (flow duration = 65.67%) (35th Percentile); (b) 15000 cms (flow duration = 43.88%) (57th Percentile); (c) 20000 cms (flow duration = 26.35%) (73rd Percentile); and (d) 25000 cms (flow duration = 11.92%) (87th Percentile)] for consecutive LmMR sites downstream i.e., from Red River Landing to Bayou Sara (RRL – BS), Bayou Sara to Baton Rouge (BS – BTR), Baton Rouge to College Point (BTR – CP), College Point to Bonnet Carre (CP – BC) and Bonnet Carre to Carrollton (BC – CAR). Information on the range of each flow types can be found in section 2.3. Notations for slope trends are same as those of river stage trends as explained in Table 2.3

Channel Reach (from - to)	Time Period	Flow type (cms)	P-value	Slope Trend
RRL-BS	1987–2015	10000	0.0004	SD
		15000	0.02	IC
		20000	0.12	ND
		25000	0.0072	SI
BS-BTR	1987–2015	10000	0.0075	SI
		15000	0.0019	SI
		20000	0.0037	SI
		25000	0.022	SI
BTR-CP	1987–2015	10000	0.32	ND
		15000	0.14	ND
		20000	0.28	ND
		25000	0.94	ND
CP-BC	1989–2015	10000	0.283	ND
		15000	0.3	ND
		20000	0.61	ND
		25000	0.07	IC
BC-CAR	1989–2015	10000	0.98	ND
		15000	0.74	ND
		20000	0.75	ND
		25000	0.34	ND

2.4 DISCUSSION

Findings from this study suggest that the first 135-140 km reach of the LmMR below the ORCS, covering Tarbert Landing, Red River Landing, Bayou Sara and Baton Rouge, experienced significant changes in cross-sectional area, river stage and river surface slope in specific discharge regimes. However, this study did not observe any noticeable change in these

components along the lower reach of the LmMR from 140 to 327 km below the ORCS, which covers College Point, Bonnet Carre and Carrollton. Specifically, this study noticed a significant decrease in cross-sectional area during 1992-2013 and a significant increase in river stages of all flows during 1987-2015 along the first 20-25 km LmMR reach below ORCS, covering Tarbert Landing and Red River Landing (reach 1) and the 60 km reach further downstream (from about 80 to 140 km below ORCS) covering Baton Rouge (reach 3). In the 55-60 km river reach between these reaches (from about 20-25 to 80 km below ORCS) covering Bayou Sara (reach 2), a significant increase in the cross-sectional area during 1992-2013, a significant decrease in river stages of 15000 and 20000 cms flows at Bayou Sara during 1973-2015 and a significant increase in slopes of maximum annual river stages of 10000, 15000 and 20000 cms flows from Bayou Sara to Baton Rouge during 1987-2015 were observed.

Conclusive areal changes along the upper 140 km LmMR reach have not been found earlier although Little and Biedenharn (2014) also analyzed cross-sections throughout the reach during 1963-2004. They reported noticeable increase in a few cross-sectional areas from approximately 10 km above to approximately 4 km below the ORCS and negligible changes in most cross-sectional areas from Tarbert Landing to the Head of Passes. The differences in these observations from our study could be because the cross-sections in their study were at least 2 km apart from the cross-sections in our study. In this study, the sites were selected according to their exact location in river kilometers provided by USACE. With respect to river stage changes in specific discharge, however, their finding was opposite to ours only at Bayou Sara during 1993-2011 [increasing trend in RS_d/s of three specific flow conditions (low flow: 7500–9000 cms; medium flow: 15500–18000 cms; and high flow: 26500–29500 cms)]. The contrasting observations at Bayou Sara in both studies could be because of the difference in comparison

periods and flow ranges. However, they also observed inconclusive or insignificant trends in annual *RSs* of all flows for the lower LmMR reach (with different study sites) further downstream from Baton Rouge to Carrollton (reach 4) to match our findings. Previously, Winkley (1977) also found increasing river stages across several discharge ranges from approximately 6000 to 14500 cms at Red River Landing but for the period between early-1940s and mid-1970s. Recently, Mossa (2013) reported an increase of approximately 2 m in river stages for specific discharges of 5000, 10000 and 15000 cms respectively at Tarbert Landing (about 5 km upstream of Red River Landing) between mid-1930s and early 2010s. A few other studies also analyzed long-term river stage trends for the LmMR, but they used Natchez and Vicksburg, about 95 and 210 km upstream of Tarbert Landing respectively as the locations for their analysis (Biedenharn and Watson 1997, Wasklewicz et al. 2004). Biedenharn and Watson (1997) found increasing river stage trends at both locations during 1972-1994, while Wasklewicz et al. (2004) found decreasing river stage trends at Vicksburg and non-significant trends at Natchez during 1887-1999. With respect to river surface slope trends, Beidenharn et al. (2000) compared pre-cutoff (1880s to 1930s) and post-cut off (1943-1992) slopes along the LmMR, however, approximately 930 to 95 km upstream of Tarbert Landing. One of their conclusions that slopes during the post-cutoff periods was more variable than the pre-cutoff slopes resembles with the noticeable variability this study observed in slopes along the upper three LmMR reaches during 1987-2015.

Several factors could have caused these multi-decadal morphological and hydrological changes along the first three LmMR reaches. The channel length of LmMR from Memphis, TN (approximately 690 km upstream of Tarbert Landing) to Tarbert Landing was artificially shortened by 30% (about 274 km in length) following the construction and execution of 14

meander cut-offs at several locations along this reach during 1929 and 1942 (Winkley 1977, Winkley 1994, Smith and Winkley 1996). Several significant morphological and hydraulic alterations were reported throughout the LmMR channel during the post-cutoff periods such as, continuous widening of channel with increased pool depth (Winkley 1977, Biedenharn et al. 2000), increase in minimum river stages (Elliott et al. 1991), subtle variation in channel roughness (Stanley Consultants 1990, Biedenharn et al. 2000) and significant increase in channel slope in a few locations (Biedenharn et al. 2000). Although the cut-offs were executed specifically from approximately 50 to 600 kms above Tarbert Landing, it is likely that these reported changes could also be occurring along the substantial portion of LmMR reach downstream from Tarbert Landing. A few studies noted that the effects on back water flows on river stages and channel bed along the LmMR reach such as depositional back water zones and divergent offshore plumes cannot be neglected (Chatanantavet et al. 2012, Lamb et al. 2012, Nittrouer et al. 2012). Furthermore, local modifications in the LmMR over small patches during 1973-2015, such as opening of Morganza Spillway during 1973 and 2011 floods and Bonnet Carre Spillway during 1973, 1993 and 2011 floods, construction of river training dikes in reach 3 (Pokrefke et al., 1995), and dredging to maintain navigational depths could also have subtle effects on the LmMR channel alternations.

The spatiotemporal changes in LmMR cross-sections and river-stages and slopes in the four discharge regimes along the first three reaches and non-significant changes in these components along the fourth reach can also be linked to bed adjustment pertaining to sediment deposition and erosion. In this regard, the study proposes a schematic model for channel adjustment along the LmMR reach over the last three decades based on the aforementioned changes in cross-sections, river stages and river surface slopes (Figure 2.18). In the model, the study deduces that over the

last three decades the LmMR reaches 1 and 3 have probably been aggrading gradually over time with higher sediment deposition, while reach 2 has probably been degrading gradually with higher sediment erosion (Figure 8). I also deduce that no significant change has occurred along reach 4 of the LmMR over the last three decades (Figure 8). Following two important phenomena seem to contribute significantly to sediment deposition along reach 1:

a) Reach 1 starts just below the ORCS, from where ~ 25 % flows are diverted to the Atchafalaya River (Copeland *et al.* 1992). The reduced flows along the Mississippi River exist since the ORCS establishment in 1963 and have lower velocities which further can aid in sediment deposition along the reach.

b) Reach 1 consists of a few sediment channel bars, three of which were recently investigated by Wang and Xu (2015) and Wang and Xu (2016). Wang and Xu (2015) reported that the total surface area of three channel bars located at 18, 24 and 26 km downstream from the ORCS respectively increased by 7.3% during the 2011 spring flood in the LmMR. Similarly, Wang and Xu (2016) estimated that the three bars accumulated a total of approximately 36 million tons sediment load during 1985-2013. These observations support our argument that river stages along reach 1 were probably increasing gradually over the last three to four decades because of higher sediment deposition which possibly resulted in decrease in cross-sectional area along the reach.

This study further hypothesizes potential existence and significant growth of sediment channel bars along reach 3 based on the observations of identical morphological and hydrological changes between reaches 1 and 3. However, channel bars probably either do not exist or did not experience noticeable sediment accumulation along reaches 2 and 4 because contrasting

morphological and hydrological changes were observed along reach 2 and non-significant alternations were observed along reach 4.

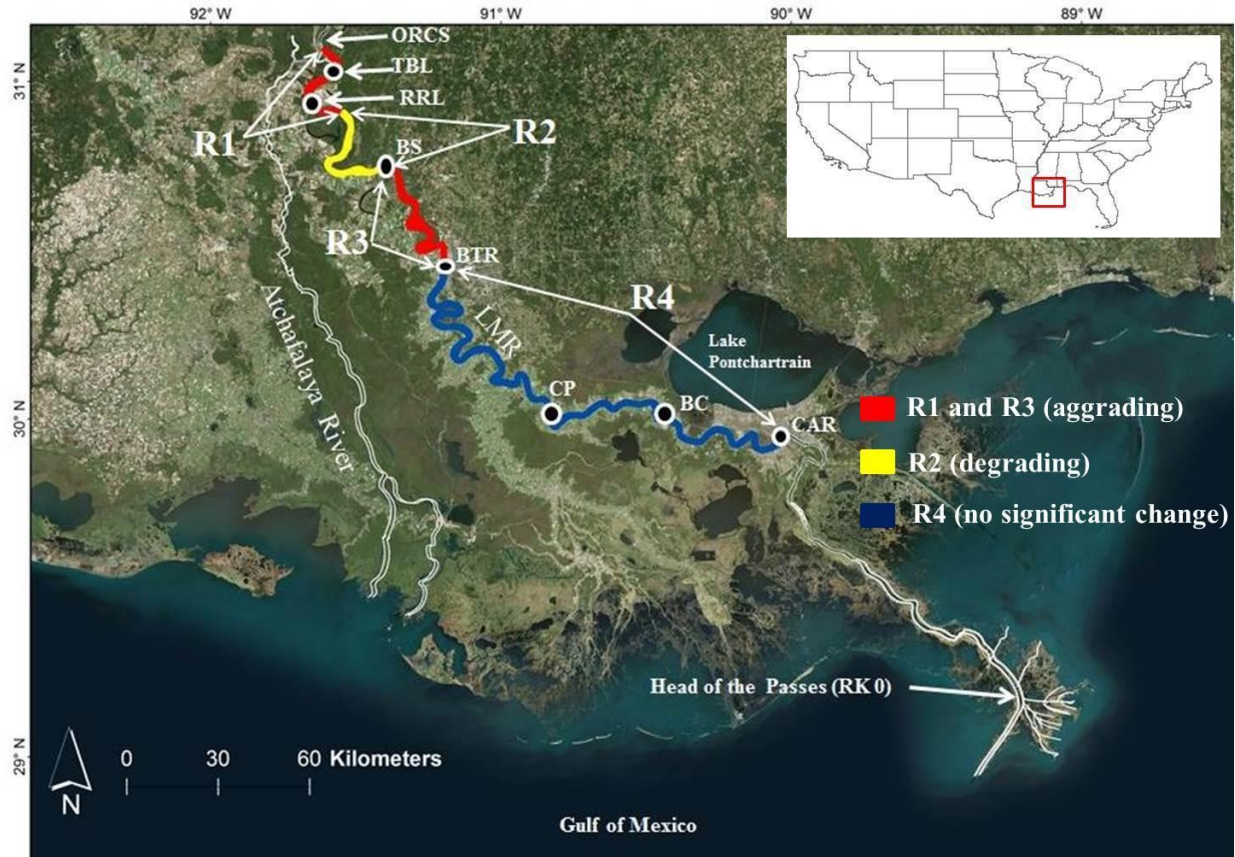


Figure 2.18: Schematic model showing aggrading, degrading, and unchanged reaches along the Lowermost Mississippi River during 1987–2015. Changes along the reaches have been deduced according to the study observations of cross-sectional area change and river stage and slope change in specific discharge regimes.

The possible alternative riverbed adjustment trend which the study deduced along reaches 1, 2 and 3 and negligible sediment deposition along reach 4 has been quantifiably supported by a short-term sediment budget study by Allison *et al.* (2012). They reported highest sediment load at Tarbert Landing [470 million tons (MT)] and significantly lower loads downstream at St. Francisville (at rk 416, about 11 km downstream from Bayou Sara) (271 MT) and Baton Rouge (277 MT) respectively during 2008-2010. These findings indicate that substantial sediment load (199 MT) was trapped between Tarbert Landing and Bayou Sara (near St Francisville), while

almost all load was eroded from Bayou Sara to Baton Rouge. They calculated a sediment load of 264 MT for only one location further downstream from Baton Rouge: Belle Chasse (at rk 121.6, approximately 43 km downstream from Carrollton). Close proximity between the sediment loads at Baton Rouge and Belle Chasse (difference of 13 MT in 3 years) in their study coincides with our observation that the lowermost 187 km reach is nearing dynamic equilibrium with negligible sediment deposition. A few recent studies found high long-term annual sediment and sand loads (30 to 40 years) at Tarbert Landing (Rosen and Xu 2014: *3180 MT sediment load during 1980-2010*; Nittrouer and Viraparelli 2014: *936 MT sand load during 1973-2012*; Joshi and Xu 2015: *1115 MT sand load during 1973-2013*). Also, Allison and Meselhe (2010) estimated that annual sediment load at Tarbert Landing was higher than St. Francisville by 20 MT/year during 1981-2004. These studies provide some evidence of higher multi-decadal sediment deposition along reach 1. However, long term sediment loads at other locations downstream from St. Francisville have not been quantified till date. Sediment and sand loads in all these studies were quantified from their corresponding rating curves; hence, all the loads are subjected to their corresponding error ranges.

The model proposed by this study on channel bed adjustment along the first 327 km of LmMR from the Old River Control Structure to Carrollton, New Orleans could have important implications on riverine management further downstream from Carrollton to Head of Passes too. Currently, sediment diversions have been planned only along the LmMR reach below Carrollton although a substantial portion of sediment load seems to be trapped along the first 140 km downstream of ORCS (approximately 335 to 200 kms above Carrollton). Therefore, sediment management along LmMR could benefit if sediments trapped along reaches 1 and 3 are systematically outsourced to reach 4. The sediment outflow from reach 4 to proposed diversion

sites below Carrollton can be achieved without further engineering the LmMR as the study deduced that reach 4 is probably approaching its dynamic equilibrium.

2.5 CONCLUSIONS

This study used the hydrographic survey measurements conducted in 1993, 2004 and 2013 as well as daily river discharge and stage records over the past three decades to assess the long-term channel morphological changes at seven locations along a 327-km reach of the Lowermost Mississippi River, one of the most regulated alluvial rivers in the world. The study found significant changes in cross-sectional area, river stage and river surface slope in specific discharge regimes along the first 140 km downstream of the LmMR's diversion to the Atchafalaya River (i.e. ORCS), covering Tarbert Landing, Red River Landing, Bayou Sara and Baton Rouge. Specifically, the first 20-25 km reach (reach 1) and the reach further downstream from 80 to 140 km (reach 3) showed continuous decrease in cross-sectional area and increase in river stage and river slope under all flow conditions. However, the 55-60 km reach in between (i.e., from 20-25 km to 80 km below ORCS) (reach 2) experienced exactly opposite trends i.e., increase in cross-sectional area and decrease in river stages. Furthermore, the remaining 187 km reach (i.e., from 140 to 327 km) (reach 4) had insignificant changes in its cross-sectional area, river stage and river surface slope. The study links these changes to channel bed adjustment pertaining to sediment deposition and erosion partially and propose that the reaches 1 and 3 have probably experienced sediment deposition; reach 2 has probably experienced bed erosion; and reach 4 is probably approaching dynamic equilibrium over the past three to four decades. Therefore, substantial amount of sediments potentially useful in land building purposes appear to be trapped along the first 140 km LmMR reach below ORCS, while sediment flow seems higher along the next 187 km reach. These findings suggest that large alluvial rivers with intensive

human interventions go through noticeable spatial and temporal changes in their corresponding bed adjustment processes. Such information can have relevant implications for riverine sediment management, channel engineering, and coastal land restoration in the world's sinking deltas fed by regulated alluvial rivers.

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CHAPTER 3: ASSESSMENT OF SUSPENDED SAND AVAILABILITY UNDER DIFFERENT FLOW CONDITIONS OF THE LOWERMOST MISSISSIPPI RIVER AT TARBERT LANDING DURING 1973-2013

3.1 INTRODUCTION

River deltas comprise approximately five percent of Earth's total land area and over 500 million people reside in them (Ericson et al. 2006, Syvitski et al. 2007). They are important regions in both economic and environmental sectors as they act as commercial centers and also provide a plethora of natural resources (Overeem et al. 2010, Rosen and Xu 2013). However, many river deltas around the world are facing land loss as the consequence of human and natural factors including river engineering (Turner 1997, Meade and Moody 2010), accelerated subsidence (Gagliano et al. 1981, Yuill et al. 2009), reduced riverine sediment supply (Kesel 1988, Thorne et al. 2008, Meade and Moody 2010), disconnection of the river with its floodplains (Xu 2014), coastal land erosion (Reed and Wilson 2004), and relative sea level rise (Georgiou et al. 2005).

One renowned example of river deltas facing land loss problem is the Mississippi River Delta Plain (MRDP) in south USA. The MRDP has been losing substantial amount of land since the early 20th century (Craig et al. 1979, Gagliano et al. 1981, Scafe and Turner 1983, Meade and Moody 2010). A recent study on MRDP land loss (Couvillion et al. 2011) reported a land disappearing rate of 43 km²/year since 1985. Potential of the MRDP land loss due to river engineering had long been recognized. More than a century ago, Corthell (1897) already warned: "If certain levee structures were placed in a manner that fresh water and sediments, along with vital nutrients, were laid to waste off the mouth of the Mississippi River, their deltaic regenerative properties would be lost and unrecoverable." However, the land loss issue captured major public attention only from the late 1970s [e.g., Craig et al 1979, Gagliano et al. 1981, Scafe and Turner 1983, Britisch and Dunbar 1993]. During the last decade, in the wake of

Hurricane Katrina, there has been an increasing concern over the issue in general public and scientific communities, which led to intensive efforts by the state and federal governments for finding solutions in offsetting coastal land loss (LDNR 1998, CPRA 2012). One of such solutions is diversion of the Mississippi River for outsourcing the river water and sediments to coastal marshes for stabilizing the deltaic system. The United States Army Corps of Engineers (USACE) has constructed three notable river diversions in the lowermost Mississippi River reach, namely, Caernarvon (river kilometer, or rk 131), Davis Pond (rk 190) and West Bay (rk 8), of which only West Bay focuses solely on sediment retention and capture (Rosen and Xu 2014). Also, the State of Louisiana's Master Plan for coastal restoration (2012) proposed six large to small water (discharge from 141 to 7079 cubic meter per second, or cms) and sediment diversions (CPRA 2012, Peyronnin et al. 2013), which are still in different planning phases.

Recent reports suggested that the three executed diversions have not gained significant steps towards their objectives despite careful planning and several years of operation (Brown et al. 2009, Kearney et al. 2011). The Caernarvon and Davis Pond freshwater diversions have not induced significant salinity reduction (Howes et al. 2010, Kearney et al. 2011) and have been subjected to more vegetation loss and nutrient overloading post hurricanes Katrina and Rita (Snedden et al. 2007, Kearney et al. 2011). Similarly, the planned discharge of the West Bay diversion has been increased from 396 cms at its inception in 2003 to 765 cms currently at the cost of adverse effects in navigational route; however, it has not produced desired land growth in the surrounding area (Brown et al. 2009, LWF 2012, Heath et al. 2010).

A primary goal of the river diversion focusing entirely on sediment retention and capture is to divert flow carrying a maximum amount of sediments into adjoining drowned areas for delta restoration, without hampering the ecological, structural, hydrological and functional integrity of

the river at all (Poala et al. 2011, CPRA 2012, Peyronnin et al. 2013). In the context of this goal, Rosen and Xu (2014) analyzed the flow-sediment relationship for Tarbert Landing of the Lowermost Mississippi River (abbreviated hereafter as LmMR and defined as the 500-km reach from the Old River Control Structure to the river's Gulf outlet) to quantify sediment loads carried by varying flows during 1980–2010. They found that about half of the total annual sediment yield was produced within about 120 days every year when the river was at intermediate (18,000 – 25,000 cms) and high (25,000 – 32,000 cms) flows; hence, they recommended these flows to be diverted according to their natural cycle of occurrence during the year. Allison et al. (2012) quantified short-term sediment budgets for different locations along the LmMR and suggested that years with high annual flow yielded high sediment input in the system and vice-versa, highlighting the advantage of sediment diversions during high flows.

Suspended solids in the Mississippi River have been found to be composed of a high proportion of fine clay/silt particles (< 0.0625 mm) and a low proportion of coarser particles (> 0.0625 mm) (Mossa 1996, Allison et al. 2012). Studies by Nepf (2004) and Nittrouer et al. (2012) postulated that sand may play a much more critical role in new land building in the Mississippi River delta than fine clay/silt. The importance of sand transport for the Mississippi River deltaic development has been increasingly recognized (Roberts et al. 2003, Nittrouer et al. 2011, Nittrouer et al. 2012, Nittrouer and Viparelli 2014). Therefore, analysis of the relationship of total suspended sediment with river hydrology alone is not enough for developing effective sediment management plans. Although the sediment assessments by Rosen & Xu (2014), Allison et al. (2012) and Nittrouer and Viparelli (2014) provide critical information for understanding sediment availability in the LmMR, they give little insights into the actual quantity of riverine sand under different flow regimes. The information about the actual sand availability can be

crucial for developing management practices in maximizing sand capture in the LmMR.

Understanding sand–discharge relationship for the LmMR not only is urgent for the river itself but also can help in providing reference information for riverine sediment analysis and coastal land restoration in other sinking river deltas in the world. Furthermore, understanding riverine sand behavior under different flow regimes is also important for research on future river engineering and coastal restoration in combating land loss due to climate-change induced sea level rise.

This study aims to determine sand availability under different flow regimes at Tarbert Landing of the LmMR from 1973 to 2013. The site provides the longest, most regular and most updated discharge and sediment records in the LmMR. Hence, comprehensive study of flow–sediment interaction at this site is important for effective execution and planning of implemented and proposed diversion projects. The specific objectives of the study include: (1) assessing hydrologic effects on sand transport, (2) quantifying daily sand loads and analyzing their seasonal and annual trends, (3) developing a hydrograph-based sand availability scheme for five river stages classified by the U.S. National Oceanic and Atmospheric Administration (NOAA), and (4) assessing extreme events of sand transport and their recurrence. NOAA uses stage records from the Red River Landing site, approximately 1.5 km downstream of the Tarbert Landing gauge station, for its flood warning prediction of the LmMR, whereby five flow stages are classified (NWS 2015): 1) Low Flow Stage (river stage: < 9.8 m); 2) Action Flow Stage (river stage: 9.8 – 12.1 m); 3) Intermediate Flow Stage (river stage: 12.1 to 14.6 m); 4) High Flow Stage (river stage: 14.6 to 16.8 m); and 5) Peak Flow Stage (river stage: > 16.8 m).

This study mainly focuses on analysis of sand concentration trends across low, medium and high discharge regimes, development of discharge-sand rating curves to calculate sand load for

each day at Tarbert Landing from 1973 to 2013 and identification of discharge regimes transporting highest amount of sands. Apart from this daily discharge has also been analyzed by identifying its monthly and annual trend and its duration curve. Daily discharge analysis is crucial for identifying its short- and long-term relationship with sand transport in the LmMR.

3.2 METHODS

3.2.1 Study Site

The Tarbert Landing river gauge station (31°00'30"N, 91°7'25" W) is located at river kilometer 493 (river mile 306.3) of the Mississippi River. The station is below the Old River Control Structure (ORCS) (Copeland and Thomas 1992) (Figure 3.1) that diverts approximately 25% (under the normal flow conditions) of the Mississippi River's water into the Atchafalaya River. The site provides the most updated and most comprehensive sediment records for the LmMR where both the United States Geological Survey (USGS) and United States Army Corps of Engineers (USACE) have a monitoring station (USGS Station ID: 07295100 and USACE Gauge ID: 01100). ORCS was built in 1963 with the primary goal of preventing a large amount of Mississippi River water (> 30%) from entering the Atchafalaya River (Willis 2009, Xu 2010). Discharge at Tarbert Landing is, therefore, manipulated by ORCS based on specific river flow conditions.

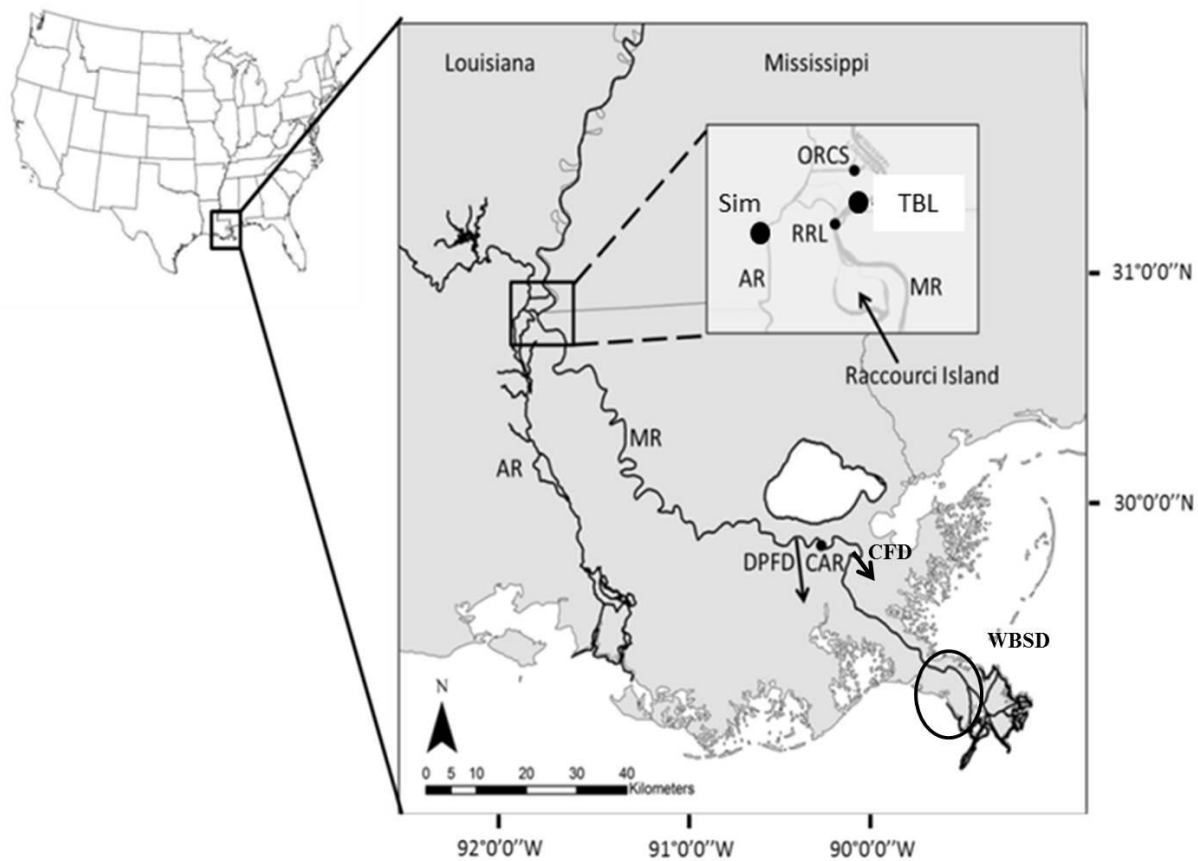


Figure 3.1: Study area map (modified from Rosen and Xu 2014) showing the location of the LmMR at Tarbert Landing (TBL) (USGS Station ID 07295100 and USACE Gage ID 01100). MR and AR denote the courses of the Mississippi and Atchafalaya Rivers respectively; ORCS is the Old River Control Structure; “Sim” denotes Simmesport (USGS Station ID 07381490) site of the Atchafalaya River; RRL is Red River Landing, the gauging station for USGS just below TBL consisting of river stage records and CAR denotes Carrollton, New Orleans. The three Mississippi River diversions introduced earlier have also been shown in the figure: Davis Pond Freshwater Diversion (DPFD), Caernarvon Freshwater Diversion (CFD) and West Bay Sediment Diversion (WBSD).

3.2.2 Flow and Sediment Concentration Data

Records on mean daily discharge (Q_d in cms) were collected for Tarbert Landing from USACE for the period from 1 January 1973 to 31 December 2013. For the same period, measurements on suspended sediment concentrations (SSC) in milligram per liter (mg/l) and corresponding percentage of silt/clay (fine sediment) fractions in SSC (i.e. diameter < 0.0625 mm) were collected from USGS. USGS carries out depth-integrated suspended sediment

sampling every 12 to 26 days using several isokinetic point samplers (i.e. P-61, P-63, D-96, D-99) ranging from 4-8 verticals and each vertical consisting of 2 to 5 samples (Thorne et al. 2008, Beverage 1987, Edwards 1999, Skinner 2007 – these studies also cover in depth analysis of *SSC* collection and processing techniques and error adjustments). A specific example of sediment sampler is shown in Figure 3.2. Also, a flowchart of the selection of sediment samplers in a particular sediment sampling project along the Atchafalaya and Lower Mississippi Rivers respectively is shown in Figure 3.3. From 1973 to 2013, a total of 1043 *SSC* samples were collected, processed and documented for Tarbert Landing. During these 41 years, each month had 1 to 3 sampling dates; therefore, it is assumed that the *SSC* data have a sufficient, unbiased representation across all seasons and flow regimes. The discharge and sediment concentration data were used to compute sand loads as described in section 3.2.5 below.

3.2.3 NOAA's River Stages and their Corresponding Flow Regimes

For its flood warning prediction, NOAA defined five river stages at Red River Landing. In their study on long-term suspended sediment transport at Tarbert Landing, Rosen and Xu (2014) identified corresponding discharge for these stages: discharge < 13000 cms for Low Flow Stage, 13000 – 18000 cms for Action Flow Stage, 18000 – 25000 cms for Intermediate Flow Stage, 25000 – 32000 cms for High Flow stage, and > 32000 cms for Peak Flow Stage. These regimes were further used several times in our study, for e.g. in frequency analysis, duration curves, and sand distribution and transport trends across these regimes.



Figure 3.2: An example of depth integrated sampler used by United States Geological Survey (USGS) personnel while sampling suspended sediment concentration (SSC in mg/l) in the Atchafalaya River. The same samplers are used to sample SSC in the Lowermost Mississippi River. Picture courtesy: Dr. Y. Jun Xu.

3.2.4 Sand Concentration in River Discharge

Using the percentage of silt/clay fractions in suspended sediment concentration, first silt/clay concentration (SSC_f) were calculated by multiplying the percentage with SSC . Sand concentration (SSC_s in mg/l) for each sampling event was then quantified by subtracting the SSC_f (mg/l) from SSC (mg/l). The distribution of SSC_s across a daily river discharge (Q_d) range was then analyzed by building two types of SSC_s (y-axis)– Q_d (x-axis) plots: P–1 and P–2. Average SSC_s and their percentage changes within pre-selected Q_d intervals (every 3000 cms) were plotted against those Q_d intervals in P–1. Similarly, individual SSC_s were fitted against their

corresponding Q_{ds} in P-2. The upper limit of the Q_d range in P-1 after which average SSC_s began to decrease following a continuous increase (27000 cms) gave the point for separating increasing and decreasing SSC_s in P-2. Hence, all SSC_s values for $Q_d \leq 27000$ cms were defined as increasing sand, while all SSC_s values for $Q_d > 27000$ cms were defined as decreasing sand in P-2.

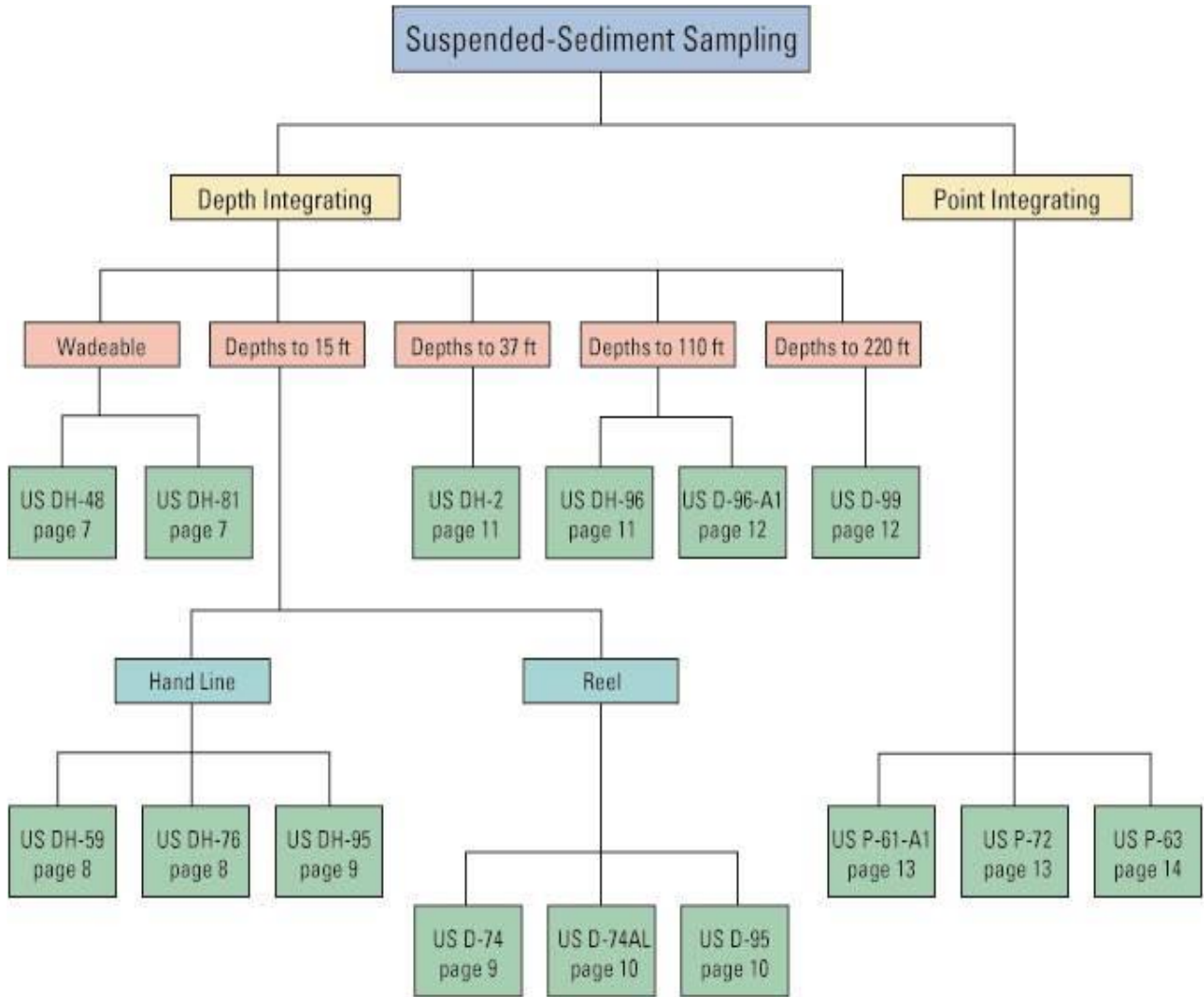


Figure 3.3: Flowchart showing the procedure used by United States Geological Survey (USGS) to select sediment samplers for a particular sampling project along the Atchafalaya and Lowermost Mississippi Rivers. Figure courtesy: Dr. Y. Jun Xu.

3.2.4 Sand Concentration in River Discharge

Using the percentage of silt/clay fractions in suspended sediment concentration, first silt/clay concentration (SSC_f) were calculated by multiplying the percentage with SSC . Sand concentration (SSC_s in mg/l) for each sampling event was then quantified by subtracting the SSC_f (mg/l) from SSC (mg/l). The distribution of SSC_s across a daily river discharge (Q_d) range was then analyzed by building two types of SSC_s (y-axis)– Q_d (x-axis) plots: P–1 and P–2. Average SSC_s and their percentage changes within pre-selected Q_d intervals (every 3000 cms) were plotted against those Q_d intervals in P–1. Similarly, individual SSC_s were fitted against their corresponding Q_d s in P–2. The upper limit of the Q_d range in P–1 after which average SSC_s began to decrease following a continuous increase (27000 cms) gave the point for separating increasing and decreasing SSC_s in P–2. Hence, all SSC_s values for $Q_d \leq 27000$ cms were defined as increasing sand, while all SSC_s values for $Q_d > 27000$ cms were defined as decreasing sand in P–2.

3.2.5 Development of Discharge-Sand Load Rating Curves

Daily sand load (DSL_s in tonnes/day) was computed by multiplying SSC_s with the corresponding daily discharge (Q_d in cms) for all the sampling dates during 1st January, 1973 and 31st December, 2013 as:

$$DSL_s = Q_d \times SSC_s \times 0.0864 \quad (3.1)$$

where 0.0864 is a unit conversion factor for converting the sand mass to tonnes per day.

There were nine outliers out of a total of 1043 sediment sampling events for the entire 41-year study period. These ~1% outliers were 4 to 6 times higher than the long-term standard deviation of sand concentrations; hence, were decided to be removed from further analysis. A natural logarithm (ln) was taken for the two variables, DSL_s (dependent; y) and Q_d (independent; x), and both linear and polynomial rating curves were applied for the relation between them. The evaluation of all applied rating curves were based on four criteria: regression coefficient of the curves (R^2 must be ≥ 0.8), root mean square errors of the predicted (or calculated) DSL_s (RMSE) (the lower the better), standard error (SE) of the rating curves (in ln units) (also, the lower the better) and a graphical assessment (good visual agreement between corresponding calibrated and predicted DSL_s) (Sykes 1993, Philips et al. 1999, Sadeghi et al. 2008).

To achieve the ‘predicted DSL_s ’, ‘log transformed (ln) Q_d ’ in the rating curve equations were fitted to get ‘predicted ln DSL_s ’ at first and then thus obtained ‘predicted ln DSL_s ’ were transformed back by taking their exponential values. Potential log-biasing in this retransformation procedure was also checked using the following correction factor (CF) given by Duan (1983) and modified by Gray et al. (2015) because firstly it does not require normality of residuals and secondly residuals for a few rating curves in our analyses were not normally distributed (P-values < 0.05 in Shapiro-Wilk tests).

$$CF = \frac{\sum_{i=1}^n \text{Exp}(e_i)}{n} \quad (3.2)$$

where e_i is the difference between i^{th} observations of ‘measured log DSL_s ’ and ‘predicted log DSL_s ’ and n is the total number of samples used in the given rating curve.

Single linear and polynomial rating curves were applied for the whole period at first, however, all four criteria to evaluate rating curves approach were not met here: lower R^2 (0.69 for linear and 0.7 for polynomial rating curve) (Table 3.1), comparatively higher RMSE (71067 for linear and 67950 for polynomial rating curve) (Table 3.2), comparatively higher SE (0.823) (Table 3.2), and poor visual agreement between corresponding measured and predicted $DSL_{s,s}$ (Figure 3.4). Low sample size of sediment concentrations during each year stopped us from applying sand rating curves annually during 1973-2013. Also, rating curves in decadal intervals can minimize year to year variability in sediment samples and give robust average-annual predictions over decadal periods [supplementary information in Nittrouer and Viparelli (2014)]. Therefore, linear and polynomial rating curves were further applied for the following approximately decadal intervals in continuum: 1973–1985 ($n = 463$), 1986–1995 ($n = 242$), 1996–2005 ($n = 187$), and 2006–2013 ($n = 142$). The prerequisite of $R^2 \geq 0.8$ was met for three of the four periods (1973–85: linear $R^2 = 0.8$, polynomial $R^2 = 0.84$; 1996–2005: linear $R^2 = 0.81$, polynomial $R^2 = 0.83$; 2006–13: linear $R^2 = 0.82$, polynomial $R^2 = 0.87$) (Table 3.1), so corresponding rating curves for these periods were subjected to further evaluation using other three criteria. However, the period 1986–95 had R^2 s (R-squares) < 0.8 (0.57) for both rating curves (Table 3.1). So, each year was checked with annual linear and polynomial rating curves to find the years responsible for lowering the combined linear and polynomial R^2 s in this period (Appendix A1). I found all R^2 s during 1986–90 (0.15–0.51) in one cluster, substantially lower than all R^2 s during 1991–95 (0.69–0.92) in another cluster (Appendix A1). Hence, based on approximation of individual R^2 s of annual rating curves, I combined the two periods 1986–90 ($n=118$) and 1991–95 ($n = 124$) for further evaluation of their corresponding rating curves.

Finally, I found that polynomial discharge-sand load rating curves during the four durations: 1973–1985, 1991–1995, 1996–2005 and 2006–2013 met all the four criteria and provided DSL estimates most approximate to the measured $DSL_{s,s}$ (Tables 3.1, 3.2; Figure 3.5). I also found that use of correction factors overestimated $DSL_{s,s}$ slightly (for polynomial curves) as well as substantially (for linear curves) as compared to their corresponding calibrated measurements (Table 3.2; Figures 3.4, 3.5). Hence, based on evaluation of these overestimations and previous arguments regarding unreliability of the correction factors (Walling and Webb 1988, Khaleghi et al. 2015), polynomial sand rating curves categorized into aforementioned four periods without correction factor were decided to be used to calculate sand loads for each day from 1973 to 2013 except for the period 1986–1990. The reason for excluding rating curve analysis from 1986–1990 and the procedure followed to calculate daily sand loads during this period have been explained in section 3.2.6 further down.

Table 3.1: Discharge-sand load rating curves developed for Tarbert Landing of the LmMR. Here, $x = \ln(Q_d)$ (the independent variable) and $y = \ln(DSL)$ (the independent variable).

Period	Discharge – Sand Load Rating Curve	Model	R^2
1973 - 2013	$y = 2.2046x - 10.394$	Linear	0.69
	$y = -0.4685x^2 + 11.091x - 52.388$	Polynomial	0.70
1973 - 1985	$y = 2.1964x - 10.214$	Linear	0.80
	$y = -0.6865x^2 + 15.312x - 72.613$	Polynomial	0.84
1986 - 1995	$y = 2.3031x - 11.947$	Linear	0.57
	$y = 0.1371x^2 - 0.274x + 0.1185$	Polynomial	0.57
1986 - 1990	$y = 1.4283x - 4.2019$	Linear	0.36
	$y = -0.1473x^2 + 4.1608x - 16.823$	Polynomial	0.36
1991 - 1995	$y = 2.8142x - 16.427$	Linear	0.83
	$y = -0.5842x^2 + 13.993x - 69.687$	Polynomial	0.86
1996 - 2005	$y = 2.0516x - 8.7022$	Linear	0.81
	$y = -0.4666x^2 + 10.9x - 50.514$	Polynomial	0.83
2006 - 2013	$y = 2.2267x - 10.204$	Linear	0.82
	$y = -0.6382x^2 + 14.3x - 67.139$	Polynomial	0.87

Table 3.2: RMSEs of DSLs predicted through discharge-sand load rating curves for each period in Table 1. Here, SE is the standard error and CF-Poly is the Duan correction factor used in polynomial rating curves, while CF-Lin is the Duan correction factor used in linear rating curves. ‘No CF’ represents DSLs calculated without applying correction factors during their retransformation from predicted ln DSLs while ‘CF’ represents DSLs calculated by applying the correction factors during the retransformation procedure.

Period	RMSE - No CF (Polynomial)	RMSE - No CF (Linear)	SE	CF- Poly	CF- Lin	RMSE - CF (Polynomial)	RMSE - CF (Linear)
1973 - 2013	67950	71067	0.823	1.586	1.592	75091	98817
1973 - 1985	61604	72892	0.596	1.194	1.213	62099	85875
1986 - 1990	41021	41248	1.132	1.841	1.662	181902	129574
1991 - 1995	62625	71692	0.572	1.141	1.174	63491	81031
1996 - 2005	48444	55213	0.505	1.155	1.152	48899	61483
2006 - 2013	50261	81456	0.496	1.122	1.13	51409	94689

3.2.6 Non-Rating Curve Approach for Sand Load Calculation

For the period of 1986–1990, three of the four criteria to evaluate rating curves approach were not met: lower R^2 (0.36 for both polynomial and linear rating curves) (Table 3.1), comparatively higher SE (1.132) (Table 3.2) and poor visual agreement between corresponding measured and predicted DSLs (Figure 3.6). Therefore, calibrated sand concentration measurements (117 samples) and daily discharge were used to calculate sand loads for each day during this period. Here, starting from 1986, the earliest available sand concentration of the year was assumed to be equal to all consecutive days of missing concentration until the next value was available. Also, last available concentration of the earlier year was used for filling values of missing days of the current year if the earliest concentrations did not start from 1st day of the year. Finally, DSLs for non-sand rating curve years were calculated using the formula in equation (3.1).

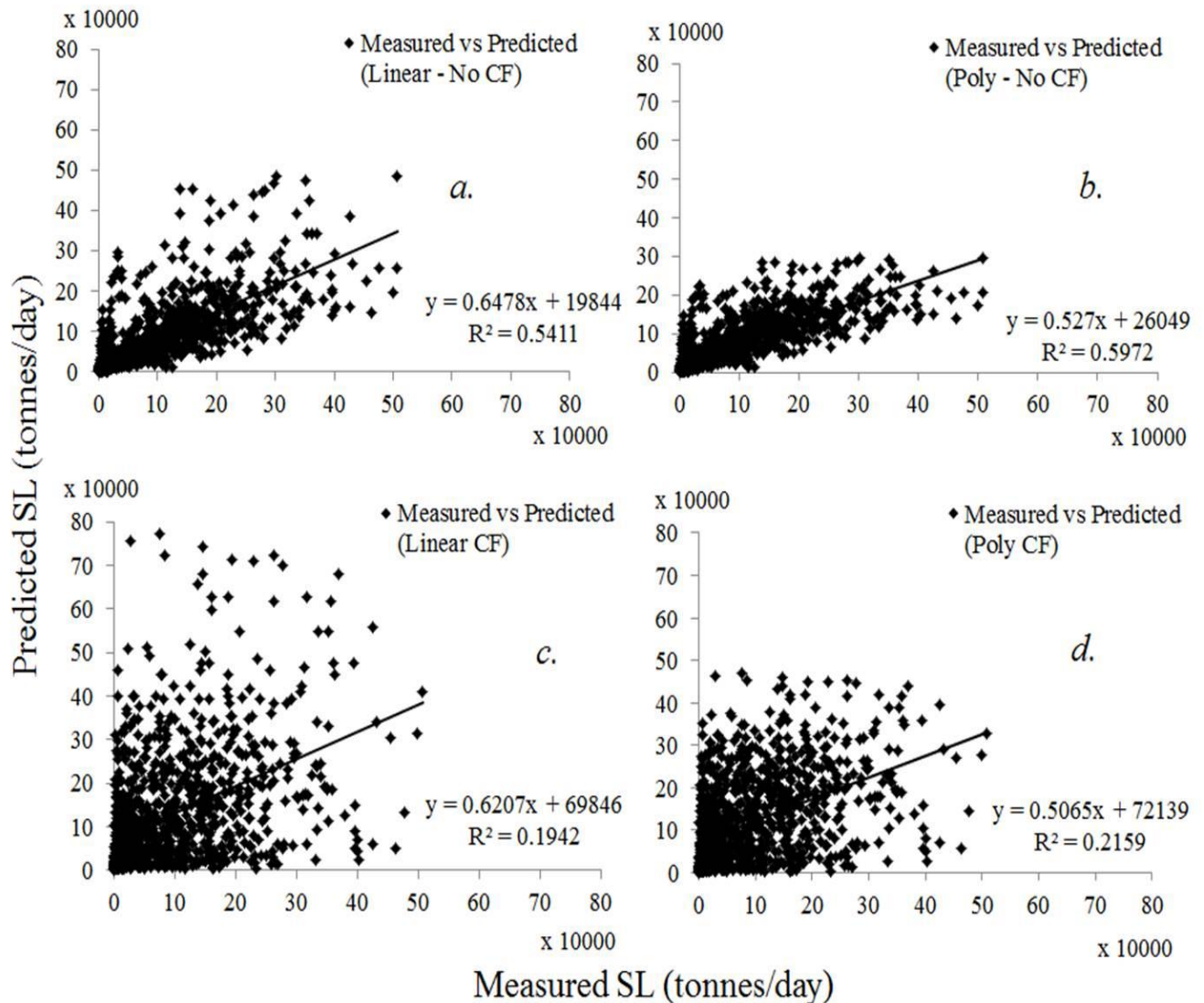


Figure 3.4: Scatter plots showing comparison between sand loads calculated from sand concentrations measured, processed and calibrated by USGS (Measured SL) and those predicted from single sand-rating curve (either linear or polynomial) (Predicted SL) at Tarbert Landing from 1973 to 2013. Here, linear rating curves were used for predicting SLs in “a” and “c” while polynomial rating curves were used for predicting SLs in “b” and “d”. Also, Duan correction factors were applied in predicted SLs of curves “c” and “d” (denoted by “CF” in the figure) while the SLs in curves “a” and “b” were predicted without correction factors (denoted by “No CF” in the figure).

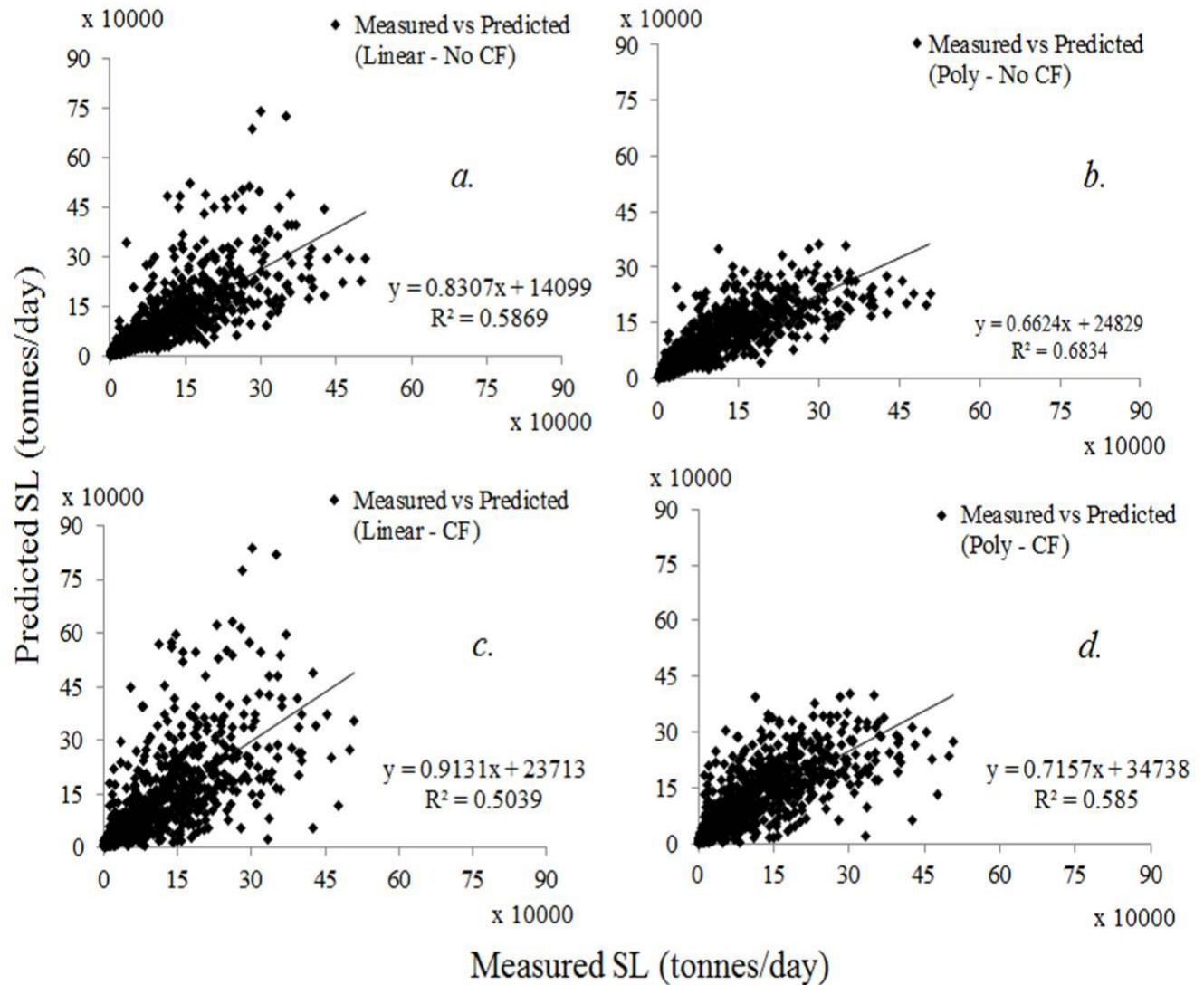


Figure 3.5: Scatter plots showing comparison between sand loads calculated from sand concentrations measured, processed and calibrated by USGS (Measured SL) and those predicted from several sand-rating curves (Predicted SL) at Tarbert Landing from 1973 to 2013. Specific terminologies pertaining to parts “a”, “b”, “c” and “d” of this figure i.e., Linear, Poly, CF, and No CF are same as explained in Figure 2. It is noted that both predicted and measured SLs during the period 1986–1990 were eliminated in this comparison because of the low R2 value of both rating curves during this period (please see Table 3.1).

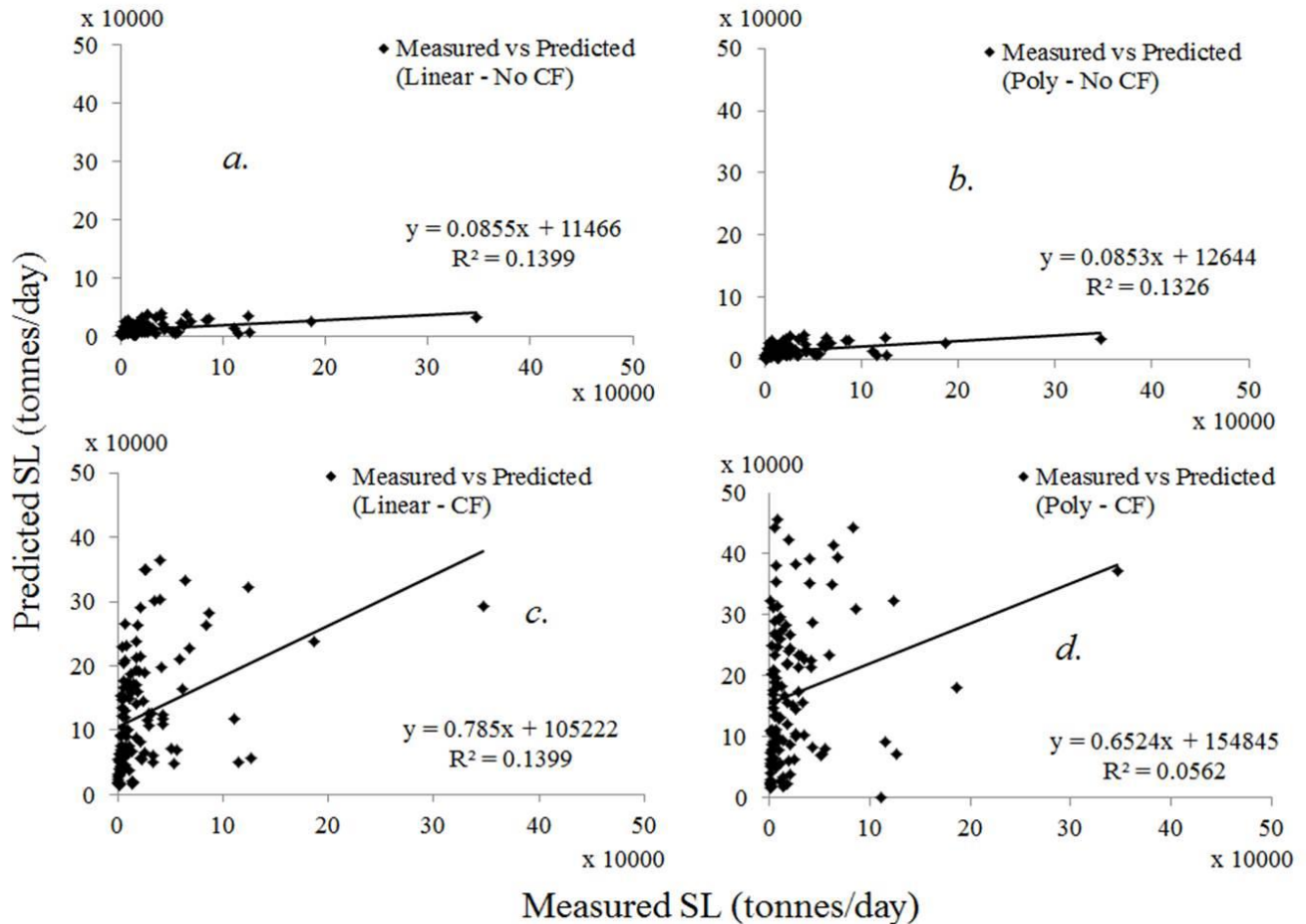


Figure 3.6: Scatter plots showing comparison between sand loads calculated from sand concentrations measured, processed and calibrated by USGS (Measured SL) and those predicted from single sand-rating curve (either linear or polynomial) (Predicted SL) at Tarbert Landing from 1986 to 1990. Specific terminologies pertaining to parts “a”, “b”, “c” and “d” of this figure i.e., Linear, Poly, CF, and No CF are same as explained in Figure 3.2.

3.2.7 Range of Error Associated with Predicted Sand Loads

Two types of errors (E–1 and E–2) in the SL estimates were considered (it must be noted that the standard errors discussed earlier in section 3.2.5 accounted for the entire models rather than individual estimates). E–1 is associated with the methods used by USGS for depth-integrated sampling and calibration of SSCs. It has previously been reported to be approximately $\pm 10\%$ of the total calibrated SSCs, $SSC_{s,s}$ and $SSC_{f,s}$ (Guy and Norman 1970, Fransworth and Warrick 2007, Mckee et al. 2013). E–2 is associated with dependent variables (ln SL) in the rating curves. The confidence intervals (CI) for each ‘ln predicted SL’ at 95% level of significance in their

rating curves were provided with the help of their corresponding E-2s in our analysis (Figure 3.7). This study estimated an approximate E-2 of $\pm 15\%$ in all SLs predicted from rating curve approach (based on confidence interval plots, RMSEs and percentage difference between measured and predicted SLs which averaged -13.4% during the four periods). Thus the total error in SL measurements and predictions (E-1+E-2) during rating curve years was about $\pm 25\%$. Only E-1 was selected for all estimates during 1986–1990 because the rating curve approach was not used in this period. Therefore, error range for SL estimates during 1986–1990 was $\pm 10\%$. For convenience and consistency in reporting, an error range of $\pm 18\%$ was used for all the SL estimates during 1973–2013 (approximately ~average of 25 and 10).

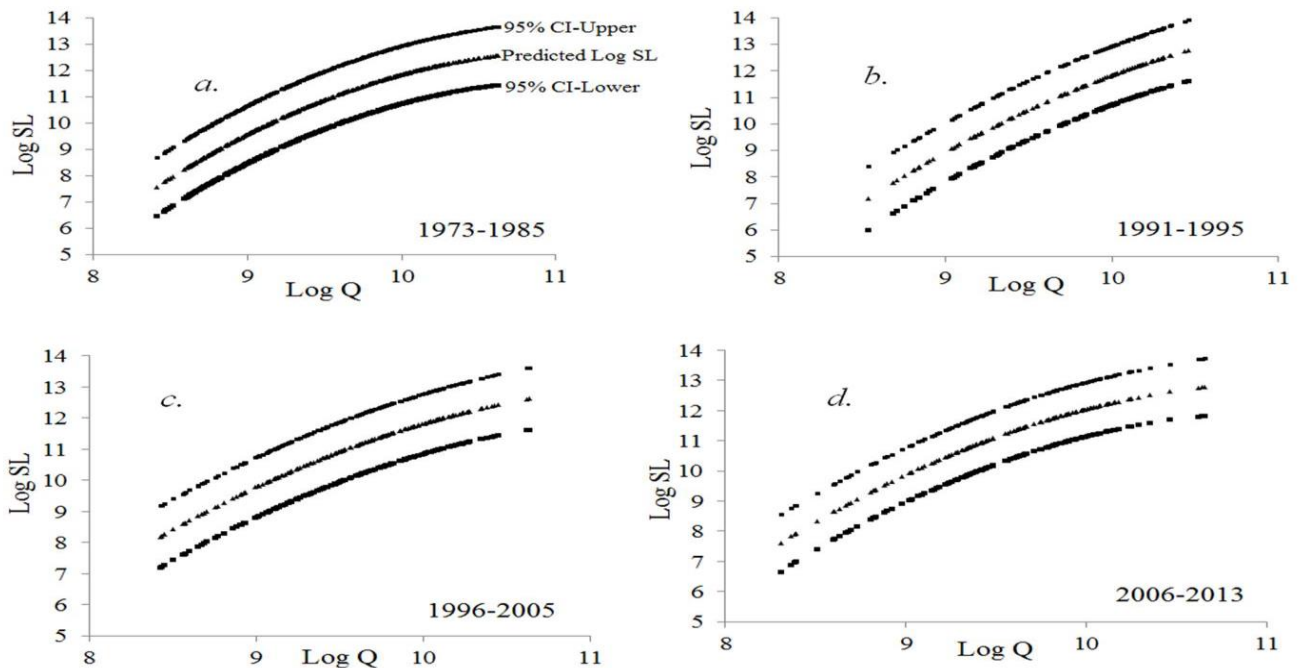


Figure 3.7: Confidence interval (CI) for the all ‘ln predicted SL’ values at 95% confidence level in accordance to their corresponding SSCs-Qd rating curves during the four periods as shown at Tarbert Landing. It is noted that in all four periods (a, b, c and d), uppermost and lowermost curves represent the upper and lower limits of the CI, while the middle curve represents all individual ‘ln predicted SL’ values as given in a.

3.2.8 Daily, Annual and Seasonal Sand Load Trends

Daily Sand Loads (DSL) were calculated using aforementioned methods of rating curve (1973–1985, 1991–1995, 1996–2005, 2006–2013) and non-rating curve (1986–1990) approaches. The sum of DSLs from 1st January to 31st December during each year gave their corresponding annual SLs. Maximum, minimum and average DSLs and annual SLs were plotted against their corresponding years for information regarding daily and annual SL trends throughout the study period. Similarly, monthly SLs were calculated by averaging DSLs for each month separately from 1973 to 2013. Maximum, minimum and average monthly SLs were plotted against their corresponding months to analyze their seasonal trends.

3.2.9 Frequency Analysis of Sand Loads

This study analyzed the amount of sand transported at Tarbert Landing during 1973-2013 under different river flow conditions, i.e. six frequencies on the flow duration curves (1, 5, 10, 20, 50, and 75%) and five river stages (Low, Action, Intermediate, High, and Peak). The Gumbel distribution (Gumbel 1956, Kotz 2000) was used for analyzing annual maximum and minimum DSLs, while the Weibull distribution (Menon 1963, Engelhardt 1975) was used for analyzing total annual sand loads (SL) at Tarbert Landing. All annual maximum/minimum DSLs and total annual SLs during 1973 and 2013 were sorted in descending order separately at first. The non-exceedance probabilities $\{F(X)\}$ for maximum and minimum DSLs were obtained with the Gumbel distribution (Eqn. 3.3), while the non-exceedance probabilities for total annual SLs were obtained with the Weibull distribution (Eqn. 3.4) as given below:

$$\text{Gumbel } F(X) = e^{-e^{-\left(\frac{X-a}{b}\right)}} \quad (3.3)$$

$$\text{Weibull } F(X) = 1 - \frac{m}{n+1} \quad (3.4)$$

where X is annual maximum/minimum DSL (tonnes/day) or total annual SL (megatonnes), m is the rank of the annual SL, n is the total number of years in the distribution, and a and b are the Gumbel distribution parameters that were calculated through:

$$a = \mu_x - 0.5772 b \quad (3.5)$$

$$b = \frac{S_x \sqrt{6}}{\pi} \quad (3.6)$$

where μ_x is the average and S_x is the standard deviation of the annual maximum and minimum DSLs.

Maximum and minimum DSLs (Q_p) for the return periods $\{T(X)\}$ of 2-, 5-, 10-, 20-, and 40-years were calculated using the Gumbel distribution as:

$$Q_p = K(T)S_x \quad (3.7)$$

where the frequency factor $K(T)$ is defined as:

$$K(T) = -\frac{\sqrt{6}}{\pi} \left\{ 0.5772 + \text{Ln Ln} \left[\frac{T(X)}{T(X)-1} \right] \right\} \quad (3.8)$$

A frequency factor is computed for a certain return. This study computed frequency factors of -0.1643, 0.7195, 1.3046, 1.8658, and 2.4163 for the 2-, 5-, 10-, 20-, and 40-year return periods, respectively. Annual SLs for the same return periods were estimated using a linear interpolation from the Weibull distribution of annual SLs [i.e. $1 / \{1-F(X)\}$].

3.3 RESULTS

3.3.1 Long-Term River Flow Conditions

Daily discharge (Q_d) at Tarbert Landing from 1973 to 2013 averaged 15027 cms, varying from 3143 to 45844 cms (Figure 3.8). During this period, average Q_d was lowest in 2000 (9558 cms) and highest in 1993 (21844 cms). Similarly, average Q_d fell within the Low flow stage (< 13000 cms) for 11 years (1976, 1977, 1980, 1981, 1987, 1988, 2000, 2005, 2006, 2007 and 2012), Intermediate flow stage (18000–25000 cms) for 7 years (1973, 1979, 1983, 1991, 1993, 2008 and 2009), and Action flow stage (13000–18000 cms) for the remaining 23 years (Figure 3.8). Also, years with higher average Q_d s had higher minimum and maximum Q_d s as compared to years with lower average daily Q_d s (Figure 3.8). Additionally, Low, Action, Intermediate, High and Peak flow stages accounted for about 50, 17, 21, 9 and 3% of all the discharge events throughout the study period respectively (Figure 3.9, Table 3.3). Also, 1, 5, 10, 20, 50 and 75% flows corresponded to the flow intervals of 37943–45844, 26931–45844, 22256–45844, 13082–45844 and 8325–45844 cms respectively (Figure 3.9).

Seasonally, average Q_d increased continuously from January to its maximum in April (16550 to 22468 cms), then decreased continuously from May to its minimum in October (21696 to 8171 cms) inferring maximum river flow during spring (March, April and May) (Figure 3.10). For the remaining two months in the year, average Q_d followed an increasing trend again (9702 cms in November and 14581 cms in December) (Figure 3.10). Also, the maximum Q_d was observed in May (45844 cms) while the minimum Q_d was observed in July (3143 cms) (Figure 3.10).

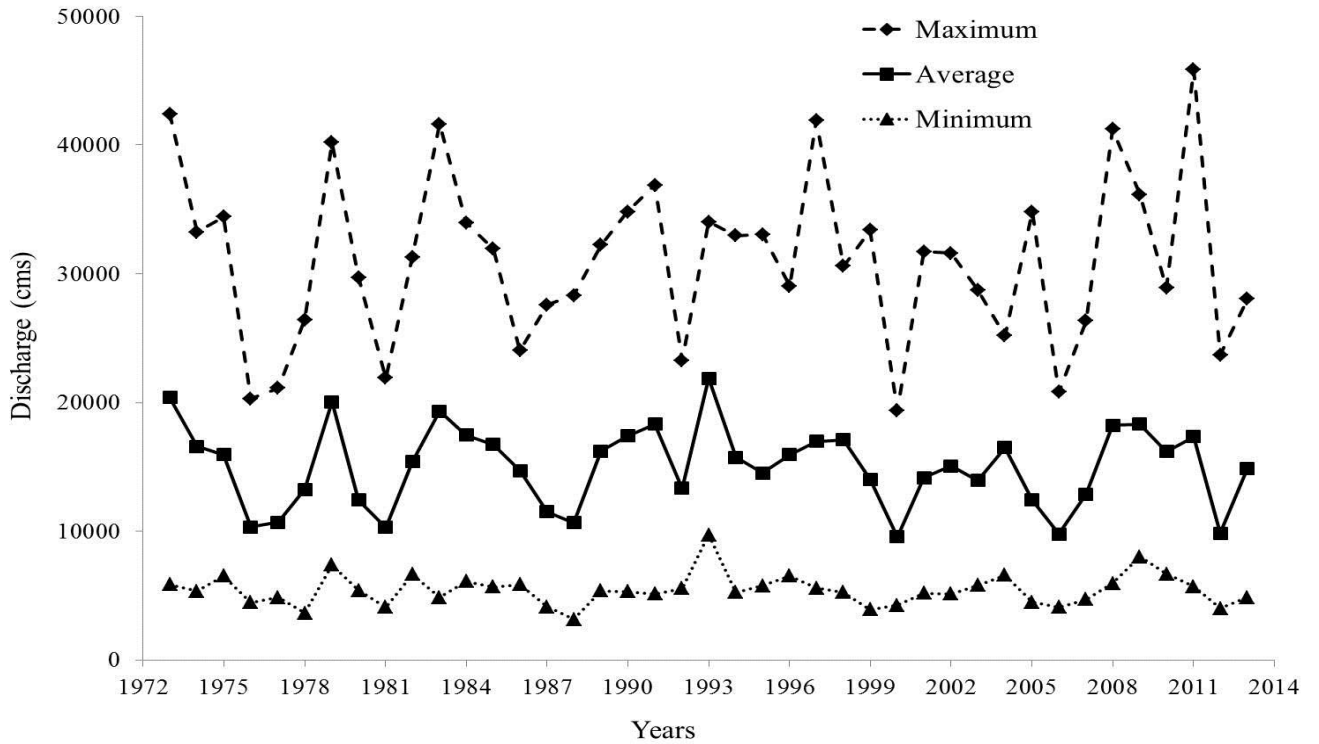


Figure 3.8: Annual mean, maximum, and minimum of daily discharge at Tarbert Landing of the LmMR.

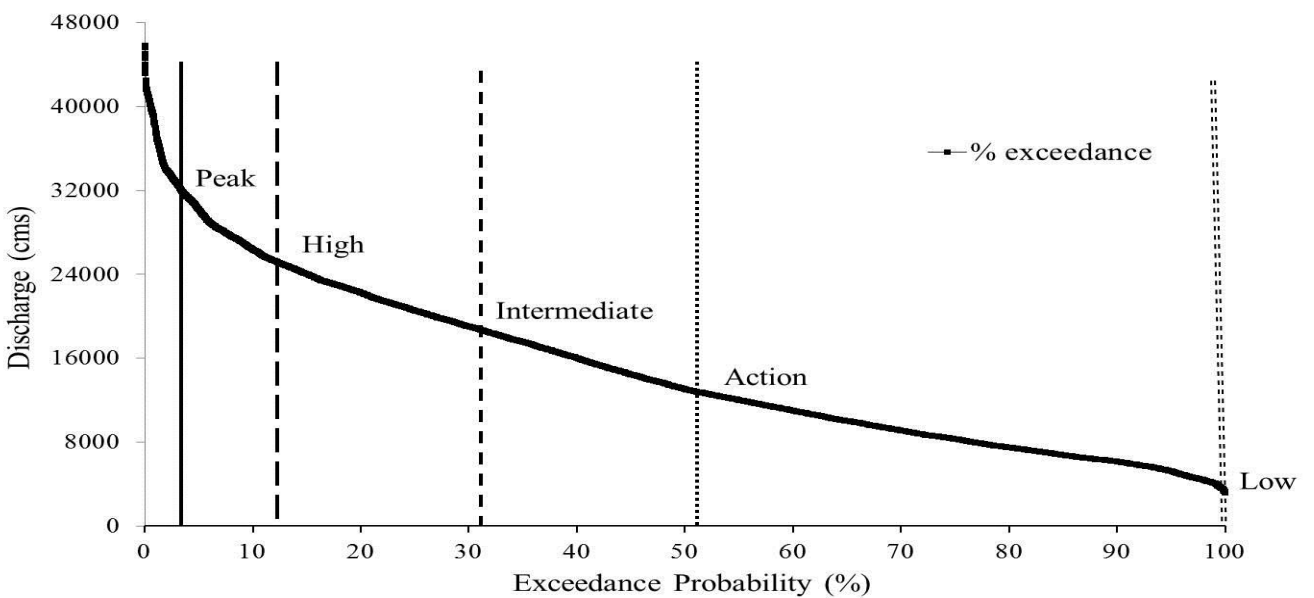


Figure 3.9: Flow duration curve for Tarbert Landing of the LmMR during 1973- 2013. The vertical dash lines represent the exceedance probabilities for five river stages as defined by NOAA, i.e. Peak, High, Intermediate, Action and Low Flow Stages.

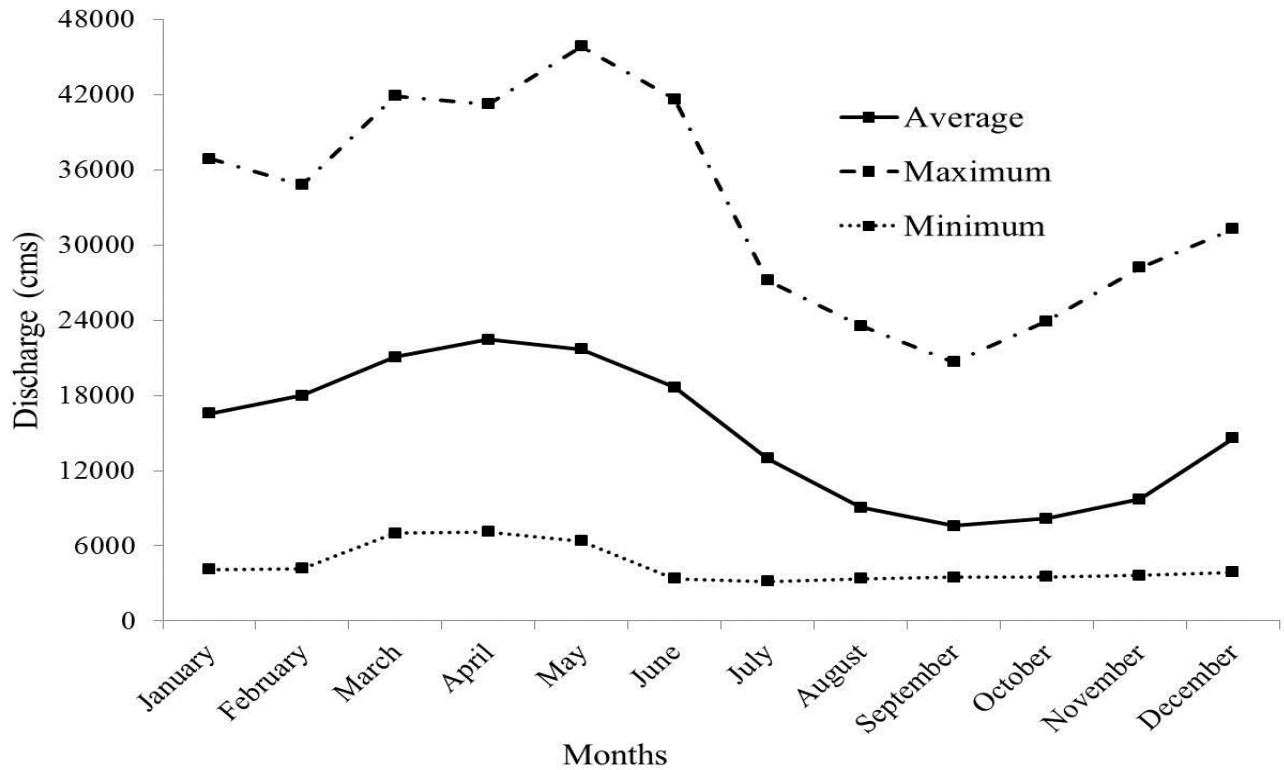


Figure 3.10: Seasonal trend of monthly mean, maximum, and minimum of daily discharge at Tarbert Landing of the LmMR during 1973-2013.

Table 3.3: Long-term flow conditions based on NOAA’s Mississippi River flow stages at Tarbert Landing of the LmMR from 1973 to 2013.

Flow Stage (m)	Discharge Range (cms)*	Occurrence (%)
Low (< 9.8)	< 13000	49.70
Action (9.8–12.1)	13000 - 18000	16.82
Intermediate (12.1–14.6)	18000 - 25000	20.74
High (14.6–16.8)	25000 - 32000	9.33
Peak (>16.8)	> 32000	3.41

*The discharge ranges for Intermediate, High, and Peak Flow Stages are adopted from Rosen and Xu [17].

3.3.2 Sand Concentrations under Different Flow Regimes

Average SSC_s s and their percentage changes at Tarbert Landing showed early increasing trend from the lowest Q_d interval (3000–6000 cms) (Figure 3.11). Average SSC_s for the lowest Q_d interval (3000–6000 cms) was about 11 mg/l which increased up to about 91 mg/l between

24000 and 27000 cms Q_d (715% increase) (Figure 3.11). Further, average SSC_s s fluctuated for higher Q_d intervals, i.e. they first decreased up to approximately 70 mg/l for Q_d interval between 30000 and 36000 cms (715 to 529%), then increased up to approximately 103 mg/l for the next interval between 36000 and 39000 cms (529 to 832%), then decreased up to about 72 mg/l (832 to 552%) for the next interval between 39000 and 42000 cms and finally increased up to about 82 mg/l (552 to 642%) for the highest Q_d interval (42000–45000 cms) (Figure 3.11). Similar trends were also observed in individual SSC_s values across the entire Q_d range. SSC_s s showed an early increasing trend even with lower discharge levels (about 6000 cms) which continued until substantially high flows (27000 cms with $R^2 = 0.36$) (Figure 3.12). The elevated concentrations remained almost constant ($R^2 = 0.0061$) for higher flows (> 27000 cms) (Figure 3.12).

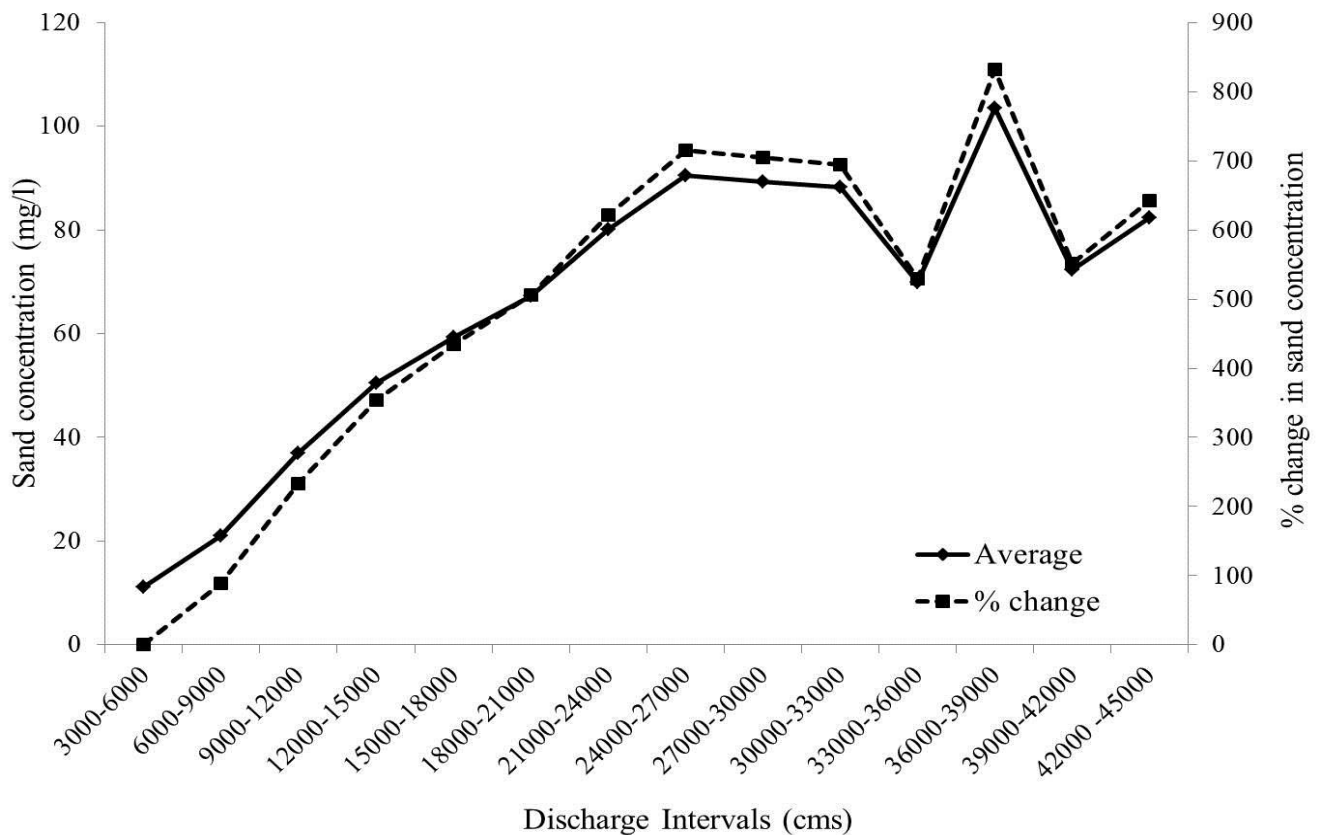


Figure 3.11: Average sand concentrations and percentage change with each 3000 cms increment of discharge at Tarbert Landing of the LmMR during 1973-2013.

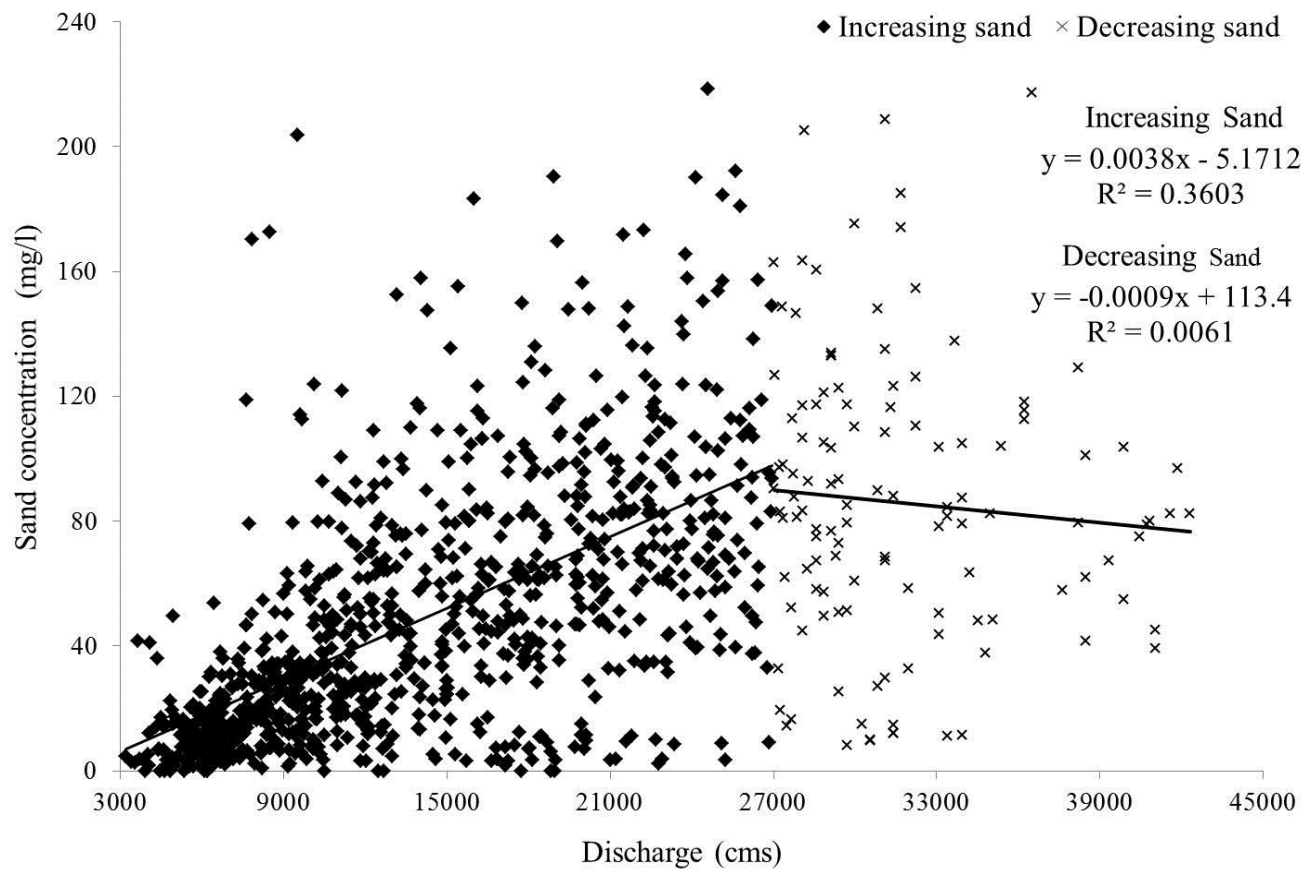


Figure 3.12: Distribution of sand concentration with discharge at Tarbert Landing of the LmMR during 1973-2013.

3.3.3 Daily, Annual and Seasonal Trend of Sand Loads

Daily Sand Loads at Tarbert Landing from 1973 to 2013 averaged 74474 tonnes, varying from 258 to 444626 tonnes (Figure 3.13). During this period, average DSL was lowest in 1987 (9300 tonnes/day) and highest in 1993 (143322 tonnes/day) (Figure 3.13). Average DSL was lower than 20000 tonnes for 4 years (1986, 1987, 1988 and 1989), higher than 100000 tonnes for 9 years (1973, 1979, 1983, 1991, 1993, 2008, 2009, 2010 and 2011), and either > 20000 or < 100000 tonnes for the remaining 28 years (Figure 3.13). As with average Q_d , years with higher average DSLs had higher minimum and maximum DSLs as compared to years with lower average DSLs (Figure 3.13).

Annual sand load from 1973 to 2013 averaged 27.2 MT, ranging from 3.37 to 52.30 MT and producing a total sand amount of 1114.82 MT for the entire 41-year study period (Figure 3.13). Annual SL was lower than 10 MT for 4 of 41 years (1986, 1987, 1988 and 1989), higher than 40 MT for 8 years including the Mississippi flood years of 1973, 1993 and 2011, and either > 10 MT or < 40 MT for the remaining 29 years (Figure 3.13). Also, annual SL averaged 26.3 MT from 1973 to 1999 (28.8 MT from 1972 to 1979, 19.3 MT from 1980 to 1989, 32 MT from 1990 to 1999) which later increased to approximately 29 MT from 2000 to 2013 (Figure 3.13). Despite the low average annual SL between 1986 and 1989, there was no continuous increasing or decreasing trend (even for 2/3 years) in annual SL (Figure 3.13).

Seasonal trend of the average DSL was similar to that of the average Q_d . Average DSL increased continuously from January to its maximum in May (i.e. 86315 to 137387 tonnes/day), then decreased from June to its minimum in September (106426 to 14935 tonnes/day) inferring maximum sand transport during spring (March, April and May) (Figure 3.14). For the remaining three months in the year, average DSL followed an increasing trend again, i.e. 20871 tonnes/day in October to 70092 tonnes/day in December (Figure 3.14). Also, maximum DSL was observed in June (444626 tonnes/day) while minimum DSL was observed in August (258 tonnes/day) for the whole period (Figure 3.14).

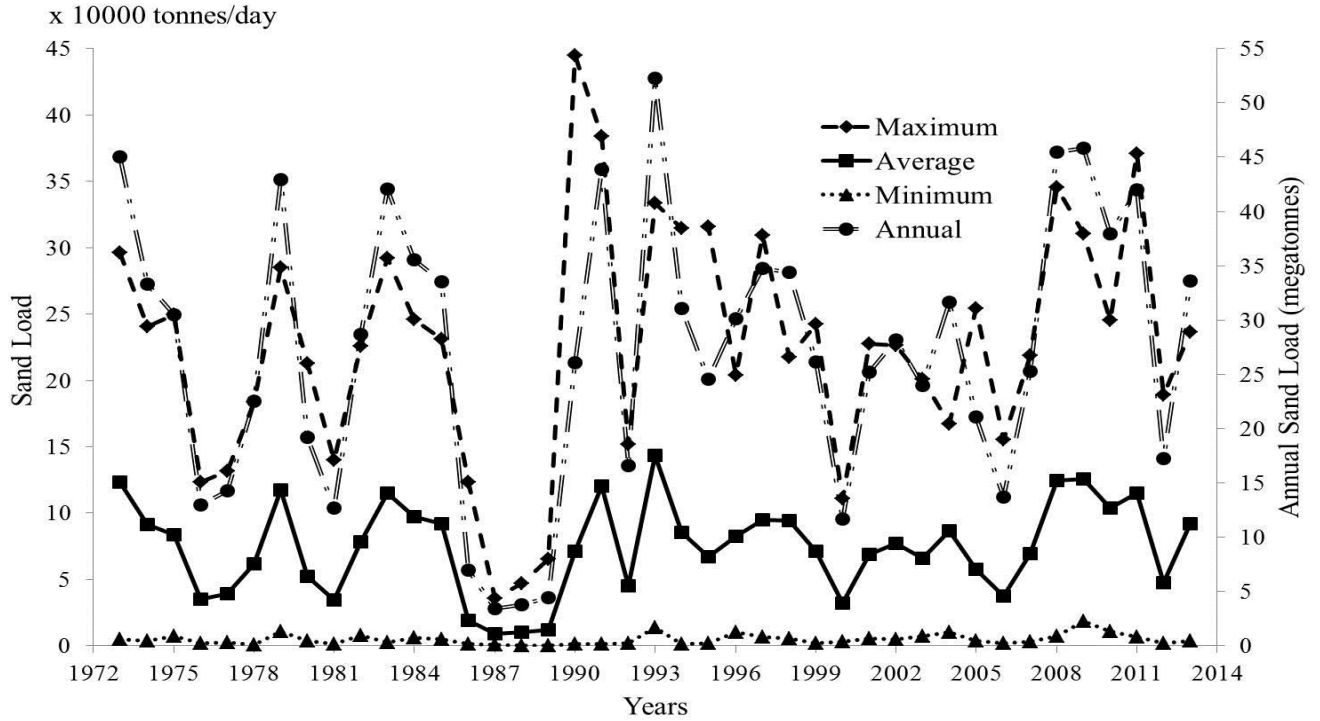


Figure 3.13: Annual mean, maximum, and minimum of daily sand loads and total annual sand loads at Tarbert Landing of the LmMR.

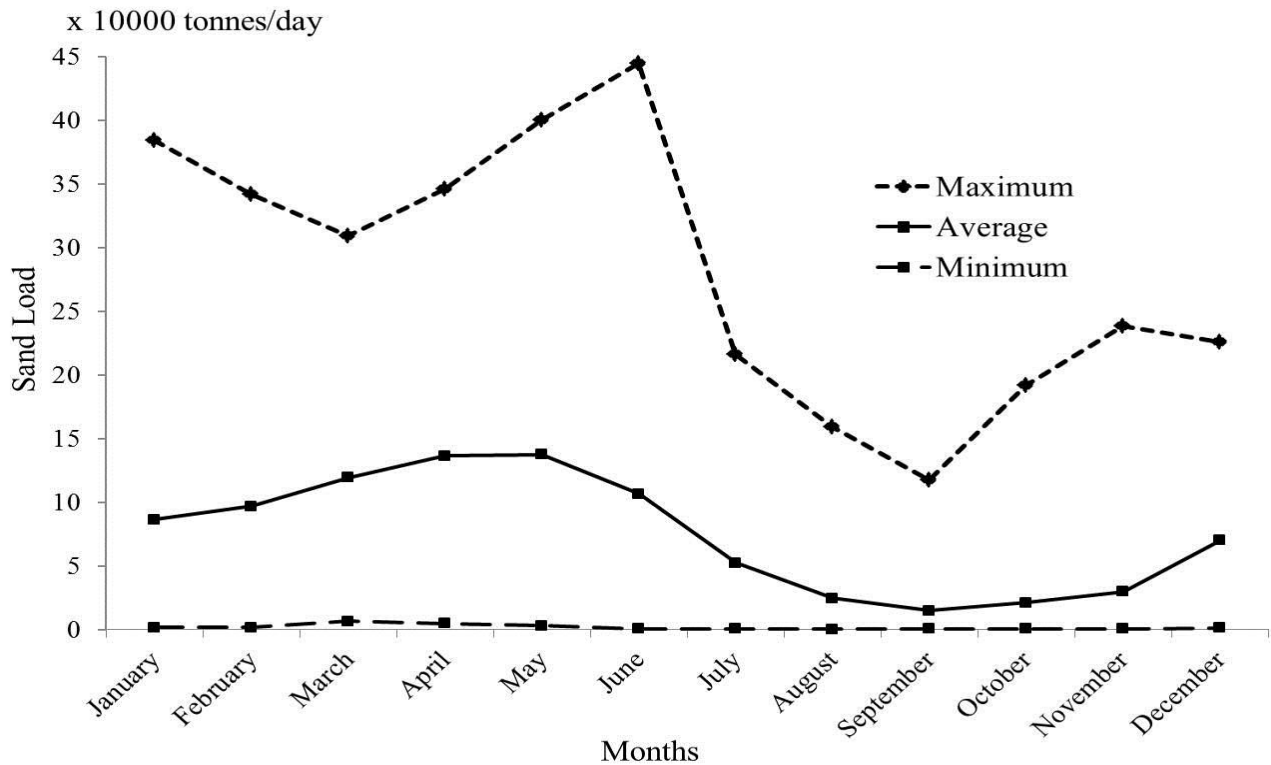


Figure 3.14: Seasonal trend of monthly mean, maximum, and minimum of daily sand load at Tarbert Landing of the LmMR during 1973-2013.

3.3.4 Sand Load Distribution with River Discharge

Hydrologically, with respect to the NOAA’s river stages, Intermediate, High and Peak Flow Stages together carried majority of the total SL (793.4 MT; 71%) within an average of 122 days per year (Table 3.4). Individually, Intermediate, High and Peak Flow Stages carried approximately 384 (34%), 266 (24%) and 143 (13%) MT of SLs for average durations of 76, 34 and 12 days/year respectively, while, Low and Action Flow Stages carried approximately 146 (13%) and 175 (16%) MT of SL respectively for relatively longer average durations of 181 and 61 days/year (Table 3.4). Also, 50 and 75% of flow regimes produced majority of total SL in the area, i.e. 966 (87%) and 1082 MT (97%) respectively (Table 3.5). Similarly, 1, 5, 10 and 20% of flow regimes also produced few to slightly more than half of total SL, i.e. 46 (4%), 196 (18%), 340 (31%) and 571 MT (51%), respectively (Table 3.5).

Table 3.4: Sand transport under five river stages at Tarbert Landing of the LmMR from 1973 to 2013.

Flow Stage	Sand Load (MT)	% of total SL (1114.8 MT)	Total # of days	Average no. of days/year
Low	146.24	13.12	7440	181
Action	174.89	15.69	2518	61
Intermediate	384.26	34.47	3104	76
High	266.15	23.87	1397	34
Peak	143.00	12.85	510	12

Table 3.5: Sand transport within 1, 5, 10, 20, 50, and 75% flow regimes at Tarbert Landing of the LmMR from 1973 to 2013.

Total Sand Load (MT)	Sand Load (MT) in flow regimes					
	1%	5%	10%	20%	50%	75%
1114.80	45.63	196.21	340.18	571.36	966.40	1082.50
% of total SL	4.09	17.60	30.51	51.25	86.69	97.10

Linear relationship between all annual flow volumes (km^3) above the low and action flow stages (discharge ≥ 18000 cms) and corresponding annual sand loads (MT) showed that intermediate, high and peak flow stages jointly accounted for about 66% variation in sand loads during each year from 1973 to 2013 ($R^2 = 0.66$) (Figure 3.15). The relationship further suggested that about 66% of sand loads were produced by these three stages jointly during each year of the study period.

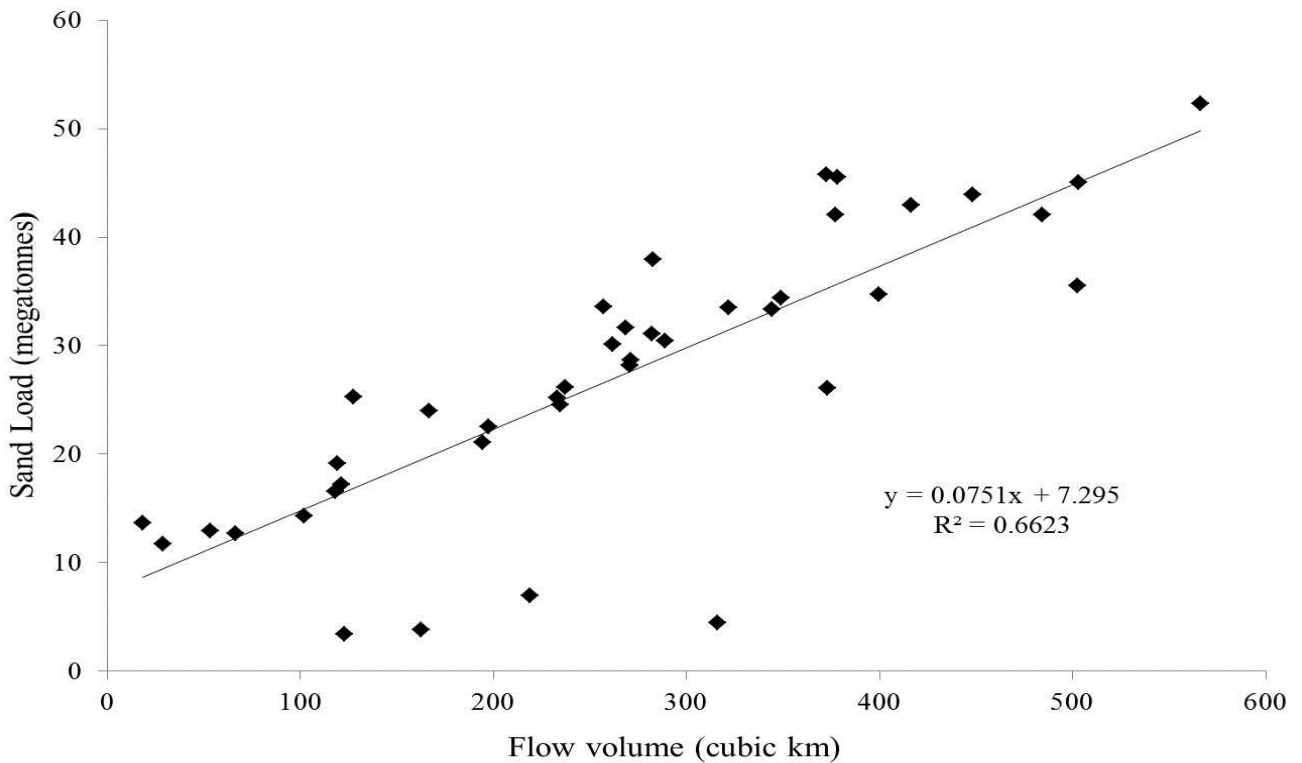


Figure 3.15: Annual flow volume above the Low and Action flow stages (discharge ≥ 18000 cms) versus annual sand load at Tabert Landing of the LmMR during 1973- 2013.

3.3.5 Maximum and Minimum Sand Loads For Different Return Periods

Averages of maximum and minimum DSLs for each year throughout the whole study period at Tarbert Landing were 226981 and 4865 tonnes/day, while their standard deviations were 90595 and 4015 tonnes/day respectively (Table 3.6). Based on these means and standard

deviations, parameters a and b in Gumbel distribution were found to be 186209 and 70637 for highest DSLs and 3058 and 3131 for lowest DSLs during each year respectively (Table 3.6).

Table 3.6: Mean (μ_x), Standard Deviations (SD) (S_x) and respective parameters (a and b) in Gumbel distribution for maximum and minimum DSL (tonnes/day) at Tarbert Landing of the LmMR from 1973 to 2013.

Distributions	Mean and SD	Gumbel parameters	Value
Maximum DSL	$\mu_x = 226981$	A	186209
	$S_x = 90595$	B	70637
Minimum DSL	$\mu_x = 4865$	A	3058
	$S_x = 4015$	B	3131

Non-exceedance probabilities of maximum and minimum DSLs {Gumbel $F(X)$ } and total SLs {Weibull $F(X)$ } for each year from 1973 to 2013 are represented by Figure 3.16. For longer return periods of 20 and 40 years, it was predicted that DSLs at Tarbert Landing can reach a maximum of 396 and 446 thousand tonnes and a minimum of 12 and 15 thousand tonnes respectively (Table 3.7). Similarly, for shorter return periods of 2, 5, and 10 years, maximum DSL predictions were 212, 292, and 345 thousand tonnes respectively, while minimum DSL predictions were 4, 8, and 10 thousand tonnes respectively (Table 3.7). This study also predicted that in the next 2-, 5-, 10-, 20-, and 40-years total annual sand load can reach as much as 28.2, 40.28, 44.78, 45.76 and 51.68 MT respectively (Table 3.7).

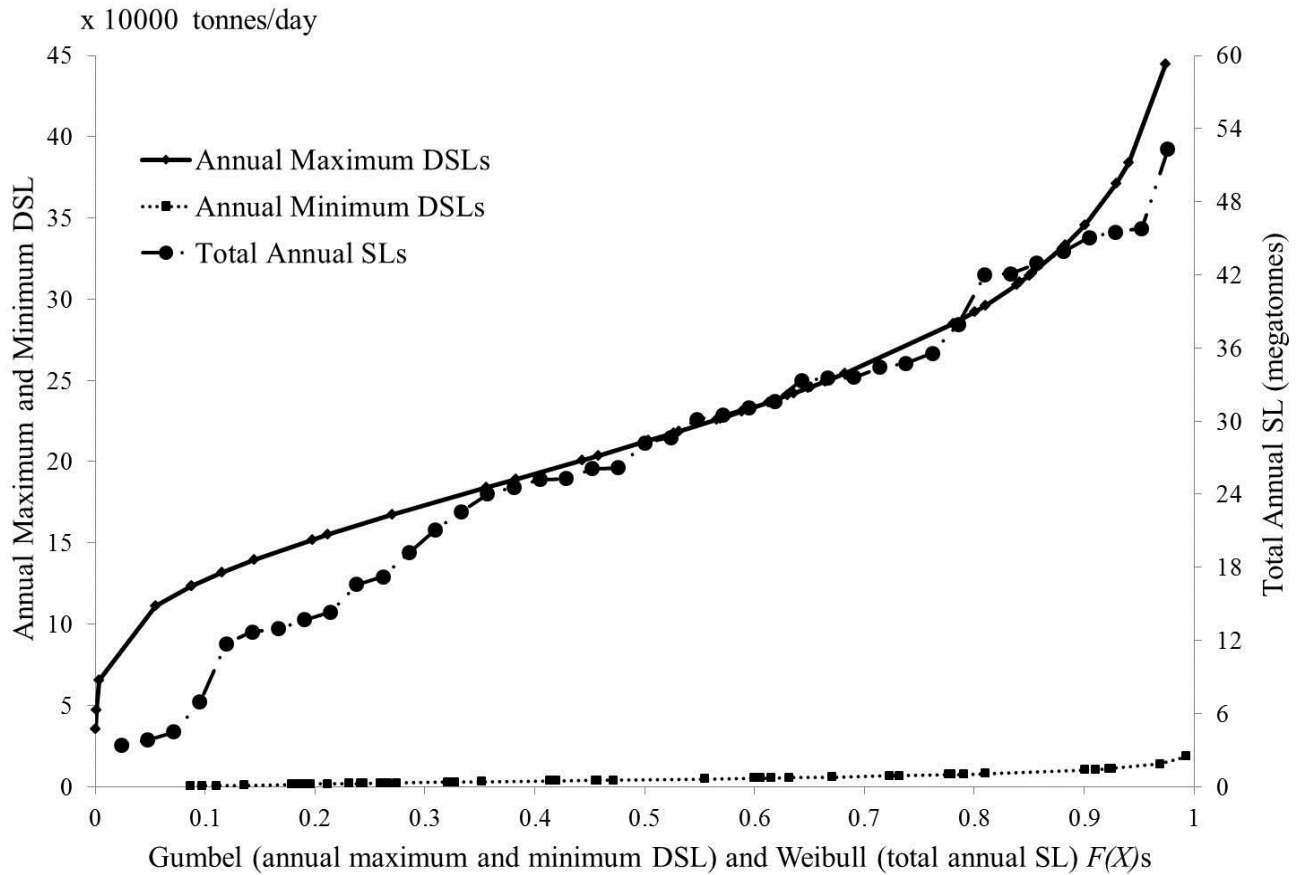


Figure 3.16: Non-exceedance probabilities of the Gumbel distribution for maximum and minimum DSLs and Weibull distribution for total SLs each year at Tarbert Landing of the LmMR from 1973 to 2013.

Table 3.7: Gumbel distribution based prediction of maximum and minimum DSLs and Weibull distribution based prediction of total annual SLs for the 2-, 5-, 10-, 20-, and 40-year returns at Tarbert Landing of the LmMR.

Return Period (years)	Extreme Sand Loads		
	Annual SL (MT/yr)	Maximum DSL (x 1000 tonnes/day)	Minimum DSL (x 1000 tonnes/day)
2	28.20	212	4
5	40.28	292	8
10	44.78	345	10
20	45.76	396	12
40	51.68	446	15

3.4. DISCUSSION

3.4.1 Long-Term Trend of Sand Loads in the LmMR

This study presents sand transport estimates for each individual year along with their error range ($\pm 18\%$), providing a comprehensive range of sand transport in the past four decades. Previously, Nittrouer and Viraparelli (2014) reported an average annual sand transport of about 24 MT for Tarbert Landing during 1973 and 2012, which is about 12% lower than estimates in this study for average annual sand transport (27 MT) during 1973 and 2013. This difference falls within the total error range of all SL estimates in this study ($\pm 18\%$). The relatively small difference between the two estimates may be caused by different estimation approaches: Nittrouer and Viraparelli used linear rating curves at decadal intervals for daily sand load estimation while this study used a combination of five-yearly to approximately decadal polynomial rating curves and monthly sand concentration records. The SL estimate for 2013 (31 MT) in this study, which was not included in Nittrouer and Viraparelli's analysis, was about 14% higher than 41-year long average SL estimate in this study; however, this difference also falls within the error range ($\pm 18\%$).

In their short-term sediment budget study, Allison et al. (2012) reported an annual SL of 73.5, 62.2 and 78.9 MT for the water years of 2008, 2009 and 2010, respectively, resulting in a total SL of 214.6 MT. These estimates are 62%, 36% and 108% higher than the calendar-based estimates for these three years in this study (45.5 ± 8.1 , 45.8 and 38.0 ± 6.84 MT, respectively), or nearly doubled of this study's estimate for the entire three years (129.3 ± 23.27 MT). These two sets of estimates cannot be compared directly because of the different time base; however, it seems that Allison et al. (2012) overestimated annual SLs for 2008, 2009 and 2010 water years at Tarbert Landing. Allison et al.'s SL estimates for 2008, 2009 and 2010 respectively were

numerically higher than 38, 36 and 42 of 45 annual SL estimates provided by USACE for all water years from 1952 to 1996 (Fillippo 2010). Also, the rating curve which Allison et al. (2012) used to calculate DSLs for each day during the three years had a comparatively lower R^2 (0.62) (information from the supplementary files of Allison et al. 2012) and no other criteria for model validation which could have resulted in greater variability between calibrated and estimated SLs. Furthermore, their estimates do not fall within the error range for annual estimates during these three years in this study. These three arguments provide essential support for questioning the reliability of their estimates.

This study found a very low sand transport during 1986 and 1989. Only 19 ± 1.9 MT of sand was discharged during this 4-year period, making an average annual SL of just 5 MT, i.e. less than one fifth of the long-term average annual SL of 27 MT. Nittrouer and Viraparelli [36] also reported low average SL for a period longer than these four years (1980 to 1989) (about 11 MT), however, they did not separate SLs for each year during the 4-year period. The notable abrupt drop in sand transport during these four years may have been a result from the 4-year severe drought in the Southeastern and Midwestern United States between 1986 and 1989 as reported by Cook et al. (1988) and Trenberth and Guillemot (1996). During this drought period, both discharge and sediment concentrations of the LmMR were considerably lower than those of other years in the past four decades.

The declining trend of total suspended sediment load input in the LmMR during the last several decades has been well documented (Blum and Roberts 2009, Allison and Meselhe 2010, Horowitz 1993, Meade and Moody 2010). However, Rosen and Xu (2014) contradicted this trend by suggesting that suspended sediment input has slightly increased in the river for the recent two decades (from 1990 to 2010), although no statistical significance was found. The

findings for sand transport in this study (the coarser sediment fraction) are identical with Rosen and Xu (2014) as this study also found a stronger increasing trend in sand loads starting from 1990 – the average annual sand load from 1990 to 2013 (30 MT) was clearly higher than that during 1973 and 1989 (23 MT). The higher sand transport in the past two decade has been mainly resulted from the increased discharge during the same period of time.

3.4.2 Hydrologic Control for Sand Transport in the LmMR

The findings of this study suggest that notable sand load present in the LmMR can best be diverted during its intermediate, high and peak flow stages (discharge ≥ 18000 cms) within only approximately four months each year. This study found that maximum river flow and sand transport both occurred during spring (March, April and May); therefore, it is highly likely that the three river stages are prevalent during spring and scarce during other seasons of the year. Highest sand transport by these three stages can be linked to their rapid increase in discharge regimes from nearly 6000 to 27000 cms and very slow and inconsistent decrease in regimes post 27000 cms. Sand concentrations seem to have reached their peaks during the intermediate and early high flow stages (discharge: 18000–27000 cms), hence, resulting in the highest sand loads.

There is no previous work available for comparison to these findings of long term sand load availability with river discharge. Rosen and Xu (2014) seems to support findings of this study, but they analyzed the availability of total suspended sediments with river discharge as compared to the total sand load in this study and emphasized that intermediate and high river stages combined carry highest sediment loads, however, peak stage contributes relatively little in sand transport. Biedenharn and Thorne (1994) argued that discharge between 17,000 and 40,000 cms transport more suspended sediments than other discharge regimes. Differences in weights and volumes of sediment and sand concentrations may be the reason behind subtle differences in

flow regimes reported to carry highest sediment and sand loads in these studies. This study also found that almost the entire total sand load (97%) in the LmMR was transported by 75% of total water discharge throughout the study period. This discharge regime includes almost half of the lower flow stage along with all other Mississippi River stages (> 8325 cms) at Tarbert Landing. The sand behaviors found in this study – 1) increasing rapidly with increasing discharge, however, decreasing slowly beyond a given discharge regime just after reaching its climax; and 2) maximum sand percentage transported by substantially less flow volume percentage – can be compared with other large river systems in the world with a sinking delta. Such information can help planning for deltaic land protection through effective sand management.

3.4.3 Future Likelihood of Sand Transport in the LmMR

The frequency analysis in this study reveals that the LmMR at Tarbert Landing has the potential to transport substantial amount of sand every day in the next 40 years (4 to 446 thousand tonnes). Based on the sand yields at different river stages, it is argued that the intermediate, high and/or peak river stages will possibly transport higher DSLs in shorter periods while low and/or action stages will possibly transport lower DSLs in longer periods of time. The findings in this study further indicated that annual sand load has potential to reach as much as 52 MT in the next 40 years. Based on the observations regarding linear relationship between annual flow volumes in intermediate, high and peak flow stages and annual SLs, it is also argued that years with high average daily discharge and annual flow would produce high annual sand loads within the given return periods and vice-versa. Previous studies have analyzed several year peaks for suspended sediment loads and concentrations (Hicks et al. 2000, Trambly et al. 2008) and even for river flows and stages (Yue et al. 1999, Yurekli et al. 2012) in different rivers around the world. However, to the best knowledge of the author, maximum and minimum DSLs and

annual SLs for short- and long-term return periods have not been analyzed for any river location till date. So, this study could not compare these sand estimates in the LmMR with any other study.

The peak high and low DSLs and peak annual SLs vary between Tarbert Landing and other sites in the LmMR and the variation is based on sand-flow relationship and sand percentage in sediment load. Quantification of peak SLs at other sites is beyond the scope of this study. However, the analysis of daily and annual sand loads for several return periods can be helpful in speculating the importance of sediment diversion as per sand amount present at the site. It is also possible to incorporate the maximum/minimum DSLs and annual SLs for several return periods into any proposed land loss model for the MRDP. This can be done by quantifying the percentage loss of sand when given land area (km^2) was lost in 'n' (where $n = 2, 5, 10, 20, \text{ or } 40$) years and/or the amount of sand required to attain a goal of restoring certain land (km^2) in 'n' years.

3.5. CONCLUSIONS

This study is the first comprehensive analysis of 4-decade long sand transport under different flow conditions in the Lowermost Mississippi River. Findings from this study show that majority of sands at Tarbert Landing are transported during the intermediate, high and peak river flow stages, and that their most effective capture can be achieved within 120 days of a year when discharge is greater than 18,000 cms. It is also predicted that the LmMR will most likely transport 4 to 446 thousand tonnes of sand every day over the next 40 years, during which annual sand load can reach as high as 52 million tons. Such considerably high sand loads are a precious resource for coastal Louisiana and should be effectively captured for offsetting land loss in the Mississippi River Delta before they are lost to deep waters of the Gulf of Mexico. To achieve

this goal, river engineering and sediment management should consider applications using hydrograph-based sand availability approach for maximum sediment capture. This may have implications for impeding coastal land loss in other sediment-starving deltas in the world.

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CHAPTER 4: BEDLOAD AND SUSPENDED LOAD TRANSPORT IN THE 140-KM REACH DOWNSTREAM OF THE MISSISSIPPI RIVER AVULSION TO THE ATCHAFALAYA RIVER

4.1 INTRODUCTION

Studies have found that sediment supply from many rivers in the world to the oceans has decreased substantially in the past several decades (Walling and Fang 2003, Vorosmarty et al. 2004, Syvitski and Saito 2007). The reduction estimates are mostly in suspended sediment load; for instance, Meade and Parker (1985) reported 3.5 times decline in suspended sediment load of the Colorado River from 1930s to 2000s; Yang et al. (2003) reported 100 megatons (MT)/year decline in sediment load of the Yangtze River from 1950s to 1990s; and Meade and Moody (2010) noted 3.5 times decrease in sediment load of the Mississippi River from early to late 1900s. Although these studies have improved the understanding of the trend of riverine suspended sediment loads to the world's coasts, however, our knowledge of bed sediment transport in these rivers is very limited. Such knowledge can aid in assessing riverine sediment transport, channel morphodynamics and long-term future of the river deltas.

Bed sediment loads can vary largely from 1 to 33% of the suspended loads in alluvial rivers, depending on sediment particle size (Gomez 1991, Kesel et al. 1992, Church 2006). Direct measurements of bed sediment transport are difficult and scarce in most alluvial rivers globally (Gomez 1991, Holmes 2010). Bed sediments are generally intermixed with sand particles (coarser sediment particles > 0.063 mm in diameter) of different sizes (Gomez 1991). Coarser sediments varying from 0.063 to 1.2 mm in sizes are difficult to be distinguished as true bedloads or suspended loads because sometimes they move by traction (rolling, sliding) and/or saltation and sometime they move by suspension (Gomez 1991, Nittrouer et al., 2008). Leopold and Emmett (1997) emphasized the problem of intractability between bedloads and suspended loads

because they did not find any sampling device that provided reliable bedload measurements moving along the riverbed. Therefore, bedloads are generally reported in terms of their transport rates which can be defined as the mass of bed material moving across a wetted riverbed for a given discharge regime in unit time (Southard 2006). Bedload transport rates, suspended sediment, and suspended sand loads have mostly been studied separately. Their combined effect on the total sediment supply in rivers, however, still needs to be investigated. Such an analysis can provide relevant information for river engineering and sediment management.

The total sediment supply constitutes of both bedload and suspended load and contributes substantially to spatiotemporal changes in channel adjustment and morphology in alluvial rivers (Montgomery and Buffington 1997, Parker et al. 2007, Turowski et al. 2010). However, many previous studies on sediment supply have either ignored bedload (Holeman 1968, Milliman and Meade 1983, Milliman and Syvitski 1992) or applied it as a fixed fraction of the sediment load (Hindall 1976, Griffiths and McSaveney 1986, Whipple and Tucker 2002). In all latter studies, bedload was given a fixed percentage based on tables proposed by Maddock and Borland (1950) and further expanded by Lane and Borland (1951). Both Maddock and Borland (1950) and Lane and Borland (1951) put the tables as best estimates of bedload percentage in different river systems. However, their estimates could possibly be subjected to considerable errors as they did not measure and/or quantify either the suspended loads or bedloads in any of the river types. In addition to these limitations in suspended load and bedload partitioning, interactive relationship between the two components also remains poorly understood. Quantifying bedload transport and investigating the relationship between bedload and suspended load can be especially beneficial for sediment management along regulated alluvial rivers with reduced sediment supply.

The lowermost 500-km reach of the Mississippi River from the Old River Control Structure to the Gulf of Mexico (i.e., lowermost Mississippi River: abbreviated as LmMR hereafter) in the southern USA is a renowned example of alluvial rivers with reduced sediment supply over time. The reduced sediment supply has contributed to land loss in the Mississippi River Delta Plain (MRDP, river delta associated with the LmMR) over the last several decades (Craig et al. 1979, Gagliano et al. 1981, Couvillion et al. 2011). Meade and Moody (2010) concluded that mean annual sediment load for the LmMR at its uppermost location, Tarbert Landing (TBL) [at 493 river kilometers (*rk*) above the river's Gulf outlet] reduced by about 3.5 times [from ~400 million tons (MT)/year to 115 MT/year] from pre- to post-human interference period (late 1800s to late 1950s). Rosen and Xu (2014) estimated annual sediment loads at Tarbert Landing during 1980-2010 and noticed a 12 MT/year decline in the loads from 1993. Horowitz (2010) estimated annual sediment loads at Tarbert Landing and the next downstream location of the LmMR, St Francisville (St F) at *rk* 419 (about 71 *rk* downstream of Tarbert Landing) during 1980-2007. The study reported that the mean annual sediment loads declined at Tarbert Landing and St Francisville by 21 and 41 MT/year respectively after 1993. Long-term trends for suspended sand load have also been reported previously (Nittrouer and Viraparelli 2014, Joshi and Xu 2015), but only at Tarbert Landing. The critical role of suspended sand loads in building new lands for the MRDP has been previously recognized (Coleman et al. 1998, Roberts et al. 2003, Nepf 2004, Nittrouer et al. 2012). Thus, quantification of sand loads at locations downstream from Tarbert Landing can help in clarifying their potential sand storage and delta building capacity.

In their recent assessment of river stages and cross-sections along the LmMR, Joshi and Xu (2017) found that the uppermost 140 km reach of the LmMR below its diversion to the Atchafalaya River (near Old River Control Structure) had potentially trapped substantial amount

of sediments over the last three decades. They argued about a need for quantifying long term bed and suspended loads at the locations in which riverbed adjustment was found i.e., Tarbert Landing, Bayou Sara (BS) (at *rk* 427) (about 8 *rk* upstream of St Francisville) and Baton Rouge (BTR) (at *rk* 367.5). The United States Geological Survey (USGS) data for suspended sediment concentrations upon which sediment and sand load calculations are based can be found for at least four decades (1973-2015) at Tarbert Landing and one decade (2004-2015) at Baton Rouge, but no such data is available for Bayou Sara. Nearest long term data (1978-2015) which can analogue sediment loads at Bayou Sara are available at St Francisville, about 8 *rk* upstream from Bayou Sara.

Majority of the long term suspended sediment and sand load budgets for the LmMR have only been carried out at Tarbert Landing. There are limited, discontinuous flow and sediment studies between Tarbert Landing and Baton Rouge. Allison and Meselhe (2010) and Horowitz (2010) analyzed sediment budgets at St Francisville during 1981-2004 and 1981-2007, respectively. Further, studies quantifying suspended loads for the other locations downstream from St. Francisville are scarce and are limited to very short periods (three years in maximum). For example, Allison et al. (2012) carried out a short-term suspended load budget investigation at four sites covering approximately 372 km of the LmMR reach during 2008-2010. With respect to bedload, Nittrouer et al. (2008) estimated bedform transport rates in the LmMR but only for its lowermost reach between *rk* 167 (near New Orleans) and 0 (near the river's gulf outlet). In addition, Nittrouer et al. (2008) did not consider water discharge, river velocity and sediment transport equations in their analysis. Pereira et al. (2009) applied a 1-dimensional mobile-bed model (HECRAS 4.0) along the LmMR reach from Tarbert Landing to Venice (about 17 km above the river's gulf outlet). However, their study compared between several bedload equations

only and did not quantify bedload trends for any period. Nittrouer et al. (2011b) estimated the transport rates along the LmMR reach, however, their analysis only considered backwater flow velocities with no consideration of size of bed materials. Recently, Knox and Latrubesse (2016) quantified bedload during 2003-2011, but only at Tarbert Landing. To our best knowledge, no study exists on quantifying multi-decadal suspended loads synchronously at multiple locations along the uppermost 140 km of the LmMR. Similarly, comprehensive analysis of decadal trends in bedloads based on cross-sectional area, river discharge and stage, river velocity, and grain size are also unavailable along the uppermost LmMR.

Hence, this study aims to assess sediment transport by quantifying bedload and suspended load along the first 140 km of the Lowermost Mississippi River below its diversion at the Old River Control Structure to the Atchafalaya River. Quantifying bedload and suspended load along the upper LmMR can help in comparing spatiotemporal trends between bedloads and suspended loads, understanding their interactive relation and allocating sites with maximum sediment trapping capacity. This may have relevant implications in ongoing sediment diversion projects (both executed and planned) (CPRA 2012, Dean et al. 2013) and land restoration efforts along the LmMR reach. The specific objectives of this study include: (1) quantifying bedload transport at three locations of the uppermost 140 km reach of the LmMR (including Tarbert Landing); (2) quantifying long term daily, seasonal and annual suspended sediment and sand loads at two locations downstream of Tarbert Landing; (2) comparing the preexisting suspended loads at Tarbert Landing with matching periods of quantified suspended loads for other two locations downstream of Tarbert Landing; and (4) investigating the relationship between bedload and suspended load along the LmMR.

4.2 METHODS

4.2.1 Study Site Selection

This study focused on three locations covering the first 140 kilometers of the LmMR: Tarbert Landing, St Francisville and Baton Rouge (Figure 4.1). The first location is approximately 10-15 kilometers downstream of the river's diversion to the Atchafalaya River. The diversion is facilitated by an engineering complex, the Old River Control Structure (ORCS), which was constructed in 1963 for preventing the Atchafalaya River (AR) from capturing the bulk of Mississippi River water (> 30%). Post-ORCS construction, about 25% of the Mississippi River water is diverted into the Atchafalaya River artificially under normal flow conditions.

The three locations consist of monitoring stations jointly managed by the United States Geological Survey (USGS) and United States Army Corps of Engineers (USACE). The duration and availability of daily discharge, daily river stage and sediment records useful for this study vary according to the locations specifically (see sections 4.2.2 and 4.2.3). Since long-term sediment and sand-load analyses have been carried about at Tarbert Landing previously, this site was used only for bedload estimation. However, sediment load, sand load and bedload were analyzed at St Francisville and Baton Rouge.

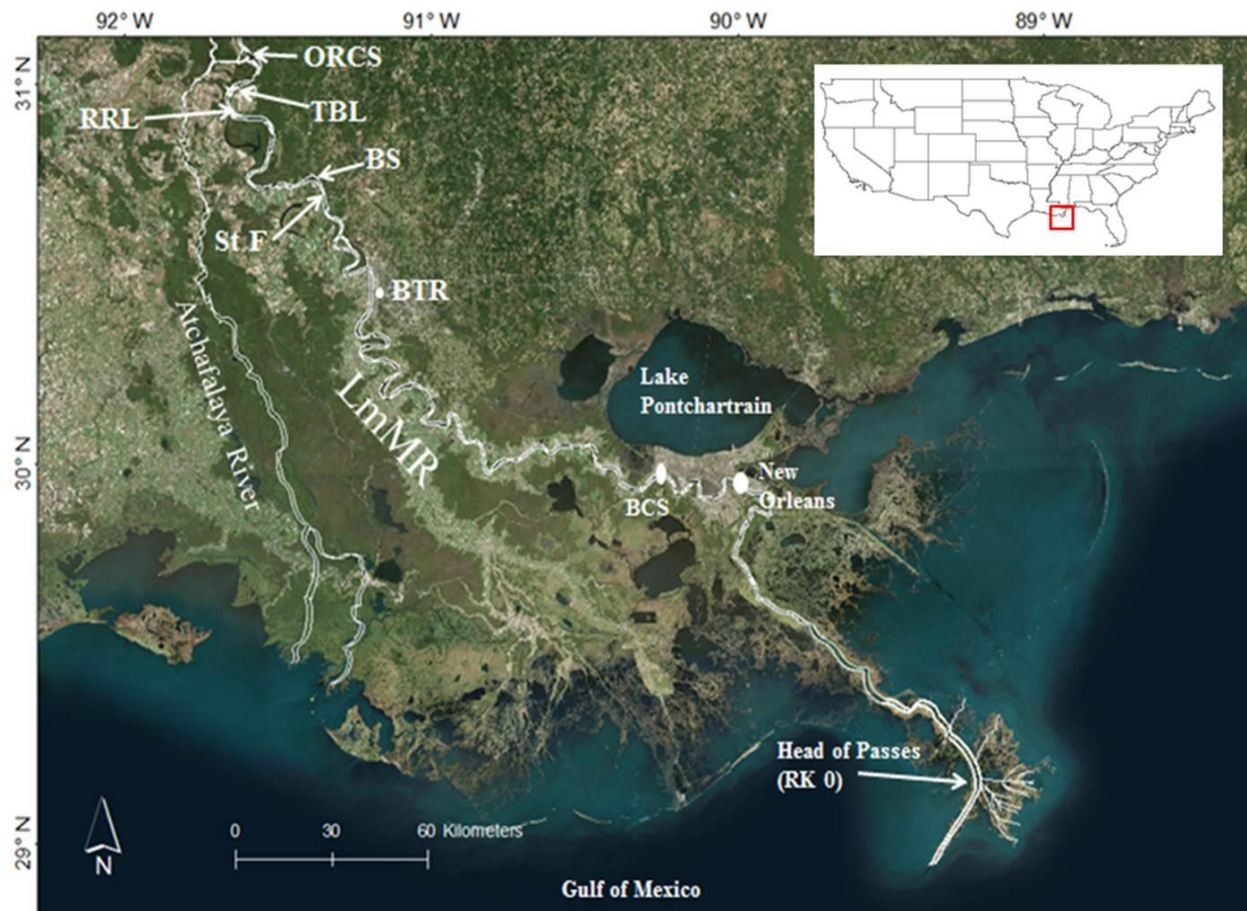


Figure 4.1: The Lowermost Mississippi River and the location of three sites used to analyze bedload and suspended load below the Old River Control Structure (ORCS): (1) Tarbert Landing (TBL) at river kilometer (or rk) 493, (2) St Francisville (St F) at rk 419 and (3) Baton Rouge (BTR) at rk 367.5. The Red River Landing (RRL) (at rk 486.5) just below TBL consists of long term river stage records from USGS gauge present at the site. Also, Bayou Sara (BS) (at rk 427) (about 9 rk above St F) is the nearest reference station for long term river stage at St F. BCS is the Bonnet Carre Spillway which is about 19 rk upstream of New Orleans.

4.2.2 River Stage, Discharge and Bathymetric Data

Daily River Stage records (RS_d in m) for Tarbert Landing were collected from the USACE gauge station at Red River Landing (about 4 rk downstream from Tarbert Landing) during 1973-2015, while RS_d s for St Francisville were collected at Bayou Sara (about 8 rk upstream of St Francisville) during 1978-2015. In addition, RS_d s were also collected at Baton Rouge during 2004-2015 from USACE. Similarly, daily discharge records (Q_d in cms) were collected from 1

January 1978 to 31 December 2015 and 1 January 2004 to 31 December 2015 at Tarbert Landing (from USACE) and Baton Rouge (from USGS) respectively. Both USACE and USGS did not have daily discharge records for St Francisville. However, the Q_d at Tarbert Landing was used for daily sediment and sand load estimations at St Francisville because the river discharge is approximately same for corresponding river stages at Tarbert Landing and St Francisville (Joshi and Xu 2017). River discharge measurements were used for suspended load analysis specifically and both river stage and discharge measurements were used for bedload analysis.

For this study, bathymetric data were collected at Tarbert Landing, St Francisville and Baton Rouge during 2004 and 2013 from USACE. USACE conducted hydrographic surveys along the LmMR reach from Black Hawk, Louisiana (rk 521.4, just above the ORCS) to the river's Gulf Outlet at Head of Passes (rk 0) in 1992, 2004 and 2013. The surveys consist of river channel cross-sections (*CS*) at 400-600 m intervals collected using single beam fathometer and multibeam side scan sonar. Each *CS* runs across the river (perpendicular to the river flow) at a given point and includes river bank and river bed elevation at given widths. The annual bed elevation was deduced from the three cross-sections bathymetric measurements, which were further used to quantify bed load transport rates at the sites.

4.2.3 Sediment and Sand Concentration Data

Records on suspended sediment concentration (*SSC*) (mg/l) and percentage of silt clay fractions in *SSC* (particles with diameter < 0.0625 mm) were collected from USGS at St Francisville (during 1978-2015) and Baton Rouge (during 2004-2015). USGS uses depth-integrated suspended sampling measures with the help of several isokinetic point samplers for collecting *SSC* records in the sites. A total of 437 *SSC* samples were collected at St Francisville, while 149 *SSC* samples were collected at Baton Rouge during their corresponding sampling

periods, respectively. The sampling records are assumed to be sufficient and unbiased across all years, seasons and flow regimes because USGS had carried out 1 to 3 sediment measurements for each month during sampling periods at the corresponding sites. More details about SSC collection, processing techniques, error adjustments and reliability of the records can be found in several reports published by USGS (Beverage 1987, Edwards and Glysson 1999, Skinner 2007).

4.2.4 Bedload Transport Estimation

In this study, the Engelund-Hansen (1967) sediment transport equation was used to estimate daily bedload transport rates at Tarbert Landing, St Francisville and Baton Rouge of the uppermost 140 km of the LmMR reach during 2004-2015. This equation ignores the use of critical shear stress and has been reported by other studies (e.g., Engelund and Fredsoe 1976, Van Rijn 1984, Bates et al. 2005) to be more accurate than other sediment transport equations. Engelund-Hansen used the stream power concept (Bagnold 1966) and the similarity principle to develop the following relationship between friction factor (f), dimensionless bedload discharge (Φ) and dimensionless bed shear stress (θ) for alluvial channels [as noted in its simplest and most direct form by Stevens and Yang (1989)]:

$$f \Phi = 0.1 \times \theta^{\frac{5}{2}} \quad (4.1)$$

The components f , Φ , and θ in equation (2) can be given by the following formulae:

$$f = \frac{2gds}{V^2} \quad (4.2)$$

$$\Phi = \frac{q_s}{\gamma_s \sqrt{(S_g - 1) D_{50}}} \quad (4.3)$$

$$\theta = \frac{dS}{(S_g - 1) D_{50}} \quad (4.4)$$

where, g is the acceleration due to gravity (9.81 m/sec^2); S is the slope of the channel; d is the channel depth in meters; V is the water velocity along the channel in m/sec; q_s is the bedload transport rate in kilogram/sec per meter of width (kg/sec-m); Y_s is the specific weight of the sediment (2650 kg/m^3); D_{50} is the grain size (i.e., average diameter for corresponding sediment particles in meter); and S_g is the specific gravity of sediment (2.68).

Furthermore, the bedload transport rate can be calculated by substituting for f , ϕ , Θ , and Y_s in equation (4.1) as follows:

$$q_s = \frac{0.05 \times Y_s \times V^2 \times d^{\frac{3}{2}} \times S^{\frac{5}{2}}}{D_{50} \times g \times (S_g - 1)^2} \quad (4.5)$$

Finally, the daily bedload transport rate (in tons/day) at the three locations along the LmMR was calculated by:

$$Q_s = 95.24 \times RW \times q_s \quad (4.6)$$

where 95.24 is a unit conversion factor for converting bedload in kg/sec-m to tons/day-m and RW is the daily river width at the location.

The methods for estimating channel depth, slope, flow velocity, river width, and grain-size in equations 4.5 and 4.6 are explained in the following sections from 4.2.4.1 to 4.2.4.5.

4.2.4.1 River Depth (d)

The daily river depth at Tarbert Landing, St Francisville and Baton Rouge during 2004-2015 was obtained by subtracting the average annual riverbed elevation (RE_{bed}) at a given location from the daily river stage in the location. The average annual RE_{bed} at each location was obtained from USACE bathymetric measurements for the years 2004 and 2013 (see section 2.2). At all locations, riverbed elevations were further interpolated for each year during 2005-2012 and 2014-2015 considering the following two criteria:

- a) If RE_{bed} in 2004 < RE_{bed} in 2013, RE_{bed} was increasing.
- b) If RE_{bed} in 2004 > RE_{bed} in 2013, RE_{bed} was decreasing.

Finally, the rate of increase (*ROI*) in RE_{bed} was added consecutively from 2004 to 2015 in increasing riverbeds (i.e., RE_{bed} in 2005 = RE_{bed} in 2004 + *ROI*, RE_{bed} in 2006 = RE_{bed} in 2005 + *ROI* and so on), while the rate of decrease (*ROD*) in RE_{bed} was subtracted consecutively in decreasing riverbeds (i.e., RE_{bed} in 2005 = RE_{bed} in 2004 - *ROD*, RE_{bed} in 2006 = RE_{bed} in 2005 - *ROD* and so on).

4.2.4.2 Riverbed Slope (S)

Riverbed slope between two consecutive cross-sections at a given location is the difference between riverbed elevations of both cross-sections (higher – lower) divided by the distance between the cross-sections (400-600 m – see section 2.2). For this study, riverbed slopes were calculated annually at each location during 2004-2015.

4.2.4.3 Average Flow Velocity (V)

The velocity of water discharge (in m/s) at Tarbert Landing, St Francisville and Baton Rouge for each day during the period 2004-2015 was calculated as:

$$V = \frac{Q_d}{A} \quad (4.7)$$

where, Q_d is the daily water discharge in m³/s and A is the daily cross-sectional area of the river channel at each location in m². The daily cross-sectional area at each location during the period was further calculated as the product of daily river depth (d in meter – see section 4.2.4.1) and daily river width (RW in meter – see section 4.2.4.4 below).

4.2.4.4 River Width (RW)

River width measurements are not available for any of the three sites along the LmMR. Therefore, to estimate the daily river width, Landsat 7 Satellite images with geographic

references (in .tiff format) were first collected during 2004-2015 using the USGS Earth Explorer tool (Figure 4.2). USGS Earth Explorer had 2-4 images for each month during 2004-2015, such that each image was captured on separate days. For this study, 55 images of LmMR at Tarbert Landing, 37 images at St Francisville and 42 images at Baton Rouge were collected during 2004-2015. The images were collected for days representing the lowest to highest river stages at Tarbert Landing, St Francisville and Baton Rouge along the LmMR. All images were opened in ArcMap 10.2 and the corresponding river widths at all locations were measured using the ‘Measure’ tool (Figure 4.2). Now, a linear-trend line was fit between the river widths (dependent: y) and their corresponding river stages (independent: x) at each location. Thus obtained were trend-line equations at Tarbert Landing, St Francisville and Baton Rouge (Table 4.1). They were further used to estimate daily river widths at these locations during 2004-2015 respectively.

Table 4.1: Trend-line equation between river width (y : dependent) and river stage (x : independent) for Tarbert Landing (TBL), St Francisville (St F) and Baton Rouge (BTR) of the LmMR during 2004-2015. These equations were further used for estimating daily river width from daily river stages at the three locations.

Station	Trend-line Equation	R^2
TBL	$y = 20.258x + 1122.8$	0.85
St F	$y = 12.881x + 1165.9$	0.82
BTR	$y = 30.218x + 428.3$	0.93

4.2.4.5 Representative Grain Sizes

The representative grain sizes (D_{50}) for each site for the calculation of bedload transport rates was deduced from the information table (Table 1) provided by Nordin and Queen (1992).

According to their data, 1.7% coarser sediments (> 0.063 mm) in the LmMR were between 0.063 and 0.125 mm in size, 96.2% coarser sediments were between 0.125 and 0.25 mm, and 99.9% of

the coarser sediments were between 0.25 and 0.5 mm. Therefore in this study, we used three sediment sizes of 0.125, 0.25 and 0.5 mm for all study sites to represent 99.9% of the bedload sediments in the river reach.



Figure 4.2: Screenshot of the Landsat 7 Satellite image for Tarbert Landing of the Lowermost Mississippi River. The image was collected in .tiff format using the USGS Earth Explorer tool. The red horizontal line represents the river width of the LmMR at Tarbert Landing on the date of imagery. The image was directly opened in Arc Map 10.2 and then the river width was measured using the ‘Measure’ tool. The same procedure was followed for measuring river width at Tarbert Landing, St Francisville and Baton Rouge for, respectively, 55, 37 and 42 days during 2004-2015.

4.2.5 Development of Discharge-Sediment and Discharge-Sand Rating Curves

The procedure used by Joshi and Xu (2015) was followed to develop discharge-sediment and discharge-sand rating curves at St Francisville and Baton Rouge, respectively. Daily sediment load (DSL in tonnes/day) was computed by multiplying SSC with the corresponding Q_d for all the sampling dates at both sites as:

$$DSL = Q_d \times SSC \times 0.0864 \quad (4.8)$$

where 0.0864 is a unit conversion factor for converting the sand mass to tons per day.

Similarly, sand concentration (SSC_s in mg/l) was calculated by subtracting silt/clay concentration [SSC_f (mg/l) = % silt/clay \times SSC] from SSC. Then SSC in equation 4.8 was replaced by SSC_s for calculating daily sand loads (DSL_s in tonnes/day) for all sampling dates at both sites.

The dependent variables, DSL or DSL_s (y) and the independent variable, Q_d (x) were transformed to their natural logarithm (ln), and the relationship between them was evaluated by subjecting them to various linear and polynomial rating curves. Then, the “log transformed (ln) Q_d s” were fitted in the rating curve equations to get “predicted ln DSL and DSL_s ”. Then, the “predicted ln DSL and DSL_s ” were transformed back (by taking their exponential values) to attain the “predicted DSL and DSL_s ”. Correction factor (CF) given by Gray et al. (2015b) as a modification of Duan (1983) was applied to check the potential log-biasing in the retransformation procedure. Finally, all rating curves were evaluated according to the following four criteria: regression coefficient of the curves ($R^2 \geq 0.8$), root mean square errors of the predicted DSL and DSL_s (RMSE) (the lower the better), standard error (SE) of the curves (in ln units) (also, the lower the better) and a graphical assessment (good visual agreement between corresponding calibrated and predicted DSL s and DSL_s s respectively) (Sykes 1993, Philips et al. 1999, Joshi and Xu 2015).

At first, single linear and polynomial sediment and sand rating curves were applied for the corresponding whole periods at both stations (i.e., 1978-2015 at St Francisville and 2004-2015 at Baton Rouge). At St Francisville, the four evaluation criteria did not meet for single sediment and sand rating curves: low R^2 (0.7 and 0.75 for linear and polynomial sediment rating curves; 0.74 and 0.78 for linear and polynomial sand rating curves) (Tables 4.2 and 4.3); comparatively

higher RMSE (186620 and 174238 for linear and polynomial sediment rating curves; 66486 and 59781 for linear and polynomial sediment rating curves) and SE (0.805 for sediment and 0.496 for sand rating curves) (Tables 4.4 and 4.5); and a poor visual agreement between corresponding measured and predicted *DSL*s and *DSL_s*s (Figures 4.3 and 4.5). Therefore, approximately decadal linear and polynomial rating curves were further applied at this station because decadal intervals have been previously reported to minimize both intra- and inter-annual variability in sediment samples [Nittrouer and Viparelli (2014), Joshi and Xu (2015)]. At Baton Rouge, interestingly, single polynomial rating curves met all four evaluation criteria (Tables 4.2 through 4.5, Figures 4.3 and 4.5).

Finally, all the evaluation criteria were met at St Francisville using polynomial sediment rating curves during the periods: 1978-1987, 1988-1997, 1998-2007 and 2008-2015, and polynomial sand rating curves during the periods: 1978-1987, 1988-1996, 1998-2007, 2008-2015. They gave the predicted *DSL*s and *DSL_s*s most approximate to their corresponding calibrated measurements from USGS (Tables 4.3 and 4.4, Figures 4.3 and 4.5). It was also found that the use of a correction factor improved the RMSEs and decreased differences between predicted and calibrated *DSL*s, while overestimated *DSL_s*s. Hence, correction factors were used for sediment rating curves only at this station. The year 1997 had a very low R^2 for sand rating curves (Lin: 0.58 and Poly: 0.61) which was reducing R^2 s and increasing RMSEs and SEs when combined with its preceding or succeeding decade (i.e., 1988-1996 and 1998-2007). Therefore, *DSL_s* for 1997 at St Francisville was calculated using a non-rating curve approach (described in the following section 4.2.6). Similarly, at Baton Rouge a single polynomial rating curve with no correction factor gave the best approximation between predicted and calibrated *DSL*s and *DSL_s*s, respectively.

Table 4.2: Discharge-suspended sediment load rating curves developed for St Francisville (St F) and Baton Rouge (BTR) of the LmMR. Here, $x = \ln(Q_d)$ (the independent variable) and $y = \ln(DSL)$ (the dependent variable).

Station	Period	Discharge – Sediment Load Rating Curve	Model	R ²
St F	1978 - 2015	$y = 1.3785x - 1.403$	Linear	0.7
		$y = -0.6481x^2 + 13.681x - 59.14$	Polynomial	0.75
	1978 - 1987	$y = 1.4571x - 1.3486$	Linear	0.79
		$y = -0.4501x^2 + 9.9418x - 41.202$	Polynomial	0.81
	1988 - 1997	$y = 1.4832x - 1.9091$	Linear	0.77
		$y = -0.6171x^2 + 13.218x - 57.489$	Polynomial	0.82
	1998 - 2007	$y = 1.6499x - 3.624$	Linear	0.81
		$y = -0.5798x^2 + 12.599x - 55.148$	Polynomial	0.84
	2008 - 2015	$y = 1.1938x + 0.5659$	Linear	0.66
		$y = -0.8644x^2 + 17.718x - 78.173$	Polynomial	0.81
BTR	2004- 2015	$y = 1.4679x - 2.0093$	Linear	0.77
		$y = -0.6416x^2 + 13.751x - 60.636$	Polynomial	0.82

Table 4.3: Discharge-suspended sand load rating curves developed for St Francisville (St F) and Baton Rouge (BTR) of the LmMR. Here, $x = \ln(Q_d)$ (the independent variable) and $y = \ln(DSL_s)$ (the dependent variable).

Station	Period	Discharge – Sand Load Rating Curve	Model	R ²
St F	1978 - 2015	$y = 2.4916x - 13.512$	Linear	0.74
		$y = -0.949x^2 + 20.491x - 98.512$	Polynomial	0.78
	1978 - 1987	$y = 2.4591x - 12.768$	Linear	0.81
		$y = -0.5452x^2 + 12.737x - 61.046$	Polynomial	0.82
	1988 - 1996	$y = 2.5655x - 14.027$	Linear	0.81
		$y = -0.8396x^2 + 18.465x - 89.021$	Polynomial	0.84
	1997	$y = 2.3645x - 13.001$	Linear	0.58
		$y = -1.1882x^2 + 25.326x - 123.47$	Polynomial	0.62
	1998 - 2007	$y = 2.8754x - 17.322$	Linear	0.81
		$y = -0.7322x^2 + 16.701x - 82.383$	Polynomial	0.82
2008 - 2015	$y = 2.4618x - 13.512$	Linear	0.74	
	$y = -1.4879x^2 + 30.908x - 149.05$	Polynomial	0.86	
BTR	2004- 2015	$y = 3.2306x - 20.967$	Linear	0.85
		$y = -0.6648x^2 + 15.957x - 81.709$	Polynomial	0.86

Table 4.4: Root mean square errors (RMSEs) of Daily Sediment Loads (*DSL*) predicted through discharge-sediment load rating curves for each period at St Francisville (St F) and Baton Rouge (BTR) as shown in Table 1. Here, SE is the standard error and CF-Poly is the Duan correction factor used in polynomial rating curves, while CF-Lin is the Duan correction factor used in linear rating curves. “No CF” represents *DSL*s calculated without applying correction factors during their retransformation from predicted *ln DSL*s while “CF” represents *DSL*s calculated by applying the correction factors during the retransformation procedure.

Station	Period	RMSE - No CF (Polynomial)	RMSE - No CF (Linear)	SE	CF- Poly	CF- Lin	RMSE-CF (Polynomial)	RMSE-CF (Linear)
St F	1978 - 2015	174238	186620	0.496	1.099	1.13	170877	193579
	1978 - 1987	171919	198282	0.418	1.076	1.091	169392	205935
	1988 - 1997	162465	187405	0.472	1.081	1.109	160521	197703
	1998 - 2007	122371	139538	0.414	1.075	1.084	121050	144344
	2008 - 2015	101945	162710	0.434	1.04	0.65	100445	197449
BTR	2004 - 2015	105616	129019	0.401	1.123	1.081	111393	134824

Table 4.5: Root mean square errors (RMSEs) of Daily Sand Loads (*DSL*s) predicted through discharge-sand load rating curves for each period at St Francisville (St F) and Baton Rouge (BTR) as shown in Table 1. Specific terminologies in the table i.e., No CF, SE, CF-Poly, CF-Lin, are same as explained in Table 4.3.

Station	Period	RMSE - No CF (Polynomial)	RMSE - No CF (Linear)	SE	CF- Poly	CF- Lin	RMSE-CF (Polynomial)	RMSE-CF (Linear)
St F	1978 - 2015	59781	66486	0.805	1.6	1.57	61998	104085
	1978 - 1987	54362	69469	0.655	1.291	1.324	58797	92190
	1988 - 1996	50127	53568	0.705	1.343	1.369	52548	78803
	1998 - 2007	35912	41464	0.738	1.408	1.398	40349	61274
	2008 - 2015	29785	60848	0.743	1.204	1.374	30397	86911
BTR	2004 - 2015	46263	77483	0.683	1.216	1.253	51084	105184

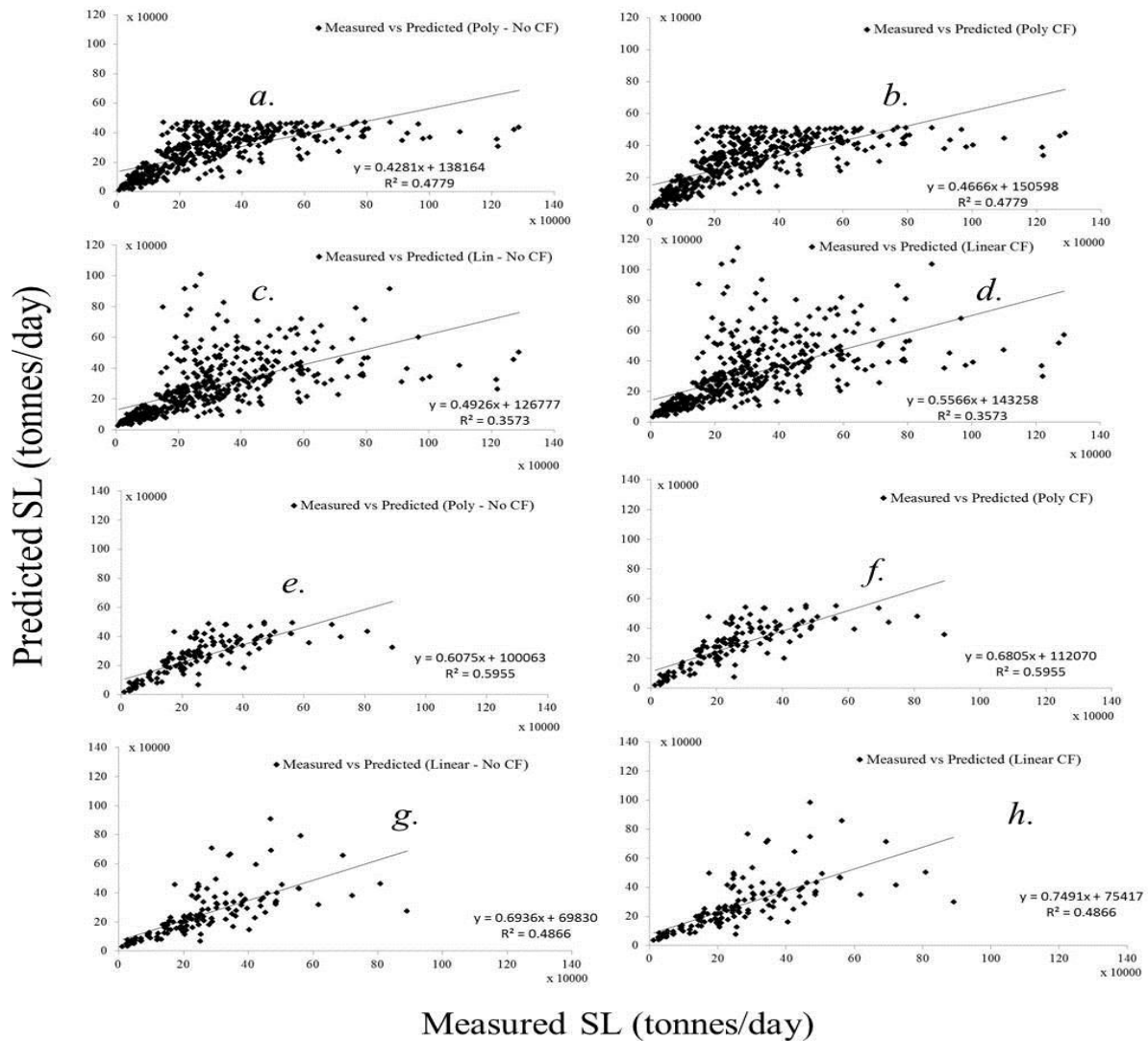


Figure 4.3: Comparison of sediment loads calculated from SSC records measured, processed, and calibrated by USGS (Measured SL) with those predicted from single sediment rating curves [either linear ((Lin) or polynomial (poly))] (Predicted SL) at St Francisville during 1978-2015 (a, b, c, and d) and Baton Rouge along the Lowermost Mississippi River during 2004-2015 (e, f, g, and h). It is to note that Duan correction factors were applied for the curves denoted by “CF” in the figure (b, d, f, and h), while the remaining curves denoted by “No CF” in the figure were analyzed without correction factors (a, c, e, and g).

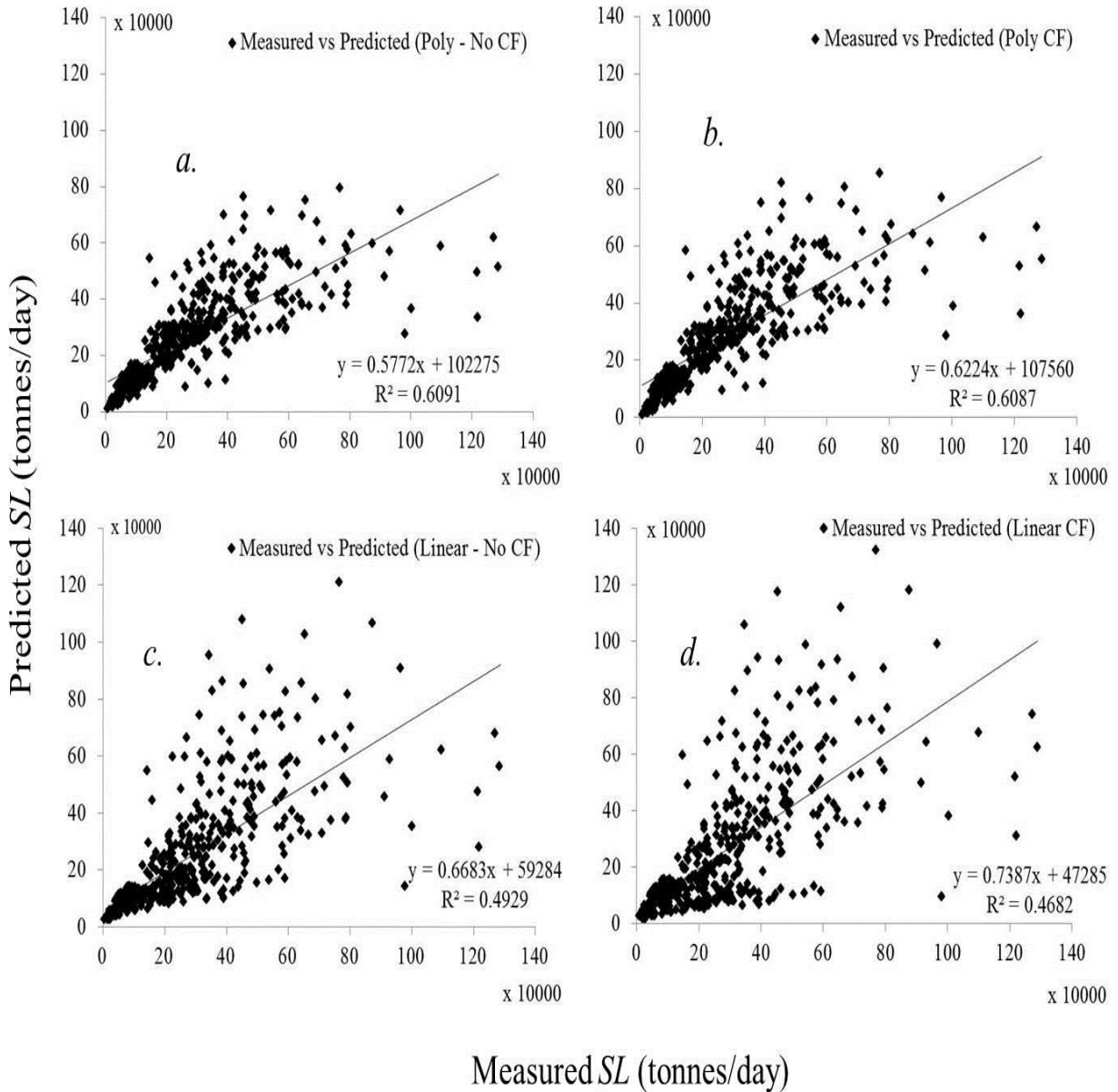


Figure 4.4: Comparison of Measured SL (please see caption of Figure 2 for definition) with those predicted from several sediment rating curves (Predicted SL) at St Francisville of the Lowermost Mississippi River during 1978-2015. Specific terminologies found in this figure such as Lin, Poly, CF, and No CF are same as explained in Figure 4.3.

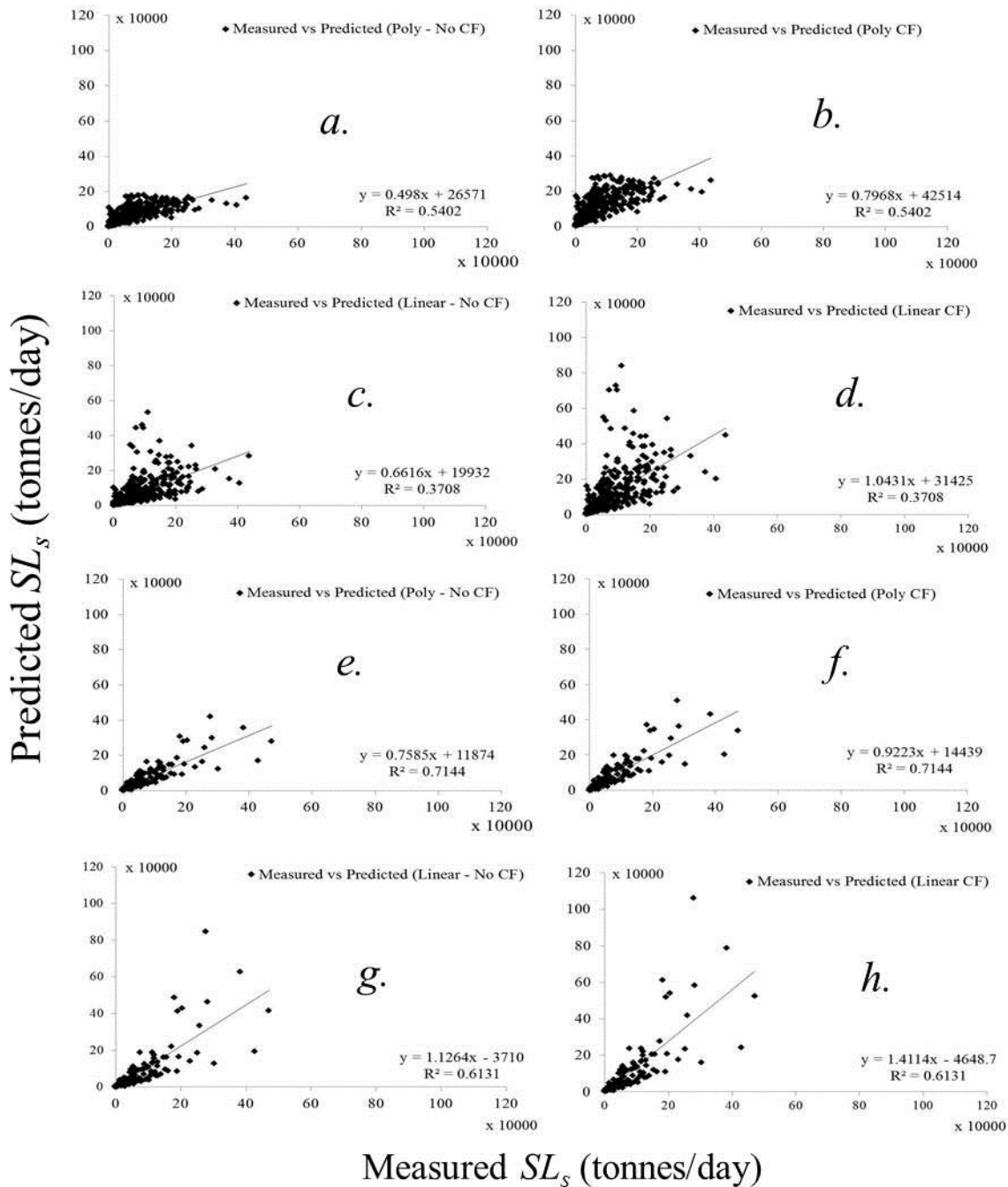


Figure 4.5: Comparison of sand loads calculated from SSC records measured, processed and calibrated by USGS (Measured SL_s) with those predicted from single sediment rating curves [either linear ((Lin) or polynomial (poly))] (Predicted SL_s) at St Francisville of the Lowermost Mississippi River during 1978-2015 (a, b, c, and d) and BTR during 2004-2015 (e, f, g, and h). Specific terminologies found in this figure i.e., ‘CF’ and ‘No CF’ are same as explained in Figure 4.3.

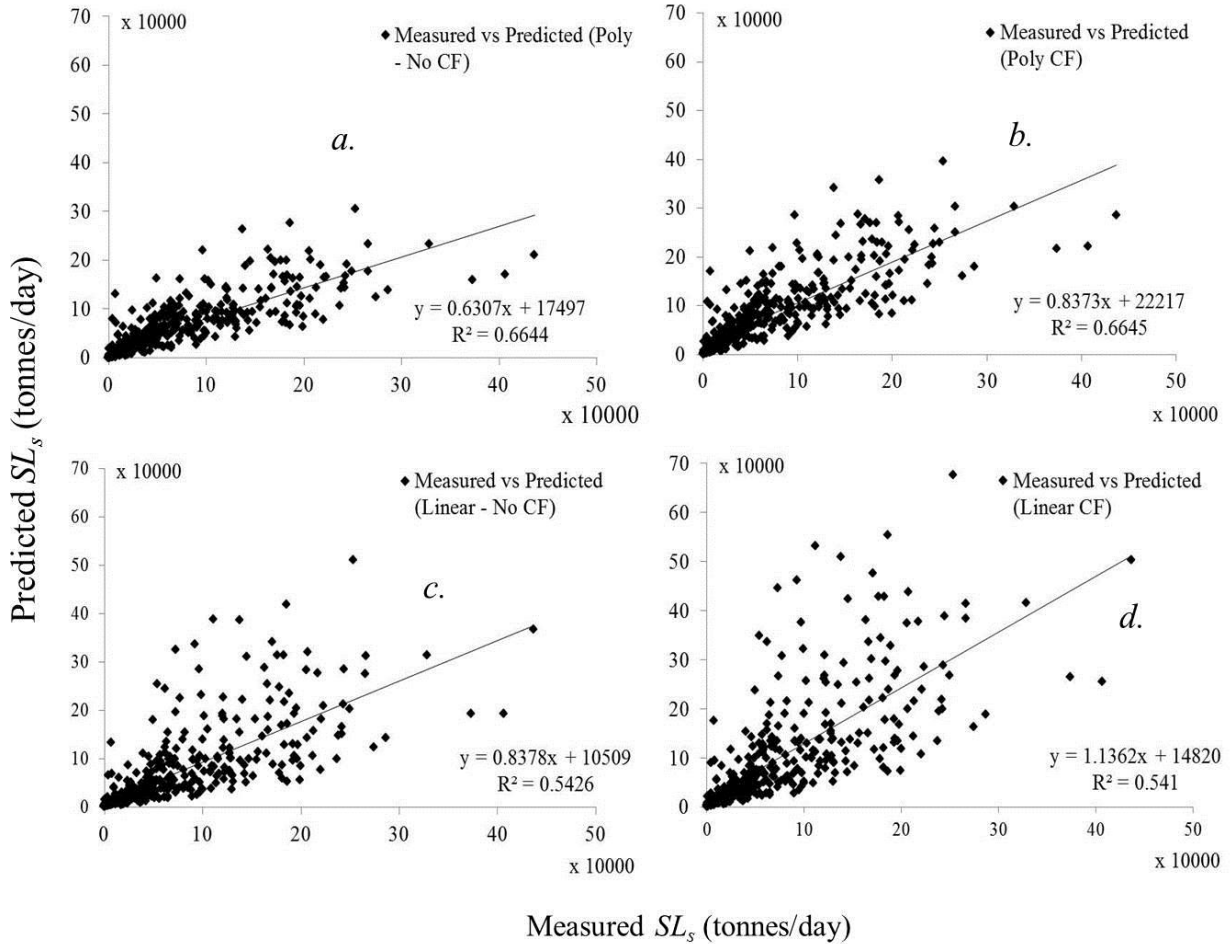


Figure 4.6: Comparison of Measured SL_s and Predicted SL_s (please see the caption of Figure 4 for definition) at St Francisville of the Lowermost Mississippi River during 1978-2015. Specific terminologies found in this figure such as Lin, Poly, CF, and No CF are same as explained in Figure 4.3. It is to note that both predicted and measured SL_s during 1997 were eliminated in this comparison because of the low R^2 value of both rating curves during this year (please see Table 4.2).

4.2.6 Non-Rating Curve Approach for Sand Load Calculation

A non-rating curve approach was used for prediction DSL_s at St Francisville during 1997 because of the reasons mentioned in above section 4.2.5. In this method, the sand concentration for the first sampling date of the year was supposed to be equal to all consecutive days of missing concentrations until the next sampling date. In addition, the concentration of the first

sampling date was used for all non-available dates earlier that year. Finally, all DSL_s s during 1997 at St Francisville were calculated using the formula in Equation (4.8).

4.2.7 Annual and Seasonal Bedloads and Suspended Loads

Annual bedload transport rates (Q_s) at Tarbert Landing, St Francisville and Baton Rouge were calculated as the sum of daily Q_s between 1 January and 31 December for the three locations. The error range value for annual bedload transport rates was considered as $\pm 24\%$ based on the accuracy of Engelund-Hansen equation noted by Van Rijn (1984). Van Rijn (1984) reported that bedloads measured in three field sites and one lab condition were 61 to 87% (average 76%) of the corresponding bedloads computed from the Engelund-Hansen equation.

Annual suspended sediment and sand loads at St Francisville and Baton Rouge were also calculated as the sum of DSL and DSL_s between 1 January and 31 December for both sites. The error range value of $\pm 18\%$ given by Joshi and Xu (2015) was used to adjust for errors in annual sediment and sand loads. These loads were used to analyze daily and annual sediment and sand load trends both locations. Similarly, monthly sediment and sand loads were used to analyze their seasonal trends. The annual and monthly sediment and sand loads were also compared with pre-existing sediment and sand loads at Tarbert Landing for overlapping periods.

4.3 RESULTS

4.3.1 Bedload Transport Rates

Total and annual bedload rates (Q_s) increased gradually from Tarbert Landing to Baton Rouge along the LmMR during 2004-2015 for all representative grain sizes (Figures 4.7, 4.8 and 4.9). The total Q_s for grain size of 0.125 mm were found to be 82.8, 83.6 and 96 MT at Tarbert Landing, St Francisville and Baton Rouge respectively during the 12 years (Figures 4.7 through 4.10). Similarly, annual Q_s for the same grain size of 0.125 mm averaged 6.9 million tons

(MT)/year, ranging from 2.3 (in 2006) to 12.8 MT/year (in 2015) at Tarbert Landing (Figures 4.7 and 4.10); 7 MT/year, ranging from 3.5 (in 2006) to 10.3 MT/year (in 2008) at St Francisville (Figures 4.8 and 4.10); and 8.1 MT/year, ranging from 2.2 (in 2014) to 19.4 MT/year (in 2004) at Baton Rouge (Figures 4.9 and 4.10). When the representative grain size decreased by half, the annual Q_s for all three locations along the LmMR also decreased by half during 2004-2015 (Figures 4.7 through 4.9). Therefore, the annual Q_s for the grain size of 0.25 mm were half of the annual Q_s for the grain size of 0.125 mm at Tarbert Landing, St Francisville and Baton Rouge in each of the 12 years during 2004-2015 (Figures 4.7, 4.8 and 4.9). Further, the annual Q_s for the grain size of 0.5 mm were half of the annual Q_s for the grain size of 0.25 mm in each year (Figures 4.7, 4.8 and 4.9).

Specifically, annual Q_s for all grain sizes experienced an increasing trend at Tarbert Landing specifically from 2006 to 2015 (2.3 MT/year in 2006 increased to 12.8 MT/year in 2015 for grain size of 0.125 mm; 1.2 MT/year in 2006 increased to 6.4 MT/year in 2015 for grain size of 0.25 mm; and 0.6 MT/year in 2006 increased to 3.2 MT/year in 2015 for grain size of 0.5 mm) (Figure 4.7). At Baton Rouge, the trends in bed load transport rates were exactly opposite. In this location, annual Q_s for all grain sizes experienced a decreasing trend throughout the study period (19.4 MT/year in 2004 decreased to 2.3 MT/year in 2015 for grain size of 0.125 mm; 9.7 MT/year in 2004 decreased to 1.2 MT/year in 2015 for grain size of 0.25 mm; and 4.8 MT/year in 2004 decreased to 0.6 MT/year in 2015 for grain size of 0.5 mm) (Figure 4.9). At St Francisville, the location between Tarbert Landing and Baton Rouge, annual Q_s for all grain sizes did not experience any significant change during 2004-2015 (Figure 4.8). On a few occasions, annual Q_s for all grain sizes increased or decreased abruptly for two to three years in continuum at all three locations (Figures 4.7 through 4.10).

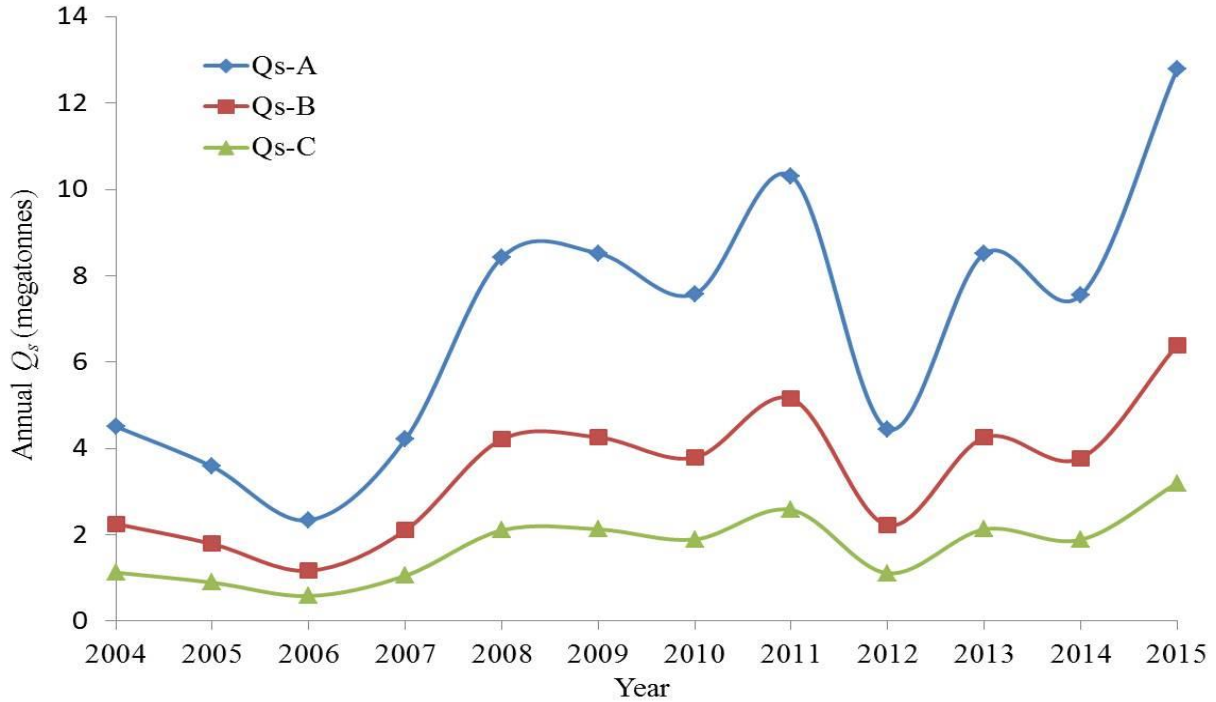


Figure 4.7: Annual bedload transport rates (Q_s) at Tarbert Landing of the Lowermost Mississippi River. Note: A, B and C represent the transport rates for representative grain size (D_{50}) of 0.125, 0.25 and 0.5 mm respectively as selected for this analysis (please see section 4.2.4.5).

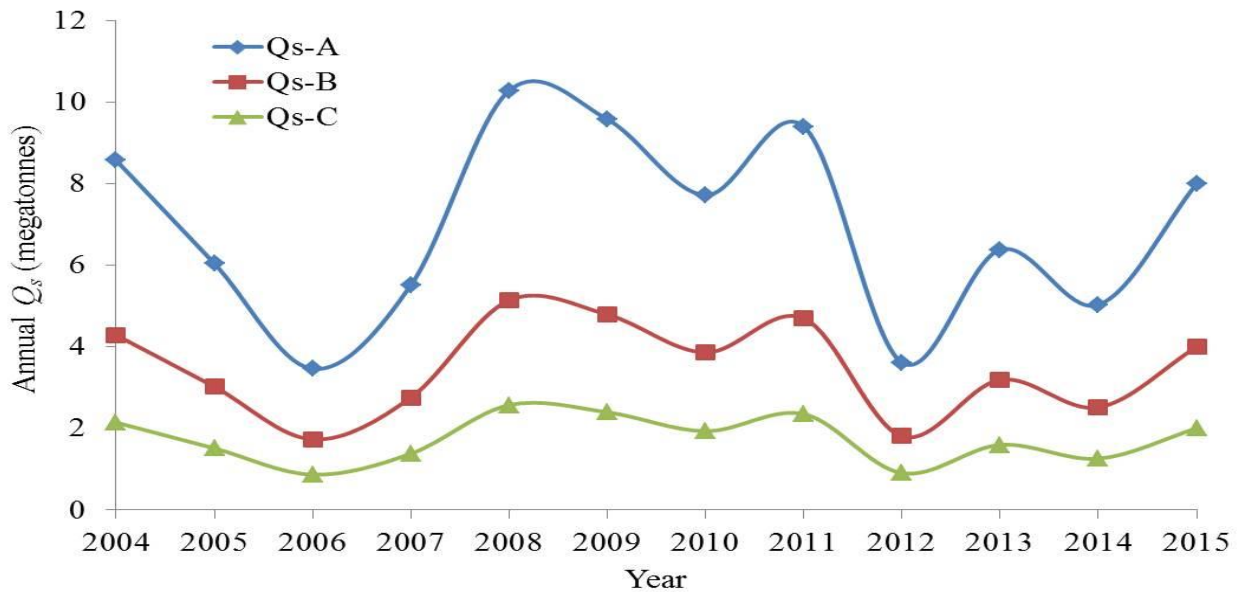


Figure 4.8: Annual bedload transport rates (Q_s) at St Francisville of the Lowermost Mississippi River. Note: A, B and C represent the transport rates for representative grain size (D_{50}) of 0.125, 0.25 and 0.5 mm respectively as selected for this analysis (please see section 4.2.4.5).

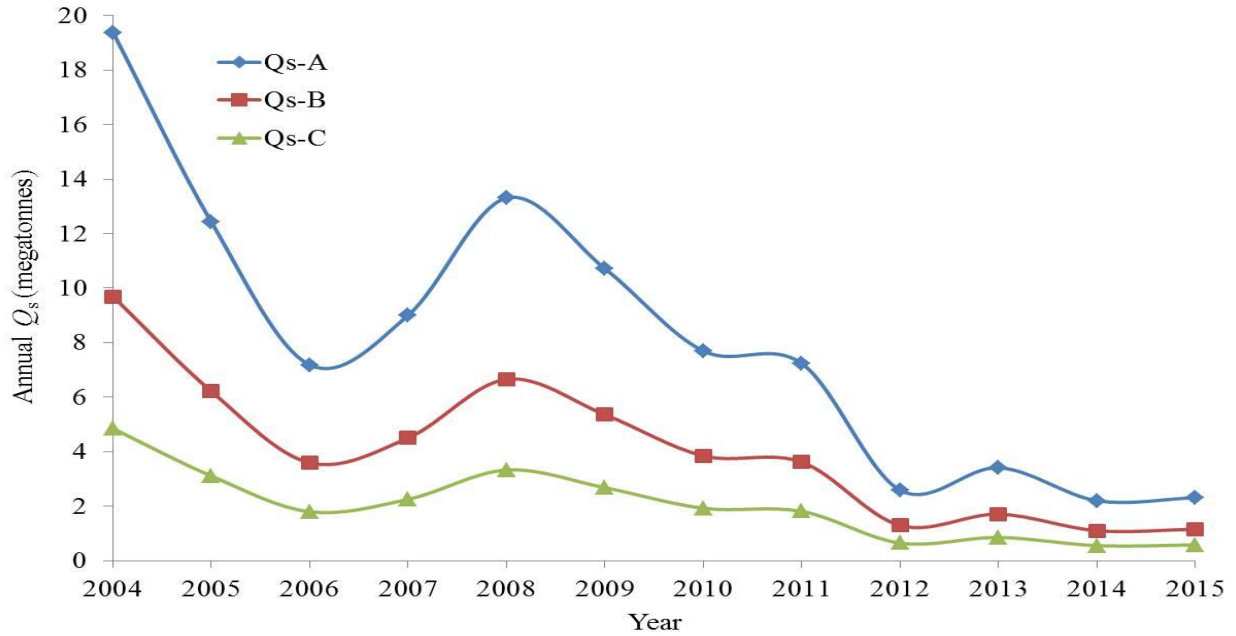


Figure 4.9: Annual bedload transport rates (Q_s) at Baton Rouge of the Lowermost Mississippi River. Note: A, B and C represent the transport rates for representative grain size (D_{50}) of 0.125, 0.25 and 0.5 mm respectively as selected for this analysis (please see section 4.2.4.5).

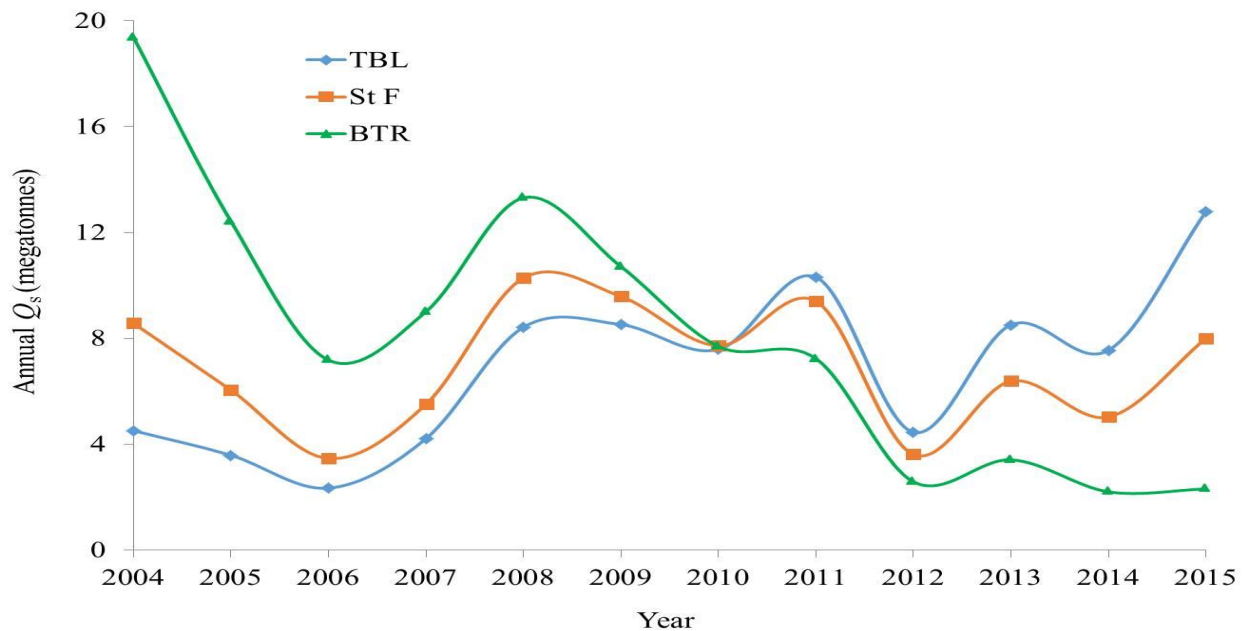


Figure 4.10: Annual bedload transport rates (Q_s) at Tarbert Landing (TBL), St Francisville (St F), and Baton Rouge (BTR) of the Lowermost Mississippi River for a grain size (D_{50}) of 0.125 mm. Note: Annual Q_s for grain size of 0.25 mm were exactly half of annual Q_s for grain size of 0.125 mm, while annual Q_s for grain size of 0.5 mm were exactly half of annual Q_s for grain size of 0.25 mm at all stations. Therefore, annual Q_s for grain sizes of 0.25 and 0.5 mm had similar trends as annual Q_s for grain size of 0.125 mm at all locations.

Monthly averages of daily bedload rates (Q_s) along the LmMR during 2004-2015 showed linearly increasing trends with monthly averages of daily river discharge (Q_d) and river stage (RS_d) at Tarbert Landing and St Francisville respectively, however, the increasing trends with both variables were not eminent at Baton Rouge (Figures 4.11 and 4.12). The rate of increase of Q_s with both variables was highest at St Francisville ($R^2 = 0.95$ for Q_s vs Q_d linear trend line and 0.84 for Q_s vs RS_d trend lines) (Figures 4.11 and 4.12) and second highest at Tarbert Landing ($R^2 = 0.83$ for Q_s vs Q_d linear trend line and 0.77 for Q_s vs RS_d trend lines) (Figures 4.11 and 4.12). At Baton Rouge, however, the relationship of monthly Q_s with monthly Q_d and RS_d appeared to be more scattered during the 12-year study period ($R^2 = 0.33$ for Q_s vs Q_d linear trend line and 0.32 for Q_s vs RS_d trend lines) (Figures 4.11 and 4.12). These relationships were noted down for representative grain size of 0.125 mm. Exactly same relationships of monthly Q_s with monthly Q_d and RS_d were found for the other two grain sizes (0.25 and 0.5 mm) at each location along the LmMR during 2004-2015 (figures for these two grain sizes were not kept here to avoid repetition).

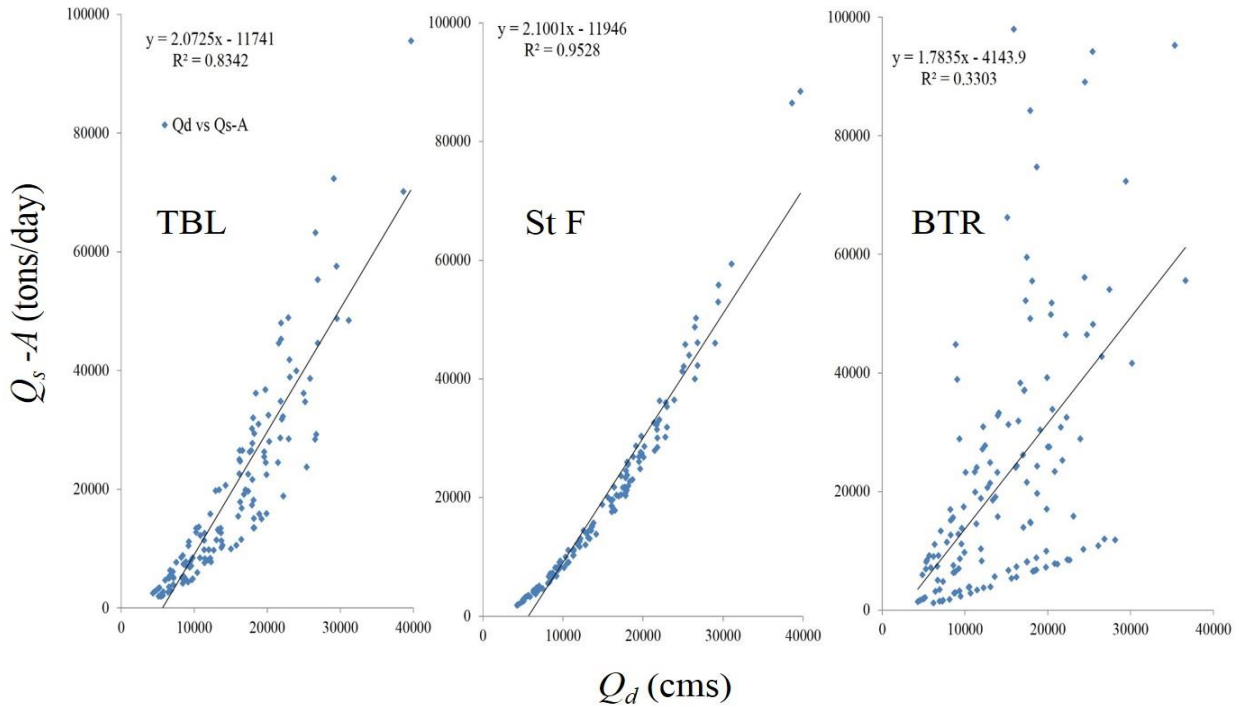


Figure 4.11: Relationship of monthly average of daily discharge (Q_d in cms) with the monthly average of daily bedload transport rates (Q_s in tons/day) for representative grain-size of 0.125mm (A) at Tarbert Landing (TBL), St Francisville (St F) and Baton Rouge (BTR) of the Lowermost Mississippi River during 2004-2015.

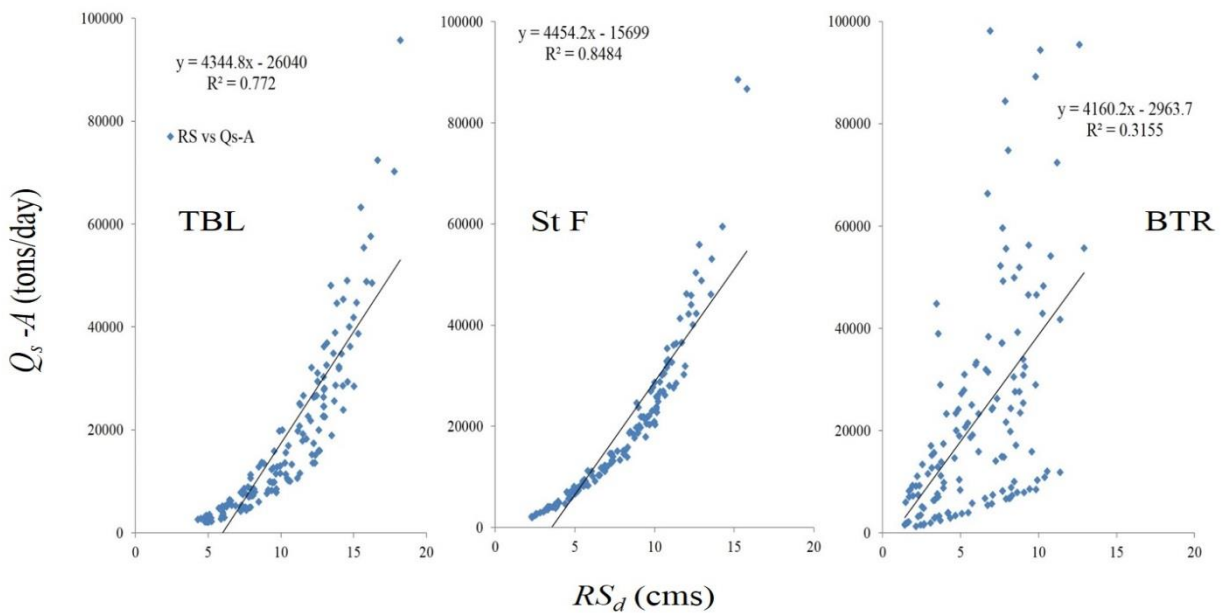


Figure 4.12: Relationship of monthly average of daily river stages (RS_d in m) with the monthly average of daily bedload transport rates (Q_s in tons/day) for representative grain-size of 0.125mm (A) at Tarbert Landing (TBL), St Francisville (St F), and Baton Rouge (BTR) of the Lowermost Mississippi River during 2004-2015.

4.3.2 Suspended Sediment Loads

Annual sediment loads (SL) at St Francisville averaged 97.06 million tons (MT) from 1978 to 2015, ranging from 39.97 MT in 2012 to 178.71 MT in 1979 (Figure 4.13). The total sediment amount for the entire 38-year study period was found to be 3688.33 MT (Figure 4.13). Annual SL was lower than 50 MT for 3 of the 41 years (2000, 2006, and 2012), 50 to 100 MT for 19 years (including the Mississippi flood year of 2011), 100 to 150 MT for 12 years and more than 150 MT for the remaining 4 years (Figure 4.13). Annual SL was higher for approximately the first-half of the study period (117.3 MT from 1978 to 1999), however, it decreased substantially towards the latter-half (68.95 MT from 2000 to 2015) (Figure 4.13). Also, annual SL was more than 100 MT only for one year (103.35 MT in 2004) during this period. Long-term continuous increasing or decreasing trend (even for 3/4 years) in annual SL was not found at St Francisville despite a few instances of abrupt decrease during for 2 years in continuum (Figure 4.13).

At Baton Rouge, annual SL averaged 67.17 MT from 2004 to 2015 and ranged 28.33 MT (in 2006) to 92.88 MT (in 2009) (Figure 4.13). During this period, the total sediment amount was found to be 806.08 MT (Figure 4.13). Annual SL was lower than 50 MT for 2 out of 12 years (2006 and 2012), while either > 50 or < 100 MT for the remaining 10 years (Figure 4.13). The long-term continuous increasing or decreasing trends in annual SL were not found at this station (Figure 4.13). This result was similar to that of St Francisville.

Both sites had slightly different seasonal trends of average *DSL*s. At St Francisville, average *DSL* during 1978-2015 increased each year from January to its maximum in April (i.e. from 313955 to 427400 tonnes/day), then decreased from May to its minimum in September (from 401143 to 99043 tonnes/day), showing the highest sediment transport during early spring months (Figure 4.14). Average *DSL* increased again for the remaining three months of the year i.e.,

110,000 tonnes/day in October to 287,000 tons/day in December (Figure 4.14). At Baton Rouge, however, average *DSL* during 2004-2015 decreased slightly from January to February (i.e., from 229,317 and 228,956 tonnes/day respectively) (Figure 4.14). It further increased during the three spring months from 268017 in March to 300080 tonnes/day in May (Figure 4.14), followed by a drop to its minimum in mid-fall (i.e., from 252035 in June to 75735 tonnes/day in September) (Figure 4.14). The final three months had a continuous increase in average *DSL* like that found at St Francisville i.e., 79789 (in October) to 179541 tonnes/day (in December) (Figure 4.14).

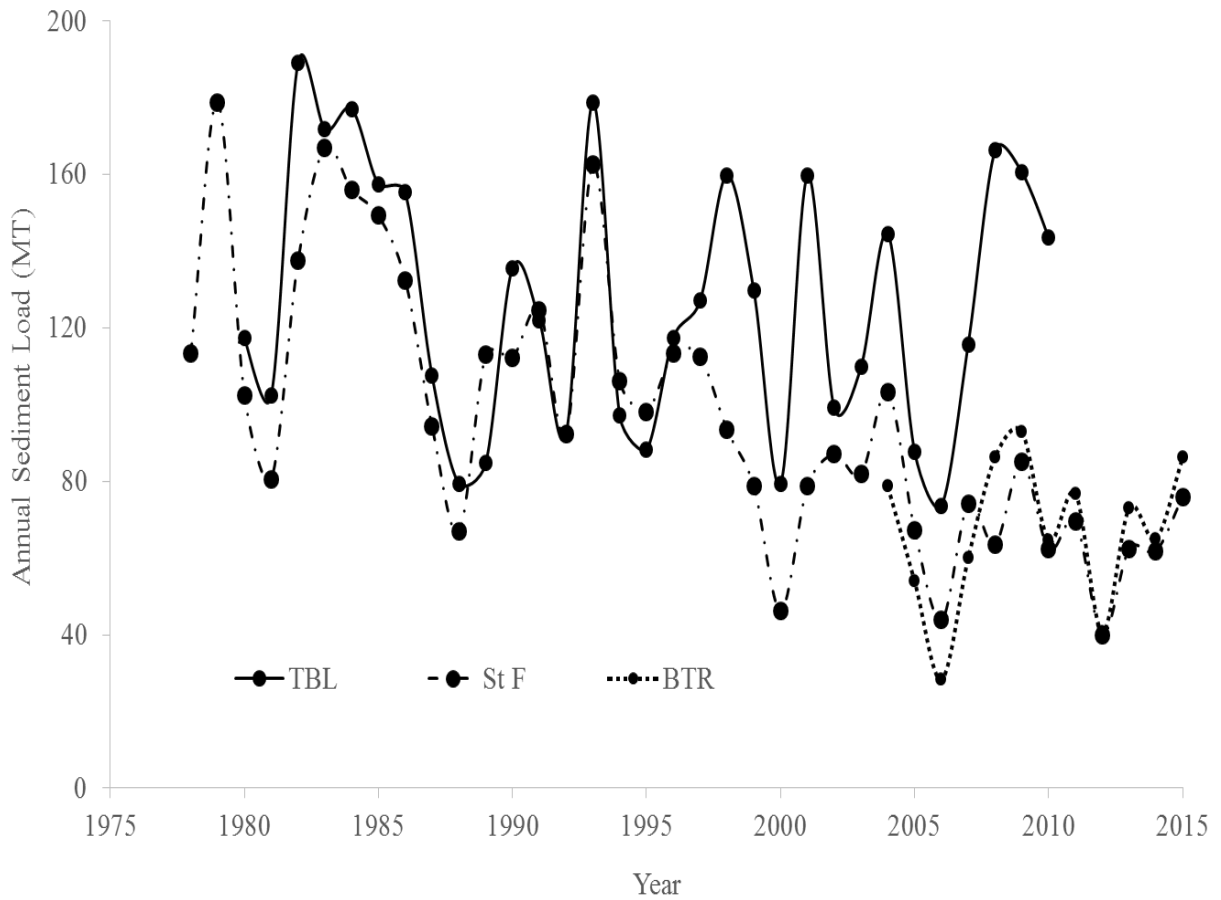


Figure 4.13: Annual Sediment Loads (SL) at Tarbert Landing, St Francisville and Baton Rouge of the Lowermost Mississippi River. Note: The annual SLs at Tarbert Landing were taken from Rosen and Xu (2014).

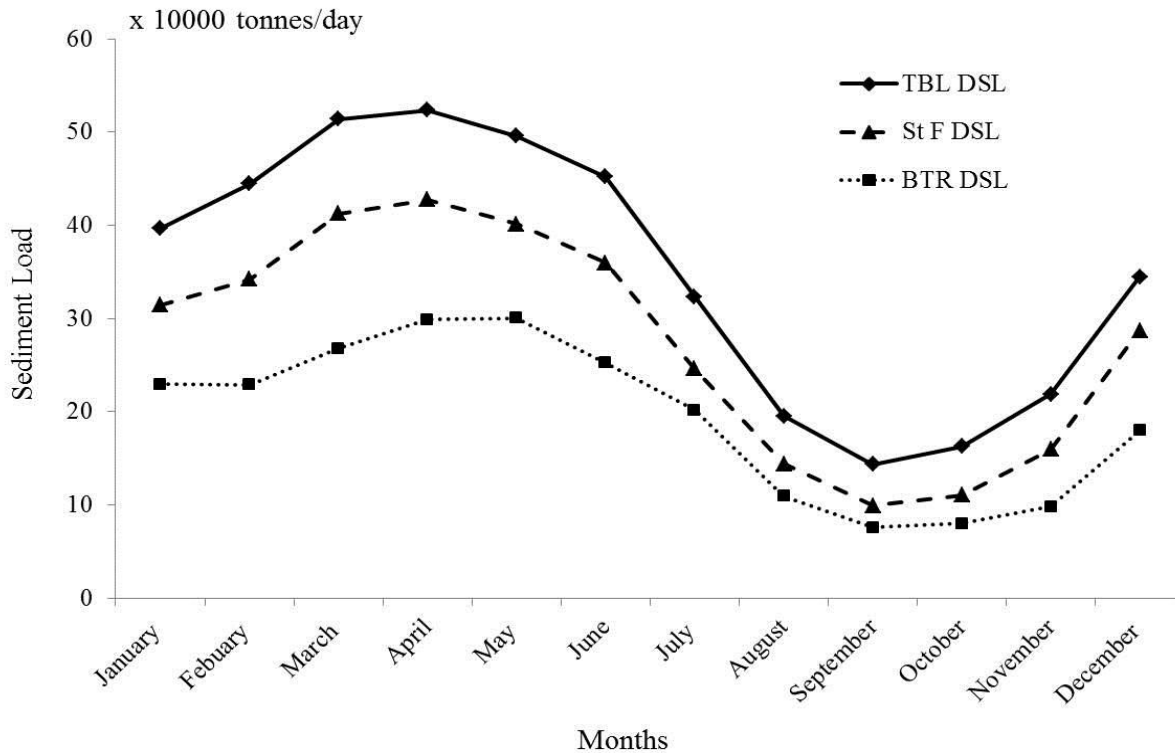


Figure 4.14: Monthly average daily sediment load at Tarbert Landing (during 1980-2010), St Francisville (during 1978-2015) and Baton Rouge (during 2004-2015) of the LmMR. Note: The seasonal trends of DSL at Tarbert Landing were taken from Rosen and Xu (2014).

4.3.3 Suspended Sand Loads

St Francisville had an annual sand load (SL_s) averaging 19.85 million tons (MT) during 1978-2015, varying from 4.9 (in 2006) to 43.13 (in 1979) MT (Figure 4.15). The total SL_s for the entire 38-year study period was 754.4 MT (Figure 4.15). Annual SL_s was lower than 10 MT for 3 of 38 years (1997, 2000, and 2006), 10 to 25 MT for 26 years (including the Mississippi flood year of 2011), 25 to 40 MT for 6 years and more than 40 MT for the remaining 3 years (1979, 1983, and 1993) (Figure 4.15). Average annual SL_s was higher for approximately the first-half of the study period (24.25 MT/year from 1978 to 1999), however, like annual SL, it decreased substantially towards the latter-half (13.10 MT from 2000 to 2015) (Figure 4.15). In fact, annual SL_s were less than 20 MT for all 16 years during the later-half as compared to 5 out of 22 years

for the first-half. Like annual SL, annual SL_s at St Francisville did not have any long-term increasing or decreasing trend (even for 3/4 years) (Figure 4.15).

At Baton Rouge, annual SL_s averaged 16.08 MT during 2004–2015, ranging from 2.93 MT in 2006 to 28.27 MT in 2009 with the total sand amount of 193 MT (Figure 4.15). Annual SL was lower than 10 MT for 4 out of 12 years (2006, 2007, 2012, and 2014), 10 to 25 MT for 6 years and higher than 25 MT for the remaining 2 years (Figure 4.15). The continuous increasing or decreasing trend (even for 3/4 years) were not found in annual SL_s s at Baton Rouge as well (like its annual sediment loads and St Francisville’s annual sediment and sand loads) (Figure 4.15).

The seasonal trends of average DSL_s s varied little during April and May. At St Francisville, average monthly DSL_s followed the same trend as average monthly DSL during 1978-2015: it increased from January to its maximum in April (i.e. 64329 to 102934 tonnes/day), then decreased from May to its minimum in September (97724 to 9687 tonnes/day) (Figure 4.16). During the remaining three months, average monthly DSL_s increased again i.e., 13450 tonnes/day in October to 58921 tonnes/day in December (Figure 4.16). At Baton Rouge, however, average DSL_s during 2004-2015 increased from January to May (i.e., 48953 tonnes/day in January to 105280 tonnes/day in May) (Figure 4.16). Further, average monthly DSL_s decreased steadily from June to its minimum in September (70101 to 4971 tonnes/day) (Figure 4.16). The final three months experienced an increase in average DSL_s at Baton Rouge like all other average monthly DSL s and DSL_s s (i.e., 8265 tonnes/day in October to 38235 tonnes/day in December) (Figure 4.16).

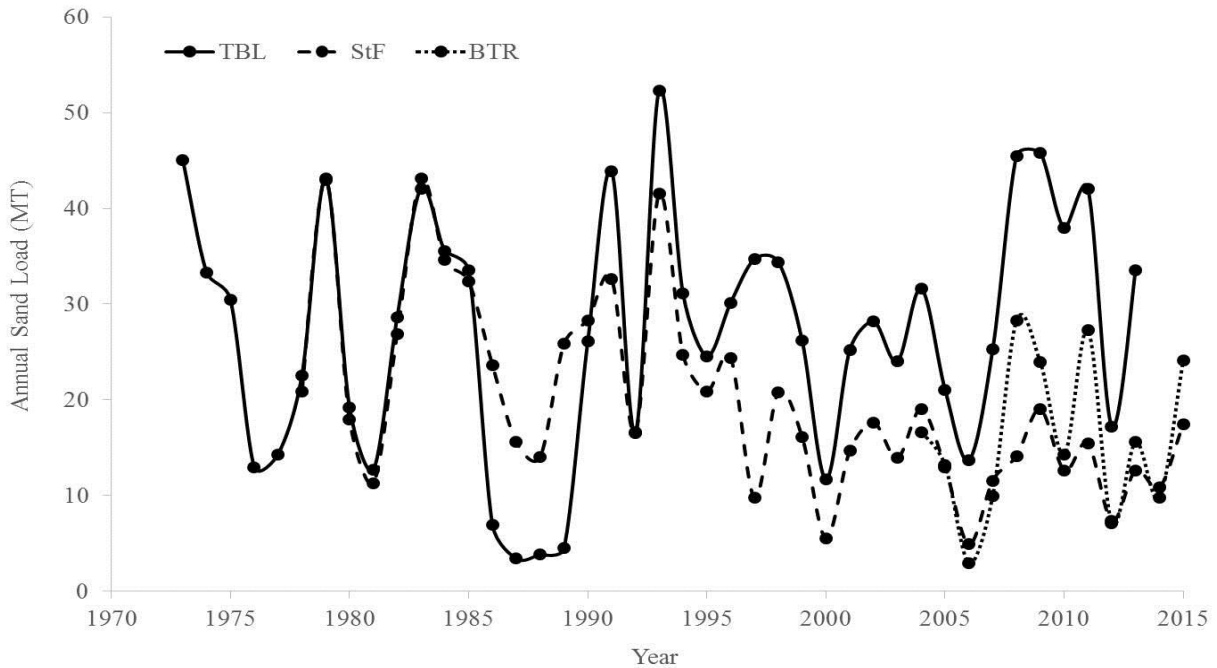


Figure 4.15: Annual Sand Loads (SLs) at Tarbert Landing, St Francisville and Baton Rouge of the Lowermost Mississippi River. Note: The annual SLss at TBL were taken from Joshi and Xu (2015).

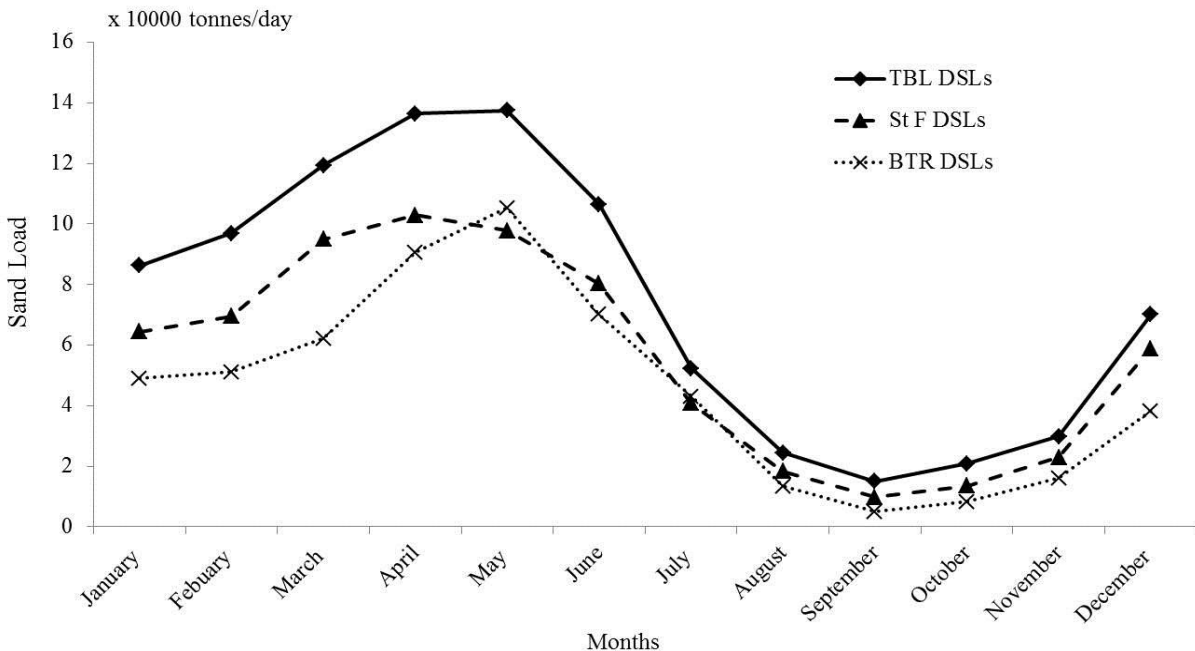


Figure 4.16: Monthly average daily sand load at Tarbert Landing (during 1973-2013), St Francisville (during 1978-2015) and Baton Rouge (during 2004-2015) of the LmMR. Note: The seasonal trends for DSLs at Tarbert Landing were taken from Joshi and Xu (2015).

4.4 DISCUSSION

4.4.1 Spatial and Temporal Variation in Bedload and Suspended Load along the LmMR

This study found gradual increase in estimated bedload transport rates (Q_s) from Tarbert Landing to Baton Rouge during 2004-2015. In addition, the 12 years showed significantly higher Q_s at Baton Rouge and lower and nearly equal Q_s at Tarbert Landing and St Francisville for all grain sizes. This study further found increase in Q_s with increase in riverbed elevation and decrease in cross-sectional area and grain-sizes at all locations. Therefore, it is suggested that lower cross-sectional area (based on lower river widths), higher bed elevation and finer bottom sediments could have contributed to higher Q_s at Baton Rouge as compared to Tarbert Landing and St Francisville. The estimated daily river widths at Baton Rouge were at least 400 m less than the widths at Tarbert Landing and St Francisville in all river stages. Similarly, riverbed elevations for each year at Baton Rouge were at least 8 and 6 m higher than the corresponding riverbed elevations at Tarbert Landing and St Francisville respectively. Demas and Curwick (1987) noted that particle size of coarser sediments proximate to the river-bottom decreased gradually from Tarbert Landing to the Bonnet Carre Spillway (about 163 km downstream of Baton Rouge). Similarly, higher Q_s in lower CSAs can imply that bed load movement can speed up in smaller cross-sectional profiles across rivers due to the clustered nature of bed materials. In larger cross-sectional profiles bed materials are probably more scattered, thus reducing the bedload movement. Daily Q_s increased almost linearly with daily river discharge and daily river stage at Tarbert Landing and St Francisville, but the trend was nearly unnoticeable at Baton Rouge. The bedload relationship with river discharge and stage at Tarbert Landing and St Francisville indicated that finer bed materials moved rapidly during higher river discharge and stage. However, bigger sized bed materials were probably difficult to transport especially during

the low river stages in low discharge regimes. Also, proximity of low flows to the riverbed probably lowers their force in the bed materials, while higher flows can exert substantially more force in the materials (Leopold and Wolman 1957, Leopold and Wolman 1970). However, the substantially higher bed elevation at Baton Rouge probably negated the linear effects of discharge on bedload transport at this location. Furthermore, the river bed elevation increased at Tarbert Landing but decreased at Baton Rouge from 2004 to 2015 (1.95 m in 2004 increased to 2.04 m in 2015 at Tarbert Landing; 10.1 m in 2004 decreased to 9.9 m in 2015 at Baton Rouge), which may have caused continuously increasing bedloads at Tarbert Landing and decreasing bedloads at Baton Rouge during 2004-2015. However, the effects of river bed elevation were not evident on temporal bedload trends at St Francisville.

Subtle temporal variability in suspended loads (during overlapping periods) was found between the lower two locations (St Francisville and Baton Rouge) along the LmMR reach. Total annual sediment loads (SL) and sand loads (SL_s) at both sites differed only by about 3 and 35 MT respectively during 2004-2015, with higher annual SL at St Francisville and higher annual SL_s at Baton Rouge (Tables 4.6 and 4.7). These differences fell considerably within the error range for suspended loads ($\pm 18\%$), thus could be statistically neglected. Allison et al. (2012) in a recent study also reported similar proximate suspended loads at both locations, but for a very short period (2008-2010) (270.8 MT SL and 53 MT SL_s at St Francisville; and 277.3 MT SL and 82.5 MT SL_s at Baton Rouge). Suspended loads at both locations, however, were considerably lower than the previous reported loads at Tarbert Landing for the corresponding coinciding periods. The total SL at St Francisville was lower than Tarbert Landing by about 843 MT during 1980-2010 [3929 MT at Tarbert Landing (reported by Rosen and Xu 2014) as compared to 3086 MT at St Francisville (in this study) (Table 6)]. Similarly, total SL_s at St

Francisville was lower than Tarbert Landing by about 253 MT during 1978-2013 [979 MT at Tarbert Landing (reported by Joshi and Xu 2015) as compared to 726 MT at St Francisville (in this study) (Table 7)]. In addition, the total *SL* at Baton Rouge was lower than Tarbert Landing by approximately 427 MT during 2004-2010 [891 MT at Tarbert Landing (reported by Rosen and Xu 2014) as compared to 464 MT at Baton Rouge (in this study) (Table 4.6)], while total *SL_s* at Baton Rouge was lower than Tarbert Landing by about 155 MT during 2004-2013 [314 MT at Tarbert Landing (reported by Joshi and Xu 2015) as compared to 159 MT at Baton Rouge (in this study) (Table 4.7)]. The seasonal trends in *DSL* and *DSL_s* in these locations were identical to the trends of total and annual suspended loads i.e., noticeably higher average *DSL* and *DSL_s* during each month at Tarbert Landing as compared to those of nearly similar monthly loads at St Francisville and Baton Rouge, respectively. Such notable reductions in suspended loads from upstream to downstream locations along a river stretch over one to four decades can imply that substantial sediment flow is likely to be restricted for long time periods by major artificial structures built at the upstream site.

Aforementioned trends in suspended loads at the three locations quantifiably support the findings made by Joshi and Xu (2017) that the first 20-25 km LmMR reach below ORCS, covering Tarbert Landing and Red River Landing has experienced sediment deposition during the last three and half decades. Also, nearly equal suspended loads at St Francisville and Baton Rouge (during overlapping periods) support another of their conclusion that the reach from Bayou Sara (which is near St Francisville) to Baton Rouge experienced sediment erosion over the last three decades. Three factors that may have contributed most to the higher suspended loads at Tarbert Landing include: (1) diversion of ~ 25% of LmMR flow to the Atchafalaya River at the Old River Control Structure (ORCS) (~ 10 to 15 km upstream of Tarbert Landing)

from 1963 (Copeland and Thomas 1992) which may have reduced water velocity near Tarbert Landing due to its proximity to the ORCS and aided in settling down suspended sediments; (2) three channel bars near Tarbert Landing which could retain riverine sediments especially during major floods, as found by Horowitz 2010, Wang and Xu 2015, and Wang and Xu 2016; and (3) coarser bottom sediments at Tarbert Landing than those of St Francisville and Baton Rouge, as documented by Demas and Curwick, 1987 and Horowitz 2010.

Table 4.6: Suspended sediment loads discharged Tarbert Landing (TBL), St Francisville (St F) and Baton Rouge (BTR) of the LmMR during overlapping periods between each site. Sediment loads for TBL were taken from Rosen and Xu (2014).

Sites	Matching Periods	Higher DSL (MT) (Site)	Lower DSL (MT) (Site)	Difference (MT)	Difference/Year (MT)
TBL-St F	1980 - 2010	3929.11 (TBL)	3086.45 (St F)	842.66	27.18
TBL-BTR	2004 - 2010	891.86 (TBL)	464.64 (BTR)	427.22	61.03
St F-BTR	2004 - 2015	809.30 (St F)	806.08 (BTR)	3.22	0.27

Table 4.7: Sand loads discharged at Tarbert Landing (TBL), St Francisville (St F) and Baton Rouge (BTR) of the LmMR during overlapping periods between each site. Sand loads for TBL were taken from Joshi and Xu (2015).

Sites	Matching Periods	Higher DSL_s (MT) (Site)	Lower DSL_s (MT) (Site)	Difference (MT)	Difference/Year (MT)
TBL-St F	1978-2013	978.71 (TBL)	726.08 (St F)	252.63	7.017
TBL-BTR	2004 - 2013	313.75 (TBL)	159.09 (BTR)	154.66	15.47
St F-BTR	2004 - 2015	192.96 (BTR)	157.89 (St F)	35.07	2.92

Substantial decline was found in average annual SL and SL_s at St Francisville after 1993 (the Mississippi River flood year). Annual SL and SL_s at St Francisville averaged approximately 124 and 27 MT/year respectively during 1978-1993, while they averaged about 78 and 15 MT/year during 1994-2015 experiencing a decline of 46 and 12 MT/year, respectively post-1993.

Previously, Horowitz (2010) noted nearly equivalent decline of 39 MT/year in annual SLs at St Francisville during 1994-2007 as compared to 1981-1993 and. Sharp declines in the suspended

loads at St Francisville post 1993 may have been caused by long overbank sedimentation followed by overbank floods along the upper and middle Mississippi River reach in 1993. The overbank sedimentation could have removed substantial stored bed/suspended sediments in the reach and eliminated several SSC sources for the LmMR reach (Horowitz 2006). There were no sediment records available to find the effects of 1993 flood on Baton Rouge suspended loads; however, there was no significant trend in annual SL and SL_s at this site during the last decade. Even the LmMR flood in 2011 did not seem to make a significant impact on the suspended loads at Baton Rouge, since there was negligible difference in average annual SL and SL_s during the two periods: 2004-2011 (pre-2011 flooding) (mean annual SL and $SL_s = 67.7$ and 17 MT respectively) and 2012-2015 (post-2011 flooding) (mean annual SL and $SL_s = 66.2$ and 14.1 MT respectively). These intra-location pre- and post- flooding suspended load trends at St Francisville and Baton Rouge indicate that floods probably have substantial impacts on suspended loads for longer periods, while negligible impacts for shorter periods.

4.4.2 Relationship between Bedload and Suspended Load in the LmMR

Monthly averages of daily bedload rates (Q_s) along the LmMR showed linearly increasing trends with monthly averages of daily suspended sediment loads (DSL) and daily suspended sand loads (DSL_s) at Tarbert Landing (during the corresponding matching periods: 2004-2010 for $Q_s - DSL$ trends and 2004-2013 for $Q_s - DSL_s$) and St Francisville (during 2004-2015), respectively (Figures 4.17 and 4.18). However, monthly Q_s showed more scattered trends with monthly DSL and DSL_s respectively at Baton Rouge (during 2004-2015) (Figures 4.17 and 4.18). These relationships were noted down for representative grain size of 0.125 mm and were exactly same for other grain sizes of 0.25 and 0.5 mm. The trends of Q_s with DSL , DSL_s , river discharge and river stage (see section 4.3.1 for the latter two) possibly imply that bedload is more dependent on

suspended load (specially suspended sand load), river discharge and river stage in upstream river locations with shallower beds, while the dependence gradually decreases as the river moves downstream and the bed elevation increases continuously.

Total and annual bedload rates (Q_s) for grain sizes 0.125, 0.25 and 0.5 mm at Tarbert Landing were about 4, 2 and 1% of the suspended sediment load and 18, 9 and 4.5% of the suspended sand load respectively during 2004-2010 (matching period for both loads at Tarbert Landing) (Figure 4.19). Furthermore, total and annual Q_s at St Francisville for the aforementioned grain sizes were respectively about 10, 5 and 2.5% of its suspended sediment load and 53, 26.5 and 13% of its suspended sand load during 2004-2015 (matching period for both loads at St Francisville) (Figures 4.19). Finally, the total and average annual Q_s at Baton Rouge for these grain sizes were approximately 12, 6 and 3% of its suspended sediment load and 50, 25 and 12.5% of its suspended sand load respectively during 2004-2015 (Figures 4.19). Most of these values were within the ranges of percentage of bedload in suspended sediment (1 to 10%) and suspended sand load (10 to 33%) noted by previous studies (Gomez 1991, Kesel et al. 1992, Church 2006; see section 4.1). However, the only noticeable outliers in this regard were substantially higher percentage of Q_s in suspended sand load of St Francisville and Baton Rouge for grain size of 0.125 mm. These higher ranges were likely because of higher bed elevation at these two locations, gradually decreasing grain sizes from upstream to downstream in the LmMR (as explained in first paragraph of section 4.4.1) and substantially lower suspended sand loads in both locations as compared to the upstream location at Tarbert Landing (see section 4.4.1).

The findings for bedload transport in this study are opposite to the trends found for total suspended load along the LmMR. Apart from the probable reasons listed for corresponding trends in both, the contrasting differences could also be possible because suspended loads were

estimated from sediment/sand-water discharge rating curves, while bedload transport rates were quantified using the concept of boundary and critical shear stresses and pre-studied sediment transport equations. Nittrouer et al. (2011b) found opposite spatial trends in Q_s than the findings of this study along the LmMR reach (i.e., gradual increase from Baton Rouge to Tarbert Landing) but only in specific river discharges limited to 11750 and 17500 cms. They estimated negligible differences in Q_s during high flows throughout the reach (from Tarbert Landing to Baton Rouge). The differences in the Q_s estimates of the two studies could be because they considered back water flows in the LmMR which were ignored in this study.

The total sediment supply (bedload + suspended sediment load) for all grain sizes during the overlapping period of 2004-2010 at all locations was highest at Tarbert Landing (~ 931, 911 and 893 MT for grain sizes of 0.125, 0.25, 0.5 respectively), and decreased gradually at two downstream locations along the LmMR (~ 550, 525 and 500 MT at St Francisville and 544, 504 and 485 MT at Baton Rouge for the three aforementioned grain sizes respectively) (Figure 4.19). Furthermore, for the two locations downstream of Tarbert Landing, the total sediment loads were a little higher at Baton Rouge than St Francisville for the grain sizes of 0.125 and 0.25 mm respectively (904 MT for a grain size of 0.125 mm and 855 MT for 0.25 mm at Baton Rouge as compared to 893 for 0.125 mm and 850 MT for 0.25 mm at St Francisville) during 2004-2015 (the matching period for both locations) (Figure 4.19). For the remaining grain size of 0.5 mm the total suspended loads were almost equal at both locations during the 12-year period (~ 830 MT) (Figure 4.19).

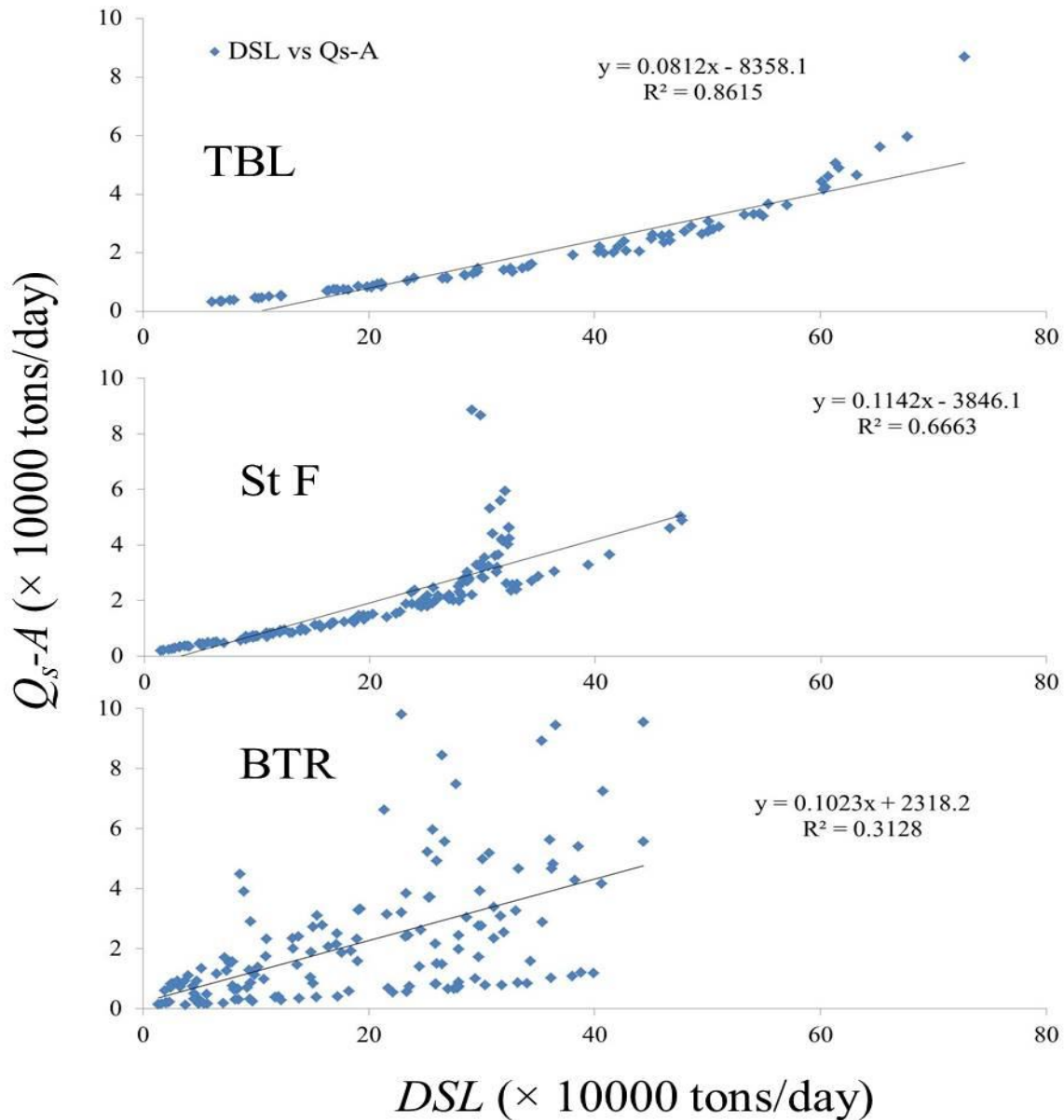


Figure 4.17: Relationship of monthly average of daily suspended sediment load (DSL in tons/day) with the monthly average of daily bedload transport rates (Q_s in tons/day) for representative grain-size of 0.125mm (A) at Tarbert Landing (TBL), St Francisville (St F), and Baton Rouge (BTR) of the Lowermost Mississippi River during. The relationship for monthly DSL and monthly Q_s was during 2004-2010 at TBL (taken from Rosen and Xu 2014) and during 2004-2015 at St F and BTR.

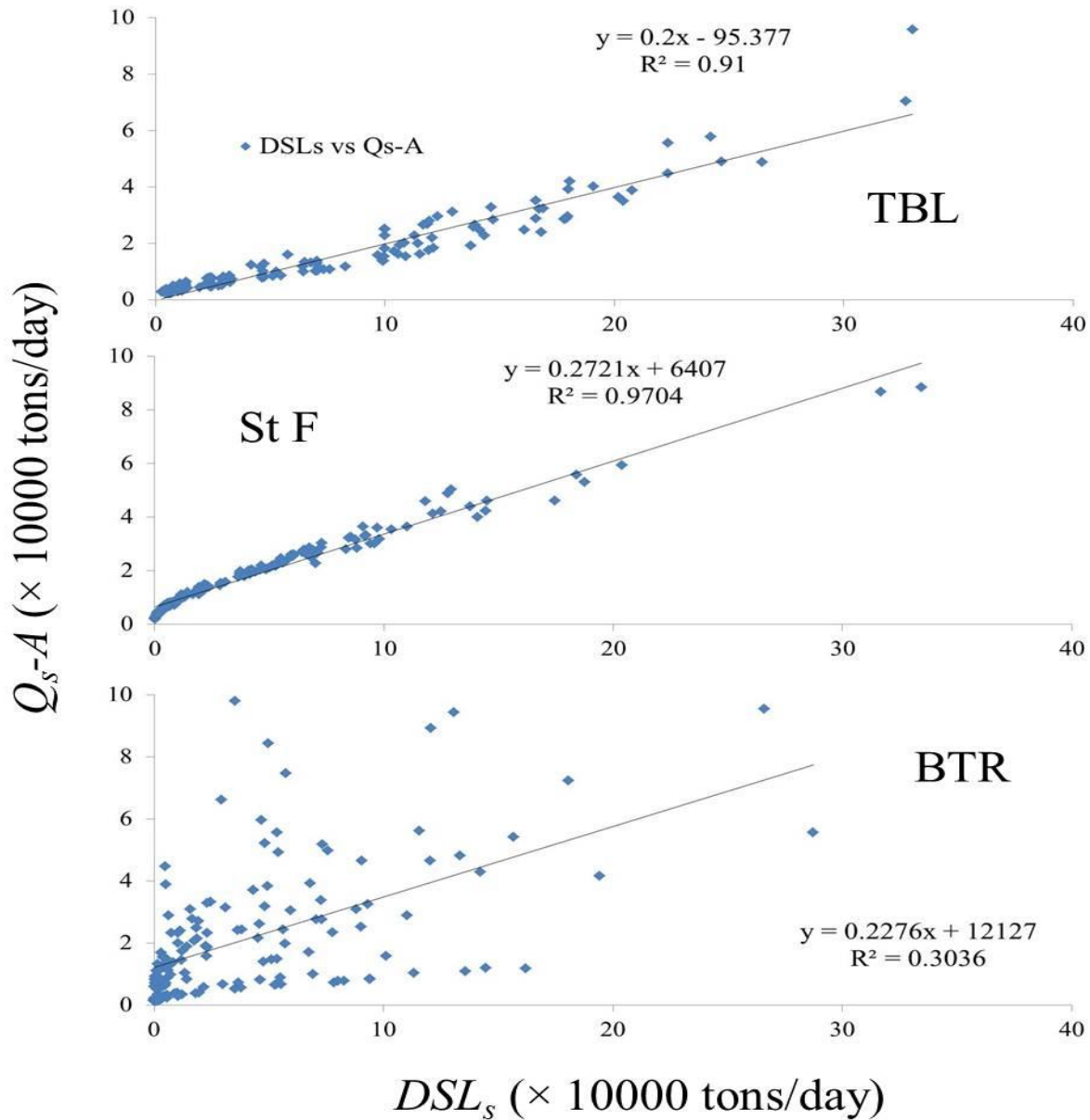


Figure 4.18: Relationship of monthly average of daily suspended sand load (DSLs in tons/day) with the monthly average of daily bedload transport rates (Qs in tons/day) for representative grain-size of 0.125mm (A) at Tarbert Landing (TBL), St Francisville (St F), and Baton Rouge (BTR) of the Lowermost Mississippi River during 2004-2015. The relationship for monthly DSLs and monthly Qs was during 2004-2013 at TBL (taken from Joshi and Xu 2015) and during 2004-2015 at St F and BTR.

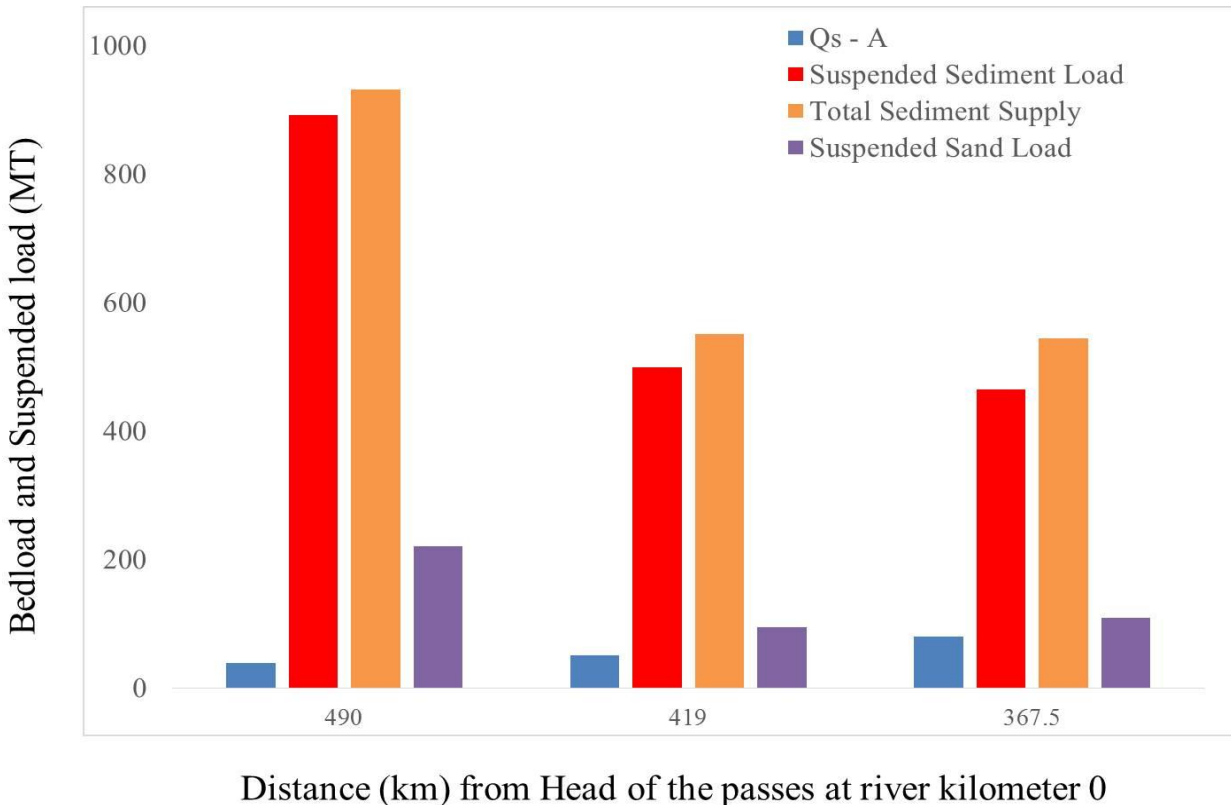


Figure 4.19: Difference between total bedload transport rates (Q_s) for representative grain size of 0.125 mm (A), suspended sediment and sand loads, and total supply at Tarbert Landing [TBL, at river kilometer (rk) 490], St Francisville (St F, rk 419), and Baton Rouge (BTR, rk 367.5) along the Lowermost Mississippi River during 2004-2010 (the matching period for these components at all three locations). X-axis distances are distance of the sites from the Head of the Passes (rk 0) near the LmMR's Gulf of Mexico outlet. Note: the suspended sand load is a coarser subset of suspended sediment load, hence, the total sediment supply at a given location along the river was calculated as the sum of total bedload and total suspended sediment load at the location.

4.4.3 Sediment Trapping in the LmMR

From this analysis, it seems likely that the first 20-25 km reach of the LmMR just below its diversion to the Atchafalaya River (covering Tarbert Landing) has been a major sediment trapping location over the last four decades. Lower bedload transport along this reach during the last decade suggests that bedloads possibly acted as sources of sand loads near the riverbed because both loads can be intermixed especially in laterally migrating sand dunes during low and medium flows (Nittrouer et al. 2011a, Nittrouer et al. 2011b, Ramirez and Allison 2013).

However, the sand particles possibly get trapped in the sediment channel bars present along this reach. Wang and Xu (2016) noted high three-decadal sediment accumulation in the three sediment bars present at 18, 24 and 26 km downstream of the Old River Control Structure respectively (total sediment load of 36 million tons during 1985-2013). This may be the primary reason of lower proportion of sand outflow between Tarbert Landing and St Francisville as compared to sediment outflow over the last three and half decades (mean annual SL at Tarbert Landing was 27% higher than St Francisville during 1980-2010, while mean annual SL_s was about 20% higher during the same period). The total sediment supply at Tarbert Landing was higher than St Francisville and Baton Rouge during 2004-2010 despite its lower Q_s during the same period (Figure 4.19; section 4.2). This observation can probably imply that the sediment trapping capacity gradually reduces downstream along the LmMR reach particularly below its uppermost 20-25 km stretch.

The importance of suspended loads for restoration of the MRDP has been previously well documented [Coleman et al. (1998), Roberts (2003), Nepf (2004) (sand loads); Biedenharn and Thorne (1994), Mossa (1996) (sediment loads)]. Continuous movement of suspended load is critical in long-term delta building and restoration processes (Roberts et al. 2003, Paola et al. 2011). Therefore, sediment management in the LmMR should focus on finding engineering solutions to move Tarbert Landing suspended loads to the downstream locations (especially to St Francisville) which can further help in planning and executing sediment diversion projects along the river subsequently. In addition, the bed and suspended load estimates in this study also indicate that significant spatiotemporal variability can occur in sediment supplies from upstream to downstream reaches of highly engineered alluvial rivers on a global scale. Information on

long-term sediment supplies along several different sediment-starved rivers can benefit the river management practices.

4.4.4 Uncertainty and Constraints in Bedload Estimation

The estimation of bedloads (Q_s) in this study is one of the few attempts in quantifying daily Q_s at multiple sites along a large regulated alluvial river for more than a decade. Most previous studies quantifying Q_s along the LmMR have applied measurements of bedform heights using multibeam echosounder surveys in their two or three dimensional models (Nittrouer et al. 2008, Abraham et al. 2010, Abraham et al. 2011, Knox and Labtrubesse 2016). Since, there were no such measurements; this study only used Engelund-Hansen equation primarily developed for and tested in laboratory conditions. Furthermore, this study did not have site-specific bedload measurements like suspended sediment concentrations to validate the estimates of bedload transport rates along the LmMR. This is a main uncertainty in the bedload estimates of this study.

There was a need to estimate annual riverbed elevation and other daily variables such as flow velocity, river width and cross-sectional area at the three sites for quantifying daily Q_s from equation (4.1). The calculations for all these parameters were subjected to potential errors. Riverbed elevations (Re_{bed}) were only available for 2004 and 2013 at all locations; therefore, Re_{bed} had to be interpolated for the period of 2005-2012 and of 2014-2015. In interpolation, the difference in Re_{bed} for 2004–2013 was only considered as overall increase or decrease, but any specific increase or decrease in Re_{bed} within the years between 2004 and 2013 was ignored. The uncertainty for average flow velocity was dependent on the errors for cross-sectional area. The calculation of daily cross-sectional area was subjected to the potential errors in estimating river width through earth explorer and arc map tools. Also, the daily cross-sectional areas at all

locations were probably overestimated because the river channel was considered as rectangle and the cross-sectional areas were measured as a product of river depth and river width. This study could not find a method to measure the cross-sectional area such that it exactly coincided with the half oval shaped riverbed cross-section.

Despite the above mentioned uncertainties, this study provides plausible estimates of bedload rates that are within previously reported Q_s ranges, i.e., 1 to 10% of suspended sediment load, or 10 to 33% of suspended sand load. A $\pm 24\%$ margin of error is given for all Q_s estimates (see section 4.2.7) to properly document estimation performance.

4.5 CONCLUSIONS

This study analyzed multi-decadal sediment transport along the first 140 kilometers of the Lowermost Mississippi River downstream from its diversion to the Atchafalaya River. The findings show that in the past decade, bedload transport rates at Tarbert Landing upstream increased slightly, while the rates at Baton Rouge downstream declined largely. Over the past two decades, suspended sediment and sand loads were consistently higher at Tarbert Landing than at St Francisville and Baton Rouge. These results indicate an accumulation of coarser sediments in the uppermost river reach (20-25 km below the Old River Control Structure, covering Tarbert Landing). Bedloads seemed to increase with the increasing suspended loads, river discharge and river stage at upstream locations (at Tarbert Landing and St Francisville); however, such a relationship was not noticeable downstream at Baton Rouge. A clear decrease in annual suspended loads was identified at St Francisville after the 1993 major flood, showing that floods can play important role in longer-term sediment transport. The study implies that substantial spatiotemporal variability can exist in sediment transport of a large alluvial river, and that sediment management in the LmMR should focus on outflowing suspended loads trapped at

Tarbert Landing systematically to other downstream locations (St Francisville and Baton Rouge), for advantages to land building along the river reach.

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CHAPTER 5: SUMMARY AND CONCLUSIONS

This dissertation research assessed the multi-decadal sediment transport and channel morphology dynamics along a 327-km reach of the Lowermost Mississippi River (LmMR) downstream from its diversion at the Atchafalaya River [from river kilometer (*rk*) 492 to *rk* 165]. The assessment was carried out in three complementary studies. The primary goals of these studies were to: 1) analyze riverbed adjustment, i.e., channel bed aggradation or channel erosion at seven locations along the 327-km LmMR reach over the last three to four decades; 2) determine suspended sand availability under various discharge regimes at Tarbert Landing (the uppermost LmMR location) during 1973-2013; and 3) quantify bedloads at Tarbert Landing, St Francisville and Baton Rouge (the three uppermost LmMR locations) and suspended loads at St Francisville and Baton Rouge (locations downstream of Tarbert Landing) over the last one to four decades. Collectively, this dissertation research was to understand sediment transport and deposition mechanics, channel transformation pattern and sediment supply in this large, highly engineered alluvial river.

The riverbed adjustment at seven locations along the LmMR was carried out using hydrographic survey measurements conducted by USACE in 1992, 2004 and 2013 as well as daily river stage and discharge stage records over the past three to four decades. In addition, sediment and sand rating curves were developed to quantify the suspended sand load at Tarbert Landing and the suspended sediment and sand loads at St Francisville and Baton Rouge. Bedload transport rates at Tarbert Landing, St Francisville and Baton Rouge were also quantified using the concept of pre-studied sediment transport equations. The main findings of this study and their possible implications are as follows.

Over the past three to four decades, the riverbed of the LmMR has changed significantly only along its first 140 km. The riverbed has possibly aggraded along the first 20-25 km LmMR reach below ORCS (reach 1) and the reach further downstream from ~80 to 140 km (reach 3). It has possibly degraded along the ~ 55-60 km reach between reaches 1 and 3 (from ~ 20-25 km to 80 km below ORCS) (reach 2). The remaining ~ 187 km of the LmMR reach (from ~ 140 to 327 km) is possibly approaching dynamic equilibrium with negligible sediment deposition. Therefore, substantial sediment load appears to be trapped along the first ~ 140 km LmMR reach, while sediment outflow seems higher along the next ~187 km reach.

With respect to the second goal, the research found that the LmMR discharged an average annual sand load (SL_s) of 27.2 million tons (MT) during 1973 and 2013, varying largely from 3.37 to 52.30 MT at Tarbert Landing (the uppermost LmMR location). The total sand load was approximately 1115 MT for the entire 41-year study period, half of which occurred during the peak 20% flow events. During the four decades, approximately 71% of total annual SL_s were produced within approximately 120 days each year, when the discharge was ≥ 18000 cubic meters per second (cms). Based on the long-term sediment assessment, this study predicts that the LmMR has a high likelihood to transport 4 to 446 thousand tons of sand every day over the next 40 years, during which annual SL_s could reach a maximum of about 52 MT.

Regarding the third objective, the study found gradually increasing bedload transport rates from Tarbert Landing [83 million tons (MT) during 2004-2015 for grain size of 0.125 mm] to Baton Rouge (96 MT during 2004-2014 for the same grain size). Further, bedload transport rates increased almost linearly with suspended loads, river discharge, and river stage at upstream locations (Tarbert Landing and St Francisville); however, the linear trend was not evident downstream of St Francisville (at Baton Rouge). The research also found significantly higher

suspended loads at Tarbert Landing [taking reference of suspended sediment load from Rosen and Xu (2014)] than those at St Francisville and Baton Rouge during corresponding overlapping periods. Bedload transport rates decreased with cross-sectional area and sediment grain size at all three locations. Total sediment load (bedload + suspended sediment load) was also substantially higher at Tarbert Landing (931 MT) and lower and nearly equal at the other two downstream locations (550 MT at St Francisville and 544 MT at Baton Rouge) during 2004-2010 (the matching period of availability of both bedload and suspended load).

Overall, the findings of this dissertation research provide crucial insights into the quantity of suspended and sand loads of the LmMR. The information can be relevant in land building schemes that rely on river-sediment diversions and various sediment management practices along the LmMR. Looking at the bigger picture, the findings indicate that a few locations along the first 140-km of the LmMR river below its diversion to the Atchafalaya River (especially reaches 1 and 3) have acted as the entrapment channels for considerably high sediment supply. In contrast, the next 187-km LmMR reach (reach 4) has had considerably lower sediment supply over the past few decades despite its higher sediment outflow capacity. Therefore, systematic outsourcing of sediments from reaches 1, 2 and 3 to reach 4 can benefit sediment management along the LmMR. Also, a hydrograph-based approach for retaining maximum sediment load should be considered.

Although this dissertation research investigated long-term sediment transport and riverbed adjustment along the LmMR, its findings can also benefit other lowland river systems proximate to the coast. For instance: (1) the morphological changes along the LmMR reach indicate that significant spatiotemporal variability can occur in riverbed adjustment processes of other greatly engineered lowland alluvial rivers around the world; (2) information on the adjustment processes

along different sediment-starved reaches of the LmMR found in this study can be used to select sediment trapping sites and to develop land building schemes that use river-sediment diversions; (3) higher sediment entrapment along the uppermost LmMR for three to four decades indicate that dams, reservoirs and other artificial structures constructed upstream river locations restrict substantial sediment transport downstream; and (4) riverbed elevation, backwater effects and size of bottom sediments substantially control bedload transport in alluvial rivers.

APPENDIX A1: SUPPLEMENTAL TABLE FOR CHAPTER 3, SECTION 3.2

Annual discharge-sand load rating curves developed for Tarbert Landing of the LmMR specifically during the period 1986-1995.

Year	No of Samples (n)	Discharge – Sand Load Rating Curve	Model	R ²
1986	27	$y = 0.9057x + 0.684$	Linear	0.14
		$y = -0.8658x^2 + 17.012x - 74.858$	Polynomial	0.15
1987	23	$y = 1.0772x - 1.3125$	Linear	0.27
		$y = 0.2148x^2 - 2.9014x + 17.059$	Polynomial	0.27
1988	21	$y = 1.4869x - 4.955$	Linear	0.51
		$y = 0.0868x^2 - 0.0875x + 0.5817$	Polynomial	0.51
1989	23	$y = 1.5635x - 6.1185$	Linear	0.40
		$y = -0.1272x^2 + 3.9797x - 17.559$	Polynomial	0.40
1990	24	$y = 0.6572x + 4.4327$	Linear	0.14
		$y = 1.0228x^2 - 19.059x + 99.171$	Polynomial	0.16
1991	24	$y = 2.9061x - 17.418$	Linear	0.87
		$y = 1.6022x^2 + 33.368x - 161.5$	Polynomial	0.92
1992	25	$y = 2.6355x - 14.51$	Linear	0.72
		$y = 1.7706x^2 - 30.732x + 142.46$	Polynomial	0.77
1993	31	$y = 1.9324x - 7.3808$	Linear	0.69
		$y = 0.037x^2 + 1.2055x - 3.813$	Polynomial	0.69
1994	23	$y = 3.0803x - 19.08$	Linear	0.84
		$y = -1.6631x^2 + 35.256x - 174.26$	Polynomial	0.87
1995	21	$y = 2.8179x - 17.115$	Linear	0.82
		$y = -1.6093x^2 + 33.441x - 162.32$	Polynomial	0.87

APPENDIX A2: PERMISSION TO REPRINT CHAPTER 2



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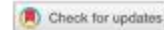
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Recent changes in channel morphology of a highly engineered alluvial river – the Lower Mississippi River

Sanjeev Joshi and Xu Y. Jun

School of Renewable Natural Resources, Louisiana State University Agricultural Center, Baton Rouge, LA, USA

ABSTRACT

Changes in channel morphology provide relevant insights into sediment transport and deposition in alluvial river systems. This study assessed three to four decades of morphological changes at seven locations along a 327-km reach of the Lower Mississippi River (LMR) to better understand channel adjustment processes of this large alluvial river. The assessment included analysis of three cross-sectional areas at each location during the period 1992–2013, as well as analysis of the changes in river stage and maximum surface slopes under four flow conditions over the last three to four decades. We found that the first 20–25 km LMR reach below its diversion to the Atchafalaya River and the reach from 80 to 140 km experienced significant riverbed aggradation, while the reach in between (i.e. from 20 to 80 km) experienced riverbed degradation. The lower 187-km reach (i.e. from 140 to 327 km) showed negligible sediment trapping. These findings may have relevant implications for management of river sediment diversions along the LMR and other large alluvial rivers in the world.

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River channel; specific river stage analysis; flow conditions; river surface slope change; Lower Mississippi River

Introduction

Alluvial rivers are well defined by constant interaction of flow, sediment transport, and channel morphology dynamics. Bathymetry of alluvial rivers can affect hydrodynamics, hence sediment transport and deposition, which, in turn, can change geomorphological properties of the river (Bridge, 1993; Merwade, 2009). Similarly, river stage, river surface slope, and discharge are three other important factors affecting riverbed dynamics over time. Therefore, changes in river stage and river surface slope over time within the same discharge regime can indicate riverbed adjustment, i.e. channel bed aggradation or channel erosion (Leopold & Wolman, 1957, 1970; Van Rijn, 1993). Previous studies have explored river bathymetry (Biedenharn, Thorne, & Watson, 2000; Harman & Clifford, 2006; Harman, Clifford, Thorne, & Biedenharn, 2005) and river stage and slope in specific discharge regimes separately (Biedenharn & Watson, 1997; Pinter, Ickes, Wlosinski, & Van der Ploeg, 2006; Wasklewicz, Grubaugh, Franklin, & Gruelich, 2004); however, there is still ambiguity over how these components interact to affect long term sediment transport and deposition in river systems. Such information can be especially useful for management of regulated rivers

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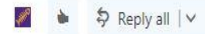
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Dear MDPI and Water team,

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Article

Assessment of Suspended Sand Availability under Different Flow Conditions of the Lowermost Mississippi River at Tarbert Landing during 1973–2013

Sanjeev Joshi and Y. Jun Xu *

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School of Renewable Natural Resources, Louisiana State University Agricultural Center, 227 Highland Road, Baton Rouge, LA 70803, USA; sjoshi2@tigers.lsu.edu

* Correspondence: yjxu@lsu.edu; Tel.: +1-225-578-4169; Fax: +1-225-578-4227

Abstract: Rapid land loss in the Mississippi River Delta Plain has led to intensive efforts by state and federal agencies for finding solutions in coastal land restoration in the past decade. One of the proposed solutions includes diversion of the Mississippi River water into drowning wetland areas. Although a few recent studies have investigated flow-sediment relationships in the Lowermost Mississippi River (LmMR, defined as the 500 km reach from the Old River Control Structure to the river's Gulf outlet), it is unclear how individual sediment fractions behave under varying flow conditions of the river. The information can be especially pertinent because the quantity of coarse sands plays a critical role for the Mississippi-Atchafalaya River deltaic development. In this study, we utilized long-term (1973–2013) records on discharge and sediments at Tarbert Landing of the LmMR to assess sand behavior and availability under different river flow regimes, and extreme sand transport events and their recurrence. We found an average annual sand load (SL) of 27.2 megatonnes (MT) during 1973 and 2013, varying largely from 3.37 to 52.30 MT. For the entire 41-year study period, a total of approximately 1115 MT sand were discharged at Tarbert Landing, half of which occurred during the peak 20% flow events. A combination of intermediate, high and peak flow stages (*i.e.*, river discharge was $\geq 18,000$ cubic meter per second) produced about 71% of the total annual SL within approximately 120 days of a year. Based on the long-term sediment assessment, we predict that the LmMR has a high likelihood to transport 4 to 446 thousand tonnes of sand every day over the next 40 years, during which annual sand loads could reach a maximum of 51.68 MT. Currently, no effective plan is in place to utilize this considerably high sand quantity and we suggest that river engineering and sediment management in the LmMR consider practices of hydrograph-based approach for maximally capturing riverine sediments.

VITA

Sanjeev Joshi was born in 1985 in Kanchanpur, Nepal, a small developing country in southern Asia. He first accomplished his intermediate in science Radiant Higher Secondary School, Kanchanpur, Nepal in 2002. Then, he earned his Bachelor of Science degree in Forestry from the Institute of Forestry, Pokhara, Nepal in 2007. He earned his M.Sc. degree in forestry from the School of Renewable Natural Resources (RNR), Louisiana State University (LSU) in December 2012. Later, in August 2014, Sanjeev joined the watershed hydrology lab of School of RNR, LSU after working as a Graduate Research and Teaching Assistant in the Department of Geography, University of South Carolina for one and half year. In August 2017, he will receive a PhD in Watershed Science from the School of RNR.