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Assessing Morphodynamics of the Lower Mississippi River from 1985 to 2015 with Remote Sensing and GIS Techniques

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ASSESSING MORPHODYNAMICS OF THE LOWER MISSISSIPPI RIVER FROM 1985 TO
2015 WITH REMOTE SENSING AND GIS TECHNIQUES

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 Department of Geography & Anthropology

by

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ABSTRACT

The Lower Mississippi River is one of the most highly engineered rivers in the world. The river is now completely regulated by a combination of levees, artificial cutoffs, bank revetments, and dike fields; however, the river engineering has also complicated the geomorphological response to the sediment brought in the river. This dissertation research examined morphodynamics of the middle portion of the Lower Mississippi River from Vicksburg, Mississippi (river kilometer: 737) to Red River Landing, Louisiana (river kilometer: 486) to elucidate river engineering effects on sediment transport, storage, and distribution. The Old River Control Structure (ORCS) diverts approximately 25% of the Mississippi River into the Atchafalaya River. Hence, the research also assessed the river diversion on downstream channel morphology and sediment deposition. Results showed that the highly regulated river favored the development of mid-channel and attached bars. The average volume of a single mid-channel bar is over twice that of an attached bar and over four times that of a point bar. Overall, in the past three decades, the total volume of the 30 bars between Vicksburg and ORCS has increased by 110,118,000 m³ or 41%. Increased dike length contributed significantly to the bar volume increase. Downstream of the ORCS, three bars had a net volume gain of 30,271,000 m³ (206%). Sediment trapping on the bars was prevalent during the period 1990-1995 and 2007-2011 when large floods occurred. In particular, a single flood in the spring of 2011 increased the volume of these three bars by 1.22×10^6 m³ (4.4%). In the past 30 years, the 33 emerged channel bars along the 258-km reach trapped 168 MT sediment and currently, the total mass of their emerged portions accounts to 584 MT. These findings show that river engineering in the Lower Mississippi River has greatly affected sediment transport and deposition patterns. As a potentially useful resource for coastal protection and restoration of the sediment-starving

Mississippi River Delta, future river management should develop engineering strategies to mobilize the tremendous sediment store downstream of the river.

CHAPTER 1. INTRODUCTION

A large river delta is typically formed where an alluvial river enters the ocean and supplies sediment more rapidly than the redistribution rate by waves and tides. Sediment by water discharge of the rivers, accommodation space of the basins and coastal wave energy are the main contributors for deltas' morphodynamics (Galloway, 1975). Deltas and their estuaries are critical for ecology, global and local economies, and are major centers of population and agriculture (Ericson et al., 2006). However, human impacts, including accelerated sediment compaction on the deltas because of oil, gas, and ground water extraction, substantial sediment trapping in the upstream rivers owing to man-made structures, and extensive floodplain engineering, have caused significant degradation of the deltas (Day et al., 2007; Syvitski et al., 2009; Syvitski et al., 2005).

The Mississippi River Delta was formed by six major delta complexes prograding into coastal Louisiana over the past 7,000-8,000 years (Fisk, 1944). Shifting courses of the Mississippi River deposited sediment over an area of approximately 30,000 km² (Britsch and Dunbar, 1993a). However, overbank flooding and sedimentation have been eliminated because of the extensive construction of levee systems along the Mississippi River after the Great Mississippi River Flood of 1927. Concurrently, the Mississippi River Delta has lost about 4,900 km² land since 1932 (Couvillion et al., 2011). Except for the isolation of the river from the Mississippi River Delta, dam construction in the Upper Mississippi River Basin before the 1950s has largely reduced sediment transported to the Lower Mississippi River. For example, ~50% of riverine sediment was found trapped by dams in the upper reaches of the river. This has contributed to the delta loss over the past century (Blum and Roberts, 2012). Blum and Roberts

(2009) predicted that without enough sediment input, an additional 10,000-135,000 km² of Mississippi River Delta would be submerged by the year 2100.

The Mississippi River Delta is not only home to more than two million people but also has a great importance in national energy production, petrochemical industry, shipping, fisheries, and coastal wetlands. In the recent decade, federal and state agencies have intensified their efforts to protect and restore Louisiana's coast. In 2017, the Coastal Protection and Restoration Authority of Louisiana (CPRA) published the latest Louisiana Coastal Master Plan that guides various projects helping maintain and build the Louisiana's coastal land. Many of these projects utilize sediment from the Mississippi River to restore and create coastal marshes (CPRA, 2017). In particular, these projects are proposed to utilize large sediment diversions and dredged materials (i.e. Long Distance Sediment Pipeline, LDSP) to deliver the riverine sediment into the previous floodplain. The success of these projects will largely rely on available sediment in the river. Therefore, investigating riverine sediment transport, deposition, storage, and distribution is crucial for developing effective strategies and plans for saving Louisiana's coast.

Riverine sediment can deposit to form different types of bars within river channels. Occurrence and development of the bars are major components of the morphodynamics of alluvial rivers. In general, the growth of point bars within the concave sides of channels usually results in river meandering. Before intensive human modifications in the Lower Mississippi River (i.e. before 1930), point bars were the most common bar type in the river. A previous study estimated that point bars stored more than 95% of the riverine sediment in the channel, while the channel bed only stored ~5% of sediment (Kesel et al., 1992). After 1930, construction of levee systems along the Lower Mississippi River changed the river from a freely meandering alluvial river to a highly confined channel. In addition, a series of engineering modifications, including

artificial bend cutoffs, bank stabilization by revetments, and constructions of dike fields, profoundly influenced morphodynamics of the Lower Mississippi River (Harmar and Clifford, 2007; Harmar et al., 2005; Kesel, 2003; Nunnally and Beverly, 1986; Rijksdienst voor de IJsselmeerpolders and Wilkerson, 1974; Smith and Winkley, 1996). For example, Harmar et al. (2005) found that the Lower Mississippi River adjusted the number, size, location, and shape of crossings and pools after a post-cutoff period (i.e. 1949-1964) as responses to the additional energy created by the cutoffs. Kesel (2003) found that the volume of channel bars increased significantly between Cairo, Illinois and Red River Landing, Louisiana during the period of 1948-1963. The study from Smith and Winkley (1996) indicated that the highly regulated Lower Mississippi River tended to form mid-channel bars because of the confined riverine sediment.

River diversions remove water from rivers and can impose primary changes on flow and sediment transport (Church, 1995). Upstream 505 km from the Mississippi River mouth, a portion (approximately 25%) of the river's water is diverted into the Atchafalaya River by a control structure - Old River Control Structure (ORCS) built in 1963. The diversion structure maintained by the United States Army Corps of Engineers was built to prevent possible course changing from the Mississippi River to the Atchafalaya River. During the 1973 large Mississippi flood, the ORCS almost failed because severe scour developed underneath the structure. In 1988, an auxiliary structure was built to alleviate the pressure on the main control structure during large floods. In 1990, the Sidney Murray Hydroelectric Plant was completed to benefit from the resource as well as to decrease the pressure of other ORCS structures (Mossa, 2016). The analysis of the hydrographic surveys conducted in 1963 and 1975 following the operation of the ORCS in 1963 found significant bed aggradation (i.e. $30 \times 10^6 \text{ m}^3$) downstream of the ORCS (Little and Biedenbarn, 2014). From 1948 to 2012, the average width of the 115-km channel

between the ORCS and Baton Rouge reduced by about 115 m and sediment of over 2 m depth was deposited on the thalweg (Knox and Latrubesse, 2016). All these findings indicate ORCSs have largely affected the downstream channel morphology.

Morphodynamics of the Lower Mississippi River over the past century has been investigated by a number of studies (Harmar and Clifford, 2007; Harmar et al., 2005; Kesel, 2003; Kesel et al., 1992). However, these studies mostly used old hydrographic survey data before the 1970s, which does not reflect the river morphodynamics responding to the recent river engineering, such as the construction of numerous dike fields during the 1970s and 1980s. Dike fields are built to enhance navigation, improve flood control, and protect erodible banks (Copeland, 1983). However, substantial sediment deposition and bar growth were observed within the dike fields (Alexander et al., 2012; Kesel, 2003; Nunnally and Beverly, 1986; Smith, 1986), which may have greatly influenced sediment transport in the Lower Mississippi River. Quantitative estimation of the correlation between dike fields and sedimentation and bar growth is necessary for navigation and sediment management.

The goal of this dissertation research aimed to answer a principal question of how much sediment is currently trapped on large channel bars in the Lower Mississippi. To achieve this goal, three interrelated studies were conducted, and this dissertation attempts to introduce them in three separate chapters as standalone journal publications. Following this Introduction, the second chapter presents a study assessing morphologic changes of 30 large emerged bars located in a 223-km reach of the Lower Mississippi River from Vicksburg, MS to the ORCS from 1985-2015. The third chapter focuses on the 3-decadal morphological changes of the 10-km channel and the three large emerged bars downstream of the ORCS to elucidate the long-term effects of river engineering including diversion, revetment and dike constructions. Chapter four describes a

study on how a single flood in the Mississippi River can affect the morphological changes of large emerged channel bars. Chapters two, three, and four are written as stand-alone manuscripts that were recently published in *Geomorphology*, *Journal of Hydrology: Regional Studies*, and *Water*.

CHAPTER 2. DYNAMICS OF 30 LARGE CHANNEL BARS IN THE LOWER MISSISSIPPI RIVER IN RESPONSE TO RIVER ENGINEERING FROM 1985 TO 2015

2.1 INTRODUCTION

Over the past century, sediment delivery from many rivers in the world to coastal areas has significantly decreased (Vorosmarty et al., 2003; Walling, 2006; Walling and Fang, 2003). This is especially the case with the world's large alluvial rivers. For instance, the annual average suspended sediment load from the Mississippi River to the Gulf of Mexico has decreased from 400 million metric tons (MT) before 1900 to 172 MT during the last three decades (Meade and Moody, 2010). The annual average sediment load from the Yangtze River to the East China Sea has declined by 40% in the 2000s when compared to that during the 1950s and 1960s (Yang et al., 2006). Dam construction in the main and tributary channels of these rivers have been attributed to be mainly responsible for the sediment loss (Blum and Roberts, 2009; Hu et al., 2009; Meade and Moody, 2010; Yang et al., 2006). While the direct effect of river dams on siltation has been intensively investigated worldwide, relatively little is known about how changes in river flow downstream owing to dam construction and other river engineering practices, such as channel cuts, levee and dike building, may have affected in-channel sediment trapping in the lower reach of these rivers.

A few recent studies found considerable quantities of sediment trapping in the Lower Mississippi River. Nittrouer and Viparelli (2014) described large channel bars exposed on the riverbed during the 2012 Mississippi River drought, postulating that the Lower Mississippi River is a sand reservoir channel that could supply stable sand to the coastal area in the next several

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centuries by bed scour between Cairo, Illinois, and Knox Landing, Louisiana. Channel bars are integral to the morphodynamics of alluvial rivers. Their formation and development were widely studied in rivers and streams with few engineering modifications (Ashworth, 1996; Hooke, 1986; Hooke and Yorke, 2011; Luchi et al., 2010). In the Lower Mississippi River, point bars were found as the major reservoir for in-channel sediment storage before the 1920s when intensive human modifications were introduced to the river (Kesel et al., 1992). Alternatively, Kesel (2003) noticed degradation of the point bars in the Lower Mississippi River during the 1970s and the 1980s. Kesel also found that the bars between Cairo and Red River Landing changed in number and size during 1935-1963, while the few bars downstream of the Red River Landing showed little change. Smith and Winkley (1996) pointed out that mid-channel bars tended to form in the Lower Mississippi River owing to the confined channel with limited natural meander cutoffs. While it is increasingly recognized that sediment trapping in the Lower Mississippi River may have been progressive in the past decades, there is, in general, a knowledge gap about sediment trapping in channels bars in the lower reaches of the large and highly regulated Lower Mississippi River. As one of the most engineered rivers in the world, the Lower Mississippi River has undergone various hydraulic alterations for navigation safety and flood control including the construction of levees, dike fields, meander cutoffs, and bank revetments. These practices could have dramatically influenced formation and evolution of channel bars.

During the 1970s and 1980s, many dike fields were constructed in the Lower Mississippi River for channel stabilization and navigation safety during low river flows (Harmar et al., 2005; Pinter et al., 2006; Smith and Winkley, 1996). While several studies have investigated the effects of dike fields on changes of river surface area (Nunnally and Beverly, 1986) and flood trends (Pinter et al., 2008), few studies have quantitatively analyzed the correlation between

sedimentation and dike fields. In a recent study, Alexander et al. (2012) reported significant sediment deposition within the void space of in-channel dikes in the Lower Mississippi River. Very recently, Wang and Xu (2016) conducted a study on the development of a 10-km long channel in the Lower Mississippi River from 1985 to 2015, and they found the rapid growth of a point bar, for which the construction of in-channel dikes has been one of the main contributing factors. The constructed dike fields in the Lower Mississippi River may have had important effects on sediment storage and bar development in this alluvial river.

Decreasing sediment delivery from rivers, coupled with artificial levees, constrain the sediment supply to deltaic floodplains (Syvitski et al., 2009; Yang et al., 2011). Morton et al. (2005) reported that approximately 4000 km² of the low-lying coastal land in the Mississippi River Delta had been submerged since the 1930s. Previous studies (Barras et al., 2003; Britsch and Dunbar, 1993a) found a peak delta-plain land loss of 60–75 km² yr⁻¹ from the 1960s to the 1980s. With accelerating sea level rise and land subsidence, the Mississippi River Delta has been projected to continue losing more than 13,000 km² of land by the year 2100 (Blum and Roberts, 2009; Blum and Roberts, 2012). Large sediment diversions from the Lower Mississippi River are being proposed for coastal land restoration in the Mississippi River Delta (CPRA, 2012). Sufficient riverine sediment supply is crucial for sustaining the delta by these diversions. As an important morphologic feature of alluvial rivers, bars can be temporary and long-term sediment stores (Hooke and Yorke, 2011). Assessing sediment volume of channel bars in the Lower Mississippi River can provide information useful in the development of effective strategies and plans for regional sediment management and river sediment diversion efforts.

Utilizing satellite images and river stage records from 1985 to 2015, this study aimed to determine sediment quantity and dynamics of emerged channel bars in a 223 km reach of the

Lower Mississippi River from Vicksburg, Mississippi, at river kilometer (RK) 737 to the Mississippi– Atchafalaya River diversion at RK 515. Specifically, the study accomplished the following objectives: (1) to characterize the morphology of 30 emerged channel bars along the river reach over the past three decades, (2) to develop rating curves of bar surface area with the river stage for each emerged bar, (3) to quantify the emerged volumes of the bars and their changes based on the rating curves, and (4) to investigate changes in bar sand mass from 1985 to 2015.

2.2 STUDY SITE

The Lower Mississippi River, starting from the river’s confluence with the Ohio River at Cairo, Illinois (RK 1536), to the river’s outlet in the Head of the Passes (RK 0), to the Gulf of Mexico (Figure 2.1), is one of the most highly regulated rivers in the world. The river was trained through artificial cutoffs, levees, dikes, and bank revetments under the management of the U.S. Army Corps of Engineers (USACE) for flood control and navigation safety. To prevent the river from avulsing into the Atchafalaya River in Louisiana at RK 505, the Old River Control Structure (ORCS) was built in 1963, which allows approximately 30% of combined flow of the Mississippi and Atchafalaya rivers at the latitude of Red River Landing (RRL in Figure 2.1) to be diverted through the Atchafalaya River. The discharge upstream of the ORCS during the past three decades has averaged $19,413 \text{ m}^3 \text{ s}^{-1}$ (Figure 2.2). Little difference was found when comparing available discharge data between Vicksburg and upstream of the ORCS during 2008-2015 (Figure 2.2).

In the 500 km reach from the ORCS to the Head of the Passes at the Gulf of Mexico, there are only about a dozen emerged channel bars and most of them are located within the upper 200 km reach. In the 223 km river reach immediately upstream of the ORCS, there are 30 large

emerged channel bars identified at a river stage of 14.67 m (Figure 2.1). This river reach (i.e., from Vicksburg at RK 737 to the ORCS at RK 515) is well confined by levees on the floodplain along the west bank close to the river channel and the upland along the east bank within a range of approximately 20 km. A cumulative length of over 250 km of concrete revetments was installed in the 1960s and 1970s to prevent bank erosion (Hudson and Kesel, 2006; Hudson et al., 2008). Dike fields were also intensively constructed in the reach. This river reach underwent seven artificial cutoffs in the early of the twentieth century (Harmar and Clifford, 2007; Harmar et al., 2005). Currently, the channel has an average bankfull width of approximately 1100 m.

Two gauging stations operated by the USACE are located within the study reach at Vicksburg, Mississippi (USACE ID# 15145; RK 702), and Natchez, Mississippi (USACE ID# 15155; RK 586) (Figure 2.1). From 1985 to 2015, the highest river stages reached 31.45 m at Vicksburg and 24.11 m at Natchez in 2011, and the lowest river stages were recorded in 1988 at 13.60 m at Vicksburg and 6.12 m at Natchez (Figure 2.3). The average river stage at Vicksburg is about 6 m higher than that at Natchez (20.95 m vs. 14.33 m), but the stage difference between the two locations varies depending on low or high flows (Hudson et al., 2013). Upstream and downstream of the study reach, there are another two USACE gauging stations: at Greenville, Mississippi (91°9'39" W, 33°17'22" N; RK 855), and Red River Landing, Louisiana (USACE ID# 01120; RK 487). The average river stage at Greenville (31.45 m) is about 21 m higher than that at Red River Landing (10.19 m). It should be noted that all stage data used in this study is based on the elevation above the National Geodetic Vertical Datum of 1929 (NGVD 29).

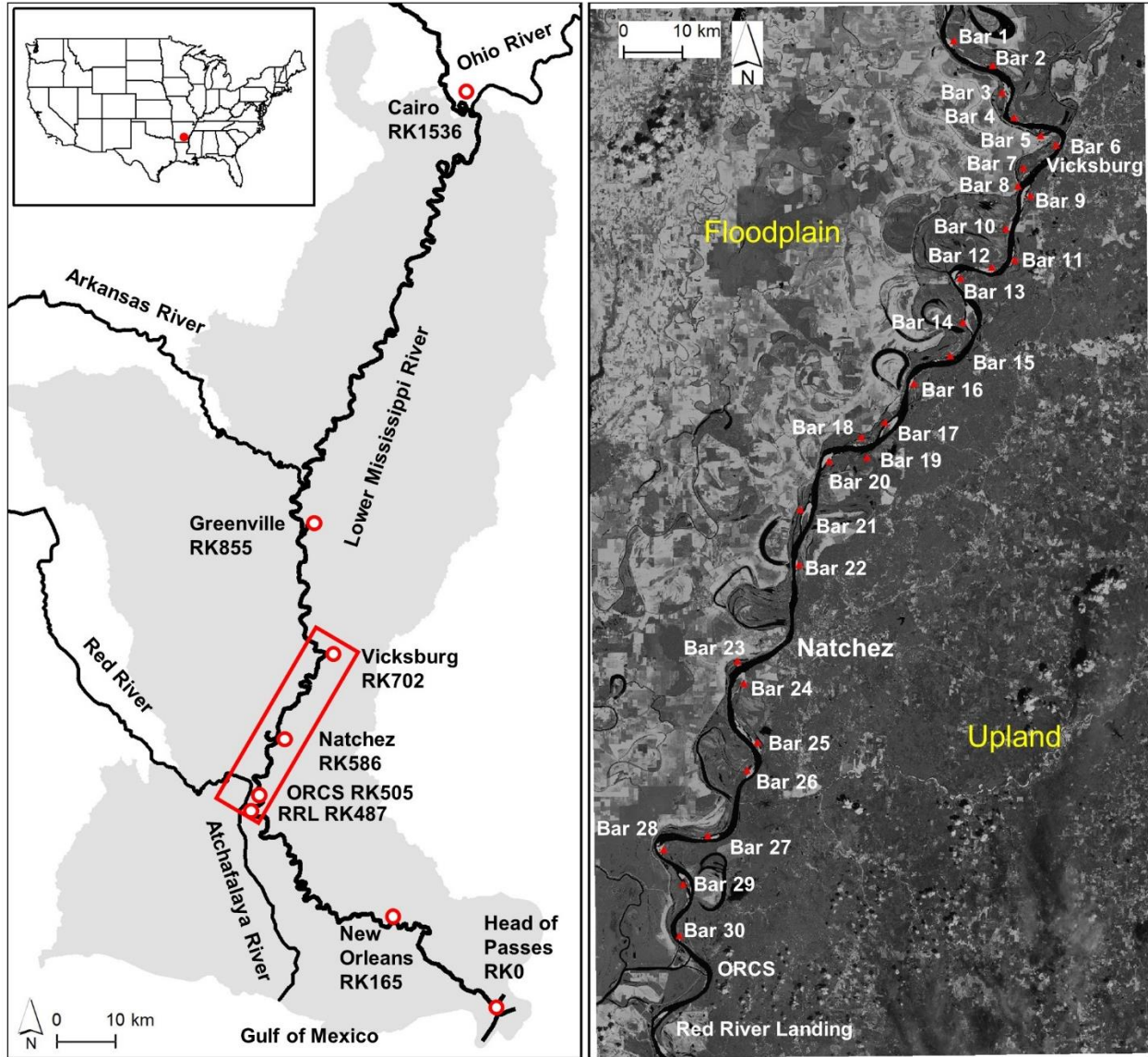


Figure 2.1. Geographical location of the Lower Mississippi River (left). The study reach is located between RK 737 (River Mile 458) and RK 515 (River Mile 320), in which 30 large emerged bars are identified (right). The U.S. Army Corps of Engineers operates four gauging stations at Greenville (RK 855), Vicksburg (RK 701), Natchez (RK 585), and Red River Landing (RRL, RK 487). The long-term river stage records from these stations were used for determining bar surface area at different river water levels. A portion of the Mississippi River is diverted into the Atchafalaya River through the Old River Control Structure (ORCS) at RK 505.

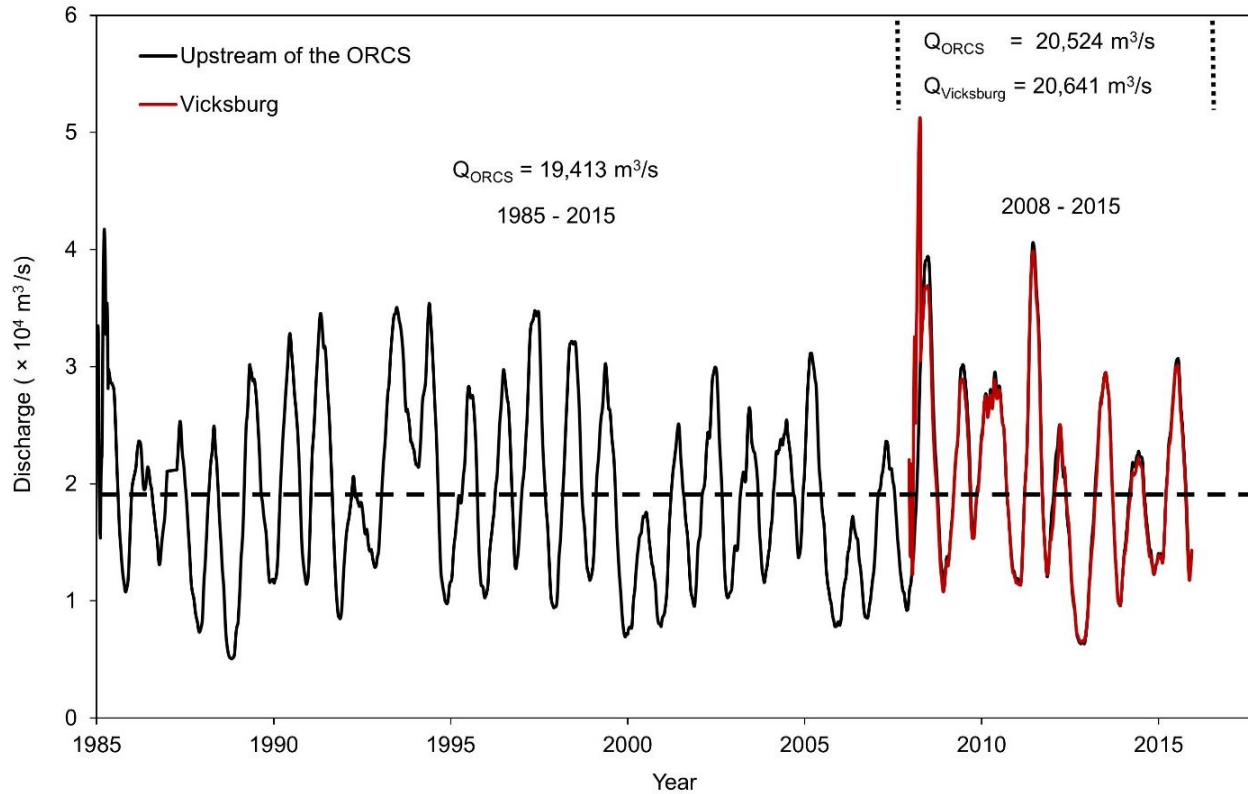


Figure 2.2. The 120-day moving average of the Mississippi River discharge above the Old River Control Structure (ORCS) during 1985-2015 and at Vicksburg during 2008-2015 (only available data for Vicksburg). The discharge above the ORCS was calculated as the sum of the discharge from the Old River Outflow Channel (water diverted into the Atchafalaya, USACE ID# 02600Q) and Tarbert Landing gauging station (RK 493, water remained in the Mississippi main stem, USACE ID# 01100Q). The average discharge during 2008-2015 at the two locations showed little difference, i.e. $Q_{\text{Vicksburg}} = 20,641 \text{ m}^3 \text{ s}^{-1}$ and $Q_{\text{ORCS}} = 20,524 \text{ m}^3 \text{ s}^{-1}$. The horizontal dash line shows the 30-yr average discharge (i.e., $Q = 19,413 \text{ m}^3 \text{ s}^{-1}$) upstream of the ORCS.

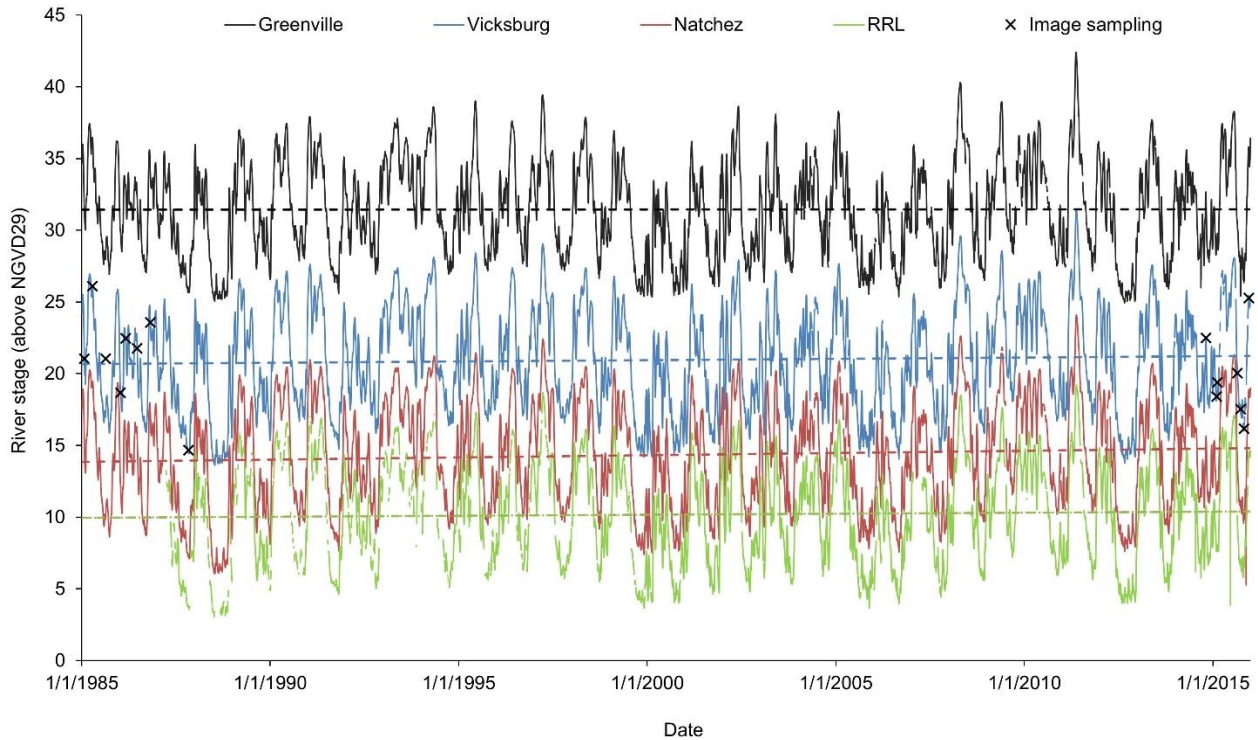


Figure 2.3. Daily river stage from 1985 to 2015 above the National Geodetic Vertical Datum of 1929 (NGVD 29) at Greenville, Vicksburg, Natchez, and Red River Landing (RRL). All stage data were obtained from the U.S. Army Corps of Engineers. On average, the water level at Vicksburg is about 6 m higher than that at Natchez and 11 m higher than that at RRL, while it is approximately 10 m lower than that at Greenville. Black crosses indicate the dates of the collected satellite images used in this study and their corresponding stages at Vicksburg.

2.3 METHODS

2.3.1 Bar Types, Areal Parameters, and Dike Assessment

Bar morphology was identified from cloud-free Landsat Surface Reflectance images that were downloaded from the U.S. Geological Survey (USGS) website (<https://earthexplorer.usgs.gov/>). By examining the river stage at Vicksburg, two images taken on 08/22/1985 (Landsat 5) and 09/26/2015 (Landsat 8) having a similar river stage (17.32 m vs. 17.54 m) were selected to determine the morphologic changes of the bars. The near-infrared band (band 4 for Landsat 5 and band 5 for Landsat 8) in each image was digitized in ArcGIS 10.3 (ESRI, Redlands, California, USA) to obtain the length, width, and surface area of each of

the 30 bars. Bar types were classified based on the method from Hooke and Yorke (2011). In addition, two images (taken on 03/02/1986 and 10/25/2014) were used to estimate morphologic changes of the reach over the past three decades. River stages on these two dates were relatively high (22.47 m vs. 22.49 m), providing favorable conditions for river bank identification.

In the 223 km study reach, dike fields currently exist within 24 of the 30 bars. To clarify the correlation between dike fields and bar volume change, dike information including dike amount and the total length of the dikes in each dike field was acquired in the 2013 Vicksburg District navigation bulletin (USACE, 2013). Dike length was directly measured in Adobe Acrobat Professional (San Jose, CA, USA) by using the “Measurement” tool.

2.3.2 Collection of Satellite Images and River Stage Records

The volume of emerged channel bars can be estimated by utilizing satellite imagery and river stage data. This method has been developed and successfully used to estimate the volume change of three large channel bars downstream from the ORCS (Wang and Xu, 2015; Wang and Xu, 2016). The technical process of the estimation is described in sections 3.2-3.4.

Daily river stage records at the Greenville, Vicksburg, Natchez, and Red River Landing gauging stations were obtained for the periods of 1985-2015 (for Greenville, Vicksburg, and Natchez) and 1987-2015 (for Red River Landing) from the USACE. All cloud-free Landsat Surface Reflectance images during 1985-2015 were collected from the USGS. To develop a numeric relationship between river stage and bar surface area (i.e., a surface area – river stage rating curve, see more in the following section), we selected two sets of satellite images, one at the beginning and another at the end of the study period, which covered a wide range of river stages at Vicksburg and Natchez (Table 2.1 and Figure 2.3). The selected images — eight images in 1985/86/87 and seven images in 2014/15 — were taken from low to high river stages (from

14.67-26.10 m in 1985 at Vicksburg), allowing the establishment of the surface area – river stage rating curves for each of the 30 bars. The low and high river stages mentioned here were referenced to the historic river stages shown in Figure 2.3.

Table 2.1. Dates and image numbers of Landsat Surface Reflectance images used for estimation of bar volume in 1985 and 2015 at different river stages (above NGVD 29) at Vicksburg when the images were captured.

Volume estimation in 1985			Volume estimation in 2015		
Date	River stage (m)	Image Number	Date	River stage (m)	Image Number
10/31/1987	14.67	LT50230381987304XXX04	10/28/2015	16.17	LE70230382015293EDC00
8/22/1985	17.32	LT50230381985234XXX05	9/26/2015	17.54	LC80230382015269LGN00
1/13/1986	18.66	LT50230381986013XXX01	2/6/2015	18.42	LE70230382015037EDC00
1/26/1985	21.04	LT50230381985026XXX04	2/14/2015	19.38	LC80230382015045LGN00
6/22/1986	21.77	LT50230381986173XXX04	8/25/2015	20.04	LC80230382015237LGN00
3/2/1986	22.47	LT50230381986061XXX05	10/25/2014	22.49	LC80230382014298LGN00
10/28/1986	23.57	LT50230381986301XXX03	12/15/2015	25.29	LC80230382015349LGN00
4/16/1985	26.10	LT50230381985106XXX04			

2.3.3 Development of a Rating Curve of Bar Surface Area by River Stage

In each of the selected 15 images, the 30-m resolution near-infrared band (band 4 for Landsat 5/7 and band 5 for Landsat 8) was digitized to obtain the surface areas of each of the 30 bars in ArcGIS 10.3. Bare soil and water have a clear boundary in these bands. To balance the accuracy and efficiency, a 1:40,000 image scale was selected for the digitization. In order to test the validity of this image scale, we also downloaded 2.4-m Quickbird imagery covering the area from Google Earth Pro. We compared the surface areas of bars 14 and 21 digitized from Landsat imagery at a scale of 1:40,000 with those digitized from Quickbird imagery at different scales from 1:10,000 to 1:40,000. We found that the difference in surface areas digitized from the two image sets (both taken on 01/30/1998) at different scales was very marginal, i.e., mostly less than 1%.

There was a 21 m river stage difference between Greenville and Red River Landing; therefore, a specific stage for each of the 30 bars should be developed based on the stages of the four gauging stations. Three water slope profiles between Greenville and Vicksburg, between Vicksburg and Natchez, and between Natchez and Red River Landing were created to calculate the stage differences between each bar and the Vicksburg gauging station (Table 2.2). These estimated values were used thereafter to calculate the specific stage for each bar (e.g., 2.34 m should be added to all Vicksburg stages to obtain correct stages for bar 1). This river stage difference (RSD) between each bar and Vicksburg (Table 2.2) is very helpful for quickly estimating the specific stage for each bar and the subsequent bar volume calculation.

Table 2.2. Specific river stages for each of the 30 bars were estimated by three water slope profiles between Greenville and Vicksburg, between Vicksburg and Natchez, and between Natchez and Red River Landing. The estimated results were transformed to the river stage difference (RSD) between each bar and Vicksburg gauging station. Bar 6 is located at Vicksburg. Therefore, its RSD is 0 m.

Bar	RSD (m)	Bar	RSD (m)	Bar	RSD (m)
1	2.34	11	-1.17	21	-4.58
2	1.51	12	-1.32	22	-5.19
3	1.30	13	-1.83	23	-6.50
4	0.88	14	-2.14	24	-6.50
5	0.36	15	-2.55	25	-7.00
6	0.00	16	-2.95	26	-7.40
7	-0.36	17	-3.36	27	-8.10
8	-0.61	18	-3.97	28	-8.75
9	-0.51	19	-3.97	29	-9.15
10	-1.07	20	-4.18	30	-9.55

For each bar, 15 correlations between bar surface areas and the corresponding river stages were developed, eight for 1985 and seven for 2015. Rating curves were plotted as river stage on the x-axis and bar surface area on the y-axis for each of the 30 bars (Figure 2.4a-c). A regression equation was developed for each of the bars. The coefficient of determination (R^2) and standard

error of the estimate (SE) were used to evaluate the goodness of fit of the regression. The R^2 for most of the regression equations exceeded 0.95, indicating an excellent goodness of fit.

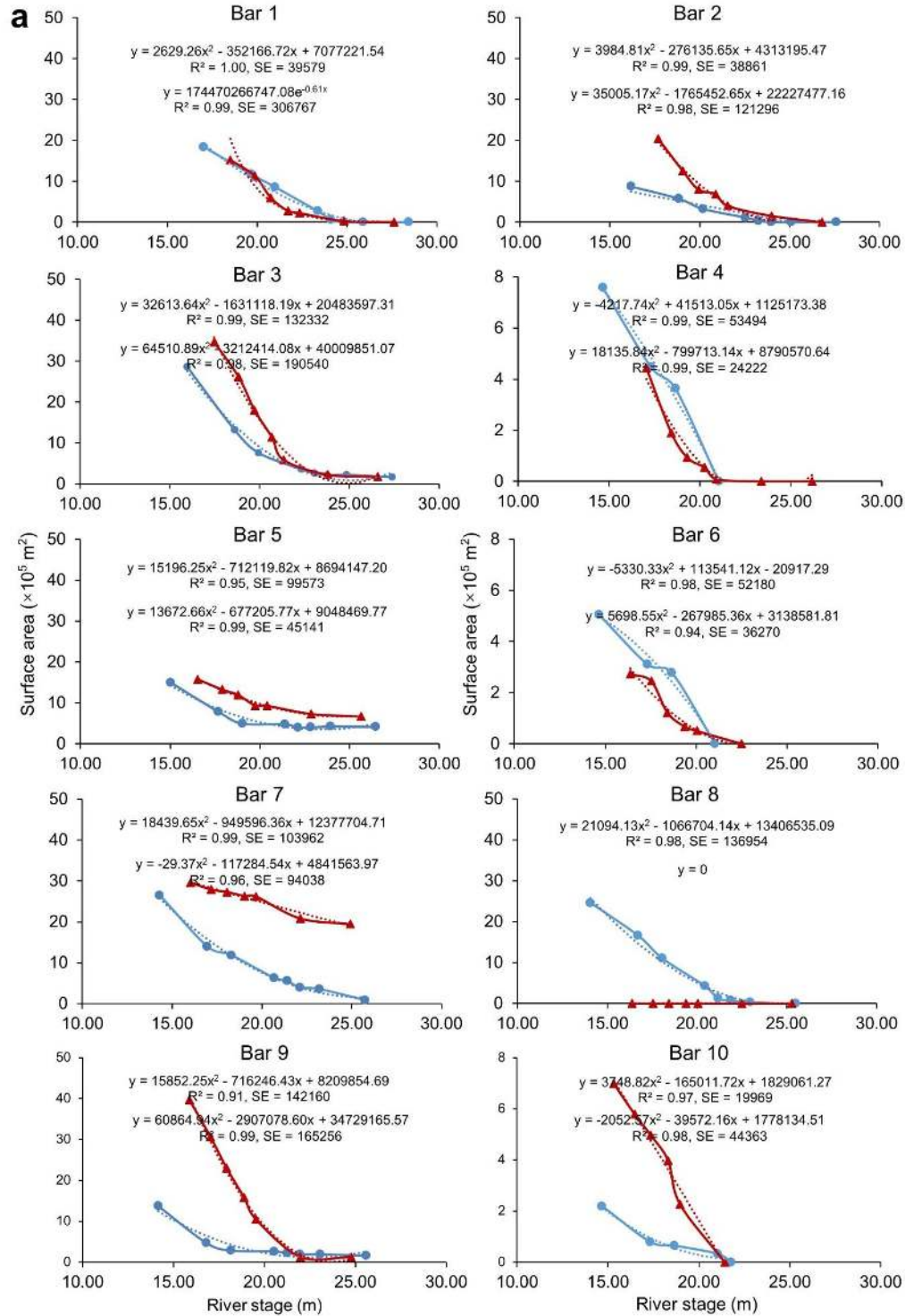
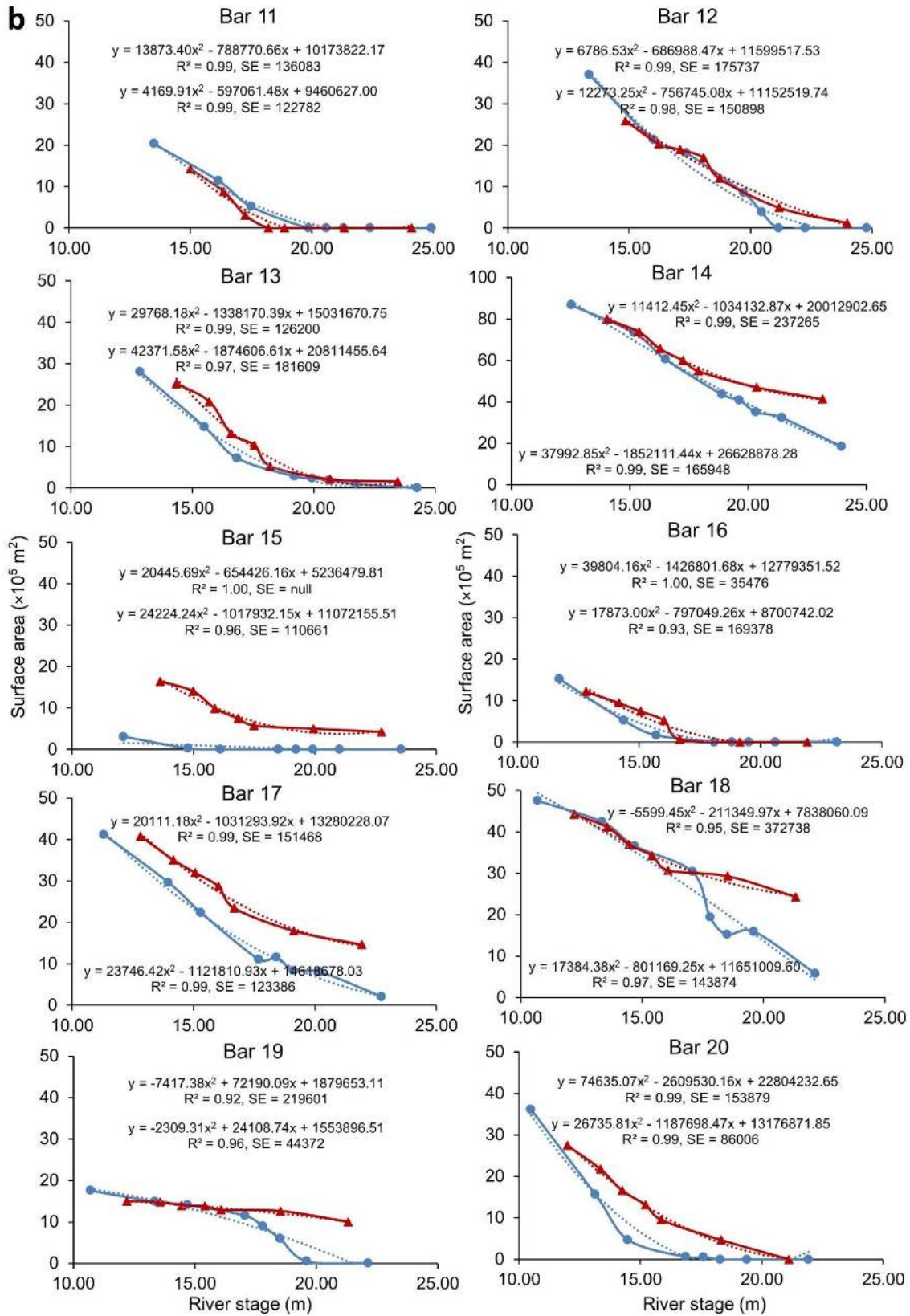
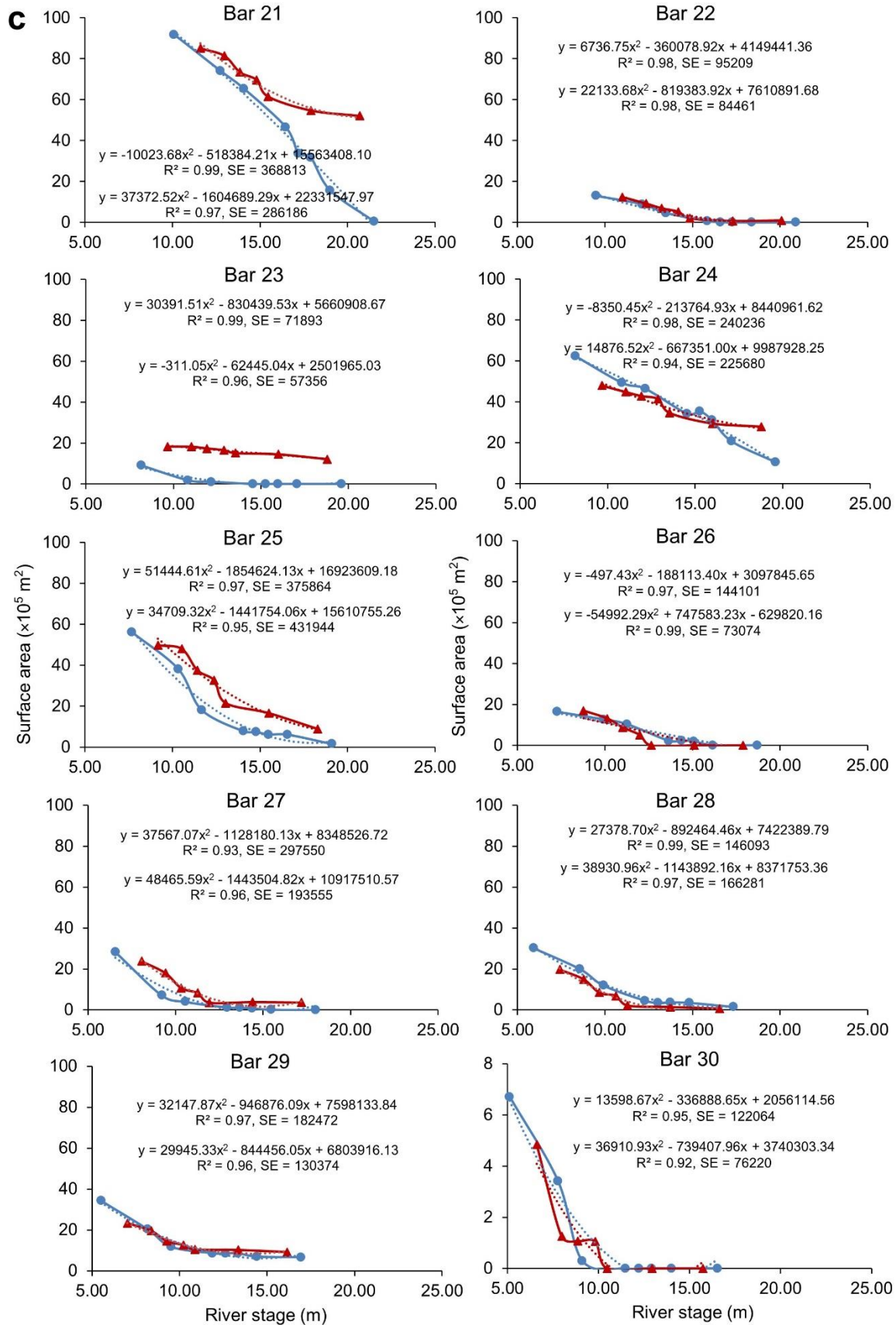


Figure 2.4. Rating curves of bar surface areas and river stages for the 30 studied bars located between Vicksburg and the Old River Control Structure in 1985 (blue) and 2015 (red) (a, bar 1-10, b, bar 11-20, and c, bar 21-30). Regression equations were given for the 1985 rating curve (top) and the 2015 rating curve (bottom), along with their coefficient of determination (R^2) and the standard error of the estimate (SE). (fig. cont'd.)



(fig. cont'd.)

C



2.3.4 Bar Volume Estimation

Volumetric analysis for the studied channel bars was performed using the developed rating curves. Specifically, volume (V_s) of each bar between the highest stage (D_h) and the lowest stage (D_l) was calculated by an integral with the surface area – river stage rating curves, which is described by (Wang and Xu, 2015) as below:

$$V_s = \int_{D_l}^{D_h} (ax^2 - bx + c) dx = \left(\frac{ax^3}{3} - \frac{bx^2}{2} + cx \right) \Big|_{D_l}^{D_h} = \left(\frac{aD_h^3}{3} - \frac{bD_h^2}{2} + cD_h \right) - \left(\frac{aD_l^3}{3} - \frac{bD_l^2}{2} + cD_l \right) \quad (1)$$

To compare the bar volume between the beginning and the end of the study period, the common stage range (16.17-25.29 m) between the two periods at Vicksburg should be used in the integral processes (Table 2.1). This range should be adjusted based on the difference values between each bar and the Vicksburg station. Detailed bar volume calculations are shown in Figure 2.5. The volume of bar 1 in 2015 was the area enclosed by the 2015 rating curve, the x-axis, and the vertical line at a river stage of 18.51 m (16.17 + 2.34 m) (Figure 2.5). The enclosed area was then calculated by integrating the rating curve between 18.51 and 27.63 m (25.29 + 2.34 m). For its volume calculation in 1985, the lower stage remained the same (18.51 m), but 24.81 m was used as the upper bound instead of 27.63 m in the integral. This is because the bar was fully submerged at this stage and using 27.63 m as the upper bound would incorporate a negative area and underestimate the bar volume in that year.

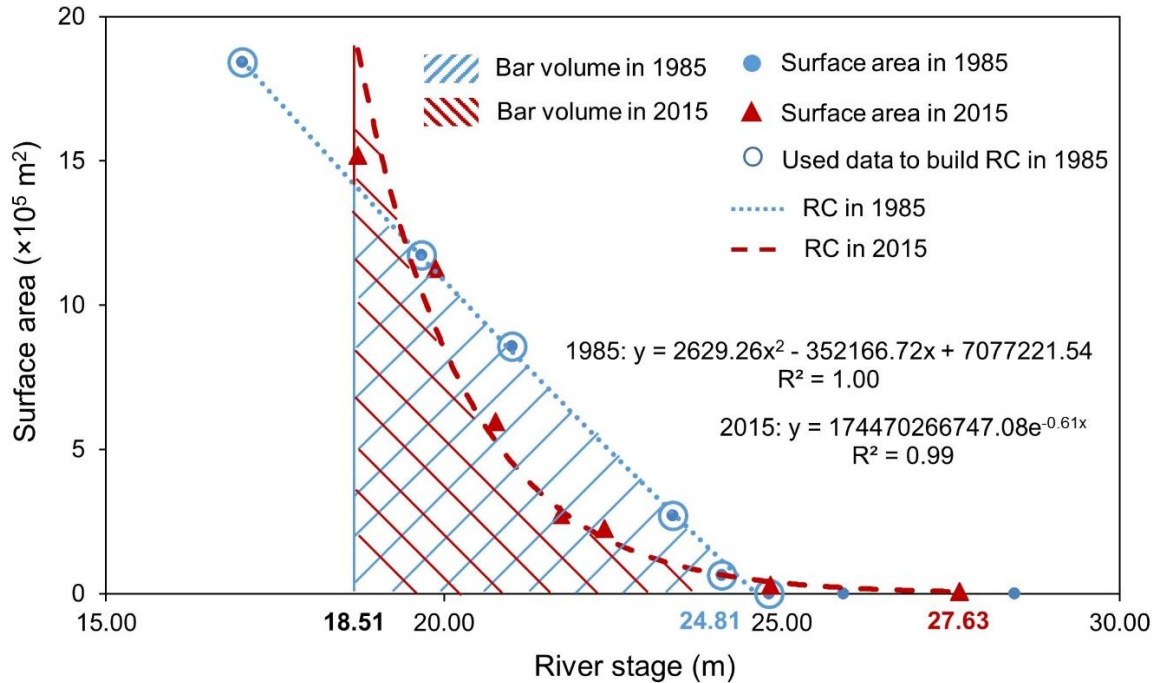


Figure 2.5. An example using bar 1 for illustrating how surface area – river stage rating curves (RC) were used in an integral (Eqn. 1) to calculate bar volumes at two different time points. The volume of bar 1 in 1985 was calculated by integrating $y=2629.26x^2 - 352166.72x + 7077221.54$ for the river stage range from 18.51 to 24.81 m, while the volume of the same bar in 2015 was calculated by integrating $y=174470266747.08e^{-0.61x}$ for the river stage range between 18.51 and 27.63 m.

2.4 RESULTS

2.4.1 Morphologic Changes of Channel Bars

Overall, the 223 km study reach showed little channel morphologic change from 1985 to 2015 (Figure 2.6). The entire 223 km river reach seemed to be well regulated by levees and bank revetments (Hudson et al., 2008). However, more than half of the channel bars had substantial changes (i.e., > 20%) regarding surface area, average length, and width over the past 30 yr (Table 2.3). Sixteen bars became elongated with an average length increase of over 2100 m, 14 bars showed an average increase in their width of 100 m, and 13 bars increased their surface area substantially. However, one bar (bar 8) experienced a drastic change: the bar had a total emerged surface area of 1,659,838 m² in 1985 at a river stage of 17.32 m (Table 2.3) but became

completely unrecognizable in 2015 at a river stage of 17.54 m (Figure 2.6). For the entire 223 km river reach, the total surface area of emerged bars increased by 11,368,000 m² or 21% over the past three decades (Table 2.3).

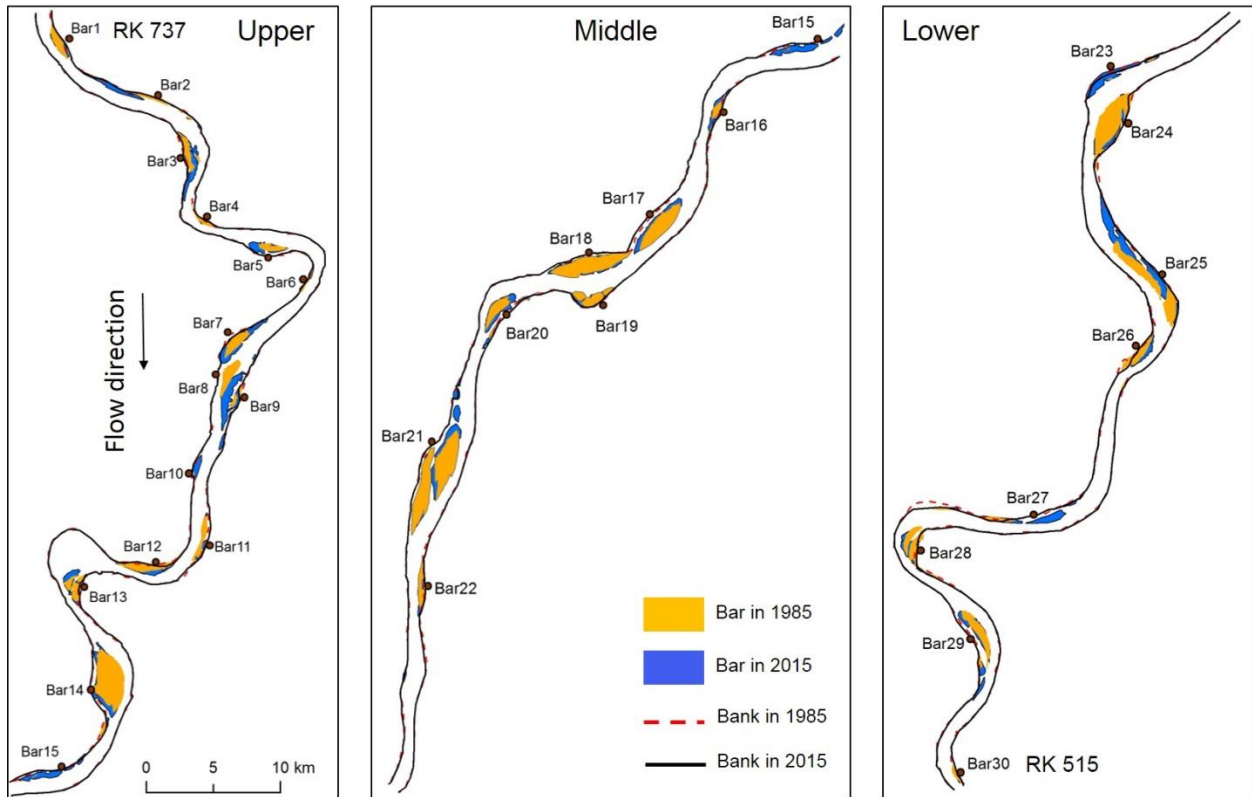


Figure 2.6. The changes of channel morphology and bar surface area from 1985 to 2015. Both were from digitized Landsat images at similar river stage (i.e., 22.47 vs. 22.49 m for the channels, 17.32 vs. 17.54 m for the bars).

Table 2.3. Location, types, and characteristics of 30 emerged channel bars and the associated dike fields in the 223 km river reach from Vicksburg to the Old River Control Structure on the Lower Mississippi River. Length and width of the bar were measured based on two Landsat images acquired in 1985 and 2015 at a similar river stage, i.e., 17.32 m vs. 17.54 m. Letters P, A, M, and C indicate the point, attached, mid-channel, and concave bars, respectively.

Bar No.	Bar location (RK)	Bar type	Area (m ²)		Length (m)		Mean width (m)		Length/width		Dike	
			1985	2015	1985	2015	1985	2015	1985	2015	count	Total length (m)
1	737	P	1,174,454	1,125,786	2900	2600	400	400	7.3	6.5	4	885
2	724	A	575,382	1,259,187	3400	5300	200	200	17.0	26.5	9	3090
3	721	P	1,312,559	2,613,244	3200	5300	400	500	8.0	10.6	2	1561

(table cont'd)

Bar No.	Bar location (RK)	Bar type	Area (m ²)		Length (m)		Mean width (m)		Length/width		Dike	
			1985	2015	1985	2015	1985	2015	1985	2015	count	Total length (m)
4	715	P	447,134	190,469	2700	1500	200	100	13.5	15.0	0	0
5	707	A	788,644	1,326,710	2200	3000	400	400	5.5	7.5	5	2849
6	702	P	311,083	245,240	2200	2200	100	100	22.0	22.0	0	0
7	695	A	1,399,252	2,788,984	2600	4600	500	600	5.2	7.7	5	4635
8	692	M	1,659,838	0	3200	0	500	0	6.4	0.0	0	0
9	690	A	471,831	3,065,586	2200	6000	500	500	4.4	12.0	11	6035
10	681	A	79,455	578,966	500	1700	200	300	2.5	5.7	0	0
11	679	A	1,145,388	883,066	4000	3500	300	300	13.3	11.7	3	1609
12	676	P	2,135,650	2,030,134	6100	3700	400	500	15.3	7.4	3	2092
13	666	P	1,479,338	2,080,450	2000	3100	700	700	2.9	4.4	3	2752
14	660	M	7,332,004	7,370,591	7000	6500	1000	1100	7.0	5.9	10	3943
15	652	A	30,802	1,409,389	400	5500	80	300	5.0	18.3	5	3621
16	644	P	519,210	945,790	3100	3400	200	300	15.5	11.3	3	1320
17	636	M	2,962,987	3,509,584	4100	4700	700	800	5.9	5.9	3	1915
18	624	A	4,242,336	4,116,048	5700	5400	700	800	8.1	6.8	4	3187
19	624	A	1,492,600	1,487,528	3200	3200	500	500	6.4	6.4	3	2189
20	620	P	1,565,135	2,177,144	2800	3200	600	700	4.7	4.6	4	2655
21	612	M	7,394,675	8,147,754	7400	11000	1000	700	7.4	15.7	6	5263
22	600	A	889,899	916,277	3100	3100	300	300	10.3	10.3	3	966
23	576	C	184,476	1,826,337	2000	5700	100	300	20.0	19.0	7	4554
24	576	P	4,933,310	4,478,392	6200	5400	800	800	7.8	6.8	2	1561
25	566	A	3,820,684	4,804,826	6900	10000	600	500	11.5	20.0	6	4136
26	558	P	1,268,204	1,312,503	3200	2600	400	500	8.0	5.2	4	2253
27	544	P	714,719	1,804,285	4600	5800	200	300	23.0	19.3	3	1625
28	531	P	2,001,435	1,500,955	3800	2200	500	700	7.6	3.1	2	1320
29	523	M	2,041,391	1,962,538	4400	6900	500	300	8.8	23.0	0	0
30	515	P	342,071	125,167	2000	1900	200	100	10.0	19.0	0	0
Average			1,823,865	2,278,721	3,570	4,480	439	469	9.7	11.6		

The 30 channel bars in this river reach included 13 point bars, 11 attached bars, five mid-channel bars, and one concave bar in 1985 (Tables 2.3 and 2.4). The attached bars, the mid-channel bars, and the concave bar showed significantly elongation. The average length of all types of bars increased by 743 m ($p=0.045$) from 1985 to 2015, while the average width of the bars had no statistically significant change (-17 m, $p=0.56$), resulting in a significant increase of

length/width ratio from 1985 (9.7) to 2015 (11.6) (Table 2.3). Except for the mid-channel bars, all other bar types had an increase in surface area, with the largest change occurring in the attached and concave bars (Table 2.4). The surface area of the mid-channel bars had a slight, insignificant decrease (401,000 m² or 2%). Currently, the total surface area each of the point, attached, and mid-channel bars ranges from 31% to 34%, while the total surface area of the concave bars accounts for just 3% of the total bar surface area (Table 2.4).

Table 2.4. Decadal morphologic changes by bar type of the 30 studied channel bars from Vicksburg, MS to the Old River Control Structure, MS of the Lower Mississippi River.

Bar type (count)	Average length (m)		Average width (m)		Total surface area (m ²)		Percentag e of area change	Percentage of the total bar area	
	198 5	201 5	198 5	201 5	1985	2015		1985	2015
Point (13)	340 0	330 0	400	400	18,204,00 0	20,630,00 0	13%	33%	31%
Attached (11)	310 0	470 0	400	400	14,936,00 0	22,637,00 0	52%	27%	34%
Mid-channel (5 ^a)	520 0	580 0	700	600	21,391,00 0	20,990,00 0	-2%	39%	32%
Concave (1)	200 0	570 0	100	300	184,000	1,826,000	892%	0%	3%
Total (30)	360 0	430 0	400	400	54,715,00 0	66,083,00 0	21%	100 %	100 %

^a The amount of mid-channel bars reduced from 5 to 4 in 2015 due to the disappearance of bar 8.

2.4.2 Current Bar Volume, Mass, and Spatial Distribution

In 2015, the 29 emerged channel bars had a total volume of $378,183 \times 10^3 \text{ m}^3$ (Table 2.5). While bar 21 amassed a volume of $58,573 \times 10^3 \text{ m}^3$, bar 30 was only about 1% of the volume of bar 21 ($628 \times 10^3 \text{ m}^3$). The 29 bars had an average volume of $13,041 \times 10^3 \text{ m}^3$, with the largest volume centered in the middle of the river reach. The eight bars located between RK 665 and RK 612 (bars 14-21) had a combined volume of $192,543 \times 10^3 \text{ m}^3$, accounting approximately 51% of

the total volume of the 29 bars (Figure 2.7). Based on the spatial distribution of the bar volume, the 223 km river reach was divided into three sub reaches: A, B, and C. The average bar volume in reach B was 3,565,611 m³/km, which was more than three times larger than that in reach A (1,165,819 m³/km) and reach C (1,048,464 m³/km).

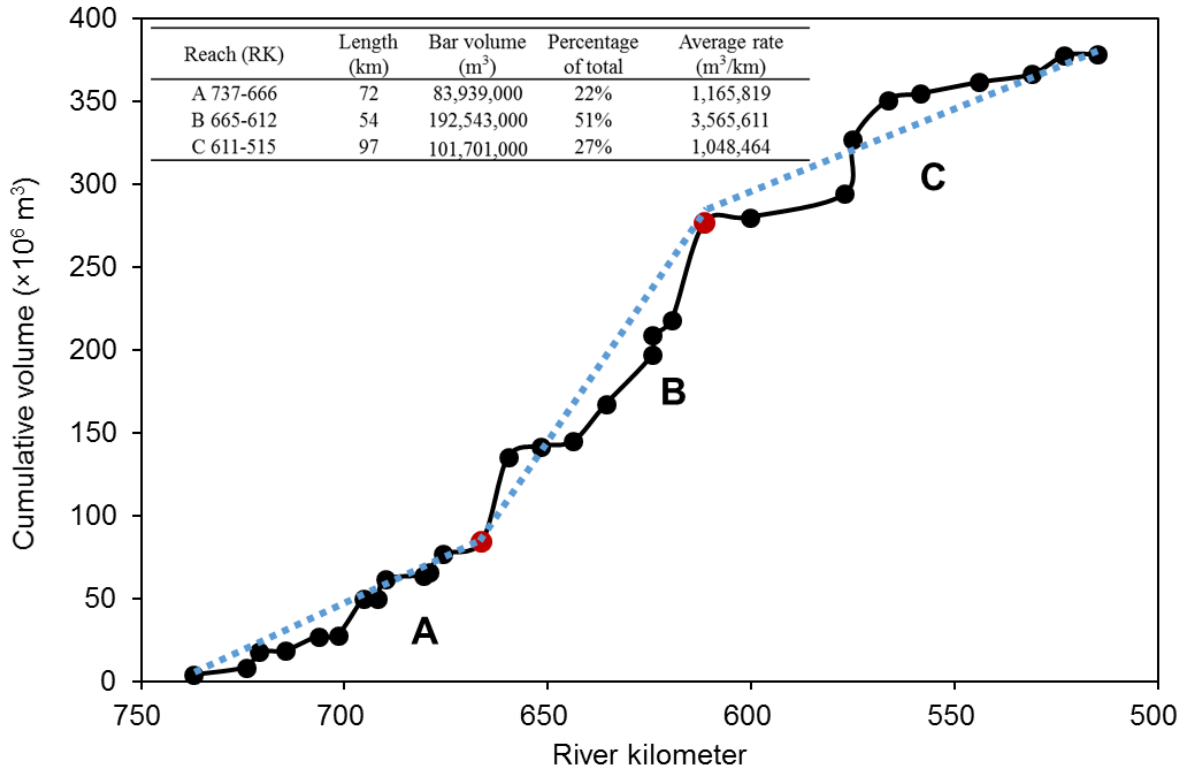


Figure 2.7. The cumulative volume of the 30 emerged bars in the river reach from Vicksburg, MS to the Old River Control Structure, MS of the Lower Mississippi River. Based on the change rates, the 223-km reach can be divided into three sub-reaches (A, B, and C). Dashed blue lines are the slope of the curves in reaches A, B, and C. Most of the sediment are currently stored in the middle of this river reach.

The channel bars contained nearly pure coarse sands (Figure 2.8). The average bulk density of the bar sediment from the surface up to 1.5 m was 1.4 t/m³, based on measurements of sediment core samples collected from different locations on bar 24. Assuming the bulk density as representative for all studied bars, the total mass of $529,456 \times 10^3$ t of sediment would be currently stored in the 29 emerged bars. Bar 21 currently stored the most sediment ($82,002 \times 10^3$

t), while bar 30 had the least (879×10^3 t). The sediment mass of the 29 bars averaged $18,257 \times 10^3$ t.

Table 2.5. Emerged volume and mass currently (2015) found in the 30 channel bars from Vicksburg, MS to the Old River Control Structure, MS of the Lower Mississippi River.

Bar number	Bar volume (m ³)	Bar mass ^a (metric ton)	Bar number	Bar volume (m ³)	Bar mass ^a (metric ton)
1	3,557,000	4,979,800	16	3,160,000	4,424,000
2	4,748,000	6,647,200	17	22,454,000	31,435,600
3	9,083,000	12,716,200	18	29,432,000	41,204,800
4	946,000	1,324,400	19	11,795,000	16,513,000
5	8,595,000	12,033,000	20	9,383,000	13,136,200
6	675,000	945,000	21	58,573,000	82,002,200
7	22,254,000	31,155,600	22	3,431,000	4,803,400
8 ^b	0	0	23	14,120,000	19,768,000
9	11,440,000	16,016,000	24	32,896,000	46,054,400
10	2,303,000	3,224,200	25	23,705,000	33,187,000
11	2,246,000	3,144,400	26	3,880,000	5,432,000
12	10,699,000	14,978,600	27	6,868,000	9,615,200
13	7,393,000	10,350,200	28	4,789,000	6,704,600
14	50,993,000	71,390,200	29	11,384,000	15,937,600
15	6,753,000	9,454,200	30	628,000	879,200

^a Based on the measurement of the average bulk density of the bars, 1.4 t/m³.

^b The bar was emerged in 1985 and became unrecognizable in 2015.



Figure 2.8. The channel bars in the Lower Mississippi River contain nearly pure coarse sand. The average bulk density of the sands from the surface to 1.5 m deep is about 1.4 t/m³.

A significant difference in sediment storage was found between different bar types. The four mid-channel bars amassed the most sediment ($143,404 \times 10^3 \text{ m}^3$) making up 38% of the total bar volume, while the concave bars stored the least at 4% (Table 2.6). The average sediment deposition was highest on the mid-channel bars ($35,851 \times 10^3 \text{ m}^3$), 2.5-5 times higher the averages for the other bar types.

Table 2.6. Volume and mass by types of the 30 channel bars in 2015 from Vicksburg, MS to the Old River Control Structure, MS of the Lower Mississippi River.

Bar type	Count	Total volume (m ³)	Average volume per bar (m ³)	Total mass (metric ton)	Percentage of total
Point	13	93,957,000	7,227,000	131,539,800	25%
Attached	11	126,702,000	11,518,000	177,382,800	34%
Mid-channel	4 ^a	143,404,000	35,851,000	200,765,600	38%
Concave	1	14,120,000	14,120,000	19,768,000	4%
Total	29	378,183,000	13,041,000	529,456,200	100%

^a The amount of mid-channel bars reduced to 4 in 2015 due to the disappearance of bar 8.

2.4.3 Changes in Bar Volume and Mass Over the Past Three Decades

From 1985 to 2015, the total volume of the 30 emerged bars increased by $110,118 \times 10^3 \text{ m}^3$, or 41% of their initial volume (Figure 2.9). Among of them, 21 bars gained a combined volume of $121,925 \times 10^3 \text{ m}^3$ sediment, with bar 21 showing the largest increase ($17,463 \times 10^3 \text{ m}^3$). Nine bars lost volume by a total of $11,807 \times 10^3 \text{ m}^3$, with bar 8 showing the largest volume loss ($5,682 \times 10^3 \text{ m}^3$) and becoming unrecognizable in 2015. The decrease in volume (by the percentage of the total volume loss) was produced by seven point bars (46%), one mid-channel bar (48%), and one attached bar (6%) (Figure 2.9). Overall, all of the bar types increased in volume over the past three decades. Excluding the one single concave bar, the attached bars increased in volume by the largest amount, both in volumetric ($56,339 \times 10^3 \text{ m}^3$) and percentage (80%) terms (Table 2.7).

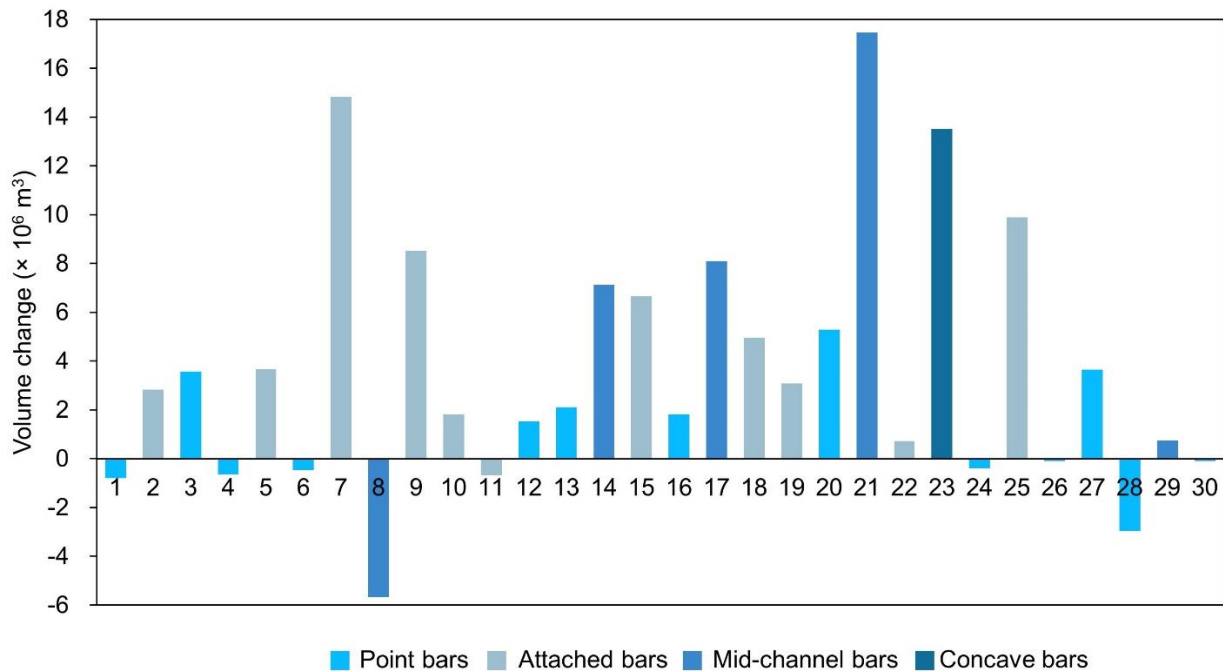


Figure 2.9. Volume changes of the studied 30 emerged bars from Vicksburg, MS to the Old River Control Structure, MS in the Lower Mississippi River between 1985 and 2015.

Table 2.7. Volume changes by types of the channel bars from Vicksburg, MS to the Old River Control Structure, MS of the Lower Mississippi River between 1985 and 2015.

Bar type	Count	Total volume in 1985 (m ³)	Total volume in 2015 (m ³)	Total volume change (m ³)	Percentage of change	Percentage of total bar volume	
						1985	2015
Point	13	81,439,000	93,957,000	12,518,000	15%	30%	25%
Attached	11	70,363,000	126,702,000	56,339,000	80%	26%	34%
Mid-channel	4 ^a	115,670,000	143,404,000	27,734,000	24%	43%	38%
Concave	1	593,000	14,120,000	13,527,000	2281%	0%	4%
Total	29	268,065,000	378,183,000	110,118,000	41%	100%	100%

a The amount of mid-channel bars reduced to 4 in 2015 due to the disappearance of bar 8.

The largest volume percentage changes occurred for the attached bar 15 (73-fold increase) and the concave bar 23 (23-fold increase), while bar 8 had the largest decrease rate (100%) (Figure 10). In total, the increased bar volume was equivalent to $154,165 \times 10^3$ t of sediment.

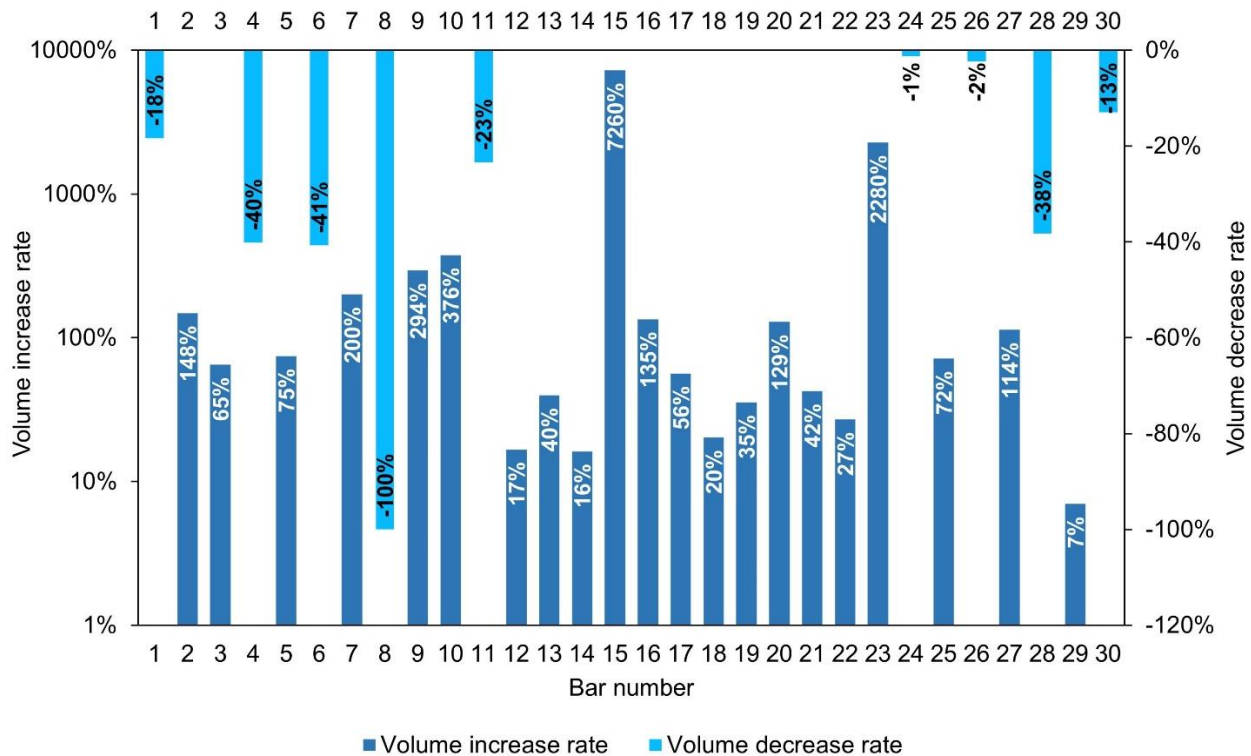


Figure 2.10. Volume change rates of the 30 bars during the period of 1985-2015. The Y-axis for volume increase rate is on a logarithmic scale.

Similar to the spatial distribution of the current bar volume, bar growth in the past three decades occurred mainly on bars 14-25 in the middle of the studied river reach, which together accounted for about 71% ($78,232 \times 10^3 \text{ m}^3$) of the total volumetric increase of the 30 bars. The four bars with the largest increases in volume (bars 21, 7, 23, and 25) accounted for about 51% of the total volumetric increase. Bars that had decreased in volume were usually located near the downstream portion of the enlarged bars, and no adjacent bars that experienced sediment loss were observed (Figure 2.9).

2.5 DISCUSSION

The Lower Mississippi River is one of the most highly regulated rivers in the world. It is also one of the world's largest alluvial rivers, transporting annually over 120 MT of suspended sediment to the lower 500 km of the river (Rosen and Xu, 2014) and another 54 MT of suspended sediment to its distributary, the Atchafalaya River (Rosen and Xu, 2015) in the past three decades. When an alluvial river is confined by levees and its river bank is stabilized by revetments, channel wandering is impossible, and sediments are either transported to the lower reach or deposited in the channel. In a study on channel morphologic changes using early hydrographic surveys from 1880 to 1963, Kesel (2003) reported that the emerged channel bars in the Lower Mississippi River from Cairo, Illinois, to Red River Landing, Louisiana, tended to adjust their number and size as responses to the river engineering. Our study shows that while Lower Mississippi River's channel is well confined, the adjustment of the bars in this reach has continued in the past 30 yr, and that the bars increased their emerged volume by 41%.

In an active meandering river, point bars are the dominant bar type, both in number and area, and the size of the point and attached bars are significantly larger than mid-channel bars (Hooke and Yorke, 2011). In the 223 km study reach, however, point bars are not dominant in

either amount (i.e., 13 out of 30 bars) or total surface area (31% of the total surface area) compared to the other bar types such as attached (34%) and mid-channel bars (32%) (Table 2.4). In the upper part of the Lower Mississippi River between Cairo and Red River Landing, point bars were major sediment storage sites during 1880-1914 before intense human modifications to the river (Kesel et al., 1992). However, Kesel (2003) noticed the degradation of point bars in the Lower Mississippi River during the 1970s and 1980s. In our study, the volume of more than half of the point bars (7 out of 13) decreased in the past 30 yr. Although the total volume of point bars increased slightly, the proportion of the total bar volume of the reach declined from 30% to 25% during 1985-2015. On the contrary, sediment was increasingly stored in the mid-channel and attached bars (Table 2.6).

The findings demonstrate that significant changes occurred in sediment storage sites in this highly regulated channel. During the period of 1985-2015, attached bars experienced the largest increase in both surface area and volume. It is interesting to examine the reasons behind these large morphologic changes. We investigated the development of attached bar 15 (with the highest volume increase rate of 7240%) by examining four Landsat images taken in 1985, 1995, 2005, and 2015 (note that these image dates had similar river stages of 17.3-17.5 m). In 1985, a relatively small (400 × 90 m) bar existed in the lower part of the reach with one single dike located along the right bank (Figure 2.11a). By 1995, five dikes had been built along the whole bank, and the bar had become much larger (Figure 2.11b). From 1995 to 2015, the surface area of the bar increased significantly, and the dike field area had been mostly covered by the bar (Figure 2.11c-d), as evidenced by the rapid growth of the attached bar 15 around the dike field. Therefore, the increased bar volume was closely associated with the construction of the dike field.

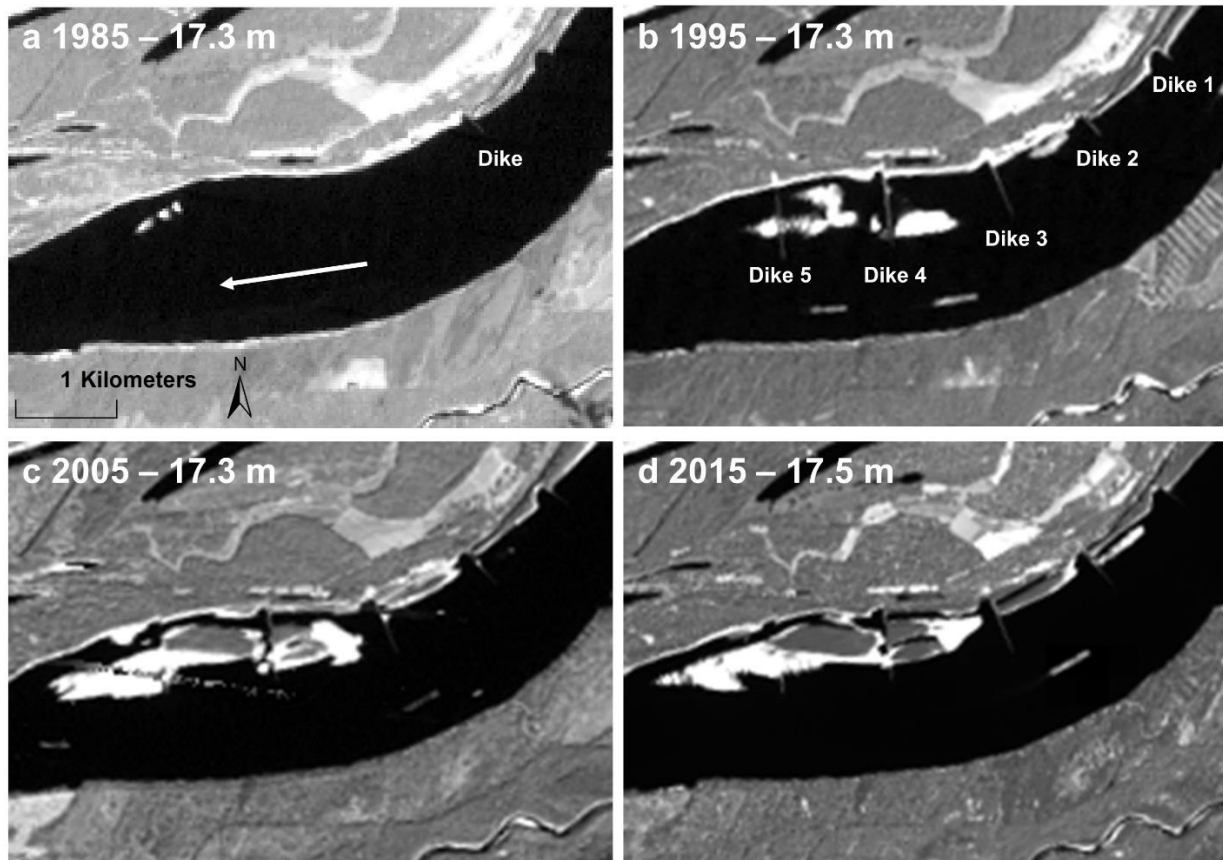


Figure 2.11. The rapid growth of bar 15 from 1985 to 2015 due to the construction of a dike field. River stages were very similar (i.e., 17.3 – 17.5 m) on these four days when the satellite images were taken.

Impermeable spur dikes exist within 24 of the studied 30 bars (Table 2.3). The total length of the dikes in each dike field ranged from 885-6035 m. The sediment volume trapped in these 24 bars is about 96% of the total volume of the 30 bars. Although sediment deposition adjacent to and within dike fields were widely observed in the Middle Mississippi River (Watson et al., 2013), concerns exist about the mechanics of dike field sedimentation and its relation to dike location, dike field design, flow hydrology, and sediment flow (Nunnally and Beverly, 1986). The quantitative estimation of the bar volume in the present study provides an opportunity to further explore the correlation between dike characteristics (e.g., amount and length) and the sedimentation around dikes.

An examination of the correlation between increased bar volume during 1985-2015 of all bar types and the dike fields shows that there is a positive linear relationship between bar volume and the total length of the dikes in a dike field ($R^2 = 0.62$; $p < 0.0001$) (Figure 2.12b), while there is no significant correlation to the number of dikes ($R^2 = 0.17$; $p = 0.08$) (Figure 2.12a). In Figure 2.13b, bar 9 appears to be an outlier (i.e., it is associated with the longest dikes of ~6000 m, but a relatively low increase in volume). In fact, this was caused by the river engineering that took place around this bar during 1985-2015 (Figure 2.13). In 1985, bar 8 was a large mid-channel bar (Figure 2.13a). If no actions were taken, the continuous growth of this bar might have threatened navigation safety. In 1995, several dikes had been built within bar 7 (Figure 2.13b), which closed the secondary channel around bar 7 and increased flow velocity in the main channel. As a result, most of bar 8 was flushed away. In 2005, bar 8 had completely disappeared, while the sizes of bars 7 and 9 increased significantly (Figure 2.13c). Compared to 1995, the main channel width had decreased by ~700 m in 2005. The much narrower channel may have increased the flow velocity substantially and scoured the channel bed, thus confining the lateral growth of bar 9. Overall, the relatively low volumetric increase of bar 9 during 1985-2015 was caused by the construction of dike fields within bar 7 and the corresponding channel narrowing. If bar 9 is excluded in the regression analysis, the total length of the dikes in a dike field displays a much stronger relationship with the increase in bar volume ($R^2 = 0.86$; $p < 0.0001$) (Figure 2.12b). Therefore, we conclude that the substantial changes in bar morphology found in our study were mainly caused by the construction of dike fields during the 1970s and 1980s.

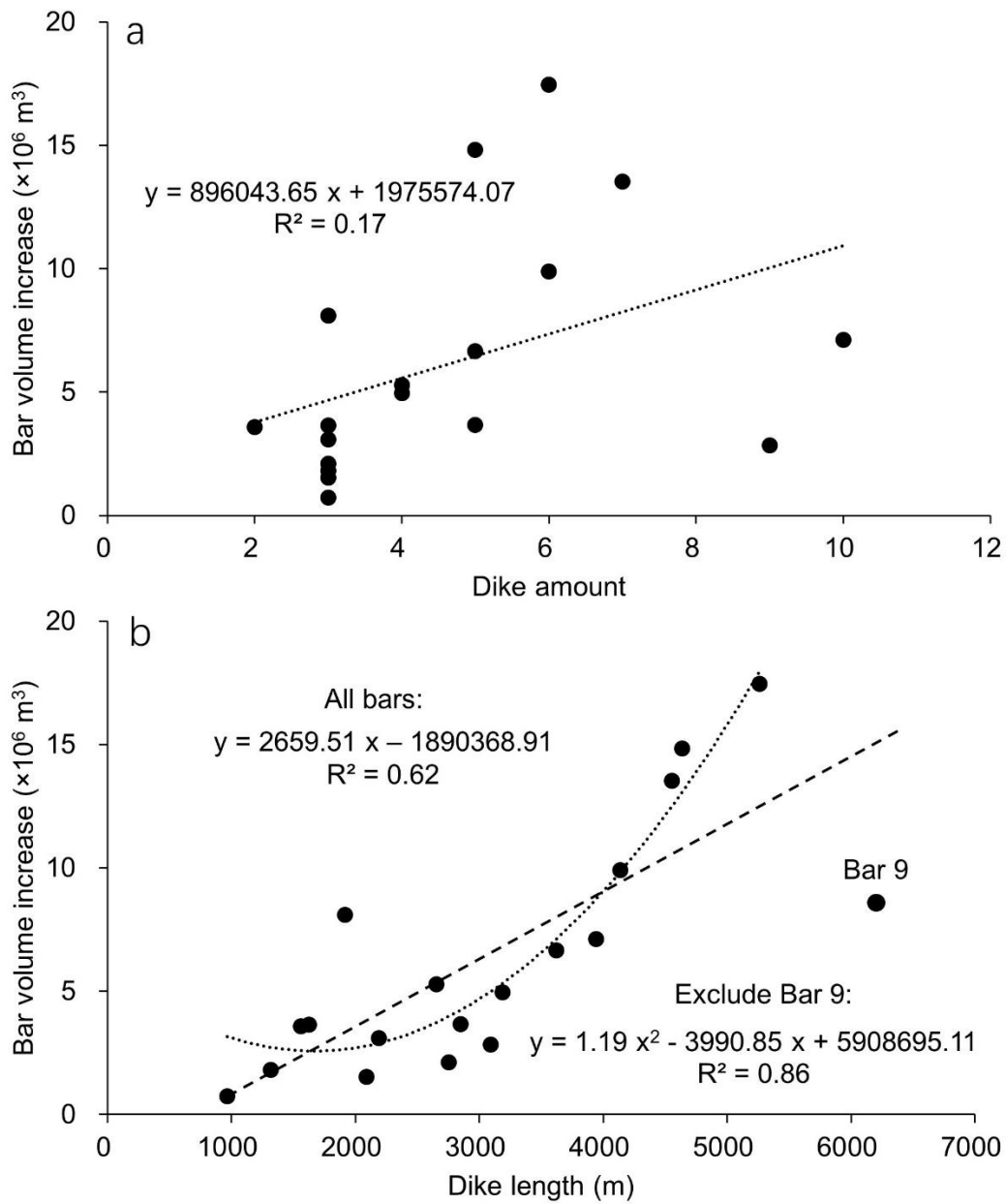


Figure 2.12. Regression analysis between bar volume increase during 1985-2015 and the dike amount (a) and the total dike length (b) in the corresponding dike fields.

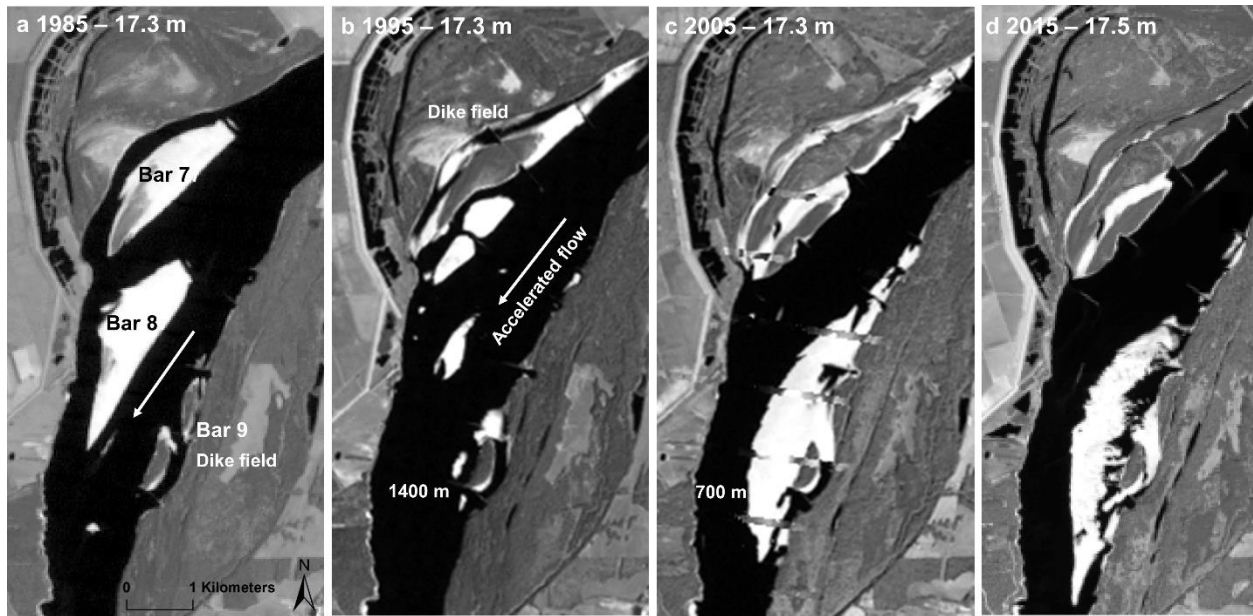


Figure 2.13. Morphologic changes of bars 7, 8, and 9 from 1985 to 2015. There were two dike fields near bars 7 and 9. Bar 8 was a mid-channel bar in 1985. However, it was fully unrecognized in 2015 due to the construction of the dike field around bar 7. The river channel narrowed by about 700 m over the past three decades due to the growth of bar 9.

In 1985, the bar volume in reaches A, B, and C accounted for 21%, 55%, and 31% of the total volume of the 30 bars, which was very similar to the spatial volume distribution in 2015. This may suggest that the depositional pattern in this 223 km river reach remains the same and that there was no significant sediment transfer among reaches A, B, and C over the past three decades. Interestingly, the bars that decreased in size usually were located downstream from bars that increased in size, which may suggest that the growth of a channel bar may potentially result in the degradation of its adjacent downstream bar (Figure 2.9). Overall, the channel and bar positions have remained relatively fixed in the study reach. There were also few changes in bar type from 1985 to 2015, with the exception of bars 7 and 25 that changed from side bars to attached bars. Although substantial morphologic changes occurred in the bars, the average width of the bars changed little, indicating that bars usually do not develop laterally in this highly regulated river reach. Development of the bars in the future should not be as rapid as the past if

no new dike fields are built. However, we infer that the bars still have a substantial ability to trap riverine sediment by vertical accretion. The formation of mid-channel bars in the Lower Mississippi River was considered as the sediment response to the fixed channel, where the channel cannot laterally migrate by the development of point bars (Smith and Winkley, 1996). Although only four mid-channel bars currently exist in the 223 km study reach, mid-channel bars are about 3-5 times the average volume of attached bars and point bars, suggesting that mid-channel bars could develop into the dominant depositional feature in a regulated alluvial river. According to Hooke's (1986) development theory of mid-channel bars, in the future these four mid-channel bars could develop laterally and become attached to the bank, thus trapping a large amount of sediment.

Although the 378,183,000 m³ total bar volume at present is tremendous, it is likely an underestimation of actual sediment storage of these bars. This is because that we only calculated the volume in certain ranges of the river stage. The shapes of the surface area – river stage rating curves (Figure 2.4) demonstrate that the submerged bar volume between low water plane and channel bed could be large. In the future, submerged portions of the bars can be estimated using the developed rating curves once bed elevations near the bars are measured.

Sediment reduction in the Lower Mississippi River in the past century has been attributed mainly to the dam construction in the upper Mississippi River Basin (Blum and Roberts, 2009; Blum and Roberts, 2012). The findings of this study show that the large emerged channel bars in the LMR have also trapped a large amount of sediment, primarily sands. In a modeling study, Nittrouer and Viparelli (2014) predicted that the sand load at Know Landing, Louisiana (RK 505) would not reduce in the next six centuries because potential bed scouring between Cairo, IL (RK 1536) and Memphis, TN (RK 1182) would sustain the sand transport downstream to the MRD.

However, the modeling study did not consider the effect of large emerged channel bars in trapping riverine sands in this studied river reach. It is very likely that large channel bars located within the ~1000-km channel from Cairo to Knox Landing could trap substantial sand. Further studies are needed to elucidate sand trapping capacity upstream of Vicksburg as well as the relevance of the sediment loss to the downstream channel morphodynamics.

The average annual suspended sand load (SSL) delivered into the last 500-km Mississippi River was estimated at about 27 MT during the period from 1973 to 2013 (Joshi and Xu, 2015). The ~530 MT sediment stored on the emerged bars (nearly pure coarse sand) by this study would be equivalent to ~20 years' total SSL discharged into the LMR. Since the mid-2000s Louisiana Coastal Protection and Restoration Authority (CPRA) has been implementing a Long Distance Sediment Pipeline (LDSP) project to dredge sands from the Mississippi River (CPRA, 2017). Construction of the LDSP began in 2013, and the pipeline has so far borrowed and transferred nearly 10 million cubic yards of Mississippi River sediment to support marsh and ridge creation projects in the Barataria Basin south of New Orleans. The LDSP remains in place as a permanent pipeline corridor for future project use. There is no doubt that future success of the project will largely depend on sand availability. The large quantity of sand found in this study on the channel bars in LMR can be a precious resource of sediment for coastal restoration. River engineering strategies and solutions should be developed to utilize the resource for the restoration of the downstream sinking MRD.

2.6 CONCLUSIONS

This study is a comprehensive assessment of a 30-yr record of large-scale bar morphology in a highly regulated alluvial river. The results of this study show that the river engineering practices in the past have been successful in confining the channel of this 223 km

reach of the Lower Mississippi River. The levees and revetments have regulated the river flow, allowing very little change in channel position. However, significant changes have occurred in channel bars, both morphologically and volumetrically. The bars have become elongated and have trapped a large quantity of coarse sediment. In terms of bar development, our study reveals that a highly regulated river may favor the growth of attached and mid-channel bars. This depositional characteristic is a reflection of sediment transport adjustment to the artificial cutoffs, levees, and revetment constructions for channel stabilization for navigation safety and flood control. In particular, the total dike length in a dike field exhibited a strong relationship with increased bar volume. Furthermore, our study found a total emerged bar volume of 378,183,000 m³ from the river channel's 30 bars and a combined volume increase of 110,118,000 m³ in the past three decades. Assuming a bulk density of 1.4 t/m³, these volumes are equivalent to a sand mass of approximately 530 million metric tons. In the future, the tremendous quantity of sediment (nearly pure sand) could be potentially utilized for river diversion efforts downstream to save the sediment-starved Mississippi River Delta if suitable engineering strategies are developed.

CHAPTER 3. LONG-TERM GEOMORPHIC RESPONSE TO FLOW REGULATION IN A 10 - KM REACH DOWNSTREAM OF THE MISSISSIPPI - ATCHAFALAYA RIVER DIVERSION

3.1 INTRODUCTION

The Louisiana Gulf coast in the USA has experienced one of the highest sea-level rises over the past century (Ivins et al., 2007). Concurrently, the Mississippi River Delta has undergone rapid land loss since the early 20th century (Britsch and Dunbar, 1993b; Craig et al., 1979; Gagliano et al., 1981; Scaife et al., 1983). Since 1932 a total land loss of approximately 4900 km² has been reported for Louisiana's delta plain (Couvillion et al., 2011). A number of natural and human factors have been attributed to the problem including river engineering (Meade and Moody, 2010; Turner, 1997), accelerated subsidence (Gagliano et al., 1981; Yuill et al., 2009), reduced riverine sediment supply (Kesel, 1988; Meade and Moody, 2010), disconnection of the river with its floodplains (Xu, 2014), coastal land erosion (Wilson, 2004), and relative sea level rise (Georgiou et al., 2005). Couvillion et al. (2013) projected that, if no actions were taken, at least another 2118 km² land of Louisiana's coast would be lost over the next 50 years. This land loss possesses a serious threat to the energy industry, river transportation, and commercial fisheries in this region, all of which have the level of national importance.

Currently, large sediment diversions are being proposed for restoring and protecting the sinking Louisiana's coast by diverting river water and sediment into the wetlands and estuaries surrounding the Lower Mississippi Rivers (LMR) (CPRA, 2012). Studies have been conducted extensively in the recent years on design and site selection of diversions (Gaweesh and Meselhe, 2016; Meselhe et al., 2012; Nittrouer et al., 2012), magnitude of diversion discharge (Wang et al.,

This chapter previously appeared as “Wang, B., Xu, Y.J. Long-term geomorphic response to flow regulation in a 10-km reach downstream of the Mississippi – Atchafalaya River diversion. *Journal of Hydrology: Regional Studies*, 2016 (8):10-25.”. See Appendix B for the reprint permission.

2014), and operation strategy (Allison et al., 2014; Rosen and Xu, 2014). A few studies have also looked at potential impacts of river diversions on upstream and downstream sediment transport through modeling (Brown et al., 2013), short-term channel responses to opening of a large river spillway (Allison et al., 2013), wetland ecosystems (Couvillion et al., 2013), vegetation cover (Kearney et al., 2011), and physiochemical conditions of estuaries (Das et al., 2012; Lane et al., 2007). However, studies on long-term effects of large river diversions on downstream channel morphology and sediment transport are scarce. Such information should be tightly associated with the design of proposed diversions because the morphological response of the river reach may affect flood conveyance, channel stability and sediment supply to downstream reaches (Surian, 1999).

River diversions remove water from rivers and impose primary changes on flow and sediment transport (Church, 1995). To date, a number of studies have focused on the effects of diversions on downstream channel morphology and sediment deposition. For instance, for the rivers in montane environments, Baker et al. (2011) found that decreased flow velocity and fine sediment deposition downstream of diversions on 13 streams in the western America. Gaeuman et al. (2005) reported that water diversions eliminated moderate flood events which caused vegetation encroachment in the channel and corresponding channel narrowing. However, Ryan (1997) found the subtle change in subalpine channels downstream of diversions. For alluvial rivers and reaches, Caskey et al. (2015) reported that simplifying and narrowing impacted by diversion-induced flow alteration in single-thread, straight and meandering, alluvial channels on low to moderate gradient (<3%) valley segments. Wang et al. (2008) predicted that sediment deposition would develop along the whole reach in the long term downstream of the large water diversions in the Lower Yellow River. In general, these studies illustrate that the morphological

responses of the downstream channels to the diversions are not only related to the changes in flow regimes and sediment availability but also to the bed types, channel slope, and geometry.

In the LMR, the extensive modifications have been undertaken since the 1920s. Artificial cutoffs, levee and dike construction, bank revetment, and reservoir building along major tributaries have largely complicated the geomorphological response of the river reach (Harmar et al., 2005). The river engineering has forced channels to adjust, often resulting in the development of mid channel bars (Smith and Winkley, 1996). However, in his assessment on channel bars of the Lower Mississippi River, Kesel (2003) showed that the bar size and volume from 1880 to 1963 in the lowermost Mississippi River had little change. It has been debated whether this trend has remained in the past several decades. Therefore, studying historical changes of channel bars near diversions can help better understand possible geomorphic responses of a river reach to its proposed future diversion, The Mississippi–Atchafalaya River diversion at the Old River Control Structure (ORCS), with three shortly downstream large channel bars and nearby revetments and dikes, offer an excellent case to study the effects of these engineering practices on channel morphology and bar dynamics in the Lowermost Mississippi River. Little and Biedenharn (2014) recently completed an assessment on the riverbed from the ORCS to the mouth of Mississippi River outlets using single beam bathymetric data acquired in 1963, 1975, 1992, 2004 and 2012 (Little and Biedenharn, 2014). However, there was little information on bar emergence and sediment deposit because their work mainly focused on the bed elevation change. This, along with the relative coarse time resolution of the surveys, makes it difficult to discern the individual effects of the river engineering practices on bar and channel form changes

The purpose of this study is to examine morphological changes of the 10-km long river channel, and the three emerged channel bars nearly downstream of the diversion during 1985-

2015. Specially, we utilized satellite images and long-term hydrologic data to (1) examine the impacts of the diversion on flow regime, (2) interpret the morphological change of the river channel, and (3) quantitatively estimate variations of surface area and volume of three large channel bars located in the studied reach. The main goal of this study is to elucidate the effects of the large river diversion, revetments and dikes on the morphology of river channel and emerged channel bars. Such information can be helpful for the design of engineering projects in advance to reduce possible hazards in flood protection and navigation safety downstream of the proposed large sediment diversions in the LMR or elsewhere.

3.2 STUDY AREA

The lowermost Mississippi River is defined as the last 500-km long river reach from the Mississippi-Atchafalaya River diversion - the Old River Control Structure (ORCS) (31°04'36" N, 91°35'52" W) to the river's Gulf outlet (Figure 3.1). The ORCS was built to prevent the majority of Mississippi River water from being captured by the Atchafalaya River (AR). The overbank structure, low sill structure, and outflow channel were completed in 1963. An auxiliary inflow channel and a hydroelectric station were built in 1987 and 1991, respectively. Latitude flow is defined as water in the MR and AR flow across the latitude of Red River Landing (30° 56' 20.4") which is an important term in the diversion management. The often-quoted number of diverted flow by the ORCS is 30% of latitude flow, but the percentage varies in every year, fluctuating between 15% and 29% (Mossa, 1996).

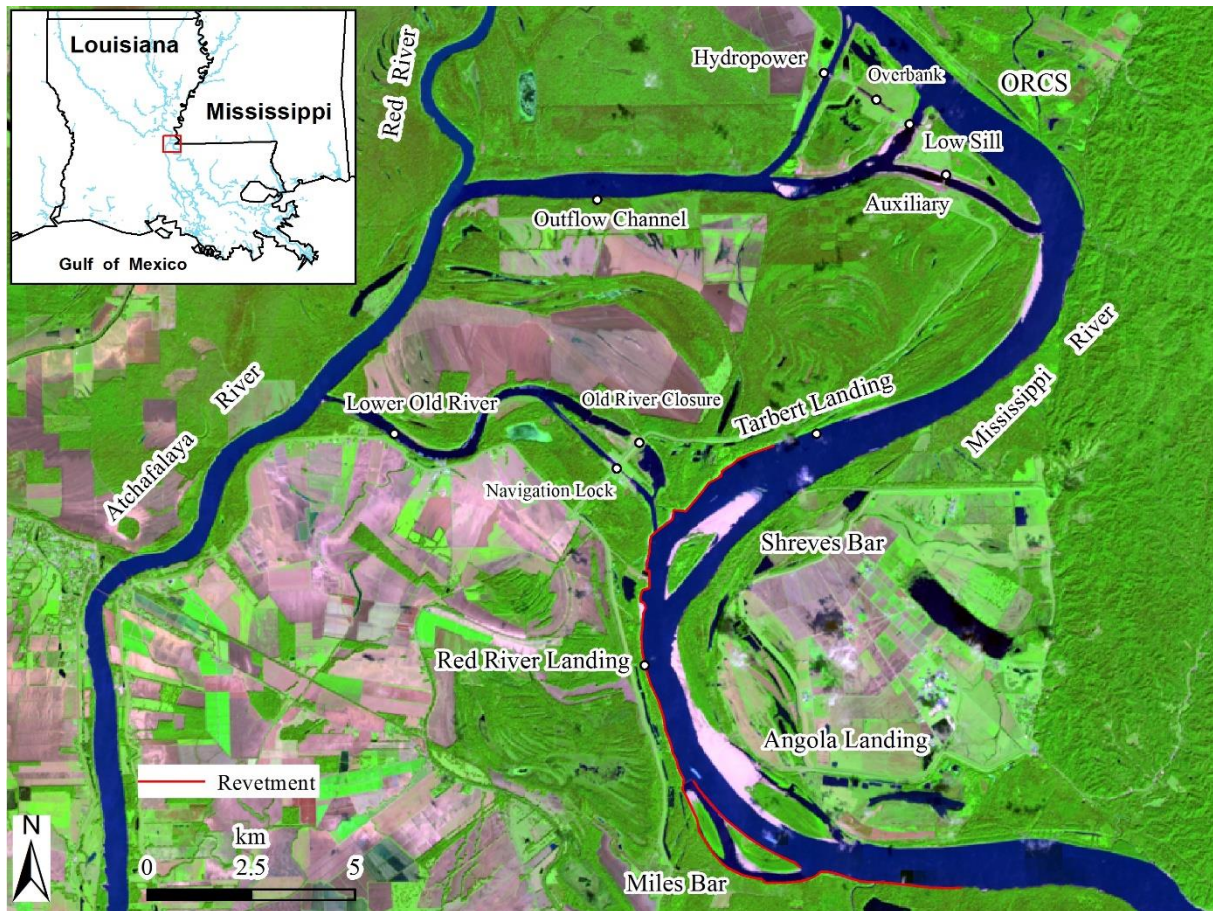


Figure 3.1. Three large channel bars – Shreves Bar, Angola Landing and Miles Bar locate in a 10-km long reach which is shortly below the Mississippi-Atchafalaya River diversion - Old River Control Structures (ORCS). The ORCS includes hydropower project, overbank, low sill and auxiliary structures. All three channels in the ORCS divert water from the Mississippi River to the Atchafalaya River. The Lower Old River is a navigation channel and controlled by navigation lock. Two gauging stations - Tarbert Landing and Red River Landing are shown. The west bank of the 10-km studied reach is protected by revetment. In addition, one revetment was built in front of Miles Bar.

The 10-km long river reach investigated in this study is located shortly downstream of the ORCS. The reach includes two mid-channel bars – Shreves Bar and Miles Bar and one point bar – Angola Landing, and they are located approximately 18, 24, and 26 kilometers downstream of the ORCS (Figure 3.1), respectively. In addition to the flow regulation by the diversion, several river engineering constructions exist in the reach which include a trenchfill revetment through

the middle of Miles Bar, stone dikes on the east bank of the river and one single dike near Miles Bar. These constructions were done between September 1990 and June 1996 (Copeland et al., 2010). In addition, the whole west bank of the reach is also protected from erosion by revetments.

Several gauge stations are located in the reach. Red River Landing (RRL) gauge station measures daily river stage data and the available data is from 1987 (30°57'39" N., 91°39'52" W; river kilometer 487, or river mile 302.4; USACE Gauge ID: 01120). The U.S. National Oceanic and Atmospheric Administration (NOAA) uses the station's stage for lowermost Mississippi River flood prediction. Tarbert Landing (TBL) gauge station (31°00'30" N, 91°37'25" W), located at river kilometer 493 (river mile 306.3), about 16 kilometers downstream the ORCS, provides the discharge data spanning the longest period for the lowermost Mississippi River where both the U.S. Geological Survey (USGS) and the U.S. Army Corps of Engineers (USACE) have a monitoring station (USGS Station ID: 07295100 and USACE Gauge ID: 01100).

3.3 METHODS

3.3.1 Data Collection

Satellite images and river stages are two major sources of data used in this study. A series of cloud-free satellite images covering the study area (Path 23 Row 39), Landsat Surface Reflectance Climate Data Record (CDR), were collected from the USGS for the period from 1984 to 2015. CDR is a derived product from level-1 data of Landsat 4-5, Landsat 7 and Landsat 8 processed by the Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) (Wolfe et al., 2004). LEDAPS is designed for atmospheric correction by considering the impacts of water vapor, ozone, geopotential height, aerosol optical thickness, and digital elevation. High accuracy 6S (Second Simulation of a Satellite Signal in the Solar Spectrum) radiative transfer codes (Kotchenova and Vermote, 2007; Vermote et al., 1997) were used in

LEDAPS to generate the products including Top of Atmosphere (TOA) Reflectance, Surface Reflectance, Brightness Temperature, and masks for clouds, land, and water (Masek et al., 2006). In our study, the products of surface reflectance and water mask were used to acquire the channel morphology and surface area of the channel bars. The images with atmospheric correction are beneficial for the estimation of surface area change in the long term.

Daily river stage data at Red River Landing (Station ID: 01120) were collected for the period from 1984 to 2015 to determine emerged surface area of the channel bars. For the same period, daily river discharge at Old River Outflow Channel (OROC) (Station ID: 02600) and Tarbert Landing (Station ID: 01100) were also collected to characterize flow conditions in the studied river reach. The discharge at OROC included the discharge in Hydropower project, Auxiliary structure and Low Sill structure (Figure 3.1).

3.3.2 Estimation of Channel Morphology and Surface Area Change of the Bars

River stage affects the appearance of channel morphology and the size of the emerged surface area of the channel bars. Therefore, the long-term estimation of them by satellite images must ensure that the river stages on the days when images were captured were similar. Besides, the suitable time interval of the images is important to reveal the morphological changes of the channel and bars well. Based on these criteria, eight images with 4 or 5-year time interval were selected from 1985 to 2015 (Table 3.1). The river stages on these dates were very close (6.42 - 6.72 m).

River channel and bar outlines in each of these images were digitized in ArcGIS 10.3 software (ESRI, Redlands, California, USA). Shortwave band – band 5 (1.55 – 1.75 μm) of the image was used in the digitization because land and water can be easily differentiated in this band.

Table 3.1 Landsat CDR images used for estimation of the change in bar surface area and the dates and river stages when the images were captured.

Date	River Stage (m)	Landsat CDR products No.
22 Aug 1985	6.42	LT50230391985234XXX04
24 Nov 1990	6.46	LT50230391990328XXX05
21 Oct 1995	6.55	LT50230391995294XXX02
21 Aug 1999	6.54	LE70230391999233EDC00
25 Sep 2003	6.68	LT50230392003268LGS01
20 Sep 2007	6.51	LT50230392007263CHM01
17 Oct 2011	6.42	LT50230392011290EDC00
18 Sep 2015	6.72	LE70230392015261EDC00

3.3.3 Estimation of Volume Change of the Bars

The method of surface area – river stage rating curve has been successfully applied to estimate the volume change of Shreves Bar, Angola Landing, and Miles Bar before and after the 2011 spring Mississippi River flood (Wang and Xu, 2015). In their study, the rating curves for each of the three bars before and after the flood were built by a series of river stages (x-axis) and corresponding surface areas of the bar (y-axis) (Figure 3.2). The emerged surface areas at different river stages can be acquired from corresponding images used the method described in section 3.2. The rating curves were best fitted by 2nd-order polynomial equations (Figure 3.2b).

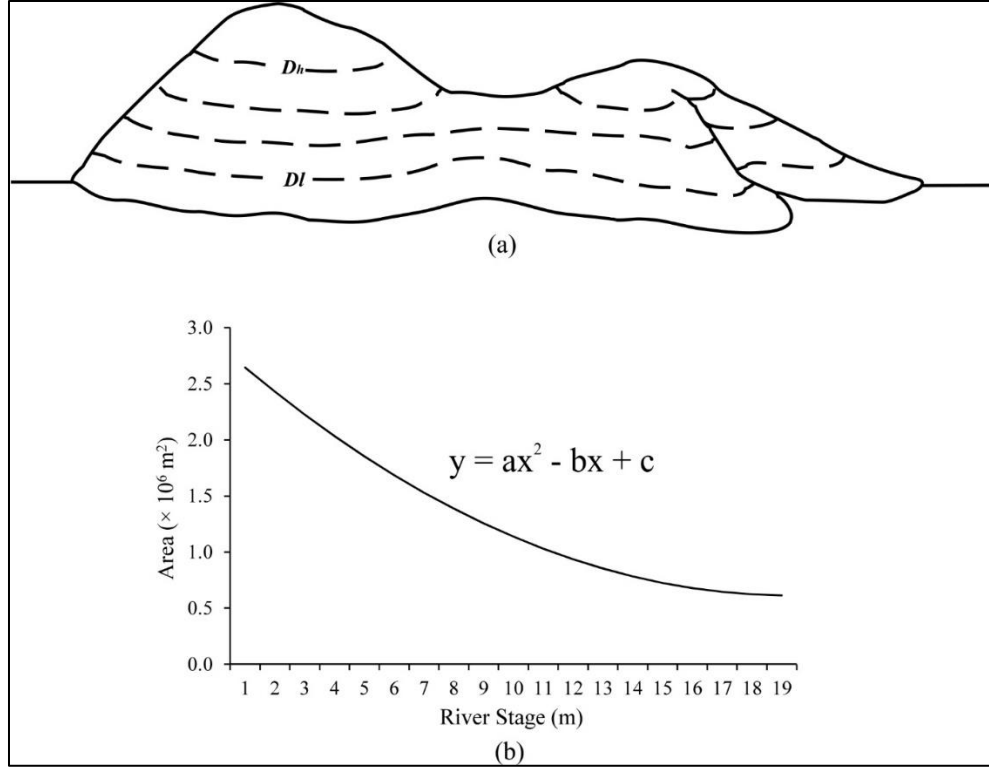


Figure 3.2. (a) Diagram of a channel bar with its fluctuating emerged surface area in the relation with river stage height. D_h and D_l are the highest and lowest river stage; (b) A surface area – river stage rating curve, which usually can be best fitted by a second order polynomial equation according to Wang and Xu (2015).

Volume (V_s) of each bar between the highest stage (D_h) and the lowest stage (D_l) then was calculated by integral based on the surface area – river stage rating curves (Wang and Xu, 2015):

$$V_s = \int_{D_l}^{D_h} (ax^2 - bx + c) dx = \left(\frac{ax^3}{3} - \frac{bx^2}{2} + cx \right) \Big|_{D_l}^{D_h} = \left(\frac{aD_h^3}{3} - \frac{bD_h^2}{2} + cD_h \right) - \left(\frac{aD_l^3}{3} - \frac{bD_l^2}{2} + cD_l \right) \quad (1)$$

where V_s is the bar volume, D_h is the highest river stage, D_l is the lowest stage, and a , b and c are constants.

In the present study, the volumes of the three bars in 1985 and 2015 are needed to estimate. For building the rating curves of the three bars in these two years, ideal situation is that

enough cloud-free images in each year exist to cover a large range of river stage which helps to acquire more surface areas in the year. However, the examination of river stages and images found that the amount of available images are not able to build the rating curves in 1985 and 2015. After careful consideration, instead, eight images captured during 1984 and 1986 were selected to build the rating curve in 1985 (Table 3.2). The river stages associated with these images were from 5.5 to 15.3 m. In addition, eight images taken in 2013 and 2014 were used to estimate the bar volume in 2013 because no enough images can develop the rating curves in 2014 and 2015. The river stages associated with these images were from 5.5 to 15.3 m. The common range of the river stages in these two periods was from 6.1 to 15.3 m which were used as the limits of integration to estimate the bar volume.

Table 3.2. Dates and product numbers of Landsat CDR images used for estimation of the change in bar volume at different river stages when the images were captured.

Date	Stage (m)	Landsat CDR products No.	Date	Stage (m)	Landsat CDR products No.
Volume estimation in 1985			Volume estimation in 2013		
07 Nov 1984	11.0	LT50230391984312XXX02	29 Apr 2013	14.3	LC80230392013119LGN01
09 Dec 1984	12.0	LT50230391984344XXX03	15 May 2013	15.9	LC80230392013135LGN01
16 Apr 1985	15.3	LT50230391985106XXX03	04 Sep 2013	7.5	LC80230392013247LGN00
22 Aug 1985	6.4	LT50230391985234XXX04	07 Nov 2013	6.1	LC80230392013311LGN00
21 May 1986	9.3	LT50230391986141XXX03	27 Feb 2014	9.8	LC80230392014058LGN00
24 Jul 1986	9.8	LT50230391986205XXX05	05 Jul 2014	11.5	LC80230392014186LGN01
25 Aug 1986	5.5	LT50230391986237XXX04	23 Sep 2014	9.1	LC80230392014266LGN00
28 Oct 1986	12.9	LT50230391986301XXX03	25 Oct 2014	10.7	LC80230392014298LGN00

The standard error of the estimate (SE) was used to measure the error of these rating curves.

$$SE = \sqrt{\frac{\sum(\hat{y}-y)^2}{N-P}} \quad (2)$$

where SE is the standard error of the estimate, \hat{y} is the predicted value and y is the actual value, N is the sample size, P is the number of the parameters in the model, for linear regression, $P = 2$, for second order polynomial regression, $P = 3$. SE calculates the average distance between observed values and the regression line. Smaller SE indicates smaller prediction error. Coefficient of variation (CV) as the ratio of SE to the mean of the observed values was also used to estimate model error.

3.4 RESULTS

3.4.1 Long-term Hydrologic Conditions

Over the past 30 years (1985-2015), daily discharge at Tarbert Landing of the lowermost Mississippi River averaged 14,968 cubic meter per second (cms), varying from 3143 cms in the extremely dry year of 1988 to 45,845 cms in the flood year of 2011 (Table 3.3). During the same period, the river was diverted through the Old River Outflow Channel (OROC) with a daily average of 4,365 cms, fluctuating from zero flow for 26 days in 1987 and a high discharge of 19,001 cms in May 2011. Therefore, the ratio of the diverted Mississippi River to the total discharge at TBL and OROC varied from 0% to 38%, with an average ratio of 23%. The ratio did not change with the total discharge but often had an opposite tendency (Figure 3.3). Seasonally, discharge of the lowermost Mississippi River is high during the winter and spring and low during the summer and early fall. Despite the flow seasonality, on average 24% of the river during the seasons was still diverted into the Atchafalaya River (Table 3.3). In a long-term river flow study at Tarbert landing, Rosen and Xu (2014) separated the corresponding flow regimes <13,000 cms for Low Flow Stage, 13,000–18,000 cms for Action Flow Stage, 18,000–25,000 cms for Intermediate Flow Stage, 25,000–32,000 cms for High Flow stage, and >32,000 cms for Peak Flow Stage.

Table 3.3. Long-term (1985-2015) and seasonal discharge at Tarbert Landing (TBL) and Old River Outflow Channel (OROC). Ratio values are the proportion of diverted river at OROC from the Mississippi River.

	Discharge (cms)				
	1985 - 2015	Average values for each season			
	Annual mean (<i>min - max</i>)	Spring	Summer	Fall	Winter
TBL	14,968 (3,143 - 45,845)	21,303	13,862	8,499	16,226
OROC	4,365 (0 - 19,001)	6,068	4,438	2,689	4,250
Total	19,333 (4,191 - 64,676)	27,370	18,299	11,188	20,475
Ratio	23%	22%	24%	24%	21%

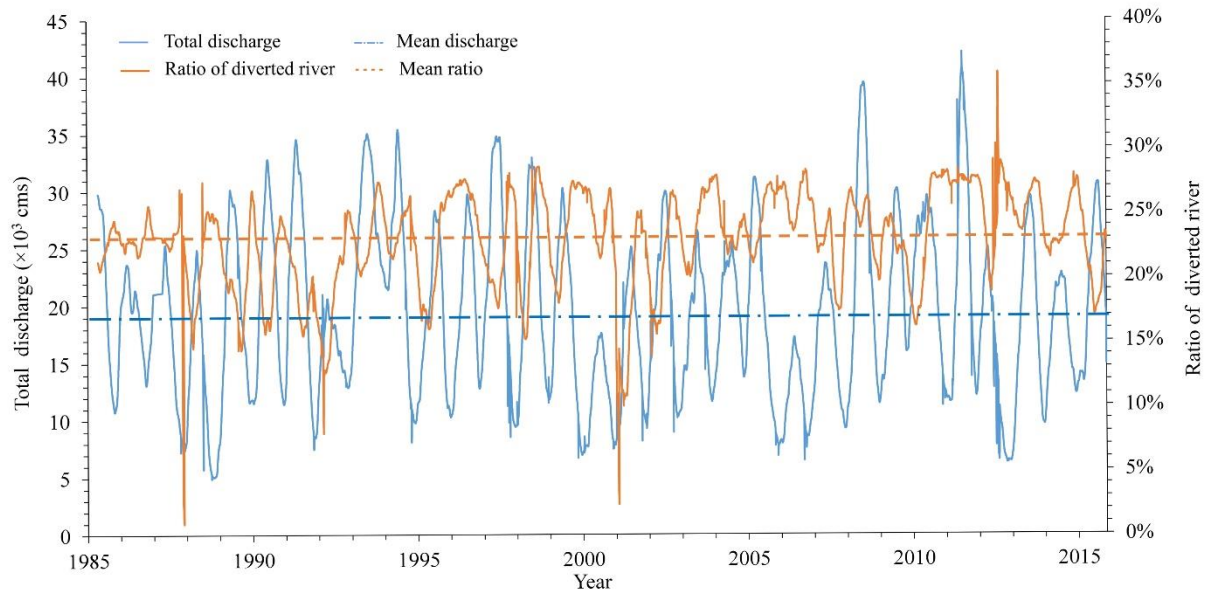


Figure 3.3. The long-term trend of flow at the Mississippi-Atchafalaya River diversion. Total discharge is the sum of discharge at Old River Outflow Channel (OROC) and at Tarbert Landing (TBL); Ratio of diversion is the ratio of discharge at OROC to the Total discharge of the Mississippi River. Both of these two discharges were presented with a 120-day moving average. The upper line and the lower line indicate the mean ratio of diverted water (23%) and mean total discharge (19,333 cms), respectively. The long-term discharge data were obtained from the U.S. Army Corps of Engineers.

The discharge – river stage rating curves in 1988, 1999 and 2015 (Figure 3.4) showed a continuous change in their relationship over the past 30 years. For instance, at the discharge of 6,000 cms, the corresponding daily mean river stage was 4.9 m in 1988, 5.5 m in 1999 and 6.2 m in 2015. Overall, there was an increase of 1.3 m in river stage from 1988 to 2015 for a same quantity of discharge. The rising trend of the river stage is more apparent at higher flows, for instance, at a discharge between 14,000 to 22,000 cms, the river stage increased by approximately 1.5 m from 1988 to 2015.

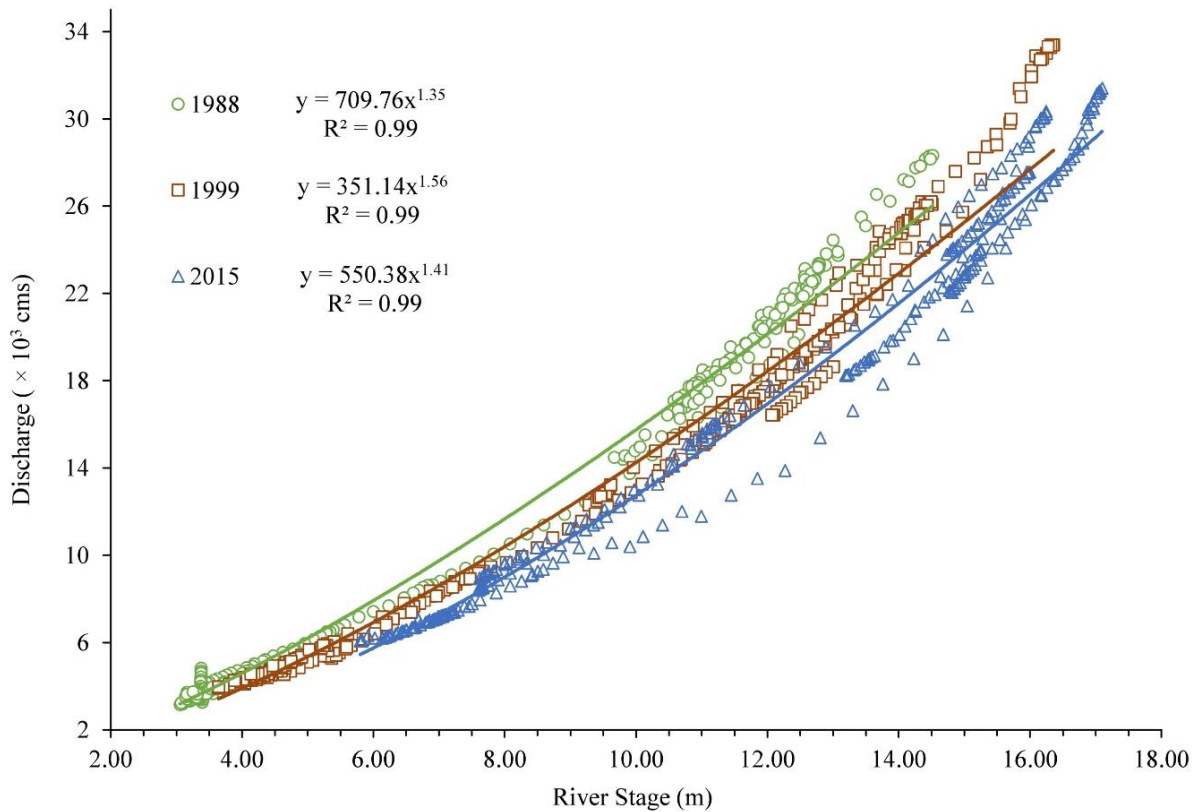


Figure 3.4. Changes in the relationship between daily mean river stage and discharge downstream of the Mississippi-Atchafalaya River diversion over the past 30 years. The river stage data were collected at Red River Landing, the discharge data were collected at Tarbert Landing, and these data were obtained from U.S. Army Corps of Engineers and U.S. Geological Survey.

3.4.2 Morphological Change of the River Channel

Over the past 30 years, the studied 10-km long river reach below the Mississippi-Atchafala River diversion experienced marginal changes on its west bank, but significant changes on its east bank (Figure 3.5). As a whole, the reach can be divided into three different segments based on the variation of the east bank. The east bank of the upper reach (U) has been eroding since 1985, causing the channel to widen by about 150 m. In the middle reach (M), the east bank experienced substantial sediment trapping, narrowing the channel by about 550 m. Comparing to the upper and the middle reach, the lower reach (L) showed the most dynamic change: during the 5-year period 1985-1990, the channel was significantly widened by about 360 m; in the following 5 years, the channel widening continued for another 120 m on both east and west banks; however, in the last 20 years, the channel width declined by about 1000 m. In the west bank, about 400 m channel narrowing also occurred in 2003–2015.

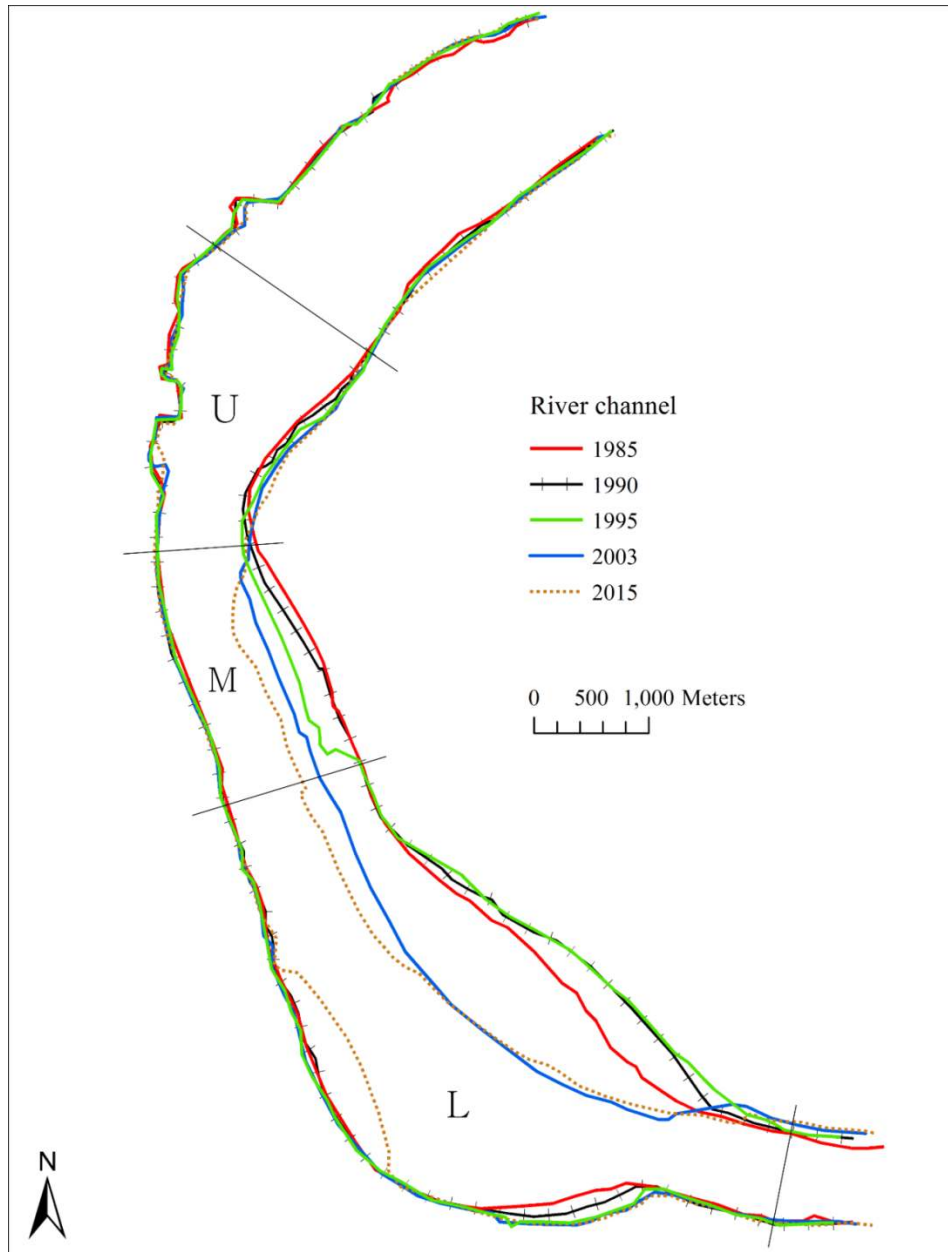


Figure 3.5. Morphological change of a 10-km long river channel downstream of the Mississippi-Atchafalaya River diversion from 1985 to 2015. The middle (M) and the lower (L) section of the channel experienced substantial sediment deposition on their east banks, causing the channel narrowed by 800 m in average.

3.4.3 Long-term Change in Bar Size

Over the past 30 years, the three major bars nearby downstream of the Mississippi-Atchafalaya River diversion showed a significant change in their size and shape (Figure 3.6). Located nearest to the river diversion, Shreves Bar showed first a slight decline in its surface area during 1985–1990, then a steady longitudinal increase, leading to a continuous elongation to the present day (from 2,700 m to 3,800 m). The fastest increase rate of it was between 1990 and 1995 (Figure 3.7). Located six kilometers downstream of Shreves Bar and two kilometers upstream of Miles Bar, the size of Angola Landing was very small in 1985. However, the point bar showed a remarkable, continuous growth since 1985: Angola Landing was only a 1,200-m long narrow strip in 1985 (Figure 3.6a); by 1999, it had grown to a 6,500-m long, 600-m wide large point bar (Figure 3.6b–d). On the whole, the bar rapidly increased before 1999, but had no large increase during 1999–2007, and then had a nearly tripled increase from 2007 to 2011 than the period 2003–2007 (Figure 3.7). When compared with Shreves Bar and Angola Landing, Miles Bar was the largest bar in 1985. The bar showed a significant elongation from 1985 to 1990 (Figure 3.6b) but a large decline of its emerged surface area during the 1990s (Figure 3.6b–d). Afterwards, Miles Bar had a continuous increase as a new bar grew along the west bank (Figure 3.6e–h). The increase rate of it has slowed down since 2003 (Figure 3.7).

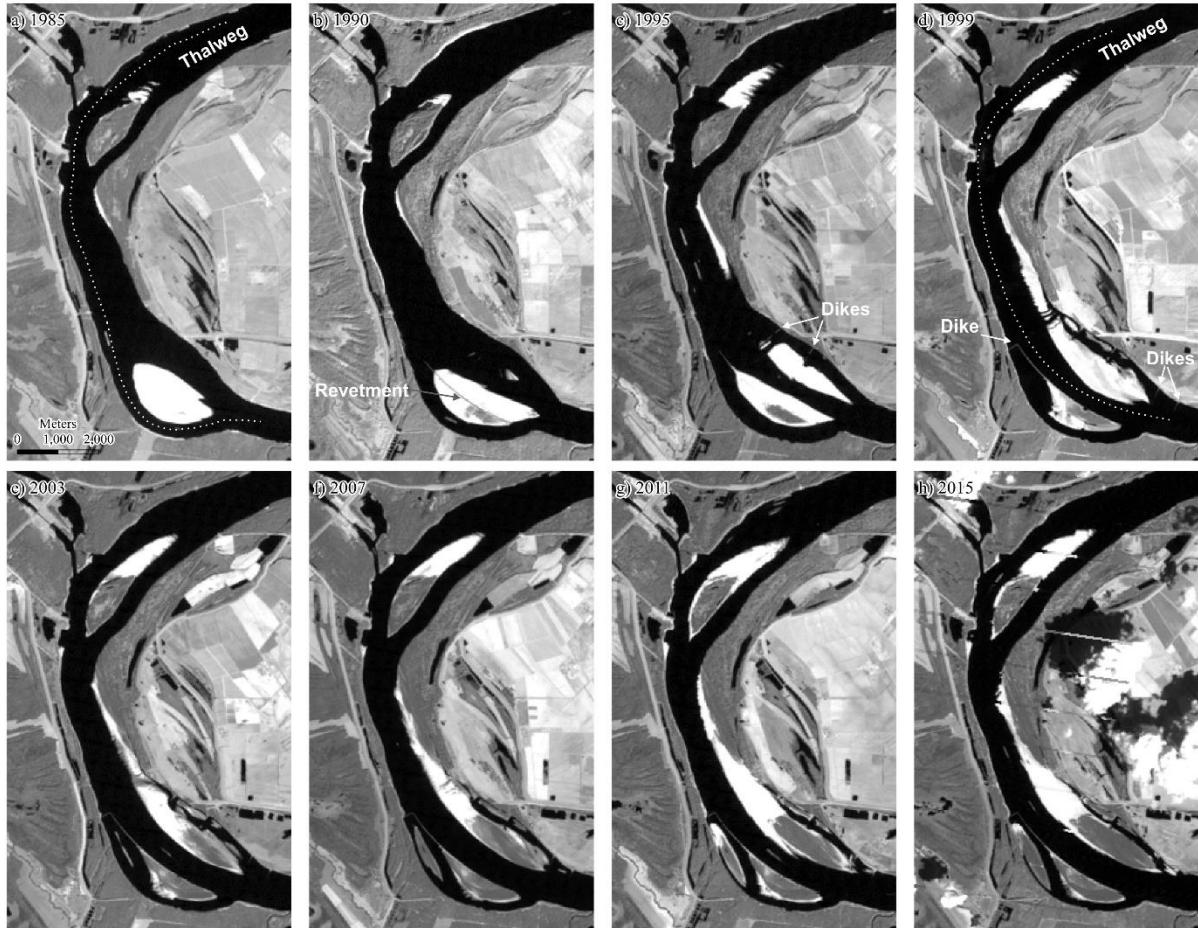


Figure 3.6. Morphological changes of Shreves Bar, Angola Landing and Miles Bar downstream of the Mississippi-Atchafalaya River diversion over the past 30 years. The river stage is close in each image (6.42-6.72 m). The construction of a trenchfill revetment through the middle of Miles Bar and the dikes on the east bank of the river and on the Miles Bar head in the early 1990s greatly changed the morphology of the channel and the bars. The trenchfill revetment caused the sediment on its east side was rapidly removed by river flow in 1990-1999 (Figure 3.6b-d). The revetment then became the new river bank which narrowed the main channel. The thalweg was also shifted to the east side of Miles Bar (Figure 3.6d). During the same period of revetment construction, 5 spur dikes were built along the east bank of the reach (4 visible in Figure 3.6c-d).

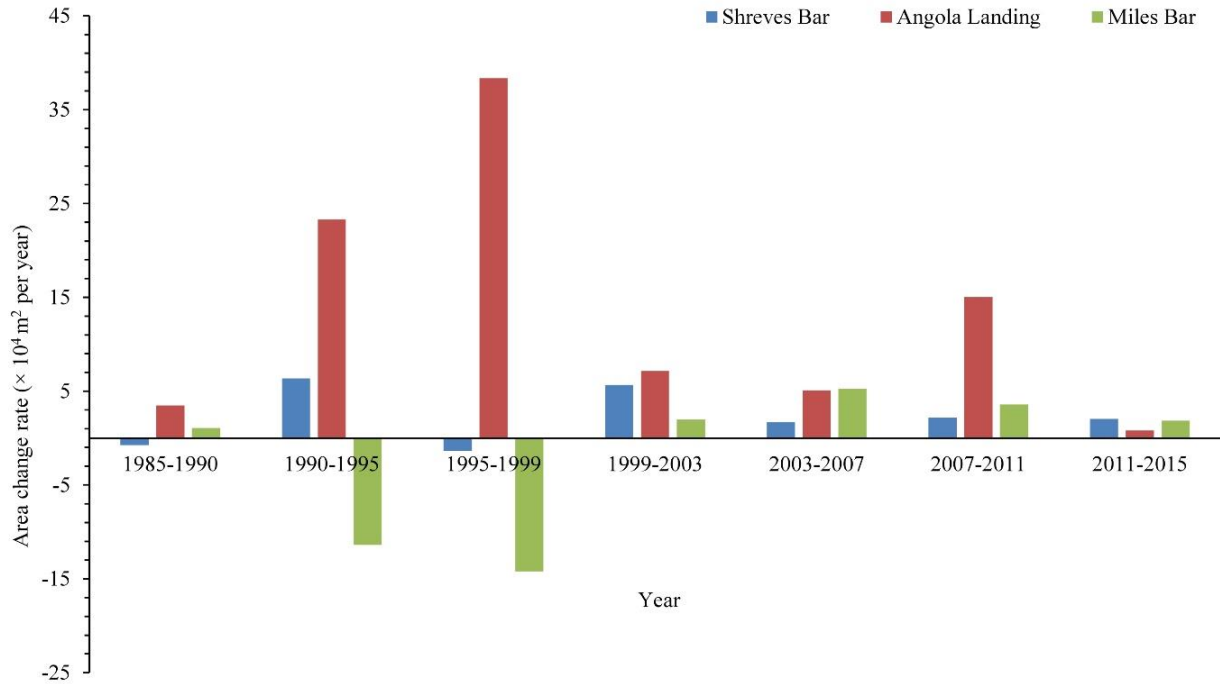


Figure 3.7. The annual change rate of the emerged surface area of three large channel bars downstream of the Mississippi-Atchafalaya River diversion in different periods of 1985 to 2015.

As a whole, over the past 30 years, the total emerged surface area of the three major bars downstream of the Mississippi-Atchafalaya River diversion increased by 4,107,000 m² or 119% of that in 1985 (Table 3.4). Angola Landing had a much higher increase (36 times of that in 1985 or 3,996,000 m²) when compared with Shreves Bar (53% or 687,000 m²). On the contrary, the emerged surface area of Miles Bar showed a 28% net decrease (or -576,000 m²).

Table 3.4. Estimation of surface area by satellite images and their changes comparing to the last dates (*italic*) for three large channel bars near the Mississippi-Atchafalaya River diversion in 1985-2015.

Date	Shreves Bar	Angola Landing	Miles Bar
EmergEd Area and changes (m ²)			
22 Aug1985	1,303,600	115,300	2,046,000

(table cont'd.)

Date	Shreves Bar	Angola Landing	Miles Bar	
Emerged Area and changes (m ²)				
24 Nov 1990	1,265,400 (-38,200)	288,800 (+173,500)	2,099,200 (+53,200)	
21 Oct 1995	1,582,900 (+317,500)	1,453,500 (+1,164,700)	1,529,700 (-569,500)	
21 Aug 1999	1,528,900 (-54,000)	2,987,600 (+1,534,100)	961,600 (-568,100)	
25 Sep 2003	1,755,700 (+226,800)	3,273,600 (+286,000)	1,041,000 (+79,400)	
20 Sep 2007	1,823,300 (+67,600)	3,477,400 (+203,800)	1,251,600 (+210,600)	
17 Oct 2011	1,909,900 (+86,600)	4,078,900 (+601,500)	1,394,800 (+143,200)	
18 Sep 2015	1,991,000 (+81,100)	4,111,300 (+32,400)	1,469,600 (+74,800)	
Period	Area change in the long term (m ²)		Total	
1985–2015	687,400	3,996,000	-576,400	4,107,000
Δ%	53%	3466%	-28%	119%

3.4.4 Emerged Surface Area – River Stage Rating Curve

The sizes of the three studied bars at different river stages were assessed for two short time periods: 1984-1986 and 2013-2014 (Table 3.5), in order to develop a rating curve of surface area – river stage for each of the bars. During 1984-1986, the lowest and highest river stages when a satellite image was taken were 5.5 m and 15.3 m. While Shreves Bar was never submerged, Miles Bar was submerged at the river stage of 11.0 m and Angola Landing at the river stage of 12.0 m. During 2013-2014, the lowest and the highest river stage were 6.1 m and 15.9 m, and all three bars stood above the highest river stage.

Table 3.5. Estimated surface areas of the three large channel bars and the corresponding river stages in each day.

Date	River Stage (m)	Shreves Bar	Angola Landing (m ²)	Miles Bar
07 Nov 1984	11.0	1,027,300	16,900	0

(table cont'd.)

Date	River Stage (m)	Shreves Bar	Angola Landing (m ²)	Miles Bar
09 Dec 1984	12.0	971,300	0	0
16 Apr 1985	15.3	922,200	0	0
22 Aug 1985	6.4	1,271,300	125,500	1,946,200
21 May 1986	9.3	1,012,900	48,900	569,100
24 Jul 1986	9.8	1,010,100	33,500	412,200
07 Nov 1984	5.5	1,556,500	159,100	2,532,500
09 Dec 1984	12.9	964,400	0	0
29 Apr 2013	14.3	811,600	1,785,600	881,900
15 May 2013	15.9	784,300	1,717,200	836,300
04 Sep 2013	7.5	1,413,500	3,753,800	1,287,400
07 Nov 2013	6.1	1,784,700	4,192,300	1,433,200
27 Feb 2014	9.8	1,005,700	2,869,400	1,127,800
05 Jul 2014	11.5	883,900	1,971,000	1,008,300
23 Sep 2014	9.1	1,102,200	3,353,000	1,273,800
25 Oct 2014	10.7	928,900	2,684,100	1,205,700

As expected, a highly close relationship between river stage and emerged surface area of the bars was found for the 1984-1986 and 2013-2014 periods. The relationships were best fitted by a 2nd-order polynomial equation, except for Miles Bar during 2013-2014, for which a linear regression was applied (Figure 3.8). All the regressions achieved a high regression coefficient (R^2 , 0.92 to 1.00), as well as a satisfactory range of standard error (SE) and coefficient of variation (CV, mostly < 5%) (Table 3.6), showing the credibility of using the rating curves for predicting the emerged bar sizes with the river stages during the periods.

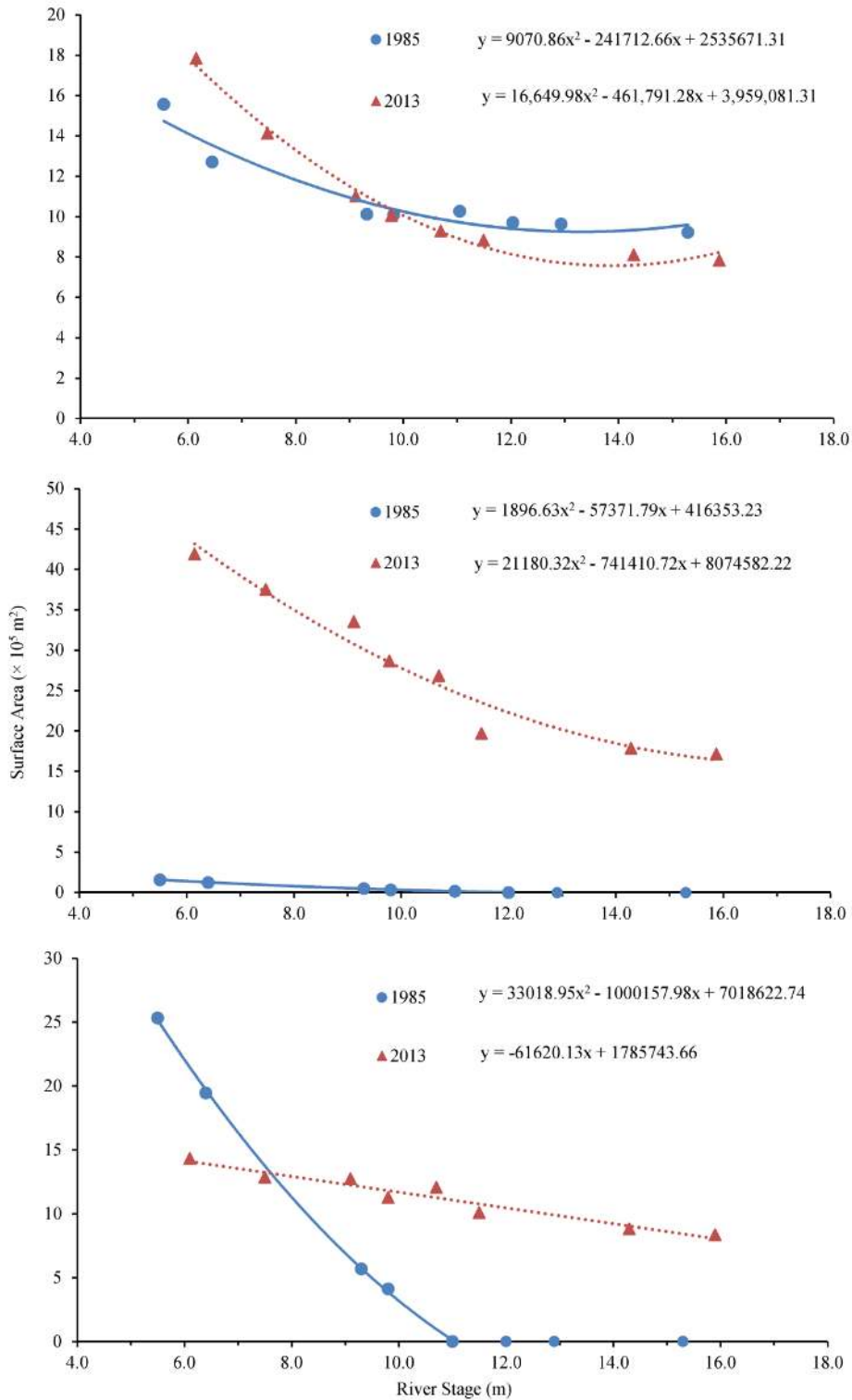


Figure 3.8. Rating curves of emerged surface area – river stage for Shreves Bar (top), Angola Landing (middle), and Miles Bar (bottom) downstream of the Mississippi-Atchafalaya River diversion.

Table 3.6. Estimation of the surface area – river stage rating curves for three large channel bars downstream of the Mississippi-Atchafalaya River diversion in 1985 and 2013. The standard error of mean (SE) and coefficient of variation (CV) are calculated for each of the rating curves.

Year	Bar	R ²	SE (m ²)	CV
1985	Shreves Bar	0.92	69,965	6%
	Angola Landing	1.00	2,595	4%
	Miles Bar	1.00	27,944	3%
2013	Shreves Bar	0.99	40,385	4%
	Angola Landing	0.96	228,661	8%
	Miles Bar	0.94	57,176	5%

3.4.5 Long-term Change in Bar Volume

The volumes of Shreves Bar, Angola Landing and Miles Bar in 1985 and 2013 were estimated by taking integrals of the rating curves of surface area – river stage developed for the bars. Based on the estimation, in 1985, Shreves Bar, Angola Landing, and Miles Bar had a bar volume of $9,677 \times 10^3 \text{ m}^3$, $342 \times 10^3 \text{ m}^3$, and $4,641 \times 10^3 \text{ m}^3$ between the river stage of 6.1 m and 15.3 m, respectively (Table 3.7). In 2013, for the same river stage range, these three bars (in the same order as above) had a bar volume of $9,583 \times 10^3 \text{ m}^3$, $24,985 \times 10^3 \text{ m}^3$, and $10,363 \times 10^3 \text{ m}^3$, showing a marginal change in volume for Shreves Bar (-1%) but a 123% growth for Miles Bar and a near 72-fold increase for Angola Landing. As a whole, the volume of the three bars increased more than doubled over the past 30 years.

Table 3.7. Changes in volume of three large channel bars downstream of the Mississippi-Atchafalaya River diversion during 1985–2013.

Bars	Volume (m ³)		Mass* (metric ton)		
	1985	2013	Δ	Δ (%)	Δ
Shreves Bar	9,677,000	9,583,000	-94,000	-1%	-113,000
Angola Landing	342,000	24,985,000	24,643,000	7206%	29,572,000
Miles Bar	4,641,000	10,363,000	5,722,000	123%	6,866,000
Total	14,660,000	44,931,000	30,271,000	206%	36,325,000

* Based on the assumption of the bulk density of the bars is 1.2 metric tons per cubic meter.

Assuming a bulk density of 1.2 metric tons per cubic meter of the bars, the change in bar volume from 1985 to 2013 represents a deposition of $29,572 \times 10^3$ metric tons of sediment on Angola Landing and of $6,866 \times 10^3$ metric tons of sediment on Miles Bar. The mass change on Shreve Bar was marginal (-113,000 metric tons). In total, 36 million metric tons (MT) of riverine sediment were trapped on the three bars between river stage of 6.1 m and 15.3 m.

3.5 DISCUSSION

By examining historical maps and aerial images, Kesel (2003) found that the emerged channel bars in the Mississippi River from Cairo, Illinois to Red River Landing, Louisiana tended to adjust the amount and size from 1880 to 1963, while the bars below Red River Landing had fewer channel bars and showed little variation in size. However, the results presented in this study indicate that dramatic changes of channel bars near Red River Landing did occur after 1985. With an average of 23% water loss through the Mississippi-Atchafalaya River diversion, flow power and sediment transport potential were largely reduced in the river downstream of the diversion and therefore, caused consequently downstream sediment deposition. It is evidenced by the rapid growth of Miles Bar during 1988-1991 (Figure 3.9a-b) and the significant channel widening (360 meters) during 1985-1990 in the lower section of the reach (Figure 3.5). At the time, no other engineering practices functioned except the diversion. The rapid development of Miles Bar supports the argument by Smith and Winkley (1996), who concluded that the most significant morphological response of the Lower Mississippi River to river engineering since the 1920s was the formation of mid-channel bars. Brown et al. (2013) also pointed out that the adjustment of channel morphology downstream of the diversion might include the formation of point bars and/or lateral bars.

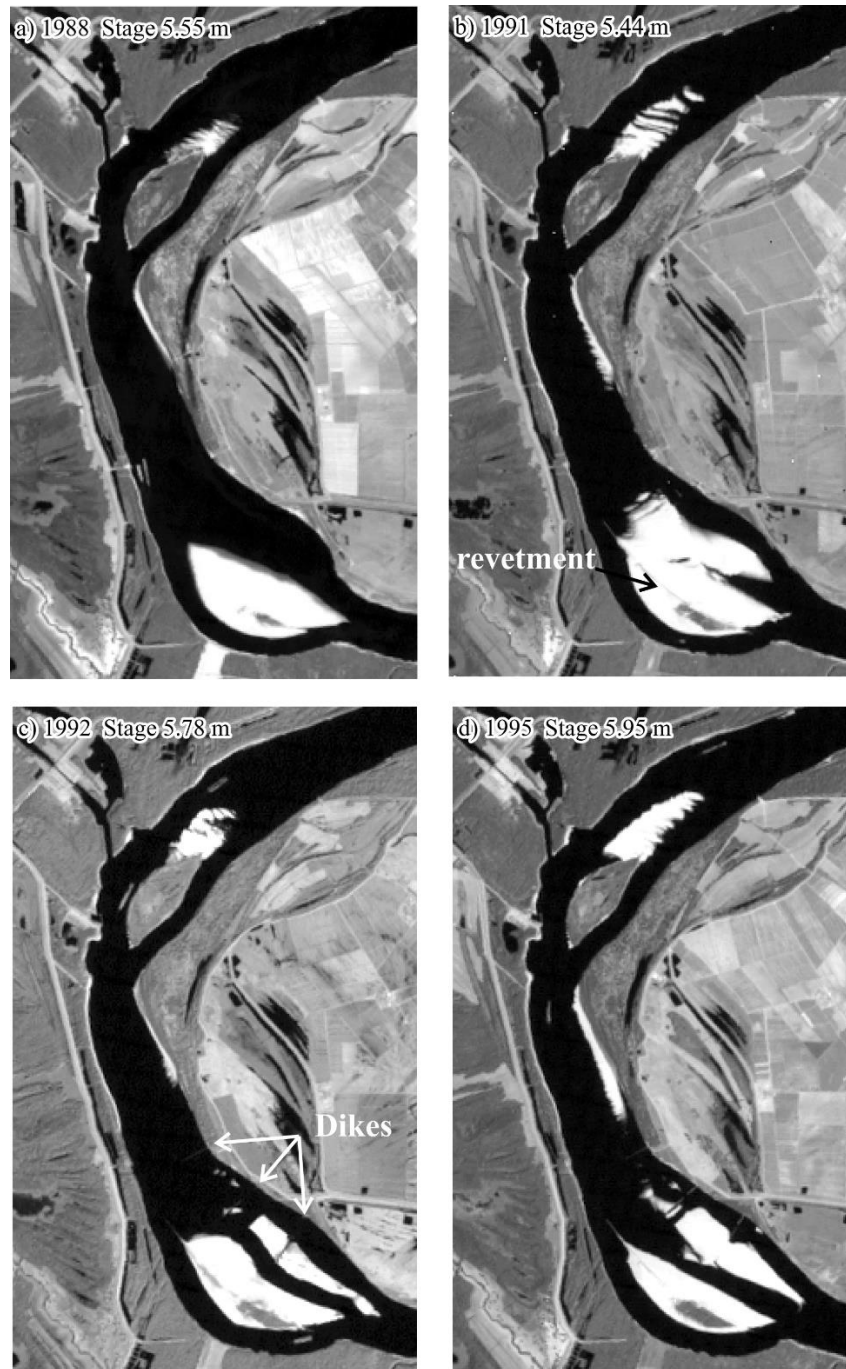


Figure 3.9. Morphological changes of Shreves Bar, Angola Landing, and Miles Bar from 1988 to 1995. The river stage heights were similar on the four dates when the satellite images were taken. (a) and (b) show the rapid growth of Miles Bar during 1988-1991. (c) and (d) show the initial bar tail of Angola Landing was from the braided Miles Bar. In addition, showing the rapid development of the Angola Landing during 1992-1995.

In addition to the flow regulation by the Mississippi-Atchafalaya diversion, the dike and revetment constructions within this 10-km reach are partially responsible for the morphological change of the river channel and the bars. Dikes are generally used to enhance navigation, improve flood control and protect erodible banks (Copeland, 1983). However, sediment deposition usually occurs in the void areas between each of the dikes (Alexander et al., 2012; Nunnally and Beverly, 1986; Smith, 1986). In the studied reach, the most significant effect of dikes was to stop further bank erosion after 1995 (Figure 3.5). However, how these dikes affected the sediment dynamics in the reach? To address this question, a set of satellite images taken before and after the dike construction were examined.

Before the engineering practices, Miles Bar was well-developed and occupied most of the channel in 1988 (Figure 3.10). If no river engineering had been undertaken, more flow would have been redirected into the main channel (near west bank), and the channel should deepen, which may cause instability and further bank erosion (Figure 3.10) (Ashworth et al., 2000). In the meantime, the secondary channel near the east bank may be most likely clogged with sediment, and finally, the bar would attach to the river bank based on the development theory of mid-channel bars (Hooke, 1986). However, with the construction of trenchfill revetment in 1991 (Figure 3.9b), sediment deposit on its east side was removed, and a new main channel was formed (Figure 3.9c). The built of dikes constrained the flow between the area of dike field and the trenchfill revetment. As a result, the sediment deposition on the dike field formerly belonged to Miles Bar which was not washed away but became a new bar core of lower Angola Landing in 1992 (Figure 3.9c). For that reason, we conclude that the initial development of lower Angola Landing was not mainly induced by the construction of dikes but the combination results of the rapid growth of Miles Bar and the trenchfill revetment. On the whole, the development of the

trenchfill revetment and the spur dikes in the studied reach, although developed a new navigation channel and largely changed the bar morphology, barely affected the remarkable tendency of sediment deposition induced by the operation of Mississippi-Atchafalaya River diversion. In fact, about 1.5 m stage increase at same discharge over the past three decades (Figure 3.4) also proved that sediment deposition occurred in the whole reach but not only around the dike field. Apart from the dikes, the single dike built near the bar head of Miles Bar closed the secondary channel and initiated the development of a new bar during the period 1999-2011(Figure 3.6d–e).



Figure 3.10. Morphology of the channel and Shreves Bar, Angola Landing and Miles Bar in 1988 at a low river stage of 3.29 m.

In a short-term study on morphological change of meander point bars, Kasvi et al. (2015) found that the flood event plays an essential role in point bar evolution: the longer the inundation of the bar, the more probable it gets net deposition. Wang and Xu (2015) reported that Shreves Bar, Angola Landing, and Miles Bar trapped a substantial amount of sediment during the 2011 Mississippi River flood. In that single flood, the surface area and volume of the three bars increased by 7.3% and 4.4%, respectively, and at least 1.0 MT sediment was deposited on the bars. In this present study, the rapid bar growth from 1992 to 1995 (Figure 3.9c-d) was very likely mainly a consequence of the “Great Flood of 1993” which created the highest mean annual discharge at Tarbert Landing (21,880 cms) in the past three decades and caused a sharp drop in the long-term rate of suspended sediment concentrations in the Lower Mississippi River (Horowitz, 2010). There is little doubt that floods could accelerate the development of channel bars. However, for the growth of Angola Landing during 1992-1995, the effects of the ORCS cannot be excluded, as evidenced by the rapid growth of Miles Bar prior to the revetments and dikes constructions. Also, the fastest growth of Angola landing occurred, in fact, during the period of 1995-1999, although the mean annual discharge (15,709 cms) was slightly lower than the period of 1990-1995 (16,860 cms). This may be resulted from the increased bend curvature due to the migration of the main channel which may cause the remarkable lateral growth of the bar (Blanckaert, 2011). The 80% larger bar area in 1995 than 1990 was probably more beneficial for sediment capture. Overall, the morphological changes of Angola Landing during 1990-1995 and 1995-1999 demonstrate that the development of a channel bar is not only determined by river flow (e.g., reduction by river diversions or increase by floods) but also related to bend growth and morphology of bar itself. The slower growth of Angola Landing during 1999-2007 was consistent with the finding of Pyrcce and Ashmore (2005) that as the development of a point

bar, bedload transport across the bar would decrease. Although transport along thalweg increases, deposition would only occur along the bar margin. This is reasonable because more flow and sediment would be transported downstream with increased thalweg incision. In addition, the low mean annual discharge from 1999 to 2007 (13,138 cms) further reduced the inundation time of Angola Landing. However, the four years from 2008 to 2011 were all flood years with a mean annual discharge of 17,507 cms. The rapid growth of Angola Landing during this period further demonstrates that floods can highly promote the development of the bar even in a relatively mature bend. It is not surprised that the lowest areal increase rate occurred in 2011–2015, during which no floods occurred and more important, the river bend appeared to be in equilibrium at present.

Although our estimate showed a doubled increase in volume for the three bars from 1985 to 2013, this increase ($30 \times 10^6 \text{ m}^3$) is likely an underestimation of sediment deposition because only the emerged volume of the bars, i.e., a river stage height between 6.1 m and 15.3 m, were calculated. Based on the actual geometry, the surface area of these bars (and most river channel bars) becomes larger with decreasing river stage. Therefore, it is highly likely that a large quantity of sediment (probably sands) is deposited on the bases of these bars below the river stage of 6.1 m. Little and Biedenharn (2014) estimated a total sediment volume increase of $31 \times 10^6 \text{ m}^3$ for the same river reach (excluding Shreves Bar) from 1992 to 2012. This estimate for 20 years was higher than our estimate for 30 years and, considering riverbed aggradation from 1985 to 1992, the actual sediment deposition in the reach from 1985 to 2013 should be much larger than $31 \times 10^6 \text{ m}^3$. The findings further indicate that accumulation of sediment in subaqueous areas of the bars may have occurred.

According to Joshi and Xu (2015), a total of 789 million metric tons (MT) sand load would have been discharged at Tartbert Landing from 1985 to 2013. Our conservative estimate of sediment deposition on the three bars is 36 MT (mostly coarse sediment by field observation) which only accounts for a relatively small portion of the total discharged sand load (i.e., 4.6%). However, there are hundreds of emerged channel bars located in the Lower Mississippi River between Cairo, Illinois and the ORCS, and many of them extend several kilometers. The sediment deposited on these bars in the long term could be an astronomical number. The success of proposed sediment diversions in the Lower Mississippi River greatly relies on enough riverine sediment supply (Davis, 1997; Thorne et al., 2008). The trapped sediment on the emerged channel bars should be considered as a precious resource for coastal restoration in the sinking Mississippi River Delta. Future studies are needed to estimate the amount of sediment deposited on those channel bars and to explore the ways to mobilize the sediment resources downstream.

3.6 CONCLUSIONS

This study contributes to a quantitative understanding of large river diversion effects on channel morphology and sediment deposition nearby downstream. The utilization of 3-decadal satellite images and daily hydrological data allowed a long-term and continuous assessment of the morphological changes, rather than event-based short-term studies. Based on the results, we conclude that diversion of the Mississippi River into the Atchafalaya River has caused significant changes in the channel morphology and sediment deposition on channel bars nearby downstream. The greatest change was the rapid growth of a point bar on the convex bank, amassing a total volume of 30,271,000 m³ (approximately 36 million metric tons of sediment, assuming a bulk density of 1.2 t/m³). The construction of revetments and dikes in the river reach has also contributed to the changes, especially the distribution of sediment deposition. The

findings highlight the importance of location-specific strategies in large river diversions for future flow and sediment regulation. Furthermore, the study demonstrates the great usefulness of remote sensing in quantifying long-term changes in sediment deposition on river channel bars.

CHAPTER 4. SEDIMENT TRAPPING BY EMERGED CHANNEL BARS IN THE LOWERMOST MISSISSIPPI RIVER DURING A MAJOR FLOOD

4.1 INTRODUCTION

The Mississippi River Delta (MRD), a 25,000 km² dynamic region on the southeastern coast of Louisiana in the USA, has been experiencing rapid land loss since the early 20th century (Britsch and Dunbar, 1993b; Craig et al., 1979; Gagliano et al., 1981; Scaife et al., 1983). The loss rate varied from 17 km²/yr in 1913 to 102 km²/yr in 1980 and averaged about 43 km²/yr during 1985-2010 (Couvillion, 2011; Kesel, 1988). In the past 80 years, a total of 4877 km² coastal land have lost (Couvillion, 2011). A number of factors have been attributed to the rapid land loss, including riverine sediment reduction due to upstream dam construction and river engineering, subsidence, and sea level rise (Boesch et al., 1994). It has been projected that, if no actions were taken, at least another 2118 km² land of Louisiana's coast would be lost over the next 50 years (Couvillion et al., 2013; Day et al., 2007). This possesses a severe threat to the energy industry, river transportation, and commercial fisheries in this region, all of which have the level of national importance.

Sediment from the Mississippi River (MR) is a precious resource for sinking coastal Louisiana. Currently, diversions of the lowermost MR are being proposed for introducing the riverine sediment to various wetland habitats on the sinking coast of the Mississippi River Delta (CPRA, 2012). The success of these projects will rely not only on the selection of river diversion locations but also on the actual sediment availability along the lowermost MR. The need for such information is especially critical at the planning stage because it is essential that river

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engineering helps maximally capturing the sediment resource while ensuring navigation safety and flood protection.

A number of studies have been conducted on sediment availability assessment for the Mississippi-Atchafalaya River System (MARS). For the Mississippi River main channel at Tarbert Landing, Meade and Moody (Meade and Moody, 2010) reported an average annual suspended sediment load (SSL) of 145 million metric tons (MT) over the period 1987-2006. For the same location, a report by the U.S. Army Corps of Engineers (Filippo) gave an average annual SSL of 134 MT for the decade 1989-1998 and a nearly 10% reduced load (123 MT) for the following decade. In a recent study, however, Rosen and Xu (Rosen and Xu, 2014) reported an average annual suspended sediment load of 126 MT for the four decades of 1980-2010, with an insignificant but slightly increasing trend from 1990 to 2010. For the Mississippi River's largest tributary, the Atchafalaya River at Simmesport, Xu (Xu, 2010) reported an average annual suspended sediment load of 64 MT over the period 1975–2004, while the USACE report (Filippo) gave an annual SSL of 48 MT for 1999-2008 and 75 MT for 1989-1998. In spite of the discrepancy among the reports, these estimates provide insights into magnitude and timing of riverine sediment in MARS. However, the locations for which sediment loads were made are far from the river mouths: Tarbert Landing is located nearly 500 km upstream from the outlet of the MR main channel to the Gulf of Mexico, while Simmesport is approximately 220 km from the mouth of the Atchafalaya River main channel to the Gulf of Mexico. Therefore, it is not clear how much of the sediment loads estimated for the two far-upstream locations can actually reach the coast.

In recent years, research on sediment availability of the MARS has focused on assessing sediment loss downstream Tarbert Landing and Simmesport. In their sediment budget study for

the upper 182-km reach of the Atchafalaya River Basin, Rosen and Xu (Rosen and Xu, 2015) found an annual sediment trapping of ~10% from 1980 to 2010, spatially occurred mainly in the lower basin areas with larger swamp and open water areas. In a shorter-term sediment budgeting for the flood years, 2008 - 2010, Allison *et al.* (Allison et al., 2012) reported that nearly half of the total annual suspended sediment on the MR and Red River were trapped between the Old River Control Structures and the Mississippi-Atchafalaya exits to the Gulf of Mexico. For the MR main channel, they found an annual sediment loss of about 67 MT total suspended sediment within the 74-km river reach between Tarbert Landing and St. Francisville, part of the east side of the MR is not leveed. Therefore, Allison *et al.* attributed the loss to a possible overbank sedimentation and river channel bed accumulation. In a follow-up study, Smith and Bentley (Smith and Bentley, 2014) could, however, only find a marginal sedimentation (2 MT/yr) from the three flood years on the unleveed flood plain, the previously assumed large overbank storage area. This quantity of sediment makes only 3% of the Allison et al.'s estimate, leaving 97% of the estimated sediment loss uncounted for.

The MR has been extensively modified for flood control and navigation since the 1920s (Harmar et al., 2005). The modifications included the construction of levees, bank revetments, artificial cutoffs, training dikes and reservoirs on the major tributaries (Smith and Winkley, 1996). As a result, the river channel was constrained to accrete and shift laterally to form natural cutoffs of meanders. Instead, the vertical accretion on bars occurred as a morphological response of the alluvial river (Biedenharn and Thorne, 1994; Smith and Winkley, 1996). Despite the general observations existed, quantitative studies of channel bars in the MR are scarce, and they are limited to headwater areas and gravel bed channels (Hooke, 1986; Li et al., 2014;

Wintenberger et al., 2015). After a thorough literature review, we could not find any studies on lower MR channel bar dynamics and believe our study to be the first.

From May to June in 2011, an unprecedented flood of the Mississippi River occurred because of the combination of snow melt and heavy rain. The river crested 19.32 m at TBL on the 18th of May 2011, which was nearly 75 cm higher than the crest stage of the 1927 MR flood (18.57 m). A field river sampling in the lowermost Mississippi River during 12-14 May 2011 (Ramirez and Allison, 2013) found a sharp rise in sediment concentrations. This large river flood provides a unique opportunity for assessing changes in large emerged channel bars in the lowermost MR. We hypothesized that during this extreme flood event, a substantial quantity of riverine sediments, especially sands, would be trapped by channel bars. In this study, we utilized satellite images taken before and after the 2011 spring flood to first quantify the change in surface area of the channel bars and then to estimate the associated change in volume of these channel bars. The primary goal of the study was to assess flood effects on channel bar dynamics and sediment accumulation in the lowermost Mississippi River. Estimation of possible sediment accumulation on these bars is essential for understanding the sediment availability for designing and operating the proposed diversion in the lowermost Mississippi River.

4.2 STUDY AREA

The channel bars investigated in this study are located shortly downstream the river diversion control structure of the lowermost Mississippi River, the Old River Control Structures (ORCS) (31°04'36" N, 91°35'52" W). ORCS diverts the MR into two channels (Figure 4.1): the Mississippi River main channel and the Atchafalaya River. Under normal flow conditions, about 25% of the Mississippi River's water is diverted into the Atchafalaya River that also carries the entire flow of the Red River. The control structure is designed to prevent the Mississippi River

from changing its course to the Atchafalaya River by seeking a shorter course to the Gulf of Mexico (Mossa, 2013). During high flows, a larger volume of the Mississippi River's water is allowed to the Atchafalaya River, in order to reduce flood risk downstream to the cities of Baton Rouge and New Orleans.

According to the common classifications of position and shape (Hooke, 1995), the study area includes two mid-channel bars - Shreves Bar and Miles Bar - and one point bar - Angola Landing, and they are located approximately 10, 14, and 17 kilometers downstream of the ORCS (Figure 4.1), respectively. All the three bars are located within a meander with the elongated Shreves Bar on the top and the Miles Bar at the end of the meander.

In this study, we obtained daily river stage data from the Red River Landing (RRL) gauge station ($30^{\circ}57'39''$ N., $91^{\circ}39'52''$ W; river kilometer 487, or river mile 302.4; USACE Gauge ID: 01120), which is the closest gauge station to the studied channel bars. The U.S. National Oceanic and Atmospheric Administration (NOAA) uses the station's stage for lowermost Mississippi River flood prediction. We also collected river discharge and sediment records from the Tarbert Landing (TBL) gauge station ($31^{\circ}00'30''$ N, $91^{\circ}37'25''$ W), which is located at river kilometer 493 (river mile 306.3), about 8 kilometers downstream the ORCS. The station provides the longest discharge and sediment records for the lowermost Mississippi River where both the U.S. Geological Survey (USGS) and the U.S. Army Corps of Engineers (USACE) have a monitoring station (USGS Station ID: 07295100 and USACE Gauge ID: 01100). One thing that needs to be pointed out here is that the sediment records at Tarbert Landing are currently under review by the USGS due to possible errors.

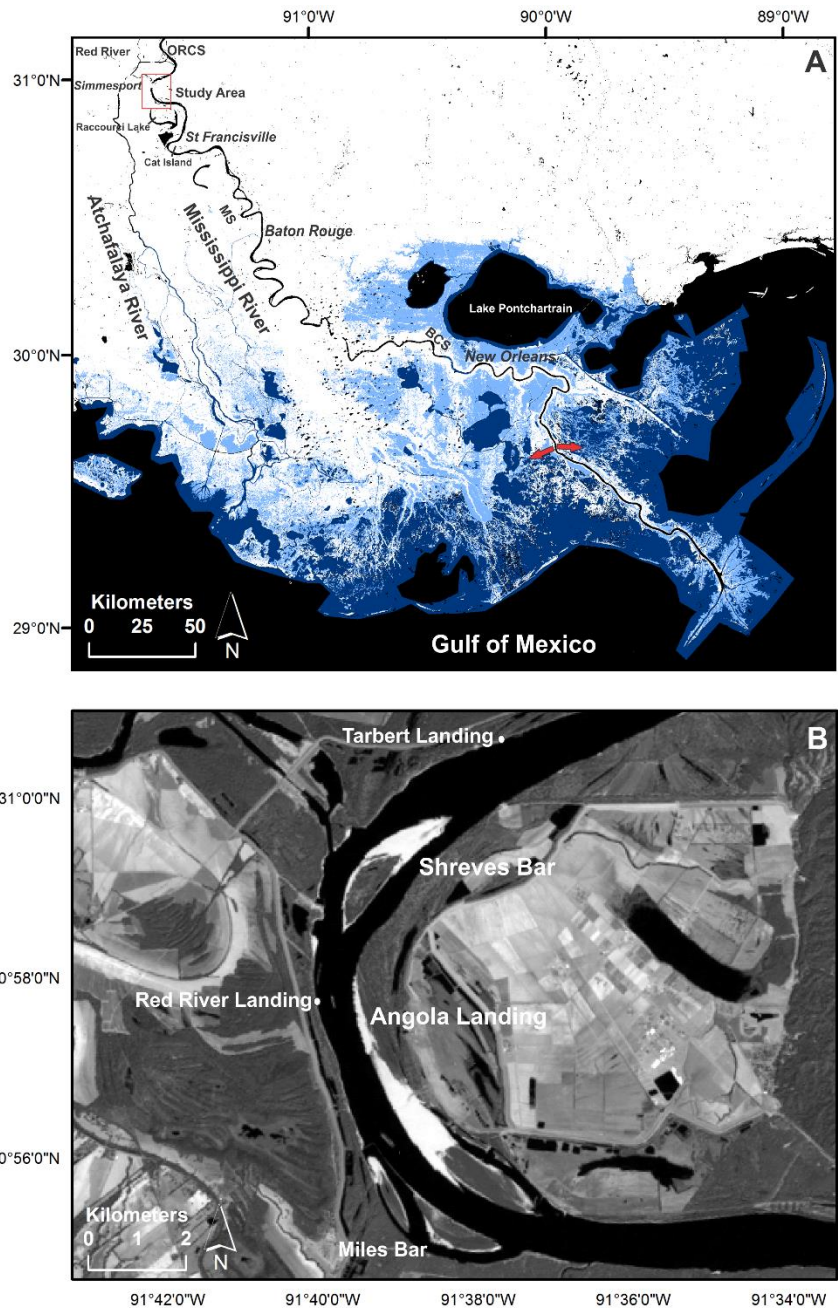


Figure 4.1. (A) Map of southeastern Louisiana, with the locations of Old River Control Structure (ORCS), Morganza Spillway (MS), Bonnet Carré Spill Way (BCS), cities, and proposed sediment diversions (red arrow). Blue region is the potential sinking area for the period up to 2050 based on the elevation and sea level trend data from USGS and NOAA (NOAA, 2012). (B) The locations of Shreves Bar, Angola Landing and Miles Bar, Tarbert Landing (TBL) and Red River Landing (RRL).

4.3 LONG-TERM HYDROLOGIC CONDITIONS AND THE 2011 SPRING FLOOD

Long-term (1973 - 2013) average discharge of the Mississippi River at TBL is 15,027 cubic meter per second (cms), varying from 3143 cms in 1988 to 45,844 cms in 2011. Seasonally, discharge of the lowermost Mississippi River is high during the winter and spring and low during the summer and early fall. For its flood warning prediction for the lowermost MR, NOAA defines five flow stages at RRL: (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). Using a stage-discharge analysis, Rosen and Xu (Rosen and Xu, 2014) separated the corresponding flow regimes < 13,000 cms for Low Flow Stage, 13,000 – 18,000 cms for Action Flow Stage, 18,000 – 25,000 cms for Intermediate Flow Stage, 25,000 – 32,000 cms for High Flow stage, and > 32,000 cms for Peak Flow Stage.

During the spring of 2011, extreme flooding conditions prevailed along the MR due to a combination of snow melt and heavy rain. The river stage at RRL reached High Flow Stage (i.e., 14.6 m) in early May and remained above the stage in June. The river crested 19.32 m on May 18, 2011. The average stage at RRL was 18.21 m in May and 16.86 m in June.

4.4 ESTIMATION OF BAR AREA AND VOLUME CHANGES

4.4.1 Collection of Satellite Imagery and River Stage Data

A total of 22 cloud-free Landsat Surface Reflectance Climate Data Record (CDR) images (Path 23 Row 39) taken in 2010, 2011, and 2012 were collected from USGS (<http://earthexplorer.usgs.gov/>) (Table 4.1). Level-1 Landsat 4-5 Thematic Mapper (TM) and Landsat 7 Enhanced Thematic Mapper Plus (ETM+) data were processed using the Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) (Wolfe et al., 2004). LEDAPS

considers water vapor, ozone, geopotential height, aerosol optical thickness, and digital elevation when it deals with atmospheric correction (Kotchenova and Vermote, 2007; Vermote et al., 1997). The CDR products include Top of Atmosphere (TOA) Reflectance, Surface Reflectance, Brightness Temperature, and masks for clouds, cloud shadows, adjacent clouds, land, and water (Masek et al., 2006). In our study, the product of surface reflectance was utilized to acquire surface areas of the bars because it is easier to detect area change over time without the atmospheric effect. In addition, the mask product of water and land was used to aid to delineate the outlines of the bars.

Table 4.1. Dates and product numbers of Landsat CDR images used in this study and the corresponding daily river stages at Tarbert Landing of the Mississippi River.

Before the flood			During and after the flood		
Date	River Stage (m)	Landsat CDR products No.	Date	River Stage (m)	Landsat CDR products No.
08/03/10	12.05	LE70230392010215EDC01	05/26/11	18.93	LT50230392011146CHM01
08/27/10	9.97	LT50230392010239EDC00	06/03/11	18.50	LE70230392011154EDC00
12/09/10	8.71	LE70230392010343EDC00	06/11/11	17.45	LT50230392011162EDC00
01/02/11	7.18	LT50230392011002CHM01	07/13/11	13.76	LT50230392011194EDC00
01/26/11	6.84	LE70230392011026EDC00	08/22/11	9.35	LE70230392011234EDC00
02/11/11	7.55	LE70230392011042EDC00	08/30/11	8.66	LT50230392011242EDC00
02/19/11	7.85	LT50230392011050EDC00	09/07/11	8.63	LE70230392011250EDC00
03/15/11	14.12	LE70230392011074EDC00	10/01/11	7.17	LT50230392011274EDC00
04/16/11	13.86	LE70230392011106EDC00	10/17/11	6.42	LT50230392011290EDC00
			10/25/11	5.80	LE70230392011298EDC00
			11/02/11	6.65	LT50230392011306EDC00
			11/10/11	6.79	LE70230392011314EDC00
			01/29/12	11.77	LE70230392012029EDC00

To identify river flow conditions in connection with the satellite images, river stage records at RRL were collected for August 2010 - January 2012 from USACE (<http://rivergages.mvr.usace.army.mil/WaterControl/stationinfo2.cfm?sid=01120&fid=RRL1&dt=S&pcode=HG>). The data were also used to develop numeric relations between surface area of the channel bars and the river stages (see more in sections 4.2 and 4.3).

4.4.2 Estimation of Bar Surface Area Changes

For estimating area change of the bars, satellite images were chosen following two rules: (1) images must be taken within several months before and after the flood because this could maximally reflect the change of surface area was caused by the flood; and (2) images taken dates must have similar river stages which are necessary for comparing area change. Based on these rules, the images taken on 01/02/2011 and 10/01/2011 were chosen, when the river stage was at 7.18 m and 7.17 m, respectively.

It is important to choose one suitable band in the image to digitize the boundary of the channel bars. In general, the near-infrared band - band 4 (0.76 – 0.90 μm) and shortwave band - band 5 (1.55 – 1.75 μm) are good at differentiating land and water because water has almost no reflection and shows near black color in these bands. However, in band 4 image, bare soil on the channel bars displays a similar character with vegetated soil on the river bank. This makes it difficult to distinguish the bar from bank soil. Therefore, band 5 was used to digitize the bar. The digitization process was performed in ArcGIS 10.3 (ESRI, Redlands, California, USA). For reducing feature identification error, all images were digitized at the same scale and followed the same rules made by the operators. Because the purpose of the digitization is to estimate area change before and after the flood, the difference computation of areas may further reduce the error.

ERDAS IMAGINE 2013 (Leica Geosystems Geospatial Imaging, LCC, Georgia, USA) was used to assess the distribution of the area change. Through subtracting the band 5 values of the post-flood image by the band 5 values of the pre-flood image, we obtained the threshold values that were used to locate the change of surface feature. Because the display values in the surface reflectance image are multiplied by 10000, therefore, the value of water body is usually

lower than 100, whereas bare soil in the bars is over 3000. As a result, after the subtraction, larger positive values (+3000) indicated water changed to land and the smaller negative values (-3000) indicated land changed to water.

4.4.3 Estimation of Bar Volume Changes

Previous research has proved multi-temporal multibeam echosoundings, mobile, and terrestrial laser scanning, and Acoustic Doppler Current Profiler are able to efficiently estimate the dynamics of channel bars by determining the elevation change of the bars (Kasvi et al., 2013; Lotsari et al., 2014; Williams et al., 2015; Wintenberger et al., 2015). However, these studies usually focus on the mechanisms of the morphological change, primarily, in a relatively small study sites (a few hundred meters). Our research aims to quantify the sediments trapped by large bars caused by a rare flood. The tools mentioned above, however, are not useful for achieving this objective because there is usually no measurements taken before rare flood events which makes it impossible to estimate the volume variation of the bars (Eaton and Lapointe, 2001). Therefore, a surface area – river stage rating curve was developed for each of the three bars based upon available satellite images taken before and after the flood.

Firstly, the areas of the three bars were calculated in each image followed the method described in 4.2. However, with the increase of the stage, some area was submerged, and it was difficult to tell the outlines of the bars. For solving this problem, the bar outlines on the day that had the lowest stage were used as baselines to make sure the bar outlines on other days within these baselines. The image used here was taken on 10/25/2011. The river stage on that day was 5.80 m which were very close to the lowest stage (5.65 m) in 2011. Another problem was that with the increase of the river stage, especially when it was over the flood stage (14.63 m), bars which were partly covered by the water turn into the dark in band 5 image, which could cause an

underestimation of the surface area. By comparison, band 4 was used as a substitute to estimate the bar surface area when the river stage was over 14.63 m. Secondly, according to the surface areas at different stages, the rating curve was assumed to be a polynomial curve because the area usually becomes smaller with the increase of the river stage (Figure 4.2).

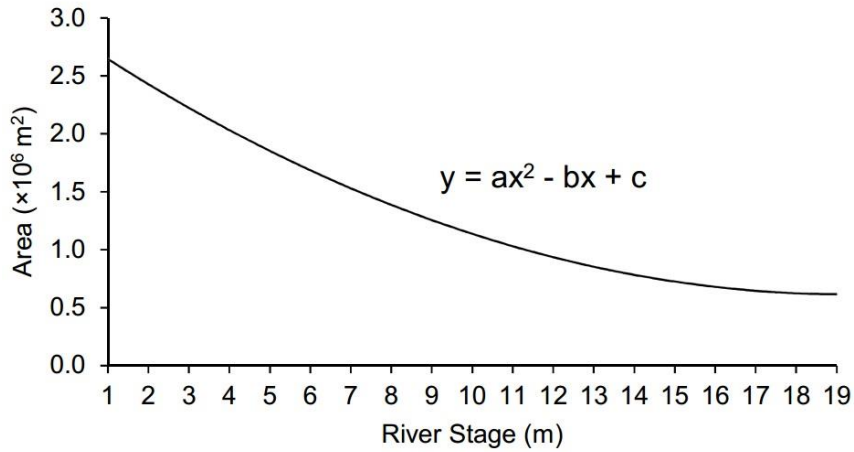


Figure 4.2. The hypothetic relationship between channel bar surface area and river stage at Tarbert Landing of the Lower Mississippi River.

The standard error of the estimate was used to measure the error of the rating curve:

$$SE = \sqrt{\frac{\sum(\hat{y}-y)^2}{N-P}} \quad (1)$$

where SE is the standard error of the estimate, N is the sample size, P is the number of the parameters in the model, \hat{y} is the predicted value and y is the actual value.

The channel bar volumes (V_s) pre and post the 2011 spring flood were calculated for each bar based on the integral:

$$V_s = \int_{D_l}^{D_h} (ax^2 - bx + c) dx = \left(\frac{ax^3}{3} - \frac{bx^2}{2} + cx \right) \Big|_{D_l}^{D_h}$$

$$= \left(\frac{aD_h^3}{3} - \frac{bD_h^2}{2} + cD_h \right) - \left(\frac{aD_l^3}{3} - \frac{bD_l^2}{2} + cD_l \right) \quad (2)$$

where V_s is the channel bar volume, D_h is the highest river stage, D_l is the lowest stage, and a , b and c are constants.

4.5 RESULTS

4.5.1 Surface Area Change of Shreves, Angola Landing, and Miles Bars

The false color images (band 432) show the bars before, during and after the 2011 spring flood (Figure 4.3). White color indicates bare soil areas and red color indicates vegetated areas. Before the flood, when the river stage was at 7.18 m, bare soil and vegetated area were apparently visible in the satellite image. With the increase of the stage to 18.93 m on 05/26/2011, all bare soils and part of the vegetated areas on the bars were inundated (Figure 4.3B). After the flood when the river stage dropped to 7.17 m, which was nearly the same river stage same as that before the flood, sediment accumulation could be seen along the bars. Miles Bar used to be a single bar (image not shown) and became braided in the recent decade. All the heads of these channel bars appeared to mainly sand accumulation, and their tails were covered by vegetation.

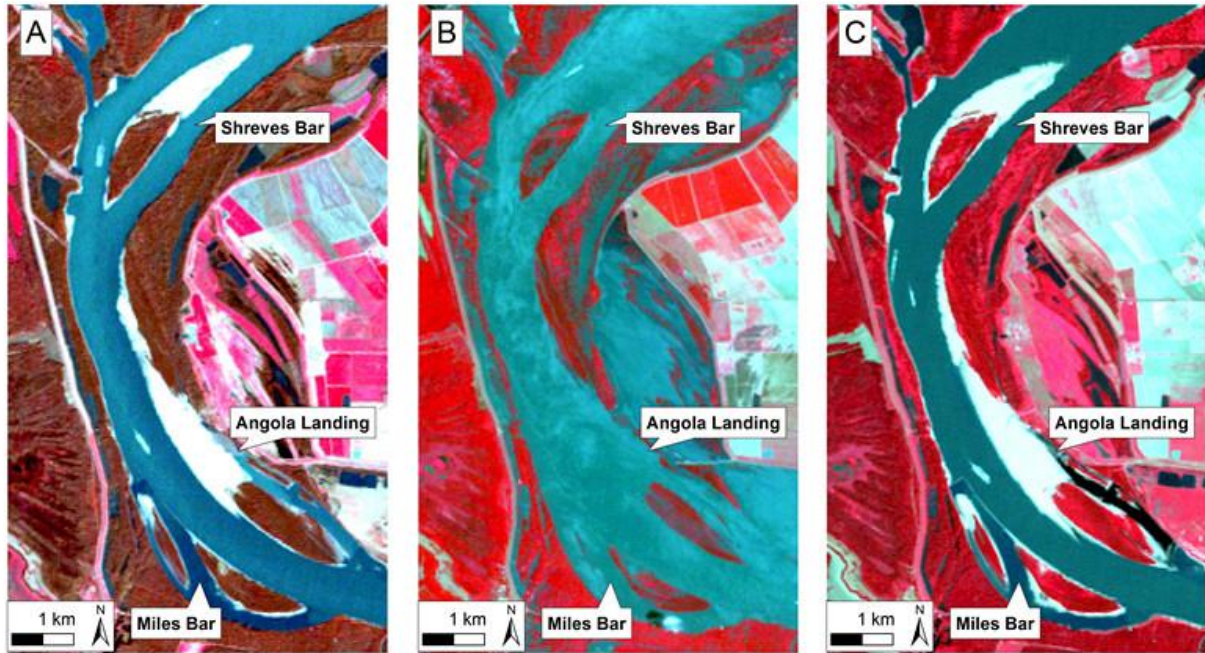


Figure 4.3. False color images (band 432) showing bare soil (white) and vegetated areas (red) of three large channel bars near Tarbert Landing of the Mississippi River on 01/02/2011 (A), 05/26/2011 (B), and 10/01/2011 (C).

There were both gain and loss of the surface area in the three studied bars after the flood (Figure 4.4). Area loss occurred mainly in the northern part of the Shreves Bar while area gain occurred in the western and eastern sides. A minor area loss was found at Angola Landing and the main gain occurred along the western side. For Miles Bar, land gain occurred on the west side of the braided bars.

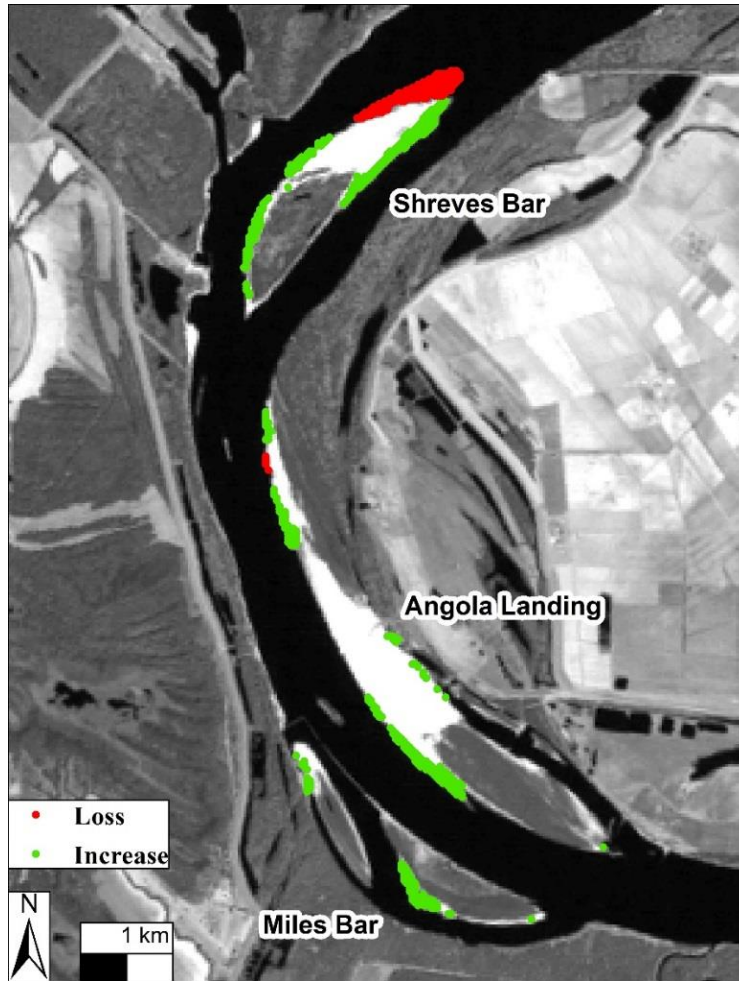


Figure 4.4. Changes in the surface area of three large mid-channel bars near Tarbert Landing of the Mississippi River after the 2011 spring flood.

As a whole, all three bars showed a net gain from 01/02/2011 to 10/01/2011 (Table 4.2). The surface area of Shreves Bar increased from $1.74 \times 10^6 \text{ m}^2$ to $1.80 \times 10^6 \text{ m}^2$ (or a 3.5% increase). Angola Landing showed a $0.23 \times 10^6 \text{ m}^2$ increase (or an 8.3% increase) of its surface area from $2.78 \times 10^6 \text{ m}^2$ before the flood to $3.01 \times 10^6 \text{ m}^2$ after the flood. The Miles Bar increased from $1.26 \times 10^6 \text{ m}^2$ to $1.40 \times 10^6 \text{ m}^2$ (or an 11.1% increase). The total surface area increases of the three bars following the 2011 spring flood amounted to 0.42 km^2 (or a 7.3% increase).

Table 4.2. Changes in the surface area of three large channel bars near Tarbert Landing of the Mississippi River before and after the 2011 Spring Flood.

	River Stage (m)	Shreves Bar	Angola Landing ($\times 10^6 \text{ m}^2$)	Miles Bar	Total
01/02/2011	7.18	1.74	2.78	1.26	5.79
10/01/2011	7.17	1.80	3.01	1.40	6.21
Δ		+0.06	+0.23	+0.14	+0.42
Δ (%)		+3.5%	+8.3%	+11.1%	+7.3%

4.5.2 River Stage – Surface Area Rating Curves for Shreves, Angola Landing, and Miles Bars

The pre- and post-flood surface areas estimated with 22 satellite images for the three bars were given in Table 4.3. The relationships between the surface areas and the river stages taken on the dates were found best represented by a second order polynomial equation, where the increase of area associated with a decrease of river stage (Figure 4.5). The correlation coefficients (R^2) of the rating curves were all high, i.e., above 0.98. The surface area – river stage curves based on the equations show that the three post-flood curves are all above the pre-flood curves. Interesting is that the post-flood area of Miles Bar was clearly higher than its pre-flood area in the lower river stage, but became unchanged in the higher river stage, indicating the bar's greater horizontal expansion. On the other side, Shreves Bar and Angola Landing both showed comparably smaller area change in the lower river stage, but an increasing change in the higher river stage, suggesting a greater vertical expansion.

Table 4.3. Estimated surface areas of three large channel bars in the lowermost Mississippi River and the river stages of the dates when the satellite images were taken.

Flood	Date	River Stage (m)	Shreves Bar	Angola Landing ($\times 10^6 \text{ m}^2$)	Miles Bar
Before the flood	08/03/10	12.05	0.93	0.94	0.85
	08/27/10	9.97	1.19	1.89	0.96
	12/09/10	8.71	1.41	2.33	1.07
	01/02/11	7.18	1.74	2.78	1.26
	01/26/11	6.84	1.81	2.92	1.31
	02/11/11	7.55	1.68	2.73	1.25
	02/19/11	7.85	1.55	2.50	1.11
	03/15/11	14.12	0.61	0.73	0.73
	04/16/11	13.86	0.75	0.72	0.69
During and after the flood	05/26/11	18.93	0.72	0.69	0.57
	06/03/11	18.50	0.73	0.70	0.62
	06/11/11	17.45	0.76	0.75	0.66
	07/13/11	13.76	0.84	0.85	0.76
	08/22/11	9.35	1.33	2.16	1.11
	08/30/11	8.66	1.44	2.41	1.12
	09/07/11	8.63	1.40	2.37	1.21
	10/01/11	7.17	1.80	3.01	1.40
	10/17/11	6.42	1.91	3.26	1.39
	10/25/11	5.80	2.18	3.70	1.64
	11/02/11	6.65	1.88	3.25	1.43
	11/10/11	6.79	1.82	3.10	1.39
	01/29/12	11.77	0.94	1.06	0.85

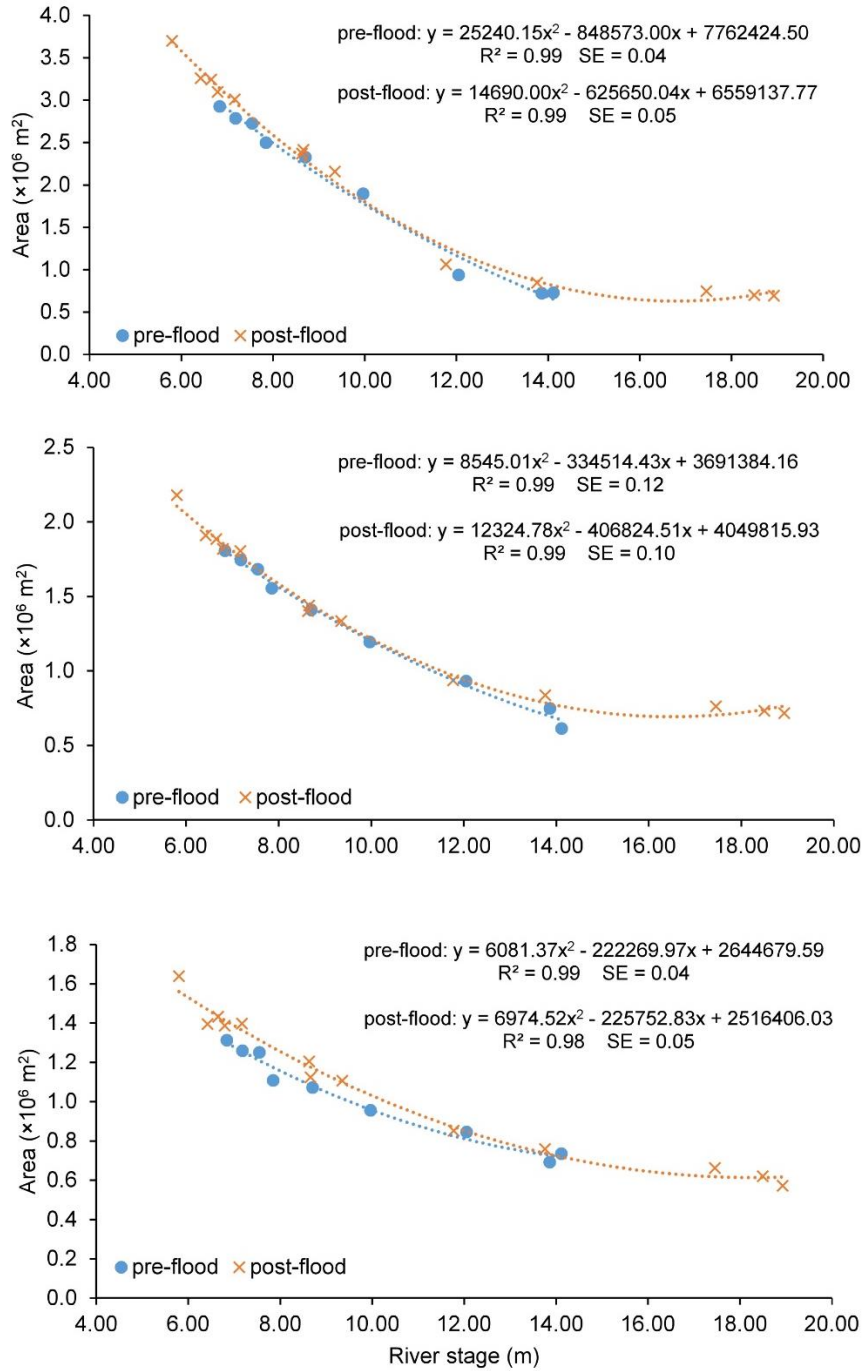


Figure 4.5. Rating curves of surface area – river stage for Shreves Bar (top), Angola Landing (middle), and Miles Bar (bottom) near Tarbert Landing in the lowermost Mississippi River. SE ($\times 10^6 \text{ m}^2$) is the standard error of the estimate.

4.5.3 Volume Change of Shreves, Angola Landing, and Miles Bars

For comparison of the bar volume changes, the same range of river stages was used for the three studied bars. The stage range was 6.84 m - 14.12 m, based upon which the bar volumes were calculated for the pre- and post-flood periods (see Equation 1). The estimated volume of the three channel bars all increased after the 2011 spring flood (Table 4.4). The volume gain for Shreves Bar, Angola Landing, and Miles Bar was $0.24 \times 10^6 \text{ m}^3$, $0.53 \times 10^6 \text{ m}^3$ and $0.46 \times 10^6 \text{ m}^3$, respectively, or in a percentage rate of 2.8%, 4.3%, and 6.7%. The total volume gain of the three channel bars above the river stage of 6.84 m was $1.22 \times 10^6 \text{ m}^3$ or a 4.4% increase.

Table 4.4. Changes in volume of three large channel bars near Tarbert Landing in the lowermost Mississippi River before and after the 2011 spring flood.

	Shreves Bar	Angola Landing ($\times 10^6 \text{ m}^3$)	Miles Bar	Total
Pre-flood	8.46	12.23	6.90	27.59
Post-flood	8.69	12.76	7.35	28.81
Δ	0.24	0.53	0.46	1.22
Δ (%)	+2.8%	+4.3%	+6.7%	+4.4%

4.6 DISCUSSION

Kesel (Kesel, 2003) analyzed the historic channel bar size and volume from 1880 to 1963 in the Mississippi River. It was concluded that there were few bars in the Lower Mississippi River and there was relatively little change in their bar size and volume. However, our findings indicate that one single river flood can have effects on the surface area and volume of the channel bars in the river reach. The increase of surface area is 0.06 , 0.26 and $0.14 \times 10^6 \text{ m}^2$ for Shreves Bar, Angola Landing and Miles Bar, respectively. These numbers are all greater than the standard error of the estimate for their respective rating curves, which means the area change estimated by the digitation is statistically meaningful. Located in the middle of the river channel,

Shreves Bar showed the large gain and loss in its surface area after the 2011 flood (Figure 4.4). In general, for channel bars, heavier materials such as gravels and coarse sands on bar heads are resistant to flow (Li et al., 2014) and erosion occurs on bar margins (Tsujiimoto, 1998). The 2011 extreme flood, however, caused a substantial erosion of the bar head of Shreves Bar with sediment deposition on its margins. The erosion was caused by high stream power during the flood which removed the sediments on bar head. For the deposition on bar margins, it may be caused by lateral accretion at the low flow after the flood. Ashworth *et al.* (Ashworth et al., 2000) studied the evolution of a mid-channel bar in a large sand-bed braided river, and they found the high flow during the flood produced high sediment transport rates and caused bar-top vertical aggradation while the falling and low-stages caused lateral accretion. They reported the possible reason for lateral growth was flow divergence at the bar head. Based on their theory, the deposition occurred on the eastern side of Shreves Bar was caused by the lateral accretion. The slower flow inside of the bend of Shreves Bar caused deposition on the bar's west side. Due to the erosion, 0.06 km² net increase of surface area of Shreves Bar was the lowest increase among the three bars. The deposition for Angola Landing and Miles Bar were both inside bends depositions. Angola Landing had more deposition suggests that the larger the sandbar, the more capacity it has to capture the sediment during the flood.

In this study, we estimated a total volume increase of 1.22 million m³ for the three studied bars during the 2011 spring flood. It is important to note that 1) the estimation is made for the bar area above the river stage of 6.84 m at RRL, and 2) the estimation is based on the assumption that the bars have a uniform geometry. Although we are not certain, how the volume below the 6.84 m river stage has changed, the estimation is likely a gross underestimation of actual changes in the subaqueous area of the three studied channel bars. At the stage of 14.12 m,

the submerged area included all bar heads and part of bar tails of Shreves Bar and Angola Landing, and nearly half of Miles Bar. Because sediment size on the bar surface becomes finer along the bar [17], it suggests there would be muddy sediment deposited on tails of the bars during the flood. At the range of stage below 6.84 m, it is no doubt that there was a large amount of sediment trapped there during the flood. In addition, the surface area – river stage rating curve was utilized to estimate the volume change covering the post-flood period (July 2011 to January 2012) which was a flood recession period. Studies have reported that part of the newly deposited sediments could be eroded during the falling limb of floods (Mueller et al., 2014; Wintenberger et al., 2015). It suggests that the calculated volume after the flood was possibly less than the actual captured volume during the flood. Therefore, it is reasonable to believe that the 1.22 million m³ volume gain is a conservative estimate of the trapped sediments by the three bars during the 2011 flood.

The sediments trapped by the three channel bars during the 2011 spring flood can contain all grain sizes of sediment. Based on a recent field trip and observation four years after the 2011 spring flood, sediments trapped on the bars should primarily be sands. Assuming a bulk density of 1.2 metric tons per cubic meter (i.e., a typical bulk density for silt – pure soil), the total volume of trapped sediment during the 2011 flood would be about 1.5 million metric tons. Joshi and Xu (2015) analyzed the long-term relationship between discharge and sand load for Tarbert Landing and developed a daily discharge (q) – daily sand load (S) rating curve as below:

$$\ln(S) = -0.6382 \ln(q)^2 + 14.3 \ln(q) - 67.139 \quad (R^2=0.87, SE=0.496) \quad (2)$$

Daily total sand load from March 1, 2011, to August 31, 2011, was calculated according to this rating curve (Figure 4.6). During this flood period, daily sand load fluctuated between 28,642 and 371,010 metric ton/day, and a total sand load was about 34.0 MT. If our 1.5 MT

estimate of trapped sediment was pure sand, that would be only about 4.4% of the total sand load passing the three bars.

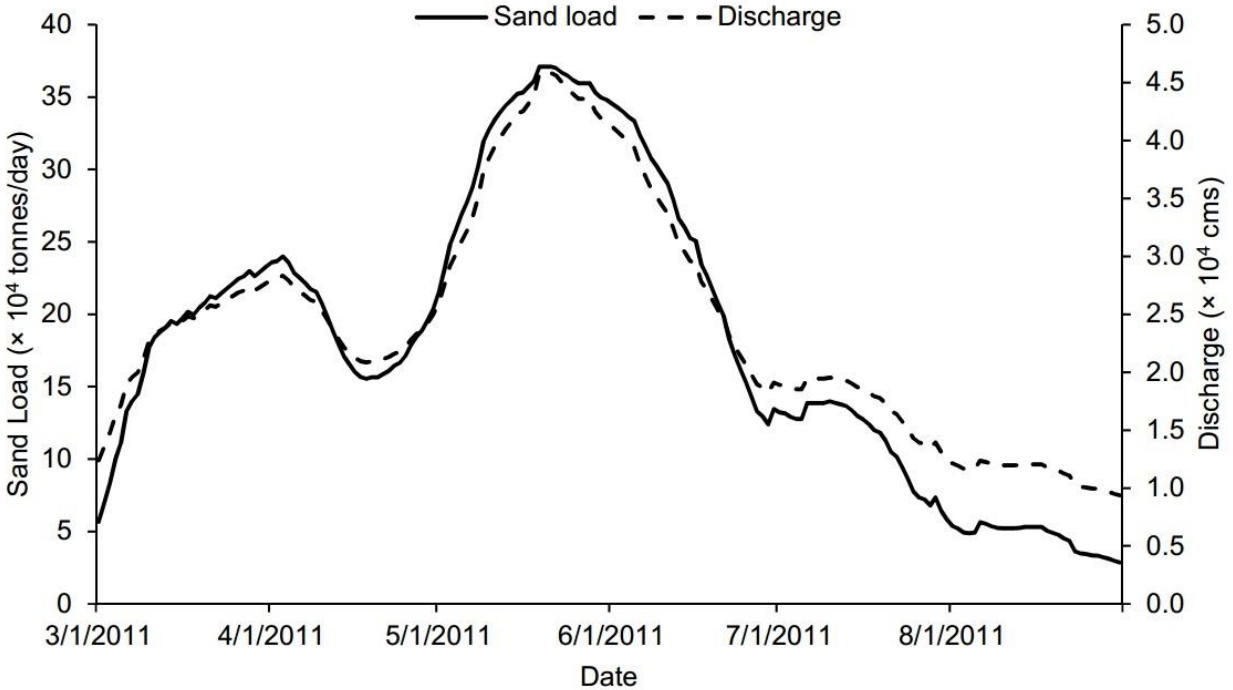


Figure 4.6. River discharge (cms) and estimated daily sand load (t/day) at Tarbert Landing pre and post the 2011 Mississippi River spring flood.

From their study on a 3-year sediment budget (2008-2010), Allison et al. (Allison et al., 2012) reported an average loss of 67 MT/yr total suspended sediment in the river reach from TBL to St. Francisville at river kilometer 419, and 80% of the sediment loss was sand, i.e., about 54 MT/yr sand. They attributed the large loss to a deposition in the channel bed and overbank storage. In a follow-up study by Smith and Bentley (Smith and Bentley, 2014), however, only about 2 MT/yr muddy sediment deposited by overbank storage was found in the unleveed Cat Island and Raccourci Lake regions. Considering our 1.5 MT sediment trapping in the three bars, a large quantity of the sediment loss is still uncounted for. There are other large channel bars in the river reach between the Tarbert Landing and St. Francisville. These bars could also have

trapped substantial sediments during the flood. Further study is needed to elucidate the role of these bars in sediment accumulation in the lowermost MR.

A large amount of sediment may have also been transported to downstream of the study site during the flood. Kroes et al. (2015) reported 1.03 MT of sediment was deposited in the Atchafalaya River Basin through the Morganza Spillway, located right below our study site, in a 54-day release period during the 2011 flood. The Bonnet Carré Spill Way (BCS), a 2300-m-width flood control construction located in about 51 km upstream of downtown New Orleans which allows floodwater from the Mississippi River to flow into the Lake Pontchartrain. It diverted 4.9 million m³ sand during the 42 days operation from May 9 to June 20 in 2011 (Nittrouer, 2013). Through the comparison, we found the increased volume in the three bars was about 25% of the total diverted sand by BCS. Although the BCS was not designed for maximizing sediment capture, there is little doubt that a large amount of sand was transported downstream.

For the suggested sediment diversions by Louisiana Coastal Protection and Restoration Authority (CPRA, 2012) which may be only operated in the certain time periods, such as during Intermediate Flow Stage and High Flow Stage or the rising limb of flood pulses (Hooke, 1995; Mossa, 1996). Our findings presented here indicate that if the sediment diversions open during these periods, the channel bars in the Lower Mississippi River can trap a considerable amount of sediment which may impair the capacity of diverting sediment to the river surrounding wetland. Numerous studies have reported a reduction of sediment loads in the Lower Mississippi River during the past century (Boesch et al., 1994; Kesel, 1988; Kesel, 1989). Increasing evidence suggests that significant amount of sediment is being trapped in the lower MR (Mossa, 2013; Smith and Winkley, 1996). However, the MR delta ecosystem would be better served if the

sediment could be delivered to the areas of the delta that are currently subsiding (Figure 4.1), though solutions for providing such delivery are in need of development. Nonetheless, this sediment, which may well exceed 1×10^9 MT, is a critical resource that is essential for the recovery of the Mississippi River Delta, and it needs to be carefully managed. There is a dozen of large mid-channel and point bars in the river reach below the studied sites, and it is not clear how much sediment these bars could trap under normal and during high flow conditions.

4.7 CONCLUSIONS

This study is the first quantitative assessment of a major flood on morphological changes and the associated sediment accumulation of emerged channel bars in the lowermost Mississippi River. The findings show that channel bars in this intensively managed river are capable of trapping a substantial quantity of sediment during a flood. Long-term change of the channel bars may have profound effects on downstream river channel morphology and sedimentation, and the accumulated sediment could be used as a critical source for restoring the sinking Mississippi River Delta. There is a need to further investigate other large channel bars in the lowermost Mississippi River, in order to quantify the sediment accumulation rate over the past several decades. The study demonstrates that the rating curve approach with multi-temporal satellite images is statistically significant in assessing areal and volumetric changes of channel bars and it can be very helpful to achieve the objective.

CHAPTER 5. SUMMARY AND CONCLUSION

This dissertation research examined morphodynamics of the Lower Mississippi River to (1) determine sediment quantity and dynamics of 30 large emerged channel bars in a 223 km reach of the Lower Mississippi River between Vicksburg, Mississippi (RK737) and the Mississippi–Atchafalaya River diversion (RK 515) from 1985 to 2015, (2) investigate morphological changes of the 10-km long river channel, and the three emerged bars shortly downstream of the diversion during 1985-2015, and (3) assess how a large flood affected morphology of emerged channel bars. The primary goal of this dissertation research is to answer a central question - how much sediment is currently trapped on large channel bars in the Lower Mississippi? The answer to this question will improve our understanding of riverine sediment transport, deposition, and distribution in the Lower Mississippi River, which is urgently needed to help develop effective strategies and solutions for Louisiana’s coastal restoration and protection efforts. The Mississippi River Delta is rapidly losing land owing to a combination of multiple factors, chief of which is the reduction in riverine sediment supply. The continuous land loss directly threatens the livelihood of hundreds of thousands of Louisianans, the existence of precious coastal wetlands, and the nationally relevant energy, petrochemical, shipping, and fisheries industries. The State of Louisiana is conducting various projects to help maintain and/or build coastal land, and many of these projects rely on available sediment in the Mississippi River. Hence, this dissertation research makes a contribution to the investigation of sediment transport, deposition, storage, and distribution in the Lower Mississippi River, which is crucial for developing effective strategies and plans to save Louisiana’s sinking coast. Major findings from the research are summarized below.

- (1) River engineering, especially dike field constructions, have largely affected channel bar development in the middle portion of the Lower Mississippi River. The 223 km reach of the Lower Mississippi River between Vicksburg and Old River Control Structures showed little channel meandering from 1985 to 2015 because of the channel confinement by levees and revetments. However, the 30 emerged channel bars have changed their morphology and volume substantially. The average length of the bars increased by 743 m, while the average width showed no statistically significant change. The volume of the 30 emerged bars increased by $110,118 \times 10^3 \text{ m}^3$ (or 41%) over the past three decades, which is equivalent to $154,165 \times 10^3 \text{ t}$ of sediment trapped on these bars, based on the measured bulk density of 1.4 t/m^3 . Currently, these bars amassed a total amount of $378,183 \times 10^3 \text{ m}^3$ (or 530 million metric tons) sediment. Approximately 51% of the total sediment stored on the eight bars located between RK 665 and RK 612. The average volume of mid-channel bars was 2.5-5 times larger than the other types of bars. The construction of dike fields in the reach strongly affected sediment transport and channel bar development.
- (2) Diversion of a large alluvial river can strongly affect sediment transport downstream. From 1985 to 2013, the 10-km long river reach downstream of the Mississippi-Atchafala River diversion experienced substantial changes in both channel morphology and three large emerged bars within the reach. The middle and the lower sections of the channel (RK 486-480) experienced considerable sediment deposition on their east bank, causing the channel to narrow by 800 m in average. The total emerged surface area of the three bars increased by $4,107,000 \text{ m}^2$ or 119%. The total volume of the three bars increased $30,271,000 \text{ m}^3$ (206%), which is equivalent to

36,325,000 metric tons in mass, based on the estimated bulk density of 1.2 t/m^3 (i.e., a typical bulk density for silt – pure soil). In particular, Angola Landing showed a near 72-fold volumetric increase (i.e., $24,643,000 \text{ m}^3$), while Shreves Bar had little change in its volume. Overall, we conclude that diversion of the Mississippi River into the Atchafalaya River has caused significant changes of downstream channel morphology and sediment deposition on channel bars. The construction of revetments and dikes in the river reach has also contributed to the changes, especially the distribution of sediment deposition.

- (3) River floods can have large impacts on sediment transport, bar migration and hence channel morphology. During the 2011 Mississippi flood, the three bars downstream of the Mississippi-Atchafalaya River diversion were mostly inundated in May and June. I studied morphologic changes of the bars using 22 Landsat images acquired before and after the flood. Results showed that the total emerged surface of the three bars increased approximately 0.42 km^2 (7.3%) because of the flood. The total volume gain of the three channel bars was $1.22 \times 10^6 \text{ m}^3$ or a 4.4% increase. Assuming a bulk density of 1.2 t/m^3 , the total volume of trapped sediment during the 2011 flood would be about 1.5 million metric tons. This study firstly estimated a major flood on morphological changes and the associated sediment accumulation of emerged channel bars in the Lower Mississippi River. The findings indicated that channel bars in this highly regulated river are able to trap a substantial quantity of sediment during a flood.
- (4) Highly regulated alluvial rivers develop their own characteristics in sediment transport, erosion, and deposition. Channel bars are major reservoir for in-channel sediment. To measure their morphodynamics is extremely important for

understanding the sediment dynamics of the channel. By measuring that morphodynamics, this dissertation research offers an important insight into channel and bar morphodynamics located within a 258-km reach in the Lower Mississippi River. Under the current river management, which mainly targets at navigation safety and flood controls, the large emerged channel bars in the Lower Mississippi River are capable of trapping a large amount of sediment. The coarse sediment trapped in the bars is an extremely important material source for restoration and protection of coastal Louisiana. It is hoped that suitable river engineering strategies and solutions are developed in the future to mobilize them downstream to the coastal Louisiana.

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APPENDIX A: PERMISSION TO REPRINT CHAPTER 2



Geomorphology

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Dynamics of 30 large channel bars in the Lower Mississippi River in response to river engineering from 1985 to 2015

Bo Wang, Y. Jun Xu  

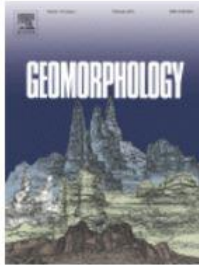
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Highlights

- Channel bar types, areas and volumes in the Lower Mississippi River were assessed
- Dike fields strongly affected sediment transport and channel bar development
- Emerged portion of all studied 30 bars stored ~ 530 million tons of coarse sand
- Attached and mid-channel bars showed the largest volume increase from 1985 to 2015
- More than half of 13 point bars degraded in the studied 223-km river reach



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APPENDIX B: PERMISSION TO REPRINT CHAPTER 3

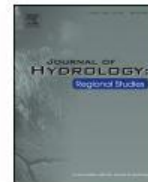
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Long-term geomorphic response to flow regulation in a 10-km reach downstream of the Mississippi–Atchafalaya River diversion



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ABSTRACT

A recent study reported considerable sediment trapping by three large channel bars downstream 18–28 km of the Mississippi–Atchafalaya River diversion (commonly known as the Old River Control Structure, ORCS) during the 2011 Mississippi River flood. In this study, we analyzed 3-decadal morphological changes of the 10-km river channel and the three bars to elucidate the long-term effects of river engineering including diversion, revetment and dike constructions. Satellite images captured between 1985 and 2015 in approximate 5-year intervals were selected to estimate the change of channel morphology and bar surface area. The images were chosen based on river stage heights at the time when they were captured to exclude the temporal water height effect on channel and bar morphology. Using a set of the satellite images captured during the period of 1984–1986 and of 2013–2014, we developed rating curves of emerged bar surface area with the corresponding river stage height for determining the change in bar volume from 1985 to 2013. Two of the three bars have grown substantially in the past 30 years, while one bar has become braided and its surface area has shrunken. As a whole, there were a net gain of 4,107,000 m² in surface area and a net gain of 30,271,000 m³ in volume, an equivalent of approximately 36 million metric tons of sediment assuming a bulk density of 1.2 t/m³. Sediment trapping on the bars was prevalent during the spring floods, especially during the period of 1990–1995 and of 2007–2011 when large floods occurred. The results suggest that although revetments and dikes have largely changed the morphology of the channel and the bars, they seem to have a limited impact on the overwhelming trend of sediment deposition caused by the river diversion.

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APPENDIX C: PERMISSION TO REPRINT CHAPTER 4

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Open Access Article

Sediment Trapping by Emerged Channel Bars in the Lowermost Mississippi River during a Major Flood

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Abstract

The formation of channel bars has been recognized as the most significant sediment response to the highly trained Mississippi River (MR). However, no quantitative study exists on the dynamics of emerged channel bars and associated sediment accumulation in the last 500-kilometer reach of the MR from the Gulf of Mexico outlet, also known as the lowermost Mississippi River. Such knowledge is especially critical for riverine sediment management to impede coastal land loss in the Mississippi River Delta. In this study, we utilized a series of satellite images taken from August 2010 to January 2012 to assess the changes in surface area and volume of three large emerged channel bars in the lowermost MR following an unprecedented spring flood in 2011. River stage data were collected to develop a rating curve of surface areas detected by satellite images with flow conditions for each of the three bars. A uniform geometry associated with the areal change was assumed to estimate the bar volume changes. Our study reveals that the 2011 spring flood increased the surface area of the bars by 3.5% to 11.1%, resulting in a total surface increase of 7.3%, or 424,000 m². Based on the surface area change, we estimated a total bar volume increase of 4.4%, or 1,219,900 m³. This volume increase would be equivalent to a sediment trapping of approximately 1.0 million metric tons, assuming a sediment bulk density of 1.2 metric tons per cubic meter. This large quantity of sediment is likely an underestimation because of the neglect of subaqueous bar area change and the assumption of a uniform geometry in volume estimation. Nonetheless, the results imply that channel bars in the lowermost MR are capable of capturing a substantial amount of sediment during floods, and that a thorough assessment of their long-term change can provide important insights into sediment trapping in the lowermost MR as well as the feasibility of proposed river sediment diversions. [View Full-Text](#)

Keywords: channel bars; fluvial geomorphology; channel dynamics; sediment transport; lowermost Mississippi River

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