Long-term sediment transport and delivery of the largest distributary of the Mississippi River, the Atchafalaya, USA

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Abstract River engineering in the Mississippi-Atchafalaya River system and changing land use practices in the Upper Mississippi River Basin have reduced sediment loads and modified sediment distribution to the continental shelf of the northern Gulf of Mexico. Concurrently, the Louisiana Gulf coast has been subject to the highest rate of relative sea-level rise of any region in the United States. This study investigated suspended sediment transport and delivery from the Atchafalaya River, a 187-km-long river-swamp system that carries about 30% of the Mississippi River's water into the Gulf of Mexico. The study modelled long-term (1975–2004) riverine sediment fluxes, assessed land area changes in the Atchafalaya Bay, and analysed the relationship between riverine sediment supply and the delta fan process. The study showed a sediment inflow of 6.4×10^7 tonnes year^{-1} and a sediment outflow of 5.8×10^7 tonnes year^{-1} in the Atchafalaya. Seasonally, sediment loads were highest in the spring and lowest in the late summer, corresponding to the river's hydrologic conditions. For the past 30 years, the Atchafalaya retained 9% of the inflow sediment, which is considerably lower than the double-digit percentage rates of deposition reported for the period from the 1930s to the 1960s. Satellite image analyses found rapid land accretion in the Atchafalaya Bay during the past two decades. Much of the newly created land area was quickly vegetated, stabilizing the small delta lobes against sediment resuspension.

Key words suspended sediment; riverine sedimentation; sediment rating curve; coastal land accretion; Atchafalaya Bay; Mississippi-Atchafalaya River; Gulf of Mexico

INTRODUCTION

The Louisiana Gulf coast has experienced one of the highest sea-level rises over the past century (e.g. Dixon *et al.* 2006; Ivins *et al.* 2007). Concurrently, river engineering and changing land use practices in the Upper Mississippi River Basin have reduced sediment loads and modified sediment distribution to the continental shelf of the northern Gulf of Mexico (Horowitz, 2010; Meade & Moody, 2010;). As a result, the Louisiana Gulf coast has been subject to the highest rate of relative sea-level rise of any region in the United States. Morton *et al.* (2005) found that approx. 4000 km^2 of low-lying coastal land on Louisiana's delta plain have been submerged since 1930. Previous studies (British & Dunbar, 1993; Barras *et al.*, 2003) reported peak delta-plain land losses of 60–75 km^2 year^{-1} from the 1960s to the 1980s. These studies indicate that riverine sediment is a precious resource to coastal Louisiana, and its effective management is of long-term strategic importance.

While much of Louisiana's coastline is eroding and sinking, the mouth of the Atchafalaya River has been gaining land since the early 1970s. The river is the largest distributary of the Mississippi River and currently carries about 30% of the Mississippi's waters into the Gulf of Mexico. Several researchers (Shlemon, 1975; Rouse *et al.*, 1978; Roberts *et al.*, 1980) reported their observations of the early sub-aerial delta development in the shallow Atchafalaya Bay after the 1973 flood. In the past two decades, a number of studies were conducted to investigate sedimentary processes in the bay area (e.g. Wells *et al.*, 1984; Kemp, 1986; Roberts *et al.*, 1987; Huh *et al.*, 1992; Allison *et al.*, 2000; Draut *et al.*, 2005). These studies mainly focused on near-shore sedimentation rates, stratification, and sediment composition. They often quantified sediment input from the river system with early records of river discharge and sediment concentrations, which may not accurately represent the current condition of sediment transport in the Atchafalaya. Furthermore, most of these studies used flow and sediment data collected at Simmesport, which is located close to the beginning of the 187-km-long Atchafalaya River Basin. A recent study using sediment traps at several transects within the basin showed a sedimentation rate ranging from about 2 to 42 mm/year (Hupp *et al.*, 2008), indicating that a large quantity of the riverine suspended sediment may not reach the continental shelf.

The objective of the present study was to quantify inflow and outflow of daily, monthly, and annual suspended sediment in the Atchafalaya River for the period from 1975 to 2004, to determine: (1) what role the river basin plays in sediment transport, (2) what actual quantity of sediment is delivered from the river to the continental shelf, and (3) how hydrologic regimes affect sediment retention and delivery rates seasonally and interannually. Furthermore, the study used satellite images to assess changes in land accretion in the Atchafalaya Bay from 1982 to 2004. The ultimate goal of this study is to improve the accuracy of assessing suspended sediment transport in and delivery from the Atchafalaya River Basin.

METHODOLOGY

Study area

The Atchafalaya River is a highly regulated river system within the natural Atchafalaya River Basin located in south-central Louisiana, USA (Fig. 1). The river is formed where the total flow from the Red River is combined with part of the Mississippi River's water that is diverted through the Old River Control Structure that was built by the United State Army Corps of Engineers during the 1960s. In the 1930s the Mississippi River discharged about 20% of its total flow into the Atchafalaya River. By the early 1970s, the Mississippi discharge had increased to 40% of its total flow. To prevent total capture of the Mississippi River into the Atchafalaya River, the Mississippi discharge is regulated by the control structure at approximately 30% (mostly between 28% and 33%) since the late 1970s. Beginning from the control structure, the Atchafalaya River flows southward, first in a well-confined channel for about 87 river kilometres, and then in several braided channels through a low-land swampy area for another 100 river kilometres, discharging its water and sediment into the Gulf of Mexico through two outlets, the natural Atchafalaya channel at Morgan City and the man-made Wax Lake Outlet (Fig. 1).

The Atchafalaya River is confined by levees that surround it to the east and west for about 20–35 km in width. The levee-confined river basin, often locally named the Atchafalaya Swamp Basin, encompasses a surface area of 4678 km^2 that predominantly consists of wooded lowlands, cypress-tupelo surface flow swamps, and some freshwater marshes in the lower basin area.

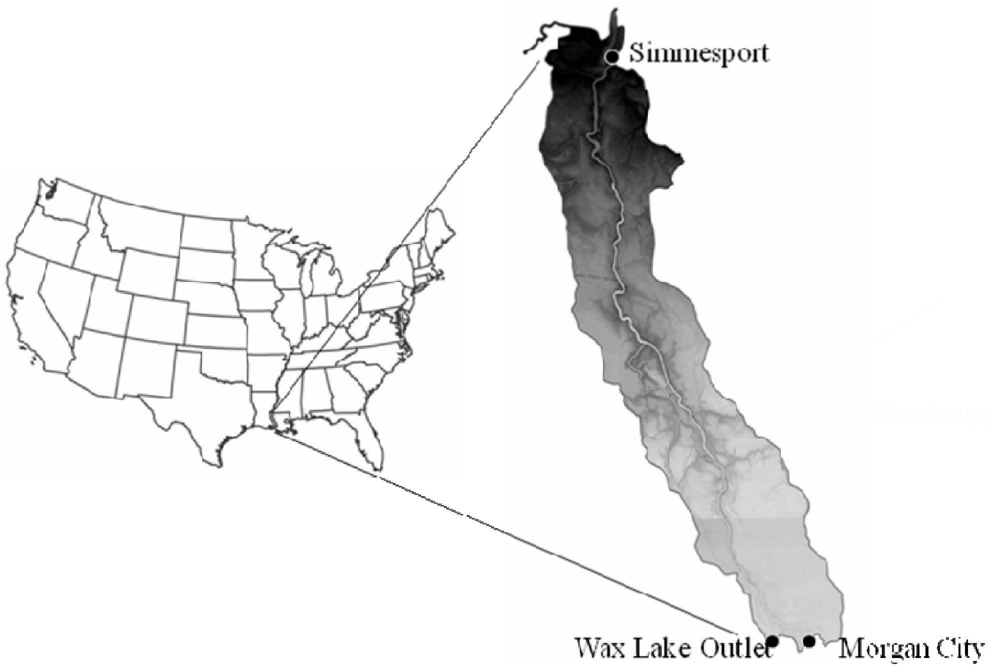

Fig. 1 The Atchafalaya River Basin in south-central Louisiana, USA.

It is the largest contiguous fresh water swamp in the United States. Climate in the Atchafalaya River Basin is humid, subtropical with typically mild winters, hot summers, and abundant rainfall (up to >1500 mm per year). The basin is home to a variety of wildlife that includes more than 170 bird species, more than 40 mammalian species, and more than 100 finfish and shellfish species (Demas *et al*., 2002).

Development of sediment rating curves

To estimate suspended sediment mass input, output, and an input–output budget for the Atchafalaya River, long-term historical records for river discharge and sediment were gathered from two US Federal agencies. Daily discharge at Simmesport (about 7.9 km from the river control structure) from 1975 to 2004 was obtained from the New Orleans District Office of the US Army Corps of Engineers. Daily discharge at Morgan City from 1986 to 2004, and at Wax Lake Outlet from 1993 to 2004 were obtained from the Louisiana Water Science Center of the US Geological Survey (USGS). Using the existing discharge records, the following equation was developed to quantify combined daily discharge from Morgan City and Wax Lake Outlet (Q_{out} in m^3 day^{-1}) for the missing dates during the period from 1975 to 2004:

$$Q_{out} = 19136.53548 + 0.90034 \times Q_{in} \qquad (1)$$

where Q_{in} is daily discharge passing Simmesport in m^3 day^{-1}. The equation obtained a regression coefficient (r^2) of 0.93.

Historical records of suspended sediment at Simmesport and Morgan City were obtained from the Louisiana Water Science Center of the USGS. Most of the records were measurements taken every 2 weeks. It was assumed that there was no difference in suspended sediment concentration of the waters leaving the Atchafalaya River Basin at Morgan City and at Wax Lake Outlet, because of the proximity between these two locations (about 8 km) and the findings from other studies (e.g. Xu & Patil, 2006; BryantMason *et al*., 2010) that show no difference in organic carbon and nitrogen concentrations and other water quality parameters measured at the two locations. Therefore, the combined discharge from the two locations and the suspended sediment concentrations measured at Morgan City were used to quantify total sediment outflow from the basin.

Sediment rating curves were developed to allow estimation of the suspended sediment loads entering the Atchafalaya River Basin at Simmesport and exiting at Morgan City/Wax Lake Outlet. As in many other studies on sediment transport (e.g. Cohn *et al.*, 1989, 1992; Nash, 1994; Jansson, 1996; Syvitski *et al.*, 2000), this study assumed that sediment loads can be described by the power law model as below:

$$L = aQ^b e^{\varepsilon} \qquad (2)$$

which can be log-transformed to:

$$\ln L = \ln a + b \ln Q + \varepsilon \qquad \text{where } \varepsilon \text{ is assumed } N(0, \sigma^2) \qquad (3)$$

where L is daily load, Q is daily discharge, and ε is an error term assumed to be normally distributed.

The model parameters were determined using the SAS software package (SAS Institute, 1996) and the following best fitting equations were found:

$$\ln L_{in} = -12.13674 + 1.53899 \ \ln Q_{in} \qquad (4)$$

$$\ln L_{out} = -18.00274 + 1.82429 \ \ln Q_{out} \qquad (5)$$

where L_{in} is daily suspended sediment load in kilograms, Q_{in} is daily discharge in cubic metres at Simmesport, and L_{out} is combined daily suspended sediment load in kilograms, and Q_{out} is combined daily discharge in cubic metres from Wax Lake and Morgan City.

Equations (4) and (5) obtained a regression coefficient (r^2) of 0.79 (n = 762) and 0.81 (n = 392), respectively.

Daily mass inflow and outflow of suspended sediment estimated from the above models were summed over time to provide monthly and annual fluxes for the 30-year period from 1975 to 2004. Annual sediment retention (L_R) in the Atchafalaya River Basin was calculated by:

$$L_R = \frac{L_{in\_tot} - L_{out\_tot}}{L_{in\_tot}} \times 100 \quad (6)$$

where L_{in_tot} is the annual total inflow of suspended sediment at Simmesport and annual total inflow of suspended sediment at Simmesport, and L_{out_tot} is the total outflow of suspended sediment at Morgan City and Wax Lake Outlet.

Assessment of the Atchafalaya Bay Delta growth

Two Landsat-TM 5 images (path/raw: 23/39) acquired on 7 December 1984 and 13 October 2004 were utilized to quantify the change in land area of the Atchafalaya Bay Delta for the past 20 years. The images were processed as follows. First, the image acquired in 1984 was rectified and registered to the image acquired in 2004 using a set of ground control points and a nearest neighbour re-sampling method. The location error of less than one pixel for these two geometrically correlated images was considered good for detecting the pixel-based change information between the images. Second, to minimize and normalize the effect of atmosphere and sun illumination geometry on the imagery, the two images were radiometrically corrected using the dark object subtraction model (Chavez, 1996), which was recommended as one of the best atmospheric correction methods for change detection applications (Song *et al*., 2001). Then, the images were classified into three categories: water, vegetated land, and non-vegetated land, with the unsupervised classification method. Finally, the land cover changes were identified with a univariate image differencing algorithm.

RESULTS AND DISCUSSION

Hydrological conditions and suspended sediment concentrations

From 1975 to 2004, discharge at Simmesport (i.e. inflow to the Atchafalaya) averaged 6500 $m^3 s^{-1}$, with a large fluctuation from 600 to 20 000 $m^3 s^{-1}$. During the same 30-year period, the average combined discharge at Morgan City and Wax Lake Outlet (i.e. outflow from the Atchafalaya) was 6400 $m^3 s^{-1}$, varying from 600 to 19 000 $m^3 s^{-1}$. The difference between inflow and outflow also may have been affected by the measurement error that could be on the order of 5–8% (Horowitz, 2003), which indicates that the long-term inflow and outflow are within measurement error. According to Horowitz (2003), the measurement error could propagate to a suspended sediment flux estimation error in a range of ±10% to ±20%. Seasonally, inflow and outflow were high from December to June, and low from July to November. During the high flow season, monthly inflows were significantly higher than monthly outflows, suggesting that the basin serves as a recharge zone from winter to late spring (Fig. 2). During the low flow season, however, monthly outflows were higher than monthly inflows, indicating that the basin serves as a discharge zone.

The inflow waters of the Atchafalaya River showed an average suspended sediment concentration of 310 mg L^{-1} with a large fluctuation from 36 to 1910 mg L^{-1}. There was a decreasing trend over the past 30 years, especially after 1985 (Fig. 3), which can mainly be attributed to changing land use practices, such as reduced soil tillage, in the Upper Mississippi River Basin since the construction of large river dams and locks was completed before that time. The concentrations of suspended sediment averaged 343 mg L^{-1} for the period from 1975 to 1985 and decreased to an average of 283 mg L^{-1} in the following 20 years. The outflow waters of the Atchafalaya River showed a 30-year average suspended sediment concentration of 280 mg L^{-1}, and a significantly decreased difference in sediment concentration with the inflow waters during the last 10 years (1995–2004, Fig. 3). This may suggest that the Atchafalaya River basin has been silted up, and that the system has reached an equilibrium state.

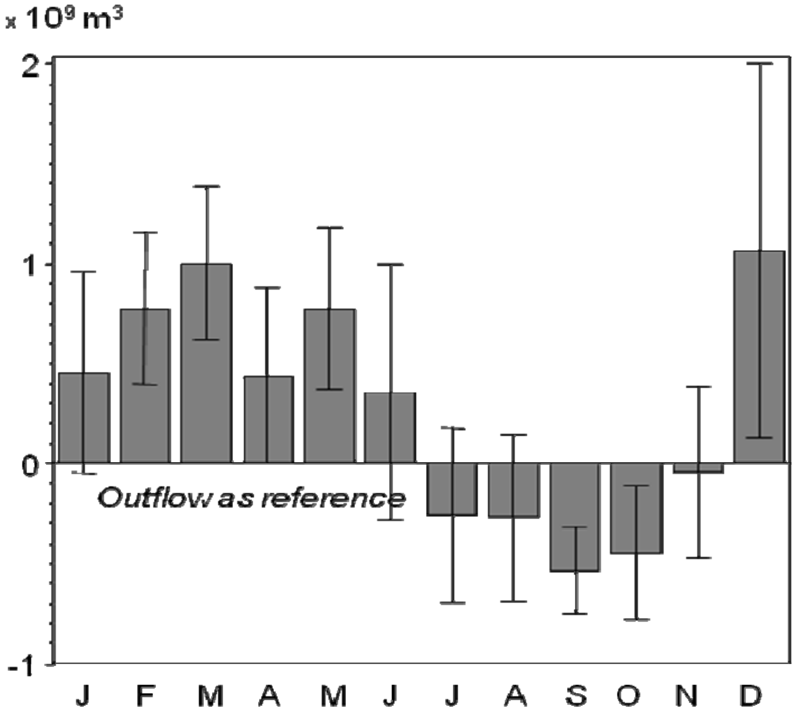

Fig. 2 Monthly average inflow-outflow budget of the Atchafalaya River Basin from 1975 to 2004 (means with error confidence limit, p = 0.95).

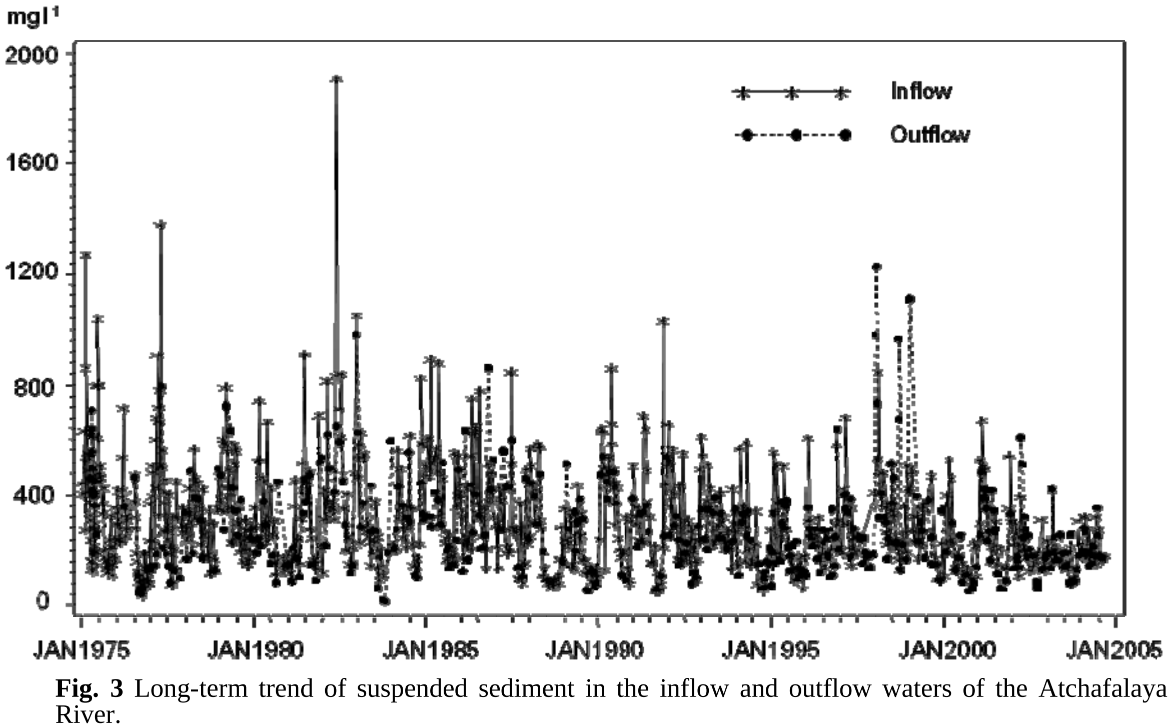

Fig. 3 Long-term trend of suspended sediment in the inflow and outflow waters of the Atchafalaya River.

Similar to the river flow, suspended sediment concentrations during the winter and spring months were significantly higher than those during the summer and autumn months. In the Upper Mississippi River Basin, more than 20 million ha have been drained through the use of subsurface tile drainage, ditches, and streams (USDA, 1987). This drainage practice, higher surface runoff, and soil tillage during the late winter and spring have contributed to the higher suspended sediment concentrations during the seasons. The sediment concentration decreased during the summer and autumn, indicating the direct influence of the runoff from the Upper Mississippi River Basin on fine sediment fluxes.

Sediment retention rates in the Atchafalaya River Basin

On average, over the past 30 years, about 180 000 tonnes of suspended sediment entered into, and about 160 000 tonnes of suspended sediment discharged out of the Atchafalaya River Basin each day. On a monthly basis, a total of 5.3 million tonnes of suspended sediment entered in, and a total of 4.9 million tonnes of suspended sediment left the river basin. Annually, the river carried in a total of 64 million tonnes of suspended sediment and carried out a total of 58 million tonnes of suspended sediment, resulting in an average retention of 6.0 million tonnes (or nearly 9%) in the river basin. Cumulatively, for the entire 30 years from 1975 to 2004, a total of 170 million tonnes of suspended sediment were deposited in the Atchafalaya River Basin.

Seasonally, suspended sediment loads were highest during the spring and lowest during the summer mainly due to fluctuations in river discharge. The retention rate of suspended sediment in the basin, however, was highest during the winter months (570 000–860 000 tonnes month^{-1}) and lowest during the autumn months (240 000–370 000 tonnes month^{-1}), corresponding with the seasonal trend of sediment inflow into the river basin. In general, the monthly sediment fluxes appeared to increase with increasing monthly river inflow until it reached a threshold of approximately 2.7×10^{10} m^3, and then decreased afterwards to a negative budget (Fig. 4). Riverine wetlands along the Atchafalaya River are backwater cypress-tupelo swamps. Hydrologically, these swamp areas serve as a retention basin when the channels' water level rises and spills onto the flood plain; when the water level falls it becomes a discharge area. The flooding and recession patterns generally contribute to sedimentation; however, when flow reaches a high threshold point, flooding also may cause surface and bank erosion, resulting in a net sediment outflow from the basin.

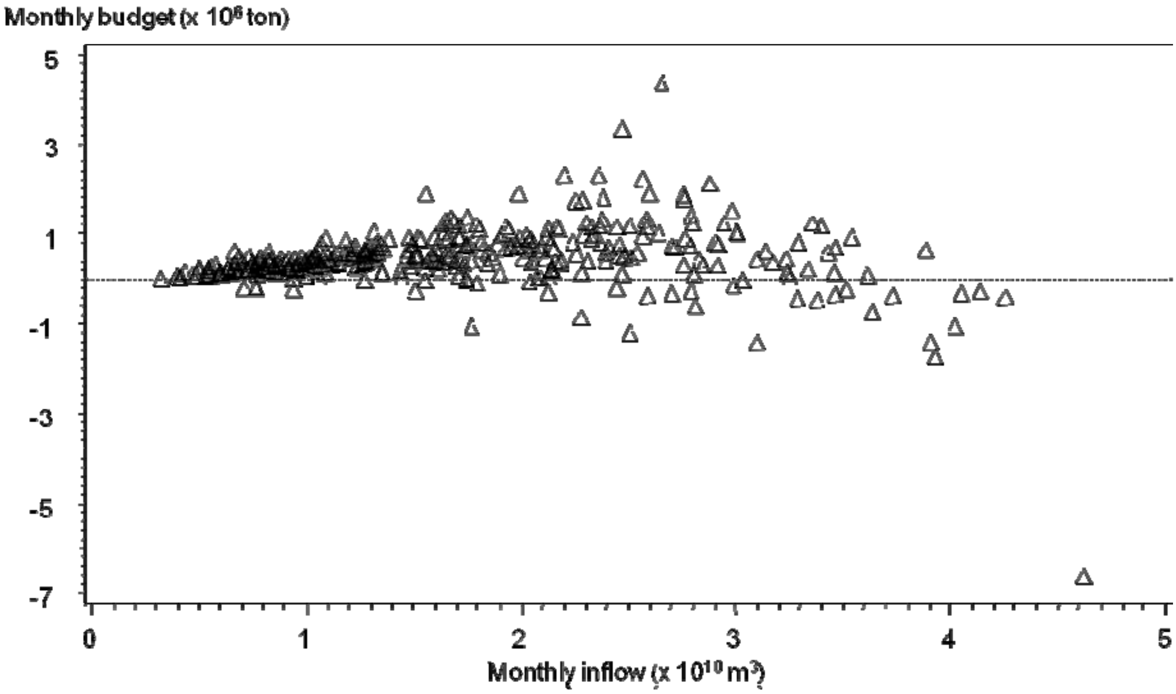

Fig. 4 Relationship of the monthly input–output budget of suspended sediment with the river inflow of the Atchafalaya.

Wells & Demas (1977) reported an average suspended sediment load of 260 000 tonnes per day at Simmesport for the period from 1964 to 1974, which represents an annual average of 95 million tonnes. Using the river discharge and a sediment concentration of 370 mg L^{-1} as average, Allison *et al*. (2000) reported a sediment load of 84 million tonnes per year at Simmesport for 1953–1989, which represents an average daily load of 230 000 tonnes. The sediment loads quantified in this study for 1975–2004 are about 30% lower than the reported loads for the previous decades, which mainly is due to the reduction of suspended sediment concentration in the Mississippi River's waters. In the past 30 years, as the sediment inflow decreased, sediment retention in the basin also decreased. However, the river basin continues to take in a large amount of suspended sediment and the hydraulic gradient of the river continues to decrease (Fig. 5).

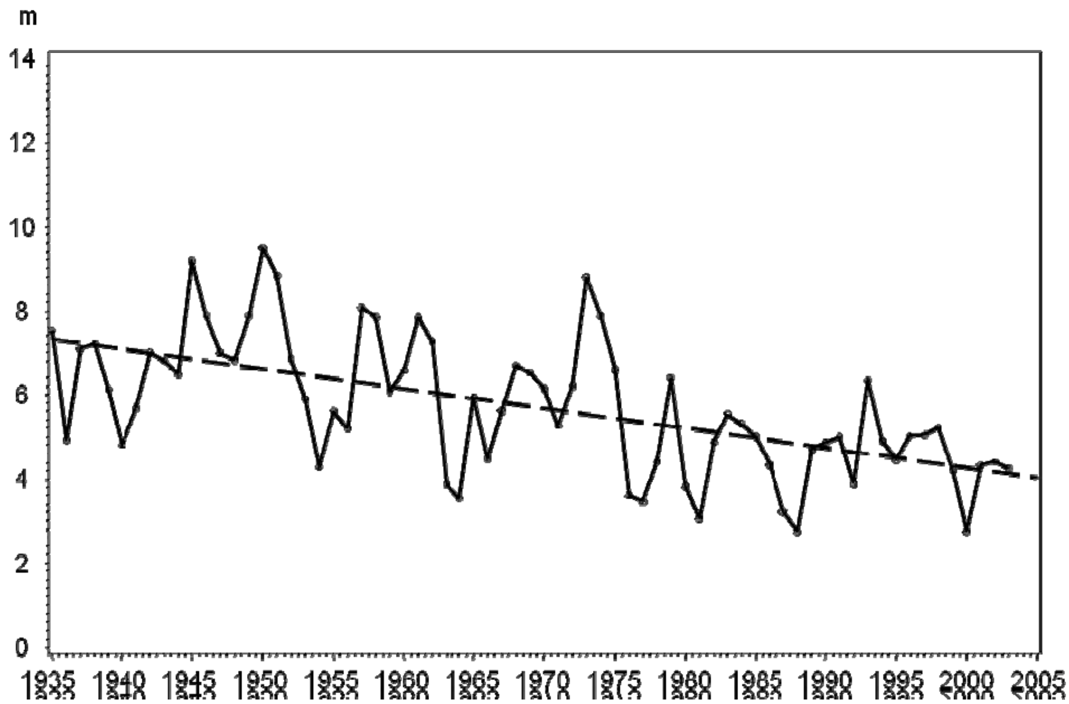

Fig. 5 Change in hydraulic gradient of between Simmesport & Morgan City, the Atchafalaya.

Sediment delivery and Atchafalaya Bay Delta growth

The satellite image assessment showed a distinct change in emerged land area of the Athafalaya Bay in the last 20 years (Fig. 6). The land area at the mouth of Wax Lake Outlet increased from 670 ha in 1984 to 4600 ha in 2004. The land area at the mouth of the Atchafalaya main channel (Morgan City outlet) increased from 1200 ha in 1984 to 3400 ha in 2004. Together, the change represents a 438% increase in land area in the Atchafalaya Bay. During this 20-year period, the Atchafalaya River delivered a combined total of 12 million tonnes of suspended sediment from its natural and man-made channels, which should have been the major source for the land accretion.

Land accretion of the Atchafalaya Delta was first reported after the flood in 1973 (Shlemon, 1975; Roberts *et al*., 1980). Allison *et al*. (2000) noted that by 1990, over 64 km^2 (or 6400 ha) of land accretion had taken place. In this study, a total land area of 8100 ha was found in the Atchafalaya Bay in 2004. Furthermore, it was found that much of the newly created land areas (>70%) were quickly vegetated. The natural vegetation succession may have greatly contributed to stabilization of the small delta lobes against sediment resuspension and hence, the rapid growth of land.

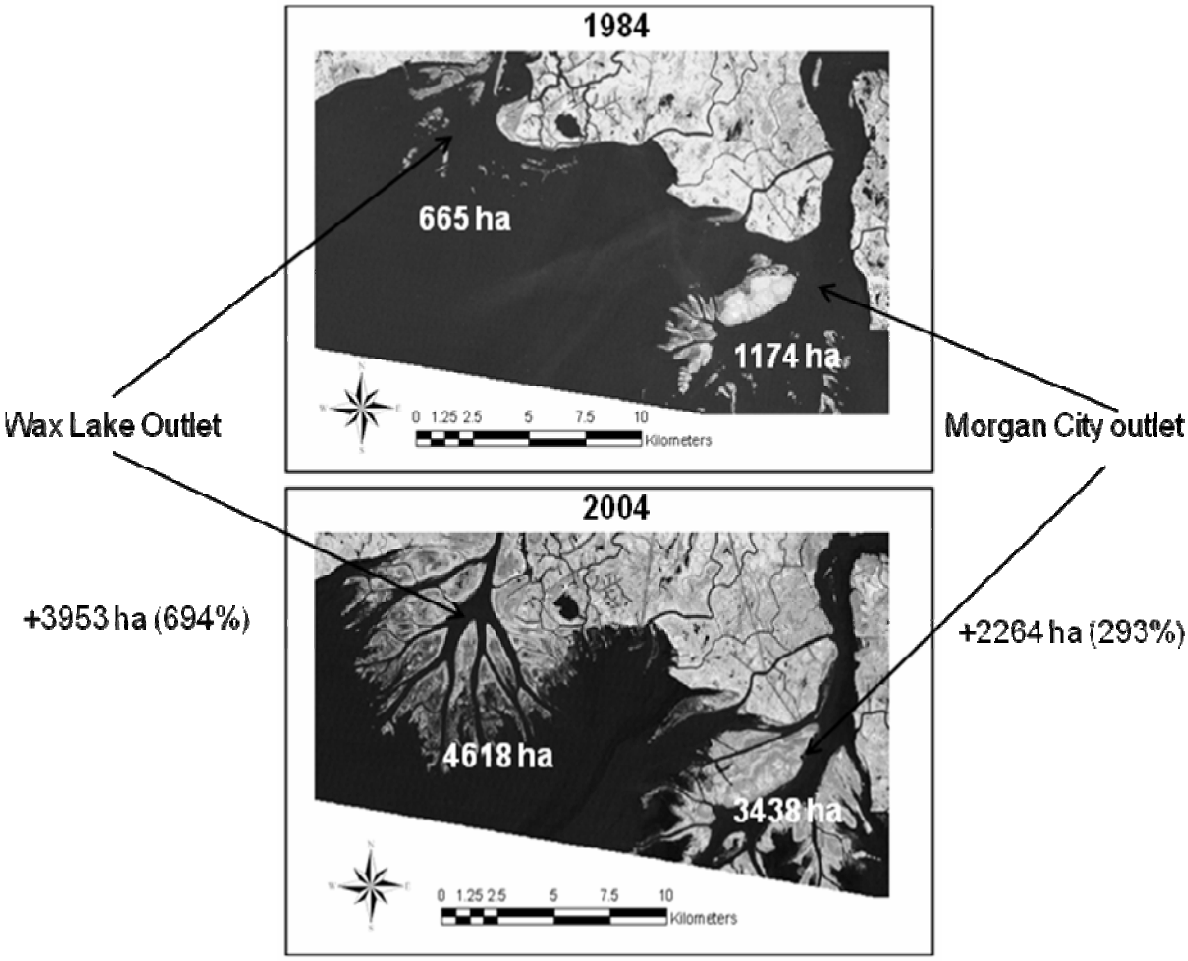

Fig. 6 Changes in emerged land areas in the Atchafalaya Bay from 1984 to 2004.

CONCLUSIONS

This study quantified the inflow and outflow of suspended sediment in the Atchafalaya River for the period from 1975 to 2004. It presents a comprehensive evaluation of the hydrology and sediment transport in this largest distributary of the Mississippi River. Based on the findings, it can be concluded that both sediment inflow and sediment retention in the Atchafalaya have decreased in the past 30 years. The basin seems to have reached an equilibrium state. The river basin continues delivering a large quantity of suspended sediment to the Atchafalaya Bay, while the channels and in-basin areas are silted up. The river hydraulic gradient continues declining, which helps reduce gravity flow and hence, contributes to sedimentation in the Atchafalaya Bay.

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