Estimation of sedimentation rates in the distributary basin of the Mississippi River, the Atchafalaya River Basin, USA

Timothy Rosen and Y. Jun Xu

ABSTRACT

The Atchafalaya River Basin (ARB) is the largest distributary basin of the Mississippi River composing anastomosing channels, backwater swamps, freshwater marshes, and wetland forests. Sedimentation in the ARB has presented management issues concerning habitat changes from open water areas to bottomland hardwood forests. A thorough understanding of sediment transport and deposition in the basin is not only required for proper management of the ARB, but is crucial for regional sediment budgets that affect the Mississippi River Delta Plain. In this study, we calculated 31 years (1980–2010) of total suspended sediment (TSS) inflow and outflow of the Atchafalaya River to quantify the long-term sediment retention in the basin. We then estimated sedimentation rates in the basin by spatially relating the retention with changes of turbid water area derived from Landsat imagery. The study found an annual average TSS inflow of 54.0 megatonnes (MT) and an annual average TSS outflow of 48.7 MT, resulting in an average annual retention of 5.3 MT. Spatially derived mean sedimentation rates were estimated between 0.06 and 0.153 mm d^{-1}. The spatial estimates for sedimentation proved promising and with more sediment data available could become an invaluable tool for managing the ARB in the future.

Key words | Atchafalaya River, floodplain, floodway basin, Mississippi River, sedimentation rate, sediment yield

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INTRODUCTION

Coastal floodplains have a large capacity to trap riverine sediment and nutrients (Hupp 2000; Noe & Hupp 2009). With catchment-wide changes to land cover and the construction of dams, levees, and river training structures, there have been major impacts on river sediment transport and the interaction of rivers with floodplains (Walling 2006; Hoffmann *et al*. 2010). Due to the variable nature of the impacts that these changes can have on coastal floodplains, it makes it important to properly track sediment dynamics and understand how this influences floodplain sediment storage and landscape habitat change.

The Mississippi River system provides a good example of how changing hydrology and sediment dynamics can affect floodplains. In the upper Mississippi River, dams and other river engineering structures on tributaries have caused decreased sediment supply to the lower Mississippi River (Meade & Moody 2010). Along the banks of the river man-made levees have confined the river to its channel to reduce flooding, but have effectively cut-off the floodplain and delta plain surrounding the river (Kesel 2003). The loss of mineral inputs and high subsidence rates has caused approximately 4,900 km^2 of land loss in the delta plain (Yuill *et al*. 2009; Couvillion *et al*. 2011).

With the need for controlling flooding and land loss, management of the Mississippi River is complicated. One area that is heavily regulated by federal and state agencies is the largest distributary of the Mississippi, the Atchafalaya River. The Atchafalaya River is confined by levees as a floodway with floodplains up to ~35 km wide. The river with its seasonally inundated floodplain, known as the Atchafalaya River Basin (ARB), comprises a levee-confined area of 3,923 km^2 (Xu 2013), and is the largest river swamp in the

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United States (Figure 1). Starting from its confluence with the Mississippi River, the Atchafalaya River is about 307 km shorter than the Mississippi River to the northern Gulf of Mexico. Due to the more favorable gradient (Fisk 1952) and in conjunction with human alterations to the Mississippi River and Atchafalaya River, a better defined channel began to form in the mid-1900s, which increased the flow volume going down the Atchafalaya River (Roberts *et al.* 1980). With fears of the Atchafalaya River capturing the majority of the discharge of the Mississippi River, the Old River Control Structure (ORCS) was completed in 1963 under the Flood Control Act of 1954. ORCS maintains approximately 25% of the discharge of the Mississippi River entering into the Atchafalaya River (Horowitz 2010). Although discharge was controlled, previous accumulation of sediments had filled many open water areas in the ARB (Tye & Coleman 1989).

With much of the ARB sediment filled major management issues have arisen regarding remaining open water areas, wetlands and habitat changes. As the ARB is a designated floodway for the Mississippi River, major flood events are regulated through the ORCS. Because of previous sedimentation, the floodway basin's ability to buffer flooding has been diminished and there are concerns that with continued sedimentation, open water and low elevation cypress forests will transition to higher elevation bottomland hardwood forest, decreasing capacity and limiting sheet flow (Atchafalaya Basin Advisory Committee 1998). Another problem related to rapid sedimentation in the ARB is that many backwater areas have become cut off and subsequently hypoxic (Sabo *et al.* 1999). This has negatively affected biological communities within the ARB (Fontenot *et al.* 2001; Rutherford *et al.* 2001). Also, there is the hope that the ARB has the potential to reduce nitrogen and phosphorus before nutrient-rich Mississippi River waters enter the Gulf of Mexico (Xu 2006, 2013).

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

The goal of this study was to add to previous work to help generate a better understanding of spatial

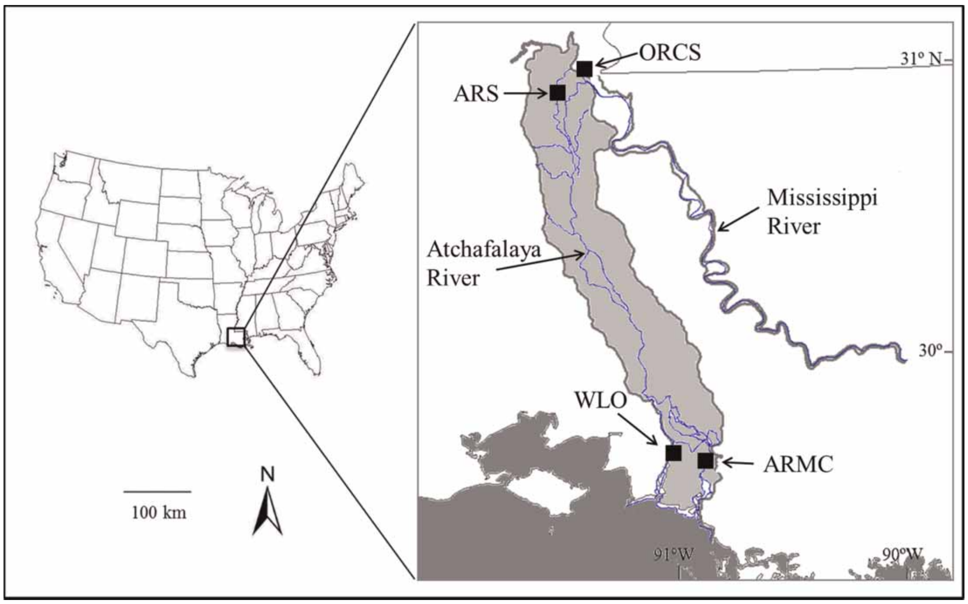

Figure 1 | Atchafalaya River Basin (gray area) with the locations of ORCS, ARS, ARMC, and WLO.

sedimentation in the ARB as well as regional sediment resources in Louisiana by calculating total suspended sediment yield entering and exiting the ARB, and expanding the use of Allen *et al*. (2008) spatial datasets. The specific objectives of this study were: (1) to derive the best estimates of total suspended sediment inflow, total suspended sediment outflow, and retained sediment in the ARB by calculating total suspended sediment yields separately for Simmesport, Morgan City, and WLO; and (2) to use remotely sensed images to estimate sedimentation rates based on the basin's sediment retention over time.

METHODS

Study area

The Atchafalaya River is formed by the entire flow of the Red River combined with approximately 25% of the Mississippi River flow. The river travels 275 kilometers through south Louisiana from Simmesport, Louisiana (ARS 30°59′00″ N, 91°12′43″ W; Figure 1) to the outlets at Morgan City, Louisiana (ARMC, 29°41′33.4″ N, 91°12′42.6″ W; Figure 1), and WLO at Calumet, Louisiana (WLO, 29°41′52″ N, 91°22′22″ W; Figure 1). The first 110 km of the river is confined to a well defined channel bordered by levees. Below this it opens up to a 25–35 km wide floodplain leveed on the east and west. The river in this section is composed of anastomosing channels. The dominant cover types of the Atchafalaya River Basin are wooded lowland and cypress-tupelo (3,581 km^2) with freshwater marshes (2,092 km^2) in the lower distributary area (USGS 2001) and some agricultural fields in the northern channelized area. Climate of the region is humid subtropical (Köppen climate classification *Cfa*).

Riverine sediment load estimation

Long-term discharge and sediment records were obtained from the United States Geological Survey (USGS, http://la.water.usgs.gov/) and the United States Army Corps of Engineers (USACE, http://www2.mvn.usace.army.mil/eng/edhd/watercon.asp). All sites used in this study are dually maintained by the USGS and USACE. Daily mean discharge data for the Atchafalaya River at Simmesport, Louisiana (ARS; Figure 1) were downloaded from the USACE New Orleans district for the time period 1 January 1980 to 31 December 2010. Daily mean discharge data were downloaded directly from the USGS website (http://waterdata.usgs.gov/la) for Lower Atchafalaya River at Morgan City, Louisiana (ARMC; Figure 1), and WLO at Calumet, Louisiana (WLO; Figure 1). Discharge measurement did not begin at WLO until June 1986 and at ARMC until October 1995. Missing discharge data for WLO and ARMC were estimated based on a relationship from Xu & Wang (in review) using the gauging station up river at ARS. The equations used were:

$$QARMC = 10894.31977 + 0.53129\ (QARS) \tag{1}$$

$$QWLO = 6290.27339 + 0.34707\ (QARS) \tag{2}$$

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

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

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

Both linear and 2nd order polynomial sediment rating curves were calculated with and without smearing correction. Smearing correction was followed using the methods of Duan (1983). For the ARS long-term (using all the data) and annual sediment rating curves were developed using linear and 2nd order polynomial regression. For the ARMC and WLO long-term (using all the data) and three year sediment rating curves were developed separately for each station using both linear and 2nd order polynomial regression. Three year intervals were used because of missing SSC values for 2006 at ARMC and 2006 and 2007 at WLO. Daily total suspended sediment load was estimated using the following formulas:

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

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

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

$$\%\,\text{difference} = [(\text{predicted value}) - (\text{measured value}) / (\text{measured value})] \times 100 \tag{6}$$

The rating curves with the best fitting parameters were selected to estimate total suspended sediment load (tonnes day^{-1}) and subsequently summed to estimate total suspended sediment yield (tonnes yr^{-1}) on the annual scale based on the calendar year (see Appendix Table A1, available online at http://www.iwaponline.com/nh/046/181.pdf). Daily total suspended sediment load estimated for spatial sedimentation rate calculation was completed by using the sediment rating curves that provided the closest approximation to the sampled data for the month in which the image was captured (see Appendix Table A2, available online at http://www.iwaponline.com/nh/046/181.pdf). Flow-weighted SSC was also calculated to determine retained SSC on the daily scale for sedimentation analysis. Flow-weighted SSC was calculated using:

$$\text{Flow-weighted concentration (mg l}^{-1}) = [\text{Daily flux(t)}]/[\text{Daily water volume (m}^3)]\,[10^6] \tag{7}$$

Sedimentation estimation

Atchafalaya River Basin turbid water layers were downloaded from the Louisiana Department of Natural Resources (LDNR) Atchafalaya Basin Program Natural Resource Inventory and Assessment System (http://abp.cr.usgs.gov/Map.aspx). Classification of the downloaded turbid water Landsat imagery was completed by methods described in Allen *et al.* (2008). There were 30 total images spanning 1983 to 2010. These images were captured under cloud-free, leaf-off conditions to minimize the effect of tree canopy obscuring water conditions. Each image was classified into six different categories; Land, Open Turbid Water, Open Non-Turbid Water, Flooded Land Turbid Water, Flooded Land Non-Turbid Water, and Aquatic Vegetation. Only Open Turbid Water and Flooded Land Turbid Water classes were used because these areas were inferred to be directly influenced by the Atchafalaya River. From these 30 images, only 20 images were used for sedimentation rate calculation because they had a net positive amount of suspended sediment retained. Retained amounts were determined as the difference between total suspended sediment load entering at ARS and exiting at ARMC and WLO for the day of the image capture. A lead was applied to ARS to compensate for the amount of time water takes to travel from ARS to ARMC and WLO. The mean lead was 2 days but varied between 0 and 4 days. Lead times were determined by comparing peaks and troughs of the hydrograph for all three sites. Sedimentation rates were calculated using the amount of retained total suspended sediment (tonnes), several bulk densities that were representative of those reported in Hupp *et al.* (2008) and Scaroni (2011), the volume of sediment, and turbid water area (m^2) derived from the classes introduced previously. The equations used were:

$$\text{Volume (m}^3\text{ day}^{-1}) = [\text{SSL Retained (tonnes day}^{-1})]/[\text{Bulk Density (tonnes m}^{-3})] \tag{8}$$

$$\text{Sedimentation Rate (mm day}^{-1}) = ([\text{Volume (m}^3\text{ day}^{-1})]/[\text{Turbid Water Area (m}^2)])*1,000 \quad (9)$$

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

A separate sedimentation rate analysis was completed for 2010 incorporating a low water LIDAR (Light Detection and Ranging) dataset. 2010 LIDAR DEM (digital elevation model) imagery was produced by the National Geospatial Program and USGS Coastal and Marine Geology Program with horizontal resolution of approximately 1 m and vertical accuracy of 36.3 cm at the 95% confidence level, captured over the period 2 December 2010 to 7 December 2010. The turbid water image classification for 16 February 2010 was compared with the 2010 LIDAR DEM to extract elevation for the turbid water areas. These areas were subsequently classified into three different categories: water, bottom land cypress forest (BLCF), and bottom land hardwood forest (BLHW) based on elevation. Water class consisted of areas classified as Open Turbid Water at all elevations. BLCF were areas that were identified as Flooded Land Turbid Water that were at elevations between −1 and 4 m, and BLHW were areas identified as Flooded Land Turbid Water and were areas above 4 m. The bulk densities used for each class were 0.53 g cm^{-3} (water), 0.51 g cm^{-1} (BLCF), and 1.23 g cm^{-3} (BLHW). The forest classes, elevation thresholds for forest classes, and bulk densities used for this analysis were derived from Scaroni (2011).

Statistical analysis

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

RESULTS

Discharge

Mean annual (calendar year) total flow volume over the period 1996 to 2010 at Atchafalaya River Simmesport (ARS) was 199.1 km^3, with a low of 129.2 km^3 (2000) and a high of 247.6 km^3 (2009) (Figure 2). The mean discharge split between Atchafalaya River Morgan City (ARMC) and WLO was 57 to 43%. It is of note that over the period WLO gradually captured a greater portion of the discharge, with the split in 2010 being 53 to 47% (Figure 2). ARMC mean annual total flow volume was 112.3 km^3, varying between 74.0 km^3 (2000) and 137.6 km^3 (2009) (Figure 2). WLO mean annual total flow volume was 85.3 km^3, ranging from 48.8 km^3 (2000) to 115.2 km^3 (2009) (Figure 2). None of the stations had a significant temporal trend.

Suspended sediment concentration

ARS mean annual SSC was 259 mg l^{-1} and varied between 162 mg l^{-1} (2005) and 411 mg l^{-1} (2010) (Figure 3). ARMC mean annual SSC was 239 mg l^{-1}, with a low of 136 mg l^{-1} (2000) and a high of 449 mg l^{-1} (1998) (Figure 3). WLO mean annual SSC was 223 mg l^{-1}, and varied between 136 mg l^{-1} (2000) and 351 mg l^{-1} (1998) (Figure 3). ARMC had, on average, 10% higher SSC than WLO. SSC was higher at WLO than ARMC only three times. All sites had a decreasing trend, and it was significant at ARMC (Seasonal Mann-Kendall, $p = 0.0356$) and WLO (Seasonal Mann-Kendall, $p = 0.0019$).

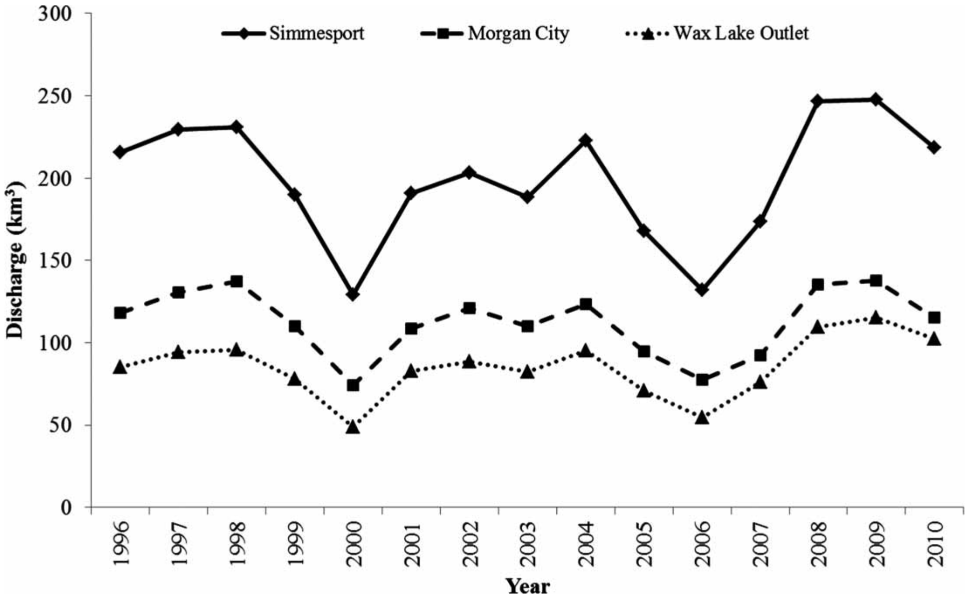

Figure 2 | Total annual discharge volume of ARS, ARMC, and WLO.

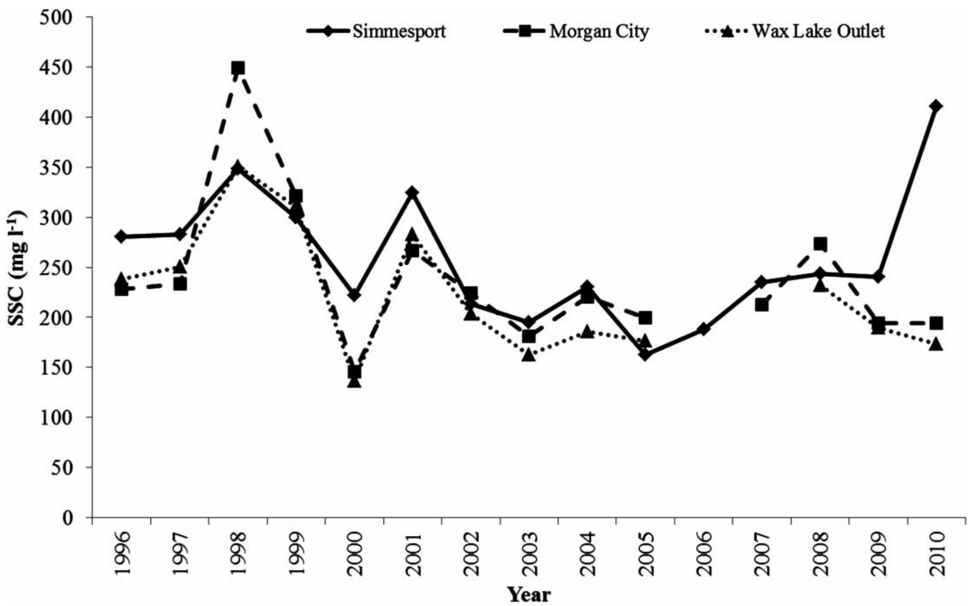

Figure 3 | SSC for ARS, ARMC, and WLO. 2007 for ARMC, and 2006 to 2007 for WLO have missing data.

Total suspended sediment yield

ARS mean annual total suspended sediment yield was 54.0 MT over the period 1996 to 2010. During the period, total suspended sediment yield varied between 26.0 MT (2006) and 88.0 MT (1998) (Figure 4). Total suspended sediment yield at ARS was influenced more by changes in SSC than discharge, with a one standard deviation increase in SSC causing a 0.71 standard deviation increase in the predicated total suspended sediment yield, whereas discharge only produced a 0.44 increase. ARMC mean annual total suspended sediment yield was 28.9 MT and ranged between 13.6 MT (2006) and 60.4 MT (1998) (Figure 4). Total suspended sediment yield at ARMC was influenced more by

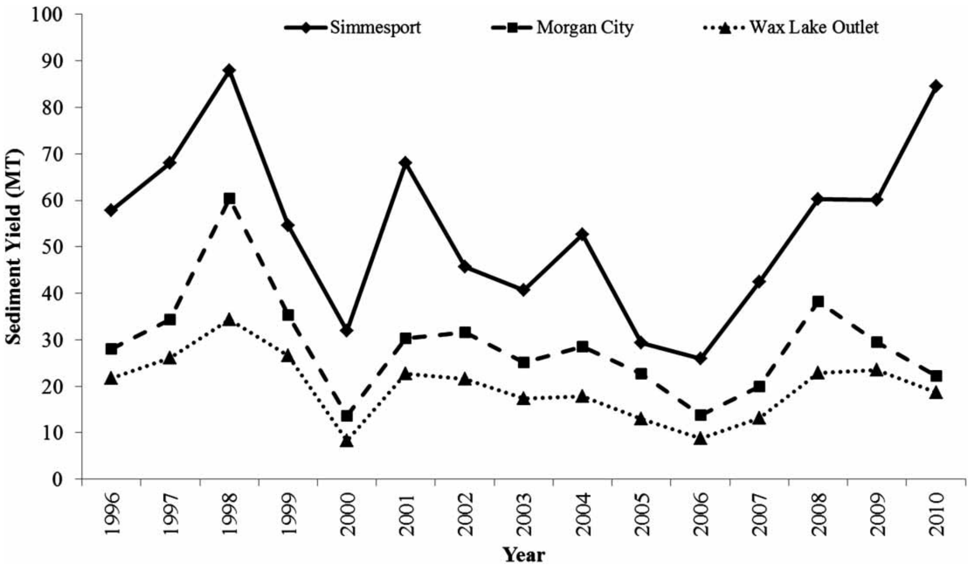

Figure 4 | Total suspended sediment yield of ARS, ARMC, and WLO.

changes in SSC than discharge, with a one standard deviation increase in SSC causing a 0.75 standard deviation increase in the predicated total suspended sediment yield, whereas discharge only produced a 0.36 increase. WLO mean annual total suspended sediment yield was 19.8 MT and ranged between 8.3 MT (2000) and 34.4 MT (1998) (Figure 4). As with the other stations, total suspended sediment yield was influenced more by changes in SSC with a one standard deviation increase producing a 0.80 standard deviation increase in predicted total suspended sediment yield, while discharge only produced a 0.41 increase. All multiple regressions were able to explain more than 90% of the variation in total suspended sediment yield. There was a decreasing trend of suspended sediment yield at each station, but this trend was not significant.

Suspended sediment retention

The difference between total suspended sediment inflow and outflow from the ARB (retained sediment) was, on average, 5.3 MT, with a low of −7.4 MT in 2002 (net export out of the ARB) and a high of 43.6 MT in 2010 (Figure 5). Years with net retained total suspended sediment averaged 12.3 MT retained and years with net export averaged 5.1 MT exported. Not including 2010, the overall mean amount of retained sediment was 2.6 MT, while only looking at years with net retained sediment the mean was 8.4 MT. The average difference between SSC entering the ARB and exiting was 33.2 mg l^{-1}. This difference varied between −51.84 mg l^{-1} (1998, higher concentration at the outlets) and 226.9 mg l^{-1} in 2010 (Figure 5). Years with net retained total suspended sediment averaged a SSC difference of 68.0 mg l^{-1}, while years with net export averaged 13.3 mg l^{-1} (higher SSC at the outlets). Not including 2010, the overall mean SSC difference drops to 18.25 mg l^{-1} and for years with net SSC retention, 39.6 mg l^{-1}. The overall mean difference between discharge inflow and outflow was 1.5 km^3 annually, with a low of −6.2 km^3 in 2002 (net discharge out of ARB) and a high of 12.1 km^{-3} in 1996. Years with net suspended sediment yield retention averaged 3.1 km^3 of retained discharge, while years with net suspended yield export averaged −0.99 km^3. SSC inflow at ARS affected the amount of retained sediment the greatest, with a one standard deviation increase in SSC at ARS yielding a 1.02 standard deviation increase in predicted retained sediment. This was followed by SSC at ARMC and WLO (one standard deviation increase produced 0.87 standard deviation decrease in retained sediment), discharge at ARS (one standard deviation increase produced 0.68 standard deviation increase), and combined ARMC and WLO discharge (one standard deviation increase produced a 0.66 standard deviation decrease in retained sediment). All four of these variables accounted for 91% of the variability in the amount of suspended sediment retained in the ARB.

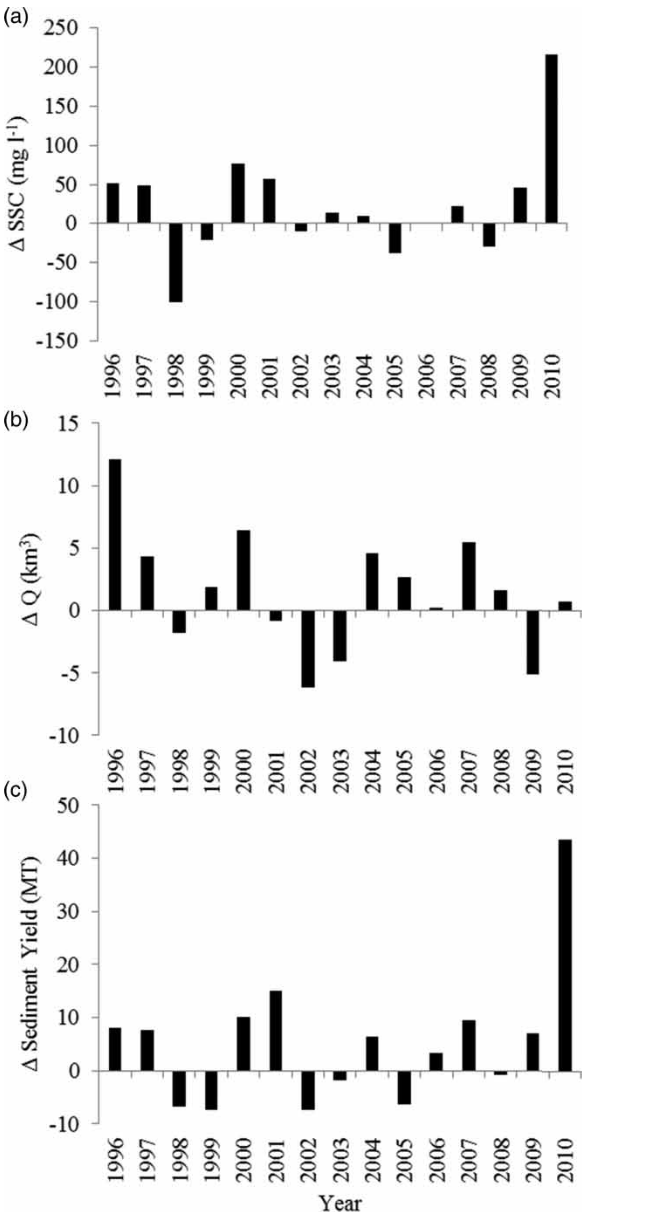

Figure 5 | Difference (Δ) between (retained in the Atchafalaya River Basin) ARS and the combined ARMC and WLO for SSC (top), discharge volume (middle), and total suspended sediment yield (bottom). Positive values are net retention and negative values are net export.

Spatially derived sedimentation rates

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

2010 analysis using LIDAR

Spatial analysis completed with 2010 LIDAR imagery and turbid water data from 2010 (Figure 6) had a total of 746 km^2 inundated with turbid water. This area was broken down to 178 km^2 of open water, 560 km^2 of BLCF, and 8 km^2 of BLHW (Table 2). A total of 58,389 tonnes of sediment was retained in ARB when this image was taken (Table 2). Sedimentation rates were calculated as open water = 0.148 mm d^{-1}, BLCF = 0.153 mm d^{-1}, and BLHW = 0.06 mm d^{-1} (Table 2). This would, if these were mean daily sedimentation rates, extrapolate out to a weighted mean (by area) annual sedimentation rate of 55.1 mm yr^{-1}.

DISCUSSION

Trend of sediment yield

This study provides the first comprehensive longer-term calculations of total suspended sediment yield exiting the ARB through ARMC and WLO. ARMC mean total annual suspended sediment yield was 28.9 MT, while WLO averaged 19.8 MT. Xu (2010) estimated 58.0 MT yr^{-1} for the outlets combined, whereas our estimate was 48.7 MT yr^{-1}. Xu (2010) did not provide separate estimates for the outlets and only used SSC from ARMC to calculate the combined sediment yield. From our study, it was identified that ARMC had 10% higher SSC than WLO. The higher SSC at ARMC as well as different time frames (1974–2004)

Table 1 | Sedimentation rate estimates with varying sediment bulk densities. Note that only dates having net positive retention of sediment load were used for image analysis

					Sedimentation rate mm day^{-1}				
Date	**Turbid water area (km^2)**	**Δ Sediment load (t)**	**Δ Flow-weighted SSC (mg l^{-1})**	**Δ Q (m^3 s^{-1})**	**BD 0.5 g cm^{-3}**	**BD 0.7 g cm^{-3}**	**BD 0.9 g cm^{-3}**	**BD 1.1 g cm^{-3}**	**BD 1.3 g cm^{-3}**
26 Jan 1985	951	130,828	182	484	0.275	0.196	0.153	0.125	0.106
13 Jan 1986	323	45,999	100	144	0.284	0.203	0.158	0.129	0.109
02 Mar 1986	456	43,443	48	522	0.191	0.136	0.106	0.087	0.073
14 Jan 1992	761	119,513	161	467	0.314	0.224	0.174	0.143	0.121
16 Jan 1993	597	248,699	253	777	0.833	0.595	0.463	0.379	0.320
05 Mar 1993	478	76,792	78	595	0.321	0.229	0.178	0.146	0.123
09 Jan 1996	203	113	19	−330	0.001[a]	0.001[a]	0.001[a]	0.001[a]	0.001[a]
25 Jan 1996	213	3,973	31	−359	0.037	0.027	0.021	0.017	0.014
16 Dec 1998	215	44,809	103	−190	0.417	0.298	0.232	0.189	0.160
20 Jan 2000	349	40,998	171	−291	0.235	0.168	0.131	0.107	0.090
05 Feb 2000	23	36,647	237	−331	3.133[a]	2.239[a]	1.741[a]	1.425[a]	1.205[a]
05 Dec 2000	147	19,138	53	105	0.260	0.186	0.145	0.118	0.100
29 Dec 2000	241	17,019	34	154	0.141	0.101	0.078	0.064	0.054
22 Jan 2001	296	23,413	66	−228	0.158	0.113	0.088	0.072	0.061
18 Feb 2002	790	30,766	23	708	0.078	0.056	0.043	0.035	0.030
22 Mar 2002	265	5,281	11	−57	0.040	0.028	0.022	0.018	0.015
04 Jan 2003	486	10,725	1	542	0.044	0.032	0.025	0.020	0.017
27 Jan 2008	577	4,651	32	−708	0.016	0.012	0.009	0.007	0.006
01 Mar 2009	280	14,288	27	−170	0.102	0.073	0.057	0.046	0.039
16 Feb 2010	755	58,389	72	−311	0.155	0.110	0.086	0.070	0.059
				AVG mm day^{-1}	0.217	0.155	0.120	0.099	0.083
				AVG mm year^{-1}	79.1	56.5	44.0	36.0	30.4

Difference (Δ) is inflow at ARS minus combined outflow of ARMC and WLO.
[a]Denotes values not used for averages.

may explain the difference in sediment yield estimates between Xu (2010) and this study. Allison *et al.* (2012) estimated total suspended sediment yield separately for the period 2008 to 2010. Their estimate for ARMC was 27.9 MT yr^{-1} and WLO was 20.5 MT yr^{-1}. This is similar to our estimate of 30.0 MT yr^{-1} (ARMC) and 21.6 MT yr^{-1} (WLO) for the same time frame. ARS mean total annual suspended sediment yield, 54.0 MT, was slightly lower than previous studies. Xu (2010) estimated ARS total suspended sediment yield at 64.0 MT yr^{-1} for 1974–2004 and Meade & Moody (2010) estimated 57.0 MT yr^{-1} for 1987–2006. Allison *et al.* (2012) estimated total annual suspended sediment yield at 71.0 MT (2008–2010), which was similar to our estimate of 68.3 MT yr^{-1} for the same time frame. Difference in these estimates can be ascribed to different time frames, a general decrease in sediment yield from the Mississippi River over the past 50 years (Meade & Moody 2010), and different sediment rating curves applied to estimate loading (Horowitz 2003).

A slight decrease in total suspended sediment yield occurred in the past 30 years, which was driven by significant decreasing SSC at ARMC and WLO. The decreasing suspended sediment yield could be linked to the decreasing SSC in the Mississippi River (Horowitz 2010; Meade & Moody 2010). Within the annual mean SSC data, there are two peaks that stick out, one in 1998 at both ARMC and WLO, and the other in 2010 at ARS. The large peak in SSC at the outlets in 1998, that was not as pronounced at ARS, could be explained by bank failures resulting from the large flood the previous year (1997, highest peak

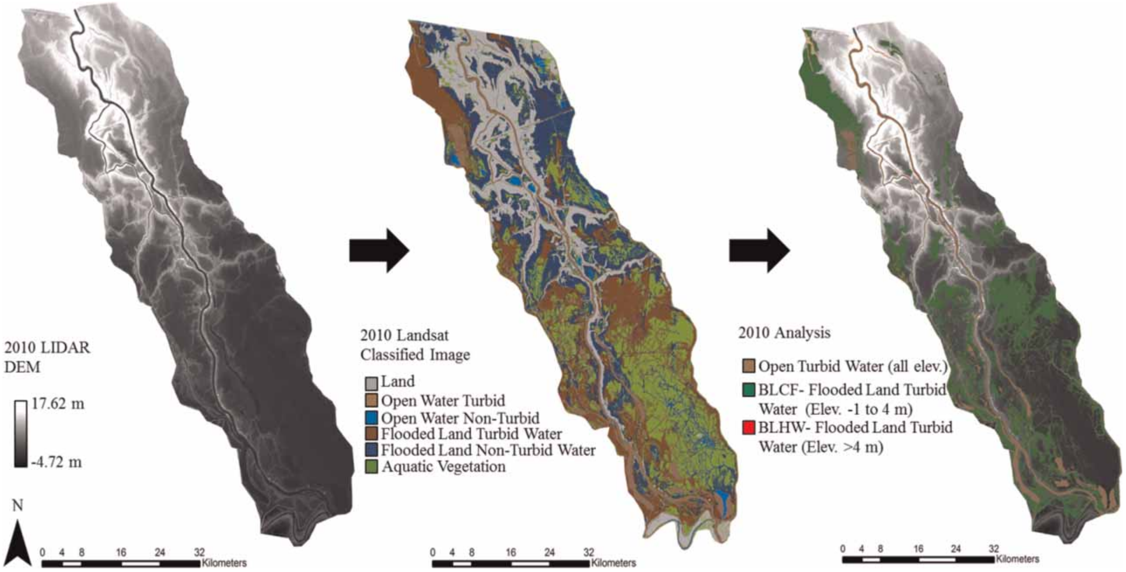

Figure 6 | Flow chart of the maps used for the 2010 analysis. From left to right; 2010 LIDAR DEM, classified image of the Atchafalaya River Basin for the 16 February 2010, and map of derived classes using the LIDAR DEM and classified image overlaid on LIDAR DEM. Classified imagery was produced by LDNR Atchafalaya Basin Program Natural Resource Inventory and Assessment System (http://abp.cr.usgs.gov/Map.aspx).

Table 2 | Turbid water area (TW), retained sediment, bulk density, and estimated sedimentation rate based of 2010 LIDAR and 2010 turbid water area estimates for open water, BLCF, and bottom land hardwood (BLHW) areas.

Stage at BLR: 5.24 m	Open water	BLCF	BLHW
TW area (km^2)	178	560	8
Retained sed (t)	13,895	43,829	665
Bulk density (g cm$^{-3)}$	0.53	0.51	1.23
Sedimentation (mm d^{-1})	0.148	0.153	0.06
Sedimentation (mm yr^{-1})	53.9	56.0	23.2

discharge for period at ARS, 18,027 m^3 s^{-1}). The Atchafalaya River at Simmesport is leveed and well confined in its channel, whereas the lower section of the river is non-engineered allowing for bank erosion and lateral migration, which in other non-engineered rivers has been documented as a major source of suspended sediment (Bull 1997; Dunne *et al.* 1998; Hudson & Kesel 2000). The peak in SSC at ARS in 2010 is harder to explain and could be either due to work on the channel or from sampling error.

Retained sediment

On average, 5.3 MT of total suspended sediment was retained annually in the ARB, which is 10% of the total suspended sediment input from ARS. Retention of sediment varied with some years with net export. Years when there was a net export averaged 5.1 MT exported or 9% more than what was input to the ARB from ARS. Years with net retention averaged 12.3 MT (22%) of total suspended sediment retained, although not including 2010, estimated retained mean total suspended sediment decreases to 8.4 MT (16%). Xu (2010) estimated an average of 5.7 MT (9%) of retained sediment (1974 to 2004). Allison *et al.* (2012) estimated 23.1 MT retained (2008 to 2010), slightly higher than our estimate, 16.6 MT, for the same time frame. Hupp *et al.* (2008) estimated from *in situ* sedimentation data an average of 5.9 MT deposited in off channel areas, although there was a net loss of sediment from the ARB during their study (2000–2003). The total amount of total suspended sediment retained (not including 2010) was 36.5 MT, which is 5% of the total suspended sediment supplied (725.8 MT). This indicates that the ARB may have reached equilibrium and more strongly resembles a fluvial system. Other studies support this observation with Hupp *et al.* (2008) describing that during their study (2000–2003) on sedimentation, there was a net export of sediment out of the ARB, and that deposited material in backwater areas was most likely being counterbalanced by either bank erosion or in channel re-suspension of sediment.

Recent findings on nitrate removal in the ARB by Bryant-Mason *et al.* (2012) also support this as there was no significant processing of nitrate, an indication of low retention time, and thus a system that is fluvial rather than palustrine or lacustrine.

The best explanatory variable for sediment retention was flow-weighted SSC entering the ARB from ARS followed by flow-weighted SSC exiting through the outlets. It is known that differing discharge regimes can cause sediment deposition or re-suspension along the lowermost Mississippi River (Galler & Allison 2008; Allison *et al.* 2012). Although, when qualitatively looking at different variables that could have affected retention or export of total suspended sediment on the annual scale it would seem that flood peak, discharge volume, and retained discharge during the same year played little or no role in the retention or export of total suspended sediment in the ARB (Table 3). This indicates that suspended sediment dynamics within the ARB are complicated by hydrological and climatological interconnections between different years. This was discussed earlier when in 1998 SSC at the outlets could have been elevated by bank failures caused by the large flood the previous year. Also, drought years when there is low discharge could induce greater channel sedimentation from low river velocity, producing greater sediment availability for the next year. Another consequence of droughts could be the drawdown of backwater areas allowing for greater accommodation for subsequent floods. This occurred in 2011, during which extreme drought conditions in Louisiana (NCDC 2011) may have helped mitigate flooding of the ARB. Another complicating factor is rapid sedimentation that could change flow patterns between years. All of these factors could have influenced the retention of sediment between different years, and make it hard to pinpoint the defining factors that control sedimentation annually in the ARB.

Sedimentation rate

The estimated mean sedimentation rates from the spatial datasets were higher than reported *in situ* measured mean sedimentation rates. Our mean sedimentation rates, estimated from a range of different bulk densities, varied between 30 and 79 mm yr^{-1}. Hupp *et al.* (2008) observed mean sedimentation rates between 1.8 and 42.0 mm yr^{-1} for various sites in the middle Atchafalaya Basin. Scaroni (2011) found mean sedimentation rates in the middle and lower Atchafalaya Basin of 5.9 (open water), 6.3 (BLHW), and 7.7 mm yr^{-1} (cypress forest). Our estimated mean sedimentation rates using discrete bulk densities for the same cover types as Scaroni (2011), were 53.9 (open water), 23.2 (BLHW), and 56.0 mm yr^{-1} (cypress forest). Our estimates are much higher than Scaroni (2011), but fall close to the higher rates from Hupp *et al.* (2008).

From the sedimentation rates estimated in this study it was possible to estimate a time range for the amount of BLCF that could be transformed to higher elevation bottomland hardwood forest. Using the low end average estimate for sedimentation from Table 1 and BLCF sedimentation rate from Table 2 (30.4 and 56.0 mm yr^{-1}), mean area for turbid water flooded land class distributed over 0 to 2 m, and assuming that the areas remain inundated year-round with sediment laden water, it can be estimated that approximately 273.2 km^2 of BLCF will be filled within 36 to 132 years. More precisely, this represents 179.3 km^2 of land at the elevation 0 m filled within 71 to 132 years, 62.0 km^2 of land at 1 m filled in 54 to 99 years, and 31.9 km^2 of land

Table 3 | Annual sediment retention in relation to flood peak, total discharge volume, and retained discharge

	Flood peak (m)			Total discharge (km^3)			Discharge retention (km^3)		
Sediment	**Low (<14.6)**	**Medium (14.6–16.8)**	**High (>16.8)**	**Low**	**Medium**	**High**	**Retained**	**Exported**	**Equilibrium**
Retained	2	5	2	3	3	3	5	2	2
Exported	0	3	3	2	2	2	3	3	0

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

at 2 m filled in 36 to 66 years. The total represents approximately 7% of the 3,581 km^2 of forested wetlands in the ARB (USGS 2001), and is most likely a conservative estimate because of the use of mean values that may underestimate sedimentation in certain areas, as well as not accounting for the effects of large floods.

There are several reasons why our estimates are higher than those obtained from *in situ* studies. The two main reasons are that bulk density may not be negatively correlated with sedimentation rates as our calculation assumes and the variation in the extent of floating aquatic vegetation (FAV) between years may have influenced classification of turbid water areas. From ARB studies, there does not seem to be a strong correlation (negative or positive) of bulk density and sedimentation rate (Hupp *et al*. 2008; Scaroni 2011). The interannual variation of FAV can be dramatic due to weather, hydrologic conditions, and the time of year of the image capture. This is especially true for 2010 where FAV was extensive and would have inflated sedimentation rate estimations. Other possible errors can stem from the total suspended sediment load calculation on the daily scale, which could be off by ±100% (Horowitz *et al*. 2001), the lack of imagery for flood periods or summer months, and the inability to specify to greater precision different bulk densities for different areas.

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

CONCLUSIONS

This study demonstrates an approach of combining riverine sediment loads and spatial information on turbid water area to derive sedimentation estimates. In the future, greater refinement of the method needs to incorporate hydroperiod, and differing SSC which could help generate more specific sedimentation estimates for smaller scale areas. It is also necessary to capture images during years that have low floating aquatic vegetation to ensure that estimation is not biased high or low. If this method is refined, the practical use for management can be extended to relate discharge, turbid water area, and sedimentation. Future management of the Atchafalaya River Basin will rely on spatial tracking of sedimentation to effectively monitor and predict where resources will be necessary to effectively maintain the river basin as a floodway and wildlife habitat. This is especially true if the Atchafalaya River Basin has transitioned into a fluvial system with limited sediment storage, making low lying areas increasingly vulnerable to habitat conversion.

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