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Suspended-sediment concentrations and loads in the lower Mississippi and Atchafalaya rivers decreased by half between 1980 and 2015

Scott V. Mize[a,*], Jennifer C. Murphy[b], Timothy H. Diehl[b], Dennis K. Demcheck[a]

[a] U.S. Geological Survey Lower Mississippi-Gulf Water Science Center, Baton Rouge, LA, United States
[b] U.S. Geological Survey Lower Mississippi-Gulf Water Science Center, Nashville, TN, United States

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ABSTRACT

The Weighted Regressions on Time, Discharge, and Season (WRTDS) model was used to derive estimates of suspended-sediment concentration (SSC) and suspended-sediment load (SSL), their dependence on discharge, and their trends with confidence intervals, for one site each on the lowermost Mississippi and Atchafalaya Rivers. The WRTDS model reduces uncertainty in SSCs related to variable streamflow conditions. Flow-normalized SSCs in each river were similar, and decreased from about 260 mg/L to 130 mg/L from 1980 through 2015; combined annual SSL in the two rivers decreased from about 200 Megatons per year (MT/y) to about 100 MT/y. Declines in SSC and SSL were more gradual from 2005 through 2015 and show signs of stabilizing. Our estimates of SSL in 2015 differ markedly from several recently published estimates of current and projected future Mississippi River SSLs, which were generally around 200 MT/y. However, these values came mostly from a different site upstream on the Mississippi River. The relationship between SSC and streamflow differed in an important way between the two rivers. SSC increased as streamflow increased for the entire range of observed streamflow in the Atchafalaya River. In the Mississippi River, SSC followed the same pattern during low and moderate streamflow but decreased at the highest streamflow that tended to occur between January and July. Since much of the water flowing in the Atchafalaya originates from the Mississippi River, the difference suggests a within-basin source of suspended sediment for the Atchafalaya River that is absent in the lower Mississippi River. These findings have important implications for the restoration of deltaic wetlands in coastal Louisiana. Accurate estimates of the SSL available in each river are crucial for understanding how effective diversions of river water into adjacent estuaries will be in sustaining these wetlands. Our study demonstrates that there might be far less sediment available than previously reported. Further, the difference in the relationship between SSC and streamflow in the two rivers is highly relevant to the ongoing discussion of coastal restoration strategies because the delta building that is occurring at the mouth of the Atchafalaya River is frequently used as a model of what could be expected with controlled diversions in the lower Mississippi River delta. The differences in the SSC behavior with changes in streamflow between the two rivers needs to be considered when results from the Atchafalaya River system are projected to those of the Mississippi River.

1. Introduction

Sediment transported by the lower Mississippi and Atchafalaya Rivers is crucial to the sustainability of coastal Louisiana wetlands, including those of the delta plain (Blum and Roberts, 2012; Khalil et al., 2010; Bentley et al., 2014; Groves et al., 2016). The majority of the sediment delivered to the coast is derived from the contiguous United States, and its estimated magnitude and recent trends are variable. While the need for a well-defined sediment budget for the Mississippi-Atchafalaya delta has long been recognized (Kesel et al., 1992; Gramling et al., 2006; Khalil et al., 2010; Allison and Meselhe, 2010; Allison et al., 2012), a consensus on the sediment source term for this budget is uncertain.

The hydrography of the lower Mississippi-Atchafalaya River basin is complex. As the Mississippi River enters its distributary system, a portion of the river is diverted west through the Old River control structure and converges with the Red River to form the Atchafalaya River (Fig. 1). Both river basins consist of a system of distributary channels, complicated by artificial levees and floodways. Typically, overall flow and sediment transport into the delta is estimated as the sum from the lower Mississippi and Atchafalaya Rivers. Two locations along each river have been used in previous studies to determine loads to the delta.

* Corresponding author.
E-mail address: svmize@usgs.gov (S.V. Mize).

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Fig. 1. Location Map.

On the Mississippi River, these locations are Tarbert Landing or St. Francisville, located 14 km (9 mi) and 18 km (53 mi) downstream from the Old River control structure, respectively. On the Atchafalaya River, these locations are Simmesport or Melville, located 8 km (5 mi) and 48 km (30 mi) downstream from the river's origin at the confluence of the Old River diversion with the Red River (Fig. 1). The combined sediment load of the Mississippi and Atchafalaya Rivers represents the ultimate source term for the complex, poorly defined sediment budget delivered downstream.

The existence of an adequate sediment source is critical for the success of diversions constructed to deliver sediment to Louisiana coastal marshes. The adequacy of the current sediment supply for the success of proposed diversions is uncertain (Maulhardt, 2015). To help guide the maintenance and restoration of coastal Louisiana wetlands, the current sediment source term as well as the most recent trajectories need to be clearly defined. Diversions without a high SSC may not be able to raise the ground level through deposition fast enough to keep pace with relative sea-level rise (Snedden et al., 2007). Furthermore, the 2012 Louisiana Master Plan (Coastal Protection and Restoration Authority, 2012) discusses the possibility of "changes in river streamflow (and associated sediment load)" but does not discuss SSC or quantify SSLs. As Knopman et al. (2014) stated, "The framework explicitly dealt with uncertainties in sea level rise, subsidence, storm frequency and intensity, economic development, and the fragility of engineered protective structures," but it does not deal with uncertainty in SSC or SSL entering the delta.

The rates and magnitudes of changes in SSC and SSL differ substantially depending on the study period, method of trend analysis, and which river and site are considered (Tables 1 and 2). To determine current values and recent trends of SSC and SSL entering coastal Louisiana through the combined Mississippi-Atchafalaya Rivers, we used the Weighted Regressions on Time, Discharge, and Season (WRTDS) model. WRTDS exhibits better estimation accuracy and lower bias in comparison to other load estimation methods and allows for more flexibility in the relationship between concentration and flow conditions (Moyer et al, 2012; Hirsch, 2014; Lee et al., 2016, Chanat et al., 2016). Our results are based on the most downstream station on each river that have sufficient long-term record and represent the most up-to-date concentration and loads being delivered to the delta complex. We also used the model to explore the seasonal variability of relations between SSC and streamflow over time. Finally, we discuss the implication of these results to coastal wetland restoration in the Gulf of Mexico. These analyses and considerations are crucial to guiding restoration efforts of coastal Louisiana wetlands optimally.

1.1. Previous studies

Previous studies in the lower Mississippi and Atchafalaya Rivers document declines in sediment loads since the 1920s (Kesel, 2003; Jacobson et al., 2009; Alexander et al., 2012). In the Mississippi River, five studies found downward trends in SSL ranging from −0.33 to −0.84 percent per year at Tarbert Landing, and two studies found declines from −1.8 to −4.4 percent per year at St. Francisville, for trend years beginning between 1959 and 1994 and ending between 1978 and 2009 (Table 1; Fig. S1). Two studies detected a gently increasing recent trend (Horowitz, 2010; Xu and Rosen, 2012; Rosen, 2013) and two other studies found no trend (Keown et al., 1986; Little and Biedenharn, 2014). Also, the studies that investigated trends in SSC typically found decreases similar to those in SSL. In general, estimates of SSL (typically the SSL of the reported trend end-year) are higher at Tarbert Landing, ranging from 109 to 161 Megatons per year (MT/y), compared to St. Francisville where the two studies conducted there

Table 1
Annual trend results and status of suspended-sediment concentrations (SSC) and loads (SSL) from previous studies in comparison to the current study in the lower Mississippi and Atchafalaya Rivers. [mg/L, milligrams per liter; MT, megatons (million metric tons); %, percent].

Reference	Data period		SSC (mg/L)			SSL (MT/year)		
	Start	End	Starting	Ending	% change per year	Starting	Ending	% change per year
Mississippi River								
Tarbert Landing								
Keown et al. (1986)	1970	1978				161	161	0.00%
Heimann et al. (2011)	1976	2009			−0.69%			−0.65%
Allison and Meselhe (2010)	1990	2004	300	246	−1.29%	134	124	−0.53%
Thorne et al. (2008)	1959	2005	377	234	−0.82%	160	135	−0.33%
Meade and Moody (2010)	1966	2005				152	109	−0.73%
Blum and Roberts (2009)	1977	2006				156	118	−0.84%
Horowitz (2010)	1994	2007	234	265	1.0%			
Xu and Rosen (2012); Rosen (2013)	1990	2010	217	279	1.4%	118	128	0.42%
Little and Biedenharn (2014)	1990	2012				105	105	0.00%
St. Francisville								
Allison and Meselhe (2010)	1990	2004	271	193	−2.1%	122	91	−1.8%
Rebich and Demcheck (2007)	1993	2004	239	187	−2.2%	157	87	−4.4%
Horowitz (2010)	1994	2007	185	168	−0.71%			
The current study*	***1980***	***2015***	***268***	***130***	***−1.40%***	***137***	***67***	***−1.4%***
	2005	***2015***	***139***	***130***	***−0.60%***	***75***	***67***	***−1.0%***
Atchafalaya River								
Simmesport								
Keown et al. (1986)	1970	1978				94	94	0.00%
Heimann et al. (2011)	1976	2009			−1.75%			−1.74%
Blum and Roberts (2009)	1977	2006				86	49	−1.5%
Melville								
Rebich and Demcheck (2007)	1993	2004	211	211	0.0%	76	44	−4.6%
The current study*	***1980***	***2015***	***249***	***133***	***−1.3%***	***58***	***33***	***−1.2%***
	2005	***2015***	***150***	***133***	***−1.1%***	***39***	***33***	***−1.4%***

* Flow-normalized suspended-sediment loads reported in megatons per year (MT/yr).

report 87 and 91 MT/year (Table 1). Substantial differences in SSC and SSL between the two long-term monitoring stations at Tarbert Landing and Simmesport and the corresponding downstream stations of St. Francisville and Melville, respectively, have been observed (Allison and Meselhe, 2010). The differences may be due to differing sample techniques and analysis, differences in sample collection depths, and depositional areas located between the two sites on each river. Fewer studies have addressed changes in SSC or SSL in the Atchafalaya River. Two studies were conducted at Simmesport and found SSLs of 49 and 94 MT/year (Table 1; Fig. S2) (Keown et al., 1986; Blum and Roberts, 2009). At Melville, Rebich and Demcheck (2007) estimated decreasing trends of −4.6 percent per year in SSL, but no trend in SSC over the ten-year period from 1993 to 2004; estimates of annual SSC and SSL for 2004 were 211 mg/L and 44 MT/y , respectively.

A few previous studies also calculated estimates of total suspended-sediment load entering the combined lower Mississippi-Atchafalaya deltas (Table 2; Fig. S3). These estimates are calculated as the sum of annual SSLs from the Mississippi and Atchafalaya Rivers, reported here as the estimates from trend end-years or as an assumed future load, depending on the study. Reported trend end-year estimates range from 255 MT/year of suspended sediment entering the delta in 1978 (Keown et al., 1986) to lower recent estimates of 131 in 2004 and 167 MT/year in 2006 by Rebich and Demcheck (2007) and Blum and Roberts (2009), respectively.

2. Methods

For the WRTDS analyses, we used SSC data collected from the

Table 2
Previously reported suspended-sediment loads (SSLs) in comparison to the current study to the Gulf of Mexico from the lower Mississippi-Atchafalaya River Basin, presented here as the sum of estimated annual SSLs from the Mississippi River and Atchafalaya River main stems. Reported values from trend year or assumed future load are based on varying methodology. [MT, megatons (million metric tons); TL, Tarbert Landing; SF, St. Francisville; S, Simmesport; M, Melville].

Reference	Data period, if reported	Mississippi River load (MT/year; estimation site, if reported)	Atchafalaya River load (MT/year; estimation site, if reported)	Summed load to the Gulf of Mexico (reported as trend end year or assumed future load)
Keown et al. (1986)	1970–1978	161 (TL)	94 (S)	255
Rebich and Demcheck (2007)	1993–2004	87 (SF)	44 (M)	131
Blum and Roberts (2009)	1977–2006	118 (TL)	49 (S)	167
Blum and Roberts (2009)		136	69	205
Kim et al. (2008)		124	84	208
Kim et al. (2009)		126		210
Winer (2011)		131		
Bentley et al. (2012)				200
Khalil and Freeman (2015)		145		
Kemp et al. (2016)		131		
The current study*	**1980–2015**	**67 (SF)**	**33 (M)**	**100**

* Flow-normalized suspended-sediment loads reported in megatons per year (MT/yr).

Table 3
Site information for each location on the lower Mississippi River and the Atchafalaya River that were used to estimate annual suspended-sediment concentrations and suspended-sediment loads using the Weighted Regressions on Time, Season and Discharge model. [USGS, U.S. Geological Survey; USACE, U.S. Army Corps of Engineers].

Site name	Site abbreviation	USGS Station id	Calibration period	Number of samples	Streamflow gage (gage operating agency)	Streamflow station identification number
Mississippi River near St. Francisville, LA	MS-STFR	07373420	1978-06-05 to 2016-02-03	446	Mississippi River at Tarbert Landing, MS (USACE)	USACE 01100Q
Atchafalaya River at Melville, LA	AC-MELV	07381495	1979-11-09 to 2016-02-04	386	Atchafalaya River at Simmesport, LA (USGS)	USGS 07381490

Mississippi River near St. Francisville, Louisiana (MS-STFR), and from the Atchafalaya River at Melville, Louisiana (AC-MELV) (Fig. 1). SSC data were collected by the U.S. Geological Survey (USGS), mostly as part of the National Water Stream Quality Accounting Network (NASQAN) and National Water Quality Network (NWQN) programs, from as early as 1979 through 2015. SSC samples were collected using isokinetic depth-integrated sampling techniques described in the USGS National Field Manual for the Collection of Water-Quality Data (USGS, variously dated). SSC data were retrieved from the USGS National Water Information System (U.S. Geological Survey, 2016). Streamflow data were not available at either water-quality site. Instead we used daily computed streamflow at Tarbert Landing (U.S. Army Corps of Engineers, 2016a) for MS-STFR and daily computed streamflow at Simmesport (U.S. Army Corps of Engineers, 2016b) for AC-MELV (Table 3).

Data used for trend analysis were screened according to the following criteria:

(1) a site must have a minimum of bimonthly results (6 SSC samples each year), (2) at least 10 years of continuous streamflow record with no more than 2 consecutive years without data, and (3) suspended-sediment samples collected across a range of streamflow conditions and across all seasons. WRTDS was selected to estimate annual mean SSC and total SSL at MS-STFR and AC-MELV. This model has been extensively described in Hirsch et al. (2010), Hirsch and De Cicco (2015), and Hirsch et al. (2015), but a brief overview is provided here. The WRTDS analysis was completed using the Exploration and Graphics for RivEr Trends (EGRET) R-package (Hirsch et al., 2015, version 2.6.0). WRTDS models concentration as a function of time, flow, and seasonal components,

$$\ln(c) = \beta_0 + \beta_1 t + \beta_2 \ln(Q) + \beta_3 \sin(2\pi t) + \beta_4 \cos(2\pi t) + \varepsilon \quad (1)$$

where

ln is the natural log,
c is suspended-sediment concentration,
β_n are fitted coefficients,
t is time,
Q is mean daily discharge, and
ε is unexplained variability.

WRTDS fits this model at about 8000 nodes across a discharge-time grid. Estimates of daily concentrations are computed by bilinear interpolation of the values on this grid (e.g. Fig. S3). Daily mean discharge values at each site are gridded by 14 equidistant values in log space, and time is gridded at 1/16th of a year. At each of these nodes, Equation 1 is fit using locally weighted regression, specifically a weighted Tobit model. At each calibration node, the observations in the dataset are weighted according to their similarity to the calibration point in terms of time, season (time of year), and discharge. Weights for the observations in the calibration dataset are assigned using a tricube weight function according to distance in time, distance in season (fractional portion of the year), and distance in discharge relative to the conditions at the calibration point. The half-window widths used for these variables in our study were 7 years for time and 0.5 year for season for both sites, and 1 and 2 natural log discharge units for discharge at MS-STFR and AC-MELV, respectively. The discharge window was narrowed for MS-STFR to better capture the downturn of the concentration-discharge relationship at high flows at this site. The half-window width for time was allowed to become larger near the beginning and end of the record so that there were always 14 years of data being used in model calibration. For each node in the time-discharge grid, the individually calibrated models are used to estimate concentration. Each model gives the natural log of concentration, which is exponentiated and multiplied by a bias correction factor to give the estimated concentration in milligrams per liter (mg/L) of suspended sediment. The bias correction factor is also specific to each node and is computed using the standard error. Daily estimates are then derived using bilinear interpolation of the estimates at the nodes. Load is then computed for each day using the daily mean discharge for the day.

Using the above method, expected values of concentration can be determined for all possible combinations of discharge, season, and time in the given dataset and provide a useful means of characterizing the behavior of concentration as a function of these variables. These estimates of the expected value of concentration are often displayed across a discharge-time grid for each site (Fig. S3 in Supplementary Material). These expected values were used to explore changes over time in concentration-discharge relationships during particular times of the year. Expected values of concentration were summarized to monthly means at given discharge magnitudes and plotted for specified months and years.

In many rivers, including the two sites used in this study, concentration and load are influenced by streamflow, and streamflow-driven variability in concentration and load estimates can obscure the overall trends in water quality at a site. Even though annual mean streamflow showed no significant changes during 1980 through 2015 (Fig. S4) at MS-STFR (Mann-Kendall, media slope: $-14\ m^3/s/yr$; $p = 0.84$) or AC-MELV (Mann-Kendall, media slope : $-7\ m^3/s/yr$; $p = 0.80$), WRTDS uses flow normalization to account for the variability of concentration or load estimates due to random, year-to-year, variation in streamflow. Specifically, for each calendar day ($n = 365$) a probability distribution of daily discharge is compiled from the observed daily discharge record. For the sites used in our study, the period of record is from 1980 through 2015 so each calendar day would have 36 daily flows values, one from each year in the period of record. Then for each day in the period of record, the calibrated models are run using each of the 36 daily flow values for the given calendar day, and the average of these 36 concentration estimates is the flow-normalized (FN) concentration for that day. For example, a FN concentration estimate for July 15, 2000 would use 36 daily flow values for July 15th across the period of record. Estimates for each combination of these 36 flow values and the July 15, 2000 date would be determined from interpolation from the grid of values described above. The FN concentration estimate for this date would use the average of these 36 concentration values. The FN load estimate for this date would be computed in the same manner except that the concentration values are each multiplied by streamflow and a conversion factor. The FN load estimate for this date is the average of these 36 load values. The method allows the estimated trends, when expressed as a percentage change, to be different for concentration and load. Like estimates of concentration and load, FN estimates of concentration and load are averaged or summed over the year to give annual estimates. FN estimates show less variability than standard estimates because FN estimates represent the behavior of concentration and load with the year-to-year variations in flow reduced. The trends reported in this analysis are the difference in FN concentration or load between the first and last years of a given trend period.

WRTDS was originally developed as an exploratory data analysis tool, and recently a bootstrap method has extended the application of WRTDS to characterize the uncertainty of annual estimates and trends. A thorough presentation of this methodology, referred to as the WRTDS Bootstrap Test (WBT), is presented in Hirsch et al. (2015) and briefly summarized here. Bootstrap replicates were developed using a time-based resampling approach where predefined blocks of consecutive days were randomly drawn, with replacement, from the period of record. Samples were drawn until the number of samples in the bootstrap replicate equaled the number of samples in the observed dataset. For this analysis, we used a block length of 200 days and 100 bootstrap replicates at each site. Each bootstrap replicate was run using the standard WRTDS analysis after which all the annual estimates of FN concentration and FN load, along with the trends calculated between two specified years, were retained. These trend estimates are used to determine the 90% confidence intervals of the annual values and trend. Also, this information provides an estimate of how likely the given trend is (likelihood) and a statistic that is functionally equivalent to a p-value. Hirsch et al. (2015) encouraged the use of a specified terminology to describe the uncertainty results from the WBT. This language is similar to the terminology used by the Intergovernmental Panel on Climate Change and is based on the likelihood of the magnitude and direction of the trend (Hirsch et al., 2015). The likelihood values are the number of upward or downward trends relative to all the bootstrap runs. We describe the trends presented here using this language (Table 2 of Hirsch et al., 2015). The uncertainty analysis was preformed using the EGRET confidence intervals (ci) R-package (version 1.0.3; Hirsch et al., 2015). The input and output data files for the WRTDS model used in the study are available from Murphy and Mize (2018).

3. Results

The temporal patterns of annual SSC and SSL estimates are generally similar between sites on the Mississippi and Atchafalaya Rivers (symbols connected by dotted lines in Fig. 2). In the 1980s, the flow-normalized SSC trends exceeded the mean concentration, 260 mg/L, in both rivers. SSC trends converged in the 1990s and appear to be relatively level at about 130 mg/L since 2005 (Fig. 2, Murphy and Mize, 2018). Annual mean SSCs at MS-STFR and AC-MELV have a similar range of values, except for a period between 1983 and 1994. During this period, SSCs at AC-MELV were considerably higher and showed a different temporal pattern than the concentrations at MS-STFR. Interestingly, during 1987 and 1988 the entire Mississippi River watershed experienced extreme drought conditions (Lins and Slack, 1999) that may correspond to the observed lower concentrations in both rivers compared to the surrounding years. After 1995, the annual SSC and SSL at the two sites were very highly associated with each other (Fig. 2).

Flow-normalized SSC (FN-SSC) and load (FN-SSL) decreased from 1980 through 2015 (solid line in Fig. 2). The largest decreases occurred prior to the late 2000s. FN-SSC decreased by about 50 percent in both rivers from 1980 to 2015 but only decreased by 6 and 11 percent from 2005 to 2015 at MS-STFR and AC-MELV, respectively (Table 4). Over the same 1980–2015 trend period, FN-SSL decreased by 51 percent at MS-STFR, from about 137 to 67 MT/y, and 43 percent at AC-MELV, from about 58 to 33 MT/y. More recent declines in FN-SSL (2005–2015) are slightly larger in the Atchafalaya River (−16%) compared to the Mississippi River (−11%; Table 4). In general, the patterns of FN-SSC and FN-SSL estimates over time are similar between the sites, except for the increase then decrease of SSC and SSL between 1980 and 1992 in the Atchafalaya River. From 1980 to the peak in 1985, FN-SSC increased by about 10 percent and FN-SSL increased by about 17% (Fig. 2). The overall decreasing trends of SSCs and SSLs at both sites agree with some previous studies (Allison and Meselhe, 2010; Rebich and Demcheck, 2007; Table 1) completed in these rivers but clearly disagree with others (Keown et al, 1986, Xu and Rosen, 2012; Rosen, 2013; Little and Biedenharn, 2014; Table 1).

4. Discussion

4.1. Decreasing suspended sediment

The drivers of the large historical declines in SSC and SSL in the Mississippi River include channel improvements, reservoir construction, and soil conservation practices (Keown et al., 1986; Meade and Moody, 2010; Tweel and Turner, 2012). The most intensive period of dam construction and channel alteration (cutoffs, revetments, and dikes) on the Mississippi and its major tributaries ran from the 1920s through the 1960s, with construction at a slower pace in the 1970s (Kesel, 2003; Jacobson et al., 2009; Alexander et al., 2012). During this entire period, direct effects of major modifications caused a large decrease in sediment load, and channels continued to respond geomorphically after construction was largely completed (Smith and Winkley, 1996; Kesel, 2003). On the Red River, a major contributor of sediment to the Atchafalaya, construction of a lock and dam system continued until 1994 (Pinkard and Stewart, 2001; Red River Waterway Commission, 2016). After 1994, SSL and SSC in the Atchafalaya appear to have declined abruptly, and thereafter their trends resemble those in the Mississippi (Fig. 2).

The increased implementation of soil conservation practices reduced the amount of sediment leaving agricultural lands throughout the smaller, contributing basins (Knox, 1987; Alexander et al., 2012). Effects of soil conservation and channel stabilization in the entire Mississippi River basin are highly variable, ranging from negligible to large decreases in sediment yield (Myers et al., 2000; Pinkard and Stewart, 2001; Garbrecht and Starks, 2009; Neal, 2014). U.S. Department of Agriculture Conservation Effects Assessment Project (CEAP) (2013) assessments indicate that soil conservation has reduced annual SSL delivered to the Gulf of Mexico from the Mississippi - Atchafalaya system by 4% relative to the no-soil-conservation case, and that implementing conservation in undertreated acres would reduce SSL another 5%.

Most analyses of SSLs from the Mississippi and Atchafalaya Rivers have detected a recent decreasing trend. Since 2005, the declines in SSL have slowed, apparently due to the geomorphic evolution of large navigable river channels toward stability, changes in land use (Meade and Moody, 2010; Morang et al., 2013), and possibly commercial dredging (Alexander et al., 2012). Current sources of sediment in the Mississippi are about 25% from channel degradation and 75% from upland erosion (White et al., 2014). In general, sand loads are stable, and changes in loads are driven by changing concentrations of silt and clay (Biedenharn et al., 2000; Heimann et al., 2011). According to Nittrouer and Viparelli (2014), sand stored in river channels will be a stable long-term source of sediment that can be transported in higher streamflow events, but this source may be sensitive to the sand supply and the amount of sand in storage (Allison et al., 2012).

Based on the recognized drivers of SSC and SSL, the declining trends are unlikely to be reversed. Existing dams and channel improvements will likely be preserved for the sake of their navigation and flood-control benefits. Strategies for reversing the declining trend in SSL include “bypassing clogged dams” (Bentley et al., 2012) but this approach could be as costly as the dams themselves were to construct (Kemp et al., 2016). Values ascribed to soil conservation (Myers et al., 2000; Garbrecht and Starks, 2009; Neal, 2014; CEAP, 2013) suggest that it will continue to be promoted.

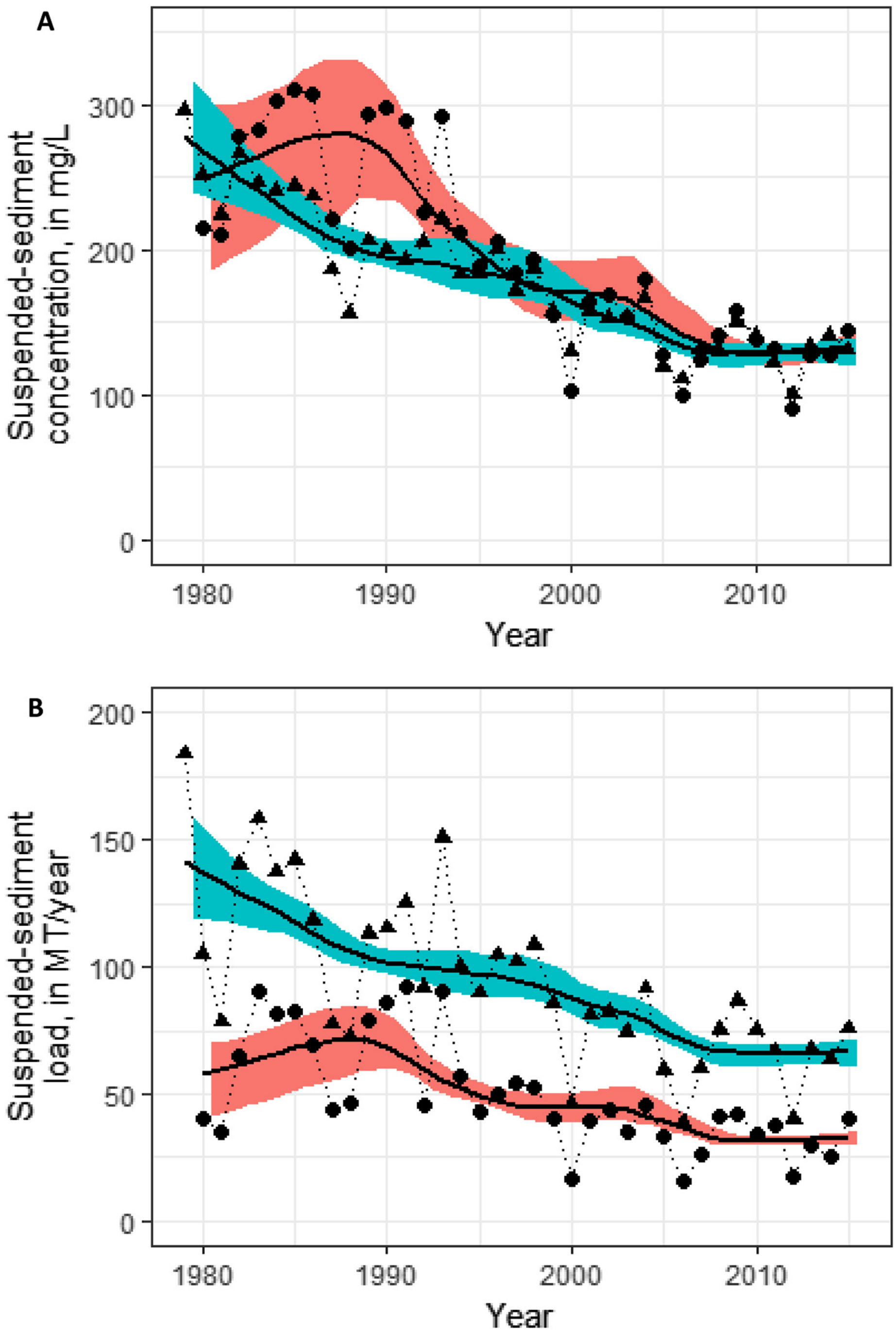

Fig. 2. Annual suspended-sediment estimates (symbols), flow-normalized estimates (solid black lines), and 90% confidence intervals (blue and red areas) for concentration (A) and load (B) at MS-STFR and AC-MELV.

4.2. Uncertainty of decreasing trends

There is a high amount of confidence in the finding of decreasing SSC and SSL from 1980 to 2015 in both rivers. Most of the histogram for the 1980–2015 trends for SSC and SSL at MS-STFR and AC-MELV plot to the far left tail of the distributions, typically with trend estimates ranging between −60 and −20 percent depending on the site (Fig. 3). These 36-year trends are considered "highly likely" with likelihoods ranging from 0.995 to 0.965 (Table 4). The shorter, more recent 2005–2015 trends are considered "very likely" with likelihoods range from 0.916 to 0.946 (Table 4). The density histograms for the 2005–2015 trends extend into positive percent changes on the right tail of these distributions (Fig. 3), thus we are less confident in these most recent declines of SSC and SSL compared to the 1980–2015 trends. Also, the p-values associated with these more recent trends are typically > 0.10 and in a strict null hypothesis testing approach, using a significance level of 0.05, would be considered not significant. However, the density histograms show that a majority of the bootstrapped runs returned negative percent changes and only the upper tail of the distribution crosses into positive values and indicate that decreases in SSC and SSL between 2005 and 2015 are more likely to have occurred than not. A standard "non-significant" result for this trend period would be far less informative.

A close inspection of FN-SSC and FN-SSL over time suggests decreases from 2005 to 2008 and then minimally varying FN-SSC and FN-SSL through 2015 (Fig. 2). This pattern is also reflected in the 90-

Table 4
Weighted Regression on Time, Discharge, and Season model flow-normalized suspended-sediment concentration, load, and trend results. [SSC, suspended-sediment concentration; mg/L, milligrams per liter; %, percent; < , less than; SSL, suspended-sediment load; MT, megatons (million metric tons)].

Trend period	SSC Trend Starting Concentration, mg/L	SSC Trend Ending Concentration, mg/L	SSC trend, in mg/L (%)	SSC trend/yr, (%/year)	Likelihood of downward SSC trend (associated p-value)
St. Francisville, Mississippi River					
1980–2015	**268**	**130**	−138 (−51%)	−3.8 (−1.4%)	Highly likely, 0.995 (< 0.02)
2005–2015	**139**	**130**	−9.5 (−6%)	−0.8 (−0.6%)	Very likely, 0.916 (0.17)
Melville, Atchafalaya River					
1980–2015	**249**	**133**	−116 (−47%)	−3.2 (−1.3%)	Highly likely, 0.985 (0.035)
2005–2015	**150**	**133**	−17 (−11%)	−1.5 (−1.1%)	Very likely, 0.916 (0.18)

Trend period	SSL Trend Starting Load, MT/year	SSL Trend Ending Load, MT/year	SSL trend, in MT/year (%)	SSL trend/year (%/year)	Likelihood of downward SSL trend (associated p-value)
St. Francisville, Mississippi River					
1980–2015	**137**	**67**	−70 (−51%)	−1,958 (−1.4%)	Highly likely, 0.995 (< 0.02)
2005–2015	**75**	**67**	−8 (−11%)	−759 (−1%)	Very likely, 0.946 (0.1)
Melville, Atchafalaya River					
1980–2015	**58**	**33**	−25 (−43%)	−699 (−1.2%)	Highly likely, 0.965 (0.067)
2005–2015	**39**	**33**	−6 (−16%)	−551 (−1.4%)	Very likely, 0.926 (0.14)
Sum Load to Gulf of Mexico		**100**			

percent confidence intervals. However, the 90-percent confidence interval envelope displays the range of concentrations and loads and does appear to allow several scenarios for this most recent 11-year period. Consistent decreases through the period appear possible for SSC and SSL at MS-STFR and SSC at AC-MELV. However, the 90-percent confidence interval for SSL at AC-MELV appears to bend and narrow around 2009 restricting the possible scenarios and suggesting a leveling off of decreasing SSL during this period (Fig. 2B).

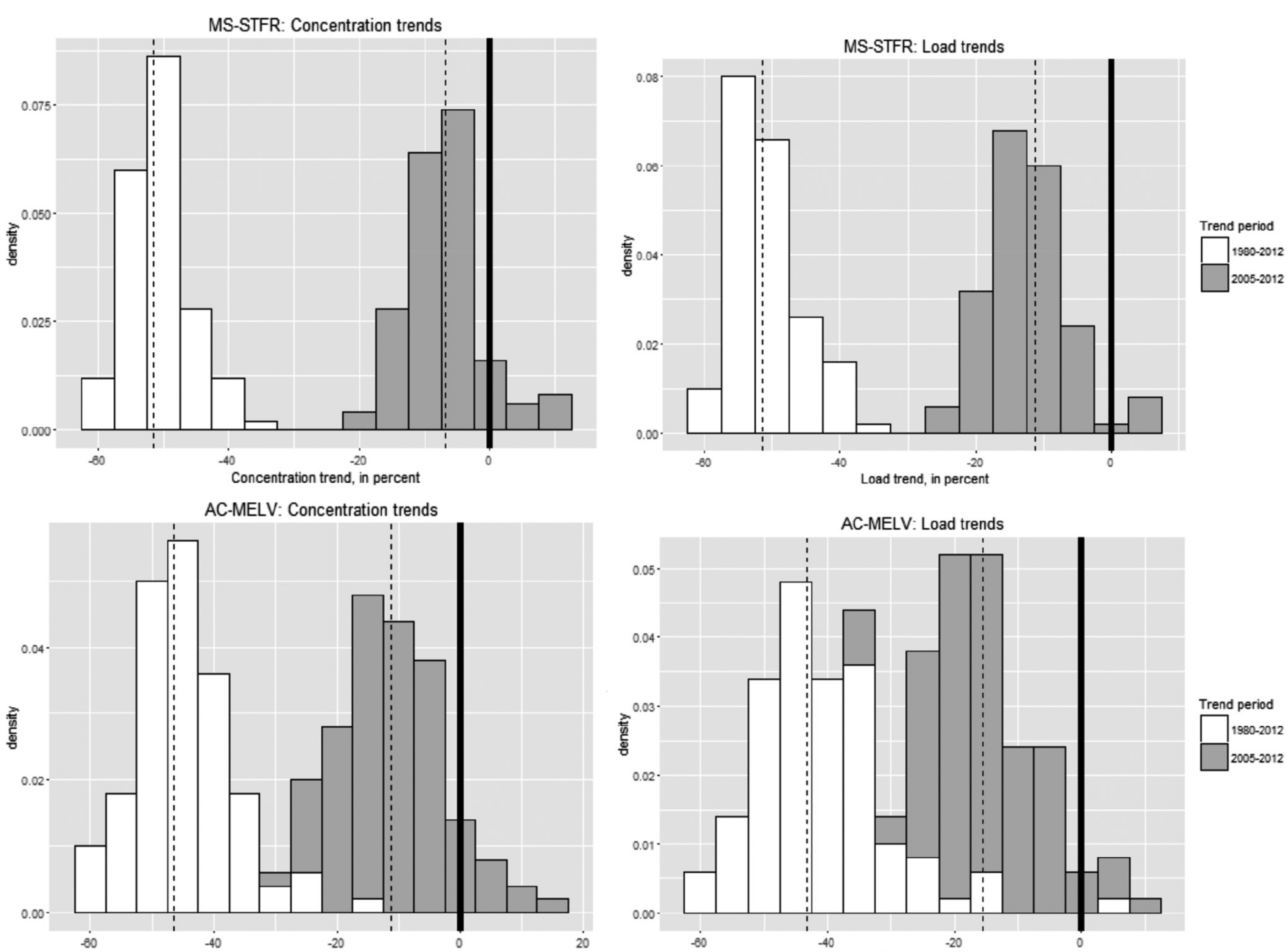

Fig. 3. Density histograms of 1980–2015 and 2005–2015 trends from bootstrapped runs for FN-SSC and FN-SSL in the Mississippi and Atchafalaya Rivers. [Dashed vertical lines are the related trend estimate for a given site and trend period, the solid black line equals 0 percent change].

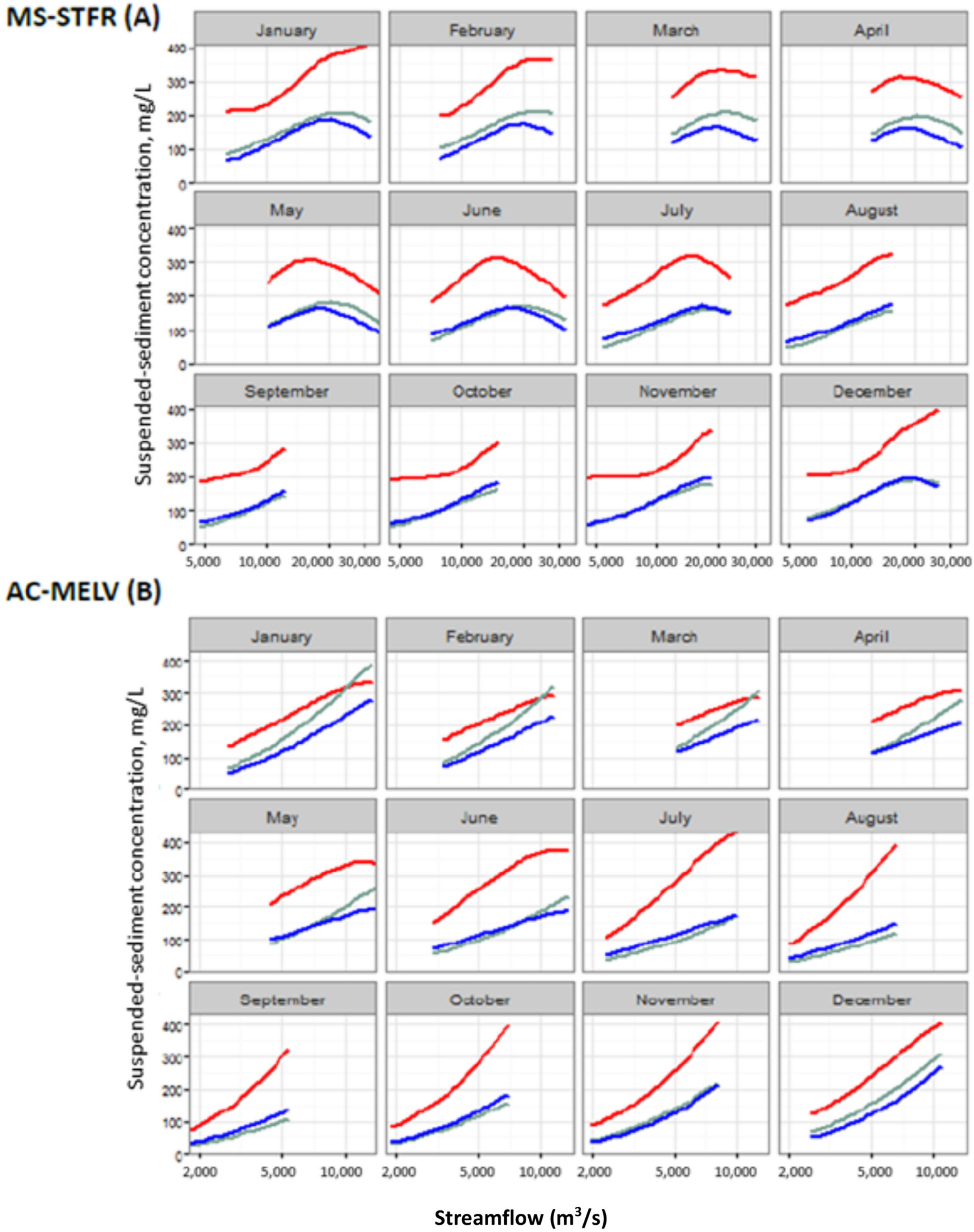

Fig. 4. Relations of suspended-sediment concentration to streamflow by month for 1980 (red line), 2005 (light blue) and 2015 (dark blue) for MS-STFR (A) and AC-MELV (B). Note, plots show only streamflow values between the 5thand 95thpercentiles for each month.

4.3. Seasonal changes in suspended sediment

The relationship between SSC and streamflow (SSC-Q) varies seasonally and between each site on the Mississippi and Atchafalaya Rivers (Fig. 4). At both sites, SSC increases with increasing streamflow; however, at MS-STFR this relationship changes at the highest flows which normally occur winter through summer (January – July). Similar to findings by Mossa (1996) and Welch et al. (2014), during these times of year and at the highest flows (flow magnitudes in this study near 20,000 m^3/s), SSCs are diluted with continued increases in streamflow. This reversal in the SSC-Q relationship is not present at AC-MELV; instead, SSC increases with increasing streamflow during all seasons. Since the dominant source of water to both rivers is the upper Mississippi River, increases in SSC related to higher streamflow that occur in the Atchafalaya but not in the Mississippi indicate an in-stream sediment source within the Atchafalaya basin that may contribute to the SSC during these scouring events. During the 2011 flood in the lower Mississippi-Atchafalaya River basin, Welch et al. (2014) noted that sequestered sand-sized material in the Atchafalaya River was more readily available for transport and more responsive to increases in streamflow. In addition, there were increases in SSLs in the Atchafalaya River and decreases in SSLs along the lower Mississippi River. The increases were attributed to resuspension of sand-sized sediment in a depositional zone located below the confluence of the Red River with the Atchafalaya River. In contrast, diversion of flow through the Old River control structure into the Atchafalaya reduced stream power and decreased the carrying capacity of the lower Mississippi River resulting in a zone of deposition between Tarbert Landing and St. Francisville and a loss of SSL as water moved downstream.

The SSC-Q relationship also varies among years (Fig. 4). At MS-STFR, the SSC-Q relationships indicate higher SSCs in 1980 (about 180–400 mg/L) compared to 2005 or 2015 (about 50–200 mg/L) across all flows and months. The decreases in SSC between 1980 and 2005 occurred across the entire range of flow (i.e. larger decreases in SSC at low or high flows are generally not observed) and across the entire year. Between 2005 and 2015, decreases in SSC also appeared to occur across the entire range of flow, except for a lower magnitude of change during winter and spring months (Jan-May). During these months, relatively larger decreases are seen during higher flows suggesting most of the observed changes in annual SSC and SSL are coming from decreases in suspended sediment during elevated flows. At AC-MELV, the SCC-Q relationships also typically indicate higher SSCs in 1980 (about 80–400 mg/L) compared to 2005 (about 50–375 mg/L) or 2015 (about 50–275 mg/L) for most ranges of flow and times of year. Decreases in SSC between 1980 and 2005 were larger at higher flows during the summer and fall (July – November), but during the winter and spring (January – May) decreases in SSC were larger at low flows (Fig. 4). Decreases in SSC between 2005 and 2015 occurred primarily at moderate and high flow during the winter and spring (December – May). Thus, in the Atchafalaya River, decreases in annual SSC and SSL appear to be driven by a combination of decreases in SSC at low and high flows depending on the time of year, whereas the more recent decreases appear to have occurred mostly due to decreases in SSC during high flows in the winter and spring.

4.4. Implications for coastal restoration

Our estimated current suspended-sediment load to the lower Mississippi-Atchafalaya delta complex was about 100 MT/year in 2015, in contrast to estimated future loads to the delta of 200 MT/year or more (Table 2) based on historical periods when SSLs and SSCs were higher than present (Table 1). For example, one series of studies obtained an average SSL for both rivers of 208–210 MT/y (Kim et al., 2008; Kim et al., 2009, Kenney et al., 2013; Bentley et al., 2014) by combining the average SSL of 84 MT/y from 1952 to 1989 in the Atchafalaya River (Allison et al., 2000) with the average SSL of about 125 MT/y from 1981 to 1992 in the Mississippi River (Horowitz, 2006). The studies that predict or assume future loads of around 200 MT/year are more consistent with historical data from earlier periods when suspended-sediment concentration and loads were higher (Blum and Roberts, 2009, 2012; Khalil and Freeman, 2015).

The success of restoration projects will depend directly on available sediment (Blum and Roberts, 2009, 2012; Bentley et al., 2014). The use of an overestimated source term in sediment budgets for coastal restoration will result in overestimates of the amount of sediment available for diversions and the amounts actually diverted. Sediment loads probably have not increased over the past 10 years (2005–2015), and considering the persistence of factors driving declines, SSC and SSL are likely to stabilize or continue to decrease, but not increase (Table 4).

Sediment deposition between upstream sites (e.g. St. Francisville, Melville) and potential restoration sites in the lowermost portions of the rivers is important and needs to be considered as part of future restoration efforts. Typical SSC and SSL trend results from other studies, many based on data collected upstream from this study, were uniformly higher in comparison (Tables 1 and 2). For example, historical concentrations and loads have been higher at Tarbert Landing compared to St. Francisville; but, Allison and Meselhe (2010) have documented a depositional area between the two locations. In the Mississippi River, Allison et al. (2012) showed minimal SSL loss from St Francisville (90.3 MT/yr) to Belle Chasse (88.3 MT/yr), thus supporting the use of St. Francisville from this study for SSC and SSL estimates for downstream restoration planning. In addition, any flood plain deposition (Smith and Bentley, 2014) and in-stream accretion of sediment occurring upstream is accounted for by using the downstream St. Francisville location. Similarly, the use of the Melville location along the Atchafalaya River serves the same purpose in this study. Historically (through 2010), loads at Melville ranged from 12.2 to 96.7 MT/yr and the combined loads from Wax Lake outlet and Morgan City ranged from 16.4 to 115.9 MT/yr (Welch et al. 2014) were similar.

Hysteresis, pulse, and similar event-scale complexities are not identifiable in WRTDS monthly results; continuous monitoring and more detailed modeling will be needed to understand, predict, and manage sediment pulses (Peyronnin et al., 2016). The timing and sources of suspended sediment are variable and complex (Mossa, 1988, 1996; Allison et al., 2014), and a strong hysteresis in the relation of SSC to streamflow indicates that sediment transport is supply-limited (Horowitz, 2010; Meade and Moody, 2010). Because of the strong hysteresis in SSC, the best time to divert suspended sediment for coastal restoration is the brief period of high SSC in the rising limb of floods. Most of the diverted SSC would be from winter and spring floods (Snedden et al., 2007; Thorne et al., 2008; Xu and Rosen, 2012; Allison et al., 2014; Peyronnin et al., 2016). Seasonal patterns between SSC and streamflow (Fig. 4) determined in this study show differences between MS-STFR and AC-MELV, which may influence approaches and timing of sediment diversions to promote restoration. For example, recent (2005–2015) streamflow at MS-STFR typically provides a SSC of no more than 200 mg/L, less than that at the highest flows, making it necessary to focus diversion on relatively brief periods of high SSC and rising streamflow. In contrast, SSC increases with increasing streamflow conditions at AC-MELV and winter flood peaks may offer opportunities to capture sediment efficiently. Contour plots of both sites (Figs. S5 and S6) showing the evolving pattern of expected concentration values as a function of time and streamflow are included in the supplementary material.

5. Conclusions

The use of WRTDS modeling to analyze suspended-sediment data from the Mississippi River near St. Francisville and the Atchafalaya River at Melville identified decreasing trends in suspended-sediment concentration (SSC) and load (SSL) since 1980, similar to several previous studies in the Mississippi and Atchafalaya Rivers. Flow-normalized SSC in the lowermost Mississippi and Atchafalaya Rivers decreased by about half from 1980 through 2015, from about 260 mg/L early in this period to about 130 mg/L. Declines in SSC and SSL from 2005 to 2015 are more gradual than the earlier decline.

The combined load of the two rivers in 1980 was close to 200 MT/y, which is about the value that some planned sediment diversions are based on. However, the present (2015) load is closer to 100 MT/y. Future SSC and SSL in both rivers are uncertain; historic declines have slowed and may stop. There is little evidence based on identified drivers of trends to suggest that suspended sediment will increase in the near future, and stabilization or slow declines in SSC and SSL appear more plausible. These recent SSC and SSL estimates from this study using the WRTDS model, which accounts for uncertainly in suspended-sediment concentrations associated with flow conditions, are useful estimates for restoration purposes. Seasonal differences in the response of SSC to streamflow between the Atchafalaya River and lower Mississippi River are substantial enough that downstream sediment-based restoration efforts are unlikely to be fully successful without taking these differences into account.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.jhydrol.2018.05.068.

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