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Influences on Discharge Partitioning on a Large River Delta: Case Study of the Mississippi-Atchafalaya Diversion, 1916-1950

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Key Points:

- The rapid increase in discharge to the Atchafalaya River between 1932 and 1950 can be explained first by widening and second by dredging.
- Minor erosion measured in the Mississippi River would have reduced Atchafalaya Discharge, had Atchafalaya Basin remained constant.
- Lacustrine Deltas in the Atchafalaya Basin did not change partitioning, as they were downstream of a reach with steep water surface slope.

Abstract

The modern Mississippi River Delta is plumbed by the Mississippi and Atchafalaya rivers, setting water and sediment dispersal pathways for Earth's fifth-largest river. The Atchafalaya River's (AR) partial annexation of discharge from the Mississippi River (MR) in the early 20th century prompted warnings of a rapid river avulsion and the construction of the Old River Control Structure to regulate flow. While this flow annexation is interpreted as a natural process in the avulsion-constructed delta, it was influenced by human activities. Here, we test how several significant changes between 1916 and 1950 influenced partitioning. Simulations show that erosion of the upper AR was the primary cause of discharge increase. Dredging in the lower AR between 1932 and 1950 produced minor increases, but was an important control on shear stress. The lower MR was also slightly erosional during the study period, and therefore hindered the discharge increase slightly. As a prototype system, attribution of discharge partitioning allows for various drivers of change to be quantitatively compared. Given the essential nature of this river junction to society, transportation, and commerce of the United States, improved attribution of discharge increases may lead to future management strategies that are broadly impactful.

1 Introduction

Many of the world's large river deltas evolve under a combination of natural and human forcings (Ganti et al., 2014; Kleinhans et al., 2011; Vinh et al., 2014; Wilson et al., 2017). However, frameworks for attributing change among several forcings that occur simultaneously remain elusive. The problem is further compounded by the complexity of many river deltas, where forcings interact non-locally through a network of many distributary channels (Bain et al., 2019; Kleinhans et al., 2012). Constraining these interactions is essential for the many large scale management and engineering initiatives that will significantly alter modern deltas to optimize for their sustainable future (Hoitink et al., 2020; Syvitski, 2008; Tessler et al., 2015). Here, we present one such case of complex interaction of many forcings across the channel network of a large river delta.

The regulation of water discharge between the Mississippi and Atchafalaya Rivers is one of the most impressive river engineering feats of the twentieth century. The Old River Control Structure (ORCS) ensures that 70% of water discharge travels down the lower Mississippi River, through the cities of Baton Rouge and New Orleans, and the largest port in the western hemisphere (Batker et al., 2014). The remaining 30% of the discharge passes through the structure and down the Atchafalaya River to build significant new delta deposits in Atchafalaya Bay (Roberts et al., 1980; J. B. Shaw et al., 2018). The ORCS was constructed for $67 million and completed in 1962, but required an additional auxiliary structure costing $206 million, completed in 1982 (USACE, 2009) for a total cost in 2009 dollars of roughly $990 million (Kenney et al., 2013).

The modern system is the product of natural processes across the geologic time (Blum, 2019; Saucier, 1994) and human activities since the nineteenth century (Kesel, 2003; Mossa, 2013). Over the Holocene, the Mississippi River delta has been dominated by semi-periodic avulsions, or the rapid abandonment of a channel course for a new course through the delta (Blum & Roberts, 2012; Fisk, 1952; Saucier, 1994). Human impacts include dredged meander cutoffs that straightened the Mississippi River's course (1831-1942), and large log jams that were removed from the Atchafalaya River (1839-1855; Mossa, 2013). At Red River Landing, where the Old River (an abandoned meander loop) connects the Mississippi and Atchafalaya rivers, a canal was dredged intermittently between 1878 and 1937 in order to maintain navigable low-water connection between the rivers (Fisk, 1952; Mossa, 2013). Between 1900 and 1932, the Atchafalaya River flowed into the Mississippi River an average of 37 days per year, with the last flow in this direction in 1945 (Latimer and Schweizer 1951; their Table 36). After the great flood of 1929, significant levee construction and dredging along the Mississippi and Atchafalaya Rivers influenced navigability and hydrology of both rivers.

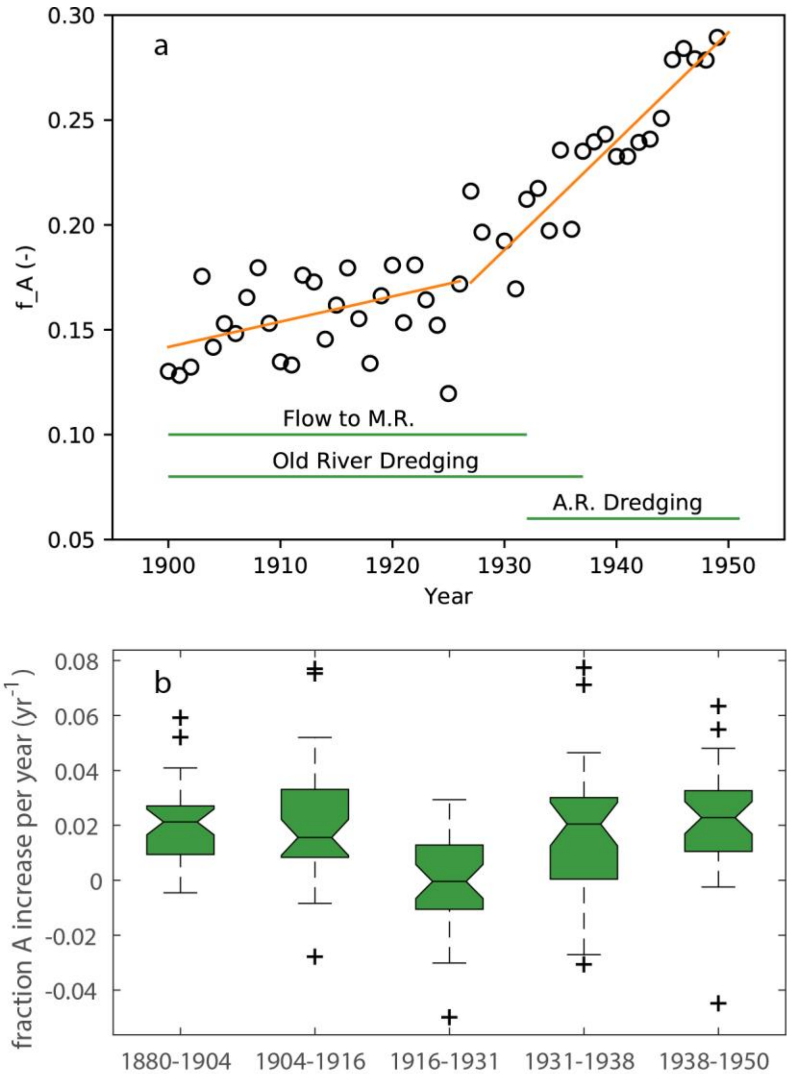

Figure 1. (a) Time series of the proportion of water entering the Atchafalaya River from the Mississippi River f_A. Orange lines are linear fits to f_A for the periods 1900-1926 and 1927-1950. Green bars indicate time periods of potentially important events. A.R. and M.R. signify Atchafalaya and Mississippi Rivers. (b) Notched box plots (Kafadar, 2014) of increase in bank-full cross-sectional area per year between USACE hydrographic surveys (0.02 = 2% average increase per year) for n=35 transects in the 66 km downstream of Red River Landing (compiled by McCain, 2016). Box shows interquartile range (IQR). Whiskers show one IQR above and below box. Plusses show outliers. Line is median. Notch is the 95% confidence interval of the median

($\pm 1.57\mathrm{IQR}\sqrt{\mathrm{n}}$). The period 1916-1931 shows statistically smaller increases than the other periods (notches do not overlap).

The ORCS was constructed between 1961-1963 because of the rapid increase in discharge down the Atchafalaya River between 1900 and 1950 (Figure 1a; Latimer & Schweitzer, 1951). Over this period, the proportion of water discharge leaving the Mississippi River and flowing into the Atchafalaya River (f_A) grew from about 0.15 in 1900 to about 0.30 in 1950, with an acceleration at some point between 1928 and 1935, when f_A was about 0.18 of annual flows (Figure 1). Increasing f_A over time was interpreted widely as the gradual and inevitable annexation of flow from the established Mississippi channel to produce a new avulsion through the Atchafalaya basin. The annexation was attributed to the gradient advantage of the Atchafalaya River relative to the existing Mississippi channel (240 km vs 496 km), that was thought to increase scouring in the Atchafalaya River (Fisk, 1952; Latimer & Schweitzer, 1951). The diversion angle and partitioning of sediment discharge were considered to have a secondary effect on the discharge increase.

The focus of this study is the events that led to the construction of ORCS. By extrapolating the rates of discharge increase and channel enlargement using an unpublished Army Corps internal report by Graves, it was estimated that the Atchafalaya River would annex 40% percent of the Mississippi's discharge between 1965 and 1975, after which the predicted avulsion would be rapid and unstoppable (Fisk, 1952; Latimer & Schweitzer, 1951). The inevitability of the natural avulsion into the Atchafalaya River reached the public consciousness through the famous essay by McPhee (1987).

The USACE analyses (Fisk, 1952; Latimer & Schweitzer, 1951) were based on empirical analyses of extensive datasets. However, quantitative analysis of the historic system's hydrodynamics, its forces and motions developed from first principles, has yet to be performed. This is partly because hydrodynamic models were still in their infancy in the early 1950s (e.g. Chow, 1959). Since then, the understanding of avulsion has advanced significantly (Kleinhans et al., 2012; Slingerland & Smith, 2004; Z. B. Wang et al., 1995). However, these advances generally rely on coupled, simplified models of fluid flow, sediment transport, and bed evolution that depart from field measurements of change and limiting their ability to inform a specific system. Hence, we found it compelling to revisit this problem with tools that could quantitatively analyze partitioning based on solid historic measurements, in order to lessen uncertainties and uncover controls of this essential river junction's evolution.

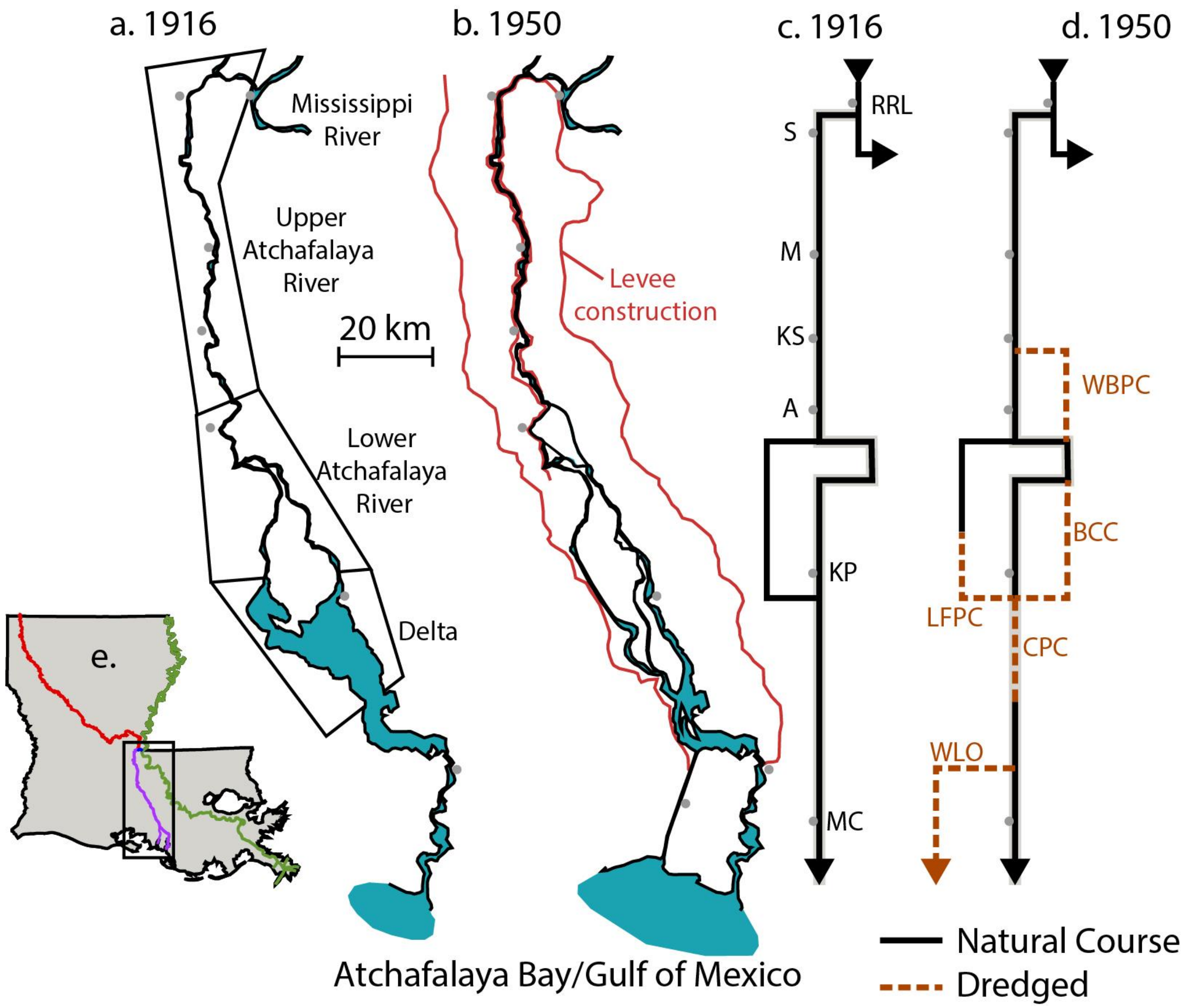

Figure 2. (a and b) maps of the Mississippi and Atchafalaya River System in 1916 and 1950. Polygons show different regions referred to in the text. Red lines in (b) are artificial levees. (c and d), Model schematics for flow routing. Arrows show flow sources (arrow tails) and sinks (arrow heads). Gray circles are hydrograph stations. The pathway which is plotted in Figs 5 and 6 is outlined in gray. RRL: Red River Landing, S: Simmesport, M: Melville, KS: Krotz Springs, A: Atchafalaya, KP: Keelboat Pass, MC: Morgan City, WBPC: Whiskey Bay Pilot Channel, BCCO: Bayou Chene Cutoff, CPC Chicot Pass Channel, Lake Fausse Point Channel. (e) Map of Louisiana, with the Mississippi River (green), Atchafalaya River (purple), and Red River (red) shown, and a box demarking the study area.

1.1 Factors potentially influencing partitioning.

We construct a relatively simple hydrodynamic model of water discharge through the Mississippi-Atchafalaya network (Figure 2) to quantitatively assess controls on the rapid increase in Atchafalaya River discharge. We isolate four potential controls: (i) the widening of the Upper Atchafalaya River, (ii) evolution of the lower Mississippi River, (iii) the dredging of channels in Lower Atchafalaya River, and (iv) the progradation of lacustrine deltas into the lakes of the lower Atchafalaya Basin.

The widening and incision of the upper Atchafalaya River between Red River Landing and the Atchafalaya, LA gauge (100 km downstream of Red River Landing; Fig. 2) has been interpreted as the key influence of increasing f_A (Fisk, 1952). Surveys by Latimer and Schweitzer (1951) show channel widening was a relatively consistent process between 1880 and 1950 (median growth 0.016-0.022 yr^{-1}), except 1916-1931 which was remarkably slow (median -0.0004 ± 0.0062 yr^{-1}; Fig. 1b). The Great Flood of 1927 cannot be isolated from historical surveys, but was the part of the period with the least change. Widening in this region may have been facilitated by a substrate of sand bodies from the historic Mississippi River that were easily erodible (Aslan et al., 2005).

The lower Mississippi river was also evolving in the early 20th century. Kesel's (2003) analysis of Mississippi River hydrographic surveys downstream of Red River Landing suggested erosion of the channel thalweg between 1935 and 1948, and interpreted it as the result of a river straightened and steepened by meander cutoffs. Stage-discharge relationships on the Mississippi River between Arkansas City, AR and Red River Landing showed similar reductions in stage for a given discharge between 1930 and about 1945 before increasing gradually after 1945 (Smith & Winkley, 1996). Our analysis of the 1916 and 1949 hydrographic surveys shows that channel thalweg (minimum elevation) did not change significantly, but the cross-sectional area of flow grew slightly, particularly in the final 200 km of the Mississippi River (downstream of New Orleans, LA). See section 5.1 for discussion. Such an increase in Mississippi River cross-sectional area should lead to decreased f_A.

Between 1932 and 1951, 97 x 10^6 m^3 of sediment dredged from the Atchafalaya River Basin (Latimer and Schweitzer, 1951). While the USACE reports mention dredging activities within the Atchafalaya Basin, they were not considered a significant factor controlling the discharge partitioning (Fisk, 1952), possibly because the dredging was focused in Grand Lake/Six Mile Lake, >100 km from ORCS. Dredging consisted of significant new channels that did not previously exist. New channels included the Whiskey Bay Pilot Channel (WBPC), The Bayou Chene Cutoff (BCC), and the Chicot Pass Channel (CPC) and the Wax Lake Outlet (WLO; Fig. 2). In the Grand Lake/Six Mile Lake region, navigation channels of the Lake Fausse Point and Grand Lake/Six Mile Lake that were 15-20' deep and 90 m (300 ft) wide. These dredged channels deepened and widened considerably between their dredging and the USACE survey of 1950. This dredging could also influence discharge partitioning. Deepening the Atchafalaya channels should increase f_A.

The fourth change to the system that could influence f_A is the growth of the large deltas in Grand Lake in the Atchafalaya Basin. Between 1916 and 1950, about 180 km^2 of lacustrine delta deposits accumulated in Grand Lake (Roberts et al., 1980; Tye & Coleman, 1989). Such deposits should act to reduce cross sectional area of flow and decrease f_A.

2 Methods and Data

2.1 Model

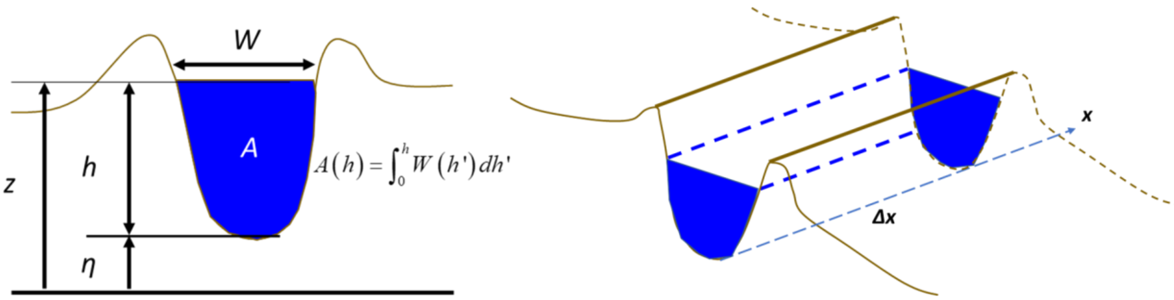

Figure 3. Schematic diagrams of hydrodynamics model. (a) Definition of cross-section area; (b) 1-D long profile of river channel with cross-sections aligned downstream.

Water discharge can be modeled through the Mississippi-Atchafalaya channel network using the backwater equation for steady, non-uniform (gradually varied) flow (Chow, 1959; Parker, 2004). This system includes channels that vary from narrow and prismatic (in the Upper Atchafalaya River) to those with significant flow outside the channel (in the Atchafalaya Delta). We thus provide a detailed derivation of the backwater equation for an arbitrary cross-section. We start from 1-D shallow water equation for arbitrarily-shaped cross-sections (Ying et al., 2004), which has been tested in channels with abrupt width contraction and expansion and trans-critical slope channel (Ying et al., 2004; Ying & Wang, 2008):

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=0 \qquad (3)$$

$$\frac{\partial Q}{\partial t}+\frac{\partial\left(Q^2/A\right)}{\partial x}=gA\left(-\frac{\partial z}{\partial x}-S_f\right) \qquad (4)$$

where t is time [T]; x is streamwise spatial distance [L]; g is gravitational acceleration [LT^{-2}]; A is the wetted cross-sectional area [L^2]; Q is the water discharge [L^3T^{-1}]; $z = \eta + h$ is the water surface elevation where η is the bed elevation and h is the water depth at the channel thalweg [L]; $S_f = C_f u|u|/\left(gA/\Gamma\right)$ is the frictional slope where C_f is the resistance coefficient, u is the cross-sectionally averaged velocity $u = Q / A$ [LT^{-1}], and Γ is the wetted perimeter [L].

For the steady, non-uniform flow in a non-bifurcating reach, Eqs. (3-4) reduce to

$$\frac{\partial Q}{\partial x}=0, \qquad (5)$$

$$\frac{\partial h}{\partial x}=S-S_f-\frac{1}{gA}\frac{\partial\left(Q^2/A\right)}{\partial x} \qquad (6)$$

where $S=-\partial\eta/\partial x$ is the channel bed slope [-].

Substituting Eq. (5) to Eq. (6), we obtain

$$\frac{\partial h}{\partial x} = S - S_f + \frac{u^2}{gA}\frac{\partial A}{\partial x}. \qquad (7)$$

Note that $\frac{\partial A}{\partial x} = \frac{\partial A}{\partial h}\frac{\partial h}{\partial x} = W\frac{\partial h}{\partial x}$, where W is channel width at the water surface as shown in Fig. 3. Hence, Eq. (7) turns to $\frac{\partial h}{\partial x} = S - S_f + \frac{u^2}{gA/W}\frac{\partial h}{\partial x}$ and since Froude number has the following relation $F^2 = \frac{u^2}{gA/W}$, we thus obtain

$$\frac{\partial h}{\partial x} = \frac{S - S_f}{1 - F^2}, \qquad (8)$$

where $S_f = C_f u|u|/\left(gA/\Gamma\right)$.

This formulation has been used as a simple way to estimate flow dynamics on large rivers (Lamb et al., 2012; Nittrouer et al., 2012; Viparelli et al., 2015; Z. B. Wang et al., 1995), but has not been previously used to model a network of many interacting channel reaches. In order to solve for h, A, u, and Q, throughout the channel network, it is broken into non-branching reaches i joined at nodes representing bifurcations and confluences. Under Froude-subcritical conditions (F^2 <1), the boundary conditions Q_i and the downstream water depth allow Eq. 8 to be solved along each reach. Reaches are linked by discharge constraints. At a node where an upstream channel a bifurcates into two channels b and c, we specify $Q_a = Q_b + Q_c$, with the discharge partitioning faction defined as $f_b = Q_b/Q_a$. At a confluence node where two channels d and e flow together to form a single channel g, $Q_d + Q_e = Q_g$. Although upstream flow ($Q_i < 0$) is potentially possible in some networks, we stipulate $Q_i \geq 0$ in this study because tidally averaged flows are always unidirectional through this system.

In addition to bathymetric transects summarized in Section 2.2, two hydraulic boundary conditions are required for a model run. First, upstream discharge (Q_0) is specified at the Mississippi River at Red River Landing (RRL; Fig. 2). The Red River also provides discharge to the system, and can be as large as 10% of the Mississippi River's discharge. However, we neglect it here because it enters the Atchafalaya River upstream of Simmesport, where Atchafalaya River discharge and f_A is measured by Latimer and Schweitzer (1951). Second, the boundary condition of water surface elevation is applied at each channel terminus where the network meets sea level, (z = 0 m MSL).

The model is solved by iteratively finding discharge partitioning values f_i that minimize disparities in water surface elevation at each bifurcation. (1) An initial set of discharge partitionings f_{i0} is chosen; (2) based on f_{i0},the water surface is solved using Eq. (8); (3) at each bifurcation, the water surface elevation at the downstream end of the upstream reach (z_{0f}) is set equal to the water surface elevation of one of the reaches d or e (z_{1d}, z_{1e}); (4) when flow has been solved throughout the network, the sum of squared difference in water surface elevation $E = \sum \Delta z^2 = \sum (z_{1d} - z_{1e})^2$ is iteratively minimized using the quasi-newton optimization technique found in MATLAB (Shanno, 1970). When a minimum of E is found, each bifurcation will have a single water surface elevation and the water surface will be nearly continuous throughout the channel network. For model runs described here, final solutions of f_i produce very small absolute water differences ($E < 10^{-6}$ m^2)

ensuring near-continuity state of the water surface across the network, and a plausible reconstruction of fluid flow.

2.2 Hydrographic Survey Data and Network Models

This study relies on detailed bathymetric and hydrological measurements collected by the US Army Corps of Engineers. Hydrographic surveys of transects were digitized from before and after the significant increase in discharge by the Atchafalaya River for validation (see section 3.1). Synthetic models focused on specific changes between 1916 and 1950 were then used to test hypotheses about the controls on Mississippi-Atchafalaya partitioning. A library of these hydrographic surveys and models are included in the supplementary material.

The pre-annexation model (R16) consisted of the most recent surveys prior to significant dredging that began in 1932. This model contained five reaches (Fig. 2c), with bifurcations at Red River Landing (RRL) and within the lower Atchafalaya River. The Atchafalaya River portion of this model consisted of hydrographic surveys collected between 1910 and 1930 published in Latimer and Schweitzer (1951, Vol. 3). The mean transect spacing was 3.5 km. The Mississippi River portion of the model was the 1913 Mississippi River Hydrographic Survey (USACE, 1915) between the Mississippi-Atchafalaya Bifurcation at Old River, and Venice, LA, where significant flow begins leaving the main channel, 17 km upstream of head of passes. The mean transect spacing was 0.3 km.

The post-annexation model (R50) consisted entirely of hydrographic surveys collected after the end of significant dredging in 1950. This model contained 11 reaches (Fig. 2d) with five bifurcations. The additional bifurcations relative to R16 were due to the Whiskey Bay Pilot Channel, Bayou Chene Cutoff, and Wax Lake Outlet. Dredging from the Lake Fausse Pointe Cut and Atchafalaya Basin Main Channel altered existing transects. The Atchafalaya River surveys are also published in Latimer and Schweitzer (1951, Vol. 3). The Mississippi River portion of this model was the 1949 Mississippi River Hydrographic Survey (USACE, 1950) between Old River and Venice.

Stage-discharge relationships were recorded at seven locations, from Red River Landing to Morgan City, Louisiana (Fig. 2c; Latimer and Schweitzer, 1951). Such relationships were recorded at various years between 1880 and 1950. The relationship from about 1916 served as a pre-annexation validation, and the relationship from about 1950 served as the post-dredge validation.

To isolate the effect of dredging within the basin, several hydrodynamic models were constructed that altered certain aspects of the two baseline models. Model R16D isolated the effect of dredging in the Atchafalaya River by adding the planned dredging within the Atchafalaya Basin, including the new channels to the 16M model (available in Latimer and Schweitzer 1951, Vol. 3). These cross-sections were generally smaller than the same cross-sections in 1950 because significant erosion and widening occurred after dredging, similar to R50, R16D had 11 reaches. Model R16A isolated the effect of channel widening in the Atchafalaya Basin by taking the R16 model but adding the 1950 cross sections of the Upper Atchafalaya River where channel width had significantly increased. Model R16M isolated the influence of changes in the Mississippi River over the study period by taking the R16 model and exchanging the 1949 Mississippi River hydrographic survey. Finally, Model R16GL isolated the effect of sediment accumulation within

Grand Lake by taking model R16 and exchanging R50 transects only within Grand Lake. Models R16A, R16M, and R16GL maintained the same transect structure as R16.

3. Results

3.1 Validation

The hydrodynamic model was validated against (a) the measured discharge partitioning (f_A ~0.18; Fig. 1) and (b) measured stage-discharge curves. An upstream discharge of Q_0 = 20,000 m^3/s was used throughout the validation and modeling process because it corresponds closely to the Mississippi Rivers average annual discharge between 1900 and 1960 (18,300 m^3/s; Latimer and Schweitzer, 1951). Preliminary models were run with discharges ranging from 15,000-35,000 m^3/s which showed gradually increasing f_A with increasing Q_0, consistent with Edmonds (2012). Variable flow discharge has an important control on centers of erosion and deposition and influences general models of avulsion (Chadwick et al., 2019; Ganti, Chadwick, Hassenruck-Gudipati, et al., 2016; Lamb et al., 2012). However, our focus is on the recorded increase in average annual flows to the Atchafalaya River, with the changing network set from data. For this reason, we leave the modeling of variable discharge through the system to future work.

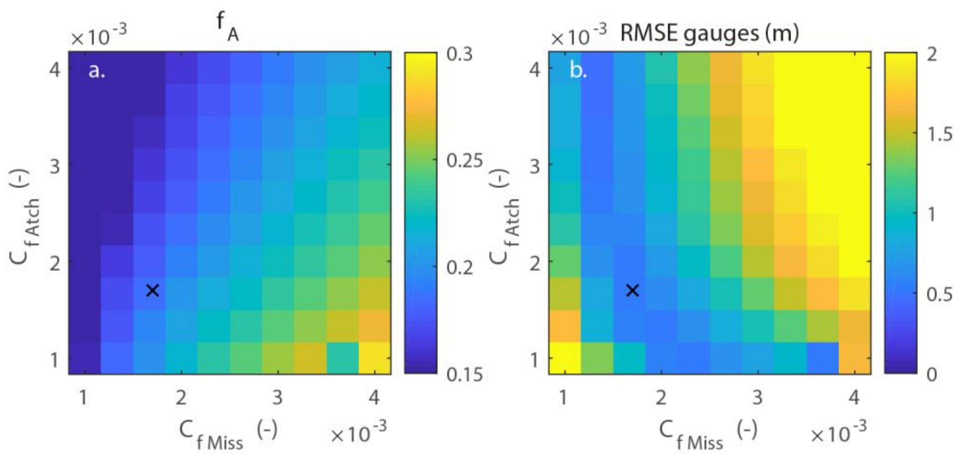

Figure 4. (a) partitioning of flow in 1916 and (b) root-mean-square error of the 7 stage-discharge gauges were used to determine an ideal combination of friction factor (C_f) in the Mississippi River (x axes) and Atchafalaya River (y axis). The black x shows the friction factors that were chosen for modeling. Results shown for upstream discharge Q_0 = 20,000 m^3/s.

Model R16 was run for a variety of friction factors in both the Mississippi River (C_{f_Miss}) and the Atchafalaya network (C_{f_Atch}) ranging from 0.001 and 0.004 (Figure 4). Partitioning (f_A) increased with increasing C_{f_Atch} and decreasing C_{f_Miss}. The root-mean-square error between measured and modeled gauge heights reached a minimum of 0.56 m for intermediate C_f, which is about 3% of 18 m average flow depth. We chose C_{f_Atch} = C_{f_Miss} = 0.0017 for this study which is consistent with the direct measurement at Tarbert Landing, Mississippi River (Karim, 1995) and the prediction of the prevailing resistance relation (Engelund & Hansen, 1967). It is slightly smaller than friction factors used to model the modern Mississippi river by Nittrouer et al. (2012; 0.003 - 0.007), but closer to the value used by Edmonds (2012; 0.0023).

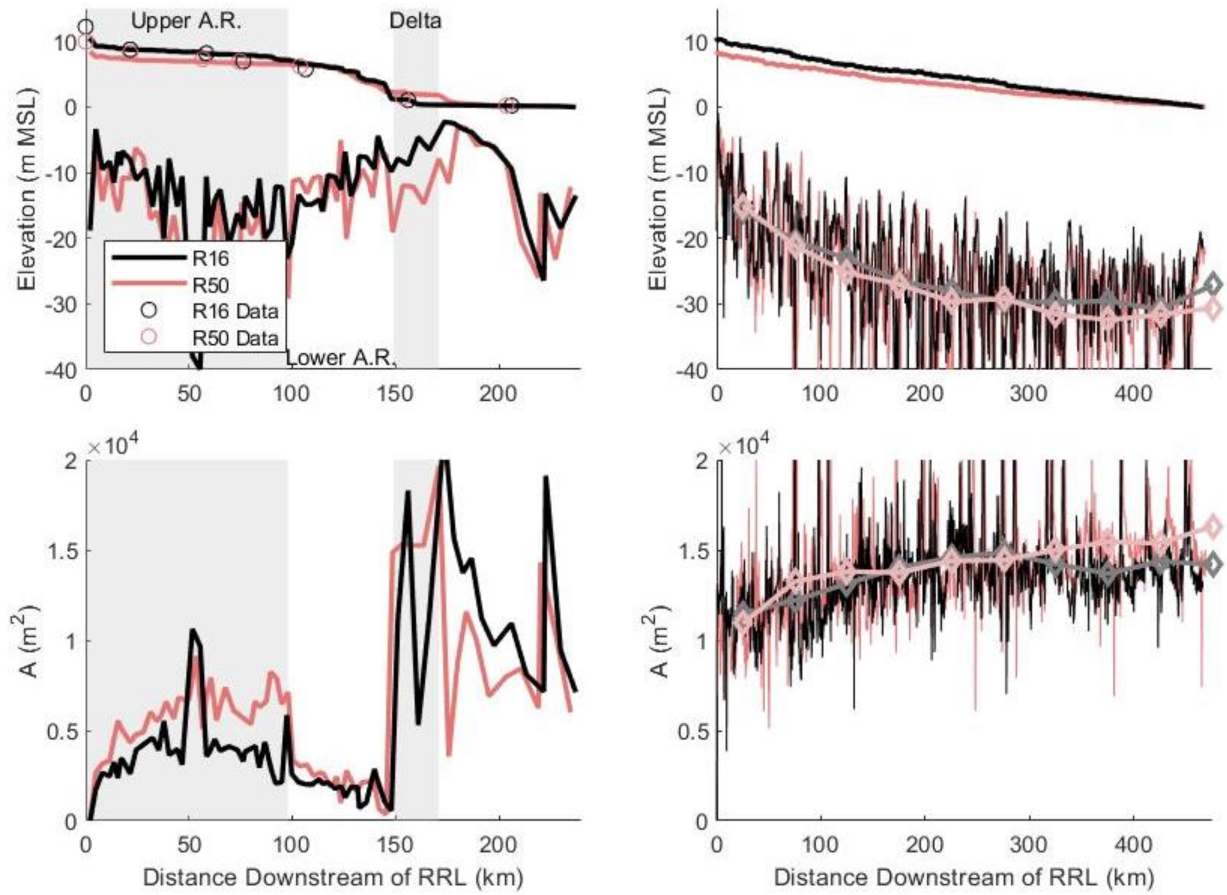

Figure 5. Results for models R16 (black) and R50 (red) under upstream discharge Q_0 = 20,000 m^3/s. Panels a (thalweg depth and water surface) and c (cross-sectional area) show the primary path through the Atchafalaya River network (see Fig. 2c,d). Circles show hydrograph heights for corresponding discharges. Panels b and d show the lower Mississippi River. Fine lines show thalweg elevation and cross sectional area for every transect. Thick lines and diamonds show 50 km averages.

Using the calibrated C_f values, discharge partitioning f_A between the Mississippi and Atchafalaya Rivers was modeled as 0.185 for R16 and 0.279 for R50. These results compare well with data showing f_A between 0.18-0.22 in 1932 and 0.28-0.32 in 1950. Model runs R16 and R50 and hydrograph data (Figure 5, Table 1) show a similar water surface profile for average annual discharge to the system. The large, low-slope channel in the upper Atchafalaya River transitions to the smaller, higher-slope channel in the lower Atchafalaya River, producing a concave down "M2 curve" (Chow, 1959) from 110-130 km downstream of Red River Landing. At the transition to the wide and shallow Grand Lake, slopes are significantly reduced again, producing a concave up "M1 curve".

The post-annexation model (R50) and data differ from their pre-annexation counterparts (R16) in terms of their slopes in the upper Atchafalaya River (for the same Q_0, but 51% increase in Q in the

Atchafalaya River; Table 1). Hydrograph data show that the stage at Red River Landing dropped 2.2 m, consistent with the modeled 2.1 m drop. Relatedly, slopes in the upper Atchafalaya River (measured over 104 km between RRL and Atchafalaya, LA) dropped 31% (hydrograph data) to 41% (models).

3.2 Partitioning Attribution

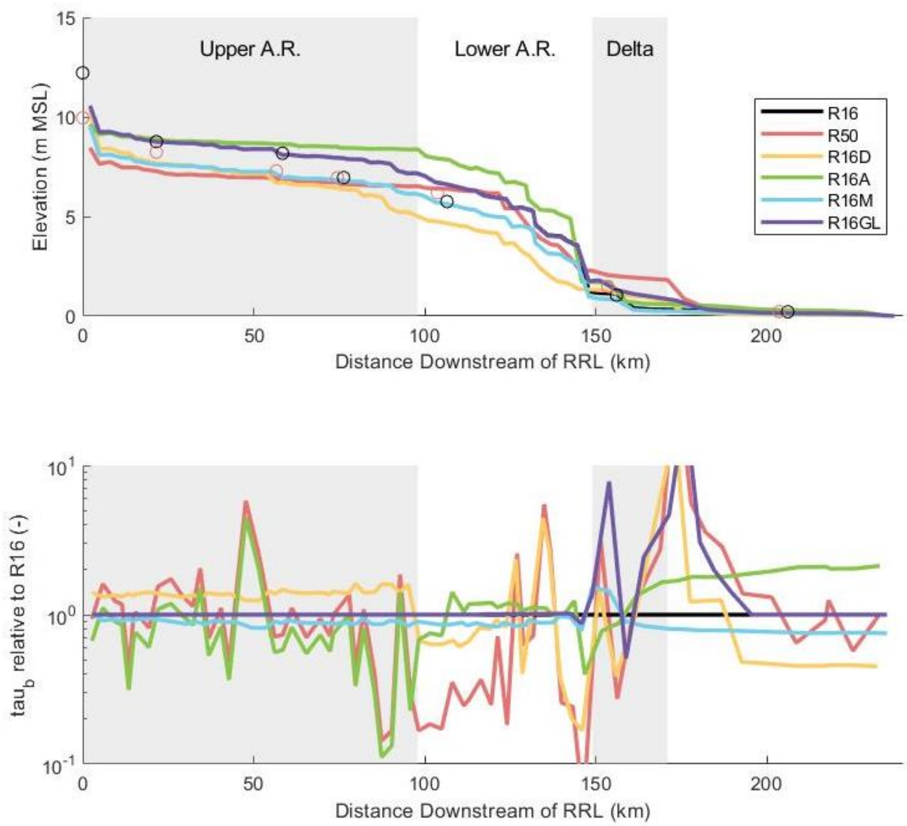

Figure 6. (a) Water surface profiles along the primary pathway through the Atchafalaya Basin (see Fig. 2) for all models. (b) Shear stress ($\tau_b = \rho C_f F^2$) along each transect divided by the shear stress from run R16. Note logarithmic y axis.

Synthetic channel networks of the Mississippi-Atchafalaya System (described in Section 2.2) were used to test how various changes between 1916 and 1950 influenced discharge partitioning (Figure 6). Two important aspects of the simulations are considered. First, model f_A is compared to the results from R16 and R50 (f_A of 0.185 and 0.279 respectively) in order to assess the control on discharge partitioning. Second, the stage change at Red River Landing is compared to the simulated stages (10.5 m and 8.4 m respectively).

Model R16A showed f_A= 0.271, or 91% of the required discharge increase from R16 to R50. However, the stage at RRL dropped to just 9.6 m, explaining only 43% of the total stage drop. Model R16D produced a partitioning of f_A = 0.197, explaining just 13% of the modeled change between R16 and R50. The stage at RRL dropped to 10.4 m, which was only 26% of the stage change there. Change was focused where dredging of new channels occurred in the lower, Atchafalaya River and produced more gradual water surface slopes.

Model R16M produced f_A = 0. 161, the only model that reduced f_A relative to R16. This is because minor increases to channel cross-sectional area of the Mississippi River acted to reduce slopes in the Mississippi River and stage at RRL to 9.5 m, thereby reducing discharge to the Atchafalaya River. The stage reduction was 47% of the total reduction in stage between R16 and R50.

Despite the growth of significant lacustrine delta deposits between 1916 and 1950, model R16GL produced essentially the same discharge partitioning and RRL stage as R16. This suggests that they had little to no impact on the discharge partitioning at the Mississippi-Atchafalaya bifurcation.

Model	**f_A (-)** **(Q_0=20,000 m^3/s)**	**Upper A.R. Slope (x10^{-5})**	**Lower A.R. Slope (x10^{-5})**	**z at RRL (m MSL)**	**Fraction of f_A change explained by model**	**Mean τ_b, Upper A.R. (N/m^2)**
Data 1932	0.18-0.22	5.71	10.02	12.2		
Data 1950	0.28-0.32	3.96	9.08	9.96		
R16	0.185	3.48	11.45	10.5		2.3
R50	0.279	2.04	8.32	8.4		1.9
R16D	0.197	5.49	7.30	10.4	13%	3.2
R16A	0.271	1.32	13.07	9.6	91%	1.4
R16M	0.161	3.50	9.94	9.5	-26%	2.1
R16GL	0.185	3.50	10.06	10.5	0%	2.3

Table 1. Hydrograph data and hydrodynamic model outputs for the Mississippi-Atchafalaya system.

5 Discussion

5.1 Attribution to the Atchafalaya partial avulsion

The proposed numerical model quantitatively depicted the increase in the proportion of discharge down the Atchafalaya River between 1916 and 1950 well (Figure 5), and clearly showed that it was the result of several simultaneous processes. Erosion of the Upper Atchafalaya River produced the largest increase in f_A. This is consistent with the original assessment of the Army Corps of Engineers (Fisk, 1952). However, dredging in the Atchafalaya river network and changes in the Mississippi river also influenced the system, while the lacustrine deltas did not.

The increase of cross-sectional area in some parts of the lower Mississippi River between 1913 and 1951 (the years of the USACE surveys) has not been previously linked to the Mississippi-Atchafalaya diversion. We attribute roughly half of the 2 m stage reduction (47% of total stage reduction) at Red River Landing to lower Mississippi River changes (Table 1). The increase in cross-sectional area occurred in two locations. First, 50-150 km downstream of Red River Landing (roughly between St. Francisville and Plaquemine, LA) in the fully alluvial reach of the river, and >300 km downstream (downstream of New Orleans, LA; Figure 4) in the alluvial-bedrock reach of the river (Viparelli et al., 2015). While reach-averaged increases to cross-sectional area were between 5 and 15% (diamonds Fig. 3d), they impacted f_A by reducing water surface slopes, and therefore the stage at Red River Landing. Lower Mississippi River erosion during the study period is consistent with previous studies (Kesel, 2003; Smith & Winkley, 1996). However, it is worth noting that since this period, the lower Mississippi River has had periods of both aggradation and degradation (Galler et al., 2003; Knox & Latrubesse, 2016; B. Wang & Xu, 2016, 2018; Wu & Mossa, 2019). Had the lower Mississippi River been aggradational during the study period, f_A may have increased more rapidly.

Dredging in the lower Atchafalaya River basin acted to increase discharge, producing 13% of the measured increase between 1916 and 1950. However, there are remarkable differences in hydrodynamics comparing the widening (R16A) or dredging (R16D) models. When widening is considered in the absence of dredging, discharge increases can only be accommodated by increased slopes in the lower Atchafalaya River (R16: $11.4\text{x}10^{-5}$, R16A $13.1\text{x}10^{-5}$) which produced higher stages and lower slopes in the upper Atchafalaya River (Fig. 6a). In contrast, when dredging is considered in the absence of widening (R16D), reduced slopes in the lower Atchafalaya River are possible (R16D: $7.3\text{x}10^{-5}$), which lead to reduced stages and higher slopes in the upper Atchafalaya River. The effects on shear stress in the upper Atchafalaya River ($\tau_b = \rho C_f u^2$) are remarkable (Fig. 6b). Shear stress is reduced by 39% due to widening (2.3 to 1.4 N/m^2; Table 1) despite a 46% discharge increase. In contrast, the 6% discharge increase of R16D increases shear stress by 39% (2.3 to 3.2 N/m^2). Hydrograph data offer a consistent story. Between 1916 and 1950, the water surface slope decreased 31% (5.71×10^{-5} to 3.96×10^{-5}; Figure 6a) in the upper Atchafalaya River but decreased only 9% in the lower Atchafalaya. The erosion and increased cross-sectional area of the upper Atchafalaya River are presumably the result of heightened shear stresses, and the period of dredging showed consistently large rates of cross-sectional area increase (Fig. 1b). Our results show that a negative feedback between widening and shear stress in the upper Atchafalaya River could limit widening, but increased channelization in the lower Atchafalaya could remove this feedback and potentially lead to greater widening.

Dredging appears to have transformed the lower Atchafalaya River. The pre-existing channels through this region did not erode during the study period (Fig. 5a,c), while dredged channels quickly became dominant. Prior to 1934, the Whiskey Bay Pilot Channel (WBPC) did not exist, and discharge was accommodated by 2-4 small channels. While many of these channels enlarged between 1932 and 1950 (Latimer and Schweitzer, 1951), dredging immediately diverted 1340 m^3/s (34%) from the lower Atchafalaya River (inferred from R16D), continued to grow after initiation through subsequent erosion, diverting 3205 m^3/s (57%) from the lower Atchafalaya River by 1950 (from R50). It is presently the dominant channel through this part of the basin. It is unclear how the lower Atchafalaya River network would have evolved in the absence of dredging, although a primary channel is eventually established in many depositional avulsions (Slingerland & Smith, 2004). However, a deeply incised, relatively straight, primary channel through the system like the dredged network (Fig. 1) seems unlikely to have formed, especially in a 16 year period.

Finally, the growth of 180 km^2 of deltas in Grand Lake did not factor in partitioning or stage at Red River Landing. These deltas did act to reduce channel cross sectional area and increase stage and slopes for R16GL by 0.7 m relative to R16 within the delta area (148-180 km downstream of RRL; Fig. 5a). However, the water surface of the R16 and R16GL collapsed on one another in the lower Atchafalaya River and were similar at all points above. Numerical models of backwater flow with smoothly varying bed topography show that stage changes decay asymptotically (Chadwick et al., 2019; Ribberink & Van Der Sande, 1985). However, the steep water surface slopes (locally 5.2×10^{-4}, $F^2 = 0.2$) associated with the M2 curve in the lower Atchafalaya River overwhelmed such gradual trends.

5.2 Limitations and Advantages

The models considered here were constructed in a deliberately simple manner so that they could be adequately run with the available historic data and allow several hypotheses to be tested. While the present study is enough to compare well with validation data and produce first order attribution, more complex models are necessary for engineering grade applications, particularly for coupling bed evolution and flows that are not averaged at a transect. Globally, coastal systems are evolving under simultaneously active natural and human drivers (Hoitink et al., 2020; Lazarus & Goldstein, 2019). The methods presented here are suitable for cases where survey data exists in order to further develop the understanding of recent, current and future channel network evolution in coastal systems worldwide.

5.3 Implications

This study facilitates a comparison to the current understanding of avulsion controls. The "setup" for avulsion was small, but consistent with prevailing models. Within 10 km of Red River Landing in 1916, the Mississippi River had a spatially averaged water surface elevation (for Q_0 = 20,000 m^3/s) of 10.2 m MSL and bed elevation of -11.3 m MSL. Compared to the minimum floodplain elevation in the region (8 m; Aslan et al. 2005), the fraction of flow depth above the flood plain (the superelevation ratio) was 0.1. This value is smaller than the mean superelevation ratio at avulsions of the Assiniboine River (0.65; Mohrig et al., 2000), Bayou Lafourche (~0.1; Törnqvist & Bridge, 2002) and laboratory experiments (0.3; Ganti et al., 2016; 0.9; Martin et al., 2009), but each dataset records avulsions with this superelevation with at least 5% frequency. On the other hand, we find it remarkable that the lower Mississippi River was slightly erosional during the pivotal 34 year of discharge increase (Figure 1). This contrasts with prevailing models which expect deposition in the main channel before and during avulsion to drive the flow reorganization (Ganti, Chadwick, Hassenruck-Gudipati, et al., 2016). Rather than "choking" the main channel, the key control on discharge increase shown was the enlargment of the upper Atchafalaya River, consistent with an incisional avulsion model (Hajek & Edmonds, 2014; Slingerland & Smith, 2004), where the excavation of the new channel is of primary importance.

The sandy, easily erodible deposits found in the upper Atchafalaya River region (Aslan et al., 2005), and the dredging at Old River between 1878 and 1937 (Mossa, 2013) may have facilitated this growth. While the delta deposits in Grand Lake are a significant depositional element, their position downstream of the M2 curve and the channels dredged through them prevented them from hindering discharge increase in the way that depositional wedges in progradational avulsions often do (Slingerland & Smith, 2004). There is good evidence that the location of avulsions in large channels with backwater flow scales with the Backwater Length; the average flow depth divided by the energy slope (Chatanantavet et al., 2012; Ganti, Chadwick, Hassenruck-Gudipati, et al., 2016; Jerolmack & Swenson, 2007; Lane, 1957). Even so, avulsion locations vary by at least a factor of 3 around this scale (J. B. Shaw & McElroy, 2016), and the understanding of this variation remains limited. Although the Atchafalaya River's course is set in this study, it reveals distinct behavior of this particular system that could influence partitioning and avulsion elsewhere.

Our work has important implications for management of the Mississippi-Atchafalaya system, and for flow management in complex networks in general. The Old River Control Structure currently regulates discharge partitioning in the system. However, stress on this regulation has occurred in the past, notably in 1973 when the Low Sill structure was damaged during a large flood (Mossa, 2016), and evolution of the channel network could impart additional stress. Large-scale coastal restoration efforts are being undertaken to make coastal Louisiana resilient to hazardous changes in the coming century (Bentley et al., 2016; CPRA, 2017; Gasparini & Yuill, 2020). These plans appear to assume constant future partitioning at ORCS, but may benefit from optimizing f_A to the wide range of restoration objectives (e.g. Kenney et al., 2013; Peyronnin et al., 2017).

For the management of flow through complex networks in general, our work stresses several things. First (and most intuitively), changes closer to a channel branch, such as the widening of the upper Atchafalaya River, affect the hydrodynamics there more significantly. Second, small changes to the largest channels of the system can significantly affect the smaller changes in the network. The minute changes to the lower Mississippi River acted to reduce stage at RRL, and could have potentially reduced f_A, had the Atchafalaya Basin not evolved. Third, this study shows that reaches like the lower Atchafalaya River - which have few or small channels, high water surface slopes, and naturally produce an M2 curve under non-flood discharges - can act as a "choke point" in the system. Increased connectivity across these reaches will reduce stage and increase shear stress upstream. Finally, apparently large changes downstream of these reaches (such as delta deposition) may not be propagated upstream in a significant way.

6 Conclusions

We present evidence that the rapid increase in water discharge into the Atchafalaya River between 1916 and 1950 can be attributed to three important changes to the Mississippi-Atchafalaya system over that period. First the relatively consistent widening of the upper Atchafalaya River produced significant increases in the fraction of water discharge entering the Atchafalaya River, as was originally interpreted by the US Army Corps of Engineers (Fisk, 1952). Significant channel dredging in the lower Atchafalaya River further also increased partitioning by increasing connectivity through a steep, low connectivity reach, potentially increasing shear stresses in the eroding channel upstream. The subtle erosion of the lower

Mississippi River acted to reduce stage at Red River Landing, and reduce partitioning. The extensive lacustrine deltas that formed in the lower Atchafalaya Basin did not significantly influence partitioning. These results demonstrate the natural and anthropogenic forcings on a large complex channel network can be isolated, and quantitatively evaluated in a manner that can aid management of important sites.

Acknowledgments, Samples, and Data

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Appendix: Notation

A	Cross-sectional Area of a channel below the water surface (L^2)
A.R.	Atchafalaya River
M.R.	Mississippi River
C_f	Dimensionless friction factor (-)
E	Error function for optimization (L^2)
F	Froude number (-)
f_i	Fraction of upstream flow entering channel reach i
f_A	Fraction of Q_0 entering the Atchafalaya River.
g	Gravitational acceleration (L/T^2)
Γ	Wetted perimeter at a cross section (L)
h	Water depth from water surface to minimimum channel elevation (L)
η	minimum bed elevation, thalweg elevation (L relative to mean sea level; MSL)
Q	Discharge (L^3/T)
Q_0	Input water discharge upstream of Red River Landing (L^3/T)
S	Bed slope ($-\partial\eta/\partial t$; -)
S_f	Frictional slope (-)
t	Time (T)
u	Water velocity, averaged across A (L/T)
W	Channel width at water surface (L)
x	Downstream coordinate (L)
z	Water surface elevation (L relative to mean sea level; MSL)

References

Aslan, A., Autin, W. J., & Blum, M. D. (2005). Causes of river avulsion: insights from the late Holocene avulsion history of the Mississippi River, USA. *Journal of Sedimentary Research*, *75*(4), 650–664.

Bain, R. L., Hale, R. P., & Goodbred, S. L. (2019). Flow Reorganization in an Anthropogenically Modified Tidal Channel Network: An Example from the Southwestern Ganges-Brahmaputra-Meghna Delta. *Journal of Geophysical Research: Earth Surface*, *0*(ja). https://doi.org/10.1029/2018JF004996

Batker, D., de la Torre, I., Costanza, R., Day, J. W., Swedeen, P., Boumans, R., & Bagstad, K. (2014). The Threats to the Value of Ecosystem Goods and Services of the Mississippi Delta. In J. W. Day, G. P. Kemp, A. M. Freeman, & D. P. Muth (Eds.), *Perspectives on the Restoration of the Mississippi Delta: The Once and Future Delta* (pp. 155–173). Dordrecht: Springer Netherlands. https://doi.org/10.1007/978-94-017-8733-8_11

Bentley, S. J., Blum, M. D., Maloney, J., Pond, L., & Paulsell, R. (2016). The Mississippi River source-to-sink system: Perspectives on tectonic, climatic, and anthropogenic influences, Miocene to Anthropocene. *Earth-Science Reviews*, *153*, 139–174. https://doi.org/10.1016/j.earscirev.2015.11.001

Blum, M. D. (2019). Organization and reorganization of drainage and sediment routing through time: the Mississippi River system. *Geological Society*, *London*, *Special Publications*, *488*. https://doi.org/10.1144/SP488-2018-166

Blum, M. D., & Roberts, H. H. (2012). The Mississippi Delta Region: Past, Present, and Future. *Annual Review of Earth and Planetary Sciences*, *40*(1), 655–683. https://doi.org/10.1146/annurev-earth-042711-105248

Chadwick, A. J., Lamb, M. P., Moodie, A. J., Parker, G., & Nittrouer, J. A. (2019). Origin of a Preferential Avulsion Node on Lowland River Deltas. *Geophysical Research Letters*, *46*(8), 4267–4277. https://doi.org/10.1029/2019GL082491

Chatanantavet, P., Lamb, M. P., & Nittrouer, J. A. (2012). Backwater controls of avulsion location on deltas. *Geophysical Research Letters*, *39*(1), n/a–n/a. https://doi.org/10.1029/2011GL050197

Chow, V. T. (1959). Open-channel hydraulics.

CPRA. (2017). *Louisiana's Comprehensive Master Plan for a Sustainable Coast*. Baton Rouge, LA: State of Louisiana. Retrieved from http://coastal.la.gov/our-plan/

Edmonds, D. A. (2012). Stability of backwater-influenced river bifurcations: A study of the Mississippi-Atchafalaya system. *Geophysical Research Letters*, *39*(8), n/a–n/a. https://doi.org/10.1029/2012GL051125

Engelund, F., & Hansen, E. (1967). *A Monograph on Sediment Transport in Alluvial Streams*. Copenhagen: Teknik Forlag.

Fisk, H. N. (1952). *Geological investigation of the Atchafalaya Basin and the problem of Mississippi River diversion*. Vicksburg, Mississippi: U.S. Corps of Engineers, Mississippi River Commission.

Galler, J. J., Bianchi, T. S., Alison, M. A., Wysocki, L. A., Campanella, R., Narasimhan, T. N., et al. (2003). Biogeochemical implications of levee confinement in the lowermost Mississippi River. *EOS [American Geophysical Union Transactions]*, *84*(44), 469–484.

Ganti, V., Chu, Z., Lamb, M. P., Nittrouer, J. A., & Parker, G. (2014). Testing morphodynamic controls on the location and frequency of river avulsions on fans versus deltas: Huanghe (Yellow River), China. *Geophysical Research Letters*, *41*(22), 2014GL061918. https://doi.org/10.1002/2014GL061918

Ganti, V., Chadwick, A. J., Hassenruck-Gudipati, H. J., & Lamb, M. P. (2016). Avulsion cycles and their stratigraphic signature on an experimental backwater-controlled delta. *Journal of Geophysical Research: Earth Surface*, *121*(9), 1651–1675. https://doi.org/10.1002/2016JF003915

Ganti, V., Chadwick, A. J., Hassenruck-Gudipati, H. J., Fuller, B. M., & Lamb, M. P. (2016). Experimental river delta size set by multiple floods and backwater hydrodynamics. *Science Advances*, *2*(5), e1501768. https://doi.org/10.1126/sciadv.1501768

Gasparini, N., & Yuill, B. T. (2020). High Water: Prolonged Flooding on the Deltaic Mississippi River. Retrieved May 19, 2020, from https://eos.org/features/high-water-prolonged-flooding-on-the-deltaic-mississippi-river

Hajek, E. A., & Edmonds, D. A. (2014). Is river avulsion style controlled by floodplain morphodynamics? *Geology*, *42*(3), 199–202. https://doi.org/10.1130/G35045.1

Hoitink, A. J. F., Nittrouer, J. A., Passalacqua, P., Shaw, J. B., Langendoen, E. J., Huismans, Y., & Maren, D. S. van. (2020). Resilience of river deltas in the Anthropocene. *Journal of Geophysical Research: Earth Surface*, e2019JF005201. https://doi.org/10.1029/2019JF005201

Jerolmack, D. J., & Swenson, J. B. (2007). Scaling relationships and evolution of distributary networks on wave-influenced deltas. *Geophysical Research Letters*, *34*(23), L23402. https://doi.org/10.1029/2007GL031823

Kafadar, K. (2014). Notched Box-And-Whisker Plot. In *Wiley StatsRef: Statistics Reference Online*. American Cancer Society. https://doi.org/10.1002/9781118445112.stat00467

Karim, F. (1995). Bed Configuration and Hydraulic Resistance in Alluvial-Channel Flows. *Journal of Hydraulic Engineering*, *121*(1), 15–25. https://doi.org/10.1061/(ASCE)0733-9429(1995)121:1(15)

Kenney, M. A., Hobbs, B. F., Mohrig, D., Huang, H., Nittrouer, J. A., Kim, W., & Parker, G. (2013). Cost analysis of water and sediment diversions to optimize land building in the Mississippi river delta. *Water Resources Research*. https://doi.org/10.1002/wrcr.20139

Kesel, R. H. (2003). Human modifications to the sediment regime of the Lower Mississippi River flood plain. *Geomorphology*, *56*(3), 325–334. https://doi.org/10.1016/S0169-555X(03)00159-4

Kleinhans, M. G., Cohen, K. M., Hoekstra, J., & IJmker, J. M. (2011). Evolution of a bifurcation in a meandering river with adjustable channel widths, Rhine delta apex. *Earth Surface Processes and Landforms*, *36*(15), 2011–2027. https://doi.org/10.1002/esp.2222

Kleinhans, M. G., Ferguson, R. I., Lane, S. N., & Hardy, R. J. (2012). Splitting rivers at their seams: bifurcations and avulsion. *Earth Surface Processes and Landforms*. https://doi.org/10.1002/esp.3268

Knox, R. L., & Latrubesse, E. M. (2016). A geomorphic approach to the analysis of bedload and bed morphology of the Lower Mississippi River near the Old River Control Structure. *Geomorphology*, *268*, 35–47. https://doi.org/10.1016/j.geomorph.2016.05.034

Lamb, M. P., Nittrouer, J. A., Mohrig, D., & Shaw, J. B. (2012). Backwater and river plume controls on scour upstream of river mouths: Implications for fluvio-deltaic morphodynamics. *Journal of Geophysical Research*, *117*(F1), F01002. https://doi.org/10.1029/2011JF002079

Lane, E. W. (1957). *A Study of the Shape of Channels Formed by Natural Streams Flowing in Erodible Material* (Missouri River Division Sediment Series Report 9) (pp. 1–106). Omaha, Nebraska: U.S. Army Corps of Engineers.

Latimer, R. A., & Schweitzer, C. W. (1951). *The Atchafalaya River study: A report based engineering and geological studies of the enlargement of Old and Atchafalaya Rivers* (Vol. 1,2,3). Vicksburg, Mississippi: U.S. Army Corps of Engineers, Mississippi River Commission.

Lazarus, E. D., & Goldstein, E. B. (2019). Is There a Bulldozer in your Model? *Journal of Geophysical Research: Earth Surface*, *124*(3), 696–699. https://doi.org/10.1029/2018JF004957

Martin, J., Sheets, B., Paola, C., & Hoyal, D. (2009). Influence of steady base-level rise on channel mobility, shoreline migration, and scaling properties of a cohesive experimental delta. *Journal of Geophysical Research: Earth Surface*, *114*(F3). https://doi.org/10.1029/2008JF001142

McCain, G. (2016). Influences of Channel Dredging on Avulsion Potential at the Atchafalaya River. *Theses and Dissertations*. Retrieved from https://scholarworks.uark.edu/etd/1559

McPhee, J. (1987, February 16). Atchafalaya. Retrieved from https://www.newyorker.com/magazine/1987/02/23/atchafalaya

Mohrig, D., Heller, P. L., Paola, C., & Lyons, W. J. (2000). Interpreting avulsion process from ancient alluvial sequences: Guadalope-Matarranya system (northern Spain) and Wasatch Formation (western Colorado). *Geological Society of America Bulletin*, *112*(12), 1787–1803.

Mossa, J. (2013). Historical changes of a major juncture: Lower Old River, Louisiana. *Physical Geography*, *34*(4–05), 315–334. https://doi.org/10.1080/02723646.2013.847314

Mossa, J. (2016). The changing geomorphology of the Atchafalaya River, Louisiana: A historical perspective. *Geomorphology*, *252*, 112–127. https://doi.org/10.1016/j.geomorph.2015.08.018

Nittrouer, J. A., Shaw, J. B., Lamb, M. P., & Mohrig, D. (2012). Spatial and temporal trends for water-flow velocity and bed-material transport in the lower Mississippi River. *Geol. Soc. Am. Bull*, *124*, 400–414. https://doi.org/10.1130/B30497.1

Parker, G. (2004). *1D Sediment Transport Morphodynamics with applications to Rivers and Turbidity Currents*. Retrieved from http://hydrolab.illinois.edu/people/parkerg//morphodynamics_e-book.htm?q=people/parkerg/morphodynamics_e-book.htm

Peyronnin, N. S., Caffey, R. H., Cowan, J. H., Justic, D., Kolker, A. S., Laska, S. B., et al. (2017). Optimizing Sediment Diversion Operations: Working Group Recommendations for Integrating Complex Ecological and Social Landscape Interactions. *Water*, *9*(6), 368. https://doi.org/10.3390/w9060368

Ribberink, J. S., & Van Der Sande, J. T. M. (1985). Aggradation in rivers due to overloading - analytical approaches. *Journal of Hydraulic Research*, *23*(3), 273–283. https://doi.org/10.1080/00221688509499355

Roberts, H., Adams, R., & Cunningham, R. (1980). Evolution of sand-dominant subaerial phase, Atchafalaya Delta, Louisiana. *American Association of Petroleum Geologists Bulletin*, *64*, 264–279.

Saucier, R. T. (1994). *Geomorphology and Quarternary Geologic History of the Lower Mississippi Valley*. *Volume 2*. DTIC Document. Retrieved from http://oai.dtic.mil/oai/oai?verb=getRecord&metadataPrefix=html&identifier=ADA299155

Shanno, D. F. (1970). Conditioning of quasi-Newton methods for function minimization. *Mathematics of Computation*, *24*(111), 647–656.

Shaw, J. B., & McElroy, B. (2016). Backwater number scaling of alluvial bed forms. *Journal of Geophysical Research: Earth Surface*, *121*(8), 2016JF003861. https://doi.org/10.1002/2016JF003861

Shaw, J. B., Estep, J. D., Whaling, A. R., Sanks, K. M., & Edmonds, D. A. (2018). Measuring subaqueous progradation of the Wax Lake Delta with a model of flow direction divergence. *Earth Surface Dynamics*, *6*(4), 1155–1168. https://doi.org/10.5194/esurf-6-1155-2018

Slingerland, R., & Smith, N. D. (2004). River avulsions and their deposits. *Annu. Rev. Earth Planet. Sci.*, *32*, 257–285.

Smith, L. M., & Winkley, B. R. (1996). The response of the Lower Mississippi River to river engineering. *Engineering Geology*, *45*(1), 433–455. https://doi.org/10.1016/S0013-7952(96)00025-7

Syvitski, J. P. M. (2008). Deltas at risk. *Sustainability Science*, *3*(1), 23–32. https://doi.org/10.1007/s11625-008-0043-3

Tessler, Z. D., Vörösmarty, C. J., Grossberg, M., Gladkova, I., Aizenman, H., Syvitski, J. P. M., & Foufoula-Georgiou, E. (2015). Profiling risk and sustainability in coastal deltas of the world. *Science*, *349*(6248), 638–643. https://doi.org/10.1126/science.aab3574

Törnqvist, T. E., & Bridge, J. S. (2002). Spatial variation of overbank aggradation rate and its influence on avulsion frequency. *Sedimentology*, *49*(5), 891–905.

Tye, R. S., & Coleman, J. M. (1989). Evolution of Atchafalaya lacustrine deltas, south-central Louisiana. *Sedimentary Geology*, *65*(1), 95–112. https://doi.org/10.1016/0037-0738(89)90008-0

USACE. (1915). *1913 Mississippi River Hydrographic Survey*. Retrieved from https://www.mvn.usace.army.mil/Missions/Engineering/Geospatial-Section/MRHB_Historic/MRHB_1913/

USACE. (1950). *1949 Mississippi River Hydrographic Survey*. Retrieved from https://www.mvn.usace.army.mil/Missions/Engineering/Geospatial-Section/MRHB_Historic/MRHB_1913/

USACE. (2009). Old River Control. U.S. Army Corps of Engineers, New Orleans District. Retrieved from https://www.mvn.usace.army.mil/Portals/56/docs/PAO/Brochures/OldRiverControlBrochure.pdf

Vinh, V. D., Ouillon, S., Thanh, T. D., & Chu, L. V. (2014). Impact of the Hoa Binh dam (Vietnam) on water and sediment budgets in the Red River basin and delta. *Hydrology and Earth System Sciences*, *18*(10), 3987–4005. https://doi.org/10.5194/hess-18-3987-2014

Viparelli, E., Nittrouer, J. A., & Parker, G. (2015). Modeling flow and sediment transport dynamics in the lowermost Mississippi River, Louisiana, USA, with an upstream alluvial-bedrock transition and a downstream bedrock-alluvial transition: Implications for land building using engineered diversions. *Journal of Geophysical Research: Earth Surface*, *120*(3), 534–563. https://doi.org/10.1002/2014JF003257

Wang, B., & Xu, Y. J. (2016). Long-term geomorphic response to flow regulation in a 10-km reach downstream of the Mississippi–Atchafalaya River diversion. *Journal of Hydrology: Regional Studies*, *8*, 10–25. https://doi.org/10.1016/j.ejrh.2016.08.002

Wang, B., & Xu, Y. J. (2018). Decadal-Scale Riverbed Deformation and Sand Budget of the Last 500 km of the Mississippi River: Insights Into Natural and River Engineering Effects on a Large Alluvial River. *Journal of Geophysical Research: Earth Surface*, *123*(5), 874–890. https://doi.org/10.1029/2017JF004542

Wang, Z. B., De Vries, M., Fokkink, R. J., & Langerak, A. (1995). Stability of river bifurcations in ID morphodynamic models. *Journal of Hydraulic Research*, *33*(6), 739–750.

Wilson, C., Goodbred, S., Small, C., Gilligan, J., Sams, S., Mallick, B., & Hale, R. (2017). Widespread infilling of tidal channels and navigable waterways in human-modified tidal deltaplain of southwest Bangladesh. *Elem Sci Anth*, *5*(0). https://doi.org/10.1525/elementa.263

Wu, C.-Y., & Mossa, J. (2019). Decadal-Scale Variations of Thalweg Morphology and Riffle–Pool Sequences in Response to Flow Regulation in the Lowermost Mississippi River. *Water*, *11*(6), 1175. https://doi.org/10.3390/w11061175

Ying, X., & Wang, S. S. Y. W. (2008). Improved implementation of the HLL approximate Riemann solver for one-dimensional open channel flows. *Journal of Hydraulic Research*, *46*(1), 21–34. https://doi.org/10.1080/00221686.2008.9521840

Ying, X., Khan Abdul A., & Wang Sam S. Y. (2004). Upwind Conservative Scheme for the Saint Venant Equations. *Journal of Hydraulic Engineering*, *130*(10), 977–987. https://doi.org/10.1061/(ASCE)0733-9429(2004)130:10(977)