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# Influences on Discharge Partitioning on a Large River Delta: Case Study of the Mississippi-Atchafalaya Diversion, 1926-1950

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**Key Points:**

- The rapid increase in discharge to the Atchafalaya River between 1926 and 1950 is explained first by natural erosion and second by dredging.
- Erosion measured in the lower Mississippi River would have reduced Atchafalaya discharge had Atchafalaya Basin remained fixed.
- Delta growth in the Atchafalaya Basin did not change partitioning, as it was 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 system. The Atchafalaya River's (AR) partial annexation of discharge from the Mississippi River (MR), particularly between 1926 and 1950, prompted warnings of a rapid river avulsion and the construction of the Old River Control Structure to regulate flow. Natural and anthropogenic causes of this discharge annexation are difficult to disentangle. Here, we develop and validate a hydrodynamic model of flow partitioning through the historic channel network. We then isolate how several key changes to the system affected discharge partitioning and stage at the AR-MR diversion. Simulations show that erosion of the upper AR can account for 73% of the water discharge increase. Dredging in the lower AR between 1932 and 1950 can account for 35% of the water discharge increase, and was also an important control on shear stress distribution. The lower MR was slightly erosional during this period, and therefore hindered the AR discharge increase. Significant lacustrine delta deposition in AR had little effect on partitioning. These findings highlight the importance of AR enlargement processes on avulsion dynamics at this site. Given the essential nature of this river junction to the 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; Kästner et al., 2017; Kleinhans, Ferguson, 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 study the influence of several natural and human-induced influences on historic discharge annexation in the complex channel network of the Mississippi Delta System.

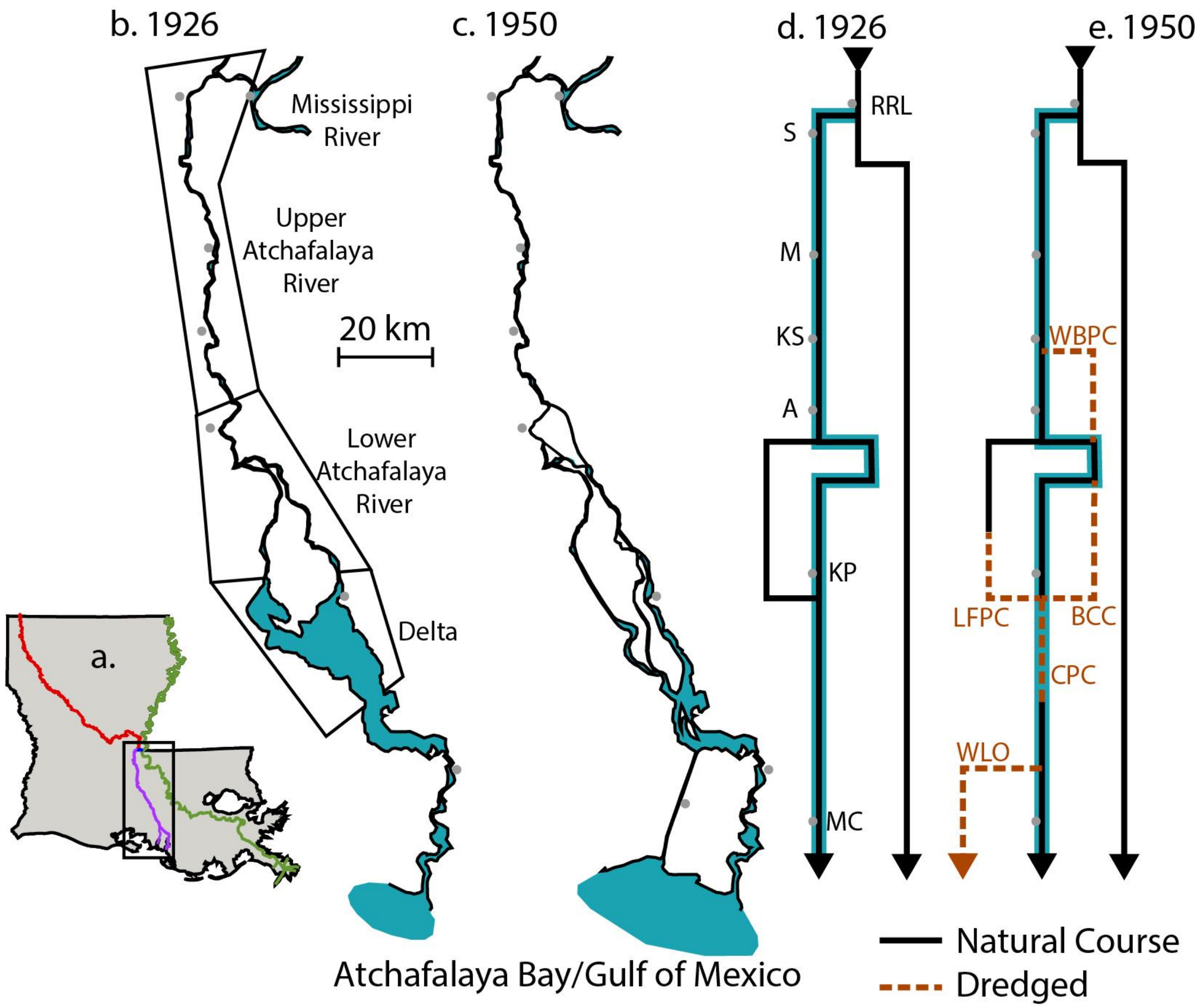


**Figure 1.** (a) Map of Louisiana showing the Mississippi River (green), Atchafalaya River (purple), and Red River (red). (b and c) Maps of Atchafalaya River in 1926 and 1950, with Mississippi course removed for clarity. Gray circles are hydrograph stations. Polygons (in b) show different regions referred to in the text. (d and e) Model schematics for flow routing. Arrow tails show flow sources and arrow heads show sinks at sea level. The pathway which is plotted in Figs 5a,c and 6 is outlined in blue. RRL: Red River Landing, S: Simmesport, M: Melville, KS: Krotz Springs, A: Atchafalaya, KP: Keelboat Pass, MC: Morgan City, WBPC: Whiskey Bay Pilot Channel, BCC: Bayou Chene Cutoff, CPC: Chicot Pass Channel, LFPC: Lake Fausse Point Channel, WLO: Wax Lake Outlet.

The modern Mississippi Delta system (Figure 1) is the product of natural processes across geologic time (Blum, 2019; Saucier, 1994). Over the Holocene, the Mississippi River delta has experienced 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). The Atchafalaya River is the most recent new course. It was initiated in the sixteenth century, and was well-established in 1765 (Fisk, 1952).

Human activities began to significantly change the system's morphology and hydrology in the nineteenth century (Kesel, 2003; Mossa, 2013). These included 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 (Fig. 1), where the Old River (an abandoned meander loop) connects the Mississippi and Atchafalaya rivers, a canal was dredged intermittently between 1878 and 1937 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).

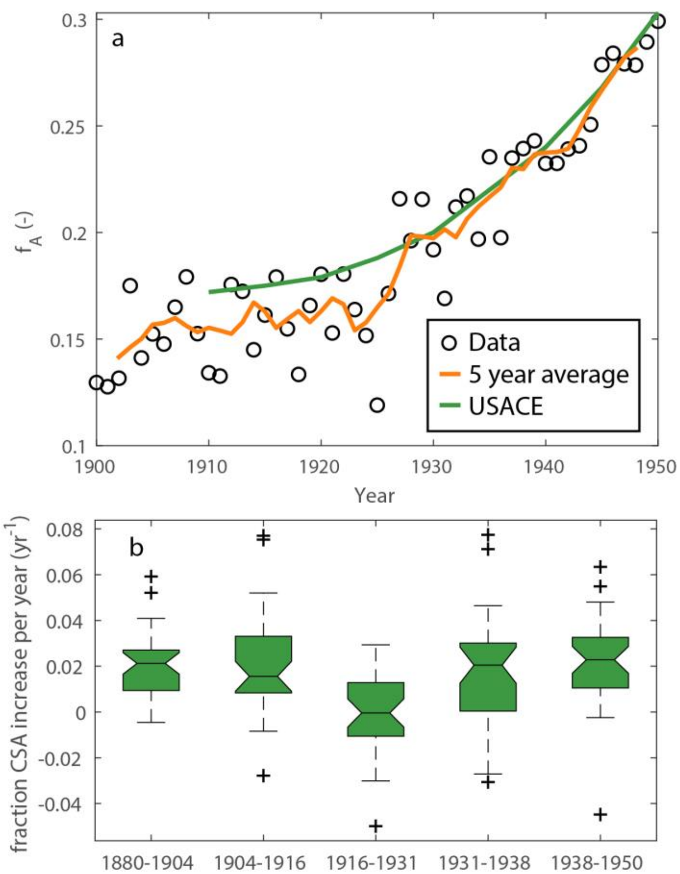


**Figure 2**. (a) Time series of the proportion of mean annual discharge entering the Atchafalaya River from the Mississippi River $f_A$. Orange line is a five-year moving average. Green line is the USACE's interpreted $f_A$ trajectory. (b) Distribution of change in upper Atchafalaya River bank-full cross-sectional area (*CSA*) for n=35 transects across five time periods (compiled by McCain, 2016; 0.02 =2% average increase per year). Transects were surveyed by USACE in the 66 km of Atchafalaya River downstream of the Red River (See Fig. 1). Notched box plots (Kafadar, 2014) with whiskers showing 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).

USACE measurements of the fraction of annual water discharge leaving the Mississippi River and entering the Atchafalaya River ($f_A$) show a period of relative discharge stability from 1900-1925 and a period of discharge annexation with rapidly increasing $f_A$ beginning in 1926 (Figure 2a). During the stable phase, $f_A$ was larger during years with more discharge, but no temporal trend is apparent. After 1926, $f_A$ increased at a roughly linear rate of 0.005 $yr^{-1}$ until 1950. This period of annexation is the focus of our study.

The increase in $f_A$ 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 (green line, figure 2a). The discharge annexation (increasing $f_A$) 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. By extrapolating the rates of discharge partitioning 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 apparent inevitability of avulsion caused the Old River Control Structure (ORCS) to be built in 1963, to regulate $f_A$. The "Control of Nature" exerted by ORCS reached the public consciousness through the famous essay by McPhee (1987).

The processes that controlled the rapid increase in $f_A$ are important, and have received insufficient attention. River avulsions control sedimentary basin filling, and the Mississippi-Atchafalaya system is considered an important modern analogue (Bhattacharya et al., 2019). Furthermore, sustainable management of modern river deltas subjected to rapid relative sea level rise requires a clear understanding of how natural and anthropogenic processes influence water, sediment, and nutrient transport pathways (Knights et al., 2020; Sanks et al., 2020). The USACE analyses (Fisk, 1952; Latimer & Schweitzer, 1951) were based on empirical analyses of extensive datasets. However, a quantitative analysis of the historic system's hydrodynamics 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, Ferguson, et al., 2012; Slingerland & Smith, 2004; Z. B. Wang et al., 1995), yet modeling of specific avulsions continues to be rare. Hence, we found it compelling to revisit this problem with physics based models that could quantitatively analyze discharge partitioning based on historic measurements, in order to lessen uncertainties and uncover controls of this essential river junction's evolution.

## 1.1 Factors Potentially Influencing Partitioning

We examine a hydrodynamic model of water discharge through the historic Mississippi-Atchafalaya network (Figure 1) to quantitatively assess controls on the rapid increase in Atchafalaya River discharge (Figure 2). 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 natural widening and incision (termed hereafter "natural erosion") of the upper Atchafalaya River between Red River Landing and the Atchafalaya, LA gauge (100 km downstream of Red River Landing; Fig. 1, 2b) has been interpreted as the key influence of increasing $f_A$ (Fisk, 1952).

Surveys by Latimer and Schweitzer (1951) show that enlargement of bank-full cross-sectional area was a relatively consistent between 1880 and 1950 (median growth 0.016-0.022 $yr^{-1}$; i.e. 1.6-2.2% increase in bank-full cross-sectional area per year), except 1916-1931 which was remarkably slow (median -0.0004 ± 0.0062 $yr^{-1}$; Fig. 2b). Erosion 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 associated increase in cross-sectional area should lead to increased $f_A$.

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 (Biedenharn & Watson, 1997; 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 4.1 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 was 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 lower Atchafalaya River and Deltas region (Fig. 1b), >100 km from Red River Landing. Dredging consisted of navigation channels that did not previously exist, including the Whiskey Bay Pilot Channel (WBPC), the Bayou Chene Cutoff (BCC), and the Chicot Pass Channel (CPC) and the Wax Lake Outlet (WLO; Fig. 1). Channels were dredged to 4.5-6.1 m (15-20 feet) deep and 90 m (300 feet) wide. Channels dredged early in this period sometimes deepened and widened considerably between dredging and the USACE survey of 1950 (Figure 3). This dredging could also 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 ("Deltas" Region, Figure 1b). Between 1916 and 1950, about 180 $km^2$ of lacustrine delta deposits accumulated, largely filling the ~3 m deep Grand Lake (Roberts et al., 1980; Tye & Coleman, 1989). While natural channels formed during this accumulation, channelization was dominated by the dredged Chicot Pass Channel (Figure 1e). Such deposits could have acted to reduce cross sectional area of flow, causing a reduced discharge for the same water surface slope in the Atchafalaya Basin, thereby decreasing $f_A$.

## 2 Model and Data

We construct a numerical model of steady, non-uniform flow through a complex channel network. The model is an adaptation of 1-Dimensional flow models (Chow, 1959; Parker, 2004) that have proven effective for tracking discharge and fluid shear stress for single-channel coastal rivers (Chadwick et al., 2019; Lamb et al., 2012; Nittrouer et al., 2012; Viparelli et al., 2015). We advance this approach by including channel bifurcations and confluences in order to resolve discharge partitioning. Discharge partitioning has been studied for an ideal branch (Buschman et al., 2010; Slingerland & Smith, 1998; Z. B. Wang et al., 1995) and in the case of a complex network (Kleinhans, de Haas, et al., 2012). Our work considers controls on discharge partitioning as a function of documented changes to channel and network morphology for the first time. Using bathymetric transects and stage-discharge relationships from before the discharge annexation (Figure 2), we validate a hydrologic model of the system. We then isolate the influence of key changes to the system by constructing synthetic networks, and assess controls on discharge partitioning.

## 2.1 Model

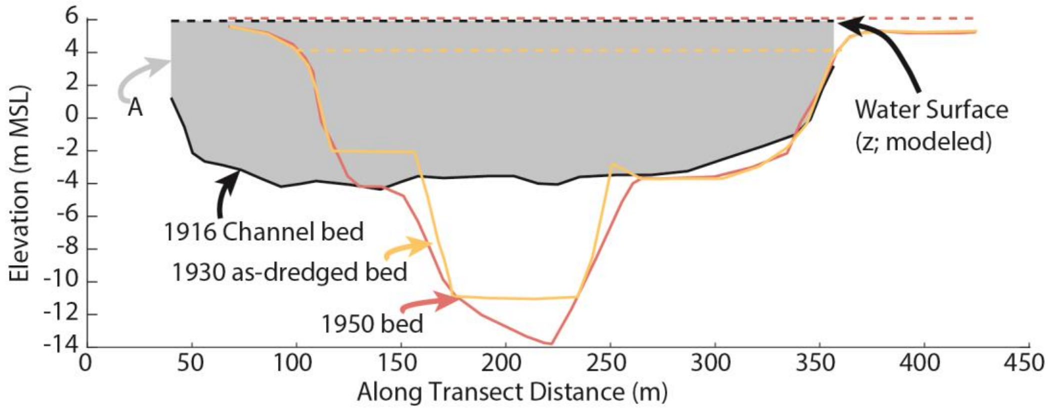


**Figure 3.** Diagram of cross section R-143, in the Atchafalaya Basin. Black, yellow, and red solid lines signify the 1916 transect used in R_pre, the 1930 transect with the planned dredging used in R_pre_D, and the 1950 transect after additional erosion used in R_post. Dashed lines show example modeled water surface elevations. The gray region is an example of cross-sectional area *A* for the R_pre.

We begin with one-dimensional expressions for conservation of fluid mass and conservation of fluid momentum:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0, \qquad (1)$$

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

where $t$ is time [T]; $x$ is streamwise spatial distance [L]; $g$ is gravitational acceleration [$LT^{-2}$]; $A$ is the wetted cross-sectional area [$L^2$] (Figure 3); $Q_i$ is the water discharge [$L^3T^{-1}$] through reach $i$; $z$ is the water surface elevation; $S_f = C_f u|u| / (gA/\Gamma)$ is the frictional slope where $C_f$ is the resistance coefficient [-], $u$ is the cross-sectionally averaged velocity $u = Q / A$ [$LT^{-1}$], and $\Gamma$ is the wetted perimeter, or $A$ divided by the wetted surface width [L]. Under steady conditions $\partial/\partial t \approx 0$, Eqs. (1-2) reduce to

$$\frac{\partial z}{\partial x} = -\frac{1}{gA}\frac{\partial (Q_i^2/A)}{\partial x} - S_f. \qquad (3)$$

For a known bathymetric transect (Figure 3), $A$ and $\Gamma$ can be calculated as a function of $z$ *a priori*: we do so in 0.1 m increments for $z$ between 0 and 25 m above sea level for all transects. With prescribed $Q_i$ and $C_f$ and known $z$ at a downstream transect, equation (3) can be solved directly without further assumptions of channel width or depth, allowing the water surface to be solved for the upstream transect.

We now extend this framework to model a network of many interacting channel reaches. In order to solve for $A$, $u$, 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. 3 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 fraction 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 $f$, $Q_d + Q_e = Q_f$. 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.

Two hydraulic boundary conditions are required for a model run (beyond the bathymetric transects summarized in Section 2.2). First, upstream discharge ($Q_0$) is specified at the Mississippi River at Red River Landing (RRL; Fig. 1). The Red River also provides discharge to the system, and can be as large as 10% of the Mississippi River's discharge. However, we do not model 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 ($z$ = 0 m MSL; at the Mississippi River mouth, the Atchafalaya River mouth, and the Wax Lake Outlet mouth in pertinent models). This terminus was chosen where significant distributary outflow began to occur, consistent with Lamb et al. (2012).

The model is solved by finding discharge partitioning values $f_i$ that minimize differences in water surface elevation at each bifurcation in the network (Fig. 1d,e). (1) An initial set of arbitrarily chosen discharge partitionings $f_{i0}$ for every channel bifurcation (including the Mississippi-Atchafalaya bifurcation) is assumed ($f_A$ set to 0.3); (2) based on $f_{i0}$, the discharge within each reach is computed by integrating equation (3) upstream from channel mouths at the Atchafalaya River, Mississippi River, and Wax Lake Outlet in some cases (Fig. 1d,e); (3) at each bifurcation, the water surface elevation at the downstream end of the upstream reach ($z_{0a}$) is set equal to the water surface elevation at the upstream end of one of the reaches $b$ or $c$ ($z_{1b}$, $z_{1c}$); (4) when flow has been solved throughout the network, the sum of squared difference in water surface elevation at each channel bifurcation $E = \sum \Delta z^2 = \sum (z_{1b} - z_{1c})^2$ is iteratively minimized using the quasi-newton optimization technique found in MATLAB (Shanno, 1970) to alter partitionings $f_i$. When a minimum of $E$ is found, each bifurcation will have a nearly equal water surface elevation ($z_{0a} \approx z_{1b} \approx z_{1c}$) 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 that are used to calculate $A$ and $\Gamma$ (Figure 3). We digitized these measurements from original documents and a library of these hydrographic surveys and models are included in the supplementary material.

The pre-annexation model (R_pre) consisted of the most recent surveys prior to significant discharge annexation. This model contained five reaches (Fig. 1d), with bifurcations at Red River Landing (RRL) and within the lower Atchafalaya River. Minor channels and over-marsh flow were neglected. The Atchafalaya River portion of this model consisted of hydrographic surveys collected between 1910 and 1926 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 near Red River Landing, 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 (R_post) consisted of hydrographic surveys collected near the end of significant dredging in 1950. This model contained 11 reaches (Fig. 1e) with five bifurcations. The additional bifurcations relative to R_pre were due to the Whiskey Bay Pilot Channel, Bayou Chene Cutoff, and Wax Lake Outlet. Minor channel and over-marsh flows were neglected. Dredging from the Lake Fausse Pointe Cut and Atchafalaya Basin Main Channel altered existing transects. These 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 (at the junction of the Mississippi and Atchafalaya Rivers) to Morgan City, Louisiana (Fig. 1b,d; Latimer and Schweitzer, 1951). Such relationships were recorded in 1880 and then every few years from 1935-1950. The relationship from 1935 served as a pre-annexation validation, and the relationship from about 1950 served as the post-annexation comparison.

To isolate the effects of key changes within the basin, several synthetic hydrodynamic models were constructed that altered certain aspects of Model R_pre (Table 1). Model R_pre_A isolated the effect of channel widening in the Atchafalaya Basin by taking the R_pre model and exchanging the 1950 cross sections of the Upper Atchafalaya River where channel area had significantly increased. Model R_pre_D isolated the effect of dredging in the Atchafalaya River by exchanging bathymetric transects from R_pre with planned dredging cross sections (i.e. Fig. 3), including the newly dredged channels such as Whiskey Bay Pilot Channel (WBPC; Fig. 1e). Model R_pre_M isolated the influence of changes in the Mississippi River over the study period by taking the R_pre model and exchanging the 1949 Mississippi River hydrographic survey. Finally, Model R_pre_GL isolated the effect of sediment accumulation within Grand Lake by taking model R_pre and exchanging R_post transects only within the Deltas Region (Fig. 1).

## 3. Results

### 3.1 Validation

The R_pre hydrodynamic model was validated against (a) the measured discharge partitioning (five year average $f_A$ = 0.17; Fig. 2) and (b) measured stage-discharge curves. An upstream discharge of $Q_0$ = 18,300 $m^3/s$ was used throughout the validation and modeling process because it is the Mississippi River's average annual discharge between 1900 and 1960 (Latimer and Schweitzer, 1951). Preliminary simulations 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).

However, our focus on the recorded increase in average annual flows to the Atchafalaya River meant that we left detailed simulation of variable discharge through the system to future work.

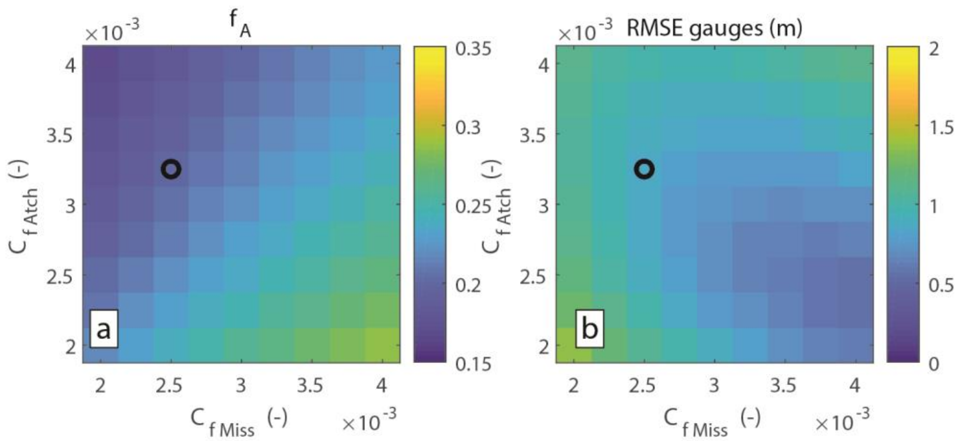


**Figure 4.** (a) modeled partitioning of flow before annexationand (b) root-mean-square error of the 7 stage-discharge gauges were used to determine an ideal combination of friction factor ($C_f$) in the Mississippi River (x axes) and Atchafalaya River (y axes). The black circles shows the friction factors that were chosen for modeling. Results shown for upstream discharge $Q_0$ = 18,300 m$^3$/s.

Model R_pre 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 $C_{f\_Miss}$. We chose $C_{f\_Atch}$ = 0.00325 and $C_{f\_Miss}$ = 0.0025 for this study, as it produced a reasonable value of $f_A$ (0.199) based on the field data, and a reasonably small value of RMSE (0.865 m), just 5% of the 18 m average flow depth. These values of $C_f$ are consistent with the direct measurement at Tarbert Landing, Mississippi River (Karim, 1995) and the prediction of the prevailing resistance relation (Engelund & Hansen, 1967). This is consistent with friction factors used to model the modern Mississippi river by Nittrouer et al. (2012; 0.003 - 0.007), and by Edmonds (2012; 0.0023).

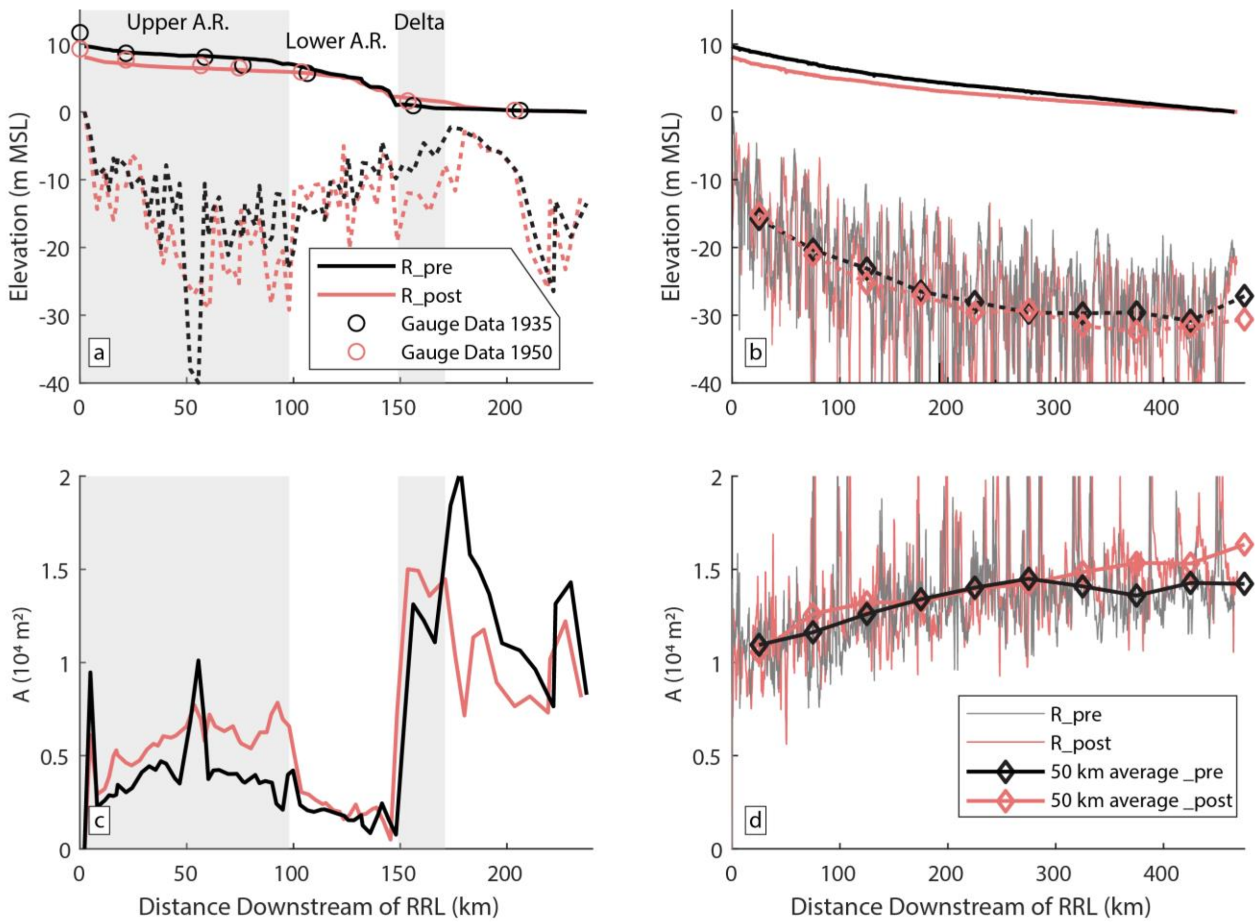


**Figure 5.** Results for models R_pre (black) and R_post (red) for upstream discharge $Q_0$ = 18,300 $m^3$/s, with $f_A$ = 0.199. Panels a (thalweg elevation dotted, and water surface solid) and c (cross-sectional area $A$) show the primary path through the Atchafalaya River network (see Fig. 1d,e). Panels b and d show the lower Mississippi River, with transect data and 50 km averages. In (a), circles indicate hydrograph elevation for the modeled $Q$ collected before (1935) and after (1950) significant discharge annexation.

Using these $C_f$ values, discharge partitioning ($f_A$) between the Mississippi and Atchafalaya Rivers was simulated for $Q_0$ = 18,300 $m^3$/s for each model of the Mississippi-Atchafalaya system. For models R_pre and R_post (the pre- and post-annexation models), $f_A$ was 0.199 and 0.278, respectively. These results compare well with data showing $f_A$ of 0.17 in 1926 and 0.29 in 1950. Model runs R_pre and R_post and measured stage-discharge relationships (Figure 5a, 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 $A$, 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 (Figure 5a, b). 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 (R_post) and data differ from their pre-annexation counterparts (R_pre) in terms of their water surface slopes in the upper Atchafalaya River (for the same $Q_0$, but 37% increase in $Q$ in the Atchafalaya River; Table 1). Hydrograph data show that the stage at Red River Landing dropped 2.4 m, consistent with the modeled 1.6 m drop. Relatedly, slopes in the upper Atchafalaya River (measured over 104 km between RRL and Atchafalaya, LA) dropped 30% in the hydrograph data and 15% between R_pre and R_post.

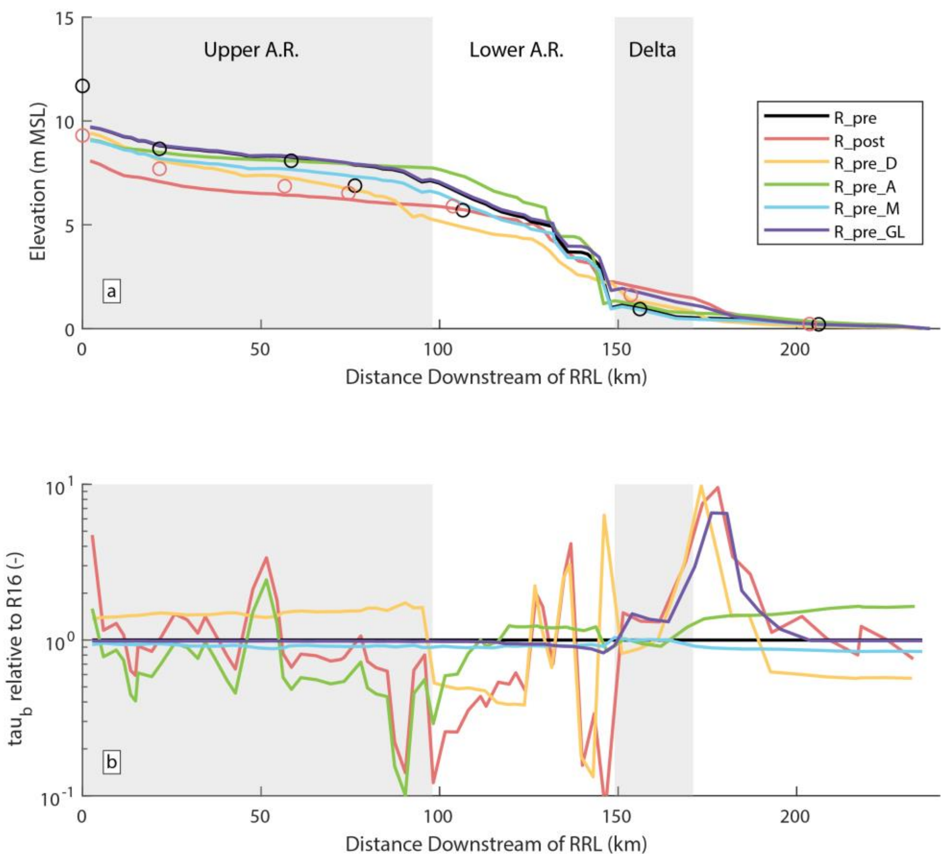


**Figure 6.** (a) Water surface profiles along the primary pathway through the Atchafalaya Basin (see Fig. 1) for all models (see Table 1). Black and red circles are water stages estimated from stage discharge measurements in 1935 (R_pre) and 1950 (R_post), respectively. (b) Fluid shear stress ($\tau_b = \rho C_f u^2$) along each transect divided by the shear stress from run R_pre. Note logarithmic y axis.

### 3.2 Partitioning Attribution

Synthetic channel networks of the Mississippi-Atchafalaya System (described in Section 2.2) were used to test how various changes during the period of discharge annexation influenced discharge partitioning (Figure 6, Table 1). Several important aspects of the simulations are considered here. First, model $f_A$ is compared to the results from R_pre and R_post ($f_A$ of 0.199 and 0.278 respectively) in order to assess the control on discharge partitioning. Second, the stage change at Red River Landing is compared to the simulated stages (9.7 m and 8.1 m respectively). Finally, the fluid shear stress ($\tau_b = \rho C_f u^2$) in the upper Atchafalaya River, a proxy for sediment transport and erosion potential, is analyzed relative to the R_pre baseline (Fig. 6b).

When the natural erosion of the Atchafalaya River was isolated (Model R_pre_A), $f_A$ increased to 0.257, or 73% of the required discharge increase from R_pre to R_post. The stage at RRL dropped to 9.1 m, explaining only 40% of the total stage drop. However, the average shear stress in the upper Atchafalaya River decreased, as increased cross-sectional area led to reduced water velocities.

The isolated effects of dredging (Model R_pre_D) produced a partitioning of $f_A$ = 0.227, explaining 35% of the modeled change between R_pre and R_post. The stage at RRL dropped to 9.4 m, only 19% of the total stage change there. Change was focused where dredging of new channels occurred in the lower Atchafalaya River (Figure 1, 6), but this led to increased water surface slopes and a 44% fluid shear stress increase in the upper Atchafalaya River.

The isolated effects of Mississippi River erosion (Model R_pre_M) showed $f_A$ = 0. 183, the only model that significantly reduced $f_A$ relative to R_pre. This is because minor increases to channel cross-sectional area of the Mississippi River (and no change in the Atchafalaya River in this synthetic model) acted to reduce slopes in the Mississippi River and stage at RRL to 9.0 m, thereby reducing discharge to the Atchafalaya River. The stage reduction was 44% of the total reduction in stage between R_pre and R_post. Fluid shear stress in the Atchafalaya River was minimally affected.

Despite the growth of significant lacustrine delta deposits between 1916 and 1950, the isolated effects of lacustrine deltas progradation (Model R_pre_GL) produced essentially the same discharge partitioning and RRL stage as R_pre. This suggests that they had little to no impact on the discharge partitioning at the Mississippi-Atchafalaya bifurcation.

**Table 1.** Hydrograph data and hydrodynamic model outputs for the Mississippi-Atchafalaya system. Models R_pre and R_post simulate the system before and after the discharge annexation between 1926 and 1950 (see Figure 2). Model R_pre_A isolates natural erosion in the upper Atchafalaya River, R_pre_D isolates the contribution dredging in the Atchafalaya Basin, Model R_pre_M isolates lower Mississippi River evolution, and Model R_pre_GL isolates deposition in Grand Lake.

| | **$f_A$ (-) ($Q_0$=18,300 m$^3$/s)** | **Upper A.R. Water Surface Slope (x10$^{-5}$)** | **Lower A.R. Water Surface Slope (x10$^{-5}$)** | **z at RRL (m MSL)** | **Fraction of $f_A$ change explained by model** | **Mean $\tau_b$, Upper A.R. (N/m$^2$)** |
|---|---|---|---|---|---|---|
| Data 1926 | 0.17 | 5.7 | 10.0 | 11.7 | N/A | |
| Data 1950 | 0.29 | 4.0 | 9.1 | 9.3 | N/A | |
| R_pre | 0.199 | 2.6 | 11.9 | 9.7 | N/A | 3.6 |

| | | | | | | |
|---|---|---|---|---|---|---|
| R_post | 0.278 | 2.2 | 7.2 | 8.1 | N/A | 2.9 |
| R_pre_A | 0.257 | 1.4 | 12.8 | 9.1 | 73% | 2.0 |
| R_pre_D | 0.227 | 4.1 | 6.0 | 9.4 | 35% | 5.2 |
| R_pre_M | 0.183 | 2.5 | 11.0 | 9.0 | -20% | 3.3 |
| R_pre_GL | 0.198 | 2.6 | 10.3 | 9.7 | -1% | 3.6 |

# 4 Discussion

## 4.1 Attribution to the Atchafalaya partial avulsion

The numerical model described here quantitatively reproduces the increase in the proportion of discharge down the Atchafalaya River over the period of discharge annexation (Figures 4, 5). The non-linearity of the hydrodynamic model prevents attribution from neatly summing to 100%, but analysis of synthetic models clearly shows that it can be attributed to several simultaneous processes. The increase in cross-sectional area of the Upper Atchafalaya River due to natural erosion (shown in R_pre_A) produced the largest increase in $f_A$ (Table 1). This is consistent with the original assessment of the Army Corps of Engineers (Fisk, 1952). However, previously unexamined factors also influenced the system, including dredging in the Atchafalaya River and erosion in the Mississippi River. The significant lacustrine delta deposition 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 42% of the 1.9 m 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 5) 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. 5d), they impacted $f_A$ by reducing water surface slopes in the Mississippi River, and therefore the stage at Red River Landing. Lower Mississippi River erosion during the period of discharge annexation by the Atchafalaya River 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, $f_A$ would likely have increased more rapidly.

There are remarkable differences in hydrodynamics for models isolating the natural erosion (R_pre_A) and dredging (R_pre_D) models of the Atchafalaya River (Fig. 6). When natural erosion is considered in the absence of dredging, discharge increases can only be accommodated by increased slopes in the lower Atchafalaya River (R_pre: $11.9 \times 10^{-5}$, R_pre_A $12.8 \times 10^{-5}$) which produce higher stages and lower slopes in the upper Atchafalaya River (Fig. 6a). In contrast, when dredging is considered in the absence of natural erosion (R_pre_D), reduced slopes in the lower Atchafalaya River are possible (R_pre_D: 6.0x$10^{-5}$), which lead to reduced stages and higher slopes in the upper Atchafalaya River.

The effects on fluid shear stress ($\tau_b = \rho C_f u^2$) in the upper Atchafalaya River are remarkable (Fig. 6b). Shear stress is reduced by 44% due to natural erosion (3.6 to 2.0 N/$m^2$; R_pre_A; Table 1) despite a 29% discharge increase down the Atchafalaya River ($Q_0$ = 18,300 $m^3$/s held constant). In contrast, the 14% discharge increase of R_pre_D increases shear stress by 44% (3.6 to 5.2 N/$m^2$). Hydrograph data offer a consistent story. Between 1932 and 1950 (dates of data collection), the water surface slope decreased 30% (5.7 x $10^{-5}$ to 4.0 x $10^{-5}$; Figure 6a) in the upper Atchafalaya River but decreased only 9% in the lower Atchafalaya. The erosion of the upper Atchafalaya River is presumably the result of heightened shear stresses, and the period of dredging (1932-1951) showed consistently large rates of cross-sectional area increase (Fig. 2b). Our results show that a negative feedback between cross-sectional area increase and shear stress in the upper Atchafalaya River could limit further erosion, but increased channelization in the lower Atchafalaya due to dredging could remove this feedback and potentially lead to greater erosion.

### 4.2 Limitations and Advantages

The model considered here were constructed in a manner so that they could be adequately run with the available historic data and allow several hypotheses to be tested. While the present study compares well with validation data and produces first order attribution, more complex models are necessary to include sediment transport, bed evolution, or the investigation of particular floods. 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.

### 4.3 Implications

This study facilitates a comparison between the historic discharge annexation of the Mississippi-Atchafalaya System to current understanding of general avulsion controls. The super-elevation of the Mississippi River at Red River Landing was small, although consistent with prevailing models. Water surface elevation peaked at 16 m MSL during large floods prior to annexation, and was 9 m MSL for average flows (Fig. 5b,d). Compared to the minimum channel bed elevation (-11 m MSL) and minimum floodplain elevation in the region (8 m MSL; Aslan et al. 2005), the fraction of flow depth above the flood plain (the superelevation ratio) was 0.05 - 0.3. This value is consistent with the superelevation ratios estimated for the avulsion that produced Bayou Lafourche (~0.1; Törnqvist & Bridge, 2002) and laboratory experiments (0.3; Ganti et al., 2016).

We also find it remarkable that the lower Mississippi River was slightly erosional (Figure 5d) during the pivotal 24 year period of discharge increase (Figure 2). This contrasts with prevailing models which expect deposition in the main channel before and during avulsion to drive the flow reorganization into the new channel (Ganti et al., 2016). Rather than the “choking” of 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), the dredging at Old River between 1878 and 1937 (Mossa, 2013), and the dredging of the Atchafalaya River between 1932 and 1951 (R_pre_D) may have assisted the natural erosion observed in the upper Atchafalaya River.

Analyses of backwater flow (eq. 3) with smoothly varying bed topography show that channel bed erosion or deposition results in changes to the flow field that propagate upstream. Such changes decay asymptotically and scale with the backwater length scale (Chadwick et al., 2019; Ribberink & Van Der Sande, 1985); roughly 500 km in the case of the Mississippi Delta (Chatanantavet et al., 2012). The stage reduction at RRL due to erosion in the Mississippi River up to 300 km downstream is an example of this (Figure 5b). However, the growth of lacustrine deltas in Grand Lake just 148-180 km downstream of Red River Landing did not factor into discharge partitioning or stage change there. While these deltas did act to reduce channel cross sectional area and increase stage in R_pre_GL by 0.8 m relative to R_pre within the delta area (Figure 6a), the water surfaces of the R_pre and R_pre_GL collapsed on one another in the lower Atchafalaya River and were similar at all points above. The steep water surface slopes (locally $-6.3 \times 10^{-4}$) associated with the M2 curve in the lower Atchafalaya River overwhelmed gradual trends stemming from non-uniform backwater flow.

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 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 natural erosion of the upper Atchafalaya River, affect the hydrodynamics at a bifurcation more significantly. Second, small changes to the largest channels of the system can significantly affect the smaller channels in the network. The 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 relatively small channels, steep water surface slopes, and naturally produce an M2 curve under non-flood discharges - can act as a “choke point” in the system. Increased connectivity caused by dredging 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.

## 5 Conclusions

We present evidence that the rapid increase in water discharge into the Atchafalaya River between 1926 and 1950 can be attributed to three important natural and human-influenced changes to the Mississippi-Atchafalaya system over that period. First, the relatively consistent natural erosion 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). Second, significant channel dredging in the lower Atchafalaya River further increased partitioning by increasing connectivity through a steep reach, potentially increasing shear stresses in the eroding channel upstream. Third, the subtle erosion of the lower Mississippi River acted to reduce stage at Red River Landing, and reduce partitioning to the Atchafalaya River. Finally, 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 in attribution and delta management.

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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 (-) |
| *CSA* | Bankfull cross-sectional area of transects, measured by USACE ($L^2$) |
| $E$ | 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 ($L/T^2$) |
| $\Gamma$ | Wetted perimeter at a cross section; $A$ divided by the wetted surface width (L) |
| $\eta$ | 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 ($-\partial\eta/\partial x$; -) |
| $S_f$ | Frictional slope (-) |
| $t$ | Time (T) |
| $u$ | Water velocity, averaged across $A$ (L/T) |
| $x$ | Downstream coordinate (L) |
| $z$ | Water surface elevation (L relative to mean sea level; MSL) |

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