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Stability of backwater-influenced river bifurcations: A study of the Mississippi-Atchafalaya system

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[1] In this paper I use numerical modeling to show that the hydraulic backwater profile creates a feedback that may stabilize river bifurcations. The numerical model simulates flow and sediment transport in the Mississippi-Atchafalaya River system without the Old River Control Structure. The results show that bifurcation evolution strongly depends on the discharge upstream of the bifurcation. At upstream discharges greater than 12600 m^3 s^{-1} the Atchafalaya River discharge increases through time at the expense of the Mississippi River. Interestingly, at upstream discharges lower than 12600 m^3 s^{-1} the opposite occurs and the Mississippi River discharge increases at the expense of the Atchafalaya River. The capture direction changes because the backwater profile of each river varies enough at high and low discharge to invert the water surface slope ratio. These results suggest that the capture direction would change at high and low flow, which would have a stabilizing effect by preventing the runaway growth of one channel. Accounting for this, I calculate that in the absence of the Old River Control Structure capture would not happen catastrophically, but rather the Atchafalaya River would capture the Mississippi River in ∼300 years from present day. **Citation:** Edmonds, D. A. (2012), Stability of backwater-influenced river bifurcations: A study of the Mississippi-Atchafalaya system, *Geophys. Res. Lett.*, *39*, L08402, doi:10.1029/2012GL051125.

1. Introduction

[2] Delta distributary networks provide homes to ∼½ billion people [*Syvitski and Saito*, 2007], and are some of the most biologically rich parts of the coastline [*Day et al.*, 2007]. These valuable distributary networks owe their existence to channel bifurcations. Bifurcations dictate network evolution because they can be stable (both channels receive water) or unstable (one channel receives water) [*Wright*, 1977; *van Heerden and Roberts*, 1988; *DuMars*, 2002; *Olariu and Bhattacharya*, 2006; *Edmonds and Slingerland*, 2007], where an unstable bifurcation is also an avulsion.

[3] The processes of channel avulsion [*Edmonds et al.*, 2009; *Hoyal and Sheets*, 2009] and channel splitting around depositional elements, such as river mouth bars [*Wright*, 1977; *van Heerden and Roberts*, 1988; *Edmonds and Slingerland*, 2007], create bifurcations with downstream bifurcate channels of different characteristic length scales [*Jerolmack and Swenson*, 2007; *Jerolmack*, 2009]. Channel splitting around river mouth bars originates at the shoreline and creates small-scale channels with lengths of ∼10 *W*, where *W* is the channel width [*Edmonds and Slingerland*, 2007]. Deltaic avulsions usually occur farther upstream and create bifurcate channels with lengths of ∼100 *W* [*Jerolmack and Swenson*, 2007]. These channels are longer because their length is set by the avulsion location that scales with the backwater profile length [*Jerolmack and Swenson*, 2007; *Chatanantavet et al.*, 2012]. A backwater profile is typically concave up and created as the water surface elevation in a river adjusts to a static elevation at the downstream boundary [*Henderson*, 1966].

[4] Most previous work has focused on the stability of bifurcations with bifurcate channels shorter than the backwater length-scale, where normal flow is a reasonable approach [e.g., *Bolla Pittaluga et al.*, 2003; *Miori et al.*, 2006]. In these cases, stable river bifurcations are usually asymmetric in width and depth and the degree of asymmetry depends on the relative widths of the bifurcate channels [*Bolla Pittaluga et al.*, 2003; *Miori et al.*, 2006], the relative water surface slopes [*Bolla Pittaluga et al.*, 2003; *Edmonds et al.*, 2010], and the upstream flow conditions [*Bolla Pittaluga et al.*, 2003; *Edmonds and Slingerland*, 2008].

[5] Understanding bifurcation stability for bifurcate channels longer than the backwater length-scale is lacking and it is not clear if stability criteria for these bifurcations are similar to bifurcations with shorter channels. The few studies that include backwater flow into bifurcation stability models have shown that the duration, or capture timescale, for backwater-influenced bifurcations varies from a few decades to multiple millennia [*Stouthamer and Berendsen*, 2001; *Kleinhans et al.*, 2008, 2011]. But it is not clear why, and previous theoretical studies cannot be easily adapted for backwater-influenced bifurcate channels, which have non-linear water surface slopes that change with discharge.

[6] In this paper I look at how backwater dynamics affect the stability of the Mississippi-Atchafalaya bifurcation. The Mississippi-Atchafalaya bifurcation is an obvious place to start because backwater dynamics shape the system [*Nittrouer et al.*, 2011b; *Lamb et al.*, 2012; *Nittrouer et al.*, 2012], and the issue of predicting bifurcation stability is important. In the early 20th century the bifurcation was unstable and many assumed the Atchafalaya River would capture all the Mississippi River's discharge [e.g., *McPhee*, 1989]. This assumption was based on two observations; the Atchafalaya River is a more attractive path because it has a steeper floodplain slope [*Aslan et al.*, 2005; *Wellner et al.*, 2005] (Figure 1a) and the Atchafalaya had gradually captured discharge from the Mississippi River since 1900 [*Wells et al.*, 1982; *Mossa*, 1996]. The Army Corps of Engineers

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Figure 1. (a) Outline map of Louisiana showing location of Mississippi and Atchafalaya rivers and the computational grid used in this study. The f.p. slope is the floodplain slope. Thick blue line in Figure 1a corresponds to model domain. (b–d) Examples of the numerical grid. Locations of images in Figures 1b–1d are marked in Figure 1a.

built the Old River Control Structure (ORCS) to control the flow going into each river and prevent capture.

[7] Interestingly, the capture hypothesis has never been tested. In this paper I use a numerical model to explore how the system would evolve without ORCS and how backwater dynamics influence bifurcation stability.

2. Methods

[8] The model of the Mississippi-Atchafalaya bifurcation was computed in Delft3D (version 3.28) using the depth-averaged shallow water equations. The computational domain begins ~45 km upstream of ORCS and ends where each river enters the Gulf of Mexico (Figure 1a). The grid is 2D in planform and follows the banks of each river (Figures 1b–1d). The computational grid consists of ~20,000 cells, which have a typical cell size of 100 m × 900 m, with the long axis oriented downstream. There are 10 cells across the Mississippi River and 20 cells across the Atchafalaya River. Sensitivity tests show that fewer cells across the Mississippi River do not affect flow division at the bifurcation. The river planform around the ORCS is complex; to honor this, the entire area was gridded and the floodplains cells were set as 'dry' in the simulations (Figure 1b). The model setup does not include tributaries, floodplains, or dynamic channel width adjustment. Exclusion of floodplains is justifiable since the man-made levees keep water in the channel at the highest floods. The largest tributary in the domain is the Red River, and model tests show that when the average Red River discharge is added to the Atchafalaya it has little impact on the results. In each run the bed and width adjust, but the channels cannot widen beyond the initial width of the channel.

[9] Seven model runs were conducted with different steady values for the discharge upstream of ORCS ranging from 5000 m^3 s^{-1} to 50,000 m^3 s^{-1}. In all runs bed roughness is a uniform Chezy value of 65 $m^{1/2}$ s^{-1}. A time step of 60 seconds was used. Bed adjustments were sped up by multiplying the bed sediment flux in each time step by a morphological scale factor set to 50. This is within the stable range [*Ranasinghe et al.*, 2011] and was verified with sensitivity tests.

[10] At the upstream boundary I specify the water discharge and sediment fluxes. The incoming discharge carries two grain sizes, one noncohesive (200 μm) and one cohesive (15 μm). At the downstream boundaries water surface elevations are set to zero. The initial bed topography in each river is from 2004 and 2006 hydrographic surveys of the Mississippi and Atchafalaya, respectively. For each river I calculated the cross-sectionally averaged centerline bed elevations every kilometer. In the subsurface there is initially 10 m of sand and 2 m of mud available for erosion, consistent with observations [*Galler and Allison*, 2008; *Nittrouer et al.*, 2011a].

[11] This model setup accurately predicts the water surface elevations in the Mississippi River to within 10–15% at different flow stages [*Nittrouer et al.*, 2011b], corroborating these boundary condition choices. To assess the sensitivity of the results I conducted repeat experiments and varied the time step, bed roughness, the grid resolution, sediment transport formulas, sediment size, and initial volume sediment in the subsurface. Varying each of these leads to a

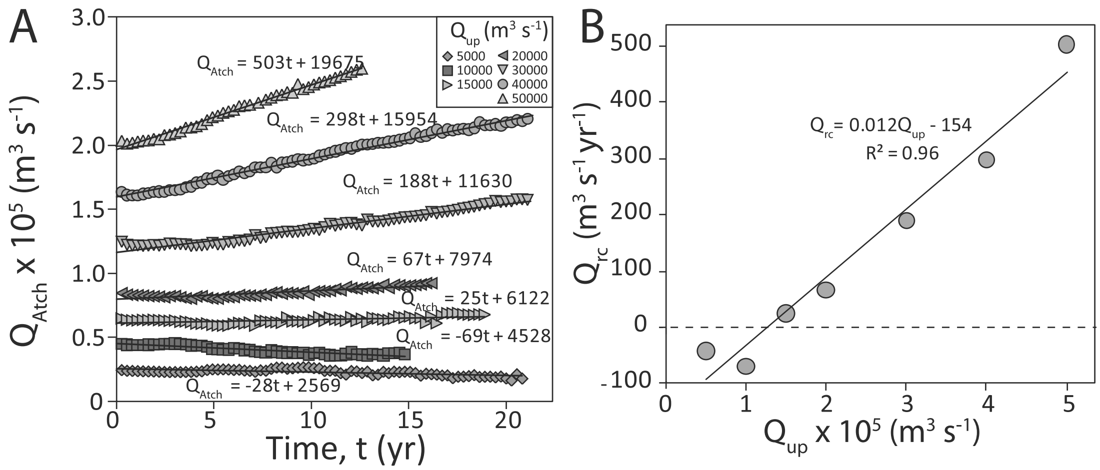

Figure 2. (a) Model simulations showing how discharge in the Atchafalaya River (Q_{Atch}) would evolve, in the absence of ORCS, for different steady discharges upstream of the bifurcation (Q_{up}). Discharges are reported every two days for the simulations and the bed is loosened on the second reported discharge. Two-day model spin up time not shown. (b) Relationship between capture rate (Q_{rc}) by the Atchafalaya and Q_{up}. Q_{rc} values are the slopes from the best-fit lines in Figure 2a. Negative and positive rates indicate flow into the Mississippi and Atchafalaya Rivers, respectively.

different solution in the details, but the behavior of the discharge ratio between the rivers is not different by more than 15%.

3. Results

[12] Presently, ORCS regulates the discharge ratio of the Mississippi to the Atchafalaya River to 2.33:1. But without ORCS, the model predicts a discharge ratio (prior to the bed adjusting to the flow field) that ranges from 1:1 to 1.5:1 depending on the upstream discharge (y-intercept in Figure 2a). When the bed starts to adjust, there is erosion and deposition in each river, especially near ORCS. This occurs as the rivers adjust to a different discharge distribution than has historically flowed through the bifurcation.

[13] Soon after the initial bed changes, one river begins capturing discharge suggesting the bifurcation is unstable. The river that captures discharge changes with the discharge upstream of ORCS (Q_{up}) (Figure 2a). At any $Q_{up} > 12600$ m^3 s^{-1} the discharge in the Atchafalaya River (Q_{Atch}) increases through time (Figure 2a) at the expense of discharge in the Mississippi River (Q_{miss}). Whereas when $Q_{up} < 12600$ m^3 s^{-1} Q_{Miss} increases at the expense of Q_{Atch}.

[14] The rate of change of Q_{Atch} also depends on Q_{up} (Figure 2a) and the slope of each time series describes the rate of discharge capture per year (Q_{rc}). A positive slope signals net flow capture by the Atchafalaya and a negative slope signals net flow capture by the Mississippi (Figure 2a). Q_{rc} increases linearly with Q_{up} and when Q_{up} is $\sim$12600 m^3 s^{-1} then Q_{rc} is zero and the bifurcation would persist in a stable configuration (Figure 2b).

4. Backwater Effects on Bifurcation Stability

[15] It seems counterintuitive that the Mississippi River could capture flow from the Atchafalaya River. After all, the Atchafalaya River is half the length of the Mississippi River (Figure 1a), and therefore if the downstream slopes are linear it would be twice as steep as the Mississippi. But, the water surface slopes are actually non-linear, which explains how the capture direction changes. For example, when Q_{up} is 10000 m^3 s^{-1} the concavity of the backwater profile in the Mississippi River extends upstream $\sim$475 km (Figure 3a) from the delta consistent with observations [*Nittrouer et al.*, 2011b]. The concavity near the bifurcation creates steeper water surface slopes in the Mississippi by up to 20% (Figure 3b) for $\sim$150 km downstream of the bifurcation. When Q_{up} is 30000 m^3 s^{-1}, the concavity of the Mississippi River's backwater profile is reduced (Figure 3a). At this point, the Atchafalaya has a steeper water surface slope and captures discharge from the Mississippi (Figure 3b).

[16] The above argument assumes that slope divergence for $\sim$150 km downstream drives flow at the bifurcation. A competing hypothesis might be that local slope divergences control flow at the bifurcation. This is unlikely because the water surface slope ratio for 20 km downstream of ORCS is nearly unity (Figure 3b) but the flow division is not (Figure 2a). This suggests that the slope divergences far downstream from the bifurcation influence flow division.

[17] Stage elevation data from gauges on each river confirm the model prediction that the slope ratio changes with Q_{up}. If the bifurcation divided flow according to model predictions when Q_{up} = 10000 m^3 s^{-1} (Q_{Atch} = 4500 and Q_{Miss} = 5500 m^3 s^{-1} (y-intercept in Figure 2a)), then stage gauge data predict that the Mississippi River would have a steeper slope (Figure 3b). When Q_{up} is 30000 m^3 s^{-1} (Q_{Atch} = 11500 and Q_{Miss} = 18500 m^3 s^{-1} (y-intercept in Figure 2a)), the stage gauge data show that the Atchafalaya would have a steeper slope (Figure 3b). The change in slope ratio with upstream discharge does not occur currently between the rivers because the flow division at the bifurcation is regulated by ORCS.

5. Capture Timescale for the Mississippi-Atchafalaya System

[18] With these results one can predict the capture timescale for the bifurcation in the absence of ORCS. For a steady upstream discharge (as in Figure 2) the discharge in one channel grows monotonically. But in an unsteady flow the

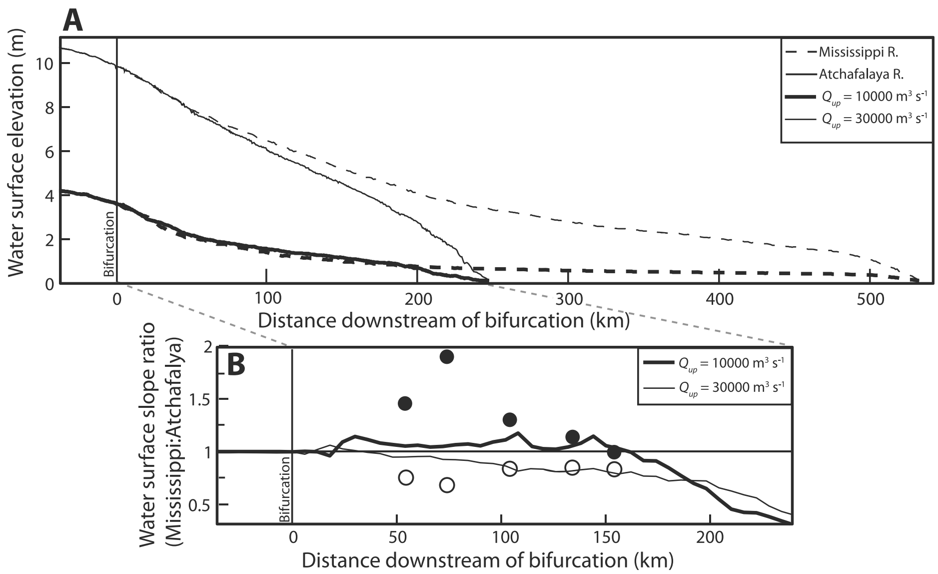

Figure 3. Model results of (a) cross-stream averaged water surface elevation profiles for the Mississippi and Atchafalaya rivers and (b) ratio of Mississippi to Atchafalaya water surface slopes averaged over 15 km bins. Open (Q_{up} = 30000 m^3 s^{-1}) and closed (Q_{up} = 10000 m^3 s^{-1}) circles refer to water surface slope ratios calculated from stage gauge data from U.S. Army Corps of Engineers. To determine the stage elevations for a given discharge, I fit a polynomial to discharge of the Mississippi and Atchafalaya Rivers (measured at Tarbert Landing, LA and Simmesport, LA, respectively) against stage elevation at five different locations for each river. All model results shown are from the beginning of the run.

growth will be non-monotonic since the capture direction changes with Q_{up} (Figure 2). The change in discharge of the Atchafalaya River, dQ_{Atch}, is calculated by integrating Q_{rc} over some duration (T) by $dQ_{Atch} = \int_0^T Q_{rc} dt$ where dt is a time step in years. Q_{rc} can be positive or negative depending on Q_{up} (Figure 2b), and $Q_{rc} = 0.012Q_{up} - 154$ and $Q_{up} = f(t)$. This assumes that Q_{rc} is constant with time and depends only on Q_{up}. On short timescales (days to weeks) these assumptions break down as events like bank slumps might affect Q_{rc}. Over longer timescales (months to years) the bed topography will adjust to the flow and these assumptions are more reasonable.

[19] To solve for how dQ_{Atch} would evolve in the absence of ORCS requires knowing Q_{up}. I take Q_{up} as the monthly-averaged discharge of the Mississippi River at Vicksburg, MS (USGS gauge 07289000) measured from 1932 to 1982. Over these 50 years the discharge at Vicksburg, MS is usually above 12600 m^3 s^{-1} resulting in a positive dQ_{Atch} of $\sim$2500 m^3 s^{-1}, or an average rate of increase of $\sim$50 m^3 s^{-1} every year. Projecting this average rate forward, it would take $\sim$300 years (+/−15%, based on sensitivity tests described earlier) for the Atchafalaya River to capture enough flow that lower Mississippi River would be dry at present day average discharge of $\sim$15000 m^3 s^{-1}[*Nittrouer et al.*, 2011a]. This estimation could be improved by accounting for channel widening and the deceleration of capture rate as capture becomes complete [e.g., *Kleinhans et al.*, 2008].

[20] These results suggest that flow unsteadiness may play a key role in creating stable bifurcations. For instance, if the hydrograph fluctuates evenly around the discharge corresponding to Q_{rc} = 0 (Figure 2b) then the bifurcation would be in dynamic steady state. Even if a bifurcation was unstable, the changing capture direction would prolong the capture timescale, which could explain some of the variability in observed capture timescale [e.g., *Stouthamer and Berendsen*, 2001].

6. Conclusions

[21] Morphodynamic modeling of coastal rivers shows that backwater dynamics can substantially affect bifurcation stability. For the case of the Mississippi-Atchafalaya bifurcation, at upstream discharges less than 12600 m^3 s^{-1}, the Mississippi River captures discharge from the Atchafalaya River because the water surface slope in the Mississippi River is steeper due to the backwater dynamics in each river. At upstream discharges greater than 12600 m^3 s^{-1} the Atchafalaya River has a steeper water surface slope and captures discharge from the Mississippi. This suggests that the capture direction reverses at high and low discharge, which would stabilize the bifurcation by preventing the runaway growth of one channel. In fact, if the Old River Control Structure did not exist it would take $\sim$300 years from today for the Atchafalaya River to capture the Mississippi River. Future work includes understanding how applicable this feedback is to other river systems.

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