

Scaling relationships and evolution of distributary networks on wave-influenced deltas

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[1] No genetic model can explain the variability in distributary network pattern on modern deltas. Here we derive scaling relationships for two processes known to create distributary channels and, with these laws, construct a simple model for distributary network evolution. The first process is mouth-bar deposition at the shoreline and subsequent channel bifurcation; the second is avulsion—the wholesale abandonment of a channel in favor of a new path. The former creates relatively small networks with power-law distributions of channel length; the latter generates relatively few, backwater-scale distributaries. Frequency-magnitude plots of channel length on natural deltas agree with theoretical predictions and show a clear separation in scale that reflects these processes: Mouth-bar distributary lengths scale with the width of the parent channel, and avulsive distributary lengths scale with the backwater length; intermediate channel lengths are relatively rare. Wave energy controls network topology by suppressing mouth-bar development, thereby preferentially eliminating smaller-scale distributaries. **Citation:** Jerolmack, D. J., and J. B. Swenson (2007), Scaling relationships and evolution of distributary networks on wave-influenced deltas, *Geophys. Res. Lett.*, 34, L23402, doi:10.1029/2007GL031823.

1. Introduction

[2] With fertile floodplains and proximity to coastal resources, deltas are home to more than a quarter of the human population; as the basic building blocks of sedimentary basins, deltaic strata are sensitive recorders of the interplay between climate and tectonics [Galloway, 1975; Syvitski, 2005; Kim *et al.*, 2006]. There is a considerable literature on the overall morphology of deltas, especially in regard to the classic triad of river-, wave-, or tide-dominance [Galloway, 1975; Wright and Coleman, 1972]. The existence of a distributary network on the delta surface, however, is often taken for granted. A cursory inspection of modern deltas (Figure 1) reveals significant variability in the distributary network, from multi-generational, branching networks, e.g. Wax Lake, to only a few large-scale distributaries, e.g. the Nile. Relatively few studies have addressed quantitatively the morphodynamics of distributary networks or the interaction of networks with shoreline dynamics, and little is known about the temporal and spatial scales of processes that evolve distributary networks [Wright and Coleman,

1972; Sun *et al.*, 2002; Syvitski, 2005; Syvitski *et al.*, 2005a; Swenson, 2005a; Parker *et al.*, 2006; Edmonds and Slingerland, 2007]. This lack of understanding hinders our ability to predict and mitigate the response of distributary networks—and the communities they support—to rising sea level and anthropogenic modification of sediment supply that, together, affect nearly all modern deltas [González and Törnqvist, 2006; Syvitski *et al.*, 2005b; Yang *et al.*, 2007]. Here we construct scaling laws for processes known to create distributary channels and, using these laws, develop a model for distributary network evolution; we then test model predictions with channel statistics we obtained for a representative set of modern deltas. To limit the scope of our analysis, we do not consider deltas with strong tidal influence.

2. Scaling Relationships

[3] Existing models of distributary growth focus on the deposition of mouth bars due to divergent flow [Bates, 1953; Wright, 1977; Wang, 1984]. Common to these models is a sediment laden jet expanding from the downstream tip of a channel and depositing a bar a distance (L_D) basinward (Figure 2a). The length of a distributary formed by mouth-bar deposition thus scales like L_D . Progradation of channel levees forces further divergence of flow around the bar and eventually leads to channel bifurcation. Recent three-dimensional modeling of coupled fluid and sediment dynamics by Edmonds and Slingerland [2007] established that L_D depends primarily on channel width B upstream of the bifurcation. We generalize the scaling form to $L_D = \alpha B$, where α is a dimensionless parameter of order ten, i.e. α is $\mathcal{O}(10)$. Repeated mouth-bar deposition and bifurcation leads to advance of the shoreline and the development of a fractal distributary network with a consistent increase in the number of channels and decrease in channel width and depth with distance from the delta apex (Figure 2b) [Olairu and Bhattacharya, 2006; Edmonds and Slingerland, 2007]. We compute a timescale of distributary formation by this process, T_D , from the ratio of distributary length scale (L_D) to progradation rate, v_p . For a delta system unaffected by waves, v_p scales like $Q_s/(BD)$, where Q_s is sediment supply and D is nearshore water depth [Swenson, 2005a]. We thus have $T_D = L_D/v_p \sim \alpha B^2 D/Q_s$. Sediment supply to deltas varies by orders of magnitude; channels widths are less variable [Burgess and Hovius, 1998; Syvitski *et al.*, 2005a; Edmonds and Slingerland, 2007]. Representative values of $Q_s \sim 10^4 \text{ m}^3 \text{ yr}^{-1}$, $B \sim 100 \text{ m}$, and $D \sim 5 \text{ m}$ give $T_D \sim 50 \text{ years}$, which agrees with the decadal to century timescales for bifurcation commonly observed in natural systems [Edmonds and Slingerland, 2007, and references therein]. An important point is that this process of

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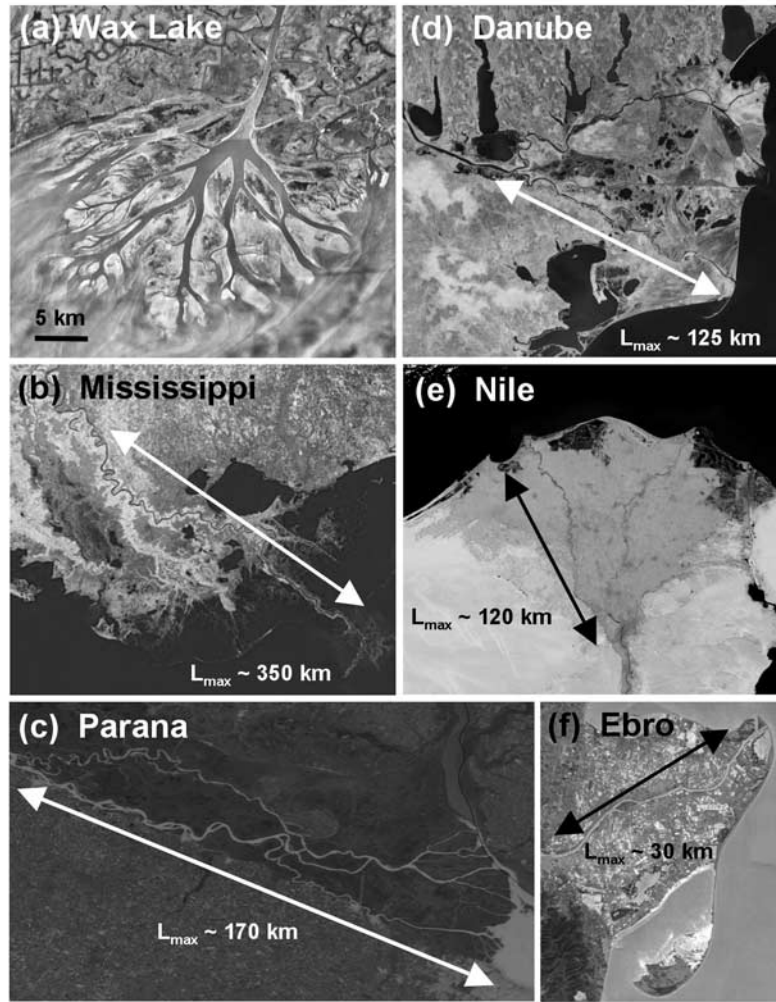


Figure 1. Satellite images of delta distributary networks. Deltas in left column are fluvial-dominated, while deltas on the right have varying degrees of wave influence (as quantified by *Wright and Coleman* [1972]). In panels (b) – (f), arrow of length L_{\max} provides scale, where L_{\max} is the backwater length computed from published data [*Mikhailova*, 2003; *Abdel-Fattah et al.*, 2004; *Jerolmack and Mohrig*, 2007]. Satellite images from NASA Visible Earth.

distributary formation is generated by a fluid-mechanical instability at the shoreline and is fueled by local progradation of the delta front.

[5] If mouth-bar-driven bifurcation were the only process that created channels, then at first order distributary networks would be quasi-fractal and scale with the size of the river, where we use channel width as a measure of river

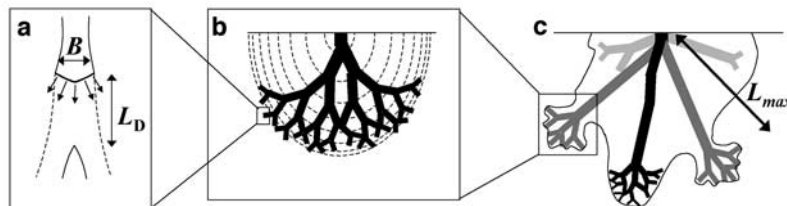


Figure 2. Cartoon illustrating unit processes of distributary formation. (a) Expansion of a turbulent jet creates a mouth bar at a distance, L_D , downstream of a channel tip on a timescale T_D . (b) On timescales smaller than the avulsive timescale (T_A), i.e. for $t < T_A$, successive progradation of leveed channels and bifurcation due to mouth-bar deposition creates a branching (fractal) distributary network. Dashed concentric curves are isochrons indicating the quasi-radial shoreline position at successive time intervals. (c) On longer timescales, $t \gg T_A$, aggradation leads to avulsion and the abandonment of the old channel network (dark gray) and creation of a large-scale avulsive distributary. Each avulsive distributary spawns a new fractal distributary network at its tip. Abandoned channels on the delta plain are erased by overbank sedimentation and wave reworking (light gray) due to relative sea-level rise.

size. While such a relationship describes some deltas, e.g. Wax Lake and Yukon Deltas [Edmonds and Slingerland, 2007], it is inconsistent with the topology of many networks. Notably, the above scaling relationship cannot explain the large distributaries on many deltas, e.g. the pair of ~ 100 -km distributaries on the Nile (Figure 1e) requires a parent channel with $B \sim 10$ km, which is an order of magnitude greater than observed. An additional, larger-scale process must be operative. Aggradation can interrupt the succession of mouth-bar bifurcations through avulsion—the abandonment of a channel in favor of a new path at a lower elevation—which arises from a gravitational instability between a superelevated channel and its floodplain [Heller and Paola, 1996]. While a detailed understanding of the process remains elusive [Törnqvist and Bridge, 2002; Slingerland and Smith, 2004], recent work suggests that channels avulse when they aggrade to an elevation of approximately one channel-depth (h) above the surrounding floodplain [Mohrig et al., 2000]. A characteristic avulsion timescale, $T_A = h/v_A$, where v_A is aggradation rate, compares well to measured residence times (centuries to millennia) for natural channels [Jerolmack and Mohrig, 2007]. Aggradation generally accompanies delta progradation, as channel lengthening requires some aggradation to maintain a transport slope; on long timescales, the aggradation rate is set by the rate of rise in relative sea level [Heller and Paola, 1996; Swenson, 2005b]. Hence, we expect avulsion to be important on larger or older deltas that have experienced significant aggradation. For a typical channel depth of a few meters and an aggradation rate of 1 mm yr^{-1} , T_A is $\mathcal{O}(10^3 \text{ yr})$; this value is consistent with field data [Törnqvist, 1994; Törnqvist et al., 1996; Stouthamer and Berendsen, 2001] and, importantly, is orders of magnitude larger than the timescale of mouth-bar-driven bifurcation (T_D).

[6] The characteristic length scale of an avulsive distributary is difficult to derive, because, in principle, avulsions create channels at a variety of scales. However, at the most basic level, deltas arise from the interaction of rivers with bodies of water. The “backwater” length characterizes this interaction, and thus we expect the maximum length of a channel created by avulsion (L_{\max}) to scale like $L_{\max} \sim h/S$, where S is the channel gradient upstream of the delta. The key point is that L_{\max} likely will exceed significantly the length scale for distributaries formed by mouth-bar-driven bifurcation (L_D)—a not surprising relationship, given that $T_D \ll T_A$. Note that the process of avulsion can act anywhere on the delta surface, whereas mouth-bar bifurcation is restricted to the shoreline.

3. Model of Distributary Network Evolution

[7] Both mouth-bar-driven bifurcation and avulsion are known to operate on deltas. What is not well known is how these fundamentally different processes work independently or in tandem—and on what spatiotemporal scales—to evolve distributary networks. On the basis of our derived scaling laws, we propose a general model for evolution of a distributary network on a delta growing under conditions of steady sediment supply, relative sea-level rise, and low wave energy. (We relax the condition on wave energy below.) When the delta is relatively young, i.e. for $t < T_A$, progradation dominates and repeated mouth-bar bifurca-

tions at the shoreline create smaller and more numerous channels, forming a fractal distributary tree that disperses flow relatively uniformly over the delta and produces radial shoreline progradation (Figure 2b). This process is a reasonable explanation for the Wax Lake Delta (Figure 1a). With continued growth of the delta, i.e. for $t > T_A$, aggradation generates superelevated channels susceptible to avulsion. Avulsion results in a dramatic redistribution of water and sediment, as the newly created distributary channel bypasses the fractal network to find a shorter route to the sea. Importantly, avulsion breaks the scale invariance of the fractal tree (Figure 2c), producing rapid progradation and deposition in one part of the delta, at the expense of flooding and sedimentation elsewhere due to relative sea level rise. The newly formed, avulsive distributary then evolves a fractal network at its tip via mouth-bar-driven bifurcation and, in doing so, creates what is known as a delta lobe. Such lobe construction is well documented on the Mississippi Delta [Törnqvist et al., 1996]. We expect a “mature” delta ($t \gg T_A$) to have one or more distributary channels formed by avulsion.

[8] Wave-driven nearshore sediment transport alters the shoreline morphology of deltas [Wright and Coleman, 1972; Galloway, 1975; Wright, 1977; Syvitski, 2005; Bhattacharya and Giosan, 2003]. In general, waves smooth shoreline roughness on a timescale $T_w \sim L^2/\kappa$, where L is a length scale (roughness) and diffusivity (κ) increases nonlinearly with wave height [e.g., Komar and Inman, 1970]. The diffusive nature of waves is readily apparent in the shoreline morphology of the Nile, Ebro, and Danube deltas (Figure 1). But how do waves affect the distributary network landward of the shoreline? Diffusion acts preferentially on small length scales, so waves should affect primarily mouth-bar formation. If T_w is small compared to T_D , then waves can effectively rework mouth bars and suppress bifurcation at channel tips. In this way, wave energy determines the lower limit of channel scale. To quantify this phenomenon, we assume that shoreline roughness scales with L_D (length scale of channels created by mouth-bar driven bifurcation) and define relative wave effectiveness, Ω , as the ratio of mouth-bar and wave timescales:

$$\Omega = \frac{T_D}{T_w} = \frac{\kappa}{v_p L_D} \sim \frac{\kappa B_o D}{Q_s L_D} \quad (1)$$

where B_o is the width of the zero-order (parent) channel. When Ω is $\mathcal{O}(1)$, mouth-bar and wave timescales are comparable and equation (1) gives a “wave footprint,” $L_{Dmin} \sim \kappa/v_p$, below which wave smearing prevents channel formation. This footprint can be measured directly from images and provides an alternative means of quantifying the relative importance of wave and fluvial processes; in addition, if Q_s , D , and B_o (or simply v_p) can be measured, then the wave footprint allows estimation of diffusivity ($\kappa \sim L_{Dmin} \cdot v_p$), a morphodynamic parameter that is notoriously difficult to constrain [Cooper and Pilkey, 2004].

4. Test of Model and Discussion

[9] Our model makes two testable predictions about the length scales of distributary channels. First, the distribution of channel length should show a separation in scale:

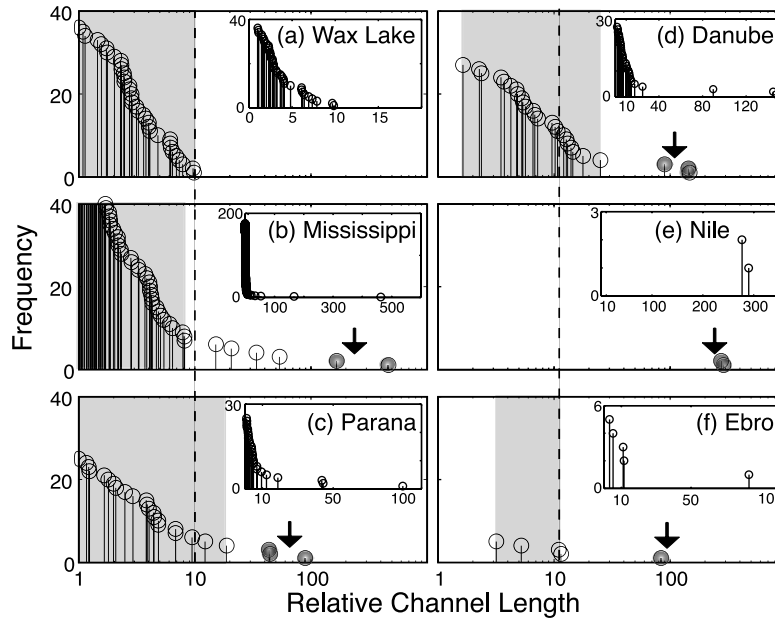


Figure 3. Distributions of relative channel length shown as (cumulative) frequency-magnitude plots for the deltas of Figure 1. Channel lengths are normalized by the width of the zero-order (parent) channel. The dashed vertical lines represent our theoretical predictions for the maximum scale of channels formed via mouth-bar-driven bifurcation; arrows denote the maximum avulsive channel length we predict from backwater calculations. Based on our mapping of network topologies, the shaded boxes highlight channels that we infer to have formed via mouth-bar-driven bifurcation; the dark circles denote channels that we infer to have formed via avulsion. Note the fine structure of channels for fluvial-dominated deltas (left column), and the suppression of this fine structure for wave-influenced deltas (right column).

Repeated mouth-bar-driven bifurcation generates a distributary network having an approximately power-law distribution of channel lengths, where the maximum channel length is on the order of ten times the width of the parent channel. Channels formed by avulsion should be larger and have the backwater length (L_{\max}) as an upper bound. Young deltas ($t < T_A$) should display only a power-law distribution of distributary length scales (Figure 2b), whereas mature ($t \gg T_A$) deltas might have one or more large distributaries formed by avulsion, spawning mouth-bar-dominated distributary networks (lobes) at their tips (Figure 2c). Strongly aggradational (mature) deltas are likely to erase older channels by overbank sedimentation and thus reinforce this separation of scales.

[10] To test this model prediction, we mapped channel lengths on a set of six natural deltas (shown in Figure 1), which we selected on the basis of 1) minimal tidal influence, 2) availability of published data on river discharge and wave climate, and 3) a sufficient range of wave energy. Frequency-magnitude plots of channel length form distinct populations (Figure 3) whose scales are in excellent agreement with model expectations. The lengths of “small” channels are less than approximately ten times the width of their parent (large-scale) distributary. The “large” channels clearly scale with the computed backwater length (Figures 1 and 3). Young, progradation-dominated deltas like Wax Lake exhibit only finer-scale channels, while mature, aggradational deltas like the Mississippi and Parana contain both scales. Somewhat surprising is the large gap between populations, indicating that intermediate channel lengths largely are

absent; only the Mississippi displays a significant number of intermediate channel lengths.

[11] A second model prediction is that wave energy suppresses the formation of distributaries by mouth-bar-driven bifurcation and thus fundamentally alters channel-length statistics. This suppression is apparent in the right-hand panels of Figures 1 and 3, which show the distributary network and its corresponding channel statistics for varying degrees of wave influence. The northern lobe of the Danube, with a moderate wave climate [Wright and Coleman, 1972], exhibits a truncation of the finest channel scales ($L_{Dmin} \sim 2$ km). The Nile, which has an order-of-magnitude larger wave energy, demonstrates how waves inhibit entirely the formation of mouth-bar distributaries ($L_{Dmin} \sim 20$ km). Finally, the Ebro, with a wave climate in between that of the Nile and Danube deltas, is intermediate in distributary network statistics as well ($L_{Dmin} \sim 4$ km): Mouth-bar distributaries are present on the modern Ebro shoreline, but waves allow only one generation of bifurcation. The wave footprint can vary spatially on the delta: The exposed southern lobe of the Danube has $L_{Dmin} \sim 50$ km, which is far larger than that of the wave-sheltered northern lobe [Giosan et al., 2005]. Note that the absence of fine-scale channel structure, as quantified by deviations from expected fractal scaling, provides a metric of the relative importance of waves.

[12] Our analysis is simplistic by design and meant to illustrate how two fundamental processes—mouth-bar-driven bifurcation and avulsion—evolve distributary networks and, further, how wave energy can affect the network

by suppressing the creation of small-scale mouth-bar distributaries. The derived scaling relationships incorporate a minimum number of river and wave parameters and thus facilitate the prediction of changes in distributary networks due to climate (e.g., sea level rise) or management practices; alternatively, the analysis should aid in the interpretation of deltaic strata. Our work is a first step to a complete morphodynamic model of distributary networks. Future work needs to address tidal forcing, which strongly affects many deltas, and the additional processes known to create and destroy distributaries, e.g. bifurcation instability, tie-channel formation, and crevassing [Galloway, 1975; Wang *et al.*, 1995; Rowland *et al.*, 2005].

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References

- Abdel-Fattah, S., A. Amin, and L. C. Van Rijn (2004), Sand transport in the Nile River, Egypt, *J. Hydraul. Eng.*, **130**, 488–500.
- Bates, C. C. (1953), Rational theory of delta formation, *Bull. Am. Assoc. Pet. Geol.*, **37**, 2119–2162.
- Bhattacharya, J. P., and L. Giosan (2003), Wave-influenced deltas: Geomorphological implications for facies reconstruction, *Sedimentology*, **50**, 187–210.
- Burgess, P. M., and N. Hovius (1998), Rates of delta progradation during highstands: Consequences for timing and deposition in deep-marine systems, *J. Geol. Soc. London*, **155**, 217–222.
- Cooper, J. A. G., and O. H. Pilkey (2004), Longshore drift: Trapped in an expected universe, *J. Sediment. Res.*, **74**, 599–606.
- Edmonds, D. A., and R. L. Slingerland (2007), Mechanics of river-mouth bar formation: Implications for the morphodynamics of delta distributary networks, *J. Geophys. Res.*, **112**, F02034, doi:10.1029/2006JF000574.
- Galloway, W. E. (1975), Process framework for describing the morphologic and stratigraphic evolution of deltaic depositional systems, in *Deltas, Models for Exploration*, edited by M. L. Broussard, pp. 87–98, Houston Geol. Surv., Houston, Tex.
- Giosan, L., J. P. Donnelly, E. Vespremeanu, J. P. Bhattacharya, C. Olariu, F. S. Buonaiuto (2005), River delta morphodynamics: Examples from Danube delta, in *River Deltas: Concepts, Models and Examples*, edited by L. Giosan and J. P. Bhattacharya, SEPM Spec. Publ., **83**, 393–411.
- González, J. L., and T. E. Törnqvist (2006), Coastal Louisiana in crisis: Subsidence or sea level rise, *Eos Trans. AGU*, **87**, 493.
- Heller, P. L., and C. Paola (1996), Downstream changes in alluvial architecture: An exploration of controls on channel-stacking patterns, *J. Sediment. Res.*, **66**, 297–306.
- Jerolmack, D. J., and D. Mohrig (2007), Conditions for branching in depositional rivers, *Geology*, **35**, 463–466.
- Kim, W., C. Paola, V. R. Voller, and J. B. Swenson (2006), Experimental measure of the relative importance of controls on shoreline migration, *J. Sediment. Res.*, **76**, 270–283.
- Komar, P. D., and D. L. Inman (1970), Longshore sand transport on beaches, *J. Geophys. Res.*, **75**, 5914–5927.
- Mikhailova, M. V. (2003), Transformation of the Ebro River Delta under the impact of intense human-induced reduction in sediment runoff, *Water Resour.*, **30**, 370–378.
- Mohrig, D., P. L. Heller, C. Paola, and W. J. Lyons (2000), Interpreting avulsion process from ancient alluvial sequences: Guadalupe Matarranya system (northern Spain) and Wasatch Formation (western Colorado), *Geol. Soc. Am. Bull.*, **112**, 1787–1803.
- Olariu, C., and J. P. Bhattacharya (2006), Terminal distributary channels and delta front architecture of river-dominated delta systems, *J. Sediment. Res.*, **76**, 212–233.
- Parker, G., et al. (2006), Large scale river morphodynamics: Application to the Mississippi Delta, in *Proceedings, RiverFlow 2006 Conference*, edited by R. M. L. Ferreria et al., pp. 1067–1076, Taylor and Francis, New York.
- Rowland, J. C., K. Lepper, W. E. Dietrich, C. J. Wilson, and R. Sheldon (2005), Tie channel sedimentation rates, oxbow formation age and channel migration rate from optically stimulated luminescence (OSL) analysis of floodplain deposits, *Earth Surf. Process. Landforms*, **30**, 1161–1179.
- Slingerland, R., and N. D. Smith (2004), River avulsions and their deposits, *Annu. Rev. Earth Planet. Sci.*, **32**, 257–285.
- Stouthamer, E., and H. J. A. Berendsen (2001), Avulsion frequency, avulsion duration, and interavulsion period of Holocene channel belts in the Rhine-Meuse delta, The Netherlands, *J. Sediment. Res.*, **71**, 589–598.
- Sun, T., C. Paola, and G. Parker (2002), Fluvial fan deltas: Linking channel processes with large-scale morphodynamics, *Water Resour. Res.*, **38**(8), 1151, doi:10.1029/2001WR000284.
- Swenson, J. B. (2005a), Relative importance of fluvial input and wave energy in controlling the timescale for distributary-channel avulsion, *Geophys. Res. Lett.*, **32**, L23404, doi:10.1029/2005GL024758.
- Swenson, J. B. (2005b), Fluviodeltaic response to sea level perturbations: Amplitude and timing of shoreline translation and coastal onlap, *J. Geophys. Res.*, **110**, F03007, doi:10.1029/2004JF000208.
- Syvitski, J. P. M. (2005), The morphodynamics of deltas and their distributary networks, in *River, Coastal, and Estuarine Morphodynamics*, edited by G. Parker and M. Garcia, pp. 143–150, Taylor and Francis, London.
- Syvitski, J. P. M., A. J. Kettner, A. Correggiari, and B. W. Nelson (2005a), Distributary channels and their impact on sediment dispersal, *Mar. Geol.*, **222–223**, 75–94.
- Syvitski, J. P. M., C. J. Vörösmarty, A. J. Kettner, and P. Green (2005b), Impact of humans on the flux of terrestrial sediment to the global coastal ocean, *Science*, **308**, 376–380.
- Törnqvist, T. E. (1994), Middle and later Holocene avulsion history of the River Rhine (Rhine-Meuse delta Netherlands), *Geology*, **22**, 711–714.
- Törnqvist, T. E., and J. S. Bridge (2002), Spatial variation of overbank aggradation rate and its influence on avulsion frequency, *Sedimentology*, **49**, 891–905.
- Törnqvist, T. E., T. R. Kidder, W. J. Autin, K. van der Borg, A. F. M. de Jong, C. J. W. Klerks, E. M. A. Snijders, J. E. A. Storms, R. L. van Dam, and M. C. Wiemann (1996), A revised chronology for the Mississippi River subdeltas, *Science*, **273**, 1693–1696.
- Wang, F. C. (1984), The dynamics of a river-bay-delta system, *J. Geophys. Res.*, **89**, 8054–8060.
- Wang, Z. B., M. Devries, R. J. Fokkink, and A. Langerak (1995), Stability of river bifurcations in 1d morphodynamic models, *J. Hydraul. Res.*, **33**, 739–750.
- Wright, L. D. (1977), Sediment transport and deposition at river mouths: A synthesis, *Geol. Soc. Am. Bull.*, **88**, 857–868.
- Wright, L. D., and J. M. Coleman (1972), River delta morphology: Wave climate and the role of the subaqueous profile, *Science*, **176**, 282–284.
- Yang, S. L., J. Zhang, and X. J. Xu (2007), Influence of the Three Gorges Dam on downstream delivery of sediment and water and its environmental implications, Yangtze River, *Geophys. Res. Lett.*, **34**, L10401, doi:10.1029/2007GL029472.

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