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Connecting the backwater hydraulics of coastal rivers to fluvio-deltaic sedimentology and stratigraphy

Anjali M. Fernandes[1,2]*, Torbjörn E. Törnqvist[1], Kyle M. Straub[1], and David Mohrig[3]
[1]Department of Earth and Environmental Sciences, Tulane University, 6823 St. Charles Avenue, New Orleans, Louisiana 70118-5698, USA
[2]The Center for Integrative Geosciences, The University of Connecticut, 354 Mansfield Road, Unit 1045, Storrs, Connecticut 06269, USA
[3]Department of Geological Sciences, The University of Texas at Austin, 2275 Speedway, M.S. C9000, Austin, Texas 78712, USA

ABSTRACT

Fluvial channels encounter a backwater reach when they approach a standing body of water, and recent studies have shown that the transition from normal flow to backwater-influenced flow is associated with sediment mass extraction through deposition. Here we test the hypothesis that systematic changes in the geometry of channel-belt deposits and sedimentary architecture occur across this transition, using data from the late Holocene Mississippi (southern USA) and Rhine (The Netherlands) fluvio-deltaic systems. We use the estimated backwater length and average channel width as characteristic length scales to non-dimensionalize the downstream trends in channel-belt width for these systems. The collapsed data follow similar trends, suggesting that the observed variations in channel-belt geometry and fluvio-deltaic stratigraphy are tied to the location of the backwater transition zone. These findings suggest a unifying hydraulic control on fluvio-deltaic channel belts and provide a new framework for predicting and understanding the properties of ancient rivers in the coastal zone.

INTRODUCTION

The coastal zone represents a fundamental transition in the pathway of sediment delivery from continents to the ocean, where fluvial processes give way to marine processes and where sediment transport is influenced by signals from both upstream (e.g., water discharge) and downstream (e.g., sea level, storm surge, river-plume dynamics). Understanding flow and sediment transport within this zone has profound significance for interpreting Earth history from continental margin strata, for elucidating the properties of subsurface reservoirs, and for optimizing coastal management and restoration. Recognizing the fundamental controls on the geometry and kinematics of channels, and the shapes of the sediment bodies they create, is a crucial step toward inverting the stratigraphic record to predict the response of coastal landscapes to changing boundary conditions.

Decades of observational data from alluvial channel belts (CBs; equivalent to channel bodies, as defined by Gibling [2006]) have documented a downstream narrowing and thickening within the coastal zone (e.g., Fisk, 1947). Current explanations for these trends include reduced lateral migration rates of channels in the coastal zone forced by (1) a downstream reduction of stream power and accompanying decreased capacity for lateral erosion (Makaske, 2001; Gouw and Berendsen, 2007); and (2) increased cohesion and decreased erodibility of floodplain strata (Kolb, 1963; Törnqvist, 1993). However, no unifying theory has yet emerged to evaluate the stratigraphic impact of backwater dynamics and to potentially enable predictions in settings where limited observational evidence exists (e.g., the deep subsurface).

*E-mail: anjali.fernandes@uconn.edu

We incorporate recent advances in characterizing the hydraulics and sediment-transport dynamics within the backwater zone (*sensu* Chow, 1959) of coastal rivers to explore spatial trends in channel form and kinematics and their relationship to CB geometry. The terminal segment of a river emptying into an ocean or lake is affected by the static body of water in the receiving basin and is known as the backwater zone L_b, with a length scale approximated by $L_b = H/S_{WS}$, where H is mean channel depth and S_{WS} is the gradient of the water surface within the normal flow reach immediately upstream of the backwater zone (Paola and Mohrig, 1996). L_b is the approximate length of the river over which the mean elevation of the channel bed is below mean sea level and where the water-surface gradient systematically diverges from the bed gradient.

A backwater zone occurs in all rivers entering a receiving basin, but it is longest in deep, lowland rivers with gentle gradients. Upstream of the backwater zone, gravity-driven normal-flow conditions dominate; within the gradually varying flow of the backwater zone, both gravity and pressure gradients are important (Chow, 1959). At low and moderate discharge, the backwater zone of the Mississippi River (southern USA) is characterized by flow deceleration toward the ocean and very low bedload transport rates (Nittrouer et al., 2011b); during large floods, increased flow depths in the normal-flow reach and relatively fixed flow depths near the river mouth lead to a steepening of the water surface, flow acceleration within the backwater reach, and an increase in bedload transport by two orders of magnitude (Nittrouer et al., 2012). Model results (Lamb et al., 2012) indicate that a discharge of 3×10^4 m^3/s marks the approximate threshold between moderate to large floods on the Mississippi River. Sediment is stored within the proximal reach of the backwater zone during low and moderate discharge, and channel-bed scour occurs in the distal backwater zone during high discharge. Sand is transported within the backwater reach primarily during high discharge, is nearly equally distributed between suspended load and bedload, and is composed of easily suspended very fine to lower medium (<300 µm) sand (Nittrouer et al., 2012).

Storage of slow-moving bedload at the backwater transition is reflected in the grain-size trend of bed material from the Mississippi River, which shows an increased rate of downstream fining associated with a reduced bed slope downstream of the point where the channel bed drops below sea level (Wright and Parker, 2005). Sediment storage at the backwater transition has some morphodynamic consequences. Bed material can be sequestered through channel-bed aggradation and/or accelerated growth of bars. Several studies (Jerolmack and Swenson, 2007; Chatanantavet et al., 2012) suggested that regional avulsions may be connected to the backwater transition and associated local channel-bed aggradation. Increased rates of lateral channel migration in the upstream portion of the backwater zone of the Mississippi River between river kilometers (RKs) 800 and 400 (Hudson and Kesel, 2000; Nittrouer et al., 2012) may be driven by enhanced sediment storage in bars, which can constrict flow and drive bank erosion

(Ikeda et al., 1981). Reduced lateral migration rates downstream of RK 300 are the likely result of loss of active bed material (Nittrouer et al., 2012), although the thick, mud-rich and cohesive substrate may be an important additional factor (Kolb, 1963). The final ~165 km of the lower Mississippi River (Fig. 1A) reflects the loss of active bed material; an estimated 25%–40% of the channel bed is devoid of an active alluvial cover, with the exposed substrate displaying grooves, potholes, and other erosional bedforms characteristic of scour (Nittrouer et al., 2011a).

The change in magnitude and frequency of bed-material flux across the backwater zone, tied to changes in transport dynamics, suggests that a concomitant change in resulting sedimentary architecture might be expected. The signature of backwater hydraulics in the ancient stratigraphic record has not been fully explored, although recent studies (Petter, 2010; Colombera et al., 2016) have made inroads into this problem with small-scale fluvio-deltaic deposits preserved in intracratonic basins. Implicit to such analyses of the sedimentary record is a requirement that backwater hydrodynamics must persist over long enough time scales that its signal can be recorded. This necessitates that the river be in a persistent state of channel-bed adjustment, and the time scale required for the channel to adjust to flood-related change must be larger than the recurrence interval of floods (Chatanantavet and Lamb, 2014; Ganti et al., 2016). Here we evaluate the long-term (10^2–10^3 yr) consequences of sediment mass extraction at the backwater transition for CB geometry and sedimentary architecture in

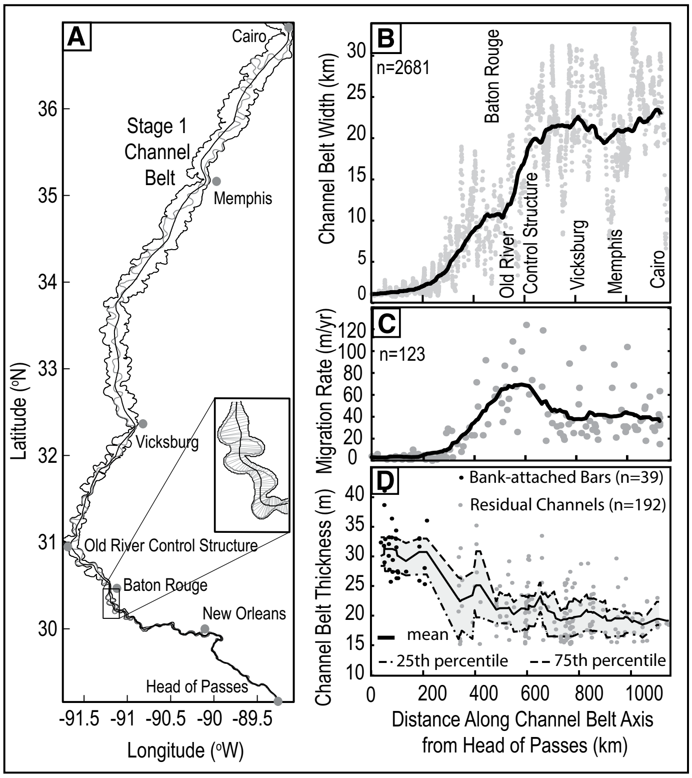

Figure 1. A: Plan view of Stage 1 channel belt of lower Mississippi River from Cairo, Illinois, to Head of Passes, Louisiana (USA) (after Saucier, 1994), showing channel-belt axis (black) and modern river (gray). Inset shows dense spacing of channel-belt width measurements. B: Channel-belt width (gray dots) and average width calculated over 200 km moving window (black) plotted versus distance along channel-belt axis. C: Channel migration rates (gray dots) from Hudson and Kesel (2000) and mean rates over 200 km moving window (black) plotted versus distance along channel-belt axis. D: Thickness of channel-belt deposits approximated by measurements from thickness of mud-filled residual channels (gray dots) upstream of channel belt kilometer (CBK) 300 and bank-attached bar deposits (black dots) downstream of CBK 225, plotted versus distance along channel-belt axis.

relatively large river systems, and show that fundamentally similar stratigraphic results are found in fluvio-deltaic systems of very different size.

SPATIAL TRENDS IN THE MISSISSIPPI CHANNEL BELT

We focus on the CB of the modern Mississippi River from Cairo, Illinois (USA), to the Gulf of Mexico (Fig. 1A), also known as the Stage 1 meander belt (Saucier, 1994) that has been active during the late Holocene. Georeferenced maps from Saucier (1994) were used to define the Stage 1 CB centerline (axis) and boundaries, as well as the modern Mississippi River channel (Fig. 1A). The width of the Mississippi CB was measured at densely spaced increments (mean spacing 0.4 km, maximum spacing 1.8 km) along and perpendicular to the CB axis (Figs. 1A and 1B). To complement the planform shape data, we digitized 1596 borehole logs from throughout the lower Mississippi Valley and the Mississippi Delta, compiled by the U.S. Army Corps of Engineers. The Mississippi CB commonly scours into Pleistocene sandy and gravelly braided-river deposits that can be difficult to distinguish from the Stage 1 CB deposits. In order to avoid this ambiguity, only mud-rich residual-channel deposits from 192 boreholes are used to estimate flow depth and CB thickness upstream of channel belt kilometer (CBK; distance along CB axis) 300 (Figs. DR2 and DR3 in the GSA Data Repository[1]). Specifically, we used oxbow deposits for these measurements because these containers (oxbow lakes) are abruptly isolated during meander-neck cutoffs and therefore are reliable proxies for the original channel depth. Downstream of CBK 225, we used the thickness of bank-attached bar deposits from 39 boreholes to approximate flow depth (Fig. DR2).

Between CBKs 1200 and 650 the average CB width is 20–25 km (Fig. 1B), whereas the segment between CBKs 650 and 0 displays a reduction in CB width from ~25 km to ~2 km. Lateral migration rates decrease from ~60 m/yr to <5 m/yr between CBKs 500 and 300 (Fig. 1C). Between CBKs 300 and 0, the lateral migration rates remain very low and there is a coincident increase in CB thickness. Mean CB thickness is roughly 20 m upstream of CBK 300, increasing to ~30 m between CBKs 300 and 0 (Fig. 1D). Hence, the CB width/thickness ratio decreases by at least an order of magnitude (from >1000 to <100) between CBKs 1200 and 0 (cf. Blum et al., 2013).

Thickening of CB deposits downstream of approximately CBK 300 (Fig. 1D), very low rates of lateral channel migration (Fig. 1C), and CB widths (Fig. 1B) that approach channel widths are coincident with observed channel-bed scour and deepening of the modern river (Nittrouer et al., 2011a, 2012). These phenomena reflect conditions of coarse sediment starvation and are attributed to selective deposition of bedload in the upstream portion of the backwater zone and overall reduction in bedload flux through the backwater zone. Because the rate of channel migration is influenced by bar growth as well as floodplain cohesion (Ikeda et al., 1981), it is noteworthy that lateral migration rates (Fig. 1C) and CB width (Fig. 1B) decrease across the backwater transition, where the volume of bed-material sediment available to construct bars is also reduced.

DIMENSIONLESS SCALING OF MISSISSIPPI AND RHINE CHANNEL BELTS

As noted by Blum et al. (2013), the trends in Mississippi CB geometry suggest a connection to backwater hydraulics. We test this hypothesis using data from three well-mapped and dated late Holocene fluvio-deltaic CBs of the Rhine River system, The Netherlands (Berendsen and Stouthamer, 2001). These CBs have very different scales from that of the Mississippi River but were subject to similar rates of base-level rise (Table DR1 in Data Repository). To compare the two systems, we used estimates of backwater length to non-dimensionalize distance upstream

[1]GSA Data Repository item 2016331, morphometric data, scaling relationships, and channel-belt ages, is available online at http://www.geosociety.org/pubs/ft2016.htm or on request from editing@geosociety.org.

from the shoreline, and estimates of channel width to non-dimensionalize CB width (Fig. 2).

We used a range of mean flow depths and water-surface gradients in the normal flow reach, compiled from available field data, to estimate a range of backwater lengths. We then refined our backwater length estimates using observed trends from modern data, and accordingly selected the most reasonable flow depths (see the Data Repository). In the Mississippi system, estimates of backwater length are 281, 328, and 375 km, which correspond to low, intermediate, and high values of mean normal flow depth (18, 21, and 24 m, respectively) acquired from depths of filled oxbow lakes (Fig. 1D), and a water-surface gradient of 6×10^{-5} estimated from the channel-bed gradient in the normal flow reach (Wright and Parker, 2005), corrected for the engineered channel shortening of 230 km. The intermediate and high estimates are in good agreement with the location of the divergence between water and channel-bed elevation profiles observed between RKs 300 and 400 (Nittrouer et al., 2012). In the Rhine system, backwater length estimates yield 54, 71, and 89 km for the Nederrijn-Lek and Linge CBs, and 64, 85, and 106 km for the Waal CB, corresponding to mean normal flow depths of 6, 8, and 10 m for all three channels, and water-surface gradients of 1.1×10^{-4} for the Nederrijn-Lek and Linge and 9.4×10^{-5} for the Waal. We used low and high measures of channel width corresponding to 1200 and 1400 m for the Mississippi (Harmar and Clifford, 2006), 200 and 250 m for the Nederrijn-Lek and Linge (Berendsen, 1982), and 300 and 350 m for the Waal (Gouw and Berendsen, 2007). Trends in CB geometry from the two systems collapse remarkably well for realistic combinations of channel width and backwater length (Fig. 2; Fig. DR7).

Modern long profiles of the Nederrijn-Lek reveal a marked reduction of the water-surface gradient 70–90 km from the shoreline (Berendsen, 1982). Similar to our findings for the Mississippi, the intermediate and high estimates of backwater length agree best with these independent observations. Reconstructions of the Holocene rise of the groundwater table (Fig. DR5; Van Dijk et al., 1991; Cohen, 2005) can be used as a proxy for the evolution of CB gradients in the Rhine-Meuse Delta. This reveals a reduction in gradient 44–60 km upstream of the shoreline between 8 and 5 ka once a channel sinuosity of 1.1–1.3 is taken into account (see the Data Repository), suggesting that the backwater transition in this system was a persistent feature over the past ~8000 yr (cf. Cohen, 2005) that slowly migrated upstream in concert with relative sea-level rise.

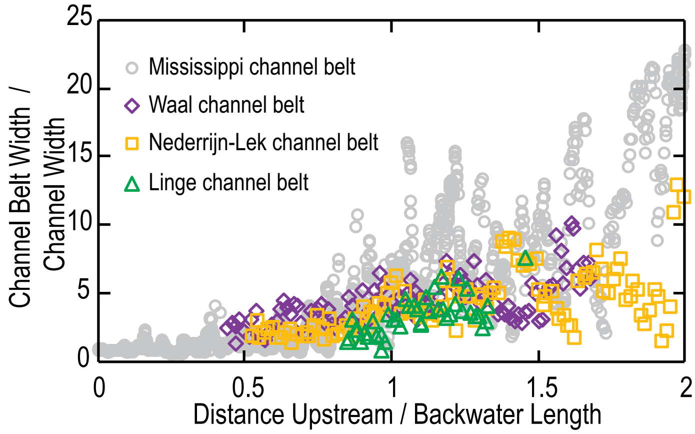

Figure 2. Planform of fluvio-deltaic channel belts from Rhine River system (The Netherlands; colored symbols) and Mississippi River (USA; gray symbols) scaled by channel width and backwater length. We used intermediate estimates of backwater length to non-dimensionalize distance upstream from shoreline (328 km for Mississippi, 85 km for Waal channel belt, and 71 km for Nederrijn-Lek and Linge channel belts), and smaller measures of channel width (1200 m for Mississippi, 300 m for Waal, and 200 m for Nederrijn-Lek and Linge) to non-dimensionalize channel-belt width.

DISCUSSION

A systematic and similar downstream reduction in the width of the four CBs studied here indicates that the backwater zone is an important length scale that defines spatial changes in CB geometry. The collapse of the non-dimensionalized data (Fig. 2) suggests that the presence of a backwater zone in both the Mississippi and Rhine fluvio-deltaic systems has a comparable impact on the long-term evolution of CB geometries. Previous studies (e.g., Karssenberg and Bridge, 2008) have related CB width to the time span of activity of the associated channel. We can likely attribute some of the remaining variability in Figure 2 to this effect. Upstream of the backwater transition, the data from the Mississippi plot systematically higher than those for the Rhine. In part, this is probably because the Mississippi CB in its upstream reach has been active at least twice as long as it was active within the backwater zone. By comparison, this disparity in the period of activity of Rhine CBs is small (Table DR1).

Figures 1B, 1C, and 2 offer the intriguing possibility of connecting the planform of CB deposits to (1) the sediment-transport dynamics and flow hydraulics of formative paleo-channels and (2) the subsurface thicknesses of resulting deposits, in the absence of other observational data. Planforms of acoustically imaged CBs are heavily relied upon to characterize reservoir potential, because the vertical resolution of standard industry seismic data is usually insufficient to define CB thickness changes. Our results (Figs. 1B and 1C) show that a reduction of CB width in the coastal zone can be related to a thickening of CB deposits where the CB width approaches channel width and exhibits very little variability. Downstream reduction in CB width is therefore not just a function of increased floodplain cohesion as has been suggested in the past (Fisk, 1947; numerous subsequent studies). Thick CB deposits in the distal backwater zone, the likely result of channel-bed scouring during high flow, are a consequence of reduced bedload flux. CB width and thickness trends, coupled with measurements from the modern Mississippi (Nittrouer et al., 2012), lead us to hypothesize that distal portions of large, lowland river systems are likely to be represented by thick, narrow, heterolithic CB deposits in the stratigraphic record. This hypothesis is supported by our observation that bank-attached bars in the distal backwater zone are composed entirely of fine sand and mud (Fig. DR3B), which is not the case in the proximal backwater zone (Fig. DR3C).

The correlation between floodplain gradient reduction and sedimentary architecture (decrease in CB width/thickness ratio) has been documented in numerous studies (e.g., Törnqvist, 1993; Makaske, 2001; Gouw and Berendsen, 2007; Blum et al., 2013), and we propose that similar phenomena may be common to most low-gradient fluvio-deltaic systems, perhaps with the exception of those in macrotidal settings. The most recent generation of alluvial-architecture models (e.g., Liang et al., 2015) has yet to explore the effect of backwater dynamics on CB geometry.

Finally, our findings also have implications for delta restoration, given that an increasing number of world deltas are currently degrading. Rebuilding delta plains requires abundant sediment, and sand is a particularly valuable resource. The backwater transition zone could potentially provide critical raw material to supply land-building projects.

CONCLUSIONS

Our dimensionless comparison of geometric trends of Mississippi and Rhine CBs suggests that the backwater zone defines a fundamental boundary within these fluvio-deltaic systems. The relative position of this boundary is similar between systems of different size, and therefore the systematic narrowing and thickening of CB deposits toward the coastline is predictable. This study defines a crucial link between river hydraulics in the backwater reach and resultant sedimentary architecture of fluvio-deltaic CB deposits, and provides a new framework for predicting alluvial stratigraphy.

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REFERENCES CITED

Berendsen, H.J.A., 1982, De genese van het landschap in het zuiden van de provincie Utrecht, een fysisch-geografische studie: Utrechtse Geografische Studies 25, 259 p.

Berendsen, H.J.A., and Stouthamer, E., 2001, Palaeogeographic Development of the Rhine-Meuse Delta, The Netherlands: Assen, Netherlands, Koninklijke Van Gorcum, 268 p.

Blum, M.D., Martin, J.M., Milliken, K.T., and Garvin, M., 2013, Paleovalley systems: Insights from Quaternary analogs and experimental studies: Earth-Science Reviews, v. 116, p. 128–169, doi:10.1016/j.earscirev.2012.09.003.

Chatanantavet, P., and Lamb, M.P., 2014, Sediment transport and topographic evolution of a coupled river and river plume system: An experimental and numerical study: Journal of Geophysical Research: Earth Surface, v. 119, p. 1263–1282, doi:10.1002/2013JF002810.

Chatanantavet, P., Lamb, M.P., and Nittrouer, J.A., 2012, Backwater controls of avulsion location on deltas: Geophysical Research Letters, v. 39, L01402, doi:10.1029/2011GL050197.

Chow, V.T., 1959, Open-Channel Hydraulics: New York, McGraw-Hill, 680 p.

Cohen, K.M., 2005, 3D geostatistical interpolation and geological interpretation of palaeo–ground water rise in the Holocene coastal prism in the Netherlands, *in* Giosan, L., and Bhattacharya, J.P., eds., River Deltas—Concepts, Models, and Examples: Society for Sedimentary Geology Special Publication 83, p. 341–364, doi:10.2110/pec.05.83.0341.

Colombera, L., Shiers, M.N., and Mountney, N.P., 2016, Assessment of backwater controls on the architecture of distributary-channel fills in a tide-influenced coastal-plain succession: Campanian Nelsen Formation, USA: Journal of Sedimentary Research, v. 86, p. 476–497, doi:10.2110/jsr.2016.33.

Fisk, H.N., 1947, Fine-grained alluvial deposits and their effects on Mississippi River activity: Vicksburg, Mississippi, U.S. Army Corps of Engineers, Mississippi River Commission, 82 p.

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

Gibling, M.R., 2006, Width and thickness of fluvial channel bodies and valley fills in the geological record: A literature compilation and classification: Journal of Sedimentary Research, v. 76, p. 731–770, doi:10.2110/jsr.2006.060.

Gouw, M.J.P., and Berendsen, H.J.A., 2007, Variability of channel belt dimensions and consequences for alluvial architecture: Observations from the Holocene Rhine Meuse Delta and Lower Mississippi Valley: Journal of Sedimentary Research, v. 77, p. 124–138, doi:10.2110/jsr.2007.013.

Harmar, O.P., and Clifford, N.J., 2006, Planform dynamics of the lower Mississippi River: Earth Surface Processes and Landforms, v. 31, p. 825–843, doi:10.1002/esp.1294.

Hudson, P.F., and Kesel, R.H., 2000, Channel migration and meander-bend curvature in the lower Mississippi River prior to major human modification: Geology, v. 28, p. 531–534, doi:10.1130/0091-7613(2000)28<531:CMAMCI>2.0.CO;2.

Ikeda, S., Parker, G., and Sawai, K., 1981, Bend theory of river meanders. Part 1. Linear development: Journal of Fluid Mechanics, v. 112, p. 363–377, doi:10.1017/S0022112081000451.

Jerolmack, D.J., and Swenson, J.B., 2007, Scaling relationships and evolution of distributary networks on wave-influenced deltas: Geophysical Research Letters, v. 34, L23402, doi:10.1029/2007GL031823.

Karssenberg, D., and Bridge, J.S., 2008, A three-dimensional model of sediment transport, erosion, and deposition within a network of channel belts, floodplain and hill slope: Intrinsic and extrinsic controls on floodplain dynamics and alluvial architecture: Sedimentology, v. 55, p. 1717–1745, doi:10.1111/j.1365-3091.2008.00965.x.

Kolb, C.R., 1963, Sediments forming the bed and banks of the lower Mississippi River and their effect on river migration: Sedimentology, v. 2, p. 227–234, doi:10.1111/j.1365-3091.1963.tb01216.x.

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

Liang, M., Geleynse, N., Edmonds, D.A., and Passalacqua, P., 2015, A reduced-complexity model for river delta formation—Part 2: Assessment of the flow routing scheme: Earth Surface Dynamics, v. 3, p. 87–104, doi:10.5194/esurf-3-87-2015.

Makaske, B., 2001, Anastomosing rivers: A review of their classification, origin and sedimentary products: Earth-Science Reviews, v. 53, p. 149–196, doi:10.1016/S0012-8252(00)00038-6.

Nittrouer, J.A., Mohrig, D., Allison, M.A., and Peyret, A.-P.B., 2011a, The lowermost Mississippi River: A mixed bedrock-alluvial channel: Sedimentology, v. 58, p. 1914–1934, doi:10.1111/j.1365-3091.2011.01245.x.

Nittrouer, J.A., Mohrig, D., and Allison, M., 2011b, Punctuated sand transport in the lowermost Mississippi River: Journal of Geophysical Research, v. 116, F04025, doi:10.1029/2011JF002026.

Nittrouer, J.A., Shaw, J., Lamb, M.P., and Mohrig, D., 2012, Spatial and temporal trends for water-flow velocity and bed-material sediment transport in the lower Mississippi River: Geological Society of America Bulletin, v. 124, p. 400–414, doi:10.1130/B30497.1.

Paola, C., and Mohrig, D., 1996, Paleohydraulics revisited: Paleoslope estimation in coarse-grained braided rivers: Basin Research, v. 8, p. 243–254, doi:10.1046/j.1365-2117.1996.00253.x.

Petter, A.L., 2010, Stratigraphic implications of the spatial and temporal variability in sediment transport in rivers, deltas, and shelf margins [Ph.D. thesis]: Austin, University of Texas at Austin, 205 p.

Saucier, R.T., 1994, Geomorphology and Quaternary geologic history of the Lower Mississippi Valley: Vicksburg, Mississippi, United States Army Corps of Engineers Waterways Experiment Station, 364 p.

Törnqvist, T.E., 1993, Holocene alternation of meandering and anastomosing fluvial systems in the Rhine-Meuse Delta (central Netherlands) controlled by sea-level rise and subsoil erodibility: Journal of Sedimentary Research, v. 63, p. 683–693, doi:10.1306/D4267BB8-2B26-11D7-8648000102C1865D.

Van Dijk, G.J., Berendsen, H.J.A., and Roeleveld, W., 1991, Holocene water level development in the Netherlands' river area: Implications for sea-level reconstruction: Geologie & Mijnbouw, v. 70, p. 311–326.

Wright, S., and Parker, G., 2005, Modeling downstream fining in sand-bed rivers. I: Formulation: Journal of Hydraulic Research, v. 43, p. 613–620, doi:10.1080/00221680509500381.

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