Backwater hydrodynamics and sediment transport in the lowermost Mississippi River delta: Implications for the development of fluvial-deltaic landforms in a large lowland river

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Abstract Where rivers enter the coastal zone, gradually varying non-uniform flow conditions develop in the channel. This section of the river is referred to as the backwater segment, and for large rivers, backwater flow extends many hundreds of kilometres upstream of the river outlet. Studies from the Mississippi River document a persistent backwater zone that influences sediment mobility throughout the lowermost 500 km of the river. Reach-average shear stress varies temporally in accordance with the annual hydrograph, affecting the timing, magnitude, and grain size of transported sediment. A net reduction in shear stress restricts the downstream movement of coarse sediment, and this portion of the river's sediment load does not reach the coastline. Instead, coarse sediment is caught at the backwater transition and is sequestered in the river channel. Information about the timing and magnitude of sediment flux in the backwater segments of large rivers is critical to addressing the landscape dynamics of deltas. Research from the Mississippi River delta, where roughly 5000 km² of land has been converted to open water in the past century, is presented as a case study. The collapse of the Mississippi River delta is driven by rapid land subsidence associated with the extraction of subsurface fluids, eustatic sea-level rise, and the construction of levees, which prevent the movement of sediment to the neighbouring flood plain. Recent studies have demonstrated that current sediment loads in the Mississippi River are sufficient to offset much of the future land loss, if measures are undertaken to extract sediment for delta building. Local conditions favour the development of channel bars and such locations are optimal for river diversions that deliver sediment to the surrounding delta. Studies from the Mississippi River delta can be extended to other large river-delta systems around the world to assess appropriate measures for sustaining delta landscapes.

Key words sediment transport; river-delta stratigraphy; backwater hydrodynamics

INTRODUCTION

Backwater hydrodynamics in coastal rivers

Where rivers enter the coastal zone the water-surface profile of the river asymptotically approaches the relatively fixed elevation of the receiving basin (i.e., "M1" curve; Chow, 1959). Bed slope, however, remains constant, and the deviation between the bed and water slopes produces downstream channel deepening to the head of the river delta (Fig. 1(a)). Assuming a uniform channel width and steady water discharge, cross-sectional flow area increases and reach-average flow velocity decreases downstream, respectively (Nittrouer *et al.*, 2012a). This hydrodynamic phenomenon produces gradually varying flow and is considered a backwater condition, and the downstream changes in velocity and flow depth are described using:

$$\frac{dH}{dx} = \frac{S_0 - C_f F r^2}{1 - F r^2}$$
(1)

where *H* is flow depth, S_0 is channel bed slope, C_f is the dimensionless bed resistance coefficient, and *Fr* is the Froude number ($Fr = U(gH)^{-0.5}$; U = depth-average velocity, and *g* is gravitational acceleration; e.g. Parker, 2004, Nittrouer, 2012a). The transition from reach-average normal flow (steady and uniform flow) to backwater flow occurs at a distance upstream of the river outlet, scaled by flow depth, *H*, and the water surface slope near the outlet, *S*; this distance upstream of the outlet is known as the characteristic backwater length scale, L_b , where: $L_b = H S^{-1}$ (Paola & Mohrig, 1996).

Lane (1957) first observed these dynamic characteristics for rivers nearing the Gulf of Mexico and Great Lakes receiving basins. Lane's qualitative sketches of channel-bed and water-surface profiles show "M1" and "M2" behaviour during low and high water discharges, respectively. He surmised that cross-sectional flow area increases progressing downstream to the outlet during low discharge. However, during high discharge, the opposite occurs, whereby cross-sectional flow area must decrease progressing downstream because the fixed elevation of the receiving basin forces stage variability to diminish downstream (Fig. 1(a)). Therefore, under the condition of water discharge continuity, flow velocity must vary over space depending on water discharge: water velocity decreases progressively downstream during low water discharge, and velocity increases progressively downstream during high water discharge.

Lane's astute characterizations of backwater flow dynamics have been derived physically (e.g. equation (1); Chaudhry, 2008), and are frequently applied for engineering applications, such as evaluating dynamic interactions of flow and sediment transport within human-constructed dams and reservoirs (Chow, 1959; Parker, 2004; Snyder *et al.*, 2006). Fluvial geologists have described how a river's characteristic backwater length scale, L_b , coincides with changing channel morphologies and depositional patterns that arise as a result of morphodynamic feedbacks associated with backwater flow (Paola & Mohrig, 1996; Jerolmack & Swenson, 2007; Parker *et al.*, 2008; Lamb *et al.*, 2012; Chatanantavet *et al.*, 2012; Nittrouer *et al.*, 2012a). For example, the characteristic backwater length scale is generally considered to define the start of the river delta (Parker, 2004; Jerolmack & Swenson, 2007) because, by definition, this is the location where the receiving basin influences fluvial hydrodynamics, thus producing time and space divergences in sediment transport (Paola & Voller, 2005). Eventually sediment transport divergences generate delta sedimentation and stratigraphy, influence formation of channel avulsions that produce new distributary channels and thus the location of river-ocean depocenters (Jerlomack, 2009), and influence lateral mobility of river channels near the receiving basin (Nittrouer *et al.*, 2012a).



Fig. 1 (a) Profile of the channel bed and water-surface elevation for the Mississippi River for three water discharge conditions: low, moderate, and high water discharge. The thalweg profile (the maximum channel depth) is also shown. Note that the water surface profiles asymptotically approach sea level near river kilometre 650; this indicates the start of the transition from normal flow to backwater flow. Also note how dynamic changes in stage, particularly in relation to flow depth, decreases considerably downstream in the backwater segment: in the normal flow reach, stage roughly doubles flow depth, while in the backwater reach, the stage produces only \sim 5% increase in flow depth (b) Water surface slopes and channel bed slope for the lower 1050 river kilometres of the Mississippi River. Water slopes and channel bed slope are subequal across all water discharges in the normal flow reach, above river kilometre 650. Downstream of this location, the water surface slopes vary considerably in relation to water discharge. (After Nittrouer et al., 2011a).

For large rivers, H is 1-tens m and S is 10^{-4} - 10^{-5} , and so backwater conditions may extend many tens to hundreds of kilometres upstream of the river outlet. Because backwater conditions extend far upstream of the river-ocean interface, hydrodynamics in this river segment effectively filter the timing, magnitude, and size of sediment delivered to the downstream delta (Nittrouer *et al.*, 2011a, 2012a; Lamb *et al.*, 2012). Constraining backwater hydraulics is therefore crucial for evaluating the morphodynamic development of lowland river channels and their associated deltas.

DELTA SUSTAINABILITY: A SOCIETAL IMPERATIVE

Fluvial deltas are some of the most dynamic landscapes on Earth, building and destroying hundreds of square kilometres of land per century (Frazier, 1967). Deltas are also incredibly important for societal welfare as these environments offer an extraordinary assortment of natural resources and ecosystem services (Vörösmarty *et al.*, 2009). As a result, deltas host hundreds of millions of people worldwide and are relied upon for human security, and therefore sustaining river deltas is a societal imperative (Syvitski & Saito, 2007). Significant and extreme challenges now face fluvial-delta coastlines and the societies that inhabit them as a result of numerous influences, including: (a) cutoff of sediment supply to the delta due to, e.g. dams; (b) accelerated subsidence driven by groundwater and hydrocarbon development; (c) manipulation of the delta land and channels for navigation, agriculture and industry; (d) leveeing of channels so as to prevent avulsions and sediment overspill to locations where such sediment would otherwise build and maintain land; (e) eutrophication due to nutrient loadings; and (f) anthropogenic climate change and associated sea level rise (Vörösmarty *et al.*, 2009). These challenges continue to push deltas and the societies that inhabit them to the brink of elimination.

Moreover, deltaic coastlines constructed by major rivers are by nature extremely low-lying coastal landscapes with little topographic relief. These regions are therefore particularly susceptible to drowning and destruction because of relative sea-level rise (Blum & Roberts, 2009; Syvitski *et al.*, 2009), as well as increasing magnitude and frequency of significant oceanic storm events, and enhanced river flooding; all of these conditions are expected to increase globally in the coming decades and centuries due to ongoing climate change (Michener *et al.*, 1997). To mitigate the risk of land loss on deltas, there must be a fundamental process-based understanding of delta development, so that science can help guide countermeasures that mitigate future delta land loss (Paola *et al.*, 2011).

Importantly, sediment is the most precious resource for building and sustaining deltaic landscapes. Sediment transport studies in lower river reaches therefore have important societal applications because this science directly addresses timing and magnitude of resource (sediment) delivery to the delta coastlines. For example, constraining sediment dynamics is a first-order priority for building and validating morphodynamic models that predict the time and space evolution of delta landscapes by investigating the coupled hydrodynamic and sediment transport flow fields (Kim *et al.*, 2009). To this end, several recent studies have provided insights into how backwater hydrodynamics may impede or facilitate downstream movement of sediment and eventual delivery to the delta (Nittrouer *et al.*, 2011a; Lamb *et al.*, 2012; Nittrouer *et al.*, 2012a). This information is subsequently utilized in studies that predict landscape development from morphodynamic models (Kenney *et al.*, 2013), and the outcomes of this basic science research will continue to guide sustainability efforts on river deltas worldwide.

An important goal for delta sustainability is information transfer between basic sciences and engineering practices that are needed to nourish delta landscapes (e.g. locating and operating river diversions that disperse water and sediment from the channel to adjacent wetlands). The purpose of this paper is to combine studies that describe the hydrodynamics affecting the timing and magnitude of sediment transport in the lower reaches of river systems, to address the best-use engineering practices for the purposes of delta nourishment. This paper will focus on the Mississippi River and its delta (Fig. 2), where several recent studies have contributed field and modelling efforts that have focused on evaluating water discharge and sediment transport through the lower river. These studies have provided theoretical advancements for understanding how backwater conditions affect the timing and magnitude of sediment transport and delivery to the delta. A critical step is translating these basic science advances for applied engineering purposes. This important step is particularly salient for the societally-developed Mississippi River delta, where sustainability is crucial; therefore this system can be used as a case study for sustainability measures on other large anthropic (i.e. populated by humans with significant infrastructure development) deltas worldwide.

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THE MISSISSPPI RIVER AS AN IMPORTANT CASE STUDY

The focus of this contribution is the Mississippi River and its associated delta (Fig. 2). This system is used as a case study because several important studies that have been published in the previous ~5 years have documented the time and space linkages of sediment transport and backwater hydrodynamics, and the results of these studies are now being used to refine numerical models that predict delta development for rehabilitation efforts. Besides, there are few other better studied examples of large river systems where basic science is informing engineering practices that are used to guide actions to build a sustainable deltaic system. The products gained from Mississippi River delta studies will foster sustainability lessons for the World's other large and anthropic deltas that are under threat of destruction. The Mississippi River delta thus serves as a bellwether for coastal river systems worldwide: these landscapes will face extraordinary land loss without appropriate landscape and river-management practices (Vorosmarty *et al.*, 2009).



Fig. 2 Overview of southern Louisiana and the Mississippi River delta. "RK" refers to river kilometres above the outlet. At Red River Landing, RK 503, the Atchafalaya River distributary channel splits from the Mississippi River. The Bonnet Carré Spillway is shown (box indicates field of view for Fig. 5(a)); at this location, water and associated sediment are diverted to Lake Pontchartrain during flood events. (After Nittrouer *et al.*, 2011a).

Mississippi River delta land change: past, present and future

Since the early 20th century, nearly 5000 km² of Mississippi River delta coastline has converted to open water (Walker *et al.*, 1987; Morton *et al.*, 2005a, 2010). This catastrophic collapse of the delta is primarily attributed to: (1) rapid land subsidence associated with hydrocarbons and water extraction from the subsurface sediments (Walker *et al.*, 1987; Morton *et al.*, 2005a; Kolker *et al.*, 2011); (2) confinement of water and sediment to the main channel via levee networks that restrict movement and deposition of sediment to the adjacent delta wetlands and effectively render the main channel a sediment conduit to the river–ocean interface (Baumann *et al.*, 1984); and (3) cutting of the delta to create navigation channels for commercial purposes (Johnson & Gosselink, 1982; Turner & Boyer, 1997).

Preventing future land loss of the Mississippi River delta is imperative for many socioeconomic reasons. For example, the Port of Louisiana is the largest shipping port in the Western Hemisphere by volume trade (World Port Rankings, 2008), and southern Louisiana is home to more than 2 million people with a rich and eclectic culture (Lowe, 2008). Delta restoration for the Mississippi River system is crucial for reducing exposure of major cities (e.g. New Orleans, Baton Rouge) and infrastructure to storm surge risks, and to prevent future degradation of environmentally important and sensitive habitat (US Army Corps of Engineers, 1963; Twilley & Rivera-Monroy, 2009; Bunya *et al.*, 2010; Day *et al.*, 2012). Without action to mitigate further coastal degradation, the commercial, social, ecological, and cultural security of the United States Gulf Coast is in jeopardy.

Studies by Morton et al. (2005a) and Morton & Bernier (2010) indicate that since 1978, with the reduction in subsurface fluid extraction, anthropogenic influence on delta subsidence has been diminished, and that additional land loss could approach ~1350 km² in the coming 50 years. Despite research indicating that sediment loads of the Mississippi River have been reduced due to human influence (e.g. dam construction, levee and revetment installation; Meade & Moody, 2010), several recent studies have indicated that the current sediment load of the Mississippi River could potentially build land that may match or even outpace the predicted future land-loss values indicated by Morton et al. (2005a) and Morton & Bernier (2010). For example, Kim et al. (2009) constructed a morphodynamic model for delta development in the Mississippi River system. Using one-half of the annual sand load, the model of Kim et al. (2009) constructed land over 50 years that has an area of roughly 600 km². Moreover, this model estimate does not include contribution of organics, which have been measured to comprise 25-30% of the delta deposit by volume (Morton et al., 2005b; Wilson & Allison, 2008), nor does the model estimate include land building via contribution of fine sediment (silt and clay), which comprises ~80% of the total Mississippi River sediment load (Nittrouer et al., 2008). Adding both organics and fine sediments will substantially boost the predicted land gain from unhindered sediment dispersal and delta development. Therefore, engineered diversions offer an important mechanism for building sustainable landscapes that help maintain the footprint of the Mississippi River delta.

Backwater hydrodynamics, sediment transport, channel morphology, and morphodynamics in the lower Mississippi River

The backwater length (L_b) for the Mississippi River extends approx. 650 km upstream of the modern outlet (Figs 1, 2), coinciding with where the channel-bed elevation matches mean sea level of the Gulf of Mexico (Fig. 1). Upstream of the backwater segment, water surface slope is uniform and independent of water discharge, and is subequal to the channel-bed slope (Fig. 1(b)). In the backwater segment, the water surface asymptotically approaches the elevation of the receiving basin (Fig. 1(a)). Due to the microtidal environment of the Gulf of Mexico (tidal amplitude <0.3 m), tidal amplitudes do not have significant influences on the river stage or water discharge conditions in the Mississippi River.

Backwater conditions strongly influence the hydrodynamic properties of the lower Mississippi River (Nittrouer *et al.*, 2011a, 2012a). This, in turn, has a significant influence on the transport of sediment in the lower river. During low discharge conditions, the downstream decrease in flow velocity significantly reduces sediment transport capacity. During high flow conditions, however, a downstream increase in flow velocity raises sediment transport capacity considerably. These conditions give rise to important temporal changes in sediment transport. Bedform sediment flux (defined as the component of sediment associated with the downstream migration of bedforms) varies by two-orders of magnitude from low to high water discharge (Nittrouer *et al.*, 2008). Reach-average boundary shear stress, both measured and modelled within the lower ~165 km of the river, increases 10-fold from low to high water discharge (Nittrouer *et al.*, 2011a). It is important to point out that this significant range is not possible where normal flow conditions persist upstream of backwater influence, and the reach-average boundary shear stress (τ_b) is estimated using the depth-slope product:

$$\tau_b = \rho g H S \tag{2}$$

(where ρ is the fluid density). For the normal-flow reach, variables excluding *H* are constant, and so reach-average boundary shear stress varies commensurately according to *H* (which varies according to stage). To match the dynamic stress conditions of the backwater reach, *H* must vary

by a factor of 10, and stage data indicate that *H* increases only by a factor of two from low to high water discharge conditions. Therefore, with a transition to backwater hydrodynamics in the lower Mississippi River, there is a significant temporal range for boundary shear stress and sediment transport capacity. This condition renders "all or nothing", or "punctuated" conditions of sediment transport, whereby during low and moderate flow, sediment flux is extremely minimal, and only during high flow conditions is sediment flux robust throughout the backwater segment, delivering sediment to the Mississippi River delta (Nittrouer *et al.*, 2011a).

Channel morphology These temporal variations in sediment transport have several important influences on the morphological development of the river channel in the lower ~650 kilometres of the Mississippi River. Several studies have demonstrated, by way of field observation measurements and numerical models, diverse patterns of channel bed aggradation and erosion arising in the backwater segment of the Mississippi River (Carey & Keller, 1957; Lane, 1957; Nittrouer, 2011b; Lamb et al., 2012). Using a single-beam fathometer, Carey & Keller (1957) observed incomplete dune coverage of the lowermost Mississippi River between Baton Rouge and New Orleans (Fig. 2). They also noted that deep scour holes in bend segments exceed the upstream thalweg depth by a factor of five. These findings were surprising because lowland meandering rivers, particularly systems with large catchments and ample sediment supply, are typically covered by alluvial bedforms. Nittrouer et al. (2011b), using advanced multibeam bathymetry surveys, measured the spatial distribution of the channel bed sediment coverage for the lowermost Mississippi River from New Orleans to the outlet (165 km; Fig. 2). Their observations indicated that ~30-50% of the channel bed was devoid of active alluvial sediment (similar to the observations of Carey and Keller, 1957), and where alluvial sediment is absent, the channel is scouring into underlying substratum (Fig. 3). The substratum behaves physically as surrogate bedrock, and its exposure area, relative to active alluvial sediment, is related to the local (reach scale) radius of curvature for the channel (Nittrouer et al., 2011b). The overall exposure of the bedrock relative to alluvial cover qualifies the lower 165 km of the Mississippi River a "mixed bedrock-alluvial channel" (Howard, 1998; Nittrouer et al., 2011b).



Fig. 3 Mississippi River, at New Orleans (RK 165). Multibeam bathymetry data are used to resolve the dynamic channel bed topography and sediment composition. The image on the left was acquired during low water discharge, when bedform transport is minimal. The image on the right was acquired during high water discharge, when bedform transport increases by two orders of magnitude relative to low water discharge. In the bend segment, energetic flow removes sediment from the channel bed, exposing the eroding the underlying bedrock substratum (after Nittrouer *et al.*, 2008).

The limited alluvial cover and an erosional regime for the lower 200 km of the Mississippi River channel bed is explained by a spatially accelerating flow regime flow acceleration that persists in the lower reaches of the river during flood events. Nittrouer *et al.* (2012a) showed that adjustments in river stage spatially influence cross-sectional flow area in the backwater segment:

because the increase in river stage relative to flow depth decreases downstream (Fig. 1(a)), overbank flooding is minimized, effective channel width narrows (see Fig. 7a in Nittrouer *et al.*, 2012a), and cross-sectional area of channel flow decreases progressively downstream during floods. Water discharge is conserved because there are no outlets until \sim 30 km from the river–ocean interface, thus flow velocity must increase downstream during flood events. Additionally, Lamb *et al.* (2012) showed that flow velocity in the backwater segment of the Mississippi River is also influenced by style of lateral spreading of the discharge plume at the river outlet. The expansion of the river plume at the river outlet produces a condition of hydraulic drawdown within the lower 200 km of the river, and this accelerates downstream flow velocity within the channel. Accelerating flow in the lower reaches of the Mississippi River produces enhanced transport capacity and channel bed erosion.

Farther upstream, however, between the normal flow to backwater transition, at ~650 km above the outlet to ~250 km from the outlet (Fig. 2), the Mississippi River channel presents a completely different set of characteristics: the channel is ~30% wider relative to the lower 200 km, the width-todepth ratio increases also due to shallowing of the thalweg, and the grain size of channel bed sediment coarsens significantly (Nittrouer & Petter, 2012). These characteristics are consistent with modelling studies for this portion of the river that also show a tendency for channel bed sediment aggradation (Nittrouer *et al.*, 2012a; Chatanantavet *et al.*, 2012). Gradually varying flow arising at the backwater transition reduces sediment transport capacity, and the morphodynamic response is a downstream reduction in sediment transport which produces channel bed deposition. In effect, this is the start of deltaic deposition, whereby coarse sediment (>600 μ m) is preferentially deposited because this fraction necessitates the greatest shear stress for transport (Fig. 4). Thus, the channel bed aggrades due to sediment deposition at the normal flow to backwater transition.



Fig. 4 (a) Conceptual diagram of coarse sediment deposition occurring at the normal flow to backwater transition (after Parker, 2004). Sediment deposition drives a suite of morphodynamic responses. Farther downstream, the channel is deprived of alluvial sediment cover, exposing bedrock that is eroding in energetic bend segments. (b) Grain-size data for the Mississippi River (USACE, 1935). Note the distinct change in downstream fining at the backwater transition. Here, hydrodynamic conditions produce deposition of coarse sediments to the channel bed, thus preventing this component of sediment from downstream transport. This coarse sediment therefore does not reach the ocean.

Morphodynamic consequences There are three important morphodynamic consequences that arise because of aggradation at the Mississippi River backwater transition. First, over time, sediment deposition to the channel bed produces in-channel sedimentation that is not matched elsewhere in the fluvial system (i.e. the levees or flood plain). Therefore the channel bed aggrades with respect to the surrounding flood plain and adjacent levees. This condition leads to a greater likelihood for channel avulsions (Mohrig et al., 2000; Jerolmack & Mohrig, 2007), and because the system is relatively proximal to the receiving basin, these avulsions form new distributary channels that will relocate the river-ocean depositional region along the coastline over many tens to hundreds of kilometres (Roberts, 1997; Jerolmack & Swenson, 2007). This region of initial inchannel sediment deposition defines the upstream beginning of the coastal delta system. The second important morphodynamic consequence is increasing lateral mobility of the channel. This arises because: (1) in-channel deposition of coarse bed material sediment builds alluvial bars, which redirect the thalweg to the river banks, leading to bank erosion and widening of the river channel; uniform channel width is maintained by commensurate sediment accumulation on the interior banks (Ikeda et al., 1981; Nelson & Smith, 1989; Hasegawa, 1989). For the Mississippi River system, elevated rates of lateral mobility have been measured at the normal flow to backwater transition (Hudson & Kesel, 2000; Nittrouer et al., 2012a). Interestingly, farther downstream, lateral migration of the river nearly ceases where the river transitions from net bed aggradation to net erosion (~250 km from the outlet; Nittrouer et al., 2012a). Therefore, an important morphodynamic link exists between spatially divergent sediment flux and rates of lateral mobility within the backwater reach of the Mississippi River.

Diminishing downstream transport capacity impedes the downstream movement of coarse bed material sediment, which in turn produces in-channel deposition. This condition "starves" the downstream reaches of the coarse alluvial sediment necessary to fully cover the channel bed, so the system erodes into the underlying substrate (hence a bedrock condition). This is particularly evident in energetic bend segments in the lowermost 200 km, where nearly all alluvial material is removed from the channel bed, and transported through the bend segment during high discharge as a part of suspended load transport (Nittrouer *et al.*, 2011a,b). Moreover, as measured by the United States Army Corps of Engineers, there is a significant decline in the grain size of bed sediments progressing downstream through the backwater reach, and this is indicative of extracting coarse sediment at the backwater transition (Fig. 4(b)).

An important consideration is the significant disconnect between the downstream velocities of sediment that translates primarily as suspended load *versus* bedload. For example, suspended sediment generally moves at the velocity of the moving fluid, which may be several orders of magnitude greater than the migration rate of dune forms (a good proxy for the velocity of sediment moving as bedload transport). Therefore, while sediment flux in the backwater reach is robust during high water discharge, the sediment actually reaching the river–ocean interface during flood events is suspended and fine grain-size (<300 μ m), while coarse bedload sediments may actually never reach the delta over the life cycle of the channel (i.e. before an avulsion event abandons an active channel to form a new distributary channel; Nittrouer & Petter, 2012).

Interestingly, Lane (1957) observed that rivers near their receiving basin (backwater reach) tend to infill with ephemeral fine-grain (mud) sediment during low and moderate water discharges, with excess sediment evacuated during subsequent flood discharges. The lower 200 km of the Mississippi River are not immune to mud infill: Galler & Allison (2008) documented channel deposition of mud, including the burial of previously active sandy bedforms (Nittrouer *et al.*, 2011b) during low and moderate water discharge when transport capacity in the lower reaches was reduced to the point that mud was settling from the water column. However, ensuing high water discharge erodes fine sediment, re-entraining the sediment as suspended load. The backwater reach of the Mississippi River is effectively a big settling basin during low and moderate water discharge.

Feeding the delta The alluvial sediment transported within the lowermost reaches of the Mississippi River, and therefore the sediment that contributes to delta growth, is $<300 \mu m$, is

readily mobilized in suspension, and is almost exclusively reaching the delta during high water discharge. Meanwhile, relatively coarse sediment (>600 μ m) that is transported via classic bedload (i.e. rolling, salting, sliding) slowly moves downstream during high discharge. This coarse sediment effectively stagnates during much of the discharge year, and a mass flux imbalance develops because more sediment enters at the upstream normal flow transition than leaves at the downstream delta. This leads to in-channel sediment aggradation, which eventually produces a channel avulsion and the generation of a new distributary channel that delivers sediment to the river–ocean interface. For the Mississippi River, data indicate that the avulsion recurrence interval is roughly 800–1200 years (Frazier, 1967). Moreover, the avulsions produce relatively rapid abandonment of a channel (decades), and the relocation of the active delta lobe by as many as tens to hundreds of kilometres on the coast (Roberts, 1997).

The important consideration for sustainability of the Mississippi River delta is that there is a significant overlap between the grain-size population of *sand* in suspension compared with sand on the channel bed, throughout the lower ~250 km, downstream from where coarse bedload is extracted (Fig. 4; Nittrouer *et al.*, 2011a). The sand in transport in the lowermost segment of the river is almost entirely fine to very fine in grain size (<300 μ m; Allison & Meselhe, 2010; Nittrouer *et al.*, 2011a), and this is one reason that energetic bend segments are devoid of bed material during high discharge events: fine sand is readily suspended, removing alluvial sediment from the channel bed and exposing the underlying substrate to erosion. Finally, it should come as no surprise that the sediment nourishing the Mississippi River delta system is in fact primarily very fine to fine sand, and this is observed by grain size analyses of the modern Balize lobe of the Mississippi River, as well as the Atchafalaya and Wax Lake subdeltas (Roberts *et al.*, 2003).

Key considerations for engineering a sustainable Mississippi River delta

Model guidance The recognition that backwater flow strongly attenuates time and space properties of sediment flux through the lower ~650 km of the Mississippi River is an important step toward exploring how the river system could be effectively engineered to deliver sediment to adjacent wetlands. In essence, this is a case study in applied geomorphology. Because the Mississippi River has been harnessed as a conduit for over a century, whereby artificial levees maintain dispersal of water and sediment directly to the open Gulf of Mexico with little interaction with the deltaic landscape, key questions now concern appropriate measures that will re-establish supply of the river's sediment resource to adjacent wetlands. It is important to emphasize that the solution is not as simplistic as untaming the river and letting nature run its course: any measures would need to protect human infrastructure from flooding, as well as maintain commercial interests, which necessitate a viable navigation channel for vessels of commerce. From recent studies, insights are emerging that provide new guidance regarding efficient ways to deliver water and sediment for land building.

One key finding is that sand, rather than mud, is crucial for initiating land growth because it settles near to the fluvial source (Day *et al.*, 2008) and provides a stable substrate for vegetation growth, which then aids mud deposition (Nepf, 2004). Although ~80% of the Mississippi River sediment load is mud (Nittrouer *et al.*, 2008), 50–70% of the juvenile delta volume in the Mississippi system is sand (Roberts *et al.*, 2003). As discussed above, sand transport in the lower river is robust during high discharge events (rather than low or moderate water discharge, when sand flux stagnates). During high discharge events, sand in the lower river is partitioned nearly equally between bedload (~54%) and suspended load (~46%), although this ratio changes over space, because within energetic bend segments all sand material is removed from the bed and transported as suspended load (Nittrouer *et al.*, 2011b). While sand transport is spatially dynamic, vertical sand concentration trends in the water column nevertheless show a strong tendency to increase approaching the bed (Nittrouer *et al.*, 2011a). These observations follow theoretical models that indicate much higher concentrations of suspended load near the bottom of the channel, because sediment is suspended from the bed, and upward turbulent transport at any given depth is balanced by settling (e.g. Rouse, 1937; Yeh & Parker, 2012).

Recent numerical modelling has allowed prediction of land building via controlled diversions from the Mississippi River (Paola *et al.*, 2011) with some model scenarios indicating land growth sufficient to offset estimated future land loss (Kim *et al.*, 2009). However, uncertainties remain concerning several necessary input parameters. For example, such models use values of sediment concentration in the Mississippi River that are measured in locations hundreds of kilometres apart, which cannot capture important local effects that will impact the timing and magnitude of sediment movement through engineered diversions. And, as discussed above, sediment flux in the Mississippi varies by several orders of magnitude over time and space. This indicates the importance of constraining local, reach-scale transport conditions when predicting sand input into river diversions (Nittrouer *et al.*, 2011a, 2012a). Constraining reach scale conditions will further enhance the reliability of land building models.

Important lessons from the 2011 Mississippi River flood Fortunately, data from a recent Mississippi River flood event have provided new insights into reach-scale sand transport dynamics. This information provides a nuanced understanding for efficient engineering designs to divert water and sediment for restoration purposes. After the 1927 flood of record on the Mississippi River, the United States Army Corps of Engineers (USACE) constructed the Bonnet Carré Spillway in Louisiana to divert floodwaters from the Mississippi River to Lake Pontchartrain (Barry, 1997) so as to reduce the water discharge flowing past New Orleans (Figs 2,5). The 2011 Mississippi River flood, which had the highest peak discharge since 1927, necessitated opening the 2500-m wide Bonnet Carré Spillway for 42-days, and during this period, average spillway discharge (6010 m³ s⁻¹) amounted to 10–20% of the total river flood discharge. By design, the spillway skims the upper ~5 m of water, or 10–15% of the water column, and while not intended to be a sediment diversion design, associated sediment nevertheless is carried from the river channel into the spillway.



Fig. 5 (a) Drawing of the Mississippi River and the Bonnet Carre Spillway (see Fig. 2 for overview location). The Spillway is opened during large flood events. Water and associated sediment flow from the Mississippi River into Lake Pontchartrain. (b) Photograph of extensive spillway sand deposit in following the 2011 flood event. (c) Channel profiles, indicated how the spillway effectively "skims" the upper five metres of flow. Nevertheless, this small portion of flow provided a significant volume of sand to the spillway, due to the subaqueous sand bar directly adjacent to the structure. (after Nittrouer *et al.*, 2012b)

The 2011 flood thus provided the opportunity to quantify sand transport into the Bonnet Carré Spillway. Nittrouer et al. (2012b) measured the volume of sand in the floodway, and showed that the value compared quite favourably with the volume diverted into it, as estimated using a physical model. Their results were incredibly compelling: while the average spillway discharge amounted to 10–20% of the total river flood discharge, conservative estimates indicated that 31–46% of the total sand load carried by the Mississippi River during the period of spillway opening was diverted into the floodway. Further analysis demonstrated that bend-scale variability in river sediment concentration can strongly affect the volume of sand diverted, and that local flow and bed conditions are vital in controlling the quantity of sand routed into a spillway diversion. For example, local riverbed stress conditions and the relatively fine-grained nature of the local bed sediment ($\sim 200 \ \mu m$) generated elevated concentrations of suspended sand in the upper water column adjacent to the Bonnet Carré Spillway. These local conditions are not matched in the reaches upstream, where the bed material is coarser (~270 µm). If the upstream grain-size distributions are used to calculate the bed material extracted by a diversion skimming the upper 5 m of the flow, the computed values are only 25-33% of that calculated adjacent to the Bonnet Carré Spillway. The study thus demonstrated that local conditions, such as bend configuration and the composition of the sand bar adjacent to a diversion, favour the delivery of sand from the river into the neighbouring wetlands at substantially higher rates than for other portions of the river, such as straight reaches.

The analysis by Nittrouer *et al.* (2012b) complemented observations from the 2011 flood with USACE measurements of sand deposits from three previous spillway openings and show that ratios are within a factor of two, and thus predictions of the volume of sediment extracted from the river during previous Bonnet Carré Spillway openings matches measurements and, importantly, the 2011 event was likely not anomalous in terms of the volume of sand routed through the spillway. Why is river planform so important to consider when diverting sediment through engineered diversions? Because the positions of alluvial bars in meandering rivers, as well as their effectiveness in trapping alluvium, are coupled to planform geometry and particularly bend configuration (Garcia, 2008). The location of the Bonnet Carré Spillway with respect to the bend immediately upstream is advantageous for sustained extraction of relatively fine sand from the Mississippi River.

Another important finding from the 2011 Bonnet Carré Spillway study is that the grain size distribution of the sand deposited in the spillway consistently overlapped that of sand on the adjacent Mississippi River bar, with essentially no sediment finer than ~120 μ m, thus indicating that: (1) the riverbed entrainment stress was similar to the depositional stress on the floodway bed; (2) much of the bed sediment leaving the Mississippi River was deposited in the first 2.5 km of the spillway; and (3) any washload (mud) was transported over long distances (~10 km) to Lake Pontchartrain, likely due to bed stress throughout the spillway that was sufficient to keep mud in suspension.

The performance of the Bonnet Carré Spillway during the flood of 2011 demonstrates how future practices during flood events could be coupled with land rehabilitation efforts in southern Louisiana, and also provides a template for schemes in similar environments worldwide. The results indicate that knowledge of the local channel morphodynamics is critical to optimize the location, size and operation of a diversion structure, thereby boosting the sand delivery above that predicted using reach-averaged values.

Looking toward the future In the Mississippi delta, it has previously been suggested that: (1) the supply of sediment due to overflow from the lower Mississippi River to the adjacent wetlands was relatively trivial even before the advent of engineered levees (Turner & Boyer, 1997; Turner *et al.*, 2006), and (2) insufficient sediment supply is one of two factors that render drowning of the Mississippi delta inevitable (Blum & Roberts, 2009). The key to land building via engineered diversions, however, is the effective dispersal of sand, which creates a platform for allowing the subsequent capture of mud and formation of organic soils. An example calculation indicates that diversion of 45% of the mean annual sand load of the lower Mississippi River would

result in the construction of ~900 km² of new land over a century (Kim *et al.*, 2009). The observed diversion of 4.9×10^6 m³ of sand into the Bonnet Carré Spillway during the 2011 flood, which tapped only the top 5 m of river flow, provides new quantitative evidence of the feasibility of land building. Insofar as river sinuosity declines downstream (Nittrouer *et al.*, 2011b) and characteristic annual flood flows have lower stages than the flood of 2011, an engineered diversion downstream of the Bonnet Carré Spillway should tap flow to a substantial depth rather than skimming from the top (Kenney *et al.*, 2013). However, results from the flood of 2011 indicate that both the depth and width of any diversion structures can be optimized by locating them on the inside of bends downstream of the apex, so as to route sand from the channel. Further optimization using these findings can be obtained using numerical modelling that captures the local morphodynamics (Alison & Meshele, 2010).

CONCLUSIONS

Fluvial deltaic coastlines are extremely important for societal welfare because these regions host many hundreds of millions of people worldwide. However, deltas are subjected to increasingly severe anthropogenic and environmental stresses, and due to the extremely low topographic relief, deltas are quite susceptible to drowning as a result of accelerating sea-level rise. Deltaic rehabilitation efforts are therefore required at a global scale in order to provide delta environments with proper nourishment to stand a "fighting chance" at future survival. Fundamental to these restoration efforts is the need to re-establish water and sediment interactions between fluvial distributary channels and neighbouring deltaic wetlands. Because many deltas worldwide are anthropic, engineering remediation is likely the only acceptable solution that both delivers sediment resources while protecting infrastructure from flooding. Fundamental to designing efficient engineering services is constraining hydrodynamic conditions and sediment transport processes that arise in river systems near the ocean interface.

For large lowland rivers, such as the Mississippi River, backwater hydrodynamics play an important role modulating magnitude and timing of sediment transport in the delta system by influencing flow velocity and boundary shear stress. For example, during low and moderate water discharge, boundary shear stress decreases significantly in the lower few hundred kilometres, and transport of bed material sediment (sand) is effectively stagnated. Rising water discharge increases boundary shear stress by a factor of 10, which in turn raises bed material sediment flux by two orders of magnitude. Therefore, in the lower reaches of large rivers, delivery of sediment to neighbouring wetlands for delta restoration efforts should be timed with annual flood events. This is a critical point, because water may be conserved in the river channel during low and moderate water discharge periods, when flow depth is necessary for navigation by vessels of commerce.

Finally, as recent research has documented, much of the Mississippi River delta topset deposit is comprised of the relative coarse-grain fraction of sediment reaching the river–ocean interface (i.e. $150-300 \mu m$). Therefore, while this sediment comprises <20% of the overall sediment discharge by the river, it serves as the framework sediment for bifurcating channel networks and island deposits, and is a crucial component for building juvenile landform. Recent research has documented that extraction of very fine to fine sand is most effective where diversions are positioned adjacent to, and inside of, planform-fixed alluvial sand bars. The channel planform and ensuing hydrodynamic properties that develop locally insure that sand sediment is continuously deposited atop inner-bend bars, and therefore these locations provide a consistent supply of sand into the diversion structure.

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