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Observational and numerical particle tracking to examine sediment dynamics in a Mississippi River delta diversion

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A B S T R A C T

River diversions may serve as useful restoration tools along coastal deltas experiencing land loss due to high rates of relative sea-level rise and the disruption of natural sediment supply. Diversions mitigate land loss by serving as new sediment sources for land building areas in basins proximal to river channels. However, because of the paucity of active diversions, little is known about how diversion receiving-basins evacuate or retain the sediment required to build new land. This study uses observational and numerical particle tracking to investigate the behavior of riverine sand and silt as it enters and passes through the West Bay diversion receiving-basin located on the lowermost Mississippi River delta, USA. Fluorescent sediment tracer was deployed and tracked within the bed sediment over a five-month period to identify locations of sediment deposition in the receiving-basin and nearby river channel. A computational fluid dynamics model with a Lagrangian sediment transport module was employed to predict selective pathways for riverine flow and sand and silt particles through the receiving-basin. Observations of the fluorescent tracer provides snapshots of the integrated sediment response to the full range of drivers in the natural system; the numerical model results offer a continuous map of sediment advection vectors through the receiving basin in response to river-generated currents. Together, these methods provide insight into local and basin-wide values of sediment retention as influenced by grain size, transport time, and basin morphology. Results show that after two weeks of low Mississippi River discharge, basin silt retention was approximately 60% but was reduced to 4% at the conclusion of the study. Riverine sand retention was approximately near 100% at two weeks and 40% over the study period. Modeled sediment storage was predicted to be greatest at the margins of the primary basin transport pathway; this matched the observed dynamics of the silt tracer but did not match the behavior of the sand tracer. The degree to which the observational measurements deviate from the model predictions may indicate the relative influence of physical processes other than the mean riverine generated currents, such as tides, wind generated currents, and waves.

1. Introduction

Large river deltas are under threat worldwide in response to the effects of climate change and direct human modification of their geomorphic processes and ecosystems (Day et al., 2008; Bianchi and Allison, 2009). The vast coastal wetlands in and around deltas often support extremely productive fisheries and aquatic habitat (Boesch and Turner, 1984; Bell, 1997; Day et al., 1997) and offer inland areas valuable protection from large storms (Costanza et al., 2008). However, these wetlands are under particular threat due to very large rates of land loss (Gagliano et al., 1981; Britsch and Dunbar, 1993). This wetland loss is driven by system-wide modifications that include (1) declining sediment supply arriving from upland sources due to damming and the disruption of floodplain connectivity (Meade et al., 1990; Syvitski et al., 2007), (2) accelerating rates of eustatic sea level rise (ESLR) that can drown low elevation coastal wetlands (Blum and Roberts, 2009), (3) possible

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increases in the frequency or intensity of tropical cyclones that remove wetlands through wave attack and wholesale removal of the surficial organic layer (Morton and Barras, 2011), and (4) artificial leveeing, and re-direction and closure of delta distributary channels for flood control and to improve navigation between inland and coastal waters (Syvitski and Saito, 2007). In deltaic wetlands, the problem is greatly compounded by subsidence driven relative sea level rise (RSLR) that often exceed ESLR and are caused by both natural (e.g., Holocene sediment compaction, peat oxidation) and human (e.g., geofluid withdrawal) drivers (Syvitski et al., 2009; Yuill et al., 2009; Kolker et al., 2011; Allison et al., 2016).

One potential restoration method to maintain deltaic wetlands in RSLR conditions is to divert sediment-laden water from distributary channels into the adjacent wetland basins. While water and sediment diversions from distributary channels has been practiced in a number of deltas worldwide for various purposes (see Allison et al., 2014 for examples), preservation of existing deltaic wetlands and restoration of lost wetlands in the Mississippi delta exceeds the scope of previously attempted projects. Restoration on this scale may be possible, because, as a sediment supply-dominated delta characterized by low wave and tidal energy (Roberts, 1997), the modern (<7.5 kyr) extent of Mississippi delta's wetlands has been primarily controlled by late Holocene, depositional lobe-forming processes. Reintroduction of sediment-laden river water, which mimics the natural effects of crevasse splay formation and evolution in deltas (Kim et al., 2009; Allison and Meselhe, 2010; Paola et al., 2011; Meselhe et al., 2012; Wang et al., 2014) is a major strategy proposed in the delta's ecosystem restoration plan (LACPRA, 2012).

The key elements of future distributary channel design in deltaic wetlands for land building from diverted river water are maximizing (1) the water to suspended sediment ratio in the diversion relative to the river (Meselhe et al., 2012) and (2) the retention of sediments in the receiving area. Maximizing sediment capture, particularly of the sediment (sand and coarse silt) in suspension and available for capture by a diversion will be controlled by factors such as (1) the angular orientation and intake invert elevation of the diversion channel (Gaweesh and Meselhe, 2016; Yuill et al., 2016), and (2) proximity to bank margin sand bars (lateral or point bars) that are a significant local source of bed material load (Ramirez and Allison, 2013; Allison et al., 2014).

The concentration, grain size, and timing of the sediment captured by the diversion will impact sediment retention in the receiving area—the second key element of diversions mentioned above. For example, it is more beneficial to divert relatively coarse sediment because of its faster settling velocities and enhanced resistance to resuspension. Both sand and mud are likely critical for optimizing splay deposition: sand with rapid settling and limited consolidation forms a firm substrate for initial subaerial emergence, while fines serve to sustain existing wetlands in the basin and aid in vertical accretion when subaerial areas are colonized by vegetation (Peyronnin et al., 2016). Sediment retention efficiency in the receiving basin will also be controlled by the evolution of splay islands and channels, as can be observed in the evolution of the Wax Lake delta in Atchafalaya Bay (Roberts, 1998; Shaw and Mohrig, 2014; Shaw et al., 2016). Natural splay island development is an integral part of delta growth (Wellner et al., 2005; Esposito et al., 2013) as they provide resistance to local flow and shield inland waters from waves.

The West Bay Diversion (WBD) is the only diversion constructed to date in the Mississippi River (MR) designed for the purpose of building and sustaining wetlands by mimicking the crevasse splay process. This site provides a unique opportunity to investigate the performance of an operating sediment diversion, especially as it relates to capture efficiency and sediment retention in the receiving area (e.g., West Bay [WB]; Fig. 1). The present study utilizes a novel combination of particle tracking methods to investigate sediment movement in and around the WBD. The first particle tracking method is a field-based approach that samples the abundance of a deployed fluorescent sediment tracer. While fluorescent sediment tracers have long been used in fluvial sediment tracking studies (Kennedy and Kouba, 1970), recent laboratory advances permitting quantification of the fluorescent particle content in highly diluted concentrations (grains/kg of sediment; Marsh et al., 1997; McComb and Black, 2005) allow their wider applicability today to explore the combined influence of river currents, tides, and waves on the movement of riverine sediment (see Elias et al., 2011 for an example of the combined tracer-modeling approach similar to the present study). In the present experiment, fluorescent tracer was tracked from the river channel into and through a diversion receiving basin over three discrete time periods spanning five months. The second particle tracking method utilizes a computational fluid dynamics model to simulate the transport of individual sediment grains throughout the WBD based on the predicted flow (velocity and pressure) fields due to river currents only. The objective of this study is to utilize these particle tracking methods to characterize the behavior of riverine sediment as it passes through the WBD focusing on identifying preferred transport pathways and estimating areas of retention. The time window of analysis was kept short to increase the probability that a significant fraction of the fluorescent tracer was recovered and to minimize the amount of morphological changes that could occur within the basin relative to static bathymetry used in the model. The modeling component of this study was expanded to test how a set of engineered sand islands constructed within the receiving basin altered the predicted flow field and how, in turn, the altered flow field might have influenced basin sediment retention.

2. Study area

The WBD is an uncontrolled (earthen) diversion channel cut through the right descending bank of the MR at a point 7.6 km above the Head of Passes final bifurcation of the river channel (RK7.6; Fig. 1). The diversion was designed to renew a natural crevasse splay that was formed in 1838 and by the late 20th century had subsided and eroded into an open bay setting (i.e., West Bay) bounded by the MR bankline and remnant natural levees associated with natural Grand Pass (Coleman and Gagliano, 1964; Andrus, 2007). Completed in November 2003, the initial cut (59.4 m wide, 7.6 m deep) was designed to discharge an initial flow rate of 20,000 cfs (566 m^3/s) at the 50% duration stage of the MR. It was intended to be mechanically enlarged to a 50% stage duration flow rate of 50,000 cfs (1416 m^3/s) of the MR at Venice, Louisiana (Fig. 1) two to three years later if there was no evidence of thalweg capture (Sharp et al., 2013). While this mechanical enlargement was never carried out, the diversion cut self-evolved to 204 m wide with an average depth of 12.8 m depth by 2014 (Yuill et al., 2016). The Yuill et al. (2016) study documents how discharges through the diversion cut at moderate MR flow (15,600 m^3/s) peaked in 2009 at about 1200 m^3/s, and declined in the 2009–2014 period to about 700 m^3/s in spite of the increased cut cross-sectional area and hydraulic radius, likely due to increasing receiving basin bed elevation.

Bathymetric surveying in WB has shown that after an initial period of elevation loss, likely attributable to the passage of Hurricane Katrina in 2005 (Andrus, 2007), sediment accumulation has outpaced relative sea level rise (RSLR) causing shoaling. Kolker et al.