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Hydrodynamic controls on sediment retention in an emerging diversion-fed delta

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ABSTRACT

The morphodynamics of river-dominated deltas are largely controlled by the supply and retention of sediment within deltaic wetlands and the rate of relative sea-level rise. Yet, sediment budgets for deltas are often poorly constrained. In the Mississippi River Delta, a system rapidly losing land due to natural and anthropogenic causes, restoration efforts seek to build new land through the use of river diversions. At the Davis Pond Freshwater Diversion, a new crevasse splay has emerged since construction was completed in 2002. Here, we use beryllium-7 activity in sediment cores and USGS measurements of discharge and turbidity to calculate seasonal sediment input, deposition, and retention within the vegetated Davis Pond receiving basin. In winter/spring 2015, which included an experimental period of high discharge through the diversion, Davis Pond received 106,800 metric tons of sediment, 44% of which was retained within the basin. During this time, mean flow velocity was 0.21 m s^{-1} and mean turbidity was 56 formazin nephelometric units (FNU). In summer/fall 2015, the Davis Pond basin received 35,900 metric tons of sediment, 81% of which was retained. Mean flow velocity in summer/fall was 0.10 m s^{-1} and mean turbidity was 55 FNU. The increase in sediment retention from winter/spring 2015 to summer/fall 2015 may be due in part to the corresponding drop in water flow velocity, which allowed more sediment to settle out of suspension. Although high water discharge increases sediment input and deposition, increased turbulence associated with higher current velocity appears to increase sediment throughput and thereby decrease the sediment trapping efficiency. Sediment retention in Davis Pond is on the high end of the range seen in deltaic wetlands, perhaps due to the enclosed geometry of the receiving basin. Future diversion design and operation should target moderate water discharge and flow velocities in order to jointly maximize sediment deposition and retention and provide optimal conditions for delta growth.

1. Introduction

The morphodynamics of river-dominated deltas are largely controlled by relative sea-level rise and the supply and retention of sediment within deltaic wetlands. Over the last century, human engineering of river channels has greatly reduced the amount of sediment delivered to deltas (Stanley and Warne, 1993; Syvitski et al., 2005; Yang et al., 2005; Blum and Roberts, 2009; Meade and Moody, 2010). Dams reduce downriver suspended sediment concentration and containment levees prevent overbank deposition. Yet, despite recent reductions in fluvial sediment supply to many coastlines around the world, some rivers still carry sufficient sediment to build new deltas at their mouths [e.g. Atchafalaya and Wax Lake deltas, Louisiana (Roberts et al., 2003, Rosen and Xu, 2013, Carle et al., 2015); Río Sínu Delta, Colombia (Suarez, 2004); Río Patía Delta, Colombia (Restrepo and Kettner, 2012)]. In these cases, reduced sediment supply may be mitigated by high rates of sediment retention within the delta complex.

Today, many low-lying river deltas starved of sediment input are threatened by subsidence, sea-level rise, and other natural and anthropogenic processes such as dredging (Turner, 1997), subsurface fluid withdrawal (Kolker et al., 2011), sediment compaction (Törnqvist et al., 2008), hurricane and storm surge erosion (Barras, 2006), and eustatic sea-level rise (Blum and Roberts, 2009), which together may impair the sustainability of these landscapes. At the same time, deltas and other low-elevation coastal zones are home to over 625 million people globally (Neumann et al., 2015) and support numerous mega-cities (Syvitski and Saito, 2007). In the Mississippi River Delta (MRD; Fig. 1a), the combination of natural and anthropogenic processes has resulted in rapid land loss, with nearly 5000 km^2 of land having converted to open water over the last 80 years (Couvillion et al., 2011). Built over the last ~7500 years as distributary channel avulsions relocated sediment

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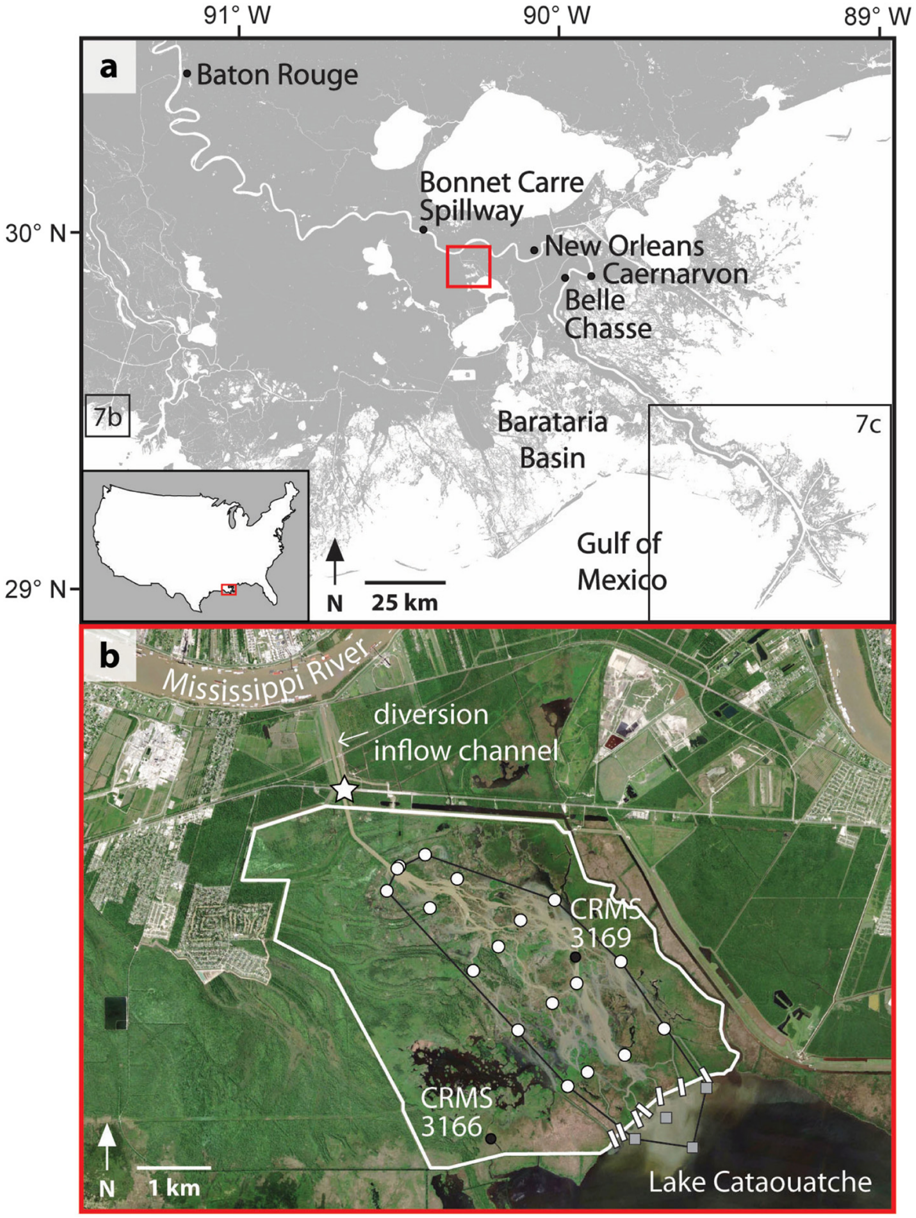

Fig. 1. (a) The Mississippi River Delta, southeastern Louisiana, USA. The red box indicates Davis Pond Freshwater Diversion (shown in detail in b). The boxes indicate locations shown in detail in Figs. 7b and c. (b) Satellite imagery of the Davis Pond area on April 6, 2016. The receiving basin is outlined in white; the coring area is outlined in black. Spring 2015 coring locations within the receiving basin are shown as white circles (note that two coring locations at the mouth of the diversion inflow channel are very close together and have symbols that largely overlap); grey squares indicate coring locations outside the receiving basin. White rectangles mark the 7 outflow channels that drain Davis Pond. The star indicates U.S. Geological Survey channel monitoring station 295501090190400 and black circles show the locations of two Coastwide Reference Monitoring System (CRMS) stations. Satellite imagery modified from Google Earth.

depocenters, the MRD is now largely in the transgressive phase of the delta cycle (Frazier, 1967; Roberts, 1997). Since the 1950s, sediment load in the Mississippi River has decreased by half (Blum and Roberts, 2009; Meade and Moody, 2010). Though growth and decay of individual delta lobes is a natural part of the delta cycle, the abovementioned anthropogenic impacts (dredging, subsurface fluid withdrawal, eustatic sea-level rise) have exacerbated land loss in the MRD, threatening coastal Louisiana's economy, infrastructure, and the overall sustainability of the delta (Turner, 1997; Blum and Roberts, 2009; Kolker et al., 2011).

Current restoration efforts in the MRD aim to maximize wetland building using the remaining sediment load in the river. Freshwater and sediment diversions play a central role in these endeavors (CPRA, 2017). These diversions are strategic, gated structures through the river levee that are designed to mimic natural deltaic land-building processes by restoring the delivery of fresh water, sediment, and nutrients to the adjacent wetlands (Roberts et al., 2003; Snedden et al., 2007; Kim et al., 2009). Interestingly, river diversions are anthropogenic countermeasures intended to mitigate land loss caused in large part by other anthropogenic activities. Each diversion structure can be engineered to optimize a variety of physical and ecological parameters specific to its location and purpose, including water discharge, velocity, and stage as well as impacts to fisheries in the basin and navigation in the Mississippi River (Allison and Meselhe, 2010, De Mutsert et al., 2017, Peyronnin et al., 2017). When river water flows through a diversion, it leaves the engineered realm and typically enters a relatively natural wetland setting. As water spreads across the wetland, it slows and drops its suspended sediments. Over time, if sediment deposition exceeds that which is lost through erosion and relative sea-level rise, wetlands may expand laterally and gain elevation (Roberts, 1997). The percent of sediment retained within a diversion receiving basin is critical in determining whether the wetlands expand or succumb to subsidence and sea-level rise. Indeed, a close analysis of Blum and Roberts

(2009) indicates that large shifts in sediment retention rate can convert projections of land loss in the MRD to land gain, even under conditions of accelerated sea-level rise.

Many interrelated factors affect sediment retention within a wetland, including vegetation type and density (Gleason et al., 1979; Braskerud, 2001; Adame et al., 2010), basin elevation gradient (Hook, 2003), and water residence time (Kleiss, 1996; Koskiaho, 2003). The purpose of this study is to further quantify hydrodynamic controls on sediment retention in a developing delta. Specifically, we compare sediment input, deposition, and retention at high and low water discharge through a river diversion. We hypothesize that optimal sediment deposition is determined by a balance between sediment supply and retention that varies with water discharge. Whereas increasing discharge delivers more suspended sediment to a developing delta, decreasing flow velocity reduces sediment throughput and leads to a greater percent sediment retention. Here, sediment throughput is defined as sediment that passes into and immediately out of a basin without being deposited. This hypothesis is tested in the receiving basin of the Davis Pond Freshwater Diversion, a sheltered, low-gradient freshwater marsh in southeastern Louisiana (Fig. 1b).

Our hypothesis implies that increasing water and sediment input to a deltaic wetland does not always lead to greater sediment deposition within the wetland. This is a novel hypothesis because previous discussions of river diversions have assumed that higher discharge is always better in terms of wetland building (e.g. Peyronnin et al., 2017). We suggest instead that there may be a tipping point along the discharge continuum, above which the increased water discharge no longer results in additional land building and increases the potential for detrimental ecosystem impacts. Diverting excess water may increase the inundation depth of wetlands and stress on vegetation (e.g. Snedden et al., 2015), intensify the flood risk for local landowners and communities (e.g. McAlpin et al., 2008), and more drastically alter the basin's salinity regime and harm local fisheries (e.g. Reed et al., 2007). Although Peyronnin et al. (2017) suggest that the operation of diversions during winter months would limit damage to vegetation and fisheries, further research is needed on this topic.

The ideal operation regime for a river diversion maximizes sediment delivery and deposition while minimizing water delivery. The water discharge associated with an ideal operation regime is expected to vary between diversions based on location, maximum discharge potential, geometry, and other site-specific characteristics. Here, we present short-term sediment accumulation rates for high- and low-flow seasons and compare them to long-term retention rates measured in the MRD and other deltas. Our findings may enhance the efficacy of engineered river diversions as restoration tools (specifically the planned Mid-Barataria Sediment Diversion in the lower Mississippi River Delta) and help ensure that optimal hydrodynamic conditions are achieved for sustainable delta building.

2. Study area

Davis Pond Freshwater Diversion is located on the right descending bank of the Mississippi River, ~30 km upstream from New Orleans, Louisiana (Fig. 1b). Davis Pond is a controlled diversion that redirects a variable amount of water from the river into a low-gradient receiving basin in upper Barataria Basin (Fig. 2a). Mean discharge through the diversion was ~36 $\mathrm{m^3\ s^{-1}}$ over the study period (Nov. 2014–Oct. 2015). Occasional periods of high discharge increase the flow up to a maximum of ~300 $\mathrm{m^3\ s^{-1}}$ and raise the water level in the receiving basin (Fig. 2b). These high discharge events typically last a few weeks and are often timed to coincide with a springtime rising limb of the Mississippi River hydrograph (Fig. 2c) when basin salinities are elevated.

Subsidence in the MRD averages ~9 mm $\mathrm{yr^{-1}}$ (CPRA, 2017; Nienhuis et al., 2017). Although subsidence is often highly spatially variable in wetland environments, recent studies suggest that subsidence in the Davis Pond area is near or slightly below the delta-wide mean (CPRA, 2017, Nienhuis et al., 2017). In the MRD, the rate of relative sea-level rise averages 13 mm $\mathrm{yr^{-1}}$ (CPRA, 2017; Jankowski et al., 2017). Meanwhile, rates of vertical accretion in the MRD are also spatially variable, but the delta-wide median value is ~11 mm $\mathrm{yr^{-1}}$ (Jankowski et al., 2017).

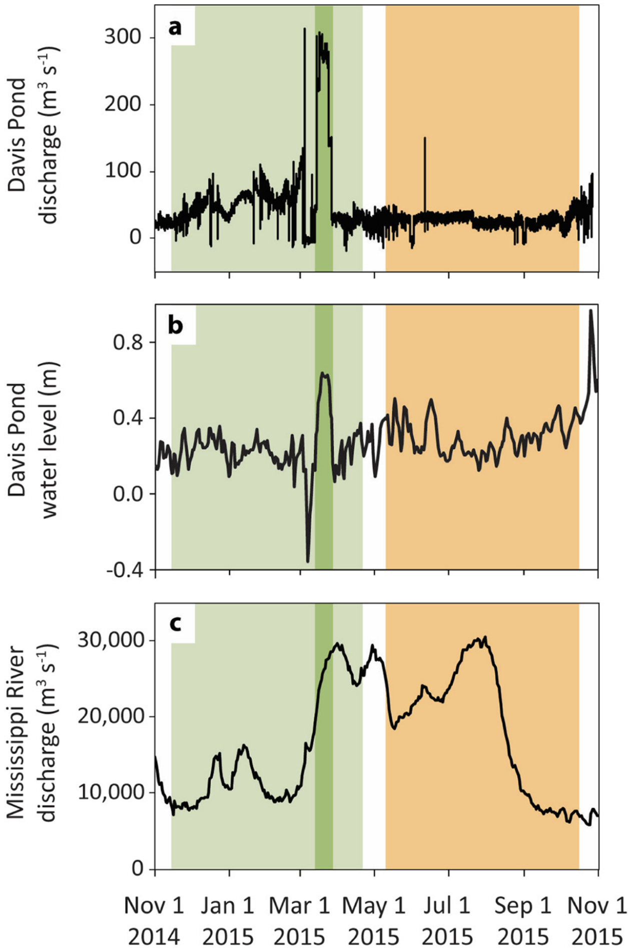

Fig. 2. Discharge through the Davis Pond inflow channel (a), water level in the Davis Pond receiving basin (b), and Mississippi River discharge at Belle Chasse (c) from Nov. 1, 2014 to Oct. 31, 2015. The two 159-day seasons used for analysis are shaded: winter/spring is in green and summer/fall is in orange. The dark green bar in the winter/spring season marks the two-week experimental high discharge event in Davis Pond.

The ~38 $\mathrm{km^2}$ receiving basin at Davis Pond is bounded by guide levees on three sides. To the south, water exits the basin primarily through seven man-made channels cut through the northwestern rim of Lake Cataouatche. From there, water flows through a series of shallow lakes and marshes, eventually reaching the Gulf of Mexico ~80 km to the south. Tidal range in Lake Cataouatche is limited to ~10 cm, and tides are diurnal. As a result, water levels in Lake Cataouatche and Davis Pond are primarily driven by meteorological conditions (wind direction and strength) and by variations in diversion discharge.

Construction of Davis Pond was completed in 2002 (http://www.mvn.usace.army.mil/About/Projects/Davis-Pond-Freshwater-Diversion/). Although freshwater diversions such as Davis Pond are primarily designed and operated to regulate salinity rather than to build land, a new crevasse splay has emerged at the mouth of the Davis Pond inflow channel. Mouthbar deposits and fringing marsh have begun to fill in previously open ponds. Today, wetlands in the receiving basin are dominated by herbaceous species (*Sagittaria lancifolia*, *Colocasia esculenta*, *Mikania scandens*, and *Polygonum punctatum*) with black willow (*Salix nigra*) colonizing higher elevation islands (CPRA, 2015).

In this study, we focus on sediment deposition occurring within the relatively small receiving basin immediately adjacent to the Davis Pond inflow channel (Fig. 1b). The wetland restoration potential of a diversion is greatest if the majority of the sediment passing through it is retained within the immediate ponding area. The concentration of sediment in a targeted area helps to offset relative sea-level rise and facilitates rapid wetland building. Although sediment that bypasses the Davis Pond receiving basin is likely trapped within the larger Barataria Basin, it is insufficient to build land across this entire area and may be considered lost, at least temporarily, from a wetland restoration perspective.

Davis Pond is one of the smallest engineered diversions currently in operation in the Mississippi River Delta. Some proposed diversions are nearly an order of magnitude larger in terms of discharge. The proposed Mid-Barataria Sediment Diversion, for example, will have a maximum discharge of ~2100 $m^3\ s^{-1}$ (CPRA, 2017). Despite the small size of Davis Pond, sediment delivery and deposition in the receiving basin are sufficient to build new land, which is clearly visible in historical satellite imagery (Supplemental Fig. 1) and analysis by the Deltares Aqua Monitor (http://aqua-monitor.deltares.nl; Donchyts et al., 2016). Additionally, critical similarities exist between Davis Pond and the Mid-Barataria diversion. Both diversions direct water and sediment into an existing framework of deteriorating wetlands rather than into an open bay. For this reason, Davis Pond is in some ways more useful as an analogue for the Mid-Barataria diversion than is the Wax Lake Delta, which is prograding into open water with no wetlands. Yet, the Wax Lake Delta is perhaps the most common analogue for the Mid-Barataria and other proposed diversions on the lower Mississippi River (e.g. Kim et al., 2009; Allison and Meselhe, 2010; Paola et al., 2011). Study of the land building at Davis Pond can better inform the design, operation, and expectations of future diversions that will be critical to restoring the MRD and other deltas around the world.

3. Methods

3.1. Calculation of seasonal sediment input

Total seasonal sediment input into Davis Pond was calculated using daily measurements of water discharge and turbidity following methods described in Allison et al. (2012). The U.S. Geological Survey (USGS) measures discharge in the Davis Pond inflow channel (29.91694° N, 90.31778° W; USGS, 2018a) and turbidity in the Mississippi River at Belle Chasse (29.85694° N, 89.97778° W; USGS, 2018b), ~70 river km downstream from Davis Pond (Fig. 1a). Allison et al. (2012) assumed that turbidity of the water entering Davis Pond is the same as that at Belle Chasse, and we make the same assumption here. Turbidity measurements made at Belle Chasse provide a good estimate of turbidity at Davis Pond because only one significant diversion of Mississippi River water exists between Davis Pond and Belle Chasse. The mean discharge through this other diversion (the Caernarvon Freshwater Diversion) was only ~13 $m^3\ s^{-1}$ during 2015, and thus was likely much too small to significantly impact downstream Mississippi River sediment loads. Furthermore, results from Allison et al. (2012) indicate that together Davis Pond Freshwater Diversion, Caernarvon Freshwater Diversion, and the Bonnet Carre Spillway (~15 river km upstream from Davis Pond; Fig. 1a) account for 50% and 26% of the observed decrease in water discharge and suspended sediment load, respectively, between Baton Rouge and Belle Chasse. The authors hypothesize that the remaining suspended sediment is deposited and stored in the basin via channel aggradation and/or overbank deposition (Allison et al., 2012). Between Davis Pond and Belle Chasse, the Mississippi River levees closely follow the banks of the river, leaving batture that is generally only 30–300 m wide. Erosion and direct runoff into the river is likely minimal. As a result, turbidity measurements at Belle Chasse provide a minimum estimate for the turbidity of the water entering Davis Pond.

Daily suspended sediment concentration of the Mississippi River at Belle Chasse was calculated by inputting daily turbidity measurements into the following best-fit linear regression based on Belle Chasse data collected by the USGS (Fig. 3):

$$TSS = 2.047 \times turbidity + 2.1827 \tag{1}$$

where *TSS*, or total suspended solids, is the mean daily suspended sediment concentration at Belle Chasse (mg L^{-1}) and *turbidity* is the mean daily turbidity at Belle Chasse (formazin nephelometric units, FNU).

Daily sediment mass input into Davis Pond, $flux_{sed}$, was calculated as

$$flux_{sed} = TSS \times q_{div} \tag{2}$$

where q_{div} is the mean daily discharge through the Davis Pond inflow channel. Total mass of sediment input through the Davis Pond diversion during each study season, $mass_{sed}$, was calculated as

$$mass_{sed} = \int_0^T flux_{sed} dt \tag{3}$$

where 0-*T* is the time interval of interest and *t* is time. Total mineral sediment input, sed_{input}, was calculated as

$$sed_{input} = mass_{sed} \times mc_{river} \tag{4}$$

where mc_{river} is the average mineral content of Mississippi River suspended sediment (81.54%; Supplemental Table 1). Where gaps existed in the USGS turbidity data (Jun. 16–Jul. 15 and Oct. 6), values were estimated by linear interpolation between the data points on either side.

3.2. Calculation of seasonal sediment deposition

To reconstruct seasonal-scale sediment deposition in Davis Pond, sediment cores 6.5 cm in diameter and 5 cm deep were collected in April and October 2015. Twenty-two coring locations (Fig. 1b and Supplemental Table 2) were selected to assess lateral and distal variability in sediment mineral content, bulk density, and deposition rate across the receiving basin. Eighteen cores were collected on the marsh platform at elevations ranging from 10 cm above to 25 cm below water level at the time of coring. The four cores most distal from the diversion inflow channel were collected in 1.5–2 m of water at the northwestern rim of Lake Cataouatche. Initial sampling occurred on April 21, 2015, following an experimental period of high discharge through the diversion from March 13 to March 26. During this period, diversion discharge increased from a mean base flow of ~36 $m^3\ s^{-1}$ to a maximum rate of ~300 $m^3\ s^{-1}$ (Fig. 2a). At this time, Mississippi River discharge was

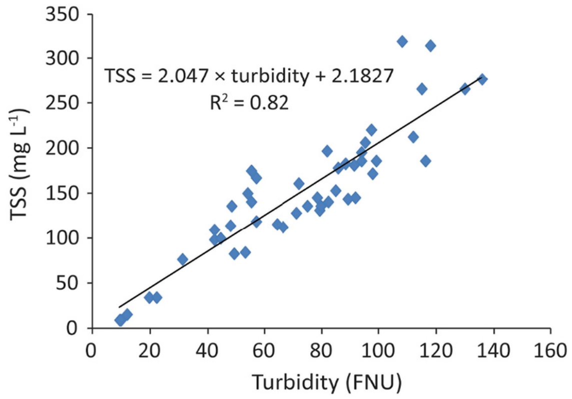

Fig. 3. Ratings curve used to predict Mississippi River TSS values from measured turbidity at Belle Chasse.

rising, nearing its first major peak of the water year (Fig. 2c). To capture seasonal variability, a second set of cores was collected on October 15, 2015, when river discharge was near minimum for the water year and mean diversion discharge had been ~36 $m^3 s^{-1}$ for the prior ~7 months.

In the lab, cores were sectioned into 1-cm depth intervals and analyzed for the following geotechnical parameters (see Supplemental Tables 3 and 4): 1) water content, determined by weighing a sample before and after it is dried at 60 °C for 24 h or until a constant weight is reached; 2) mineral content, calculated by combusting a dry sample at 450 °C for 6 h and subtracting the mass loss on ignition; 3) dry bulk density, calculated using water and mineral content (Kolker et al., 2009); and 4) new sediment deposition, determined using activity of the radioisotope beryllium-7 (^{7}Be) as measured by a low-energy gamma spectrometer (Sommerfield et al., 1999, Esposito et al., 2013; see Supplemental Figs. 3 and 4). Measurements of mineral content and bulk density were averaged over the interval of ^{7}Be detection to get a single value for each parameter per core. For cores in which no ^{7}Be was measured, mineral content and bulk density measurements from the top 1 cm were used for subsequent calculations.

Seasonal sediment deposition was measured using the presence of ^{7}Be within samples (analyzed at 1-cm depth intervals) as an indicator of newly deposited sediment. ^{7}Be adheres to mud-size particles and has a short (53-day) half-life, making it an excellent tracer of seasonal-scale sediment dynamics (Sommerfield et al., 1999; Esposito et al., 2013). If a core interval contained detectable surficial ^{7}Be, the sediments were considered to have been deposited within the last three half-lives of the isotope, or 159 days (Kolker et al., 2012). After three half-lives, the vast majority (87.5%) of the ^{7}Be has decayed. Sediments in cores containing no detectable ^{7}Be were considered to have been in place for >159 days. At each coring location, the mass of mineral sediment deposited in the previous 159 days, sed_{core} (g cm^{-2}), was calculated as

$$sed_{core} = z_{Be7} \times BD \times mc \tag{5}$$

where z_{Be7} is the depth (cm) to which ^{7}Be was detected, BD is the dry bulk density (g cm^{-3}), and mc is the mineral content (%) of the sample. Values for sed_{core} were then spatially interpolated across the 13.5 km^2 coring area for each 159-day season using a natural neighbor interpolation algorithm (Sibson, 1981) in ArcGIS to provide $sed_{deposit}$, an estimate of the total mineral mass deposited during each season.

Although the coring area encompasses only ~35% of the Davis Pond receiving basin, it includes the channels with the most active sediment transport, as visible in satellite imagery (Fig. 1b). This visual assessment is supported by data from the two Coastwide Reference Monitoring System (CRMS) stations that are located within the Davis Pond receiving basin (Fig. 1b, Supplemental Fig. 2; https://www.lacoast.gov/crms2). At CRMS station 3169, which is located within the coring area (and within the area of high sediment transport), the top 24 cm of soil show distinct surface-ward trends of increasing bulk density and decreasing organic content, suggesting input of mineral-rich sediment from the diversion. In contrast, at CRMS station 3166, which is located within the receiving basin but outside of the coring area, the top 24 cm of soil have consistently low bulk density and high organic content, suggesting little to no input from the diversion. Additionally, qualitative observations of water flow during field work supported our assertion that waterways outside of the coring area have minimal flow and appear clearer, suggesting they carry less suspended sediment. The locations of these channels remain stable over timescales relevant to this study (months to years; Supplemental Fig. 1), and thus our coring area provides a reasonable estimate of basin-wide sediment trapping.

3.3. Calculation of seasonal sediment retention

Two study seasons were defined, each the length of three half-lives of ^{7}Be (159 days) leading up to a core collection date. The winter/spring season is November 14, 2014 to April 21, 2015. The summer/fall season is May 10, 2015 to October 15, 2015. The percent of sediment retained within the receiving basin during each 159-day season, sed_{retain}, was calculated as

$$sed_{retain} = sed_{deposit} / sed_{input} \tag{6}$$

4. Results

4.1. Geotechnical parameters

New sediment deposited in the coring area ranged in thickness from 0 to 5 cm in the winter/spring (Fig. 4a, Supplemental Fig. 3) and 0 to 3 cm in the summer/fall (Fig. 4b, Supplemental Fig. 4). Controlling for distance along the basin axis, the thickness of new sediment was significantly greater in the winter/spring than in the summer/fall, according to a one-way ANCOVA statistical test ($F_{1,721} = 89.92$, $p < .0001$; Fig. 5a and b).

Spatial patterns of soil mineral content and bulk density corresponded well with field-based qualitative observations of water flow through the Davis Pond receiving basin. In the winter/spring, mineral content ranged from 56% to 96% by mass (Fig. 4c). Samples collected near the mouth of the inflow channel had the highest mineral content. Adjacent to main channels, mineral content was also high, and generally decreased with downstream distance. Cores with lowest mineral content were collected in areas of backwater marsh where flow was minimal. Soil bulk density in the winter/spring ranged from 0.1 g cm^{-3} to 0.7 g cm^{-3} (Fig. 4e). Spatial patterns in bulk density were similar to those for mineral content, with higher bulk densities near the mouth of the inflow channel and through the center of the receiving basin in areas proximal to main channels, and lowest bulk densities in areas of backwater marsh with minimal flow and low mineral content. Distributions of mineral content and bulk density were similar in the summer/fall low-flow season (Fig. 4d and f, respectively), both in terms of the range of measured values and spatial patterns across the study area. Controlling for distance along the basin axis, one-way ANCOVA statistical tests show that there were no significant seasonal differences in soil mineral content ($F_{1,721} = 0.09$, $p > .05$; Fig. 5c and d) or in bulk density ($F_{1,721} = 0.95$, $p > .05$; Fig. 5e and f). Detailed sediment core data are available in Supplemental Tables 2–4.

4.2. Seasonal sediment retention

In the winter/spring, Davis Pond received an input of 106,800 metric tons of mineral sediment from the Mississippi River, based on measurements of water discharge and turbidity. During this time, mean turbidity of the Mississippi River was 56 FNU, and mean flow velocity in the Davis Pond inflow channel was 0.21 m s^{-1}. Forty-four percent of the mineral sediment flux (47,100 metric tons) was deposited and retained within the 13.5 km^2 coring area. Fig. 4g shows the spatial distribution of new mineral sediment accumulation. Table 1 summarizes seasonal parameters affecting sedimentation.

In the summer/fall, Davis Pond received 35,900 metric tons of mineral sediment from the Mississippi River, about one-third of the sediment mass received in the winter/spring (Table 1). According to a one-way ANCOVA statistical test, mineral sediment accumulation was significantly greater in the winter/spring than in the summer/fall, controlling for distance along the axis of the basin ($F_{1,722} = 111.47$, $p <$ .0001; Fig. 5g and h). In the summer/fall, mean turbidity of the Mississippi River was 55 FNU (calculated using the 128 days of available data), and mean flow velocity in the Davis Pond inflow channel was 0.10 m s^{-1}. Although mineral sediment input decreased from the winter/spring to the summer/fall and water turbidity remained the same, sediment retention increased to 81%, as 28,900 metric tons of mineral sediment were deposited in the 13.5 km^2 coring area (Fig. 4h).

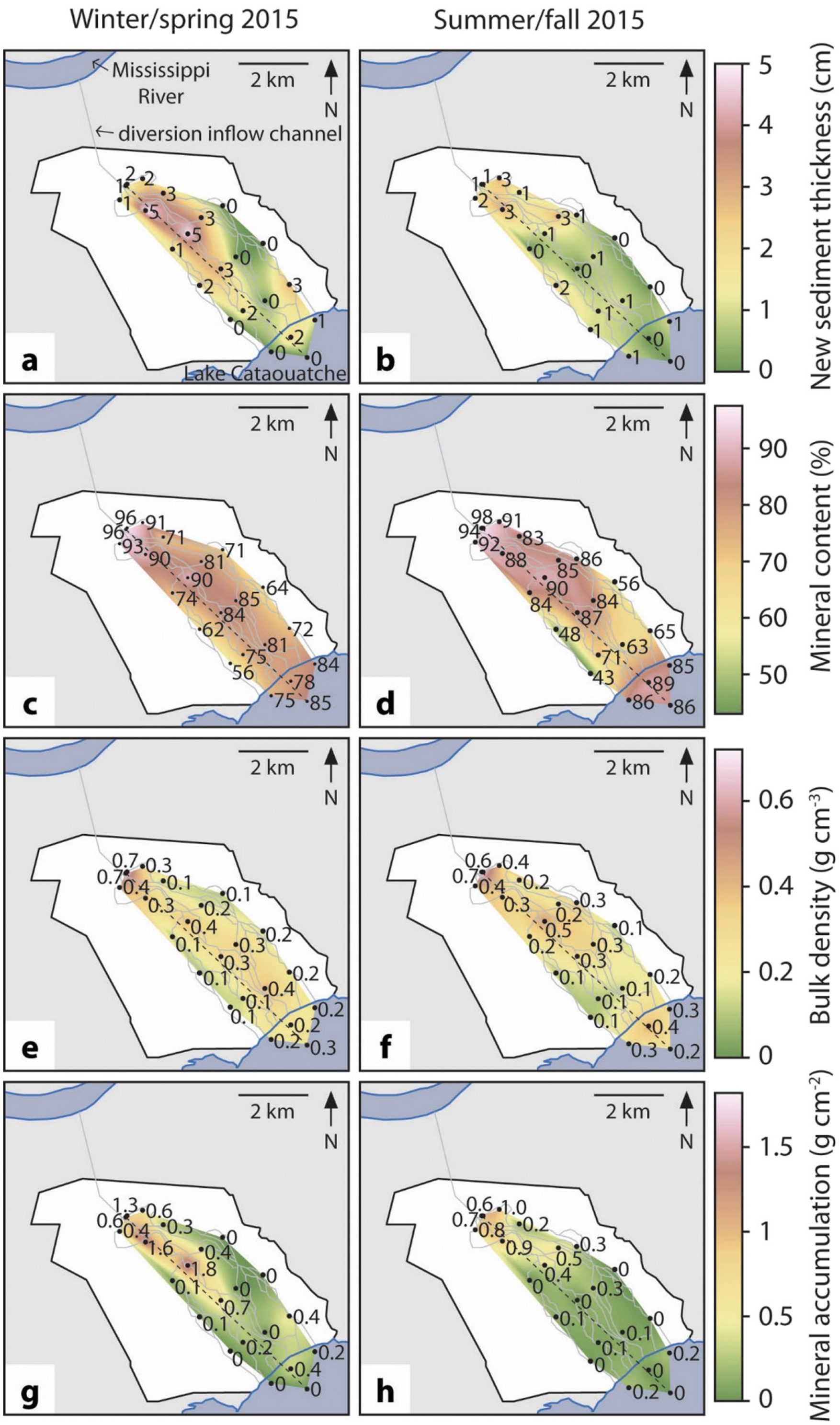

Fig. 4. Measurements and natural neighbor interpolation of new sediment thickness (a, b), mineral content (c, d), and bulk density (e, f), and calculated mineral accumulation (g, h) at 22 coring locations in the winter/spring and the summer/fall of 2015. Solid grey lines indicate major flow paths through the receiving basin (determined visually from satellite imagery, Fig. 1b). Dashed black lines indicate the lines of section used in Fig. 5.

5. Discussion

5.1. Controls on sediment retention

5.1.1. Water discharge, velocity, and turbidity

High sediment flux through the Davis Pond diversion during the winter/spring corresponds with the typical springtime rise in the Mississippi River hydrograph (Fig. 2c). Sediment stored on the riverbed is remobilized by the increased flow, increasing river TSS concentrations, and is subsequently conveyed through the diversion. The winter/spring season also included a rare two-week pulse of high discharge into Davis Pond that provided ideal conditions for the natural experiment studied here. During this time, the discharge was roughly tenfold higher and velocities roughly double those that occurred during typical diversion operations for the remainder of the winter/spring (Fig. 2a, Table 1). Increased velocity may account for the lower sediment retention in

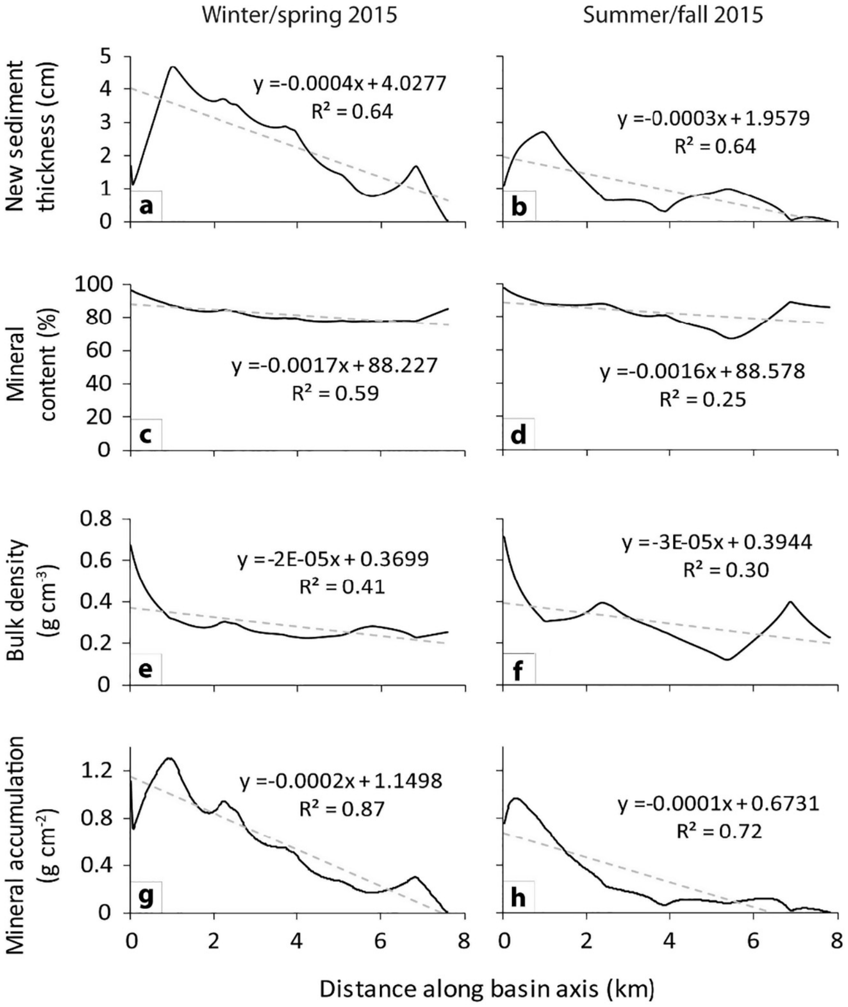

Fig. 5. Changes in soil geotechnical parameters with distance along the basin axis, in the winter/spring and the summer/fall of 2015. Each profile is constructed from the natural neighbor interpolation data shown in Fig. 4. See Fig. 4 for locations of the lines of section.

the winter/spring as compared to the summer/fall. Faster flow retains more sediment in suspension and decreases water residence time in the receiving basin. Accumulation of new sediment at the edge of Lake Cataouatche was slightly higher in the winter/spring than in the summer/fall (Fig. 4g and h), suggesting more throughput of suspended sediment during the period of elevated flow velocity. Sediment bypassed the receiving basin and settled out of suspension at the edge of the lake, where the channelized flow spread out and slowed.

In the summer of 2015, Mississippi River discharge remained unusually high, exceeding 17,000 $m^3\ s^{-1}$ until mid-August (Fig. 2c). Despite the elevated river discharge, average discharge through Davis Pond diversion in summer/fall was less than half of what it was in the winter/spring, and mineral sediment delivery to the diversion decreased by two-thirds. Though the drop in sediment input is primarily due to the decrease in diversion discharge, it is likely also due in part to a decrease in Mississippi River TSS concentration from the winter/spring to the summer/fall that is not fully captured in the average measurements reported here due to gaps in the USGS turbidity data (Fig. 6a). The USGS has continuous turbidity data for previous years, however. From the winter/spring to the summer/fall, turbidity dropped by 38% in 2013 and 13% in 2014. In a typical year, the bulk of the sediment stored on the riverbed is remobilized during the first large flood pulse of the spring (Mossa, 1996; Snedden et al., 2007). Less sediment is available for remobilization during subsequent flood pulses later in the summer.

Table 1

Summary of parameters affecting sedimentation within the Davis Pond receiving basin for the two study seasons.

Parameter	Winter/spring 2015 (Nov 14, 2014–Apr 21, 2015)	Summer/fall 2015 (May 10, 2015–Oct 15, 2015)
Mean water discharge into Davis Pond	62 $m^3\ s^{-1}$	26 $m^3\ s^{-1}$
Mass of mineral sediment input into Davis Pond	106,800 metric tons (656 metric tons day^{-1})	35,900 metric tons (220 metric tons day^{-1})
Mass of mineral sediment deposited in receiving basin	47,100 metric tons (296 metric tons day^{-1})	28,900 metric tons (182 metric tons day^{-1})
Percent of mineral sediment retained in receiving basin	44%	81%
Mean Mississippi River turbidity at Belle Chasse	56 FNU	55 FNU
Mean flow velocity in Davis Pond inflow channel	0.21 $m\ s^{-1}$	0.10 $m\ s^{-1}$

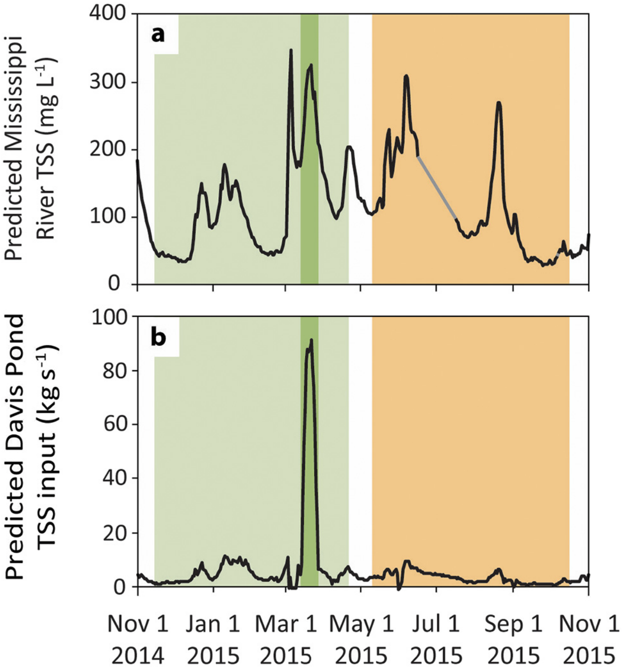

Fig. 6. Predicted Mississippi River TSS at Belle Chasse (a) and predicted TSS input into Davis Pond (b) from Nov. 1, 2014 to Oct. 31, 2015. In panel a, grey line segments indicate linear interpolations used to fill gaps in the USGS data. The two 159-day seasons used for analysis are shaded: winter/spring is green and summer/fall is orange. The dark green bar in the winter/spring season marks the two-week experimental high discharge event in Davis Pond.

5.1.2. Vegetation

In addition to hydrodynamic regime, vegetation type and density also impact sediment retention rates in wetlands. In general, wetland vegetation tends to decrease water flow velocity and thus decrease turbulence and shear stress at the soil-water interface and reduce soil erosion (Leonard and Luther, 1995; Neumeier and Ciavola, 2004; Gedan et al., 2011). Previous work has shown that vegetation biomass in marshes is typically maximized at the end of summer (Hopkinson et al., 1978), and several studies have identified linkages between vegetation density and sediment deposition in salt marshes (e.g. Kadlec, 1990; Leonard and Luther, 1995; Christiansen et al., 2000; Fagherazzi et al., 2012). In deltaic freshwater marshes, Nardin and Edmonds (2014) found that vegetation of moderate height and density maximizes sediment deposition during river floods. Thus, our fall 2015 cores from Davis Pond include material deposited over the summer growing season when vegetation conditions were near optimal for sediment trapping. This vegetation effect likely contributes to the observed increase in sediment retention from the winter/spring to the summer/fall.

5.1.3. Basin geometry and energy level

The high sediment trapping efficiency we observed in Davis Pond may partially result from the closed geometry and sheltered nature of the receiving basin (Fig. 7a). Water flows out of the receiving basin and into Lake Cataouatche via seven discrete channels, and each channel mouth is armored to prevent widening. Guide levees prevent lateral flow. This restricted geometry forces water to pond within the receiving basin, decreasing flow velocity and increasing residence time, both of which contribute to increased sediment deposition. In contrast, Wax Lake Delta is prograding into Atchafalaya Bay, restricted only by the pre-existing shoreline (Fig. 7b). Flow velocity there remains relatively high (0.05–0.73 m s^{-1} depending on the tide, Shaw and Mohrig, 2014), carrying sediment, particularly mud, out of the semi-enclosed basin. The Birdfoot Delta is an open basin, unrestricted by levees below 16.5 km above Head of Passes (Fig. 7c). Here, distributaries flow directly into the Gulf of Mexico near the edge of the continental shelf. High river velocity exports sediment into the Gulf, where it is subject to continued suspension by wind, waves, and currents. As a result, local sediment retention in the Birdfoot Delta is likely low (Wright, 1977).

Although our coring area encompasses only ~35% of the Davis Pond receiving basin, it includes all major sediment transport channels and adjacent marsh platform (Fig. 1b) and thus provides a good estimate

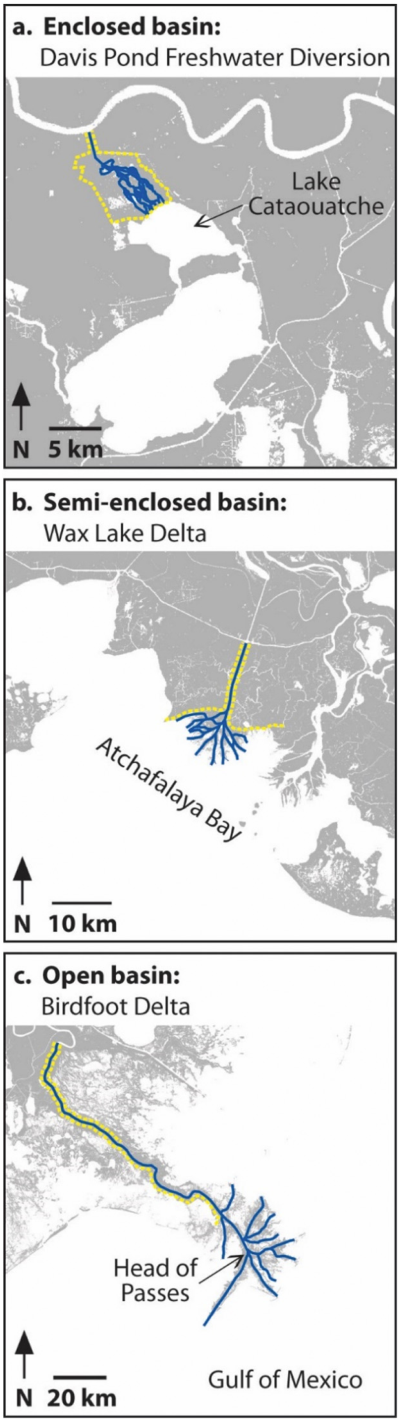

Fig. 7. Three basin geometry types. Solid blue lines indicate major water flow paths and dashed yellow lines indicate levees or restrictive shorelines. See Fig. 1a for basin locations.

of sediment retention in entire receiving basin. Any deposition that occurs in more lateral sections of the receiving basin (and thus not captured in this study) is expected to be very minor. Studies of other crevasse splays (e.g. Esposito et al., 2017) indicate that sediment deposition can be laterally extensive if the depositional basin is unconstrained. But the channels within the Davis Pond receiving basin are tightly constrained. On the west side of the basin, pre-existing topography from an 1884 crevasse splay (visible in satellite images as linear forested ridges) deflects modern channels to the southeast. To the east, intact and un-channelized marsh creates a barrier to substantial water flow. At the southern end of the basin, channel mouths are armored with rip rap and sheet piling to prevent widening and lateral migration. In addition, an examination of historical satellite imagery (Supplemental Fig. 1) shows that sediment-laden water is consistently confined to the center of the receiving basin (through time and varying water levels), coincident with our coring area. Bulk density and organic content data from CRMS stations 3169 and 3166 (Supplemental Fig. 2) further support these observations. Together, these lines of evidence strongly suggest that sediment deposition is extremely minimal in the lateral portions of the Davis Pond receiving basin. Any deposition that occurs outside of our coring area is not included in our estimates of sediment deposition, and thus our results are conservative. On the other hand, the coring area includes ~1.2 km^2 at the edge of Lake Cataouatche, which is outside of the receiving basin. Sediment deposition at the edge of Lake Cataouatche builds the initial subaqueous platform necessary for new marsh growth and thus is also useful for wetland restoration.

5.2. Comparison with other systems

Exceeding 80% during parts of the year, sediment retention in Davis Pond (Table 1) is higher than in many deltaic wetlands around the world (e.g. Nittrouer et al., 1995; Allison et al., 1998; Draut et al., 2005; Törnqvist et al., 2007; Blum and Roberts, 2009). Blum and Roberts (2009) estimate that deltas typically trap between 30% and 70% of sediment and use an estimated delta-wide trapping efficiency of 40% for their calculations of land loss in the Mississippi River Delta. Long-term (multi-decadal to century-scale) sediment retention has been measured at 39–71% in the Ganges-Brahmaputra Delta (using a field-based approach with methodologies similar to those presented in this manuscript; Allison et al., 1998), 33% in the Amazon Delta (using a mass-balance approach and a review of field-based methods; Nittrouer et al., 1995), 23% in Wax Lake Delta (using both a mass balance and a geometric approach; Törnqvist et al., 2007), and 27% in greater Atchafalaya Bay (using a mass-balance approach; Draut et al., 2005).

The spread in retention rates measured in these global deltas is largely due to the range of energy levels in their depositional environments (Roberts et al., 2015). Whereas these deltas with lower rates of sediment retention are all prograding into open water and subject to waves and currents, the Davis Pond diversion is building land within a framework of existing, sheltered marsh. This low-energy environment allows the deposition and retention of mud-size sediment. In contrast to Wax Lake Delta deposits, which are sand-dominated (Roberts et al., 2003), typical crevasse splay deposits in the MRD consist of ≥95% mud (Snedden et al., 2007; Esposito et al., 2017). Furthermore, Esposito et al. (2017) find that crevasse splays that are building into protected environments (such as Davis Pond) experience sediment retention rates that exceed 75% and may approach 100%.

Sedimentation at Davis Pond is comparable to that in the immediate ponding area of the Caernarvon Freshwater Diversion, another controlled Mississippi River diversion located ~60 km downstream. Annual mineral sediment input was 152,300 metric tons at Davis Pond (Nov. 2014–Oct. 2015; this study) and 100,000 to 130,000 metric tons at Caernarvon (Feb. 2003–January 2004; Snedden et al., 2007). During the respective study years, the two diversions experienced similar average annual diversion discharge (43 m^3 s^{-1} at Davis Pond and 42 m^3 s^{-1} at Caernarvon) despite different hydrodynamic regimes. Flood pulses at Caernarvon were more frequent (2 per year) but had lower discharge (140–200 m^3 s^{-1}) and were separated by long periods of zero or near-zero discharge. At Davis Pond, flood pulses were less frequent (1 per year) but had high discharge (280 m^3 s^{-1}) and typical non-flood discharge was well above zero (36 m^3 s^{-1}). During water years 2008–2010, water and mineral sediment input were higher for both diversions, although still within the same order of magnitude (Allison et al., 2012). During these years, Davis Pond and Caernarvon received an average of 390,000 and 273,000 metric tons of mineral sediment per year, respectively (calculated using 81.54% as the average mineral content of Mississippi River suspended sediment; Supplemental Table 1).

Seasonal rates of mineral sediment deposition and retention in Davis Pond are also comparable to the rates observed in Caernarvon. Flood season (winter/spring) deposition averaged 22 g m^{-2} d^{-1} in the Davis Pond coring area (this study) and 15–20 g m^{-2} d^{-1} (at minimum) in areas within 6 km of the Caernarvon diversion structure (Wheelock, 2003). Sediment retention during this time was 44% in Davis Pond (this study) and 48% in Caernarvon (synthesizing sediment deposition data from Wheelock, 2003 with co-incident sediment input data from Snedden et al., 2007). Non-flood season (summer/fall) deposition averaged 13 g m^{-2} d^{-1} in Davis Pond and 5 g m^{-2} d^{-1} in Caernarvon, and sediment retention was 81% in Davis Pond and 78% in Caernarvon.

5.3. Implications for coastal restoration

Efficient sediment trapping in coastal wetlands is critical in order to restore the MRD. Dam construction in the Mississippi River watershed has reduced the suspended sediment load in the river by half (Blum and Roberts, 2009). Meanwhile, the current rate of relative sea-level rise in the MRD averages 13 mm yr^{-1} (CPRA, 2017; Jankowski et al., 2017). Although the rapid progradation of Wax Lake Delta indicates that the sediment load in the modern Mississippi River is sufficient to build substantial amounts of land (Shaw and Mohrig, 2014), the remaining sediment in the river is a critical resource. For river diversions to be successful in building new deltaic wetlands in the face of subsidence and rising sea levels, sediment deposition and retention must be jointly maximized in the receiving basins. Scaling relationships for many hydrological processes are well known (e.g. Leopold, 1994) and in some cases have been validated for diversion-like settings (e.g. Snedden et al., 2007; Esposito et al., 2013; Shaw et al., 2018), providing a pathway for engineering studies to optimize water discharge and velocity in future diversions. While not the central focus of this study, diversion engineering and operation management will likely also incorporate an understanding of ecosystem impacts in the receiving basin and impacts to navigation in the Mississippi River (Allison and Meselhe, 2010; De Mutsert et al., 2017; Peyronnin et al., 2017).

Previous work has shown that high-discharge flood pulses are critical for delta building and, in some locations, may deposit enough sediment to offset relative sea-level rise (Snedden et al., 2007; Kolker et al., 2012; Esposito et al., 2013; Rosenheim et al., 2013; Carle et al., 2015; Shen et al., 2015). In Davis Pond, an experimental pulse of high discharge (March 13–26, 2015) delivered 41% of the total annual sediment supply in just 14 days (Fig. 6b). Although erosion may occur during periods of high discharge, modeling by Nienhuis et al. (2018) indicates that maximum land building in a crevasse splay occurs when rates of sediment deposition and erosion are balanced.

A conceptual model constructed from our data (Fig. 8) suggests that, for a given TSS concentration and diversion discharge capacity, moderate mean water discharge (which could encompass flood pulses and periods of lower discharge) may maximize sediment deposition in a developing delta. To construct this conceptual model, we first built a sediment input curve (blue curve, Fig. 8a) by relating observations of daily diversion discharge (Fig. 2a) to sediment input (Fig. 6b) using a power function. Next, we developed a sediment retention curve (red curve, Fig. 8a) by fitting an exponential function through our two sediment retention data points (Table 1) and setting the y-intercept to

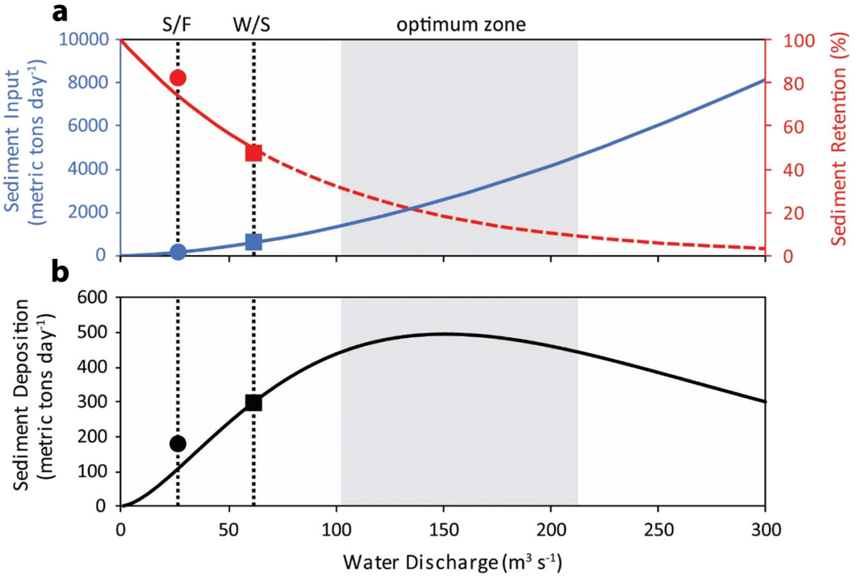

Fig. 8. (a) Conceptual model relating sediment input (blue) and retention rate (red) to diversion water discharge. The dashed portion of the retention curve offers a hypothesis for sediment retention at discharges higher that those observed in this study. (b) Receiving basin deposition rates predicted by the conceptual model. See text for details on how the curves were constructed. The shaded "optimum zone" encompasses discharges that result in ≥90% of maximum sediment deposition. Our observations for the winter/spring (W/S) and the summer/fall (S/F) seasons (Table 1) are indicated by the squares and circles, respectively.

100%. We chose an exponential function because it asymptotes to zero and sediment retention is unlikely to reach 0%, and a y-intercept of 100% because zero discharge logically produces 100% sediment retention. To generate a hypothesis about sediment retention at discharges greater than those observed in Davis Pond during our study period, we extrapolated the curve to higher discharges. Finally, we developed a sediment deposition curve (Fig. 8b) by multiplying the sediment input curve by the sediment retention curve. Our conceptual model suggests that as water discharge and sediment input increase, throughput of suspended sediment also increases, leading to a decrease in the basin sediment retention rate. Meanwhile, sediment deposition may eventually reach a maximum where further increases in sediment input no longer lead to greater deposition because the reduced retention rates at higher discharges completely offset the increased sediment input.

The range of moderate discharges that lead to near-maximum sediment deposition is considered optimum in terms of land building. For Davis Pond, discharges within this optimum range are greater than the mean discharges seen during either the winter/spring or the summer/fall seasons studied here, but notably lower than the maximum discharge of the diversion (~300 $m^3 s^{-1}$). At discharges significantly higher than those observed in the present study, we hypothesize that sediment deposition and retention will both decrease. Note that the moderate discharges we describe here as optimal are approximately double to triple the mean discharge seen in the winter/spring of 2015, which we refer to as our "high-flow" season in order to distinguish it from the low-flow summer/fall 2015 season. In reality, mean discharge during the winter/spring of 2015 was also relatively low, at only 21% of the maximum diversion discharge.

We expect that additional measurements of sediment retention (collected in future studies) will slightly alter the shape of the sediment retention curve seen in Fig. 8a and thus slightly shift the optimum discharge value (Supplemental Fig. 5). However, we expect that the shape of these curves will remain generally the same. Sediment retention cannot exceed 100% and is unlikely to drop to 0%. Thus, additional data will refine our conceptual model and it is likely that an optimum discharge will continue to be evident.

The conceptual model presented here uses parameters specific to the Davis Pond diversion. These parameters (e.g. maximum diversion discharge, rate of sediment input, measurements of sediment retention) can be changed to fit other diversions. Because no two diversions are identical, the zone of optimum discharge is expected to be different for each diversion. However, scaling relationships in hydrology (e.g. Leopold, 1994) coupled with a wealth of regional studies (e.g. Allison and Meselhe, 2010; Esposito et al., 2013; Peyronnin et al., 2017) and site-specific data provide a means by which this conceptual model can be applied to other systems in the MRD and globally.

Determining optimal flow regime conditions for river diversions is an emerging area of concern for water managers in the MRD (e.g. Peyronnin et al., 2017) and in basins around the world such as the Shatt al-Arab Delta in Iraq (Richardson et al., 2005) and the Ganges-Brahmaputra Delta in Bangladesh (Van Staveren et al., 2017). Our findings suggest that optimal discharge conditions for maximizing sediment accumulation at Davis Pond may exceed those observed here. The validity of this conclusion could be objectively assessed with future investigations that quantify retention rates under higher diversion discharge conditions, using methods applied here or perhaps with a mass-balance approach applied to continuous flux measurements made at the upstream and downstream ends of the receiving basin. Results from future studies can be used to test and refine the conceptual model presented here and adapt it for use in other delta basins.

6. Conclusions

In this study of a river diversion in the Mississippi River Delta, we quantify relationships between hydrodynamics and sedimentation in a developing delta. We reach the following conclusions:

1. Although greater water discharge delivers more sediment to the receiving basin, the corresponding rate of sediment retention is decreased, likely because more of the sediment is retained in suspension and carried out of the basin.
2. Thus, increasing discharge results in diminishing returns in terms of sediment deposition.
3. As a result, there may be an optimum that occurs at moderate discharge where sediment deposition is maximized.
4. Discharges above this optimum zone would result in decreased sediment deposition.

Findings from this research suggest that planning for future diversions may more explicitly investigate sediment trapping efficiency. Maximizing the beneficial impact of river diversions to restoration and management of coastal wetland ecosystems requires an understanding of how to achieve optimal hydrodynamic conditions for sustainable delta building. Diversions of moderate water discharge and flow velocity that discharge into enclosed receiving basins may be effective configurations to explore when planning for future sediment diversions to maximize the land-building potential of the Mississippi River's remaining sediment load.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geomorph.2019.02.008.

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Data availability

All data associated with this manuscript are available on ScienceBase: https://doi.org/10.5066/P9V7N49P.

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