Chapter 10

Mississippi Delta Restoration and Protection: Shifting Baselines, Diminishing Resilience, and Growing Nonsustainability

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1 INTRODUCTION

The Mississippi delta is arguably the most intensively studied delta in the world. Beginning in the 1930s, a series of foundational studies laid much of the framework for modern deltaic science. The works of Russell (1936), Russell et al. (1936), Fisk (1944, 1952, 1954), Fisk and McFarlan (1955), Kolb and van Lopik (1958), Saucier (1963), and Frazier (1967) provide a robust appreciation for the forms and processes important to deltas. This knowledge base was developed during a period of relatively static sea level, and now is being reevaluated in view of the "new normal," an escalation in sea-level rise forced by anthropogenetic climate change (Blum and Roberts, 2009, 2012).

The coast is where most economic activity takes place in Louisiana. Businesses are put at increased flood risk if wetlands that now protect levees by attenuating storm surge and waves continue to disappear (Barnes et al., 2015; Day et al., 2000). At-risk areas include major import-export commodity ports on the Mississippi, Calcasieu, and Sabine Rivers that are linked to internationally significant petrochemical manufacturing facilities by highway, waterway, and rail infrastructure, in addition to coastal cities housing more than 2 million (e.g., New Orleans, Houma, Lake Charles, Morgan City, the north shore of Lake Pontchartrain). Batker et al. (2014) estimated that the delta ecosystem provides between \$12 and 47 billion annually in ecosystem goods and services. The replacement cost of capital stock that will be damaged over 50 years if measures included in the CMP are not built is estimated to be \$2.1–3.5 billion. An additional loss of \$5.8–7.4 billion is projected from reduced economic activity associated with storm related impacts and abandonment of infrastructure (e.g., exodus of businesses, schools, churches, and residents) (Barnes et al., 2015). These numbers illustrate the cost of replacing the essential social fabric of the region at risk of catastrophic flooding (Glavovic, 2014). It is this existential societal threat—made real in the Hurricane Katrina and Rita catastrophes of 2005—that has led the people and leaders of Louisiana to embark on the Coastal Master Plan (CMP) to restore and protect coastal Louisiana ecosystems, communities, and infrastructure (CPRA, 2007, 2012, 2017).

We briefly describe the geologic, ecologic, and socioeconomic factors that have been important to both the building and loss of the MRD as both a landform and a place for people to live and work. We point out significant biophysical, economic, and social constraints and irreversible trends that will affect the likelihood that CMP-approved projects will be constructed and prove effective, and where there are more sustainable paths forward. Finally, we describe an alternative approach that we believe has a greater chance to enhance deltaic sustainability.

2 DEVELOPMENT OF THE DELTA

The Mississippi delta is made up of several interdistributary hydrologic basins separated by active or abandoned river distributary ridges (Roberts, 1997; Day et al., 2000; Blum and Roberts, 2012, Fig. 1). There are two physiographic provenances. The river dominated Deltaic Plain is on the east and is where active deltaic lobe formation occurred, while the Chenier Plain to the west was created by ocean waves moving muddy river sediments temporarily stored on the nearshore bottom into shore-attached mudflats soon colonized by marsh vegetation. Shore-parallel beach ridges composed of shells

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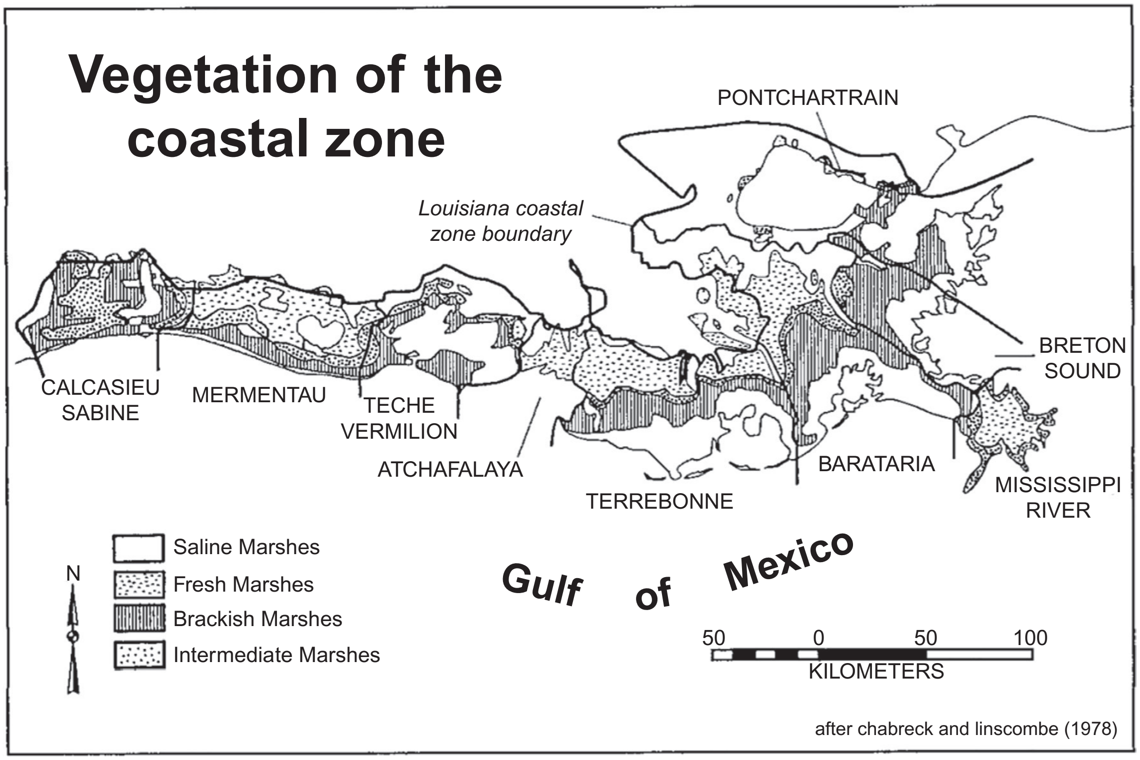

FIG. 1 Interdistributary basins and vegetation zones of the Mississippi delta. The Calcasieu-Sabine and Mermentau basins make up the Chenier Plain while the eastern seven basins form the deltaic plain. *(From Day, J., Shaffer, G., Britsch, L., Reed, D., Hawes, S., Cahoon, D., 2000. Pattern and process of land loss in the Mississippi delta: a spatial and temporal analysis of wetland habitat change. Estuaries 23, 425–438.)*

eroded out of marsh/mudflats alternate with wetlands in a strand plain that has developed over the last 4 ka. This coast is building seaward with progressively younger beach ridges approaching the active shoreline (Roberts, 1997).

The first inner shelf delta lobe (Sale-Cypremort) formed after infilling of the low-stand Mississippi River trench is now completely submerged, but significant parts of all subsequent subdeltas have been incorporated into the modern deltaic plain (Fig. 2). The deltaic surface encompassed about 25,000 km^2 of wetlands, inshore water bodies, and low relief uplands when it reached its greatest expanse in the 19th century (Roberts, 1997; Day et al., 2007, 2014; Hijma et al., 2018; Day and Erdman, 2018). These wetlands form a series of vegetation zones (Fig. 1) that are determined primarily by salinity, ranging inland from the coast, and including saline, brackish and freshwater emergent herbaceous wetlands, and freshwater forested wetlands.

After sea-level rise slowed at the end of the last glacial age and finally stabilized at near present sea level about 5000 years ago, the Mississippi delta began forming this vast deltaic wetland complex that by the 18th century encompassed about 25,000 km^2 (Roberts, 1997; Roberts et al., 2015; Boesch et al., 1994; Day et al., 1995, 2000, 2007; Hijma et al., 2018, Fig. 2). A hierarchy of energetic processes distributed water and materials through the delta from both the watershed and Gulf and exchanged the biotic products of the estuarine ecosystems with the coastal ocean. River sediment was deposited at active distributary mouths or, laterally through overbank flooding and crevasses (breaks in the natural levees).

Delta lobes formed as river channels elongated and bifurcated and were ultimately abandoned through a process of upstream avulsion in favor of shorter routes to sea level (Fig. 2). MRD subdeltas have lifespans of thousands of years and cover 100s–1000s of kilometers. Crevasses functioned at a smaller scale during high water for a few years to as long as a century to build sediment splays adjacent to the natural levee with areas of 10s–100s of km^2 (Saucier, 1963; Welder, 1959; Davis, 2000; Roberts, 1997, Fig. 3).

Most abandoned distributaries from earlier lobe building episodes nonetheless flowed with river water during major floods to maintain a skeletal framework of interconnected distributary channels and natural levee ridges not only within the youngest lobes but also in older, largely abandoned sub-deltas, while barrier islands, and beach ridges formed after lobe abandonment at the marine boundaries (Penland et al., 1988). These ridge features protect interior wetlands from hurricane surge and waves and salinity intrusion, but they have also been important to both precontact and postcolonial societies as preferred sites for human habitation and cultivation (e.g., Day et al., 2007; Xu et al., 2016; Colten and Day, 2018).

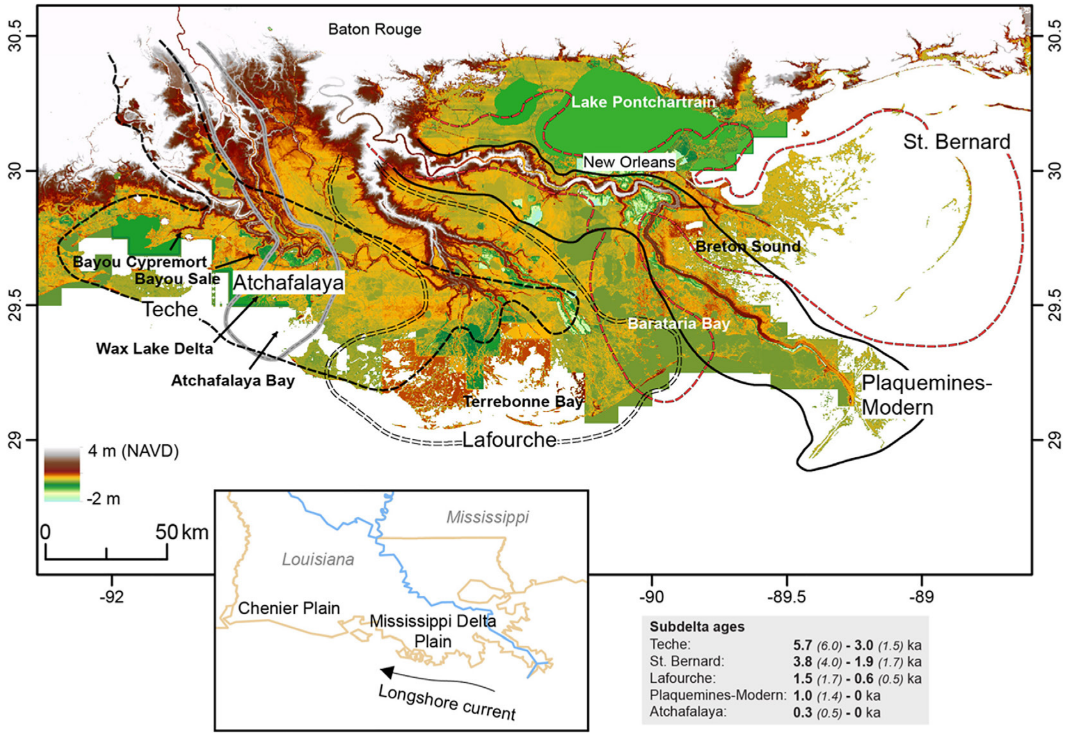

FIG. 2 Delta lobes of the Mississippi delta with times of active growth. *(Adapted from Hijma, M., Shen, Z., Törnqvist, T., Mauz, B., 2018. Late Holocene evolution of a coupled, mud-dominated delta plain-chenier plain systems, coastal Louisiana, USA. Earth Surf Dynam. 5, 689–710.)*

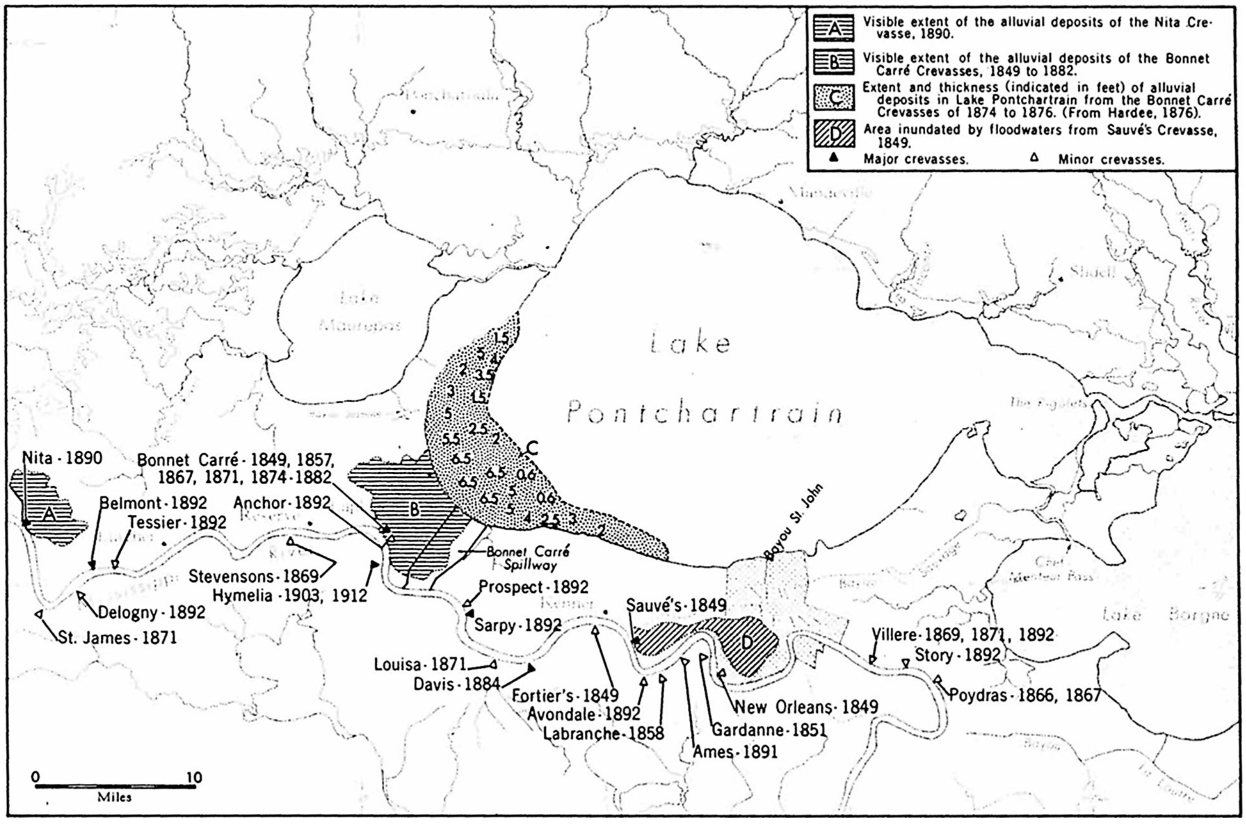

FIG. 3 Location of some of the crevasses along the Mississippi River from 1849 to 1927 including areas affected by three major crevasses (A, B, C, and D). Note that the Bonnet Carré crevasse filled in areas of western Lake Pontchartrain by more than 2 m (6.5 ft). *(From Saucier, R.T., 1963. Recent Geomorphic History of the Pontchartrain Basin. Coastal Studies Institute, Report 9. Louisiana State University, Baton Rouge, Louisiana. 114 p.)*

Human-built levees, some dating back to the 1720s, inhibited crevassing locally, but did not eliminate the process. Saucier (1963) and Davis (1993) documented hundreds of crevasses on the lower Mississippi after the arrival of Europeans. The splays overlap the natural levees to form a nearly continuous band that laterally expands both higher land and new wetlands in adjacent water bodies like Lake Pontchartrain (Fig. 3, Saucier, 1963; Davis, 2000; Allison and Meselhe, 2010; Shen et al., 2015; Day et al., 2016c). Crevassing continued even after federal investment began in a more robust artificial levee system. Colten (2017) notes that a levee breach below New Orleans in 1922 augmented the flanks of the natural levee with about 2 m of new "high" land. Also, Day et al. (2016b) report that an artificial crevasse intentionally opened at Caernarvon for 3 months during the great flood of 1927 had a peak discharge of nearly 10,000 $m^3 s^{-1}$ and deposited a layer of river sediment up to 40 cm thick over about 130 km^2.

Self-sustaining deltaic wetlands must build vertically at a rate sufficient to stay within the tidal frame and offset naturally high rates of RSLR (Baumann et al., 1984; Day et al., 2011). Most of this is due to subsidence caused by compaction and dewatering of underlying soft sediments in the upper 10 m of the sediment column (Jankowski et al., 2017). While RSLR varies spatially over short distances across the delta depending on local subsidence, mean values for the past decade from the nearly 300 stations that make up the Coastwide Reference Monitoring System (CRMS) (Steyer et al., 2003) are 13.2 to 9.5 mm-yr^{-1} for the Deltaic and Chenier Plains, respectively. RSLR includes a eustatic (global) component independently measured by satellite altimetry in the Northern Gulf of Mexico at 2 mm-yr^{-1} for the same period. Local subsidence on average makes up 85% of RSLR in the Deltaic Plain, and 79% in the Chenier Plain (Jankowski et al., 2017). Furthermore, Jankowski et al. (2017) report that at least 60% of subsidence occurs in the upper 5–10 m of the sediment/soil column.

Near the river mouths unconsolidated coarse sediment is deposited on shallow bay bottoms and in the nearshore where it is susceptible to resuspension by waves and tides. Deposition and permanent capture of these resuspended sediments on marsh surfaces takes place during storms that generate large waves along with sequential water level set-up and set-down (Day et al., 2011). Surface elevation change (SEC), and vertical accretion (VA) are marsh properties that have been systematically measured at the CRMS stations. SEC occurs as a consequence of both in situ organic soil formation and the capture and incorporation of mineral sediment inputs.

Ultimately, the river is directly or indirectly the source of all mineral sediment reaching delta wetlands. Easily suspended, fine-grained mineral sediments (silts and clays) increase marsh soil strength and bulk density while nutrients also delivered by the river enhance plant growth (Day et al., 2011). Introduction of fresh river water into adjacent deltaic estuaries displaces saltwater seaward, while dissolved iron from the continental basin precipitates toxic sulfides that otherwise build up in brackish soils and stress wetland plants (DeLaune and Pezeshki, 1988; Delaune and Pezeshki, 2003). Despite a 30-cm tide range, water level set-up and set-down of a meter or more occurs several times each winter during cold front passages, and less frequently during hurricanes in the summer and fall (Baumann et al., 1984; Perez et al., 2000).

Globally, the late Holocene has been a good time to both grow and live in a delta (Day et al., 2016a; Colten and Day, 2018). Despite the coexistence of areas of wetland building and loss, the net size of the MRD increased over all but the last century, when humans intervened in a big way (Jankowski et al., 2017; Day and Erdman, 2018). Stable sea-level concentrated land-building inputs from the continental basin (freshwater, sediments, nutrients) while also limiting the inland reach of waves and storm surge. This allowed for maturation of productive estuarine ecosystems and barrier island tracts well adapted to deltaic dynamics (Giosan et al., 2014). Because flooding by the river and by hurricanes occurs in different seasons in Louisiana, and because the availability of migratory food sources is also predictable, native peoples found higher ridges of the delta to be good sites for villages and temporary camps (Colten and Day, 2018).

Condrey et al. (2014) used journals and charts of 16th century Spanish explorers to describe what they have called the "last natural delta" of the Mississippi as it existed prior to European settlement. The delta is described in early accounts as fringed with treacherous oyster reefs and barrier islands that fronted all of the five most recent delta complexes of the Mississippi River and extended entirely across the deltaic plain. Ship crews marveled that they could refill their water casks from plumes of fresh water that extended far into the Gulf during the spring flood and nourished a vast offshore oyster reef. Condrey et al. (2014) suggest that the shoreline of the coast was advancing seaward at this time in many places. However, this changed quickly after the arrival of European colonists a couple of centuries later.

3 DETERIORATION OF THE DELTA

Human impact on the MRD was rather minor during the 18th and 19th centuries, as the delta continued to grow. Completion of mainline levees along the river, and the invasion of steam dredges and the oil and gas industry, however, reversed the long-term trend, and brought about a collapse of a quarter of the deltaic plain wetland inventory (about 5000 km^2) in less than 80 years from 1930 to 2010 (Couvillion et al., 2011). In 2005, the weakened coast was devastated by Hurricanes Katrina and Rita leading to 1800 deaths and about $200 billion in damage and reconstruction costs (Day et al., 2007).

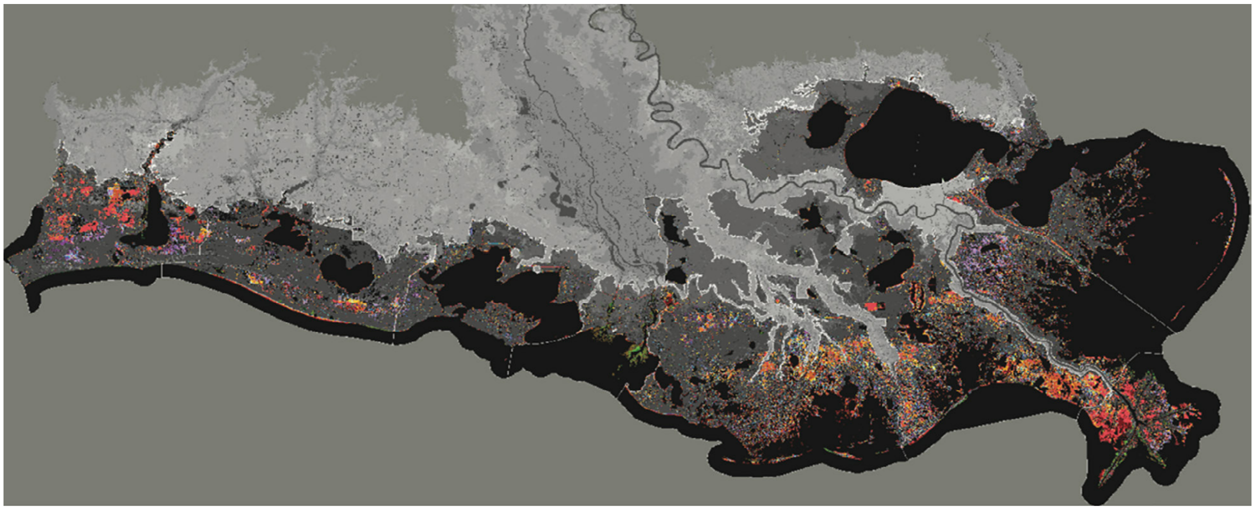

FIG. 4 Land area change in coastal Louisiana from 1932 to 2010. Red and yellow areas have high land loss rates. Note that land loss is low in the central coast and in the northeastern flank of the delta. *(Source: Couvillion, B., Barras, J., Steyer, G., Sleavin, W., Fishcher, M., Beck, H., et al., 2011. Land area change in coastal Louisiana from 1932 to 2010. U.S. Geological Survey, Scientific Investigations Map 3164, scale 1:265,000, 12 p. pamphlet. The map can be downloaded at https://pubs.usgs.gov/sim/3381/sim3381.pdf for detialed examination of specific areas of change. See also https://pubs.er.usgs.gov/publication/sim3381.)*

The devastating effects of these hurricanes were seen as a predictable result of two centuries of mismanagement of the Mississippi River and MRD, and galvanized attention to impacts of global climate change on deltas worldwide.

Couvillion et al. (2011) produced a highly detailed map of coastal land loss from 1932 to 2010 (Fig. 4). Various shades of red and yellow show areas of land loss. The map can be downloaded for examination of specific areas of change. A casual glance at this map immediately conveys two impressions. First, wetland loss has been pervasive across the coast, but especially near the mouth of the Mississippi River, in the Barataria and Terrebonne basins, and west into the Chenier Plain. Second, two areas stand out as much less affected by land loss. One is the central coast that is nourished by the Atchafalaya River that discharges into shallow bays and wetlands over a wide arc along the central Louisiana coast. This input constitutes 30% of the combined discharge of the Red and Mississippi Rivers. The other zone of lower land-loss is on the northeastern flank of the delta in the seaward reaches of the Pontchartrain estuary.

Beginning in the late 19th century, local appeals for more flood protection ultimately led to federal investment in more effective levees that largely severed the river from its deltaic distributaries and the adjacent wetlands (Reuss, 1998; Camillo and Pearcy, 2004).

A ‘levees-only’ policy that tightly controlled the Mississippi was adopted by the US Army Corps of Engineers (USACEs) in the 1880s to maximize navigation and flood control benefits from the river. This federal program proved to be a failure, driving up flow lines and leading to more disastrous levee failures and flooding. After the 1927 Mississippi River flood catastrophe, the USACE recognized that during large floods the river needed access to more offline floodplain storage and an increase in the number and capacity of emergency flood outlets in the MRD. This led to construction of the Bonnet Carré and Atchafalaya Basin floodways which have trapped a vast amount of sediment that would have otherwise reached coastal wetlands. But little sediment reaches the delta plain directly from the lower Mississippi River channel past New Orleans until the last 100 km upstream of the birdsfoot delta. Now that some sediment entering the Atchafalaya River bypasses the Atchafalaya Basin, more is reaching the central coast where two new subdelta lobes have been building since the 1970s. The Atchafalaya River continues to drive wetland building and nourishment in its bayhead deltas and adjacent marshes, and also prevent loss of marshes around the receiving bays (Day et al., 2011; Blum and Roberts, 2012; Rosen and Jun Xu, 2013; DeLaune et al., 2016; Twilley et al., 2016).

4 GLOBAL CHANGE CONSTRAINTS ON COASTAL PROTECTION AND RESTORATION

Global change forcings, especially climate change and energy scarcity, along with socioeconomic policy decisions can be expected to limit options of what is possible for coastal protection and restoration (e.g., Day et al., 2016a). Day and Rybczyk (2019, this volume) review global change drivers that will impact coastal systems. Climate change drivers are already affecting the coast and their impact will grow more severe during the 21st century. Sea level is projected to increase by 2 m or more by 2100 or shortly thereafter (DeConto and Pollard, 2016), the frequency of category four and five hurricanes is anticipated to increase, extreme weather events including heavy precipitation and droughts may become more common, and the peak discharge of the Mississippi River is projected to increase by up to 60% (Tao et al., 2014; Min et al., 2011; Pall et al., 2011; Prein et al., 2016).

Environmental migration has been underway in the coastal region for decades (Hemmerling, 2018). Intense storms prompt pulses of relocation from highly exposed communities and younger residents are gradually departing coastal communities. Numerous small communities have disappeared since the 19th century and New Orleans lost about 20% of its population after Hurricane Katrina (2005). The departures drain the social capital of the region while leaving behind more vulnerable residents (Colten, 2017). Public policy has neglected both the costs and the potential benefits of relocation.

Energy scarcity will likely become an important factor affecting delta management (Day et al., 2000; Tessler et al., 2015; Wiegman et al., 2017; Rutherford et al., 2018a, b). Recent analyses suggest that world oil production will peak in 2–3 decades (Maggio and Cacciola, 2012) implying that demand will consistently be greater than supply and that the cost of energy will increase significantly in coming decades. The planning horizon for coastal protection and restoration in Louisiana is 50–100 years, thus energy scarcity in conjunction with climate change will likely constrain our ability to manage the coast. Levee construction, barrier island restoration, and long-distance conveyance of sediments are energy intensive both in construction and maintenance (Tessler et al., 2015; Wiegman et al., 2017). Only engineered river diversions have relatively low long-term maintenance costs. We now consider how these global change drivers and public policies will impact coastal protection and restoration.

5 COASTAL PROTECTION AND RESTORATION

The State of Louisiana is now in the midst of a $50 billion, 50-year program of coastal protection and restoration called the Louisiana's comprehensive master plan (CMP) for a sustainable coast (CPRA, 2017; Wiegman et al., 2018). The vast majority of funding has yet to be identified but work has begun with the $2 billion currently in hand. The goals of the CMP are twofold, namely to protect human infrastructure in the delta with conventional flood control structures (levees, floodwalls, and pumps), and to restore natural processes to create wetlands and sustain the deltas estuarine ecosystems, all with the goal of promoting economic development and cultural traditions in the coastal zone.

The plan does not include specific projects for protecting social capital and restoring coastal cultures. The CMP has "collective goals of reducing economic losses to homes and business from storm surge-based flooding, promoting sustainable ecosystems, providing habitats for a variety of commercial and recreational activities coast wide, strengthening communities, and supporting businesses and industry" (LACMP, 2017). The 2017 CMP contains 13 structural protection projects and 23 nonstructural risk-reduction projects (elevate and flood proof buildings and help property owners prepare for flooding or move out of areas of high flood risk). These components complement a federal flood control system along the Mississippi River, the Mississippi River and Tributaries Project (MR&T), to prevent riverine flooding. The historical reliance on levees was a major factor in creating the land loss crisis and led to dramatic loss of property and life during Katrina. Restoration projects involve a number of activities such as barrier island restoration, shoreline protection and stabilization, hydrologic restoration, ridge restoration, and oyster barrier reefs. But the two most important restoration activities are river diversions and marsh creation for land building in the coastal zone. Marsh creation uses dredged sediments that are pumped in pipelines, often for long distances, to build wetlands (Wiegman et al., 2017). Diversions reintroduce river water into the coastal zone to create and restore wetlands (Day et al., 2014; Rutherford et al., 2018a, b); these will be much more effective if the reduction in fine sediment transport in the river is restored (Kemp et al., 2016). As with levees, past diversions, designed for other purposes, have contributed to ecological disruptions in the delta region. For example, fresh water flushing through the Bonnet Carré Spillway seriously disrupted local fisheries in the short term (Day et al., 2016c; Colten, 2017).

Dredging sediment for marsh creation builds land quickly, but due to relative sea-level rise the resulting marshes require periodic re-nourishment to be sustainable (Wiegman et al., 2017). After construction, diversions have minimal recurring costs but build land gradually (Day et al., 2016) and will likely last for a century or more (e.g., Bonnet Carré Spillway, Day et al., 2012). While it is clear that river diversions will be a necessary and vital aspect of coastal restoration, much uncertainty still persists about their effectiveness, potential damages, and their economic benefit in the short term (Day et al., 2016c). It is possible that they could be a detriment to the economy in the short term, as fisheries struggle to adapt to changes in estuaries such as salinity reduction brought about by fluvial inputs (Day et al., 2016c).

The CMP will spend about 50% of total funding on restoration and 50% on coastal protection. The 2017 CMP proposes $17.1 billion on marsh creation and $5.1 billion on sediment diversions (Table 1). In the 2012 CMP, marsh creation projects had an average cost of about $360,000 per hectare over a 50-year time span, while sediment diversions had an average cost

TABLE 1 2017 Louisiana Coastal Master Plan Funding Allocation by Project Type

Class	Project Type	Funding ($billions)	Percent of Funds	Prime Mover
Restoration	(Total)	25	50	N/A
	Barrier Island	1.5	3	Hydraulic Dredge, Bulldozer
	Hydrologic	0.4	1	Pump or Gravity[a]
	Marsh Creation	17.1	34	Hydraulic Dredge, Bulldozer
	Ridges	0.1	0	Excavator, Dragline or Bucket Dredge
	Sediment Diversion	5.1	10	Gravity[a]
	Shoreline Protection	0.2	0	Barge, Crane or N/A[b]
Risk reduction	(Total)	25	50	N/A
	Structural (Levees)	18.8	38	Excavator, Dragline or Bucket Dredge
	Nonstructural	6.1	12	Various
Total		50	100	N/A

[a] *Various machinery is required to build the control structures; after which the displacement of water or sediment is controlled by gravity (and pumps in some cases for hydrological restoration).*

[b] *Oyster reefs have various methods of creation; Rock armor shorelines and jetties require barges and cranes.*

Adapted from CPRA, 2017. Louisiana's Comprehensive Master Plan for a Sustainable Coast. 2017 Coastal Master Plan. Louisiana Coastal Protection and Restoration Authority, Baton Rouge by Wiegman, A., Rutherford, J., Day, J., 2018. Mississippi Delta Restoration Pathways to a Sustainable Future. Springer, Cham, Switzerland, pp. 93–111.

(including engineering, operation, and maintenance) of about $45,000 per hectare. The CMP has not compared the cost of diversions and marsh creation to the costs of supporting community relocation to reduce risk.

Davis et al. (2015) estimated that the actual cost to restore Louisiana's coastline and flood protection infrastructure would be about $90 billion, greatly exceeding the $50 billion estimate. The key environmental drivers included in the 2017 CMP are eustatic sea-level rise, subsidence, tropical storm intensity, tropical storm frequency, precipitation, and evapotranspiration. But the plan does not include increases in peak discharge of the Mississippi River (Tao et al., 2014) or extreme weather events (Min et al., 2011; Pall et al., 2011; Prein et al., 2016).

In addition, the CMP does not fully consider the full range of climate change impacts (more strong hurricanes, and more extreme weather events, drought, and increases in peak discharge of the Mississippi River) nor does it factor in the cost of economic impacts due to increasing cost of energy. It also dismisses relocation as a core option and as an unavoidable eventual cost. Large flood control projects, marsh creation, and river diversions are examples of projects that require a vast amount of energy and capital during implementation (Day et al., 2005, 2014; Tessler et al., 2015; Wiegman et al., 2017). Thus there are significant financial limitations on the CMP that could be exacerbated by fluctuations in energy prices. It is plausible that changes in the global economy, public policy, regional and global climate, and energy availability will render significant components of the CMP unaffordable in a few decades (Day and Rybczyk, 2019).

The CMP uses sophisticated modeling to project future states of the coast given restoration scenarios compared to a future without action. The models do not fully consider how humans can adapt to ongoing and future changes. Fig. 5 presents model results for the coastline and vegetation types of the 2017 CMP 50 years in the future compared to no action for a high sea-level rise scenario. Almost all saline wetlands are predicted to be lost for both the future without action and the future with action (2017 Master Plan projects). The models project that marshes will be formed by diversions south of New Orelans along the river.

6 COASTAL PROTECTION AND RESTORATION IN A CLIMATE-CHALLENGED, ENERGY-SCARCE FUTURE

The information presented thus far indicates that global change forcings and public policies will seriously impact the efficacy of the CMP. Here we address these issues and develop ideas about a more sustainable path forward.

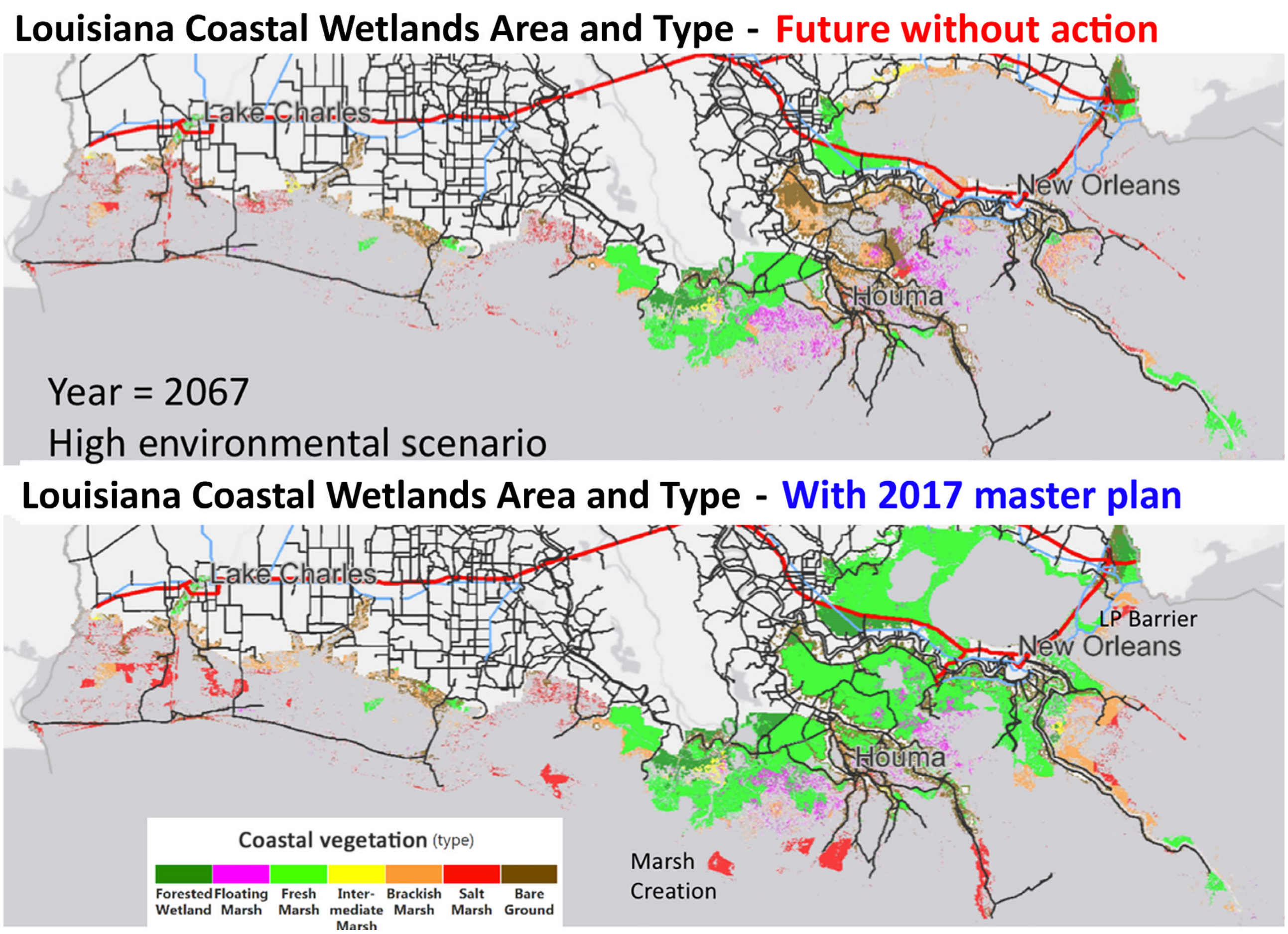

FIG. 5 A projection of the Louisiana coastline and vegetation types 50 years in the future with no action and with the 2017 Coastal Master Plan. The scenario, shown here uses a high environmental scenario, which does not include the highest estimates for eustatic sea-level rise, subsidence, and extreme weather events. In this scenario, almost all saline marshes disappear, and it is unlikely that the New Orleans metropolitan area or most natural levees would survive without protective wetlands. *(Modified from Coastal Protection and Restoration Authority, http://cims.coastal.louisiana.gov/masterplan/.)*

6.1 Flood and Storm Protection

Flood protection in southern Louisiana must confront flooding from three distinct threats including hurricane surge with accompanying waves, Mississippi River flood events, and localized extremely heavy rainfall. These different types of flood threats require different types of protection strategies accompanied by follow through on effective public policies.

6.2 Hurricane Surge and Waves

Since Hurricanes Katrina and Rita, providing adequate hurricane protection has been a central issue in Louisiana. This form of protection is absolutely necessary to continue to have viable social and economic systems in south Louisiana. Hurricane protection must take into consideration climate change and resource scarcity. Current plans include enhanced protection for New Orleans and long linear levees for much of the rest of the coast. For the New Orleans region, hurricane protection includes higher and stronger levees, structures at the entrance to Lake Pontchartrain, enhanced pumping stations for conveying rainfall in New Orleans to Lake Pontchartrain, closure of the Mississippi River—Gulf Outlet (MRGO), and elimination of the funnel associated with MRGO with a surge barrier (Shaffer et al., 2009, see Fig. 5). The CMP includes barriers across the entrance to Lake Pontchartrain, across the mid-Barataria Basin and the northeastern part of the Terrebonne Basin (see Fig. 5). These structures will have gates to prevent hurricane flooding as well as control salinity so that fresh water marshes and swamps proposed in the CMP can be maintained landward of the barriers. With rising sea level, gravity drainage will become less and less effective and at some point all of these areas may have to put under pump if they are to continue to function. This area is far larger than what exists now. The costs of pumping such large areas are likely to be unaffordable.

Hurricane protection must be integrated into coastal restoration. It also will be affected by global climate change and energy scarcity as discussed above. Climate change will require larger and stronger levees and energy scarcity is likely to make currently planned protection much more expensive, possibly prohibitively so.

6.3 The Mississippi River

After the catastrophic 1927 flood, the US government revamped its flood control system for the lower Mississippi River valley from Cairo IL to the mouth of the river—the Mississippi River and Tributaries project or MR&T. It shifted the emphasis from "levees only" to "levees and outlets" (Camillo and Pearcy, 2004; Reuss, 1998)—an acknowledgement that eliminating the natural distributaries reduced the river's ability to handle major floods and that levees alone did not offer a permanent fix. The revised system relies principally on levees but also incorporated a number of flood outlets or spillways and very large flood control and river management structures. The MR&T system is designed for the project flood with a peak discharge of about 85,000 $m^3 s^{-1}$ (3 million $ft^3 s^{-1}$). Peak discharge of the Mississippi River at Vicksburg was 64,000 $m^3 s^{-1}$ (2,278,000 cfs) in 1927 and 65,000 $m^3 s^{-1}$ (2,310,000 cfs) in 2011.

The Bonnet Carré Spillway is one of two flood relief outlets and is situated about 40 km upstream of New Orleans. It is designed to lower river levels in the city by allowing water to flow from the river to Lake Pontchartrain (Day et al., 2012). It was completed in 1933 after the flood of 1927 and has been opened 12 times beginning in 1937 with the last opening in 2018. Eight of the 12 openings occurred in the second half of its operational history indicating that large floods are becoming more common.

Tao et al. (2014) modeled the interactive effects of climate change, land use, and river management on discharge of the Mississippi River and projected that river discharge may increase by 10%–60% during this century. Assuming that peak discharge would increase by the same amounts, we plotted the peak discharge of the 2011 flood and added 10%–60%. An increase of 60% over the peak discharge for the 2011 flood would result in a peak discharge of 104,000 $m^3 s^{-1}$ (3.70 million $ft^3 s^{-1}$) exceeding the project flood by about 20% (Fig. 6). Peak flow increases of this magnitude may compromise the MR&T flood control system on the Mississippi River (Kemp et al., 2014).

Such large floods will likely increasingly threaten the functioning of the MR&T flood control system, as high discharges threaten both river levees and flood control structures. Many factors can compromise levees and lead to collapse including cavities due to rotting logs and burrowing animals, soil weakness, sand boils, and scour at the base of the levee. As John Barry notes, "the biggest danger is pressure, constant unrelenting pressure." (Barry, 1997, p. 191). Structures such as the Old River control structure, which regulates Mississippi River flow into the Atchafalaya and prevents capture of most of the flow by the Atchafalaya, could also be threatened. This structure came close to catastrophic failure due to undermining during the 1973 food (Belt, 1975, see also Kesel et al., 1974; Barnett, 2017) and may fail in the future due to a combination of a reduction of the capacity of the river channel and increased pressure during high water could threaten the control structure during a very large flood (Wang and Xu, 2015, 2016, 2018; Joshi and Xu, 2017; Xu, 2017). Given projections for an increase in the peak discharge of the river as discussed above, the potential for failure of levees and structures

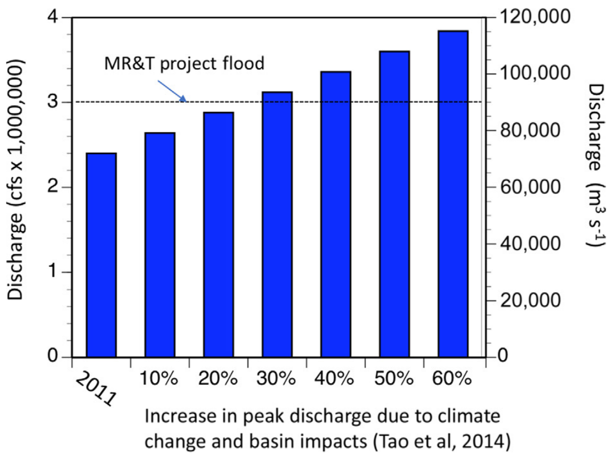

FIG. 6 Potential increase in peak Mississippi River discharge due to climate change and land use changes in the basin. MR&T is the Mississippi River and Tributaries project flood. *(Based on model projections from Tao, B., Tian, H., Ren, W., Yang, J., Yang, Q., He, R., et al., 2014. Increasing Mississippi river discharge throughout the 21st century influenced by changes in climate, land use, and atmospheric CO_2. Geophys. Res. Lett. 41(14), 4978–4986.)*

on the lower Mississippi is increasing. Increasing costs of energy as discussed above would make the cost of sustaining the MR&T flood control system much higher, perhaps prohibitively so (see Wiegman et al., 2017).

6.4 Flooding Due to Extremely Heavy Rainfall

Evidence indicates that the intensification of extreme weather events will occur in a warming climate (Coumou and Rahmstorf, 2012; IPCC, 2014). Warmer air holds more moisture, and heavy precipitation events and flooding are expected to increase in intensity with climate change (Groisman et al., 2005; Min et al., 2011; Pall et al., 2011; Prein et al., 2016). Several recent examples have occurred in the north central Gulf of Mexico. In August, 2016, nearly a meter of rain in 3 days that led to extensive flooding east of the Mississippi River in the Baton Rouge area with over 10,000 houses flooded. The 2016 storm was associated with a near stationary low-pressure area just offshore in the Gulf. In 2017, Hurricane Harvey stalled over Houston and dumped up to 1.3 m over several days. Such intense storms are occurring with a greater frequency. Because local rivers in Louisiana are low relief coastal plain rivers, the river slope is critical in regulating the quantity and rate at which water can be conveyed from large rain storms. A rising sea level will decrease the river slope and greatly exacerbate flooding of low relief areas near the coast.

6.5 A Truly Sustainable New Orleans

New Orleans is a special case for sustainable restoration planning. It is the largest metropolitan area in Louisiana and the region is economically important for the state in terms of port activity, tourism, education, and commerce. The local economy includes petrochemicals, oil and gas activity, shipping, and important fisheries. The city is also one of the most threatened areas in the nation. Katrina led to catastrophistic flooding and loss of life in the metropolitan area and the region has not fully recovered (Kates et al., 2006; Glavovic, 2014). After the storm, there was an expectation that the region would undergo fundamental changes to make the area more resilient to hurricane flooding. But almost all residential and commercial buildings were repaired in place and very few structures were raised above flood levels (Colten, 2015). Because about half the city is below sea level and future climate forcings are projected to be worse (accelerated sea-level rise, more frequent stronger hurricanes, higher peak river discharge, and more extreme weather events like the August 2016 flooding and Hurricane Harvey's impact on Houston), the continued existence of the New Orleans region will likely become increasingly untenable. If the current approach to flood protection continues, it is plausible that New Orleans may fail catastrophically before 2100. Clearly, there is a need for new approaches to integrating resilience into the metropolitan area's long-term planning that will contribute to its long-term sustainability. Of paramount importance is that the city does not remain below sea level.

Erdman et al. (2018a) proposed a bold new vision to make New Orleans truly resilient and sustainable in the 21st century and beyond. They argued that New Orleans provides a case study for all of south Louisiana, as well as cities around the world, especially those that are below sea level, that are increasingly threatened by sea-level rise and strong storms as to how settlement can continue in such a precarious location. They presented a bold design proposal for elevating the city of New Orleans as an adaptive course of action (Fig. 7). Their two-part strategy begins by reinforcing the lake edge along Lake Pontchartrain using infill to extend the higher, buildable ground. This higher ground would be fronted by a cypress swamp and urban edge. The second part of the strategy aims to build a series of leveed polders that they call a "marais" based on the French term. These polders could then be developed by filling them with river sediment, raising structures inside the polder, or managing them for aquatic and wetland systems that could also serve as flood reservoirs. The goal is to provide additional protection at the lake front and to raise all living areas to at least 5 m above sea level. The design proposal further develops edge and fill tactics to complete elevation of the city, in whole or part. Erdman et al. (2018b) review different strategies for raising structures and making them more resilient, and Colten (2018) reviews historical examples where urban land has been raised to avoid flooding threat or to enhance sewage removal.

7 MOVING FORWARD ON COASTAL PROTECTION

The following are suggestions for enhancing coastal protection in conjunction with restoration. These planned protection and restoration activities may help to enhance hurricane protection for New Orleans given that hurricane protection would be much more difficult without restored wetlands. In general, raising buildings above the 500-year flood level should be encouraged, or even mandated, in threatened areas, along with revisions to the National Flood Insurance Program to discourage rebuilding in place. The preservation of freshwater forested wetlands in the coastal zone is especially critical to hurricane surge and wave reduction (Shaffer et al., 2009, 2018). These actions along with raised elevations will result in a more secure New Orleans. Most protection envisions long, linear levee systems. In some cases, it would seem better to build

FIG. 7 Conceptual plan for raising New Orleans above hurricane flood levels. The city is fronted by a cypress swamp and an area formed by dredging from the lake that is about 5-m above sea level. Behind that is a series of polders that can be filled for development, contain raised structures or flooded to create natural habitat and flood basins. *(From Erdman, J., Williams, E., James, C., Coakley, G., 2018a. Raising buildings: the resilience of elevated structures. In: Day, J., Erdman, J. (Eds.), Mississippi Delta Restoration Pathways to a Sustainable Future. Springer, Cham, Switzerland. pp. 143–170; Erdman, J. James, C., Coakley, G., Williams, E., 2018b. In: Day, J., Erdman, J. (Eds.), Mississippi Delta Restoration Pathways to a Sustainable Future. Springer, Cham, Switzerland. pp. 171–200.)*

ring levee systems to protect specific areas. This would also eliminate some of the problem of having wetlands isolated behind levees. Wetlands should be used to help protect levees rather than being threatened by them. In some cases, a leaky levee approach is being advocated, where water control structures will allow water exchange except in times of storms. Much information on such management brings this idea into question (e.g., Wiegman et al., 2017). The massive failure of semi-impoundment management areas in the Chenier Plain during Hurricane Rita illustrates what can go wrong with this management approach. All of this suggests that any plan for the use of leaky levees should be very carefully considered and backed up by scientific study and modeling.

7.1 Managed Retreat

Over the last several decades, many residents left the lower coast for both economic and safety reasons (Bailey et al., 2014; Hemmerling, 2017; Glavovic, 2014; Colten et al., 2018). After hurricanes Katrina and Rita, this retreat greatly increased. Colten and Day (2018) and Colten et al. (2012) reported that human communities developed lifestyles adapted to a dynamic coast and that enhanced resilience. But the baselines that existed prior to the 20th century have changed and 21st century megatrends portend conditions never experienced by either coastal ecosystems or human communities. This suggests that sustainability and resilience of both natural and human systems will depend on new visions that take into consideration a future that is increasingly outside of the range of conditions that existed when these systems developed. Hemmerling (2018) concluded that successive shocks due to flooding, climate change, and economic change may lead to erosion of community resilience. These considerations suggest that moving people out of harm's way is prudent. The plan to move the Native American community of Isle de Jean Charles to higher ground serves as an example of proactive managed retreat (Louisiana Office of Community Development, 2017). There needs to be full integration of currently disconnected state planning for biophysical restoration and community safety. In addition, planners need to incorporate true community participation in the earliest stages of planning—not just to allow the opportunity for comments on fully developed plans.

There is a pressing need to determine what role this retreat will play in the economy of the coast and to include this in planning. There is a need to think about how to maintain the economy and health of the coast in a scenario of managed retreat. Natural resource activities like fishing will continue to be economically important, and perhaps more so in the future. Perhaps fishing and other resource harvest activities could move toward more of a seasonal utilization of the coast. It is important to maintain sustainable fishing communities. Perhaps a number of areas along the coast could be developed as safe fishing communities protected by strong ring levees. These areas would protect boats and other infrastructure from hurricanes and also provide temporary housing, processing, and other facilities to support the fishing industry. There is a need to give much more thought to ways that natural resource-based activities can take place without being threatened by storms.

7.2 Delta Restoration

The CMP proposes to use a variety of management approaches to restore the coast but nearly 90% of restoration funding will go to river diversions ($5.1 billion, ~20%) and marsh management ($17.1 billion, ~68%) (Table 1). Marsh creation uses dredged sediments that are pumped in pipelines, often for long distances, to build wetlands. Diversions reintroduce river water into the coastal zone to create and restore wetlands. Here, we discuss these and other approaches to delta restoration.

7.3 River Diversions—Crevasses, Large Diversions, Reactivated Distributaries

Engineered sediment diversions, which divert sediment and nutrient laden freshwater from the MR to adjacent wetlands, have been identified as critical tools in restoring the Mississippi River delta plain (MRDP) (Day et al., 2007, 2016b, 2018; Kim et al., 2009; Allison and Meselhe, 2010; Paola et al., 2010; CPRA, 2007, 2012; Wang et al., 2014; Esposito et al., 2017). Large river diversions are very expensive, costing over a billion dollars each (CPRA, 2017). After construction, however, diversions have minimal recurring costs (Day et al., 2016c). One problem is that the immediate outfall area may tend to fill in as is the case for the Bonnet Carré Spillway (Day et al., 2012). One option is to build a conveyance channel like the Wax Lake Outlet that is self-scouring. Diversion structures will likely last for more than a century. For example, the Bonnet Carré Spillway structure will be 100 years old in 15 years and will likely last many more years (Day et al., 2012, 2016).

Under natural conditions, river input to the delta plain was dramatically greater than now. Large crevasses occurred every few years with flows reaching 10,000 m^3/s and discharging tens of millions of tons of sediment/yr (Saucier, 1963; Davis, 2000; Shen et al., 2015; Day et al., 2012, 2016c). Crevasses built up the natural levee and formed large crevasse splays in adjacent wetlands. Some distributaries functioned year round but most were active seasonally. Sustainable restoration, especially with climate change, will require much greater river input than is currently envisioned and should seek to mimic the past functioning of the river. Rutherford et al. (2018a, b) showed that a very large diversion (~7000 $m^3 s^{-1}$) into the Maurepas Swamp on the east side of the river between Baton Rouge and New Orleans would build and maintain much more land than currently proposed diversions for this area.

Although the first large diversions will be constructed below New Orleans and discharge to the Barataria and Breton Sound basins (CPRA, 2017), sediment retention decreases the closer a diversion is to the river mouth. If diversions are located in the more inland parts of the delta, sediment retention will increase because of shallower water and the high trapping efficiency of forested wetlands; diversions into open waters have sediment retention efficiencies of 5%–30% (e.g., Xu et al., 2016; Blum and Roberts, 2009). Esposito et al. (2017) reported that diversions into settings that are still vegetated have sediment retention efficiencies greater than 75%. A large diversion into the Maurepas Swamp would yield several benefits. It would sustain this deteriorating 57,000 ha swamp that provides a variety of ecosystem goods and services, especially hurricane protection, for the critical New Orleans to Baton Rouge corridor (Shaffer et al., 2009, 2018; Rutherford et al., 2018a, b). It could also serve as an alternative flood outlet to the Bonnet Carré Spillway that is rapidly filling in (Day et al., 2012). An intriguing idea is that a large Maurepas diversion may relieve pressure on the Old River control structure and decrease the potential that a larger portion of Mississippi River flow will be captured by the Atchafalaya River. The Maurepas Swamp is approximately the same distance from the Old River complex as the mouth of the Atchafalaya so that the distance advantage of the Atchafalaya would be reduced and make stream capture less likely. Nienhuis et al. (2018) used Delft3D modeling to investigate the influence of vegetation and soil compaction on the evolution of a natural levee breech and showed that crevasse splays tend to heal because aggradation reduces the water slope. A way around this is to create a bifurcation at the point of the Maurepas diversion like the lower Atchafalaya and Wax Lake Outlet. This would maintain open the lower Mississippi channel past New Orleans. Control at that point could deliver sediment to the lower river below New Orleans. The birdsfoot would be abandoned with a new sub delta between New Orleans and the birdsfoot delta at Head of Passes. The Maurepas lobe would then build out into Lake Maurepas and then into Lake Pontchartrain to enhance wetlands to help protect New Orleans.

Another location for an advantageous diversion is into the Biloxi Marsh complex on the eastern flank of the deltaic plain. Because of the low subsidence of the Biloxi Marsh region, it has a greater potential for survival than wetlands in the center of the deltaic plain where subsidence rates are much higher (Nienhuis et al., 2017). The Biloxi Marsh wetlands play a critical role for hurricane protection on the southeastern flank of New Orleans. If these marshes were to disappear, the threat for hurricane flooding would increase dramatically.

7.4 Marsh Creation

Dredging sediment for marsh creation builds land quickly, but requires periodic re-nourishment to be sustainable (Wiegman et al., 2017). Wiegman et al. (2017) modeled the impact of increasing energy cost and sea-level rise on the cost of marsh creation and reported that the cost of creating 1 ha of marsh could increase to over $1 million by 2100 for the worst-case

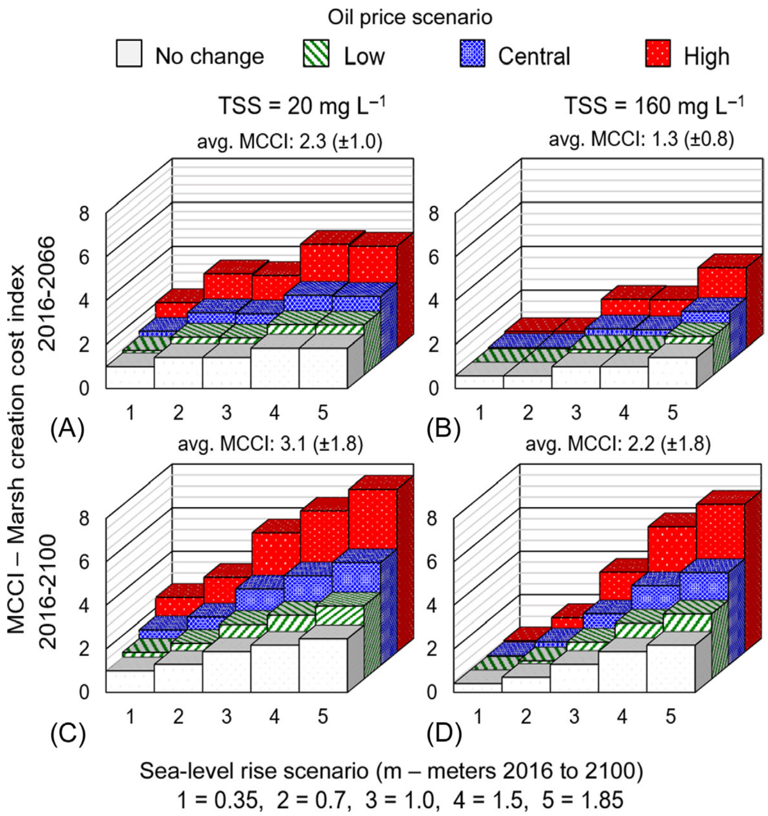

FIG. 8 The interactive effects of sea-level rise and fuel prices on the cost of marsh creation using dredged sediments. *(From Wiegman, R., Day, J., D'Elia, C., Rutherford, J., Morris, J., Roy, E., Lane, R., Dismukes, D., Snyder, B., 2017. Modeling impacts of sea-level rise, oil price, and management strategy on the costs of sustaining Mississippi delta marshes with hydraulic dredging. Sci. Total Environ. https://doi.org/10.1016/j.scitotenv.2017.09.314.)*

scenario for sea-level rise and energy price (Fig. 8). Increasing suspended sediment concentrations from river diversions raised marsh lifespan and decreased long-term dredging costs. Regardless of management scenario, sustaining created marsh suffered declining returns on investment due to the convergence of energy and climate trends. They concluded that marsh creation will likely become unaffordable during the second half of the 21st century. The model results suggest that most created marsh will succumb to rising sea level by a century from now but marsh creation can extend the life of coastal wetlands while plans are put in place to more fully utilize the resources to develop a more sustainable delta. Careful consideration should be given to tradeoffs between building marsh that is destined to disappear and other competing demands for scarce resources such as more diversions or coastal retreat.

7.5 Abandonment of Lower Delta

It is now generally accepted that the lower birdsfoot delta will have to be largely abandoned for effective coast-wide restoration. The lower delta is an anomaly compared to earlier delta lobes because it has grown to the edge of the continental shelf where most of the sediments reaching the birdsfoot delta bypasses wetlands. It is imperative that much more of the sediment reaching the river mouth is retained in the birdsfoot delta complex or further upstream. An extremely important and difficult problem is maintaining a functioning navigation channel while the lower delta undergoes abandonment. Relocation of residents and businesses in the lower delta presents an issue to policy makers who have been reluctant to address and is not a principal component of the CMP.

7.6 The Atchafalaya River Delta Region—An Underused Resource

The Atchafalaya River carries one-third of the total Mississippi flow, but this resource is not optimally used. Two new delta lobes are forming at the mouth of the river and wetland loss is low in a broad area of the central coast. Much of the sediments still flows past the emerging delta but a considerable amount of this sediment is reworked back into the headland marshes of the new delta lobes during frontal storm passages (Roberts et al., 2015). More of the discharge needs to be moved both east and west for successful restoration (see Twilley et al., 2016).

Most studies of the impact of Mississippi River water show positive impacts on coastal wetlands. The Atchafalaya and Wax Lake delta complex are part of the beginning stages of a major new deltaic lobe development fed by the Atchafalaya River distributary (Roberts, 1997; Roberts et al., 2015; DeLaune et al., 2013). Subaqueous deposition occurred in Atchafalaya Bay for much of the 20th century, first via the lower Atchafalaya River and then beginning in 1941 via the dredged Wax Lake Outlet. Both delta lobes first became subaerial during the large flood in 1973. The Atchafalaya delta lobe has a dredged navigation channel running through it, but the Wax Lake lobe has developed naturally at the end of the 26 km long artificial conveyance channel. The delta lobes have grown at about $3\,km^2\,yr^{-1}$ with areas of 160 and $100\,km^2$, respectively, by 2015 (Roberts et al., 2015).

Atchafalaya River discharge has led to mineral sediment deposition in wetlands in a broad arc from Fourleague Bay to the east to Vermillion Bay to the west (e.g., Day et al., 2011) and these wetlands have the lowest rates of land loss in the Mississippi delta. Twilley et al. (2016) analyzed wetland loss in this area compared it to wetland loss in the Terrebonne Bay complex to the east of Atchafalaya Bay that is isolated from riverine input. They measured the change in position of the 50% land:water ratio isopleth in both basins from the 1930s to the present. The 50% land:water line retreated an average of 17,000 m in the Terrebonne region with no river input compared to only 35 m in the Atchafalaya region, demonstrating the dramatic impact of river discharge. It is important to note that the Atchafalaya delta lobe complex developed in open waters of Atchafalaya, Cote Blanche, and Vermillion Bays. By contrast, the largest planned river diversions are from the Mississippi River below Baton Rouge and discharge to coastal basins with significant amounts of wetlands. Thus, these receiving basins have a much lower accommodation space and much higher friction and are expected to retain a higher percent of introduced sediments (Blum and Roberts, 2009). They are also the sites for extensive oyster cultivation and habitat for shrimp and other commercial marine life.

7.7 The Chenier Plain—Potential for Sustainable Management

The Chenier Plain was formed by downdrift sediments from the Mississippi River, especially when the river had significant discharge to the western part of the deltaic plain as it is happening now from the Atchafalaya River (Hijma et al., 2018). Coarse sediments were moved up on the shore face during storms and formed beach ridges. As new shore face accretion of fine sediments formed new marshes seaward of the beaches, the beach ridges were located inland so that the Chenier Plain has a complex series of stranded beach/dune systems called Cheniers, for the oaks growing on them. These ridges play an important role in protecting the Chenier Plain wetlands from Hurricanes. In a natural state, the Chenier ridges resulted in semi-enclosed areas that had connections with the Gulf of Mexico. This has changed with large areas of semi-impounded marshes for freshwater storage and waterfowl management.

Hurricane Rita (2005) brought into sharp focus the limitations of current management of the Chenier Plain. The combination of the salt-water intrusion via the Calcasieu Ship Channel as well as hurricane surge and the large freshwater impoundments set the stage for failure with the death of large areas of freshwater vegetation as levees were overtopped (Barras, 2009; Morton and Barras, 2011). A large body of scientific studies has shown that structural marsh management using impoundments and water control structures generally does not work (Cahoon, 1994; Boumans and Day, 1994). And the Chenier Plain is marsh management on a grand scale. Climate change and energy scarcity will make continuation of current management practices less and less tenable. Several approaches should characterize future Chenier Plain management; minimize salt-water intrusion via the Calcasieu, maximize input of resuspended sediments from the near-shore Gulf, and manage for transition to a more open internal system with brackish marshes in areas likely to be affected by future hurricanes. Hijma et al. (2018) stress that significant discharge of Mississippi River water to the western portion of the delta plain is necessary to sustain the Chenier Palin. This will demand foregrounding both restoration and public safety, rather than continuation of the traditional focus on shipping needs.

7.8 Coastal Forested Wetlands—A Vanishing Resource

Following intensive harvesting in the early 20th century, nearly a million hectares of coastal freshwater forested wetlands regenerated in the Atchafalaya, Terrebonne, Barataria, and Pontchartrain basins. Regeneration of the forests occurred during drought years when natural dry downs allowed seedlings to survive. This was important because seedlings need a dry period when they are not flooded for survival to take place. The forests in the latter three basins are now almost all completely cut off from river input and mostly unsustainable. Most are flooded continuously and are not regenerating (Shaffer et al., 2009, 2016; Keim et al., 2006; Day et al., 2012; Conner et al., 2014). Considerable areas are threatened by salt-water intrusion. Most of these forests will disappear in the 21st century without large-scale river input (Chambers et al., 2005; Shaffer et al., 2016). These forests play a particularly important role in hurricane protection because the three-dimensional structure reduces waves as well as surge (Shaffer et al., 2009). These forests also lead to water quality improvement and sequester large amounts of carbon (Shaffer et al., 2016; Lane et al., 2017; Hunter et al., 2018). Most forests are privately owned and there is considerable pressure to harvest them. But once cut, most will not regenerate because of permanent flooding. Strong public-private cooperation is necessary for the survival of these ecosystems. More sustainable management of these valuable forested wetlands should include maximizing sediment input (Rutherford et al., 2018a, b) and optimal use of freshwater resources to combat salinity intrusion (Shaffer et al., 2018).

7.9 Wasted Freshwater Resources

Freshwater wetlands make up a significant part of the Mississippi delta (see Fig. 3). These systems will become increasingly more threatened by increasing salinity due to sea-level rise and more frequent and intense droughts (Day and Rybczyk, 2019). The drought-induced brown marsh of 2000–01, which killed thousands of acres of wetlands, is a harbinger for the future (Alber et al., 2008; McKee et al., 2004). Thus, it will become necessary to fully utilize all freshwater resources. Currently, most point and nonpoint source runoff flows directly into waterbodies, bypassing wetlands and often causing water quality deterioration. Shaffer et al. (2018) identified several sources of freshwater to the coastal zone and outlined approaches to optimally use these freshwater resources to combat salt water intrusion and simultaneously improve water quality. Sources of freshwater to the coastal zone include the Mississippi River via diversions, smaller local rivers, direct rainfall on coastal wetlands, nonpoint source runoff, once-through, noncontact industrial cooling water, and treated municipal effluent. Nonpoint source runoff, which is often channelized directly into water bodies, should be rerouted to wetlands. Cooling water from the industrial complexes is a potential source of freshwater, especially along the Mississippi River below Baton Rouge (Hyfield et al., 2007). Treated, disinfected, nontoxic municipal effluent can be a continuous base flow of freshwater that has been demonstrated to restore and maintain coastal wetlands (Hunter et al., 2018). In addition to combating salt-water intrusion, such use of freshwater resources results in energy savings, wetland restoration, and enhanced carbon sequestration.

7.10 Restoration of Basin Inputs

Coastal restoration will be much more difficult unless sediment input from the basin is increased. There is a need to remobilize sediments trapped behind dams and move them to the delta, especially fine sediments. Sand transport to the delta remains sufficient to build wetlands in shallow, sheltered coastal bays fed by engineered diversions. Allison et al. (2012) reported that much of the sand fraction of the river was sequestered in overbank storage and channel bed aggradation inside the flood control levees. Nittrouer and Viparelli (2014) concluded that sand supply to the head of the Mississippi delta was unlikely to decrease for centuries. But suspended mud (silt and clay) flux to the coast has dropped from a mean of 390 $Mt\,yr^{-1}$ in the early 1950s, to 100 $Mt\,yr^{-1}$ since 1970 (Meade and Moody, 2010). Unlike sand that is deposited near where it leaves the river, fine-grained sediments can be transported deeper into receiving estuarine basins and play a critical role in sustaining existing wetlands. Practically all of this now-absent mud once flowed from the Missouri River Basin prior to the construction of nearly 100 dams in the Missouri basin. About 100 $Mt\,yr^{-1}$ is currently trapped by the large main-stem Upper Missouri River dams completed by 1953. The remaining 200 $Mt\,yr^{-1}$ is trapped in impoundments built on tributaries to the Lower Missouri in the 1950s and 1960s. In contrast, to the large dams on the upper Missouri, sediment bypassing on the lower river impoundments is part of river management. Sediment flux during the post-dam high discharge years of 1973, 1993, and 2011 approached predam levels when tributaries to the Lower Missouri contributed to flood flows. These lower Missouri river tributaries drain a vast, arid part of the Great Plains, while those entering from the east bank traverse the lowlands of the Mississippi floodplain. Both provinces are dominated by highly erodible loess soils. Reducing the continued decline in Mississippi River fine-grained sediment flux is very important now that river diversions are being built for coastal wetland restoration in the deltaic plain. Kemp et al. (2016) concluded that tributary dam bypassing in the Lower Missouri basin could increase mud supply to the MRD by 100–200 $Mt\,yr^{-1}$ within 1–2 decades. Such measures to restore the Mississippi delta are compatible with objectives of the Missouri River Restoration and Platte River Recovery Programs to restore riparian habitat for endangered species (Kemp et al., 2016).

8 SHIFTING BASELINES AND DIMINISHING RESILIENCE

Colten and Day (2018) discussed how the Mississippi delta and human occupation of the delta evolved at the same time in the context of a predictable baseline in a dynamic deltaic ecosystem. For centuries, despite the highly dynamic coastal system, both natural ecosystems and human communities flourished and coexisted in a sustainable relationship. The riverine system sustained the natural system and human communities developed lifestyles adapted to a dynamic coast which enhanced resilience. But the baselines that existed prior to the 19th century have changed and 21st century megatrends portend conditions not experienced by either coastal ecosystems or human communities over the past. This includes Native American communities over the past several millennia and colonial and postcolonial communities up to about the end of the 19th century. The megatrends include increasingly severe climate change impacts, most notably sea-level rise, stronger hurricanes, more extreme weather events, increased peak river discharge, and growing resource scarcity. These circumstances suggest that sustainability and resilience of both natural systems and human communities will depend on new visions that take into consideration a future that is increasingly outside of range of conditions that existed when these systems developed.

9 COMPREHENSIVE PLANNING—THE IMPORTANCE OF GLOBAL CHANGE

There is a pressing need to carry out planning for coastal restoration and protection to a much greater extent within a comprehensive plan that takes into consideration 21st century global change megatrends including climate change, energy scarcity, ecosystem degradation, economic constraints, and the local cultural context. There is a need to recognize the extremely high ecosystem services and their role in the future ecological, economic, and social health of the state and how these goods and services can be sustained. There is a need to really consider what is possible, what is not, and what it will take to have a sustainable system in the Mississippi delta. There needs to be an acceptance that the delta will shrink considerably (Chamberlain et al., 2018), that there will be significant population shifts accompanying managed retreat, and that the river will have to be used to the maximum extent possible. As this century progresses, much of what is being planned for coastal protection and restoration will become more expensive, perhaps prohibitively so (Tessler et al., 2015; Wiegman et al., 2017). Society will have to adapt to a much more dynamic river and delta system that cannot be controlled as it has been for the last century. The energies of nature must play a much more important role in delta management. This is ecological engineering on a grand scale that must operate in synchronization with complex social processes. This will mean living in a much more open system, accepting natural and social limitations, and utilizing the resources of the river more fully.

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REFERENCES

Alber, M., Swenson, E.M., Adamowicz, S.C., Mendelssohn, I.A., 2008. Salt Marsh Dieback: an overview of recent events in the US. Estuar. Coast. Shelf Sci. 80, 1–11.

Allison, M.A., Meselhe, E.A., 2010. The use of large water and sediment diversions in the lower Mississippi River (Louisiana) for coastal restoration. J. Hydrol. 387 (3), 346–360.

Allison, M., Demas, C., Ebersole, B., Kleiss, B., Little, C., Meselhe, E., Powell, N., Pratt, T., Bosburg, B., 2012. A water and sediment budget for the lower Mississippi-Atchafalaya River in flood years 2008–2010: implications for sediment discharge to the oceans and coastal restoration in Louisiana. J. Hydrol. 432–433, 84–97.

Bailey, C., Gramling, R., Laska, S., 2014. Complexies of resilience: adaptation and change within human communities of coastal Louisiana. In: Day, J., Kemp, G., Freeman, A., Muth, D., (Eds.), Perspectives on the Restoration of the Mississippi Delta. Springer, New York, pp. 125–140.

Barnes, S., Bond, C., Burger, N., Anania, K., Strong, A., Weilant, S., et al., 2015. Economic Evaluation of Coastal Land Loss in Louisiana. Louisiana State University and the Rand Corporation. Available from: http://coastal.la.gov/economic-evaluation-of-land-loss-in-louisiana/.

Barnett, J.F., 2017. Beyond Control: The Mississippi River's New Channel to the Gulf of Mexico. University Press of Mississippi, Oxford.

Barras, J.A., 2009. Land Area Change and Overview of Major Hurricane Impacts in Coastal Louisiana, 2004–08: US Department of the Interior. US Geological Survey Scientific Investigations Map 3080, 6 p http://pubs.usgs.gov/sim/3080/.

Barry, J., 1997. Rising Tide: The Great Mississippi River Flood of 1927 and How it Changed America. Simon Schuster, New York.

Batker, D., de la Torre, I., Costanza, R., Day, J., Swedeen, P., Boumans, R., Bagstad, a.K., 2014. In: Day, J., Kemp, P., Freeman, A., Muth, D. (Eds.), Perspectives on the Restoration of the Mississippi Delta. Springer, New York, pp. 155–174.

Baumann, R., Day, J., Miller, C., 1984. Mississippi deltaic wetland survival: sedimentation vs coastal submergence. Science 224, 1093–1095.

Belt, C., 1975. The 1973 flood and man's constriction of the Mississippi River. Science 189, 681–684.

Blum, M.D., Roberts, H.H., 2009. Drowning of the Mississippi Delta due to insufficient sediment supply and global sea-level rise. Nat. Geosci. 2 (7), 488–491.

Blum, M.D., Roberts, H.H., 2012. The Mississippi delta region: past, present, and future. Annu. Rev. Earth Planet. Sci. 40, 655–683.

Boesch, D.F., Josselyn, M.N., Mehta, A.J., Morris, J.T., Nuttle, W.K., Simenstad, C.A., Swift, D.J.P., 1994. Scientific assessment of coastal wetland loss, restoration, and management in Louisiana. J. Coastal Res. . Special Issue No. 20.

Boumans, R.M., Day, J., 1994. Effects of two Louisiana marsh management plans on water and materials flux and short-term sedimentation. Wetlands 14, 247–261.

Cahoon, D.R., 1994. Recent accretion in two managed marsh impoundments in coastal Louisiana. Ecological Applications. 4, 166–176.

Camillo, C.A., Pearcy, M.T., 2004. Upon Their Shoulders: A History of the Mississippi River Commission. Mississippi River Commission, Vicksburg.

Chamberlain, E., Tornqvist, T., Sheen, Z., Mauz, B., Sallinga, J., 2018. Anatomy of Mississippi Delta growth and its implication for coastal restoration. Sci. Adv. 4, eaar4740.

Chambers, J., Conner, W., Day, J., Faulkner, S., Gardiner, E., Hughes, M., Keim, R., King, S., McLeod, K., Miller, C., Nynam, J., Shaffer, G., 2005. In: Conservation, protection and utilization of louisiana's coastal wetland forests. Final report to the Governor of Louisiana from the Coastal Wetland Forests Conservation and Use Science Working Group. 102 pp.

Colten, C.E., Rooksby, O., Sobott, J.-K., 2015. Historic city with a poor memory. In: The Katrina Effect. Bloomsbury Publishing, London, pp. 305–330.

Colten, C.E., 2017. Environmental management in coastal Louisiana. J. Coast. Res. 33 (3), 699–711.

Colten, C.E., 2018. Raising urban land: historical perspectives on adaptation. In: Day, J., Erdman, J. (Eds.), Mississippi Delta Restoration Pathways to a Sustainable Future. Springer, Cham, Switzerland, pp. 135–142.

Colten, C.E., Day, J., 2018. Resilience of natural systems and human communities in the Mississippi delta: moving beyond adaptability due to shifting baselines. In: Mossop, E. (Ed.), Coastal Resilience. Taylor & Francis Group, CRC Press, Boca Raton, FL.

Colten, C., Hay, J., Giancarlo, A., 2012. Community resilience and oil spills in coastal Louisiana. Ecol. Soc. 17 (3), https://doi.org/10.5751/ES-05047-170305.

Colten, C.E., Simms, J.R.Z., Grismore, A.A., Hemmerling, S.A., 2018. Social Justice and Mobility in Louisiana, USA. Reg. Environ. Change 18 (2), 371–383.

Condrey, R.E., Hoffman, P.E., Evers, D.E., 2014. The last naturally active delta complexes of the Mississippi River (LNDM): discovery and implications. In: Day, J.W., Kemp, G.P., Freemen, A.M., Muth, D.P. (Eds.), Perspectives on the Restoration of the Mississippi Delta. Springer, Dordrecht, pp. 33–50.

Conner, W.H., Duberstein, J.A., Day, J.W., Hutchinson, S., 2014. Impacts of changing hydrology and hurricanes on forest structure and growth along a flooding/elevation gradient in a south Louisiana forested wetland from 1986 to 2009. Wetlands XX, 1–12.

Coumou, D., Rahmstorf, S., 2012. A decade of weather extremes. Nat. Clim. Chang. 2 (7), 491–496.

Couvillion, B., Barras, J., Steyer, G., Sleavin, W., Fishcher, M., Beck, H., Trahan, N., Griffin, B., Heckman, D., 2011. Land area change in coastal Louisiana from 1932 to 2010. U.S. Geological Survey, Scientific Investigations Map 3164, scale 1:265,000, 12 p. pamphlet. https://pubs.usgs.gov/sim/3381/sim3381.pdf.

CPRA, 2007. Louisiana's Comprehensive Master Plan for a Sustainable Coast. Coastal Protection and Restoration Authority of Louisiana (CPRA), Baton Rouge.

CPRA, 2012. Louisiana's comprehensive master plan for a sustainable coast. In: 2012 Coastal Master Plan. CPRA, Baton Rouge.

CPRA, 2017. Louisiana's comprehensive master plan for a sustainable coast. In: 2017 Coastal Master Plan. Louisiana Coastal Protection and Restoration Authority, Baton Rouge.

Davis, D.W., 1993. In: Crevasses on the lower course of the Mississippi River. Coastal Zone'93. Proceedings of the Eighth Symposium on Coastal and Ocean Management. American Society of Civil Engineers, pp. 360–378.

Davis, D.W., 2000. Historical perspective on crevasses, levees, and the Mississippi River. In: Colten, C.E. (Ed.), Transforming New Orleans and Its Environs. University of Pittsburgh Press, Pittsburgh, pp. 84–106.

Davis M, Vorhoff H, Boyer D (2015) Financing the future. Turning coastal restoration and protection plans into realities: the cost of comprehensive coastal restoration and protection. second in an occasional series. An issue paper of the Tulane Institute on water resources law and policy.

Day, J., Erdman, J. (Eds.), 2018. Mississippi Delta Restoration Pathways to a Sustainable Future. Springer, Cham, Switzerland.

Day, J., Rybczyk, J., 2019. Global change impacts on the future of coastal systems: perverse interactions among climate change, ecosystem degradation, energy scarcity, and population. In: Wolanski, E., et al. (Eds.), Future of Coasts and Estuaries. Springer, Glam, Switzerland.

Day, J., Pont, D., Hensel, P., Ibañez, C., 1995. Impacts of sea-level rise on deltas in the Gulf of Mexico and the Mediterranean: the importance of pulsing events to sustainability. Estuaries 18 (4), 636–647.

Day, J., Shaffer, G., Britsch, L., Reed, D., Hawes, S., Cahoon, D., 2000. Pattern and process of land loss in the Mississippi delta: a spatial and temporal analysis of wetland habitat change. Estuaries 23, 425–438.

Day, J., Barras, J., Clairain, E., Johnston, J., Justix, D., Kemp, P., Ko, J.-Y., Lane, R., Mitsch, W., Steyer, G., Templet, P., Yanez, A., 2005. Implications of global climatic change and energy cost and availability for the restoration of the Mississippi Delta. Ecol. Eng. 24, 253–265.

Day, J., Boesch, D., Clairain, E., Kemp, P., Laska, S., Mitsch, W., Orth, K., Mashriqui, H., Reed, D., Shabman, L., Simenstad, C., Streever, B., Twilley, R., Watson, C., Wells, J., Whigham, D., 2007. Restoration of the Mississippi Delta: Lessons from Hurricanes Katrina and Rita. Science 315, 1679–1684.

Day, J.W., Kemp, G.P., Reed, D.J., Cahoon, D.R., Boumans, R.M., Suhayda, J.M., et al., 2011. Vegetation death and rapid loss of surface elevation in two contrasting Mississippi delta salt marshes: the role of sedimentation, autocompaction and sea-level rise. Ecol. Eng. 37, 229–240. https://doi.org/10.1016/j.ecoleng.2010.11.021.

Day, J., Hunter, R., Keim, R.F., DeLaune, R., Shaffer, G., Evers, E., Reed, D., Brantley, C., Kemp, P., Day, J., Hunter, M., 2012. Ecological response of forested wetlands with and without large-scale Mississippi River input: implications for management. Ecol. Eng. 46, 57–67.

Day, J., Kemp, P., Freeman, A., Muth, D., (Eds.), 2014. Perspectives on the Restoration of the Mississippi Delta: The Once and Future Delta. Springer, New York. 194 p.

Day, J., Agboola, J., Chen, Z., D'Elia, C., Forbes, D., Giosan, L., Kemp, P., Kuenzer, C., Lane, R., Ramachandran, R., Syvitski, J., Yanez, A., 2016a. Approaches to defining deltaic sustainability in the 21st century. Estuar. Coast. Shelf Sci. https://doi.org/10.1016/j.ecss.2016.06.018.

Day, J., Cable, J., Lane, R., Kemp, G., 2016b. Sediment deposition at the Caernarvon crevasse during the great Mississippi flood of 1927: implications for coastal restoration. Water 8 (38), https://doi.org/10.3390/w8020038.

Day, J., Lane, R., D'Elia, C., Wiegman, A., Rutherford, J., Shaffer, G., Brantley, C., Kemp, G., 2016c. Large infrequently operated river diversions for Mississippi delta restoration. Estuar. Coast. Shelf Sci. https://doi.org/10.1016/j.ecss.2016.05.001.

DeConto, R.M., Pollard, D., 2016. Contribution of Antarctica to past and future sea-level rise. Nature 531 (7596), 591–597.

DeLaune, R.D., Pezeshki, S.R., 1988. Relationship of mineral nutrients to growth of Spartina alterniflora in Louisiana salt marshes. Northeast Gulf Sci. 10, 195–204.

Delaune, R.D., Pezeshki, S.R., 2003. The role of soil organic carbon in maintaining surface elevation in rapidly subsiding U.S. Gulf of Mexico coastal marshes. Water Air Soil Pollut. 3, 167–179.

DeLaune, R.D., Kongchum, M., White, J.R., Jugsujinda, A., 2013. Freshwater diversions as an ecosystem management tool for maintaining soil organic matter accretion in coastal marshes. Catena 107, 139–144.

DeLaune, R.D., Sasser, C.E., Evers-Hebert, E., White, J.R., Roberts, H.H., 2016. Influence of the Wax Lake Delta sediment diversion on aboveground plant productivity and carbon storage in deltaic island and mainland coastal marshes. Estuar. Coast. Shelf Sci. 177, 83–89.

Erdman, J., Williams, E., James, C., Coakley, G., 2018a. Raising buildings: the resilience of elevated structures. In: Day, J., Erdman, J. (Eds.), Mississippi Delta Restoration Pathways to a Sustainable Future. Springer, Cham, Switzerland, pp. 143–170.

Erdman, J., James, C., Coakley, G., Williams, E., 2018b. In: Day, J., Erdman, J. (Eds.), Mississippi Delta Restoration Pathways to a Sustainable Future. Springer, Cham, Switzerland, pp. 171–200.

Esposito, C., Shen, Z., Törnqvist, T., Marshak, J., White, C., 2017. Efficient retention of mud drives land building on the Mississippi delta plain. Earth Surf. Dynam. 5, 387–397. https://doi.org/10.5194/esurf-5-387-2017.

Fisk, H.N., 1944. Geological Investigation of the Alluvial Valley of the Lower Mississippi River. Illus. U.S. Army Corps of Engineers, Washington, DC. 78 p.

Fisk, H.N., 1952. Geological Investigations of the Atchafalaya Basin and the Problem of Mississippi River Diversion. vol. 1. U.S. Army Corps of Engineers, Mississippi River Commission, Vicksburg, MS. 145 p.

Fisk, H.N., McFarlan Jr., E., 1955. Late quaternary deltaic deposits of the Mississippi River. Geol. Soc. Am., 279–302. Special Paper No. 62.

Frazier, D.E., 1967. Recent deltaic deposits of the Mississippi River: their development and chronology. Gulf Coast Assoc. Geol. Soc Trans. 17, 287–315.

Giosan, L., Syvitski, J., Constantinescu, S., Day, J., 2014. Protect the world's deltas. Nature 516, 31–33.

Glavovic, B.C., 2014. Waves of adversity, layers of resilience: floods, hurricanes, oil spills, and climate change in the Misissippi Delta. In: Glavovic, B.C., Smith, G.P. (Eds.), Adapting to Climate Change. Springer Science, Dordrecht, pp. 369–403.

Groisman, P., Knight, R., Easterling, D., Karl, T., Hegerl, G., Razuvaev, V., 2005. Trends in intense precipitation in the climate record. J Clim 18 (9), 1326–1350.

Hemmerling, S.A., 2017. A Louisiana Coastal Atlas. Louisiana State University Press, Baton Rouge.

Hemmerling, S.A., 2018. Eroding communities and diverting populations: historical population dynamics in coastal Louisiana. In: Day, J., Erdman, J. (Eds.), Mississippi Delta Restoration Pathways to a Sustainable Future. Springer, Cham, Switzerland, pp. 201–230.

Hijma, M., Shen, Z., Törnqvist, T., Mauz, B., 2018. Late Holocene evolution of a coupled, mud-dominated delta plain-chenier plain systems, coastal Louisiana, USA. Earth Surf. Dynam. 5, 689–710. https://doi.org/10.5194/esurf-5-689-2017.

Hunter, R., Day, J.W., Lane, R., Shaffer, G., Day, J.N., Conner, W., Rybczyk, J., Mistich, J., Ko, J., 2018. Using natural wetlands for municipal effluent assimilation: a half-century of experience for the Mississippi delta and surrounding environs. In: Nagabhatla, N., Metcalfe, C. (Eds.), Multifunctional Wetlands, Environmental Contamination Remediation and Management. Springer, New York, pp. 15–81.

Hyfield, E., Day, J., Mendelssohn, I., Kemp, P., 2007. A feasibility analysis of discharging non-contact, once-through industrial cooling water to forested wetlands for coastal restoration in Louisiana. Ecol. Eng. 29, 1–7.

IPCC, R.K., Pachauri, Allen, M.R., Barros, V.R., Broome, J., Cramer, W., Christ, R., Church, J.A., Clarke, L., Dahe, Q., Dasgupta, P., Dubash, N.K., 2014. In: Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

Jankowski, K., Tornqvist, T., Fernandes, A., 2017. Vulnerability of Louisiana's coastal wetlands to present-day relative sea-level rise. Nat. Commun. 8, 14792. https://doi.org/10.1038/ncomms14792.

Joshi, S., Xu, J., 2017. Bedload and suspended load transport in the 140-km reach downstream of the Mississippi River Avulsion to the Atchafalaya River. Water 9, 716. https://doi.org/10.3390/w9090716.

Kates, R.W., Colten, C.E., Laska, S., Leatherman, S.P., 2006. Reconstruction of New Orleans after Hurricane Katrina: a research perspective. Proc. Natl. Acad. Sci. 103 (40), 14653–14660.

Keim, R., Chambers, J., Huges, M., Nyman, A., Conner, W., Day, J., Faulkner, S., Gardiner, E., King, S., McLeod, K., Shaffer, G., 2006. Ecological consequences of changing hydrological conditions in wetland forests of coastal Louisiana. In: Xu, S., Singh, V. (Eds.), Coastal Hydrology and Processes. Water Resources Publications, Highlands Ranch, CO, pp. 383–396.

Kemp, G.P., Willson, C.S., Rogers, J.D., Westphal, K.A., 2014. Adapting to change in the lowermost Mississippi River: implications for navigation, flood control and restoration of the Delta ecosystem. In: Day Jr., J.W., Kemp, G.P., Freeman, A.M., Muth, D.P. (Eds.), Perspectives on the Restoration of the Mississippi Delta: The Once and Future Delta. Springer, Dordrecht, pp. 51–84.

Kemp, P., Day, J., Rogers, D., Giosan, L., Peyronnin, N., 2016. Enhancing mud supply to the Mississippi River delta: dam bypassing and coastal restoration. Estuar. Coast. Shelf Sci. https://doi.org/10.1016/j.ecss.2016.07.008.

Kesel, R., Dunne, K.C., McDonald, R.C., Allison, K.R., Spicer, B.E., 1974. Lateral erosion and overbank deposition on the Mississippi River in Louisiana caused by 1973 flooding. Geology 2, 461–464.

Kim, W., Mohrig, D., Twilley, R., Paola, C., Parker, G., 2009. Is it feasible to build new land in the Mississippi River delta? Eos Trans. Am. Geophys. Union 90 (42), 373–374.

Kolb, C., van Lopik, J., 1958. Geology of the Mississippi River Deltaic Plain, Southeastern Louisiana. Technical Report No. 3-483. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Lane, R., Mack, S., Day, J., Kempka, R., Brady, L., 2017. Carbon sequestration at a forested wetland receiving treated sewage effluent. Wetlands https://doi.org/10.1007/s13157-017-0920-6.

Louisiana Office of Community Development. 2017. LASAFE. http://lasafe.la.gov/.

Maggio, G., Cacciola, G., 2012. When will oil, natural gas, and coal peak? Fuel 98, 111–123.

McKee, K.L., Mendelssohn, I.A., Materne, M.D., 2004. Acute salt marsh dieback in the Mississippi river deltaic plain: a drought-induced phenomenon? Glob. Ecol. Biogeogr. 13, 65–73.

Meade, R.H., Moody, J.A., 2010. Causes for the decline of suspended-sediment discharge in the Mississippi River system, 1940–2007. Hydrol. Process. 24 (1), 35–49.

Min, S.K., Zhang, X., Zwiers, F.W., Hegerl, G.C., 2011. Human contribution to more-intense precipitation extremes. Nature 470 (7334), 378–381.

Morton, R.A., Barras, J.A., 2011. Hurricane impacts on coastal wetlands: a half-century record of storm-generated features from Southern Louisiana. J. Coastal Res. 275, 27–43. https://doi.org/10.2112/JCOASTRES-D-10-00185.1.

Nienhuis, J., Törnqvist, T., Jankowski, K., Fernandes, A., Keogh, M., 2017. A new subsidence map for coastal Louisiana. GSA Today (Geologi. Soc. Am.) 27, https://doi.org/10.1130/GSATG337GW.1.

Nienhuis, J., Törnqvist, T., Esposito, C., 2018. Crevasse splays versus avulsions: a recipe for land building with levee breaches. Geophys. Res. Lett. https://doi.org/10.1029/2018GL077933.

Nittrouer, J., Viparelli, E., 2014. Sand as a stable and sustainable resource for nourishing the Mississippi river delta. Nat. Geosci. https://doi.org/10.1038/NGEO2142.

Pall, P., Aina, T., Stone, D.A., Stott, P.A., Nozawa, T., Hilberts, A.G., Lohmann, D., Allen, M.R., 2011. Anthropogenic greenhouse gas contribution to flood risk in England and Wales in autumn 2000. Nature 470 (7334), 382–385.

Paola, C., Twilley, R.R., Edmonds, D.A., Kim, W., Mohrig, D., Parker, G., Viparelli, E., Voller, V.R., 2010. Natural processes in delta restoration: application to the Mississippi delta. Annu. Rev. Mar. Sci. 3, 67–91.

Penland, S., Boyd, R., Suter, J., 1988. Transgressive depositional systems of the Mississippi delta plain: a model for barrier shoreline and shelf sand development. J. Sediment. Petrol. 58, 932–949.

Perez, B., Day, J., Rouse, L., Shaw, R., Wang, M., 2000. Influence of Atchafalaya River discharge and winter frontal passage on suspended sediment concentration and flux in Fourleague Bay, Louisiana. Estuar. Coast. Shelf Sci. 50, 271–290.

Prein, A.F., Rasmussen, R.M., Ikeda, K., Liu, C., Clark, M.P., Holland, G.J., 2016. The future intensification of hourly precipitation extreme. Nat. Clim. Chang. 7 (1), 48–52.

Reuss, M., 1998. Designing the Bayous: The Control of Water in the Atchafalaya Basin 1800–1995. U.S. Army Corps of Engineers Office of History, Alexandria, VA.

Roberts, H.H., 1997. Dynamic changes of the Holocene Mississippi river delta plain: the delta cycle. J. Coast. Res. 13, 605–627.

Roberts, H.H., DeLaune, R.D., White, J.R., Li, C., Sasser, C.E., Braud, D., Khalil, S., 2015. Floods and cold front passages: impacts on coastal marshes in a river diversion setting (Wax Lake Delta Area, Louisiana). J. Coast. Res. 31, 1057–1068.

Rosen, T., Jun Xu, Y., 2013. Recent decadal growth of the Atchafalaya River Delta complex: effects of variable riverine sediment input and vegetation succession. Geomorphology 194, 108–120.

Russell, R., 1936. Physiogaphy of lower Mississippi River Delta. Louisiana Dept. of Conservation, Louisiana Geological Survey. Geol. Bull. 8, 3–199.

Russell, R.J., Howe, H.V., McGuirt, J.H., Dohm, C.F., Hadley Jr., W., Kiffen, F.B., Brown, A., 1936. In: Lower Mississippi River Delta: reports on the geology of Plaquemines and St. Bernard Parishes. Louisiana Geological Survey, Geological Bulletin 13, Louisiana Department of Conservation, New Orleans, LA.

Rutherford, J., Day, J., D'Elia, C., Wiegman, A., Willson, C., Caffey, R., Shaffer, G., Batker, D., 2018a. Evaluating trade-offs of a large, infrequent sediment diversion for restoration of a forested wetland in the Mississippi delta. Estuar. Coast. Shelf Sci. https://doi.org/10.1016/j.ecss.2018.01.016.

Rutherford, et al., 2018b. In: Day, J., Erdman, J. (Eds.), Mississippi Delta Restoration Pathways to a Sustainable Future. Springer, Cham, Switzerland, pp. 201–230.

Saucier, R.T., 1963. Recent Geomorphic History of the Pontchartrain Basin. Louisiana State University Press, Baton Rouge.

Shaffer, G.P., Wood, W.B., Hoeppner, S.S., Perkins, T.E., Zoller, J., Kandalepas, D., 2009. Degradation of Baldcypress-water tupelo swamp to marsh and open water in southeastern Louisiana, USA: an irreversible trajectory? J. Coast. Res. 54, 152–165.

Shaffer, G., Day, D., Kandalepas, D., Wood, W., Hunter, R., Lane, R., Hillmann, E., 2016. Decline of the Maurepas swamp, Pontchartrain Basin, Louisiana and approaches to restoration. Water. 7, https://doi.org/10.3390/w70x000x.

Shaffer, G., Day, J., Lane, R., 2018. Optimum use of freshwater to restore Baldcypress-Water Tupelo swamps and freshwater marshes and protect against salt water intrusion: a case study of the Lake Pontchartrain Basin. In: Day, J., Erdman, J. (Eds.), Mississippi Delta Restoration Pathways to a Sustainable Future. Springer, Cham, Switzerland, pp. 61–76.

Shen, Z., Törnqvist, T.E., Mauz, B., Chamberlain, E.L., Nijhuis, A.G., Sandoval, L., 2015. Episodic overbank deposition as a dominant mechanism of floodplain and delta-plain aggradation. Geology 43, 875–878.

Steyer, G.D., et al., 2003. A proposed coast-wide reference monitoring system for evaluating wetland restoration trajectories in Louisiana. Environ. Monit. Assess. 81, 107–117.

Tao, B., Tian, H., Ren, W., Yang, J., Yang, Q., He, R., Cai, W., Lohrenz, S., 2014. Increasing Mississippi river discharge throughout the 21st century influenced by changes in climate, land use, and atmospheric CO_2. Geophys. Res. Lett. 41 (14), 4978–4986.

Tessler, Z.D., Vörösmarty, C., Grossberg, M., Gladkova, J., H. Aizenman, Syvitski, J., Foufoula-Georgiou, E., 2015. Profiling risk and sustainability in coastal deltas of the world. Science 349 (6248), 638–643.

Twilley, R., Bentley, S., Chen, Q., Edmonds, D., Hagen, S., Lam, N., Willson, C., Xu, K., Braud, D., Peele, R., McCall, A., 2016. Co-evolution of wetland landscapes, flooding, and human settlement in the Mississippi River Delta Plain. Sustain. Sci. 11, 711–731.

Wang, B., Xu, J., 2015. Sediment trapping by emerged channel bars in the lowermost Mississippi River during a major flood. Water 7, 6079–6096.

Wang, B., Xu, J., 2016. Long-term geomorphic response to flow regulation in a 10-km reach downstream of the Mississippi-Atchafalaya diverion. J. Hydrol.: Reg. Stud. 8, 10–25.

Wang, B., Xu, J., 2018. Dynamics of 30 large channel bars in the lower Mississippi River in response to river engineering from 1985 to 2015. Geomorphology 300, 31–44.

Wang, H., Steyer, G.D., Couvillion, B.R., Rybczyk, J.M., Beck, H.J., Sleavin, W.J., Meselhe, E.A., Allison, M.A., Boustany, R.G., Fischenich, C.J., Rivera-Monroy, V.H., 2014. Forecasting landscape effects of Mississippi River diversions on elevation and accretion in Louisiana deltaic wetlands under future environmental uncertainty scenarios. Estuar. Coast. Shelf Sci. 138, 57–68.

Welder, F.A., 1959. Processes of deltaic sedimentation in the lower Mississippi River. In: Louisiana State University, Coastal Studies Institute Technical Report. vol. 12, pp. 1–90.

Wiegman, R., Day, J., D'Elia, C., Rutherford, J., Morris, J., Roy, E., Lane, R., Dismukes, D., Snyder, B., 2017. Modeling impacts of sea-level rise, oil price, and management strategy on the costs of sustaining Mississippi delta marshes with hydraulic dredging. Sci. Total Environ. https://doi.org/10.1016/j.scitotenv.2017.09.314.

Wiegman, A., Rutherford, J., Day, J., 2018. The costs and sustainability of ongoing efforts to restore and protect Louisiana's coast. In: Day, J., Erdman, J. (Eds.), Mississippi Delta Restoration Pathways to a Sustainable Future. Springer, Cham, Switzerland, pp. 93–111.

Xu, J. 2017. What would happen if the Mississippi River changed its course to the Atcdhafalaya (Poster). American Geophysical Union Meeting, 12 December 2017. New Orleans, LA.

Xu, K., Bentley, S.J., Robichaux, P., Sha, X., Yang, H., 2016. Implications of texture and erodibility for sediment retention in receiving basins of coastal Louisiana diversions. Water 8, 26.