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Regional Sediment Processes, Sediment Supply, and Their Impact on the Louisiana Coast

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ABSTRACT

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Coastal Louisiana is geologically unique in the United States because its complex shallow geologic structure is the result of fluvial deposition (Mississippi and Atchafalaya Rivers) and marine reworking over thousands of years. Other characteristics include the preponderance of fine sediment, relative youth, and shallow nearshore slope. It has been impacted by more than 150 years of project-focused designs that have modified regional sediment transport. Because of engineering and commercial activities on the upper Mississippi River and the delta, the system is now suffering from innumerable geomorphic changes, which have produced profound social and economic consequences. Sediment to this coast has been almost totally supplied by the Mississippi's distributaries, with deltaic lobes changing over the centuries. Sediment delivery has diminished by over 50% during the last 150 years because of up-river engineering activities such as dam construction, bank stabilization, dredging, and levees. The ultimate implication of reduced sediment and rapid relative sea-level rise is that the delta can no longer grow as it did before urbanization and development of the continent. A sediment budget has been developed for the Louisiana coast based on multiyear data preceding Hurricanes Katrina and Rita. The budget is based on numerous sources and dredging data from the U.S. Army Corps of Engineers, New Orleans District. Despite the typically low-wave energy climate, sediment is transported alongshore between some cells. Also, there is significant loss offshore, possibly a consequence of storm impacts, sediment consolidation, and rapid relative sea-level rise.

ADDITIONAL INDEX WORDS: *Mississippi River, Atchafalaya River, sediment budget, delta, distributary, barrier island, Balize Delta, dredging.*

INTRODUCTION

The U.S. Army Corps of Engineers (USACE) has recently been implementing Regional Sediment Management (RSM) principles as part of projects and studies throughout the United States (Lillycrop, 2003; Lillycrop and Eng, 2003; Lillycrop *et al*., 2011; Rosati *et al*., 2001). In the past, USACE projects were designed and optimized based on local benefits. Since the 1990s, the USACE has started considering local projects within a regional framework, seeking to maintain sediments within the littoral system while minimizing adverse project effects. The coast of Louisiana is a prime example of a region that has been adversely impacted by more than 150 years of project-focused designs that have modified sediment transport processes on regional scales. Engineering and commercial activities on the upper Mississippi River and the delta have resulted in a system that is now suffering from rapid geomorphic changes. These include channeling of fluvial sediment out the mouth of the river rather than into the wetlands, reduction of sediment supply compared to the early years of the 20th century, and saltwater intrusion caused by canal construction (as discussed below). These geomorphic changes are producing profound social and economic consequences in coastal Louisiana. Consequences include costly efforts to rebuild and nourish the barrier islands, artificially divert riverine-borne sediment into the wetlands, build or improve levees for the most vulnerable urban areas, and maintain deep-draft navigation.

The USACE, New Orleans District manages the coastal region extending from the Pearl River, Mississippi, in the east to the Sabine–Neches Waterway, Louisiana, in the west (Figure 1). This area includes the Mississippi and Atchafalaya River systems and numerous river, estuarine, harbor, flood risk management, erosion control, navigation, and restoration projects. The Red River, which joins the Mississippi at the Old River Control structures, is managed by the USACE, Vicksburg District. This regional system is extremely challenging for managing sediment resources in a cost-effective manner for many reasons, including:

- Extensive damage from hurricanes, most recently in 2005 (Katrina and Rita) and 2008 (Gustav and Ike)
- Infrastructure such as canals, levees, ports, and flood-control structures

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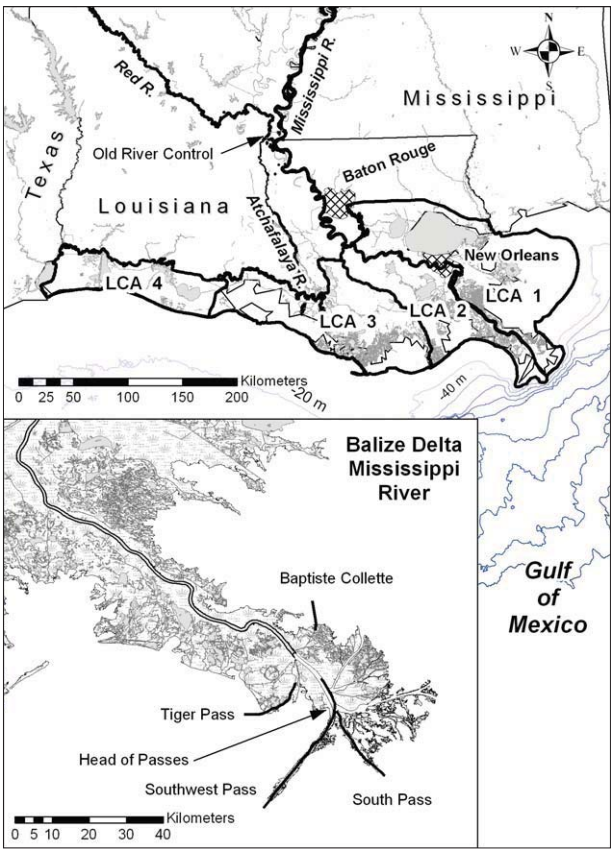

Figure 1. Study area with outlines of Louisiana Coastal Area (LCA) provinces, applied in the development of the conceptual sediment budget. Contours (in meters) from National Geophysical Data Center, rivers and coastal features from ESRI®. Insert shows the modern Balize Delta with main navigation channels.

- Heavy use as a working coast for the oil, gas, fishing, and oyster industries
- Regional subsidence and geologic faulting, resulting in one of the highest rates of relative sea-level rise in the United States (9.2 mm/yr at Grand Isle, Louisiana (Coleman, 1988; NOAA, 2012a))
- Complex geotechnical characteristics of deltaic sediments
- Fragile wetlands that are critical for fish and bird habitat

The USACE has numerous ongoing and planned projects to reduce erosion, maintain or restore habitat, and sustain the USACE's missions of providing navigation, flood risk management, and storm damage reduction within a regional sediment management framework. A regional sediment budget that accounts for the net and gross transport of sediment throughout the coastal and riverine systems and all dredging and placement activities is needed to best manage existing and future projects along this coast. To reinforce this need, the USACE requested the National Research Council of the National Academy of Sciences to review the Louisiana Coastal Protection and Restoration (LACPR) draft final technical report of 2009 (USACE, 2009). The National Research Council (2009) specifically recommended that the LACPR team needed to ensure that sediment budgets were prepared for all coastal restoration plans to ensure that adequate sediment was available for the intended restoration work. The State of Louisiana's Comprehensive Master Plan for a Sustainable Coast (Louisiana Coastal Protection and Restoration Authority, 2007) also recommended formulation of a regional sediment budget, including data analysis, numerical modeling, and assessment of dredging and placement within the region.

In this study, we developed a conceptual regional sediment budget representing existing conditions for the coastal and riverine system in southern Louisiana. A conceptual sediment budget is a qualitative model giving a regional perspective of beach, estuarine, and riverine processes, incorporating natural morphologic indicators of net (and gross) sediment transport (Dolan *et al.*, 1987; Kana and Stephens, 1992; Rosati, 2005). The conceptual budget represents the best understanding of sediment sources, sinks, and pathways within the regional system, and identifies areas with overlapping and conflicting estimates as well as regions lacking data. Therefore, a conceptual budget can be applied to direct future analysis and data collection. The conceptual model may be put together in part by reviewing existing literature and adopting existing sediment budgets for portions of the study area. Once the conceptual sediment budget has been completed, data are assimilated, analyzed, and numerical models are applied to validate the conceptual model. Here, we summarize the geologic history of the study area, discuss anthropogenic activities that have occurred over the past 100 years, review the existing knowledge for coastal sediment transport and morphology change for coastal Louisiana, and develop a regional conceptual sediment budget. The paper concludes with a summary of sediment management challenges facing coastal Louisiana.

STUDY AREA

General Setting

Two physiographic provinces dominate coastal Louisiana. West of Marsh Island is a coastal plain known as the *cheniere* (from the French *chene*, meaning oak). The cheniere plain is composed of mudflats backed by marsh with regular series of ridges composed of sand and shell hash (Williams, Penland, and Sallenger, 1992). Chenier is the commonly used geomorphic term for the stranded transgressive shore that develops downdrift of some river mouths. Louisiana Coastal Area (LCA) region 4 covers this terrain (Figure 1).

East of Marsh Island is the delta plain, a complex of marshes, active and abandoned distributaries, tidal creeks, bays, sounds, low barrier islands, and man-made channels.

Where barrier islands have developed, they tend to be only a few hundred meters long, often consist of sand veneers that overlie mud substrates (although some overlie thick tidal sand deposits), and have marsh vegetation and mud on the back-barrier. Despite their limited extent, the Louisiana Barrier Island Erosion Study documented how critical they are in protecting wetlands, bays, and estuaries behind the islands (Williams, Penland, and Sallenger, 1992). Barrier islands protect wetlands from offshore wave energy, thereby reducing mechanical erosion,

storm surge heights, and saltwater intrusion (Stone, Zhang, and Sheremet, 2005). Louisiana's barriers have been used since the 1700s for trapping, cattle grazing, recreation, privateering, and limited settlement. Settlements were often short-lived because hurricanes periodically swept over the barriers, destroying hunting and fishing camps and old-fashioned wooden hotels (such as the Ocean Club Hotel on Grand Isle, destroyed in 1893 after only one season (Ditto, 1980)). Most of the barriers are now unoccupied and only irregularly sited with recreational cabins and petroleum structures. Grand Isle and Port Fourchon have road access and year-round habitation.

During the 20th century, over 15,000 km of canals were cut through the marshes for construction, petroleum pipelines, mosquito control, access to oil and gas drilling and production sites, and as shortcuts between deeper channels (Day *et al*., 2007). Many are not maintained now and can only be used by local fishermen who know the conditions. Other channels form part of the Intracoastal Waterway (ICW) or are links from the Gulf to the Intracoastal (Figure 2). Table 1 lists the main navigation channels and inlets that reach the Gulf. These are important because much of the sediment management on this coast since the late 1800s has revolved around local, project-centric activities such as maintaining depth in navigation channels and disposing of the dredged material. As a result, rivers have been confined to their channels by levees and jetties. The ultimate consequence of this engineering process is that much of the sediment load from the Mississippi River has been directed to deep Gulf of Mexico waters, where it is lost from the littoral zone.

Sediment Sources and Losses

Mississippi River background and present conditions

The main source of sediment for coastal Louisiana is the Mississippi River, which carries fine-grained sediment in suspension, some sand in suspension (referred to as bed-material load) and sand in bedload (Meade and Moody, 2010). Bedload may account for less than 5% of the total sediment discharge (Nittrouer, Allison, and Campanella, 2008). The river and its tributaries form the fourth longest network of navigable waters in the world (CIA, 2009), allowing barge traffic to access the Ohio, Missouri, Red, Tennessee, and other rivers in the heartland of the North American continent and even allowing connection to the Great Lakes and the St. Lawrence Seaway. The complex shallow geologic framework of Louisiana's coast is the result of deposition from fluvial systems and deltaic reworking over thousands of years. During the Holocene epoch, the Mississippi River formed five major delta complexes, each one associated with a major shift in the river's course (Coleman, Roberts, and Stone, 1998). Switching of the river mouth took place about every 1,000 to 2,000 years and resulted in delta lobes, which covered about 13,000 km^2 (Figure 1 in Coleman, Roberts, and Stone, 1998). About 70% of the Mississippi's volume now flows to the Gulf through the fifth of these complexes, known as the Balize (Figure 3). The delta front of the Balize has grown out into the deep water of the outer continental shelf, which has resulted in the seaward displacement of clay-rich sediments by a variety of seafloor mass-movement processes (Coleman, 1988). Once a

Figure 2. Dulac, Louisiana (March 1981), located near the Gulf of Mexico entrance to the Houma Navigation Channel. Residents of Dulac and other towns in southern Louisiana depend on the water for their livelihoods. Although about 25 km from the Gulf, Dulac, at an elevation of 1–2 m above sea level, is highly vulnerable to flooding and was inundated by Hurricane Rita in 2005. (Photograph by A. Morang.)

Table 1. *Major Louisiana Passes and River Mouths (East to West).**

Name	Location	Structures	Navigation	Notes
Mississippi River-Gulf Outlet Canal	Chandeleur Sound	Stone dikes; NE: 4.2 km, SW: 8.8 km	Formerly: 11.6-m deep channel, then 11.0-m across Breton Sound	Built 1960–1968 as deep-draft alternative to Mississippi River. Hazardous for pleasure craft. Closed after Hurricane Katrina, deauthorized 2008 and closed to navigation 2009.
Baptists Collette Bayou	Venice to Breton Sound	Jetties: E: 2,700 m; W: 2,100 m, 160 m apart	6.1 × 76-m channel; controlling depth <1 m	Built 1978–79.
Pass a Loutre	Head of Passes E to Gulf		2 m over entrance bars	Local small craft use only.
South Pass	Head of Passes SE to Gulf	Inner and outer jetties of willow, stone, shell, concrete. Outer has deteriorated. Inner E: 2,700 m. W: similar	5.2 m project depth (MLG) × 183 m, but pilot recommended draft <4.6 m	Initial jetty construction 1875 by James B. Eads. Largely inactive now, used by tugs and barges.
Southwest Pass	Head of Passes SW to Gulf	Jetties of fascine, willow, stone, shell, concrete, and marble E: 7,770 m built, now 4,330 m; W: 6,380 m built, now 5,320 m. 1,100 m apart at seaward end	13.7 m project depth × 183 m	Jetty construction begun 1904, many repairs needed due to settlement and storm damage. Main deep-draft entrance to Mississippi River. Frequent dredging required.
Tiger Pass	Venice SW to Gulf	Stone, shell, and filter fabric jetties. N: 1430 m S: 820 m, 165 m apart	5.2 × 76-m channel; control depth <1.8 m	Built 1978–79.
Empire Waterway (Bayou Long and Bayou Fontenalle)	Empire south to Gulf	Fascine, shell, and rubble-mound. Approx. 55-m long	2.7 × 24-m channel	Floodgates at Bayou Long.
Barataria Pass at Grand Isle	Barataria Bay to Gulf, between Grand Isle and Isle Grand Terre	Timber, shell, and stone	Single jetty 710-m long, 3-m channel depth	Islands at mouth of bay change frequently.
Caminada Pass	Caminada Bay to Gulf (W. side of Grande Isle)		Depth only 1 m	Shallow, frequent shifts.
Bayou Lafourche at Belle Pass	Port Fourchon to Gulf	Steel sheet pile and stone, approx 300-m long	8 × 91 m, now located W of the original channel	Jetties built 1939. Main channel used by oil-field service and fishing vessels.
Grand Pass Timbalier and Little Pass Timbalier	Timbalier Bay to Gulf		Not maintained, depths < 2 m frequent changes	Islands at mouth of bay change frequently.
Cat Island Pass	Terrabone Bay to Gulf		< 2 m	Main entrance to Houma Navigation Channel.
Bayou Grand Caillou	Houma Nav. Canal below Dulac to Gulf		<1.5 m	Used by fishing boats.
Atchafalaya Bay Ship Channel	Morgan City and lower Atchafalaya R. to Gulf		6.1 × 122 m	Main channel to Berwick Bay, Morgan City, Intracoastal Waterway.
Southwest Pass at Marsh Island	Vermilion Bay to Gulf		< 2 m	Between Marsh Island and mainland.
Freshwater Bayou Channel	Freshwater Canal to Gulf at Paul J. Rainey Wildlife Refuge			Saltwater barrier lock 2 km north of entrance.
Mermentau River Nav. Channel	Lake Arthur to Gulf near Lower Mud Lake	Stone rubble-mound	4.6 × 61-m channel; control depth <1.5 m	
Calcasieu Pass	Calcasieu Lake to Gulf near Cameron	Brush mats, riprap stone, granite capping stone	12.8 × 243-m bar channel	First built 1893, many subsequent improvements. Deep-draft channel to Lake Charles.

Notes: * Major openings and Federal projects only; numerous minor channels not listed
MLG=Mean Low Gulf datum

Sources:
Cowdrey, 1977
Sargent and Bottin, 1989
U.S. Coast Pilot, 2010
USACE, Mississippi Valley Division, 1995
NOAA, Office of Coast Survey, 2012

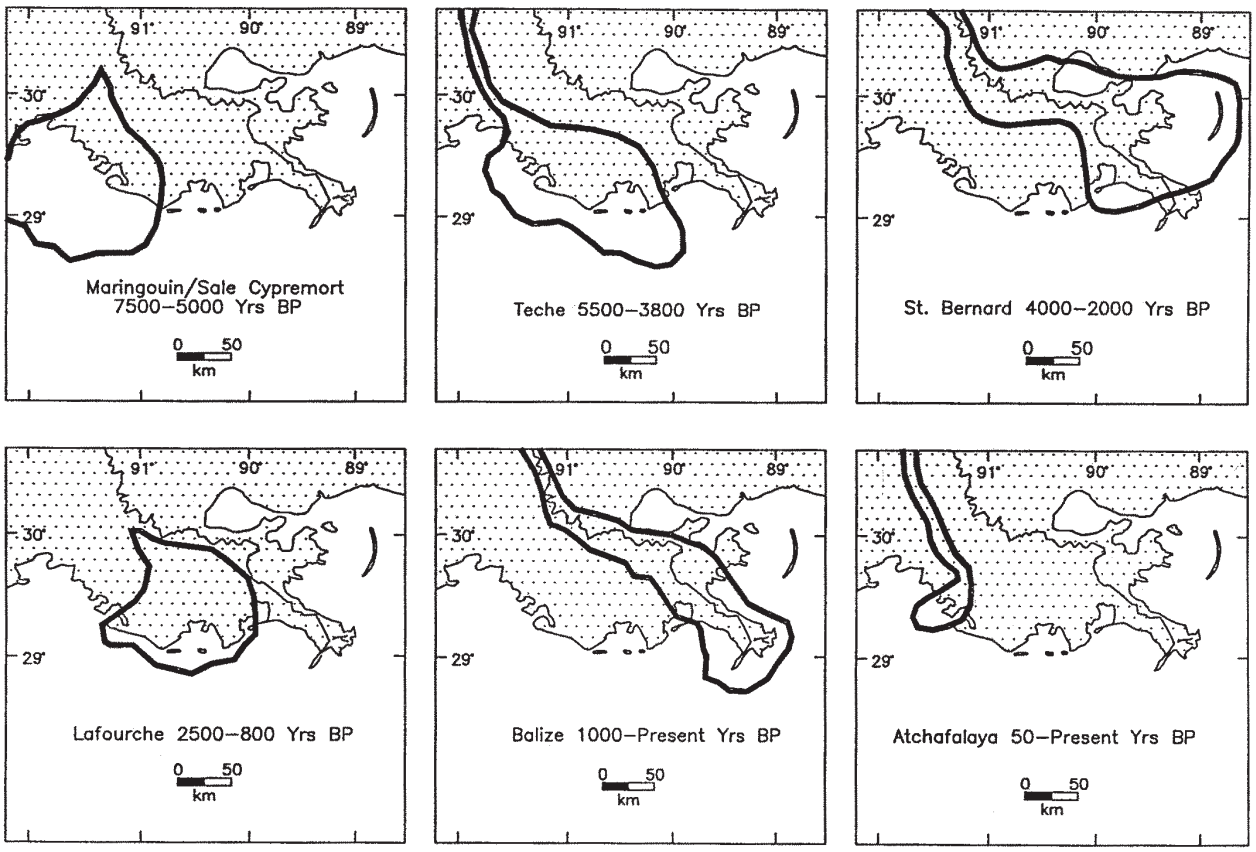

Figure 3. Mississippi River lobes during the Holocene era (from Coleman, 1988). The Atchafalaya is currently growing and would eventually take over from the Balize without human intervention. The channel down the Balize (the contemporary Mississippi River) is maintained for navigation as is the Atchafalaya River.

distributary has been abandoned, it shifts from being a fluvial system to one dominated by marine processes, and the sediments are reworked and redistributed as part of a complicated delta cycle (Coleman, 1988; Coleman, Roberts, and Stone, 1998).

At New Orleans, high water flow is about 31,000 m^3/sec (1,100,000 ft^3/sec), medium flow is about 15,000 m^3/sec (520,000 ft^3/sec) and low flow is about 5,000 m^3/sec (180,000 ft^3/sec) (U.S. Coast Pilot, 2010). These values have remained reasonably steady for at least a half-century. The U.S. Geological Survey's (USGS) streamflow program has documented that despite minor changes in precipitation, reservoir filling, runoff, evapotranspiration, extraction, and land use, mean discharge of the Mississippi has remained approximately constant from 1949 to 1997 (U.S. Geological Survey, 2005).

During periods of low flow, clay and silt transported in suspension come in contact with saltwater plumes (U.S. Coast Pilot, 2010). The saltwater plume usually progresses and regresses between Venice and New Orleans, approx. 20–180 km above Head of Passes (Galler and Allison, 2008). This interaction causes flocculation and the deposition of jellied masses of muck (locally known as slush). The slush may be as thick as 3–4 m and remains in the lower courses of the river until it is flushed out during high-water stages (U.S. Coast Pilot, 2010). The slush does not normally impede shipping but is sometimes dredged, depending on its density. During periods of high flow, the main channel as far south as Head of Passes contains freshwater (Figure 1).

Coarser sediment (sand) is transported downstream during high stages in the form of sand waves on the riverbed (Galler and Allison, 2008; Nittrouer, Mohrig, and Allison, 2011). Formerly, sand was reworked as bars at the mouths of the outlets, but in the last few decades, USACE, New Orleans District dredging data indicates that little sand moves on the bed below New Orleans (N. Powell, USACE, *oral communication*, 2008). A summary of 1996–2011 dredging data indicates that material removed from New Orleans Harbor (Miles 86–104) was almost 100% sand (Table 2). This sand was disposed of in open water, meaning it returned to the river. But in Southwest Pass, the deep-draft navigation channel, the material removed averaged 25% sand, 50% silt, and 25% clay. For additional reference, Table 2 also lists Atchafalaya River dredging.

Allison *et al.* (2012) computed a sediment budget for the Lower Mississippi River for flood years 2008–2010, using USGS and USACE monitoring stations and depth-integrated isokinetic sampler data. Total suspended load at Baton Rouge was 92.6 million tons/year, while at Belle Chasse, south of New Orleans,

Table 2. *Mississippi and Atchafalaya River dredge volumes and materials, 1996–2007.*

Channel/Reach	Dredge frequency	Average quantity per dredge event (yd^3)	Average annual quantity (yd^3)	Average annual quantity (m^3)	Sand %	Silt %	Clay %	Average annual sand vol (m^3)	Average annual silt vol (m^3)	Average annual clay vol (m^3)	Federal standard ** % used beneficially
MS River–crossings (Miles 114-230)	annually	14,620,000	14,620,000	11,178,500	100	0	0	11,178,500	0	0	0
MS River–New Orleans Harbor (Miles 86-104)	annually	1,131,500	1,131,500	865,100	100	0	0	865,100	0	0	0
MS River–Baptiste Collette	every 1–3 years	1,354,800	677,400	517,900	3	70	0	15,500	362,500	0	100
MS River–Southwest Pass*	annually	15,615,000	15,615,000	11,939,200	25	50	25	2,984,800	5,969,600	2,984,800	25
MS River–Tiger Pass	every 1–3 years	1,941,900	970,950	742,400	30	70	0	222,700	519,700	0	100
MS River–South Pass	every 7–8 years	5,993,000	799,067	611,000	45	45	10	275,000	275,000	61,100	100
Atchafalaya–bar	annually	9,000,000	9,000,000	6,881,400	7	72	21	481,700	4,954,600	1,445,100	20
Atchafalaya (Lower) Bay	annually	2,130,000	2,130,000	1,628,600	80	18	2	1,302,900	293,100	32,600	100
Atchafalaya–Horseshoe Bend	annually	1,200,000	1,200,000	917,500	80	18	2	734,000	165,200	18,400	100
Bayous Chene, Boeuf and Black	every 5–6 years	5,773,000	1,049,636	802,600	3	77	20	24,100	618,000	160,500	22
Berwick Bay Harbor	annually	1,686,000	1,686,000	1,289,100	92	8	0	1,186,000	103,100	0	Varies ***
Totals		60,445,200	48,879,553	37,373,000							

Project dredge quantities reported in cubic yards as per common use in the United States.
* Quantity includes the periodic mining of the Pass A Loutre hopper dredge disposal area.
** The Federal Standard is defined in USACE regulations as the least costly dredged material disposal or placement alternative (or alternatives) identified by USACE that is consistent with sound engineering practices and meets all federal environmental requirements, including those established under the Clean Water Act (CWA) and the Marine Protection, Research, and Sanctuaries Act (MPRSA) (see 33 CFR 335.7, 53 FR 14902) (EPA, 2007).
*** Placement into commercial sand pits for beneficial use varies depending on capacity of pits and commercial needs.
Based on New Orleans District data from years 1996 through 2011 (Edward Creef, USACE, New Orleans District, *unpublished data*, 2012).

total load had dropped to 88.3 million. At Southwest Pass, total load was down to 20.8 million tons/year. The sand load diminishes at a greater rate. Sand load at Baton Rouge was 27.9 million tons/year, and at Belle Chasse 17.8 million tons/year. But at Southwest pass, sand load was only 1.2 million tons/year. The authors concluded there has been a progressive increase in channel aggradation rates downstream of Belle Chasse between 1992 and 2003. Reduced stream power is a byproduct of multiple natural passes and man-made exits. The authors also concluded that as much as 44% of the total suspended sediment load and 80% of the sand load of the combined Mississippi and Red Rivers was impounded in the basin between the Old River Control Structures and the Mississippi and Atchafalaya outlets to the Gulf of Mexico. In summary, the proportion of sand diminishes significantly south of New Orleans, and material removed from the navigation channels averages more than 50% silt and clay.

Another sand loss is the volume mined from the river in Baton Rouge and New Orleans by commercial sand companies to use in construction or as fill. We have not been able to find tabulated quantities. Sand companies also mine sand from the Bonnet Carré Spillway after high-water events when the spillway is opened to divert water into Lake Pontchartrain (Edward Creef, USACE, New Orleans District, *oral communication*, 2012).

Reduction of sediment supply to coastal wetlands

Two major factors have reduced sediment input that formerly nurtured Louisiana's coastal wetlands. The first was reduced sediment carried by the Mississippi River and its tributaries; the second was construction of levees to control flow the along the lower river.

A number of researchers have concluded that total annual sediment coming down the Mississippi has diminished greatly over the past 150 years. Keown, Dardeau, and Causey (1986), Kesel (1988), and Meade and Moody (2010) estimated that before European settlement, the river transported over 400 million metric tons of suspended sediment annually to the Gulf (Table 3). This value has decreased by more than half in the late 20th century (145–150 million tons: Horowitz, 2010; Thorne *et al*., 2008; 200 million tons: Burgess and Hovius, 1998; Keown, Dardeau, and Causey, 1986; 210 million tons: Meade and Parker 1984; 157 million tons at Tarbert Landing: Allison *et al.*, 2012).

The reasons for sediment load reduction can be attributed to upriver anthropogenic activities (summarized in Committee on the Restoration and Protection of Coastal Louisiana, 2006):

(1) River bank stabilization and bank armoring to reduce bank calving.
(2) Dams on tributaries of the Upper Mississippi and Ohio Rivers.
(3) Sediment trapping behind dikes and training structures.
(4) Levees that reduce farm and field runoff into the main rivers.
(5) Changing land use and increased urbanization.
(6) Improved soil conservation practices.
(7) Prevention of new cutoffs.

Table 3. *Mississippi River suspended sediment load at New Orleans.*

Period	Suspended sediment transport (million tons/year)
1851–1853	396
1930–1952	298
1953–1962	112
1963–1982	82*

Source: Kesel (1988); reprinted in Committee on the Restoration and Protection of Coastal Louisiana (2006).
* Other researchers estimate up to 200 million tons/yr; see text.

Note that despite the construction of dams during the mid-20th century, the Mississippi still ranks seventh in the world in discharge of suspended sediment (Meade, 1996). The combined load of the Mississippi and Atchafalaya Rivers accounts for 70% of the mean annual sediment discharge from the conterminous United States (Horowitz, 2010).

The second main factor that reduced sediment availability for wetlands was the construction of levees in the lower delta to control the flow of the river and improve its reliability for navigation. Levees were first built for flood control by plantation owners in the 1700s (Reuss, 1998), and a systematic national effort to control the Mississippi followed the economic, political, and social turmoil caused by the 1927 flood (Barry, 1997). Artificial levees not only largely eliminated the overflow of freshwater and sediments into adjacent marshes during spring floods but have also prevented formation of crevasse splays (Day *et al*., 2007). Crevasses are breaks in natural levees, which allow large volumes of river water to spread into the adjacent marshes, thereby providing sediment and slowly building landforms known as crevasse splays. Today, levees and jetties extend to the mouth of the delta, where the suspended sediment dissipates into the Gulf of Mexico.

When levees were first built in the 19th century to control flooding and improve navigation, few people recognized their effect on delta and wetland loss, but by the late 1800s, the basic principles of settlement versus sediment input were recognized:

> It is a fact well-known to people living in the delta of the Mississippi that large tracts of land were long ago abandoned in consequence of overflow by Gulf waters, due to the shrinking of the lands. The conditions are very different now from those existing prior to the construction of the levees. There are at present no annual accretions of sedimentary matters from the periodical overflows of the river. These accretions formerly were a little more than equal to the annual subsidence of the lands (Corthell, 1897).

Most engineers and politicians then did not appreciate how critical wetlands were to fisheries and to marine and coastal ecosystems. At that time, the benefits to society were deemed to outweigh the sedimentological cost of sediment diversion:

> No doubt the great benefit to the present and two or three following generations accruing from a complete system of absolute protective levees, excluding the flood waters entirely from the great areas of the lower delta country, far outweighs the disadvantages to future generations from the subsidence of the Gulf delta lands below the level of the sea and their gradual abandonment due to this cause (Corthell, 1897).

Numerous restoration plans have been proposed in the last 30 years to allow river water to flow through the wetlands during floods, including diversions at the locations of former crevasses, but to date little has been accomplished in comparison to the continuing loss of wetlands (Committee on the Restoration and Protection of Coastal Louisiana, 2006). Today, some of the material dredged from the Mississippi River below New Orleans is placed into wetlands, thereby partially replicating the former natural overflow during high water stages. For example, 100% of

the sediment from Baptiste Collette Bayou, Tiger Pass, and South Pass is beneficially recycled, along with 24% from Southwest Pass (Table 2). "Beneficial use" means that dredged sediment is placed in wetlands or used to build bird islands. For Southwest Pass, maintenance material was not placed in wetlands from 2002 through 2008 because of the use of hopper dredges, but for 2009, 2010, and 2011, cutterhead dredges were used along with the hoppers, and all cutterhead material was beneficially placed along the banks of Southwest Pass or in the wetlands adjacent to the Head of Passes (Edward Creef, USACE, New Orleans District, *oral communication*, 2012). University of New Orleans (2001) documented pre-1999 placement of cutterhead dredged material along the banks of Southwest Pass and in East and West Bays.

Larger scale diversions could be beneficial, and Kim *et al.* (2009) predicted that in a century, diversions into Barataria Bay and Breton Sound could produce about 920 km^2 of delta even under a scenario of subsidence of 5 mm/year and sea-level rise of 2 mm/year (equal to 7 mm/year relative sea-level rise). This prediction may be too optimistic because relative sea-level rise is already greater than 7 mm/yr in some areas in southern Louisiana. For example, NOAA (2012a) reports a linear mean sea level (MSL) trend of 9.24 ± 0.59 mm/year at Grand Isle (1947–2006 data) and 9.65 ± 1.24 mm/year at Eugene Island (1939–2006 data). These are the two highest MSL rise stations in the United States. The main problem with most of these diversion plans is the conflict with commercial navigation. Recent experience has shown that directing more flow through diversions increases shoaling in the main channel, thereby requiring more dredging. In an era of decreased funding for channel maintenance, the benefits to wetlands will have to be weighed against the greater cost of maintaining deep-draft navigation. It is unrealistic to consider removing levees to allow the river to naturally overflow its banks and deposit sediments in the adjacent wetlands because of the difficulty in maintaining the deep-draft navigation channel, and annual flooding is not a realistic option for citizens along developed areas of the Mississippi River corridor (Winer, 2010).

The ultimate implication of reduced sediment supply is that the delta can no longer grow in the manner that it did for centuries before urbanization and development of the North American continent. Blum and Roberts (2009) calculated the amount of sediment stored in the Louisiana deltaic plain over the last 12,000 years and concluded that contemporary total sediment loads were significantly less than the rates of sediment storage that had resulted in the construction of the delta plain, and that modern loads would not be sufficient to sustain the remaining delta surface area even with previous (late Holocene) rates of sea-level rise. They also concluded that significant portions of the delta might be drowned because sea level is now rising much faster than during the era of delta-plain construction.

River Diversion

River diversion is another condition that has affected sediment supply to the coast around the delta. For example, historically, Bayou Lafourche was one of the major distributaries of the Mississippi River and carried approximately 12% of its discharge until it was closed in 1904 at Donaldsonville for flood protection (Curole, 2003). From that point, there was no Mississippi River input into Bayou Lafourche until 1955, when pumps were installed at Donaldsonville to maintain a flow of 7 m^3/sec (260 ft^3/sec) (Curole, 2003). Sediment input before 1904 is unknown, but during floods, it is likely that the bayou delivered significant material to the Gulf, some of which would have fed wetlands and beaches.

Atchafalaya River

In contrast to the Mississippi and most other rivers in this area, the Atchafalaya River, which flows into Atchafalaya Bay, is gradually supplying more sediment to the coastal zone. The Atchafalaya River has served as a distributary of the Mississippi River since the 1500s and has carried large volumes of water and sediment throughout this period (Fisk, 1952). During this time, sediment influx accumulated in lakes and other natural catchment basins in the upper reaches of the river. By 1778, a great raft of timber had plugged the upper reach of the Atchafalaya, effectively preventing its further enlargement. Farmers, the State of Louisiana, and the USACE made repeated attempts to clear the raft (Cowdrey, 1977). Clearing snags and log jams was one of the USACE's early civil works missions (Reuss, 1998), and the river only began to carry major amounts of sediment to the coast after log jams were cleared in 1880. A variety of measures, such as dredging a straighter channel, were undertaken in the early 20th century to make the Atchafalaya a better floodway and to improve navigation. These measures were so successful that by 1940, the channel was enlarging rapidly and there was no longer a need for maintenance dredging. By the early 1950s, most of the inland lakes achieved their maximum holding capacity and sediment began accumulating at the river's mouth in Atchafalaya Bay (Tye and Coleman, 1989). An emergent delta formed in 1973, following that year's Mississippi flood (Roberts *et al*., 2005).

The Atchafalaya River is a Federal navigation project, with a 3.7-m deep channel. Commerce transported through the channel consists of shell, logs, sand, gravel, petroleum products, sulfur, and sugar products (U.S. Coast Pilot, 2010). The total flow down the Atchafalaya River is regulated to be 30%, by law, of the combined Red River and Mississippi River totals at this latitude (31º N). To achieve the percentage, the USACE diverts a portion of the Mississippi's flow to the Atchafalaya River via a system of control structures and the Sidney A. Murray, Jr., Hydroelectric Station at Old River, Louisiana. Because of the varying inputs from the Red River, the diversion to the Atchafalaya from the Mississippi River ranges from 16% to 26% annually (1961–2007), averages computed from historical discharge data from MVN (USACE, 2011).

The Atchafalaya River may carry from 75 million (USACE data, summarized in Roberts *et al*., 2005) to 88 million tons (LaCoast, 2011) of sediment annually to the bay. The proportion of suspended sediment carried by the Atchafalaya River is higher than the proportion carried by the Mississippi River because of a large clay and silt contribution from the Red River, which feeds the Atchafalaya River just north of the Old River Control Structures (Mossa, 1990). Despite high suspended sediment transport by the Atchafalaya River, the two newly formed deltas at the Wax Lake and Berwick Bay outlets are sand-rich, containing about 70% sand (Roberts *et al*., 2005). Waves, water-level changes, and abrupt wind shifts associated with cold-front passages resuspend fine-grained sediments in the bay and

Table 4. *Coastal processes in the Northern Gulf of Mexico.**

Storm	Frequency (events/ year)	Description
Typical nonstorm conditions	Most of year	Microtidal climate with diurnal range=0.15 (equatorial) to 1 m (tropic)[1]; 0.36 m (mean) Mean annual significant wave height=0.8–1 m[1] ; wave period=4.5–5.9 sec[1] Winds most frequently from southeast, but typically below magnitude for eolian transport[2]
Cold front	20–40[1,2]	Fronts typically migrate northwest to southeast[1] Prefrontal conditions: significant deep water wave height 3–4 m; wind from south 13[3] to 36[1] km/h Frontal passage: Surge=0.3–0.4 m[1]; winds from north up to 55 km/h[3] Postfrontal: Winds from north 65–85 km/h; peak significant wave height=2.7 m (for 5 hr) and 1.5 m (for 24 hr) [1] Duration: 12–24+ h[1]
Tropical storms (TS) or Weak Hurricanes (Category 1 or 2)	TS: 0.625 (approx. every 1.6 y)[4] Weak hurricane: 0.24 (once every 4.1 y)[4]	TS peak occurrence: August–September; Hurricanes: September[1] Surge: 0.6 m (TS Isidore, September 2002); 2.2 m (Cat. 2 Georges, September 1998)[1] Wind: 160 km/hr (Georges)[1] Significant wave height: 2.3 m (TS Isidore), 2.8 m (Cat. 1 Lili, October 2002)[1]; 10 m (Georges)[5] Wave period: 12–14 s (Georges)[5]
Moderate to Severe Hurricanes (Category 3+)	0.10–0.03 (once every 10-30 y)[4]	Peak from August–September Surge: 1.2 m (Cat. 4 Frederic, August 1979)[6]; 2-4 m (Cat. 3 Andrew, August 1992)[7]; 4–5.5 m (Cat. 3 Rita, September 2005)[8] ; 6.7 m (Cat. 5 Camille, August 1969)[1]; 8.5 m (Cat 3 Katrina, August 2005)[9] ; Wind: 200 km/h (Frederic)[6] ; 210+ km/h (Andrew)[7] ; 160–220 km/hr (Rita)[10]; 260 km/hr (Katrina) [9]; 322 km/h (Camille)[1] Offshore waves: 12 m (Rita)[10] ; 14+ m (Andrew)[7] ; 17 m (Katrina)[9]

*Adapted from Rosati and Stone (2009)
[1] Georgiou, FitzGerald, and Stone, 2005
[2] Dingler and Reiss, 1990
[3] Pepper and Stone, 2004
[4] Ritchie and Penland, 1988
[5] Stone *et al*., 2004
[6] Kahn and Roberts, 1982
[7] Penland *et al*., 2003
[8] URS, 2006
[9] Interagency Performance Evaluation Team, 2006
[10] National Data Buoy Center, 2005

delta and transport them to the continental shelf (Roberts *et al*., 2005). Feng and Li (2011) computed that strong cold fronts can flush 40% of the Atchafalaya/Vermilion Bay waters out onto the continental shelf in less than a 40-hour period. An average cold front may export ~400,000 metric tons of sediment from the bay (Roberts *et al*., 2003), implying that during a typical winter of 15–20 cold fronts, 6–8 million tons of fine-grained material may move offshore. Some of this sediment is advected to the west, where it is deposited on the eastern chenier plain, creating mud flats on the coast and bedforms on the inner shelf (Draut *et al*., 2005; Roberts *et al*., 2003). Some coarse sediment may also move offshore, as documented by Kobashi and Stone (2009) for a 2006 storm with instrumentation deployed on Ship Shoal. Current meter studies conducted in the 1980s indicated that sand that reached the shelf was redistributed to the east and offshore in winter by winds associated with cold-front passages (Adams, Wells, and Coleman, 1982). It is not known if this sand contributes to the modern barrier islands.

Sea-Level Rise and the Delta

There is great uncertainty in the prediction of future eustatic sea-level rise. This is due, in part, to the uncertainty in how governments, societies, and technological innovation will respond to the projected increase in greenhouse gas emissions (IPCC, 2007; National Research Council, 1987). Regardless of possible responses, the coast of Louisiana is particularly vulnerable to any rise in eustatic sea level. Because of subsidence caused by sediment compaction, coastal Louisiana has one of the highest rates of relative sea-level rise in the United States and the world (9.2 mm/yr at Grand Isle, Louisiana (NOAA, 2012a)). This is far greater than the worldwide average of 1.7 ± 0.05 mm/yr as measured over the past century (IPCC, 2007). In addition, Louisiana has one of the lowest slopes for its above-water coastal zone of any location in the country (much of it less than 0.022:1), resulting in large horizontal flooding with only minor vertical water-elevation rise. These and other factors indicate that the terrain around New Orleans is the most vulnerable region to sea-level rise of any location along the entire United States coast (Thieler and Hammar-Klose, 2000).

Physical Processes (Waves, Tides, and Meteorology)

The normal range of tide at the mouth of the Mississippi is

about 0.3 m, with the range during storms at 0.6–1.8 m and during hurricanes from 4–5.5 m (U.S. Coast Pilot, 2010).

Compared to the Atlantic and Pacific wave climate, normal storm waves (not associated with tropical storms) in the Gulf of Mexico off the Louisiana coast are mild (Table 4). Mean annual deepwater significant wave height varies from a low of 0.75 m off the central Louisiana coast to about 0.95 m south of the Mississippi River mouth (Georgiou, FitzGerald, and Stone, 2005). Close to shore along the central coast, dominant waves (>80%) propagate from the southwest quadrant with significant wave heights of 0.1–0.8 m.

During the winter months, cold-front passages produce rapid increases in wave energy, with wave heights between 1–2 m being common in deep water (Georgiou, FitzGerald, and Stone, 2005). Although these waves are lower than those produced by tropical cyclones, about 20–30 cold fronts cross Louisiana in an average winter (Chaney and Stone, 1996). Therefore, along some parts of the state, cold fronts may be responsible for more coastal erosion than the much less frequent hurricanes (Dingler, Reiss, and Plant, 1993; Mossa and Roberts, 1990; Stone *et al.*, 2004). Fronts produce strong northerly winds, and in the larger bays, the winds generate short period steep waves. Therefore, waves associated with these fronts may be responsible for the chronic erosion along the backside of many unprotected barriers (Georgiou, FitzGerald, and Stone, 2005; Stone *et al.*, 2004).

Tropical cyclones and hurricanes are the most powerful and most damaging meteorological events that affect Louisiana's coastal zone. Stone *et al*. (1997) showed that 60% of the tropical storms and 80% of the hurricanes made landfall during August and September. Notable and deadly hurricanes that have crossed over or near the Mississippi Delta in the last half-century include an unnamed 1947 storm, Betsy (1965), Camille (1965), Andrew (1992), Georges (1998), Lili (2002), Ivan (2002), Katrina (2005), Rita (2005), and Gustav (2008). For more historical information, Williams, Penland, and Sallenger (1992) listed all recorded pre-1988 Louisiana hurricanes in their Appendix A.

When Hurricane Andrew, a Category 4 storm, crossed the Gulf, offshore wave buoys measured wave periods in excess of 17 sec and significant wave heights of approximately 6 m (Stone, Xu, and Zhang, 1995). As the system approached land, a gage in 20-m water depth recorded wave heights in excess of 9 m, which are extraordinary conditions for the Gulf.

Hurricane Katrina devastated southeastern Louisiana, Mississippi, and Alabama, and is to date the most destructive and expensive natural disaster in the nation's history. The storm made landfall near Buras, Louisiana on August 29, 2005, as an upper end Category 3 storm with sustained winds of 110 kt (200 km/h) and a central pressure of 920 mb, which ranked 3rd lowest on record for U.S. landfall storms (Knabb, Rhome, and Brown, 2005). The storm continued moving north, crossed Mississippi Sound, and made a second landfall near the mouth of the Pearl River in Hancock County, Mississippi. Katrina and Rita deposited 5–10 cm of sediment over large areas of coastal wetlands, and almost 100 km^2 of wetlands in the Breton Sound basin were converted to open water (Day *et al*., 2007). Turner *et al.* (2006) reported 5.18 cm of mud deposition from the two storms.

Hurricanes may be responsible for moving and reworking vast quantities of sediment on the shallow Gulf of Mexico shelf. Current profiler measurements made during Hurricane Ivan on September 16, 2004 recorded currents of unexpected magnitude at water depths greater than 50 m (Teague *et al.*, 2007; Wijesekera *et al*., 2010). Hurricane Lili (Category 2 at landfall on October 3, 2002) may have moved 160 million tons of sediment onto shallow areas (5–20 m) of the Atchafalaya shelf (Allison *et al*., 2007). This material was derived from a combination of land and riverine sources and reworked shelf sediments. Hurricane Katrina incised the seafloor in Barataria Bight in water depths up to 40 m (Allison *et al.*, 2007). Hurricanes Cindy, Katina and Rita moved nearly 9.1 million m^3 of sediment from Little Pass Timbalier and moved the inlet throat 160 m inland (Miner *et al.*, 2009a). Allison *et al*. (2007) concluded that tropical cyclones were a primary mechanism for keeping most of the inner shelf (<20-m water depth) swept of modern sediments, despite the large flux of Mississippi River-derived particulates moved alongshore by coastal currents. The impact of successive storms over decades may be a major additional factor generating retreat of inactive Mississippi deltaic lobes.

Unique Aspects of the Louisiana Coast

The presence of the Mississippi River and its sediment load have had dramatic impacts on the evolution of the Louisiana coastline as compared with the U.S. Atlantic and other parts of the Gulf coast and with most other trailing edge coastlines around the globe. The sediment load of the Mississippi River before European settlement was as much as 400 million metric tons per year (Kesel, 1988). The next largest sediment load river entering the Gulf of Mexico is the Brazos River, in Texas, which carries 10 million metric tons per year. Along the Atlantic coast of North America, the largest load rivers are the Susquehanna, the St. Lawrence, and the Potomac, carrying respectively 1.8, 1.4, and 1.2 million metric tons per year (Meade and Parker, 1984), which equates to about 2.2% of the Mississippi's total load. These rivers have not deposited enough sediment to fill their drowned river mouths, much less prograde deltas into the sea.

This Mississippi's immense sediment load has been a contributing factor in causing a series of deltas to sequentially form at the river mouth over the last few thousand years (Frazier, 1967; Otvos and Giardino, 2004; Törnqvist *et al.*, 1996). As a river mouth progrades into the sea it becomes hydraulically more efficient for the river to cut a shorter path to the sea (an avulsion event), though, as Aslan, Autin and Blum (2005) explain, this is not the only controlling factor in the case of the Mississippi River.

As a Mississippi River delta forms, it is largely composed of thick deposits of fine-grained sediments, which are not fully compacted when deposited. While it remains an active delta, continuing deposits of additional overburden allow the surface elevation to remain relatively stable. However, once a delta is abandoned or man-made levees constrain the river, additional sediments are not deposited over the delta's surface. As compaction continues in the relic delta, the formation subsides. Abandoned barrier islands undergo a transgressive submergence, as has happened at Ship Shoal (Coleman, Roberts, and Stone,

1998; Penland, Suter, and Boyd, 1985; Penland, Suter, and Moslow, 1986; Rosati and Stone, 2009). This type of coastal evolution is markedly different from chains of barrier islands that are largely composed of sandy deposits and are much more strongly controlled by longshore sediment transport processes.

SEDIMENT BUDGET FRAMEWORK

Regional Organization

For development of the conceptual sediment budget, we adopted delineations established for the LCA provinces (LCA, 2004) (Figure 1). Province I extends from the Chandeleur Islands to the east side of the Balize Delta, including South Pass, and also includes the Mississippi River above Head of Passes. Province II continues from the west side of South Pass through Caminada Moreau headland and ends just east of Belle Pass, the entrance to Port Fourchon. Province III has the largest coastal extent, stretching from Belle Pass through Terrebonne Bay, Atchafalaya and Vermillion Bays, ending at Freshwater Bayou. Province IV covers the chenier plain in western Louisiana from Freshwater Bayou to the Texas border at Sabine Pass. This division is useful for comparison with other studies, and is generally based on antecedent geology and modern sediment transport zones.

Methodology

A sediment budget is an application of the conservation of mass, volume, or rate of change in which sources and sinks of sediment, and placement or removal of sediment are equated to the resulting mass, volume change, or rate of change within a defined littoral cell. Sediment budget cells are typically delineated based on geologic controls, known or estimated sediment transport rates at the boundaries of the cell, knowledge of similar transport rates and engineering activities within a given cell, and/or morphologic features (*e.g.*, barrier island, ebb tidal shoal, inlet channel). The sediment budget equation can be expressed as:

$$\sum Qsource - \sum Qsink - \Delta V + P - R = Residual \quad (1)$$

Table 5. *Sediment budget cell definitions.*

Cell	Type	Description
B	Bay	Bay cells represent open but protected waters that may receive sediment from the Navigation Channel, Delta, Flood shoal, and Coastline cells. Although bays are usually sediment sinks, they may supply material to the Offshore cell under some conditions.
C	Coastline, beach, island, or wetland	A subaerial cell that may exchange sediment with the Offshore or with adjacent Coastline, Flood shoal, Ebb shoal, tidal Inlet, or Shoal cells. For most islands and for some mainland Coastline cells, storm overwash may transport material into interior Bays.
D	Delta	A Delta cell receives sediment from a river system and, if the river has a navigation channel, this cell can also receive sediment from the Navigation channel cell. Example Delta cells include the Atchafalaya and Wax Lake Deltas as well as marshes along the Mississippi River where sediment can be deposited through flooding and crevasse splays. Delta cells are typically sediment sinks.
E	Ebb shoal (or ebb tidal delta)	Ebb shoals are sediment deposits offshore of tidal inlets maintained by a balance of opposing ebb tide and wave forces. Typically, these cells exchange material with adjacent Coastlines, but may exchange with Flood shoals, Inlet, and with Offshore.
F	Flood shoal (or flood tidal delta)	Flood shoals are sediment deposits located inshore of tidal inlets as formed by flood tide currents. These shoals may exchange sediment with Bay, Inlet, and Coastlines.
I	Tidal inlet, pass, or coupe (cut)	This is the natural tidal inlet throat through which sediment is exchanged with Bay, Coastline, Ebb shoal, Flood shoal, and Offshore. If the Pass is a dredged or a jettied coastal navigation channel, it is represented with a Navigation cell.
N	Maintained Navigation channel through a tidal inlet, river, or back bay.	These cells represent channels that are dredged for navigation in the coastal zone, such as Houma Navigation Channel. Through engineering activities and natural transport, these cells deliver material to Deltas, Bays, Placement sites, and to the Offshore.
O	Offshore or nearshore	Offshore cells represent regions of the coast that are deeper than the typical nonstorm transport regime. These regions off the coast are typically a sink for sediment, but can pass sediment to other cells under conditions of onshore transport.
P	Placement site	Placement cells are those sites specifically created for placement of dredged sediments. The majority of Placement cells represent specific locations where fine-grained dredged material is deposited to help build marshes. If dredged sediment is sidecast into bays or offshore, and not placed into a designated placement site, then a Bay or Offshore cell receives the dredged sediment.
S	Shoal	This can be a subaqueous terminal island spit (the last island in the chain) and also subaqueous morphologic features like Ship Shoal. These sand bodies may be active or ancient depositional areas. These cells receive material from Coastlines or Navigation channels.

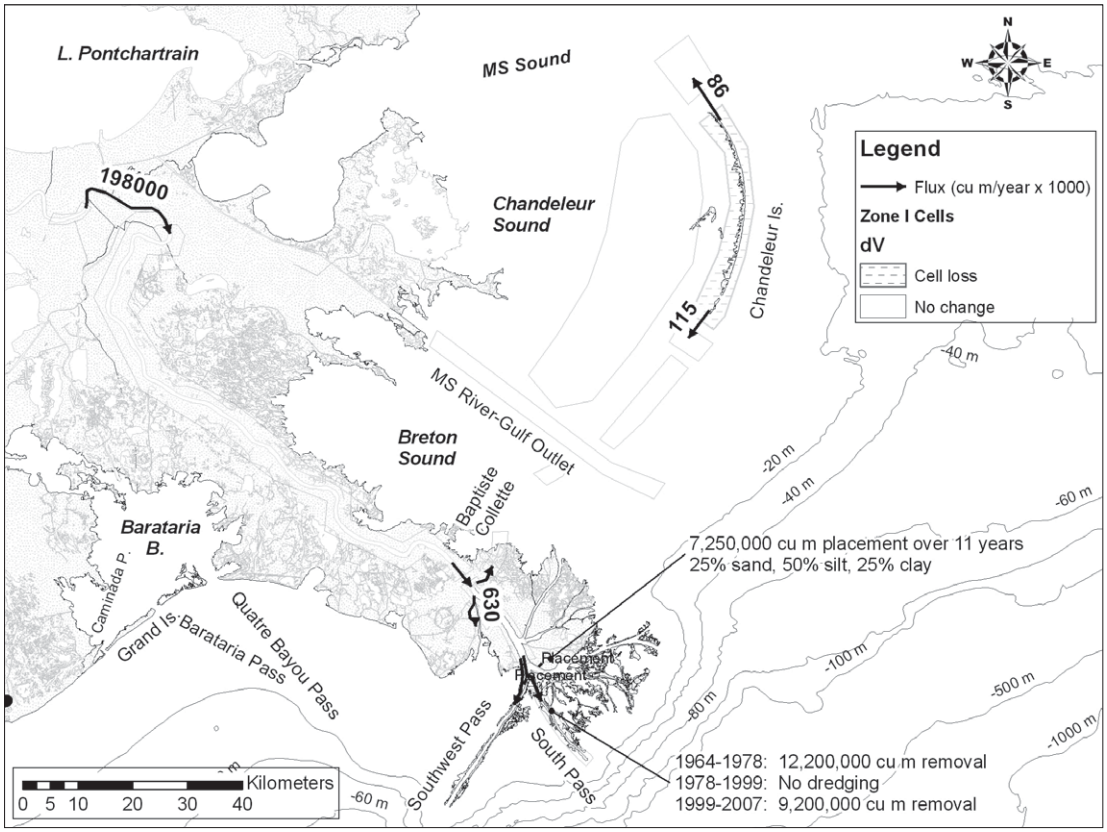

Figure 4. Province I cells, which include the Chandeleur Islands, Pass a Loutre, and South Pass. Dredging volumes from USACE, New Orleans District (*unpublished data*, 2012). The Mississippi River Gulf Outlet (MRGO) channel has been decommissioned and will no longer be dredged.

in which all terms are expressed as a volumetric change rate, Q_{source} and Q_{sink} are the sources and sinks to the cell, respectively, ΔV is the rate of net volume change within the cell, P and R are the rates of sediment placed in and removed from the cell, respectively, and *Residual* represents the degree to which the cell is balanced. For a balanced cell, the residual is zero.

All cells were drawn using ESRI ArcMap® software. The background maps consist of U.S. counties supplied by ESRI as part of the software package. The National Geophysical Data Center supplied shapefiles of water depth contours (National Geophysical Data Center, *unpublished data*, 2008) as an aid in visualization. For each cell on the map, a corresponding cell was entered in an Excel spreadsheet. The spreadsheet contained the name of the cell and a corresponding set of rows in which to enter data pertaining to sediment flux such as volume change, longshore transport, and removal (via dredging). The Sediment Budget Analysis System (SBAS-A®) (Dopsovoc, Hardegree, and Rosati, 2002; Rosati and Kraus, 1999) software was applied to visualize the budget. SBAS-A® will facilitate modifications to the budget when more analysis is completed in the future.

Types of Sediment Budget Cells

Sediment budget cells define the spatial boundaries for each sediment budget calculation and denote the existence of a complete self-contained sediment budget within its boundaries (Dolan *et al*., 1987). A nearly unlimited number of cells may be defined to characterize the sediment transport regime of a region. Sediment may pass from one cell to another, either naturally by wave and current-induced transport or artificially via dredging and placement. Ten types of sediment budget cells were defined, as shown in Table 5.

CONCEPTUAL SEDIMENT BUDGET RESULTS

A conceptual sediment budget was developed based on the technical literature to provide a regional perspective of sediment sources, sinks, pathways, and engineering activities for the Louisiana coastal zone. The conceptual budget will be applied to direct future analysis and data collection, and to be refined as additional information becomes available. The conceptual sediment budget represents long-term characterization of coastal processes in Louisiana over multiple decades to centuries. The majority of references reviewed were based on pre-Hurricane Katrina (pre-2005) geomorphology; thus, the conceptual budget developed herein represents long-term (multidecade) processes rather than present-day conditions after the severe geomorphic

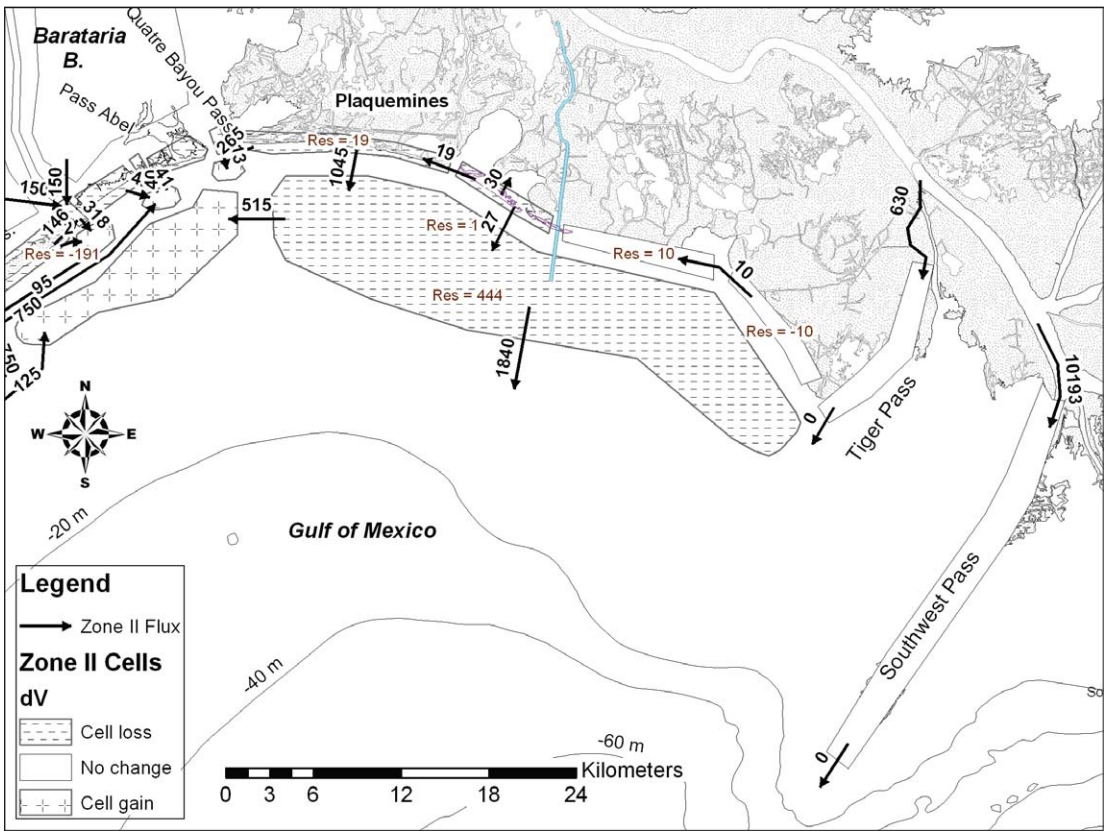

Figure 5. Province II cells, east zone, including Southwest Pass to Barataria Pass. Coastal fluxes (in 1000s m^3/yr) based on analysis of volume changes in List *et al.* (1994); river fluxes based on dredging data from USACE, New Orleans District. Residual (Res) shown for cells that are not balanced (see Eq. 1 in text)

changes wrought by Hurricanes Katrina and Rita.

Province I: Chandeleur Islands and Mississippi River Delta East

A sediment transport nodal point occurs on the south-central part of the Chandeleur Island chain (Figure 4; Ellis and Stone 2006; Georgiou, FitzGerald, and Stone, 2005; Georgiou and Schindler, 2009; Miner *et al.* 2009b). In the Chandeleurs, prior to Hurricane Katrina, the southern islands were largely armored with shell hash without much sand for transport (Penland, Suter, and Boyd, 1985). The large-scale destruction of the Chandeleurs by Hurricane Katrina has fundamentally reduced the transport rates. The storm caused the islands to lose almost 85% of their above-water area and the remnants to retreat an average of 270 m (Fearnley *et al.*, 2009; Sallenger, Wright, and Lillycrop, 2007). Sallenger, Wright, and Lillycrop noted that after landfall, what remained of the Chandeleur Islands no longer satisfied the definition of sandy barrier islands. Twelve months later, 58% of the remaining islands continued to retreat while 42% advanced. These are perched on a marsh-deltaic platform, which means very little sand is available for rebuilding.

Province II: Mississippi River Mouth to the Caminada Headland

The southeastern portion of Plaquemines Parish, from Venice to the Gulf of Mexico, includes the western lower river Gulf entrances. This terrain is primarily mud, and few published reports discuss sediment transport in this region, although there is documentation of riverine and wetland processes (Little, 2010; Wells and Coleman, 1987). The primary data source for this region is a synopsis of dredging and placement records from the New Orleans District (Edward Creef, USACE, New Orleans District, *unpublished data*, 2012; USACE, 2008).

The Plaquemines barrier shoreline has a complicated geological framework because it was influenced by different phases of deltaic evolution during the Holocene (Coleman, 1988; Coleman, Roberts, and Stone, 1998). Many barrier islands along this coast have been reduced to fragmented relics of the formerly robust islands. Georgiou, FitzGerald, and Stone (2005) estimated longshore transport to the northwest of about 10,000 m^3/yr (Figure 5). But at Shell Island, situated just northwest of the Bayou Fontenalle entrance to the Empire waterway, Campbell computed transport of up to 33,000 to the northwest,

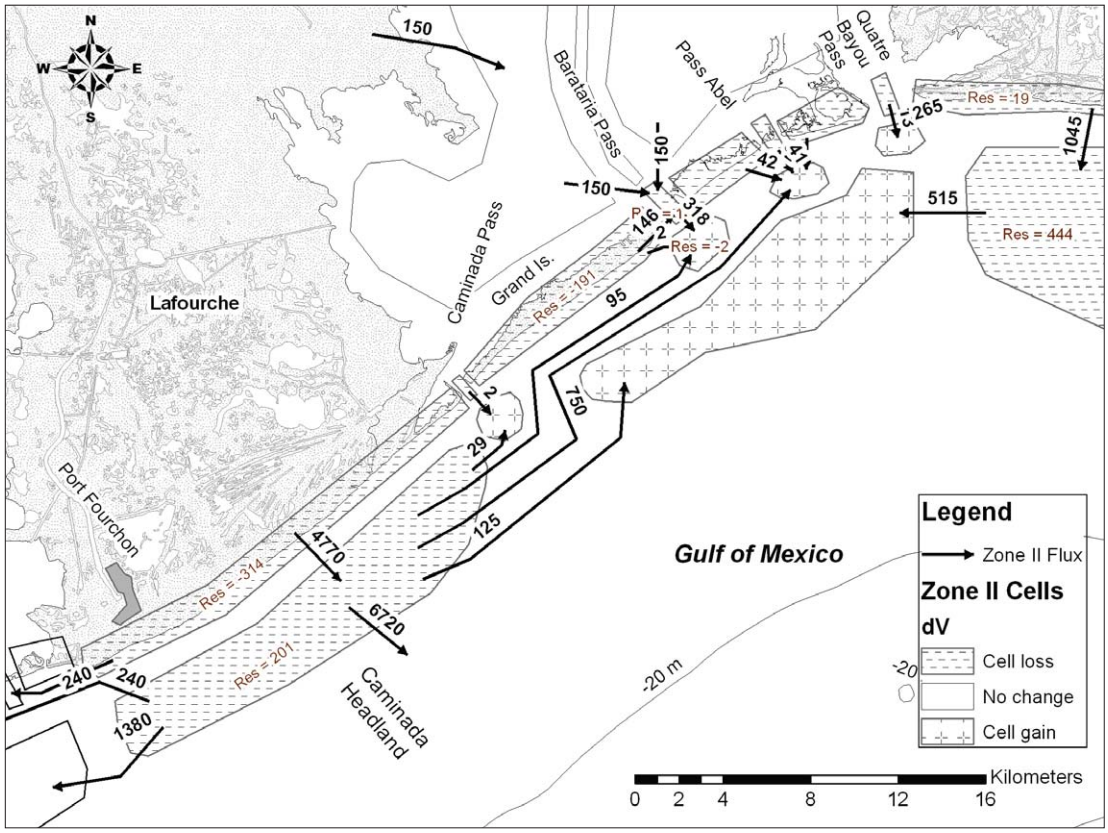

Figure 6. Province II cells, west zone, from Barataria Bay to the Port Fourchon. All flux units in m^3/yr × 1000. Residual (Res) shown for unbalanced cells.

35,000 offshore, and 40,000 m^3/yr onshore (T. Campbell, Coastal Planning & Engineering, Inc., *oral communication*, 2007).

For the Barataria Bay area, Georgiou, FitzGerald, and Stone (2005) calculated longshore transport from shoreline morphological trends (Figure 6). They concluded that about 146,000 m^3/yr of sediment moves east along Grand Isle, which in recent years has been protected with a series of detached breakwaters. Other researchers have documented lower volumes along Grand Isle. Studies in the 1930s by the Beach Erosion Board (1937) indicated that the drift divide occurred midway along Grand Isle. They reported that beach consisted of very fine sand interspersed with finely divided shell fragments and clay. Suspended sediment samples showed that most of the sand in motion was close to shore and that beyond about 80-m offshore, the water was muddy but contained little sediment volume.

The Caminada–Moreau Headland is an abandoned delta lobe that has eroded landward more than 2,800 m since the 1880s (Williams, Penland, and Sallenger, 1992). The beach along the headland consists of fine to medium quartz sand. Georgiou, FitzGerald, and Stone (2005) calculated that along the headland, net transport is about 11,000 m^3/yr to the west. But, this value may be unrealistically low and also, some material may move eastward towards Grand Isle.

Province III: Caminada Headland to Freshwater Bayou

The eastern portion of Province III includes southwest Lafourche Parish and continues westward to Raccoon Island, the westernmost of the Isles Dernieres in Terrebonne Parish (Figure 7). More literature about this section of the Louisiana shoreline may have been published than for the entire rest of the coast combined (Jaffe, List, and Sallenger, 1997; List, Jaffe, and Sallenger, 1991; List *et al.*, 1997; Miner *et al.,* 2009b; Ritchie and Penland, 1988). Most of this shore is sand and shell with deposits ranging from a thin veneer (~0.7–1 m) that overlays mud deposits at shallow depths (Campbell, 2005) to thick sand deposits in some areas (Penland, Boyd, and Suter, 1988).

The Timbalier Islands have retreated and been reworked throughout the 19th and 20th centuries. Marine reworking of relict distributary deposits formed most of these barrier islands (Penland, Boyd, and Suter, 1988). The morphology of the islands indicated that they spread westward in front of Timbalier Bay, fed by a sediment source (Bayou LaFourche) at the Caminada headland (Kulp *et al*., 2007). Then, Timbalier and Terrebonne Bays were separate entities (Figure 8), but they have now merged into one water body. As the bay enlarged because of sediment compaction and land loss (wetland destruction), the tidal prism

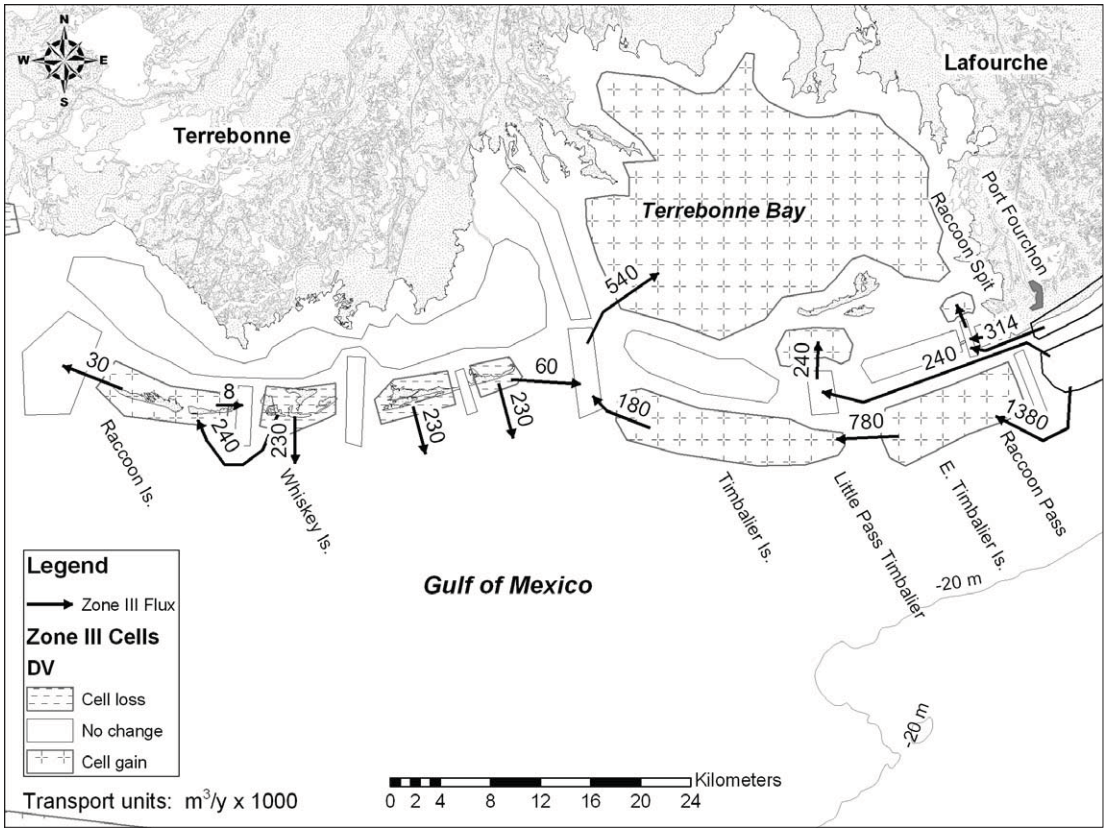

Figure 7. Province III cells, eastern zone. Fluxes based on analysis of volume changes in List *et al.* (1994).

increased, resulting in a larger tidal inlet throat and growth of the ebb tidal shoal. List *et al*. (1994) documented that from 1880 to the 1980s, the shoal volume increased from 8×10^6 to 53×10^6 m^3, which averages to nearly 450,000 m^3 per year. Much of this growth was probably from sediment removed from the barrier islands (Miner, FitzGerald, and Kulp, 2007), but it is likely that a major contribution also came from the eroding Caminada headland (Miner *et al*., 2009b). If this is the case, the westward transport might be in the range of 225,000 m^3/yr (assuming one-half of the shoal's annual growth), a value 20 times greater than that reported by Georgiou, FitzGerald, and Stone (2005). This discrepancy underscores the fact that we still have major uncertainty regarding sediment movement along the Louisiana shore.

Along the Isles Dernieres, overall sediment transport is to the west but also includes significant offshore flux. Transport patterns are complicated because of the fragmented nature of the islands. As an example of this complexity, Thomson, Khalil, and Tate (2005) calculated that at the east end of Raccoon Island, the longshore transport was about zero or slightly to the east, but it switched to about 30,000 m^3/yr to the west along the western portion of the island. These values were for the period 1989–1996, predating construction of the detached breakwaters.

Further west in Province III, the shores between Point au Fer Island to the western edge of the Province (Freshwater Bayou) are mostly mud and shell. This area also contains Louisiana's most rapidly prograding portion of coast, the two deltas at the mouth of the Atchafalaya River. The Atchafalaya River empties into Atchafalaya Bay via two channels, the main channel south of Morgan City and the Wax Lake Outlet further to the west (Figure 9). The Atchafalaya Delta has grown each year since 1973 to its present size of over 29 km^2 and now fills much of Atchafalaya Bay (Roberts *et al.*, 2003). As discussed earlier, the USACE presently controls the flow of water into the Atchafalaya basin to prevent its capturing the full volume of the Mississippi River. Left to natural processes, it would only be a matter of years before the Mississippi abandoned the current delta to follow the shorter and steeper Atchafalaya waterway to the Gulf of Mexico (Winer, 2010). If the Atchafalaya River were allowed to capture the entire flow of the Mississippi, there would be far-reaching effects on hydrology and sediment supply to the Louisiana coast as well as profound social and economic ramifications.

Province IV, Freshwater Bayou to Sabine Pass (Texas border)

This region features a flat terrain characterized by muddy

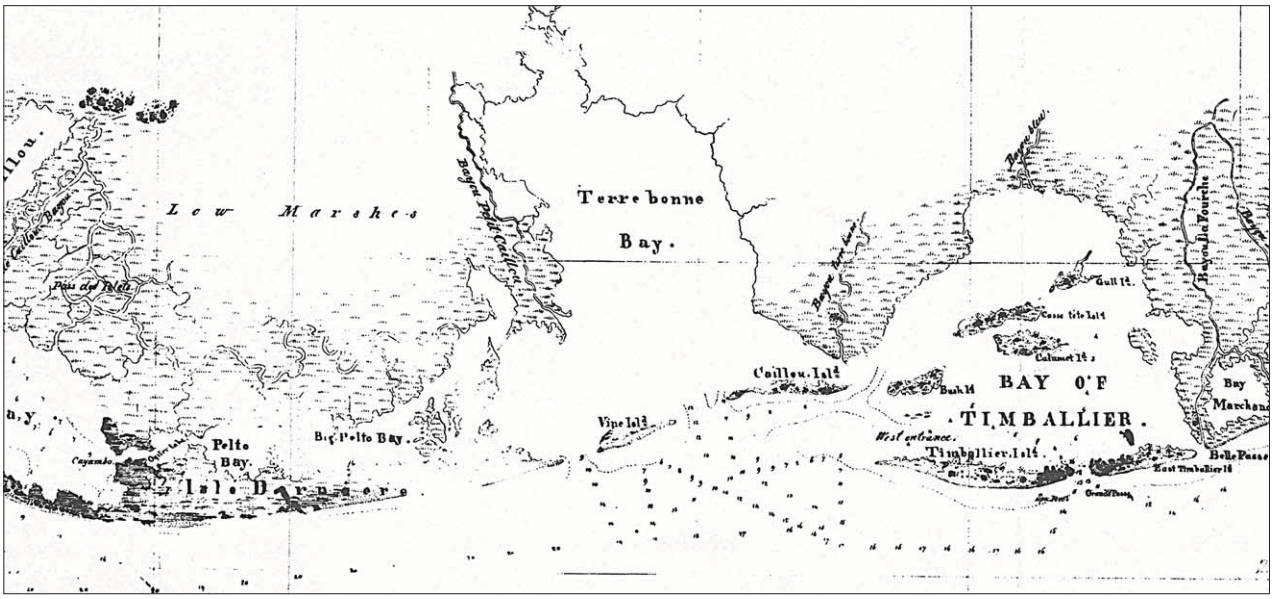

Figure 8. 1853 map of south Louisiana showing the Isles Derniers barriers and the separate Timbalier barrier chain. Timbalier and Terrabonne Bays were separate then. Cropped from Coast and Geodetic Survey lithograph of south Louisiana (NOAA, 2012c).

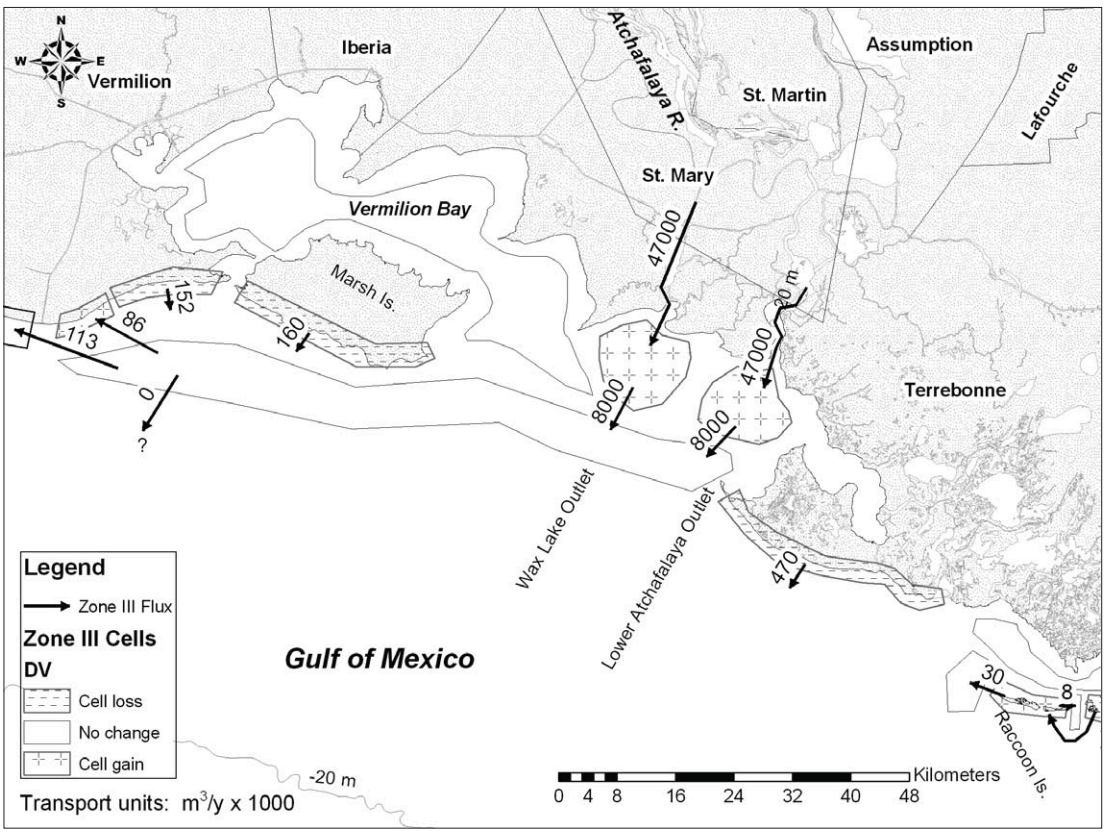

Figure 9. Province III cells, west zone. Ship Shoal (offshore) not shown.

Figure 10. Louisiana coast near Holly Beach. The town was almost totally destroyed by Hurricane Rita on September 24, 2005. The foreground shows overwash fans extending into the marsh. Photograph courtesy of Coastal Studies Institute, Louisiana State University.

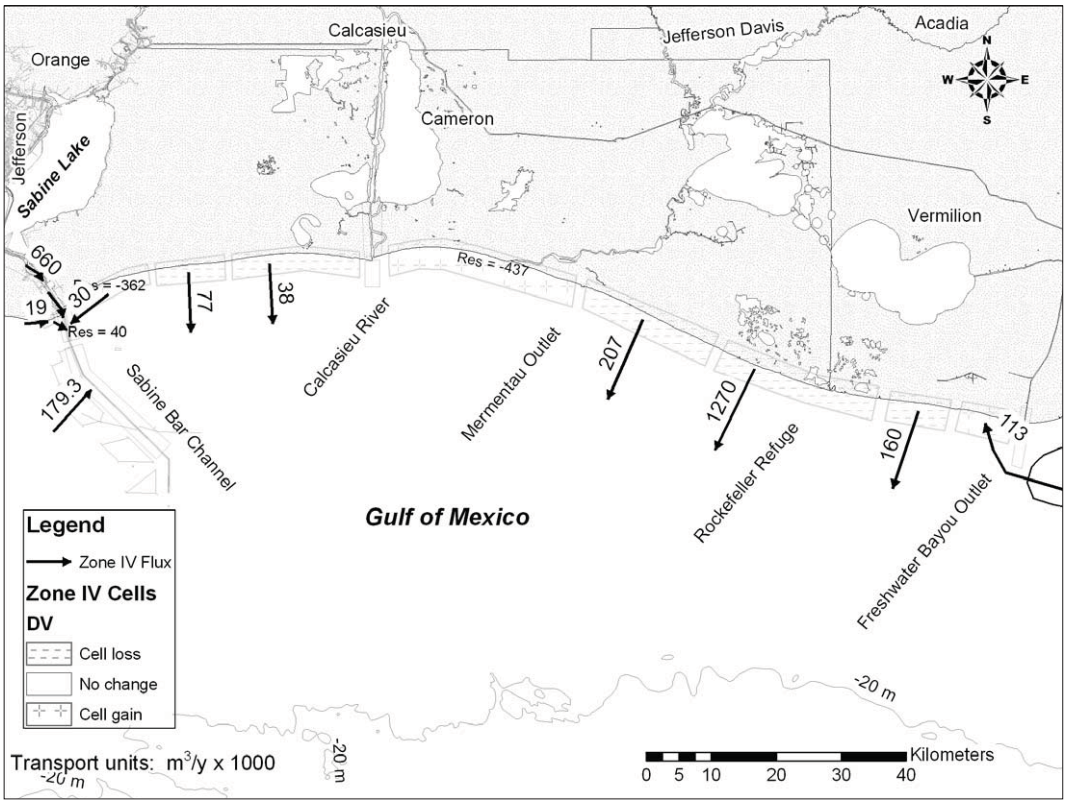

Figure 11. Province IV cells representing the Chenier Plain through Sabine Pass. Sabine flux from Morang (2006).

sediments and extensive marshes (see Georgiou, McCorquodale, and Meselhe, 2006). The generally narrow beaches consist of ribbons of mud, sand, and shell fragments, sometimes covered with veneers of fine sand. They are generally subject to low-wave energy except during hurricanes and storms generated during cold-front passages. Sand supply from inland sources or offshore deposits is limited. State Highway 82 runs atop a series of ridges or cheniers between Pecan Island and Sabine Lake. Today, these ridges comprise the only remaining hydrological barrier separating thousands of acres of brackish marsh along the southern boundary of Sabine National Wildlife Refuge from the Gulf of Mexico.

Hurricane Rita made landfall between Sabine Pass and Johnson's Bayou, Louisiana, on September 24, 2005, causing catastrophic damage to Cameron, Holly Beach, and other communities on the southwestern Louisiana shore (Figure 10). The storm, a category 3 at landfall, created a surge estimated to be up to 5-m high with winds of over 185 km/hr (100 knots; Knabb, Brown, and Rhome, 2006). Residents as far away as Dulac, south of Houma, reported water 1-m deep in their homes (interviews by the author (Morang), December 2006). Over 76,000 Louisiana residents were left homeless (Louisiana Geographic Information Center, 2005).

Unlike the rest of the Louisiana coast, the eastern shoreline of the chenier plain has been prograding seaward at rates up to 29 m/yr (Kineke *et al*., 2006). The source of sediment is the Atchafalaya River (Roberts *et al.*, 2003, 2005). Repeated cycles of cold-front passages drive transport onshore during both pre and postfront conditions. During prefront conditions, sediment is resuspended and mixed throughout the water column, with transport onshore and west as a result of onshore waves. During the postfront conditions, onshore transport also occurs due to upwelling in the lower meter of the water column and formation of a muddy, high-concentration bottom layer. Sediment accumulation is aided by attenuation of wave energy over the muddy inner shelf, which limits erosion at the beach (Sheremet and Stone, 2003; Sheremet *et al.*, 2005).

The eastern portion of the chenier plain prograded between 1812 and 1954, but then transitioned to minor erosion (Draut *et al*., 2005). Because of land management practices and dams on tributaries of the Mississippi River system, sediment load has decreased by approximately 60%, likely causing a decrease in coastal sediment supply (Draut *et al*., 2005).

The main rivers in western Louisiana are the Sabine and Neches, which flow into Sabine Lake and then to Sabine Pass. Despite their large drainage area, little sand reaches the open coast because Sabine Lake is an efficient sediment trap and most coarse material from the Sabine River is deposited in the lake (Mason, 1981). Recent studies have verified that most of the river bedload is trapped in the lower alluvial reaches of the rivers (Phillips and Musselman, 2003). Sediment samples from the Sabine Entrance Channel (USACE, Galveston District, *unpublished data*, 2006–2008) contain sand, suggesting that sand may be delivered to this portion of the channel from the adjacent beaches, from the river during high-runoff periods, from local subaqueous deposits, or sand may be moving onshore from the shallow shelf. In the past, material dredged from Sabine channel landward of the shoreline was placed in confined disposal facilities on land, therefore totally removing it from the littoral system (Morang, 2006).

In this province, each sediment budget cell has minimal interaction with adjacent cells because of the low-wave energy and resulting low-longshore transport (Figure 11). Overwash and offshore transport are likely significant sinks from the littoral zone along much of this reach. The quantities that are pushed by storm waves over the low beaches and into the marshes are still unknown, but clearly this is an important mechanism during events like hurricanes.

SUMMARY AND CHALLENGES

Unique Geomorphic Conditions

Compared to other U.S. coasts, southern Louisiana has unique characteristics that must be taken into consideration in the development of sediment budgets. These interrelated characteristics include:

(1) The Mississippi and Atchafalaya Rivers and their active and former delta lobes as the primary source of sediment for the region;
(2) Elevated rate of relative sea-level rise, which accelerates shoreline change, expansion of bays and estuaries, and tidal prisms;
(3) The abundance of fine sediments and limited sand supplies;
(4) Complex interrelationship between mineral and organic sediments; and,
(5) Low-wave energy environment that is frequently overwhelmed with moderate- to high-energy tropical and subtropical cyclones, which may become more intense in the future due to climate change.

Major Sediment Management Issues

The continuing loss of wetlands and barrier islands is the overriding coastal issue facing Louisiana. Therefore, the main sediment problems are related to finding, financing, and performing the engineering work to rebuild the barriers and wetlands and maintain them in the future.

(1) Reservoirs of sandy sediments suitable for barrier island rebuilding must be identified and quantified. The U.S. Geological Survey (USGS), the Bureau of Ocean Energy Management (BOEM) (formerly Mineral Management Service), and the State of Louisiana have conducted sand surveys for many years and developed isopach maps.
(2) Serious engineering and managerial challenges will be associated with exploiting offshore sand sources for barrier restoration. Because of the 60-year history of offshore oil and gas production, hundreds of platforms occupy the continental shelf, and oil and gas pipelines, both active and abandoned, cross much of the seabed. As a result, dredging is impossible in many areas. One proposed project, the restoration of Scofield Island, southwest of Venice, using sand mined from the Mississippi River, was deauthorized, but the feasibility study demonstrated the technical requirements (Poff *et al.,* 2011).
(3) Because of the difficulties associated with dredging sand from offshore, state and federal agencies may have to move sediment from other sources, such as the bed of the

Figure 12. Detached breakwaters, Raccoon Island. Photograph October–November 2005, after Hurricane Rita (LaCoast, 2005). Coastal Studies Institute, Louisiana State University.

Mississippi River, a greater distance than normal practice. The Coast 2050 Program and others have outlined numerous plans for diversions to allow river water at certain stages to flow into wetlands, but many of these plans were delayed because of objections by various stakeholders (Committee on the Restoration and Protection of Coastal Louisiana, 2006). Allison and Meselhe (2010) discuss some of the options and reviewed previous diversions. Ultimately, there is no choice. If new sediment is not introduced to the wetlands, they will continue to disappear as a result of compaction of underlying strata, salinity-related stresses, and storms.

(4) Can the growing delta of the Atchafalaya River be used as a sediment source? Roberts *et al*. (2003) estimated that the river delivers about 75 million tons of sediment per year to Atchafalaya Bay. Transferring some of this material to other areas to benefit wetlands would be an engineering and permitting challenge but should be manageable.

(5) Can existing barrier islands or mainland beaches be protected from storms? Experience with detached breakwaters at Grand Isle and Holly Beach Island have generally been positive. Raccoon Island is one of the most important seabird-nesting sites in Louisiana west of the Birdfoot Delta. According to the USGS (Michot and Wells, 2005), the low tide area of the island has declined from nearly 283 ha (700 acres) in the 1950s to 97 ha (240 acres) in 2003. To reduce erosion and protect this barrier island rookery from further loss, state and federal agencies built an experimental system of detached stone breakwaters in 1999 (Figure 12; Thomson, Khalil, and Tate, 2005). Hurricane Lili's limited impact in 2002 demonstrated that the breakwaters were effective (Broussard and Boustany, 2005). Some sand was lost, but the island was not breached. However, breakwaters, being forms of hard protection, are inflexible. Also, foundation conditions in southern Louisiana are poor for massive rock structures, and they lose crest elevation through time because of settlement. In preference, natural barriers are more flexible because they can roll over landward in response to storms, and soft protection in the form of sand nourishment and vegetation can be adapted as needed (Figure 13).

Infrastructure Issues

Another Louisiana coastal management issue is the protection of critical infrastructure. Despite the state's vast marshes and reputation as a sportsman's paradise, this is a working coast with infrastructure devoted to oil and gas, maritime, and fishing industries. As one example, Port Fourchon is the most active oil field service port on the Gulf Coast and is the land base for the Louisiana Offshore Oil Port (LOOP). At Fourchon Beach, south of Port Fourchon, the shoreline retreated about 2,800 m between 1887 and 1988 (Williams, Penland, and Sallenger, 1992; Chapter 4). The beach is now protected with rock breakwaters and geotextile sand-filled tubes (Figure 14). The breakwaters were assembled on barges, which were sunk in place. This port, the infrastructure, and the road access will have to be protected with major barrier island and marsh renewal programs, hurricane-protection levees, or a combination of these. Some efforts

Figure 13. Timbalier Island, May 17, 2007. The island was renourished with over 2,700,000 m^3 of sand dredged from the offshore tidal shoals. Volunteer groups planted dune grass to help stabilize the dunes. (Photograph by A. Morang.)

already underway include the West Belle Pass Barrier Headland Restoration project (CWPPRA, 2012), the Caminada Restoration project (Schleifstein, 2011), and the Barataria Basin Shoreline Restoration project (LCA, 2012).

The morphologic complexity of the Louisiana coastal zone and the inconsistencies in transport rates reported in the literature underscore how little we still know about longshore transport patterns and rates along this shore.

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Figure 14. Detached breakwaters and geotextile barriers at Fourchon Beach, 17 May 2007. Petroleum production platforms line the horizon. (Photograph by A. Morang.)

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