Journal of Coastal Research	SI	63	166–183	Coconut Creek, Florida	Spring 2013

Historical Sediment Transport Pathways and Quantities for Determining an Operational Sediment Budget: Mississippi Sound Barrier Islands

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ABSTRACT

Byrnes, M.R.; Rosati, J.D.; Griffee, S.F., and Berlinghoff, J.L., 2013. Historical sediment transport pathways and quantities for determining an operational sediment budget: Mississippi Sound barrier islands. *In:* Brock, J.C.; Barras, J.A., and Williams, S.J. (eds.), *Understanding and Predicting Change in the Coastal Ecosystems of the Northern Gulf of Mexico,* Journal of Coastal Research, Special Issue No. 63, pp. 166–183, Coconut Creek (Florida), ISSN 0749-0208.

Historical shoreline and bathymetric survey data were compiled for the barrier islands and passes fronting Mississippi Sound to identify net littoral sand transport pathways, quantify the magnitude of net sand transport, and develop an operational sediment budget spanning a 90-year period. Net littoral sand transport along the islands and passes is primarily unidirectional (east-to-west). Beach erosion along the east side of each island and sand spit deposition to the west result in an average sand flux of about 400,000 cy/yr (305,000 m^3/yr) throughout the barrier island system. Dog Keys Pass, located updrift of East Ship Island, is the only inlet acting as a net sediment sink. It also is the widest pass in the system (about 10 km) and has two active channels and ebb shoals. As such, a deficit of sand exists along East Ship Island. Littoral sand transport decreases rapidly along West Ship Island, where exchange of sand between islands terminates because of wave sheltering from the Chandeleur Islands and shoals at the eastern margin of the St. Bernard delta complex, Louisiana. These data were used to assist with design of a large island restoration project along Ship Island, Mississippi.

ADDITIONAL INDEX WORDS: *Bathymetric change, shoreline change, Ship Island, Horn Island, Petit Bois Island, channel dredging.*

INTRODUCTION

The Mississippi coastal zone consists of four barrier islands that create the offshore boundary for Mississippi Sound; four passes between the islands; four navigation channels and the Gulf Intracoastal Waterway (GIWW) serving three major ports (Gulfport, Biloxi, and Pascagoula); and the mainland coast, consisting of bays, sandy beaches, coastal structures, and wetlands (Figure 1). From west to east, the four barrier islands are Cat, Ship (West and East), Horn, and Petit Bois. These islands are up to 23-km offshore, and together with Dauphin Island, Alabama, separate Mississippi Sound from the Gulf of Mexico. The barrier islands provide the first line of defense for the mainland coast and navigation channels, serving to decrease Gulf wave energy in their shadow and potentially modify the timing and magnitude of storm surge. Four tidal passes between the islands promote exchange of sediment and water between marine waters of the Gulf of Mexico and brackish waters of Mississippi Sound. Tidal passes also interrupt the flow of littoral sand to the west from Mobile Pass ebb-tidal shoals and Dauphin Island. Petit Bois Pass is about 8-km wide, with a poorly developed channel and system of shoals separating Dauphin and Petit Bois Islands. Horn Island Pass is approximately 5.5-km wide and is occupied by the Pascagoula Ship Channel with a regularly maintained channel depth and width. Dog Keys Pass separates Horn and East Ship Island and has two entrance channels with well-developed ebb-tidal shoals. Ship Island Pass exists along the western end of Ship Island and encompasses the Gulfport Ship Channel. Water depth in passes is generally 5 m or less, except in navigation channels where maximum depths range from about 9–20 m. A series of hurricanes over the past century has significantly reduced the width and elevation of barrier beaches along the Mississippi Sound barrier islands, exposing mainland beaches, infrastructure, and navigation channels to increasing storm damage. A comprehensive evaluation of long-term sediment transport pathways and quantities requires analysis of historical shoreline and bathymetry datasets to document the evolution of beach, nearshore, and channel environments most directly influenced by major storms and incident coastal processes for quantifying net geomorphic changes at regional scale and developing detailed sediment budgets.

Barrier islands fronting Mississippi Sound have been losing surface area with time, migrating rapidly to the west (except for Cat Island), and their capacity to protect mainland beaches and infrastructure is diminishing. From 1848 to 1986, long-term island area change rates were -2.5, -1.6, -1.7, and -2.0 hectares/year for Cat, Ship, Horn, and Petit Bois Islands,

DOI: 10.2112/SI63-014.1 received 7 September 2011; accepted 1 May 2012.
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respectively (Byrnes *et al.*, 1991; McBride, Byrnes, and Hiland, 1995). Morton (2008) used the shoreline data of Byrnes *et al.*, (1991), augmented with recent shoreline surveys acquired by the Mississippi Office of Geology (1995–2002), lidar surveys (2005, 2007), and registered aerial photography (2006), to compare recent shoreline changes with historical trends relative to storms and sea-level change. Morton stated that historical change trends for the barrier islands will continue as a result of rising sea level, frequent intense storms, and reduced sand supply from channel dredging. However, a detailed analysis of bathymetric change and channel dredging records to document long-term sediment transport pathways and quantities relative to engineering activities at Horn Island and Ship Island Passes is absent from Morton (2008), as well as all previous studies. A primary component of the present analysis was to evaluate historical dredging records and bathymetric surveys to quantify sand flux throughout the littoral system and potential impact of dredging activities on transport quantities. As shown in Figure 1, the islands and mainland beaches are integrally connected with navigation channels vital to the Mississippi and Alabama economies. Thus, any modifications that potentially change sediment transport pathways and magnitudes are of critical importance to the regional sediment budget.

The littoral sand budget for barrier beaches is a balance between natural sand sources to the system, depositional zones or sinks within the system, natural sediment transport to locations outside of the littoral zone, and placement of dredged material from the littoral system (*e.g.*, navigation channel dredging; borrow site excavation) seaward of the zone of active sand transport under incident waves and currents. Historical shoreline and bathymetry data were compiled and analyzed to quantify net sand volume changes, document sediment transport pathways, and evaluate the potential impact of barrier island movement and degradation on the regional sand budget. Geomorphic changes caused by normal and storm conditions document cause and effect relationships that are often difficult to capture with short-term, site-specific process measurements. Long-term shoreline and bathymetry change analyses record net sediment transport pathways and the volume of material in transit within a barrier island system. Datasets spanning long time intervals accurately describe geomorphic evolution of coastal systems by minimizing measurement uncertainties relative to the magnitude of detected change. In other words, measured change over short time intervals is generally small relative to longer time intervals, but the uncertainty associated with survey measurements remains relatively constant.

The primary goal of this analysis is to quantify net sand volume changes associated with historical evolution of nearshore morphology and adjacent beaches for the period 1917–20 to 2005–10 in support of barrier island restoration proposed as a component of the Mississippi Coastal Improvements Program (MsCIP) (Byrnes *et al.*, 2012). Net sand transport pathways and quantities derived from this analysis provided the framework upon which island restoration quantities and geometries were designed. Study results were used to make recommendations for future operation and maintenance of navigation channels as well. All sand volume change and transport units of measure are English because quantities were derived from like units for project engineering applications. For conversion purposes, cubic meters equals cubic yards times 0.7646.

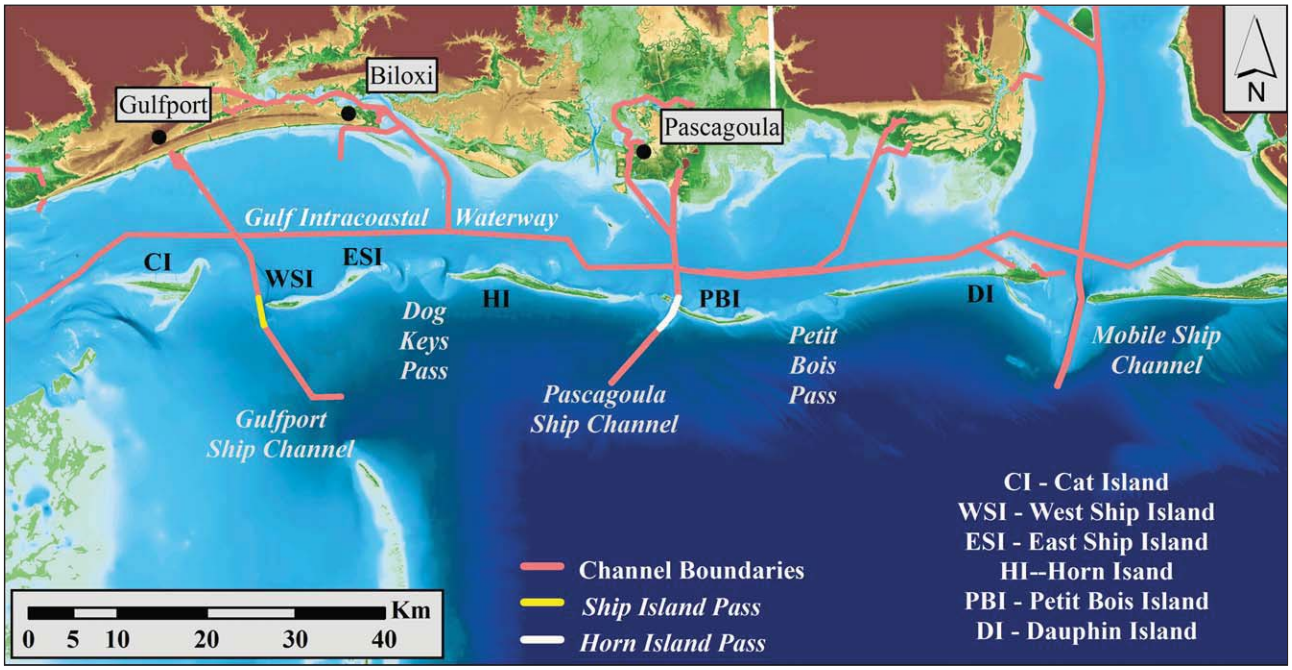

Figure 1. Mississippi and Alabama coastal deposits illustrating the barrier island system west of Mobile Pass, including navigation channels. Background surface created by Taylor *et al.* (2008) and Amante *et al.* (2011).

Coastal Geology

According to Otvos and Carter (2008) and Otvos and Giardino (2004), the Mississippi Sound barrier islands formed during a deceleration in sea-level rise approximately 5,700–5,000 years ago. At that time, the core of Dauphin Island at its eastern end was the only subaerial feature in the location of the modern barrier island system through which predominant west-directed littoral sand from the Florida panhandle via Mobile Pass ebb-tidal shoals could transit and deposit as elongate sand spits and barrier islands. Otvos and Giardino (2004) documented the growth of the Mississippi Sound barrier island system based on sediment cores that illustrate shallow shoal platform sand, capped with beach sand transported from Mobile Pass shoals, overlying muddy Holocene nearshore sediment. Eastern Dauphin Island captured and transferred large volumes of littoral sand from Mobile Pass shoals and beaches east of the pass via west-directed longshore currents. The laterally-prograding barrier island system originally extended west to the Mississippi mainland near the Pearl River, marking the seaward limit of subaerial deposition and the formation of Mississippi Sound.

Beginning approximately 3,500 years ago, the Mississippi River flowed east of New Orleans toward Mississippi Sound, creating the St. Bernard delta complex (Otvos and Giardino, 2004). Delta deposition extended over the western end of the Mississippi barrier island system, west of Cat Island. By about 2,400 years ago, fluvial sediment from the expanding St. Bernard delta created shoals as far east as Ship Island (Otvos, 1979, 1981), changing wave propagation patterns and diminishing the supply of west-directed littoral sand to Cat Island. With changing wave patterns and reduced sand supply from the east, the eastern end of Cat Island began to erode, resulting in beach sand transport perpendicular to original island orientation (Otvos and Giardino, 2004; Rucker and Snowden, 1989). Persistent sand transport from the east has successfully maintained island configuration relative to rising sea level for much of the barrier system; however, reduced sand transport toward Ship Island has allowed for increased island erosion and segmentation in response to tropical storms (Rucker and Snowden, 1989). Byrnes *et al.* (1991), Byrnes *et al.* (2012), Morton (2008), and Waller and Malbrough (1976) have documented changes in island configuration since the mid-1800s, illustrating westward migrating islands and inlets, with greatest percent changes along Ship Island where sand supply is limited at the end of the littoral transport system.

Coastal Processes

Mississippi Sound is considered a microtidal estuary because its diurnal tide range is only about 0.5 m (NOAA, 2012). The Sound is relatively shallow and elongate (east–west) with an approximate surface area of 2,000 km^2 (Kjerfve, 1986) and a tidal prism of about 1.1 x 10^9 m^3. Although tidal currents account for at least 50% of flow variance, the Sound responds rapidly to meteorological forcing, as evidenced by subtidal sea-level variations of up to 1 m and persistent net currents in the tidal passes (Kjerfve, 1986). The relatively shallow and large area of the Sound creates strong currents in tidal passes between the barrier islands, ranging from 0.5 to 1.0 m/sec and 1.8 to 3.5 m/sec on flood and ebb tides, respectively (Foxworth *et al.*, 1962). In winter months, winds from the same direction and of a sufficient magnitude are capable of lowering water surface elevations in the bays and nearshore from 0.3 to 0.6 m (USACE, 1984). Overall, circulation within Mississippi Sound is generally weak and variable, and the estuary is vertically well-mixed. Meteorological effects during the passage of cold fronts and tropical cyclones can double the strength of tidal currents (Kjerfve, 1986).

Barrier islands protecting Mississippi Sound experience a low-energy wave climate, with average significant wave height at National Data Buoy Center (NDBC) Buoy 42007 (40 km south-southeast of Biloxi, in 14-m water depth) averaging 0.7 m and 0.4 m in the winter and summer months, with associated average peak wave periods of 4 to 3.7 sec, respectively (NDBC, 2012). Wave transformation modeling by Cipriani and Stone (2001) indicate that breaking wave heights on the barrier islands range from 0.3 to 0.6 m. The Coastal Studies Institute's Wave-Current Surge Information System (WAVCIS) Station CSI-13 located near Ship Island Pass (6.9-m water depth) from June 1998 through July 2005 measured an average significant wave height of 0.08 m and associated average wave period of 2.5 sec (WAVCIS, 2012). Littoral transport along the islands is predominantly from east to west in response to prevailing winds and waves from the southeast. Reversals in longshore transport occur at the eastern ends of the islands but their impact on net sediment transport is localized and minor relative to dominant transport processes from the southeast.

The barrier islands are composed of beach sand derived from updrift beaches east of Mobile Pass and from ebb-tidal shoals at the entrance. Although Cipriani and Stone (2001) and Otvos and Giardino (2004) stated that offshore sources may provide some sediment to the barrier islands, historical onshore movement of sand from outside the littoral zone is not indicated along the barrier island system based on sediment budgets (Byrnes *et al.*, 2012). Furthermore, Cipriani and Stone (2001) discussed that a well-defined cellular structure exists for each barrier island where little sand transfer occurs between islands. However, dredging records at Horn Island and Ship Island Passes (sometimes referred to as Pascagoula Bar Channel and Gulfport Bar Channel, respectively) suggest that channel infilling from adjacent barrier islands is active, indicating the potential for sand transport between islands.

Tropical Cyclones

Byrnes, Griffee, and Osler (2010); Morton (2008); Otvos and Carter (2008); and many others have discussed the importance of tropical cyclones and other storms on sediment transport and geomorphic change throughout the Mississippi barrier island system. Geomorphic changes recorded by sequential shoreline and bathymetric surveys along the islands illustrate that storm processes dominate the signature of change. Although storm-induced cross-shore processes (*e.g.*, island breaching and washover) are important factors influencing littoral transport and island configuration, longshore currents have provided vast quantities of sand to repair storm damage and promote growth on

the western ends of the islands (*e.g.*, Byrnes, Griffee, and Osler, 2010).

The history of tropical cyclones for the Mississippi Sound barrier islands has been summarized by numerous authors (*e.g.*, Blake, Rappaport, and Landsea, 2007; Sullivan, 2009) and web portals (*e.g.*, Stormpulse, 2012; Hurricane City, 2012). For the period 1852–2009, the frequency of direct landfall varies from 10 to 12 years per storm for the central portion of the study area (Biloxi to Pascagoula) to 13–15 years per direct hurricane hit west and east of this area (New Orleans to Gulfport and Dauphin Island to Gulf Shores; Byrnes *et al.*, 2012). However, all locations have historically been impacted by a tropical storm or hurricane approximately once every 3–4 years. Cold fronts, although less intense than tropical storms and hurricanes, occur more frequently at approximately 30–40 times per year (Stone *et al.*, 2004). Chaney and Stone (1996) identified significant beach erosion along the north shore of West Ship Island primarily due to these winter storms.

Channel Dredging and Placement

Although the River and Harbor Act of March 3, 1881 authorized an initial examination of the harbors and passes at Horn and Ship Islands, it was not until June 3, 1896 and March 3, 1899 that Congress authorized channels be dredged to 6.4 and 7.9 m (21 and 26 ft) mean low water, respectively (Byrnes *et al.*, 2012). All channel dredging was driven by local industry (particularly timber) and the need for vessels to access protected harbors for loading and transporting product. Authorized project dimensions were attained at Ship Island Pass in March 1900 and at Horn Island Pass in July 1907.

As shown in Figure 1, the study area is traversed by many navigation channels, most of which have no direct influence on the littoral sand budget. However, channel dredging and placement adjacent to the barrier islands (Horn Island Pass and Ship Island Pass) must be considered when quantifying the littoral sediment budget. Table 1 provides a summary of channel dredging quantities for authorized channel dimensions at Horn and Ship Island Passes (Figures 2 and 3). Figures 4 and 5 illustrate cumulative maintenance dredging quantities since channel authorization. The timing for authorized channel dimension changes is shown on each diagram, and the rate at which sand has been extracted from the channel is documented for specific periods when channel dimensions are consistent.

Disposal of littoral sand from channel dredging during expansion (new work) or maintenance at Horn and Ship Island Passes has not been consistent for the period of sediment budget evaluation (1917–18 to 2005–10). Table 2 summarizes sand placement quantities within the active littoral zone relative to total maintenance and new work channel dredging for both passes. When the quantity of maintenance dredging equals the quantity placed in the active littoral zone, the sand budget due to engineering activities is balanced. For Horn Island Pass, the difference between littoral zone placement and maintenance dredging is about -6,283,000 cy (1917–2009; net deficit to the littoral sand budget); for Ship Island Pass, the difference is about -5,677,000 cy. However, because Ship Island Pass is the terminal location for littoral transport along the Mississippi barrier shoreline, sand removal from channel dredging cannot be considered a net loss to the natural transport system.

METHODS

Shoreline Compilation

Four regional outer coast shoreline surveys were used to document historical shoreline change between Cat Island, Mississippi (west) and Dauphin Island, Alabama (east) for the period 1847–49 to 2010. The first three surveys were compiled by the U.S. Coast & Geodetic Survey (USC&GS; presently the

Table 1. *Summary of channel dredging quantities for Horn Island Pass and Ship Island Pass, Mississippi (Byrnes et al., 2012).*

Horn Island Pass (1897–2009)				
Date	Authorized Channel Dimensions	New Work (cy)	Maintenance (cy)	
Feb. 1897–March 1948	21-ft deep, 300-ft wide (July 1907 to May 1940) 25-ft deep, 300-ft wide (June 1940 to March 1948)	1,080,765	1,633,375	(40,600 cy/year)
May 1949–Jan. 1965	35-ft deep, 325-ft wide (June 1949 to April 1961) 38-ft deep, 325-ft wide, 2.8 mile long (June 1962 to January 1965)	2,015,520	3,607,240	(232,100 cy/year)
April 1965–Sept. 1993	40-ft deep, 350-ft wide; Impoundment area along the western end of Petit Bois Island (August 1965 to September 1993)	1,305,589	14,309,352	(509,400 cy/year)
Sept. 1995–Nov. 2009	44-ft deep, 450-ft wide; Impoundment area along the western end of Petit Bois Island (January 2000 to November 2009)	4,980,040	5,399,492	(394,600 cy/year)
1897–2009	Total Dredging	9,381,914	24,949,459	(245,000 cy/year)
Ship Island Pass (1899 to 2009)				
Date	Authorized Channel Dimensions	New Work (cy)	Maintenance (cy)	
Nov. 1899–March 1948	26-ft deep, 300-ft wide, about 4,000-ft long (March 1900 to March 1948)	207,401	2,071,584	(43,200 cy/year)
Nov. 1949–Sept. 1991	32-ft deep, 300-ft wide, 8 miles long (April 1950 to September 1991)	3,679,044	10,710,570	(258,800 cy/year)
May 1992–June 2009	38-ft deep, 300-ft wide; channel realigned to the west (November 1993 to June 2009)	5,943,023	2,708,966	(173,800 cy/year)
1899–2009	Total Dredging	9,829,468	15,491,120	(141,800 cy/year)

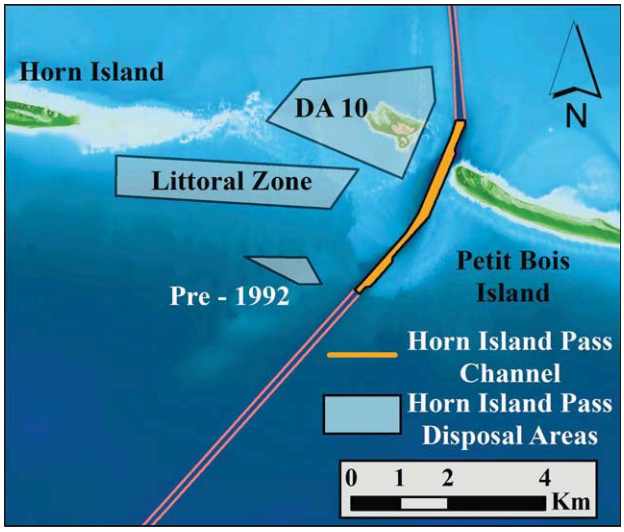

Figure 2. Location of Horn Island Pass in the Pascagoula Bar Channel and dredged material disposal sites. Dredged sand quantities from Horn Island Pass are summarized in Tables 1 and 2. Background surface created by Taylor *et al.* (2008).

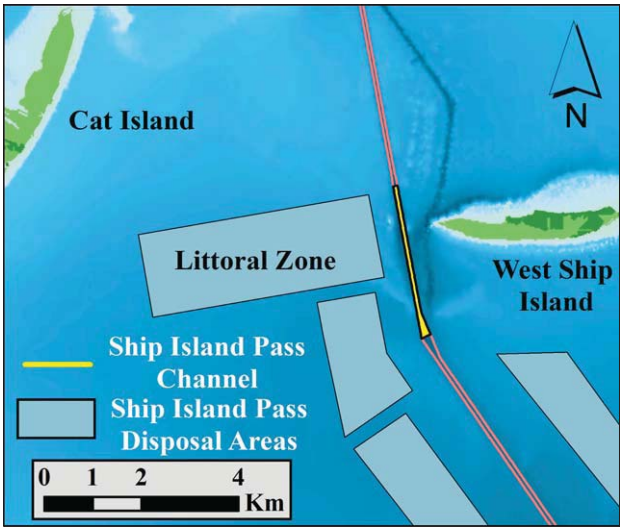

Figure 3. Location of Ship Island Pass in the Gulfport Bar Channel and dredged material disposal sites. Dredged sand quantities from Ship Island Pass are summarized in Tables 1 and 2. Background surface created by Taylor *et al.* (2008).

National Ocean Service [NOS]) in 1847–49, 1916–17, and 1950–57, and the 2010 shoreline was interpreted from high-resolution orthoimagery using on-screen Geographic Information System (GIS) digitizing procedures by Applied Coastal (Byrnes *et al.*, 2012). The 1847–49 and 1916–17 surveys were completed as field surveys using standard planetable techniques and the 1950–57 shoreline was interpreted from registered aerial imagery. Digital shoreline data for 1847–49, 1916–17, and 1950–57 were compiled at Applied Coastal from scanned USC&GS topographic sheets using techniques described in Byrnes and Baker (2003) and Baker and Byrnes (2004). All imagery was supplied by the U.S. Army Corps of Engineers (USACE) Mobile District.

When determining shoreline position change, all data contain inherent uncertainties associated with data acquisition and compilation procedures. It is important to quantify limitations in survey measurements and document potential systematic errors (Anders and Byrnes, 1991; Baker and Byrnes, 2004; Byrnes and Hiland, 1995; Crowell, Leatherman, and Buckley, 1991).

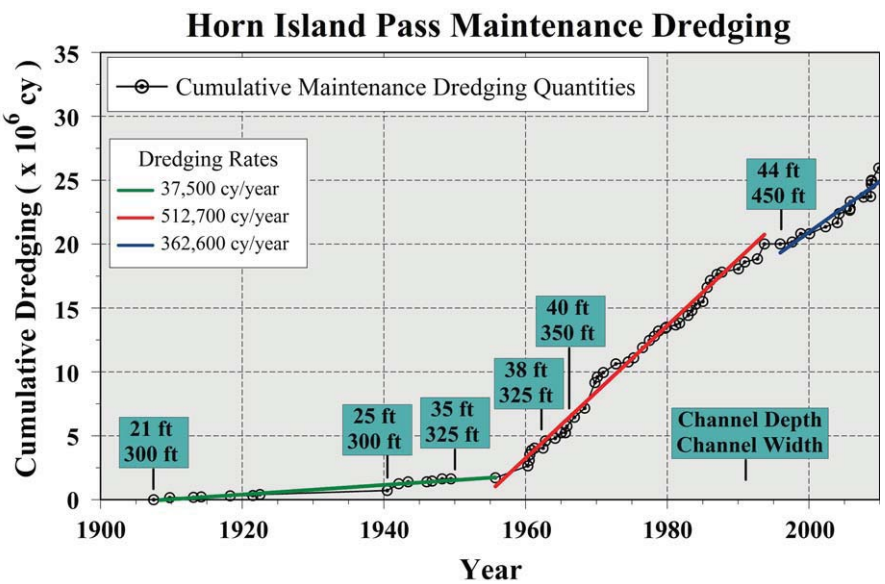

Figure 4. Cumulative maintenance dredging volumes and associated sand dredging rates for Horn Island Pass, Mississippi.

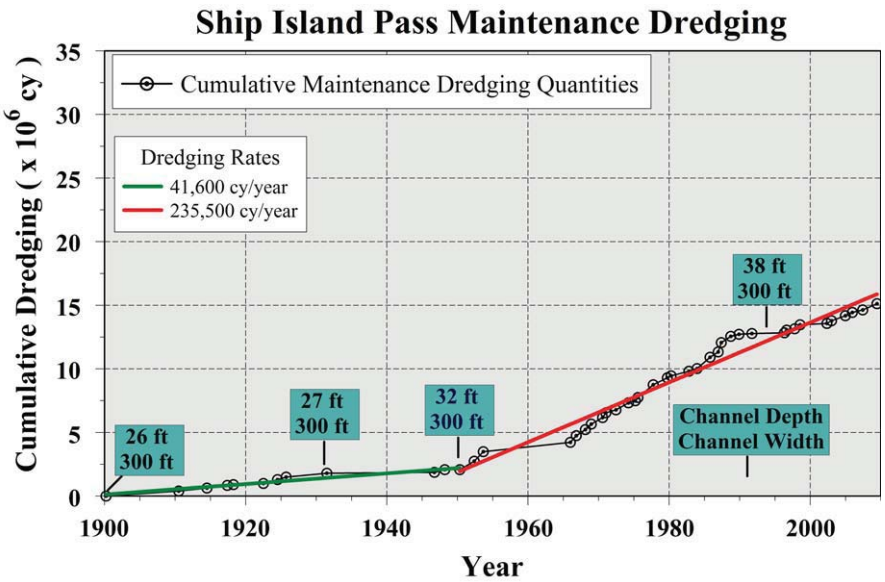

Figure 5. Cumulative maintenance dredging volumes and associated sand dredging rates for Ship Island Pass, Mississippi.

Substantial effort was spent ensuring that systematic errors were eliminated prior to change analysis. As such, measurement errors associated with present and past shoreline surveys are considered random. Regardless, data compilation uncertainties should be quantified to gauge the significance of specific measurements used for research/engineering applications and management decisions. As expected, maximum positional uncertainties are associated with the oldest shorelines (1847–49 and 1916–17) at the smallest scale (1:40,000) (see Byrnes *et al.*, 2012). However, most change estimates for the study area document shoreline advance or recession greater than these values. Overall, because random errors are considered equally distributed over long coastal reaches containing hundreds of measurements, they can be neglected statistically relative to average change calculations.

Bathymetry Compilation

Seafloor elevation measurements, compiled from historical hydrographic surveys, were used to identify seafloor morphology and change to quantify sand transport relative to natural processes and engineering activities. The Triangulated Irregular Network (TIN) method was used to form surfaces of continuous connected

Table 2. *Summary of dredged material placement quantities for Horn Island Pass and Ship Island Pass, Mississippi (Byrnes et al., 2012).*

Horn Island Pass (September 18, 1917 to June 20, 2009)						
Dredged Material Placement Location	New Work (cy)		Maintenance (cy)		New Work plus Maintenance (cy)	
DA 10 and BN	3,121,564	(34,000 cy/year)	6,853,557	(74,700 cy/year)	9,975,121	(108,700 cy/year)
Littoral Zone	1,858,476	(20,300 cy/year)	383,272	(4,200 cy/year)	2,241,748	(24,500 cy/year)
Pre-1992 Open Water (western lobe of ebb shoal)	Unknown		5,268,152	(57,400 cy/year)	5,268,152	(57,400 cy/year)
Placement Before August 1962 (offshore western lobe of ebb shoal)	1,257,815	(13,700 cy/year)	3,820,969	(41,600 cy/year)	5,078,784	(55,300 cy/year)
Unknown	2,354,809	(25,700 cy/year)	7,442,426	(81,100 cy/year)	9,797,040	(106,800 cy/year)
Total Dredging (9/18/1917 to 6/20/2009)	8,592,664	(93,700 cy/year)	23,768,376	(259,000 cy/year)	32,361,040	(352,700 cy/year)
Ship Island Pass (September 18, 1917 to November 5, 2005)						
Dredged Material Placement Location	New Work (cy)		Maintenance (cy)		New Work plus Maintenance (cy)	
Fort Massachusetts	0		1,080,301	(11,800 cy/year)	1,080,301	(11,800 cy/year)
Littoral Zone	5,943,023	(64,800 cy/year)	1,003,225	(10,900 cy/year)	6,946,248	(75,700 cy/year)
Unknown	3,723,044	(40,600 cy/year)	12,413,136	(135,300 cy/year)	16,136,180	(176,000 cy/year)
Total Dredging (9/18/1917 to 11/5/2005)	9,666,067	(109,700 cy/year)	13,703,904	(155,500 cy/year)	23,369,971	(265,200 cy/year)

triangular planes based on irregular points (Petrie, 1991). The elevation of each point in a model is determined by solving equations for its horizontal location on the triangulated surface. Therefore, only points existing in the original data sources are used to create the surface model, as opposed to grid models which interpolate evenly spaced points from original data. TIN model surfaces were used for all calculations of bathymetric volumes and change. Two regional bathymetry surfaces were established to document seafloor changes between 1917–20 and 2005–10 from hydrographic surveys completed by the USC&GS (1917–20 and 2005–06), the U.S. Geological Survey (USGS; 2008–2010), and the USACE, Mobile District survey section (USACE; 2010). DeWitt *et al.* (2012) provide a description of methods used to acquire and process bathymetry data collected by the USGS; a version 3 interim product was used for this study. Regional comparisons were made to document historical seafloor changes from the east side of Dauphin Island to eastern Cat Island and offshore to about the 11-m depth contour.

In addition to digital hydrographic data compiled by the National Geophysical Data Center (NGDC), USGS, and the USACE Mobile District, digital survey data were developed from scanned hydrographic survey sheets that were digitized at Applied Coastal using standardized digitizing and registration procedures (see Baker and Byrnes, 2004). All bathymetry datasets were combined with concurrent shoreline data to produce bathymetric surfaces relative to the North American Vertical Datum of 1988 (NAVD 88) that extend offshore from the high-water shoreline. An elevation of 1.2 m (NAVD 88) was assigned to the high-water shoreline based on berm crest elevations identified in 2010 lidar data for Horn Island (see Byrnes *et al.*, 2012).

Vertical Datum Adjustments

Because historical seafloor elevations are temporally inconsistent for the entire dataset (*i.e.*, reference tidal datums change with time), adjustments to depth measurements were made to bring all data to a common plane of reference (NOAA, 2003). These adjustments included changes in tidal datums due to relative sea-level change and differences in reference vertical tidal datums. Vertical adjustments were made to each dataset based on the time of data collection and the original reference vertical tidal datum.

USC&GS hydrographic survey data were obtained online from the NOS hydrographic survey viewer, and all data were compiled relative to the mean low water (MLW) vertical tidal datum, the average of all the low water heights for each tidal day observed at a specific tidal station over the National Tidal Datum Epoch (NTDE; 18.6-year tidal epoch, rounded to a full year cycle, over which tide observations are recorded and reduced to establish mean values for tidal datums; NOAA, 2001). Reference tidal datum epochs are necessary for measurement standardization because of periodic and secular trends in relative sea level. The MLW tidal datum, therefore, varies with changes in sea level over time depending on the 19-year cycle referenced for measurements (Foxgrover *et al.*, 2004; Harris, 1981; Hess, 2003; Marmer, 1951; Meyer, Roman, and Zilkoski, 2004). Because relative sea level changes, tidal datums at a specific site become out of date and must be updated to account for long-term vertical adjustments, such as global sea-level change, subsidence, and glacial rebound (Hicks, 1981; NOAA, 2003). As such, all bathymetric data were adjusted to a common vertical reference plane (relative to 2010) to account for changing tidal datums accompanying fluctuations in relative sea level for the period of record. In addition, all depths were referenced to NAVD 88 using the National Geodetic Survey (NGS) VDatum tool to account for spatial variations in adjustment between MLW and NAVD 88. Vertical tidal datum adjustments were based on National Oceanic and Atmospheric Administration (NOAA) tidal benchmark #8735180 (Dauphin Island, Mobile Bay) (NOAA, 2013).

Measurement Uncertainty

As with shoreline data, measurements of seafloor elevation contain uncertainties associated with data acquisition and compilation. Once systematic errors were eliminated during quality-control procedures, measurement uncertainty associated with present and past surveys was considered random over large survey areas. As such, random errors cancel relative to change calculations derived when comparing two surfaces. A method for determining limits of reliability for erosion and accretion is to quantify measurement uncertainty associated with bathymetric surfaces. Interpolation between measured points includes a degree of uncertainty associated with terrain irregularity and data density. The density of bathymetric data, survey line orientation, and the magnitude and frequency of terrain irregularities are the most important factors influencing uncertainties in volume change calculations between two bathymetric surfaces (Byrnes, Baker, and Li, 2002). Volume uncertainty relative to terrain irregularities and data density can be determined by comparing surface characteristics at adjacent survey lines. Large variations in depth between survey lines (*i.e.*, few data points describing variable bathymetry) will result in large uncertainty estimates. Additionally, surveys with track lines oriented parallel to major geomorphic features can result in large uncertainty between lines. Computing differences in surface characteristics based on survey data distribution provides the best estimate of uncertainty for gauging the significance of volume change calculations between two surfaces.

Uncertainty estimates were calculated for all bathymetric surfaces using the methods outlined in Byrnes, Baker, and Li (2002) and Byrnes, Griffee, and Osler (2010). Estimates were generated for each bathymetric surface, including the ebb shoal/channel regions. As expected, areas with greatest uncertainty were located along the channel and ebb-tidal delta at passes. To identify potential uncertainty associated with sediment transport determinations, a separate calculation was made for channel/ebb shoal areas. Overall, potential depth uncertainty ranged from ±0.26 to 0.40 m for calculations made across the entire surface, and from ±0.57 to 0.79 m for the ebb shoal/channel area specifically (see Byrnes *et al.*, 2012). Combining this information to gauge the impact of potential uncertainties associated with volume change calculations derived from surfaces resulted in a root mean square (RMS) variation of between ±0.49 m (entire surface) and ±0.98 m (inlet shoals), which translates to a net sand transport uncertainty of about ±33,000 to 53,000 m^3/yr (±43,000 to 70,000 cy/yr) (Byrnes, Griffee, and Osler, 2010). Based on the

results of this uncertainty analysis, ±0.6 m (±2 ft) was used to delineate areas considered to represent no determinable change.

DISCUSSION

Shoreline change along the Mississippi Sound barrier islands reflects the imbalance between sand supply and energy (waves, currents, and wind) required to move sand throughout the system. Natural perturbations to sand transport throughout the study area result from variations in high energy storms and normal transport processes relative to sand availability. Although shoreline change patterns (two dimensions) contain a record of the influence of coastal processes on beach response, regional assessment of inlet and nearshore morphology (three dimensions) better reveals dominant processes controlling the magnitude and direction of sand transport. These measurements provide the primary information required to develop an operational sediment budget for evaluating sand transport quantities and pathways within the coastal system.

Shoreline Dynamics

Storm-related processes are the primary cause of geomorphic change along the Mississippi Sound barrier islands. Island breaching and overwash promote northward-directed transport of sand from ocean beaches, across the islands and into Mississippi Sound. Lateral movement of Dauphin, Petit Bois, Horn, and West Ship Islands due to the dominant east to west gradient in littoral transport produces rapid island growth (west) and erosion (east), whereas sporadic events also produce cross-shore movement of sand into the Sound resulting in long-term landward migration of islands (*e.g.*, Dauphin and East Ship). Washover deposition is the geomorphic response to overwash, and inlet formation can result from island breaching (*e.g.*, Camille and Katrina Cuts). Byrnes *et al.* (2012) provide a detailed analysis of shoreline changes for the Mississippi Sound barrier islands, a summary of which is provided below to document historical response of the system to dominant incident processes.

Figure 6 illustrates net development of western Dauphin Island and eastern Petit Bois Island. Beach erosion along the Gulf shoreline of the low-lying sand spit of Dauphin Island (western two thirds of the island), in addition to sand transport onto the beach from Pelican Island (subaerial sand deposit on the west lobe of the Mobile Pass ebb shoal), supplied sand for rapid and continuous deposition at the western end of Dauphin Island between 1847 and 2010. The island grew about 8.7 km to the west during this time at an average rate of about 46 m/yr. Net westward movement forced Petit Bois Pass in the same direction, resulting in erosion along the eastern end of Petit Bois Island and net widening of the pass. Most sediment eroded from eastern Petit Bois Island was deposited along the sand spit at the western end of the island and in the navigation channel at Horn Island Pass (Figure 7). Since 1957, the west end of the island has remained in its present location because it abuts the maintained navigation channel. Before this time, westward island migration forced Horn Island Pass and eastern Horn Island to the west at about 39 m/yr. As a result, western Horn Island migrated to the west.

Minor net changes were recorded along the central portion of Horn Island as sand was mobilized from the east end of the island and transported westward by longshore currents. Sand transported to the west was deposited in a 4.7-km long, relatively wide sand spit that projected into Dog Keys Pass (Figure 8). Westward island growth produced a narrower inlet as the primary channel at Dog Keys Pass was forced westward toward Dog Island and East Ship Island. Little Dog Keys Pass (to the west of Dog Island) originated as a secondary channel at the entrance, but as Horn Island migrated westward, Dog Island (also referred to as Isle of Caprice [Rucker and Snowden, 1988]) eroded and dispersed into entrance shoals as hydraulics changed in the inlet. Presently, Little Dog Keys Pass is the deepest channel between the islands and it has had a marked influence on sand bypassing to East Ship Island.

Ship Island is the downdrift terminus of the Mississippi Sound barrier islands and is the most vulnerable island due to distance from sand source. Historical shoreline data illustrate

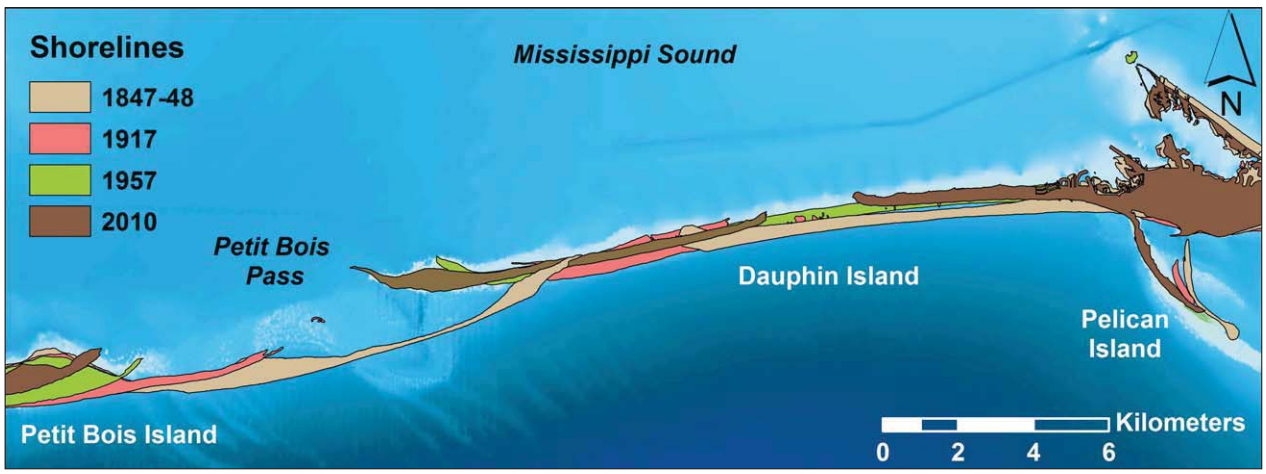

Figure 6. Composite island changes for Dauphin Island and eastern Petit Bois Island, 1847–2010. Background surface created by Amante *et al.* (2011).

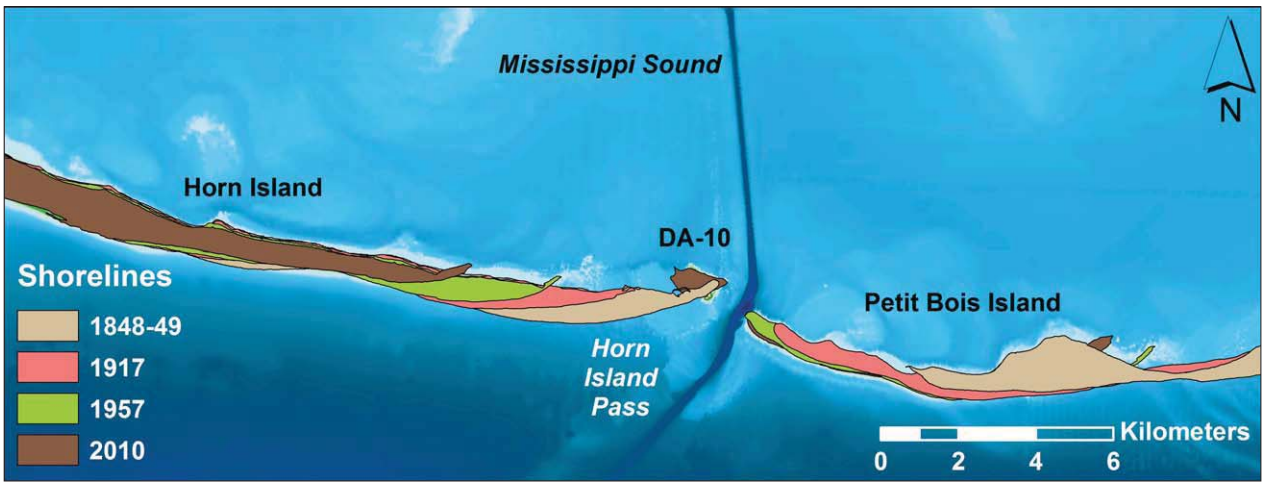

Figure 7. Composite island changes for Petit Bois and eastern Horn Island, 1848–2010. Background surface created by Taylor *et al.* (2008).

that the central portion of the island has been narrow and low, and highly susceptible to breaching during tropical cyclones (Figure 9). The east end of the island is strongly erosive, and sand transported from this area deposits at the west end of the island, which resulted in net westward migration of about 1.4 km between 1848 and 2010. Sand transport from Dog Keys Pass has never been able to counteract historical beach erosion along the eastern end of Ship Island, so chronic erosion in this area is pervasive. Camille Cut has been on the verge of closing on a few occasions since 1969 (see Byrnes *et al.*, 2012), but storms have dispersed the subaerial sand spit developed between East and West Ship Islands allowing persistent exchange of water and sediment between the Gulf and Sound. Beach erosion and overtopping along East Ship Island has been so frequent since 1969 that the island appears in danger of complete degradation within the next 10–20 years. Major changes in inlet shoal and channel morphology at Dog Keys Pass have reduced sand transfer to East Ship Island, perhaps enhancing the magnitude of erosion along the island.

Since development of the St. Bernard Delta complex between 3,500 and 1,500 years ago, Cat Island has been segregated from west-directed sand transport along the barrier islands. Changes in dominant wave orientation have promoted reworking of the beach ridge complex developed prior to formation of the St. Bernard Delta and shoals. Longshore transport has been bidirectional, causing sand spit deposition north and south of the primary beach ridge trend. Erosion of the beach ridge complex provides sand to interior portions of the island via washover. This trend has been consistent and predictable, and it is expected to continue.

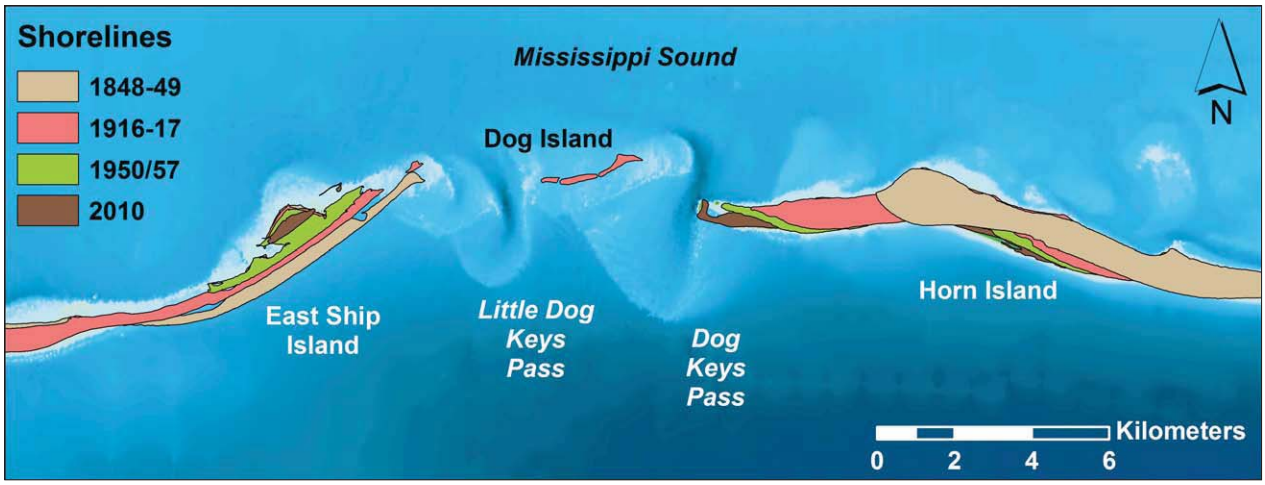

Figure 8. Composite island changes for western Horn Island and East Ship Island, 1848–2010. Background surface created by Taylor *et al.* (2008).

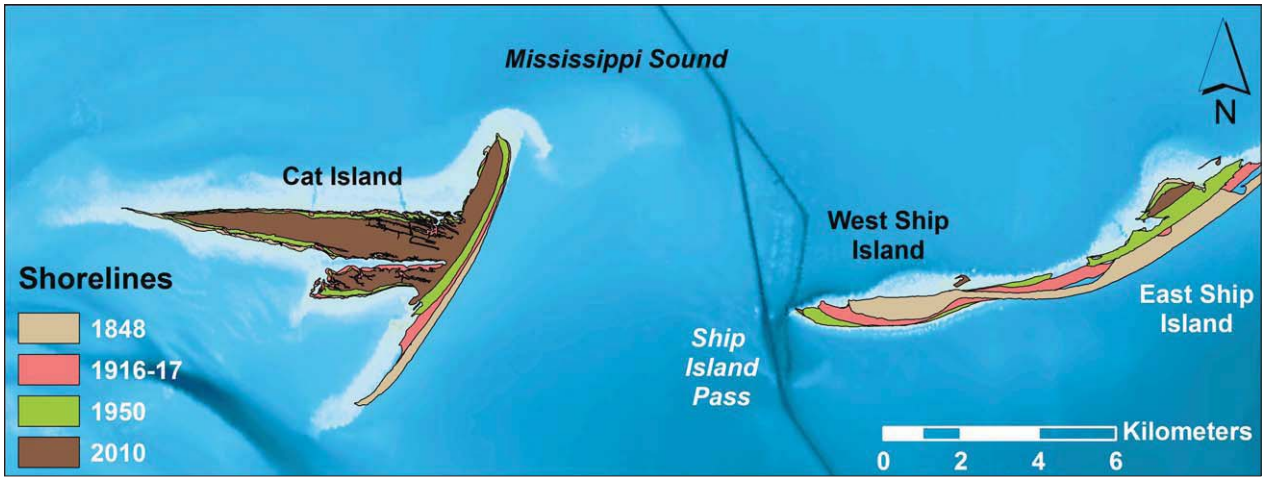

Figure 9. Composite island changes for West Ship Island and Cat Island, 1848–2010. Background surface created by Taylor *et al.* (2008).

Seafloor Morphology and Change

Although four regional bathymetric surfaces were established for the barrier islands fronting the Mississippi Sound coastal zone (see Byrnes *et al.*, 2012), only the 1917–20 and 2005–10 surfaces are used to describe large-scale variations in coastal and nearshore morphology associated with long-term sediment budget formulation. Sediment transport patterns and processes in the vicinity of the Mississippi Sound barrier islands and passes are of primary interest, and regional morphology and change provide insight regarding dominant transport pathways relative to sediment sources and sinks.

1917–20 Bathymetry

Bathymetry data for the period 1917–20 were combined with 1916–17 shoreline data to create a continuous surface from Mississippi Sound seaward to about the 15-m depth contour. The most prominent subaqueous geomorphic features throughout the study area are channels and shoals associated with passes between the barrier islands (Figure 10). A series of inlet shoals and channels reflect the redistribution and conveyance of littoral sand between barrier islands within a relatively narrow zone of sand transport bound by the 9–11-m depth contours in the Gulf and the 3–5-m contours in the Sound. This approximate 1.5–6.5 km wide nearshore region (narrower for islands, wider for passes) encompasses the zone of littoral sand transport through which islands and inlets fronting Mississippi Sound have evolved. Channel orientation is primarily north–south, and overall deposition on ebb shoals is skewed to the west. This observation is consistent with net shoreline migration, documenting the influence of net westward sediment transport along the shelf and shoreline in coastal Mississippi and Alabama.

Unlike Mobile Pass and the ebb shoal at the eastern boundary of Figure 10, inlet shoals and channels of the Mississippi Sound barrier island system do not extend far offshore, reflecting the

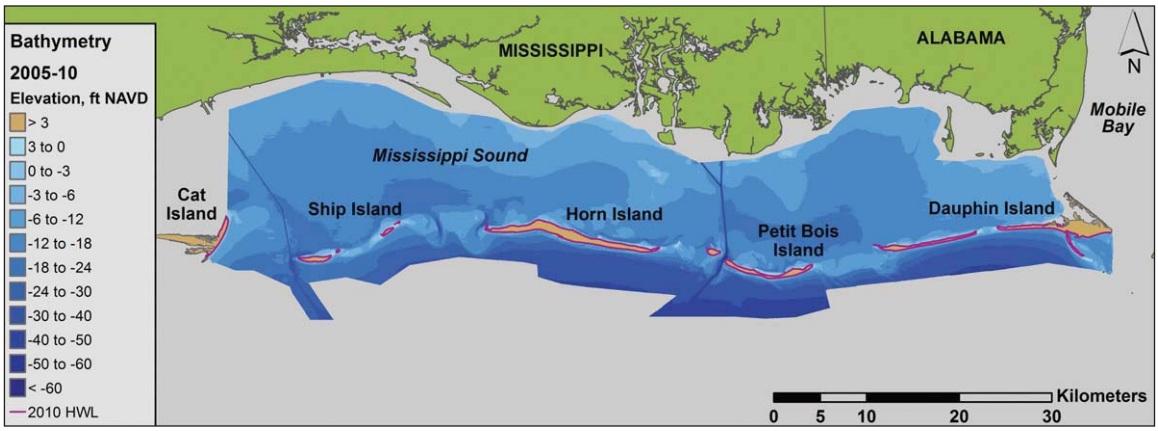

Figure 10. Regional bathymetric surface for the study area, 1917–20.

geomorphic characteristics of wave-dominated inlets. The ebb shoal at Dog Keys Pass (between Ship Island and Horn Island) is the most extensive shoal system along the barrier island chain, followed by shoals associated with Horn Island Pass (between Horn Island and Petit Bois Island). Although Ship Island Pass has the deepest natural inlet west of Mobile Pass, ebb shoal deposits are not well developed, perhaps reflecting a natural decrease in sand transport (and therefore, wave energy) toward the west end of Ship Island (terminal point in the longshore sand transport system). Between the passes, offshore contours appear relatively straight and parallel to shoreline orientation.

One notable geomorphic characteristic along the eastern portion of the study area is the approximate 8-km long breach present along central Dauphin Island. This island breach resulted from the impact of the July 1916 hurricane (Byrnes, Griffee, and Osler, 2010). Furthermore, the eastern end of Petit Bois Island illustrated marked erosion in response to this storm and westward growth of western Dauphin Island and Petit Bois Pass (see Figure 6). Channel dredging at Horn Island Pass and Ship Island Pass was initiated in the late 1890s, and by 1917, 7.6-m (25-ft) and 7.9-m (26-ft) deep channels through the outer bars (both approximately 90-m [300-ft] wide) were maintained to support commercial navigation. Initial authorized depths were consistent with natural channel depths, so the presence of well-defined dredged channels was not very evident.

2005–10 Bathymetry

A number of significant geomorphologic changes were recorded by the 2005–10 bathymetric surveys. Most obvious was that associated with island breaching on Ship and Dauphin Islands (Figure 11). From east to west, westward island growth of Dauphin Island effectively closed the main channel at Petit Bois Pass. The entrance remains as wide as it was in 1917–20, but flow within the entrance must have diminished as the main channel shoaled in response to dominant west-directed longshore sediment transport. Although the eastern end of Petit Bois continued to erode, the western end of the island experienced relatively minor changes because it abuts the Pascagoula navigation channel at Horn Island Pass. Littoral sand transported to and dredged from the channel was placed primarily in the littoral zone west of the channel since 1917–20. The small island west of the channel (Disposal Area 10 [DA 10]; see Figure 2) has been a primary dredged material disposal site since the 1970s and slowly feeds sand south and west toward Horn Island. Placement records and sequential change analysis also indicate that dredged material has been placed elsewhere on the ebb shoal that eventually supplies sand to eastern Horn Island.

Although the eastern end of Horn Island continued to erode between 1917–20 and 2005–10, subaerial deposition along the west end of the island did not keep pace. Westward growth of the island continued to shoal the inlet and push the channel west, resulting in a reduced cross-sectional area at Dog Keys Pass. The 2005–10 bathymetric surface illustrates that Little Dog Keys Pass is now deeper than Dog Keys Pass for the first time in the historical survey record (Figure 11; Byrnes *et al.*, 2012). The ebb shoal at Dog Keys Pass remains large, but the shoal at Little Dog Keys Pass has expanded substantially, implying that it has become a sink to littoral sand transport from the east. Consequently, sand transport to Ship Island has been reduced, resulting in a net deficit in sand bypassing to eastern Ship Island.

As a result of inlet shoal and channel dynamics at Dog Keys Pass, Ship Island has experienced significant changes between 1917–20 and 2005–2010. The eastern half of the island is close to becoming a shoal as the island responds to a sand deficit from Dog Keys Pass and the impact of a series of devastating tropical cyclones since 1969. Transport naturally is reduced toward Ship Island as the direction of open Gulf wave energy becomes more restricted west of Horn Island in the shadow of the St. Bernard delta.

1917–20 to 2005–10 Comparison

Fluid flow and sediment transport at and adjacent to the Mississippi Sound barrier islands results in relatively predictable seafloor changes. An analytical comparison of bathymetry data resulted in a difference plot that isolates erosion (red areas) and deposition (blue areas) for documenting sediment transport patterns and quantifying trends (Figure 12). The most significant changes during this 90-year interval were associated with erosion

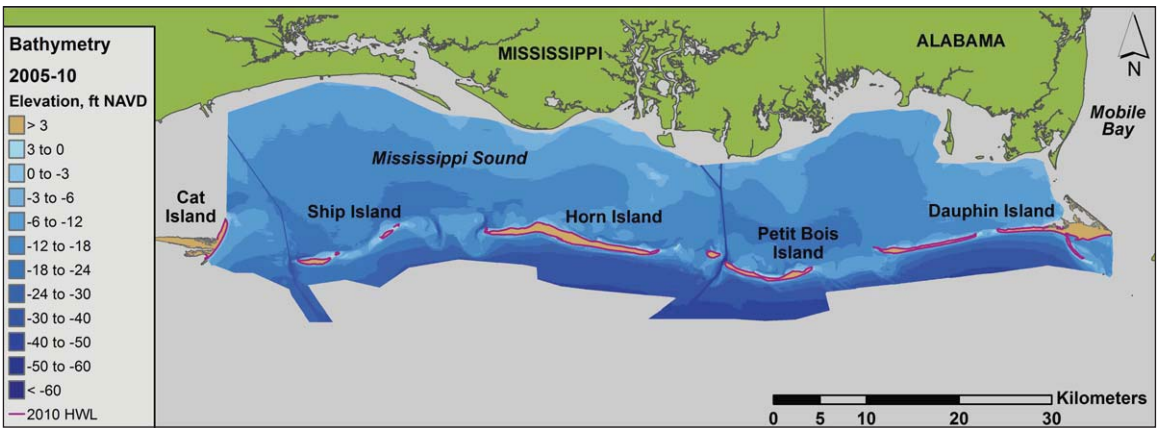

Figure 11. Regional bathymetric surface for the study area, 2005–10.

along the eastern ends of the islands and deposition along the western ends. In response, channels and shoals migrated within entrances to attain equilibrium with incident wave and current energy.

Although littoral zone transport is dominated by west-directed waves and currents, minor and localized areas of transport reversal do exist at the very eastern ends of the islands. Areas of erosion and deposition in channels and on shoals of the ebb-tidal deltas illustrate the dynamic nature of these features (Figure 12). Overall, sediment eroded from the seafloor and island beaches supplies sand for spit growth and inlet shoal formation, which in turn forces inlet channels and entrance boundaries to migrate westward in a conveyor-like process. Most coastal systems experience significant reversals in sand flux that redistribute sediment more evenly along beaches and at entrances, but for the Mississippi Sound barrier island system, net sand transport to the west is nearly equal to gross transport (addition of east- and west-directed transport). As such, long-term transport patterns are quite predictable and reliable for developing sediment budget estimates.

Net erosion along Dauphin and eastern Petit Bois Islands predominantly reflects the impact of the 1916 hurricane (see Byrnes, Griffee, and Osler, 2010); however, other tropical cyclones during this 90-year period also influenced patterns of erosion and deposition. Net deposition landward and downdrift of eroded areas is in response to storm overwash and longshore transport. Westward sediment transport along Petit Bois Island was supplied by beach erosion along the eastern end of the island and transport from Petit Bois Pass (about 440,000 cy/yr [340,000 m^3/yr]). Much of this sand was deposited in the navigation channel at Horn Island Pass (about 270,000 cy/yr [205,000 m^3/yr]), but substantial quantities also were deposited on the eastern lobe of the ebb shoal and at the western end of Petit Bois Island.

Although maintenance of the navigation channel at Horn Island Pass stabilized channel position after 1917–18, eastern Horn Island (and Pass) experienced large-scale erosion, mobilizing millions of cubic yards of sand transported west by littoral currents to create the sand spit on western Horn Island and shoal deposition in Dog Keys Pass. Most sand provided by beach erosion along East Ship Island sourced westward expansion of West Ship Island and sand shoal deposition at Ship Island Pass. Figure 12 illustrates that sand transport between Ship and Cat Islands is not measureable, meaning Ship Island Pass marks the end of longshore transport along the barrier islands.

Few changes were recorded for Mississippi Sound except adjacent to Sound channels where dredged material disposal sites exist. New work dredging associated with the Pascagoula and Gulfport navigation projects produced well-defined ship channels through the Sound and across the bar at each entrance. Maintenance of these channels has hindered westward growth of Petit Bois and Ship Islands, although the Ship Island Pass channel was repositioned 580 m westward of its original position in the early 1990s to limit channel shoaling from westward migration of Ship Island (see Figure 3). As such, Ship Island continues to migrate westward as sand is supplied to the west end of the island. Sand transport along Cat Island beaches is north and south of a position just north of central Cat Island, and sand deposition at the ends of the island is sourced by local beach erosion. Again, there is no apparent external source of sand to Cat Island beaches.

Potential Maintenance Dredging Impacts

As documented earlier, channel dredging commenced in Horn Island Pass and Ship Island Pass in the late 1890s to support local commerce. Original authorized depths were 7.6 m (25 ft) and 7.9 m (26 ft), respectively, and channel width was to be about 90 m (300 ft). By 2009, authorized channel depth at Horn Island Pass was 13.4-m (44-ft) deep (165-m [550-ft] wide), greater than that authorized for Ship Island Pass (11.6-m [38-ft] deep, 122-m [400-ft] wide). Both bar channels have accumulated millions of yards of littoral sand during this time (Horn–24.9 million cy [19.0 million m^3]; Ship–15.5 million cy [11.9 million m^3]), and new work extracted 9.4 million cy (7.2 million m^3) from Horn Island Pass and 9.8 million cy (7.5 million m^3) from Ship Island Pass. New work cannot be considered littoral sand for the period of analysis, but depending on placement location, it can add to the littoral sand budget.

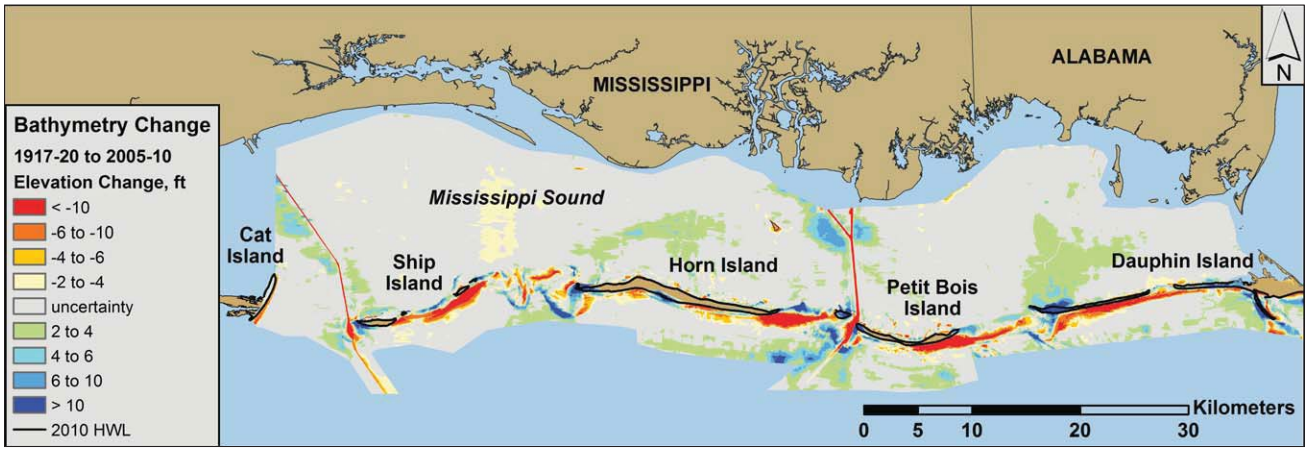

Figure 12. Bathymetric change between 1917–20 and 2005–10 for the Mississippi Sound barrier islands. Hot colors represent erosion (yellow to red), and cool colors represent deposition (green to blue).

Between 1917–18 and 2009, approximately 23.8 million cy (18.2 million m^3) of sand were extracted from the Horn Island Pass navigation channel from maintenance dredging (Table 2). During the same period, 17.5 million cy (13.4 million m^3) of sand dredged from the channel (new work plus maintenance dredging) were placed on the western lobe of the ebb shoal to be redistributed as littoral sediment. This leaves an approximate 6.3 million cy (4.8 million m^3) deficit of littoral sand from maintenance dredging, that under natural channel conditions would have a chance of being transported to downdrift beaches. Instead, it likely was disposed of offshore as part of dredging operations. This implies that without channel dredging, approximately 6.3 million cy (4.8 million m^3) of sand would have remained in the littoral system as islands and inlets migrated to the west. The direct impact of this net sand deficit to downdrift beaches is not apparent because the system is so dynamic, and it is unknown whether dredged sand would have deposited along the beach or as part of subaqueous shoals.

Ship Island Pass is located at the terminus of the longshore sand transport system. This implies that sand transport does not extend west of the pass. In fact, all bathymetric change results illustrate no measureable seafloor changes west of the channel until the Cat Island littoral zone is encountered. Furthermore, sand dredged from the channel and placed in the littoral zone disposal area west of the channel indicates transport to the south coincident with the orientation of flow in the pass. As such, littoral sand deposited in Ship Island Pass does not impact nearshore environments west of the channel because westward drift ceases to be active at this location.

Littoral Sediment Budget: 1917–18 to 2005–10

Sediment budget determination for the coastal zone involves application of the principle of conservation of mass to littoral and offshore sediment (Bowen and Inman, 1966; Rosati and Kraus, 1999; Rosati, 2005). The USACE Sediment Budget Analysis System (SBAS; Rosati, 2005) was applied to analyze transport pathways and sediment volume fluxes. Zones of erosion and accretion were identified throughout the sediment budget control areas based on bathymetric change analysis. Overall, ebb shoals at all entrances and the west ends of islands were net depositional (sediment sinks), whereas beach and nearshore environments along the east ends of the islands were net erosional (sediment sources). As stated previously, sand volume change and transport units of measure are English because quantities were derived from like units for project engineering applications. For conversion purposes, cubic meters equals cubic yards times 0.7646.

Macro-Scale Trends

The analysis period encompasses a time of significant channel dredging at Horn Island Pass and Ship Island Pass. Furthermore, it includes some of the most destructive hurricanes to impact the northern Gulf of Mexico (*e.g.*, 1916 hurricane, 1947 hurricane, Hurricane Camille, and Hurricane Katrina; Sullivan, 2009). Figure 13 illustrates the macroscale sediment budget for the study area, which summarizes details from each of the five control areas along the coast for assessing net sediment flux. Control areas are defined based on net erosion and deposition patterns along the barrier islands. Sand volume change (ΔV) is calculated as the difference between sediment input (Q_{in}) to and sediment export (Q_{out}) from a control area plus the difference between dredged material placed in the littoral zone (P) and the sum of maintenance dredging (R_m) and new work dredging (R_n) for a navigation channel.

Starting at western Dauphin Island, net sand transport into sediment budget Box 1 was 298,000 cy/yr. This value was determined by updating the sediment budget of Byrnes, Griffee, and Osler (2010) for Dauphin Island. Their original analysis used 2002 bathymetry data as the analysis endpoint. The endpoint for all bathymetry data along the Mississippi Sound barrier islands was after Hurricane Katrina, so the sediment budget of Byrnes, Griffee, and Osler (2010) was updated to include post Katrina bathymetry and lidar surveys collected by NOAA and USGS. Detailed analysis of these recent datasets yielded the sand volume flux stated above as the input boundary condition at the eastern end of the barrier island sediment budget (Figure 13).

Overall, the area encompassed by Box 1 was a net source of sediment to downdrift beaches (437,000 cy/yr), the Gulf (20,000 cy/yr), and the Sound (43,000 cy/yr). West-directed sand flux was by far the dominant direction of transport. Large quantities of sediment were deposited in Horn Island Pass channel (Box 2), but most maintenance dredging sand was placed west of the channel in the littoral zone (Figure 13; Table 2). As such, the flux of sand west to Box 3 was reduced only by about 28,000 cy/yr. North and south sediment losses to the Sound (23,000 cy/yr) and Gulf (50,000 cy/yr) were relatively small, but total sand placement offshore as part of channel dredging added to net sand export from this control area and resulted in Box 2 being a significant sediment source (about 207,000 cy/yr).

Approximately 409,000 cy/yr of sand entered Box 3 from the Horn Island Pass area heading toward Dog Keys Pass. About 19,000 cy/yr of sand eroded from the back side of Horn Island was lost to the Sound, but it is estimated that no sand from Gulf-facing beaches was transported offshore and outside the littoral zone. Overall, Box 3 was a source of sand for downdrift beaches and Dog Keys Pass. Sand flux to Dog Keys Pass (Box 4) was about 423,000 cy/yr, very consistent with transport magnitudes east of this area. Dog Keys and Little Dog Keys Pass is the largest entrance in the study area, and this dual inlet system has a very dynamic channel and shoal system. Changes in flow patterns throughout the inlet have enhanced shoal growth on both ebb shoals, creating a net sediment sink for this area (160,000 cy/yr). Furthermore, export of sand to the Sound (20,000 cy/yr) and the Gulf (100,000 cy/yr) have decreased west-directed sand flux illustrated east of Box 4. As a result, the flux of sand to Ship Island is about 35% of west-directed sand transport elsewhere in the system (143,000 cy/yr). As such, chronic erosion along East Ship Island persists because the quantity of sediment eroded from the beach and nearshore is almost three times the quantity entering Box 5 from the east. Net erosion is the only possible result under these conditions.

West Ship Island is net depositional, but a substantial amount of littoral sand deposits in the channel (156,000 cy/yr). Some dredged sand is placed on the north side of the island, but a

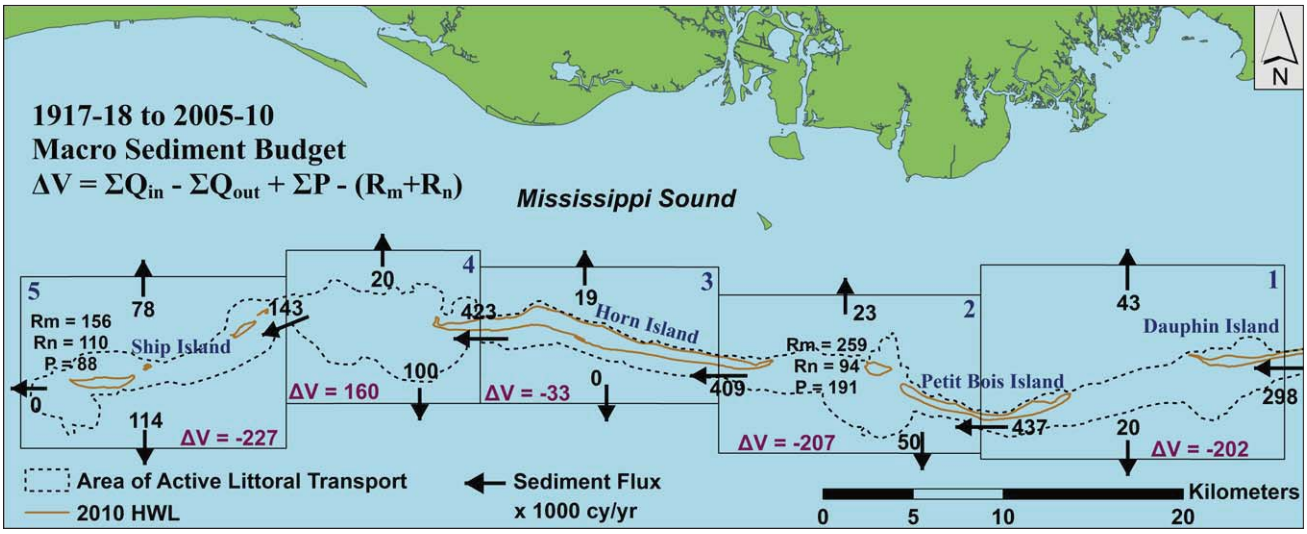

Figure 13. Macroscale sediment budget for the Mississippi Sound barrier island chain, 1917–18 and 2005–10. Arrows illustrate the direction of sediment movement throughout the system and black numbers reflect the magnitude of net sediment transport. ΔV=net volume change; Q_{in}=net transport into the control area; Q_{out}=net transport out of the control area; P=dredged material placed in the control area (littoral zone); R_m=sand volume removed from the channel via maintenance dredging; R_n=sediment volume removed from the channel via new work dredging.

majority of it is placed west of the channel where longshore transport is nonexistent. Box 5 is also a source of sediment to sound (78,000 cy/yr) and offshore (114,000 cy/yr) environments.

Operational Sediment Budget

An operational sediment budget provides details regarding sediment transport pathways and quantities based on survey measurements within defined control areas. Figure 14 illustrates detailed changes in sand movement within Box 1 for the Petit Bois Pass area. Spit growth along the western end of Dauphin Island and shoal accretion at Petit Bois Pass absorbed all sediment transported from eastern Dauphin Island (298,000 cy/yr) and approximately 25% of the sand supplied by erosion of the eastern lobe of the relict ebb shoal at Petit Bois Pass. It was estimated that approximately 20,000 cy/yr of sand was transported offshore to the Gulf and an equal amount into Mississippi Sound, combined with island erosion on the east end of Petit Bois Island to supply 437,000 cy/yr of sand to the west end of the island (Figure 14). Washover deposition created a long subaqueous shoal north of the location of the 1917 island shoreline that was partially supplied by east-directed sand transport from eastern Petit Bois Island. Erosion along the north side of the island provided sand for shoal development soundward of the active littoral zone (23,000 cy/yr).

Sand flux to the western end of Petit Bois Island created an elongated sand spit that abuts the navigation channel at Horn Island Pass. All sand excavated from the navigation channel during maintenance dredging (259,000 cy/yr; Table 2) was supplied by sand transport from the east into the navigation channel (270,000 cy/yr; Figure 15). Another 13,000 cy/yr was transported into the Sound, and 20,000 cy/yr was transported offshore to the Gulf. This implies that about 134,000 cy/yr deposited along the spit and at entrance shoals east of the channel. Although only 94,000 cy/yr of new dredging work was recorded during this time (Table 2), an additional 85,000 cy/yr of sand was eroded from the western margin of the channel and transported to the western lobe of the ebb shoal (Figure 15). Dredged material placement also contributed approximately 82,000 cy/yr of sand to the west lobe of the ebb shoal (Table 2), resulting in extensive shoal deposition and about a 30,000 cy/yr sediment export to the Gulf. Furthermore, channel dredging contributed approximately 109,000 cy/yr of sand to DA 10, presently recognized as a subaerial island adjacent to the channel west of western Petit Bois Island. Most sand placed in DA 10 has remained, but about 6,000 cy/yr from the placement site and 46,000 cy/yr from the west lobe of the ebb shoal is transported toward Horn Island. Approximately 107,000 cy/yr of sand eroded from the eastern

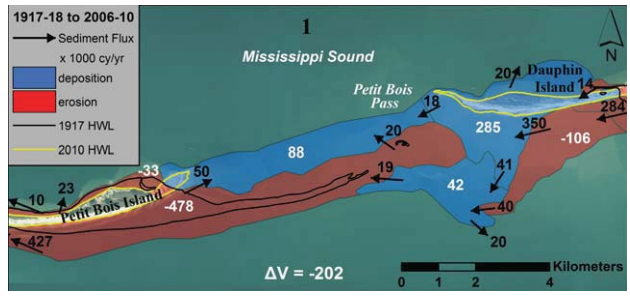

Figure 14. Detailed sediment transport pathways and quantities for Box 1 (Petit Bois Pass area) of the macro-scale sediment budget, 1917–18 and 2006–10. Arrows illustrate the direction of sediment movement and black numbers reflect the magnitude of net sediment transport in thousands of cy/yr. White numbers represent net sand volume change for defined polygons. Underlying image is from October 2008.

end of Horn Island is transported into the Sound as washover and east-directed transport from Horn Island to create an extensive subaqueous sand shoal on the western side of the pass. It is estimated that 10,000 cy of sediment is transported from this area into the Sound on an annual basis. The remaining 409,000 cy/yr of sand supplied by erosion of east Horn Island and transport through the inlet system moves westward along Horn Island (Figure 15). Although Box 2 is a net source of sediment to adjacent environments (207,000 cy/yr), most sediment exported the system via offshore placement of new work dredging (39,000 cy/yr) and maintenance dredging (123,000 cy/yr; Table 2).

Erosion and deposition along the Gulf side of central Horn Island resulted in the addition of 33,000 cy/yr of sand to the littoral transport system (Figure 16; Box 3). However, it is estimated that erosion along the north side of the island provided about 19,000 cy/yr of sediment to Mississippi Sound; no sand appeared to be transported seaward to the Gulf. Sand flux was balanced fairly well in Box 3, although a small net gain in sand transport toward western Horn Island and Dog Keys Pass was documented (423,000 cy/yr).

Sand flux to western Horn Island and into Dog Keys Pass resulted in about 243,000 cy/yr of shoal deposition in Dog Keys Pass (about 55% of the total sediment flux; Figure 17). In addition, approximately 25,000 cy/yr of sediment was transported into Mississippi Sound and an estimated 50,000 cy/yr was transported to the Gulf. The remaining sand transported to the entrance (110,000 cy/yr) continued west toward Little Dog Keys Pass and East Ship Island. In 1916, Dog Island was a beach in the entrance that remained subaerial until about 1932 (Rucker and Snowden, 1988). Although deposition on the ebb shoal at Little Dog Keys Pass has been persistent during the historical record, erosion of Dog Island and other entrance shoals during inlet evolution resulted in a net loss of sand from the area (11,000 cy/yr; Figure 17). As such, net sand flux to Little Dog Keys Pass from Dog Island and Dog Keys Pass (182,000 cy/yr) was not adequate to meet sand needs from eroding East Ship Island, given that approximately 50,000 cy/yr of sediment exited Little Dog Keys Pass to the Gulf. Even though Little Dog Keys Pass is net erosional between 1917–18 and 2007–10, only 143,000 cy/yr of the 423,000 cy/yr flux of sand into Box 4 is transported to East Ship Island (Figure 17).

The orientation of East Ship Island exposes low-lying sand beaches to direct attack by southeast waves. As such, a significant amount of sand eroded from Gulf-facing beaches is transported to the north side of the island during overwash events (about 79,000 cy/yr). Rapid beach erosion along the Gulf side of East Ship Island (see Figure 8) has exposed old interior marsh and fine-grained backbarrier deposits that are estimated to contribute approximately 60,000 cy/yr of fine-grained sediment to offshore and Sound environments (see Byrnes *et al.*, 2012). Long-term erosion along East Ship Island mobilizes about 400,000 cy/yr of sediment from the beaches, almost three times the amount of sand transported to the island from Little Dog Keys Pass. The island can only erode under these circumstances, as it has throughout the historical record (Figure 18).

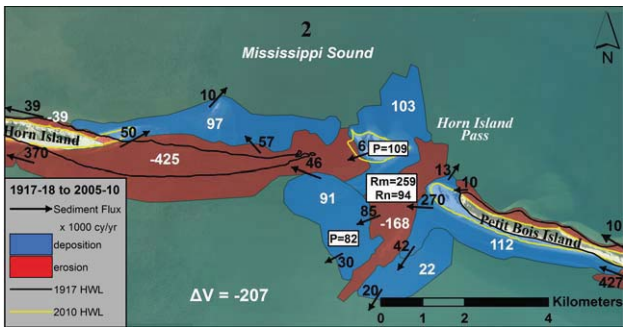

Figure 15. Detailed sediment transport pathways and quantities for Box 2 (Horn Island Pass area) of the macro-scale sediment budget, 1917–18 and 2005–10. Arrows illustrate the direction of sediment movement and black numbers reflect the magnitude of net sediment transport in thousands of cy/yr. White numbers represent net sand volume change for defined polygons. Underlying image is from October 2008.

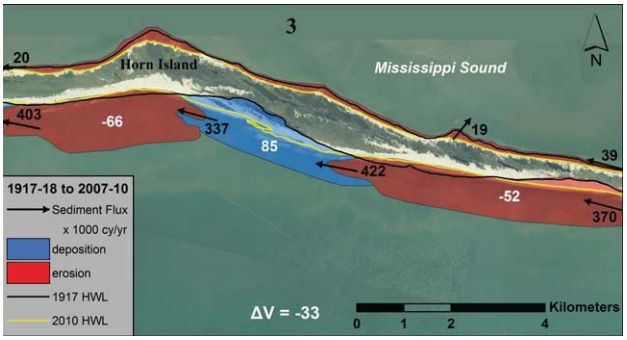

Figure 16. Detailed sediment transport pathways and quantities for Box 3 (Horn Island) of the macro-scale sediment budget, 1917–18 and 2007–10. Arrows illustrate the direction of sediment movement and black numbers reflect the magnitude of net sediment transport in thousands of cy/yr. White numbers represent net sand volume change for defined polygons. Underlying image is from October 2008.

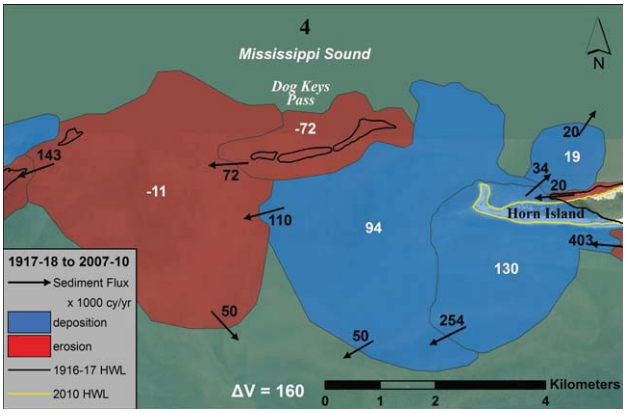

Figure 17. Detailed sediment transport pathways and quantities for Box 4 (Dog Keys Pass) of the macro-scale sediment budget, 1917–18 and 2007–10. Arrows illustrate the direction of sediment movement and black numbers reflect the magnitude of net sediment transport in thousands of cy/yr. White numbers represent net sand volume change for defined polygons. Underlying image is from October 2008.

The flux of sand to West Ship Island is approximately 335,000 cy/yr, of which 183,000 cy/yr deposits in the navigation channel; 54,000 cy/yr is transported to the Sound, where it deposits as sand shoals inside the entrance (36,000 cy/yr) and the remainder is redistributed in the Sound; 104,000 cy/yr is deposited at the end of West Ship Island and on the ebb shoal east of the pass (Figure 18). A portion of sand deposited west of the channel in the littoral zone placement area (24,000 cy/yr) appears to be migrating back toward the channel by south-directed tidal currents, although it is estimated that 44,000 cy/yr is transported offshore. Because Ship Island Pass marks the terminus for longshore sand transport along the Mississippi barrier islands, future placement of dredged channel sand on the north side of West Ship Island may be a more effective use of littoral sediment from a sand management perspective.

CONCLUSIONS

A series of devastating hurricanes along the northern Gulf of Mexico has significantly reduced the width and elevation of barrier island beaches, exposing mainland beaches, infrastructure, and navigation channels to increasing storm damage. The Mississippi Sound barrier islands provide the first line of defense for mainland habitat and navigation channels, serving to decrease Gulf wave energy in their shadow and potentially modify the timing and magnitude of storm surge. The primary goal of this study was to quantify net sediment volume changes associated with the historical evolution of nearshore morphology and adjacent beaches for the period 1917–20 to 2005–10. Net sediment transport pathways and quantities derived from these analyses (*i.e.*, operational sediment budget) provide the framework upon which island restoration quantities and geometries are being designed.

Shoreline and beach evolution for the barrier islands fronting Mississippi Sound is driven by longshore transport processes associated with storm and normal wave and current conditions. Although beach erosion and washover deposition are processes that have influenced island changes, the dominant mechanism by which sand is redistributed along the barrier islands and in the passes is by longshore currents generated by wave approach from the southeast. Sandy beaches and nearshore areas along the western Florida and Alabama coasts supply material to downdrift barrier beaches fronting Mississippi Sound. Geomorphic changes along the islands illustrate the dominance of net sand transport from east to west.

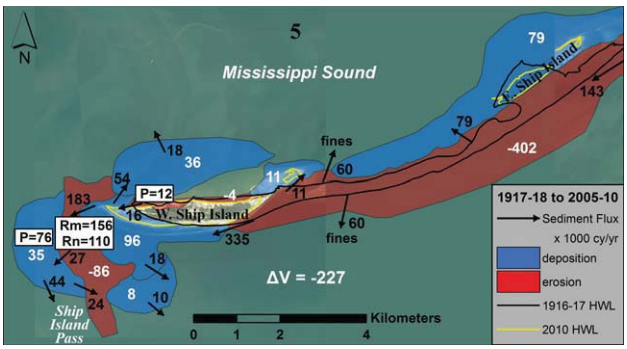

Figure 18. Detailed sediment transport pathways and quantities for Box 5 (Ship Island and Pass area) of the macro-scale sediment budget, 1917–18 and 2005–10. Arrows illustrate the direction of sediment movement and black numbers reflect the magnitude of net sediment transport in thousands of cy/yr. White numbers represent net sand volume change for defined polygons. Underlying image is from October 2008.

Sediment erosion and accretion volumes were quantified for the period 1917–18 to 2005–10 to develop an operational sediment budget. Zones of erosion and accretion were identified throughout sediment budget control areas based on bathymetric and shoreline change analysis. Overall, ebb shoals at all entrances and the west ends of islands were net depositional (sediment sinks). Beach and nearshore environments along the east ends of the islands were net erosional (sediment sources). Net west-directed transport deposits sand along the east side of passes as elongated sand spits and entrance shoals. Much of the sand dredged from Horn Island Pass has been placed on the west lobe of the ebb shoal, transferring littoral sand from east of the navigation channel to the downdrift littoral zone. However, it was determined from dredging records that approximately 6.3 million cy (4.8 million m^3) of littoral sand dredged from the channel between 1917–18 and 2009 was not returned to the littoral zone west of the channel, creating a net long-term deficit to the sand budget.

The following specific conclusions were most germane to the overall goal of the study:

(1) Beach erosion along the eastern ends of islands supplied sediment to downdrift depositional zones along the western margins of islands and as subaqueous deposition in adjacent inlets.

(2) Cross-shore beach changes (north-to-south) were present along eastern Petit Bois and Ship Islands, but the dominant direction of transport was alongshore (east-to-west).

(3) As islands migrated westward, inlet channels did the same, except where navigation channels were established and maintained at Horn Island Pass and Ship Island Pass.

(4) Ship Island is at the end of the Mississippi barrier island littoral transport system, and as such, has been the most vulnerable barrier island to erosion processes within the system.

(5) Although most barrier islands along the Mississippi coast have been subjected to storm overwash processes, only Ship Island has been breached multiple times during the historical record and continuously since Hurricane Camille.

(6) Mississippi barrier island inlet systems are primary sinks to longshore sand transport.

(7) Sediment flux along the barrier islands fronting Mississippi Sound ranges from 300,000 to 400,000 cy/yr (230,000 to 305,000 m^3/yr), with greatest net sand transport rates along Horn Island.

(8) The difference between littoral zone placement and maintenance dredging at Horn Island Pass (1917–2009) is about -6.3 million cy (net deficit to the littoral sand budget).

(9) Although the channel at Dog Keys Pass has been shoaling since the 1960s, the channel at Little Dog Keys Pass (west in the entrance) has become dominant and deeper, maintaining a wide entrance as a natural sediment trap to

sand bypassing between Horn and East Ship Islands.

(10) Ship Island is the most degraded barrier island along the Mississippi coast and is farthest from original sand sources. Historically, littoral sand trapped in Dog Keys Pass has diminished sand transport to East Ship Island, the most rapidly deteriorating island in coastal Mississippi. Given historical rates of shoreline recession (4.6 to 6 m/yr) and associated beach erosion (~400,000 cy/yr [305,000 m^3/yr]) along East Ship Island, the island is expected to become a subaqueous shoal within the next decade unless restoration measures are undertaken. Once East Ship Island becomes a subaqueous shoal, beach erosion processes will shift westward because the primary source of sand for beach deposition and island migration to the west will have dispersed.

ACKNOWLEDGEMENTS

The USACE, Mobile District, Mississippi Coastal Improvements Program (MsCIP) funded this project. Authors are grateful for assistance provided by Ms. Susan I. Rees (MsCIP Program Director), Ms. Elizabeth Godsey (USACE), Mr. John Baehr (USACE), Mr. Jason Krick (USACE), Mr. Justin McDonald (USACE), Mr. David Twichell (USGS), Mr. Jeff Williams (USGS), Mr. Jim Woods (National Park Service; NPS), Ms. Rebecca Beavers (NPS), Ms. Linda York (NPS), Mr. Bruce McCraney (NPS), and Mr. Rick Clark (National Park Service; (NPS). Special thanks to two anonymous peer reviewers, whose comments greatly improved the clarity of this manuscript.

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