Journal of

Coastal Research

The Physical Condition of South Carolina Beaches 1980–2010

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An International Forum for the Littoral Sciences

Published by

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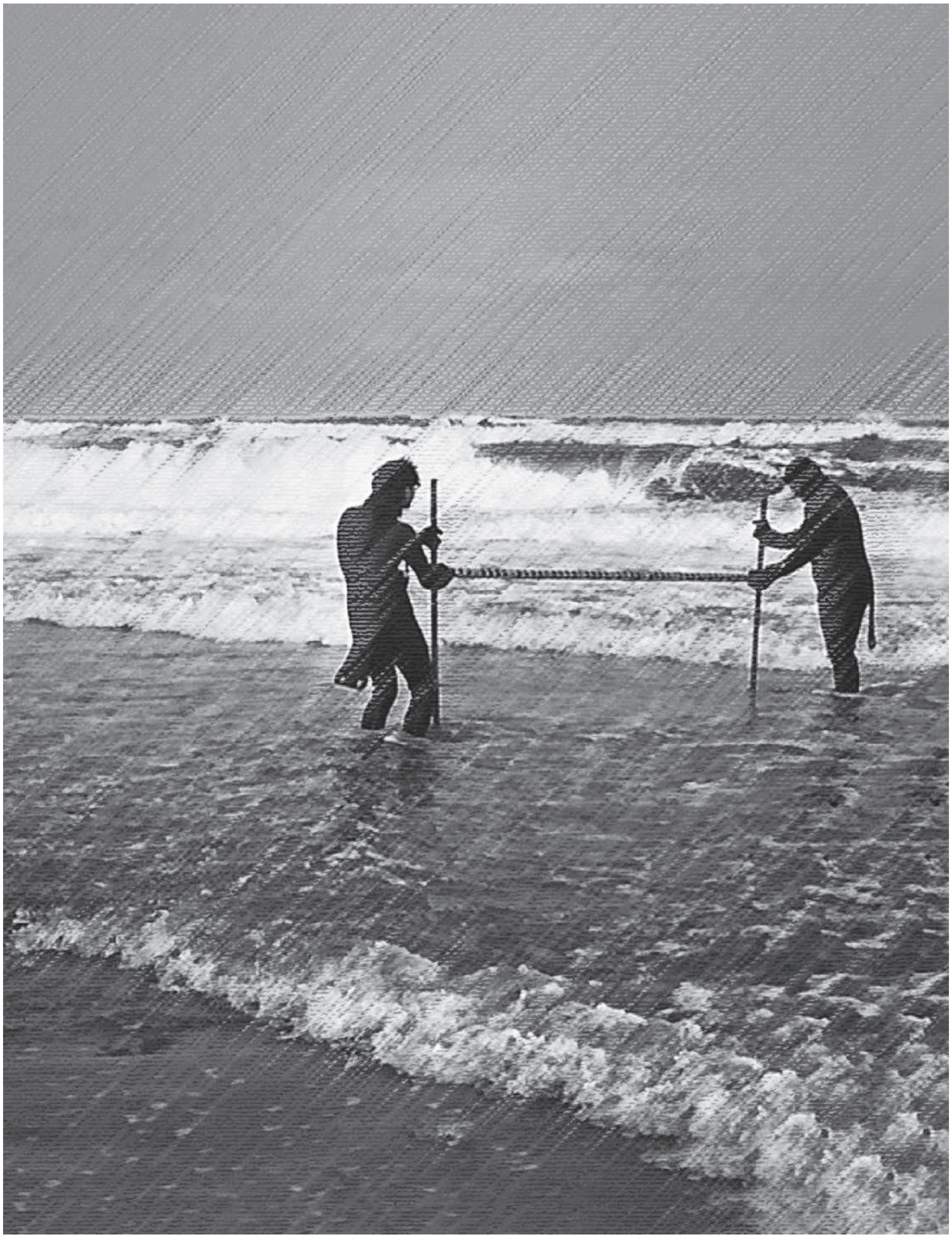
COASTAL PHOTOGRAPH BY MILES O. HAYES



Coastal Heroes John Gifford and Walt Handy running a beach profile the old-fashioned way on Plum Island, Massachusetts, *ca*. 1969. These beach-profiling surveys, carried out at numerous locations between 1964 and 1972, allowed us to determine the beach erosional/depositional patterns for sand beaches along the northern New England coast.

Journal of Coastal Research | SI | 69 | 61–82 | Coconut Creek, Florida | Fall 2013

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ABSTRACT

Kana, T.W.; Traynum, S.B.; Gaudiano, D.; Kaczkowski, H.L., and Hair, T., 2013. The physical condition of South Carolina beaches 1980–2010. *In:* Kana, T.; Michel, J., and Voulgaris, G. (eds.), *Proceedings, Symposium in Applied Coastal Geomorphology to Honor Miles O. Hayes*, Journal of Coastal Research, Special Issue No. 69, 61–82. Coconut Creek (Florida), ISSN 0749-0208.

Thirty years of monitoring surveys and shoreline erosion studies (1980–2010) along the South Carolina coast show that artificial beach nourishment and the natural process of inlet shoal bypassing have advanced the shoreline along most of the developed beaches and barrier islands. Of the ~98 mi (~161 km) of developed beaches (including public parks), fully 80% were much healthier in 2010 than in 1980, as evidenced by burial of seawalls, wider berms, and higher dunes. About 15% of the developed beaches are in approximately the same condition as in 1980; the remaining ~5% are considered in worse condition. The balance of South Carolina beaches (~89 mi, ~146 km) are principally wilderness areas with limited public access. The dominant condition of wilderness beaches is high erosion; limited new sand inputs, particularly via inlet bypassing; and accelerated recession as many of these sand-starved beaches wash over salt-marsh deposits. High erosion results from a combination of sand losses to the lagoon, winnowing of muddy marsh deposits outcropping across the receding beach, and longshore transport losses to the adjacent inlet. An estimated 75% of the undeveloped beaches in 2010 were well landward of their 1980 positions. Between 1980 and 2010, ~39.4 million yd^3 (~30.1 million m^3) of beach nourishment from external sources was added to developed and park beaches (~62.6 mi, ~102.6 km). This is equivalent to an addition of ~168 ft (~51 m) of beach width in the nourished areas. Natural shoal bypassing events appear to have added a similar magnitude of new sand along accreting beaches. Bypassing events at some beaches involved ~2–5 million yd^3 (1.5–3.8 million m^3). Ebb dominance at many South Carolina inlets is shown to play an important role in preserving the littoral sand budget, maintaining large sand reservoirs for bypassing and helping maintain the developed beaches in the state. Low rates of erosion in other areas, such as the Grand Strand, combined with large-scale nourishment have advanced those beaches well beyond historic conditions.

ADDITIONAL INDEX WORDS: *Beach erosion, barrier islands, beach nourishment, shoal bypassing, depth of closure, volume change, longshore transport, signatures of erosion, salient, decadal scale, washover, sea level rise.*

INTRODUCTION

In this paper, we provide an overview of South Carolina beach changes and their principal causes over a span of three decades (~1980–2010). Emphasis is on the developed and accessible beaches of the state (Figure 1), which comprise ~98 mi (~161 km) out of a total of ~187 mi (~307 km) of sandy coastline (OCRM, 2010). The balance of the ocean and associated inlet beaches (~48%) is undeveloped and only accessible by boat. The period 1980 to 2010 coincides with the availability of more comprehensive surveys of the littoral profile and numerous shoreline erosion assessments targeting particular sites. Many of the beach studies in recent years reported decadal-scale volume changes and led to site-specific estimates of the depth of closure (DOC), which is the seaward boundary of the active littoral zone for the time period of interest (Hallermeier, 1981; Kraus, Larson, and Wise, 1998). DOC is a fundamental parameter needed for the eventual development of comprehensive sediment budgets that incorporate inlet volumes and sand transport rates (Kraus and Rosati, 1998; Rosati, 2005).

The results herein are empirical, based on beach and inshore topography data, because coastal process measurements needed to drive shoreline change models remain sparse in time and space (Voulgaris *et al.,* 2008). Further complicating attempts to quantify volumetric erosion rates and sediment transport along South Carolina are major tidal deltas that modify the littoral transport system and produce a highly complex and compartmentalized coast. This has led to identification of certain recurring "signatures of erosion" (Kana, 1995a, 2011), which can be inferred from gradients in beach volume changes and geomorphic indicators of net sediment transport (Figure 2).

BACKGROUND AND DATABASE

The South Carolina coastline has been closely monitored for more than three decades. It is the site of several federal beach

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DOI: 10.2112/SI_69_6 received 27 July 2012; accepted in revision 30 January 2013; corrected proofs received 16 June 2013.

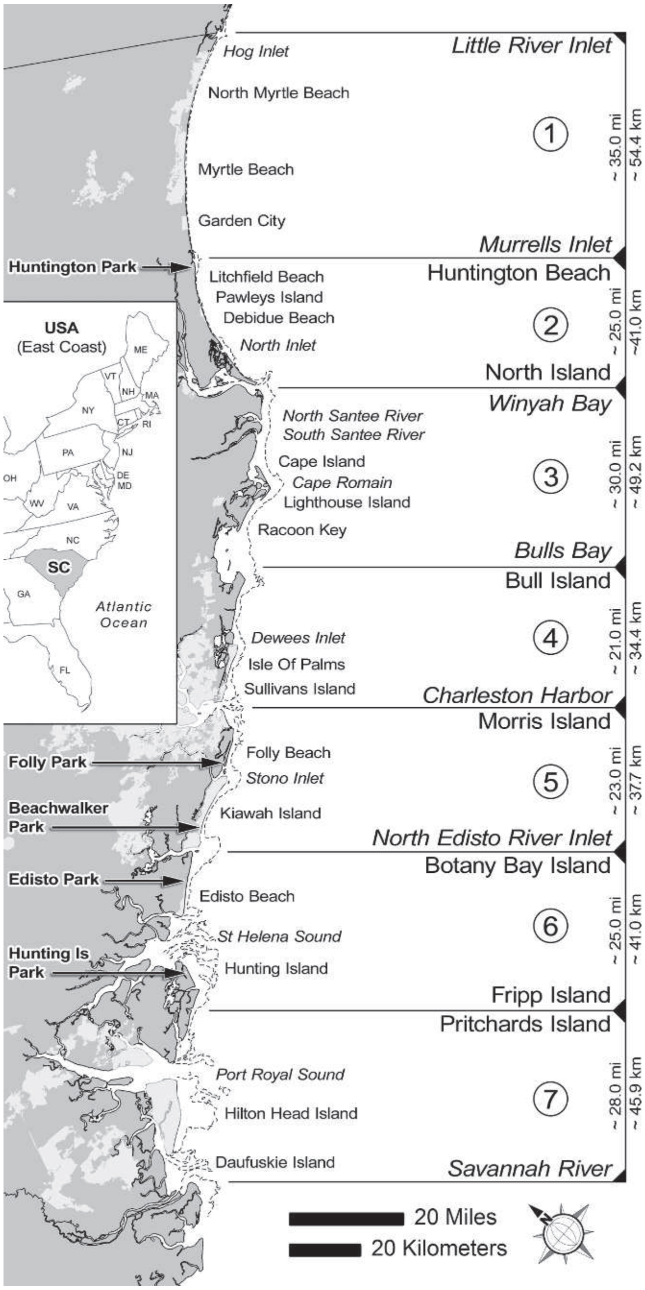

Figure 1. Vicinity map of seven South Carolina shoreline segments and localities.

erosion control projects directed by the U.S. Army Corps of Engineers (USACE) (*e.g.,* Hunting Island [1968–1984], Folly Beach [1993–2043], and Myrtle Beach [1997–2046]). The state of South Carolina and the U.S. Geological Survey in collaboration with Coastal Carolina University, Clemson University, and the College of Charleston have sponsored geologic framework studies and state-wide beach erosion surveys since the late 1980s (Barnhardt *et al.,* 2007; Gayes, 2003; SCCC-OCRM, 1991–2010).

Statewide beach monitoring was initiated by Professor Miles Hayes and his graduate students in 1972 with the founding of the Coastal Research Division (CRD) at the University of South Carolina. With sponsorship by the national Sea Grant program, CRD established a network of profiles monitored quarterly (Brown, 1977) that was used to compare and contrast modes of formation and evolution of South Carolina beaches with other settings.

Hayes (1979) coined the term “drumstick barrier island,” which at once evokes the morphology—likened to a chicken leg—of many South Carolina islands and suggests net directions of sand transport along each island (Figure 3). He demonstrated that the morphology of the coast, lengths of barrier islands, and sizes of tidal deltas are controlled by the relative energy of tides and waves (see Davis, this volume). Thus, South Carolina’s “mesotidal, mixed-energy” coast is quite different from the microtidal, wave-dominated coasts of North Carolina or Texas.

CRD spawned research companies that continue active measurements and monitoring of South Carolina developed beaches, building upon the CRD database (Hubbard *et al.,* 1977; Stephen *et al.,* 1975). Research Planning Institute Inc. (RPI) initiated systematic beach surveys of Seabrook Island in 1978, Kiawah Island in 1980, Myrtle Beach in 1981, and Isle of Palms in 1982. Coastal Science & Engineering Inc. (CSE) expanded the network of monitored beaches in the mid-1980s to include Debidue Beach (1985), Hilton Head Island (1986), Pawleys Island (1987), and Hunting Island (1988). By the late 1980s, the state of South Carolina established a state-wide network of fixed reference points for annual beach profile surveys (*e.g.,* SCCC-OCRM, 1991–2010) conducted by researchers at Coastal Carolina University since the 1990s (Gayes *et al.,* 2001).

Nearly every developed beach in South Carolina is monitored at some level today. The state network of profiles involves about 450 lines spread over nearly 100 mi (~160 km) of ocean beaches. Hundreds of additional profiles are now routinely measured along actively maintained beaches in connection with nourishment projects (*e.g.,* CSE, 2010a; Olsen Associates, 2005). The profile quality, density, and offshore coverage have improved greatly in the past decade with the adoption of real-time kinematic Global Positioning System survey technology allowing better resolution of volume changes into deeper water and more accurate estimates of the extent of the active littoral zone. The majority of profiles during the 1980s were obtained by rod and level or total station, with many extending offshore upward of 1000 ft (300 m), a distance found to capture a majority of the sand moving annually (Kana, 2011). More than 400 erosion assessment and beach monitoring reports are now available, covering individual projects, barrier islands, and regions in South Carolina (see Foyle, Alexander, and Henry, 2004; Nelson *et al.,* 2009; Sautter and Sangster, 1997, for bibliographies).

Most survey data connected with South Carolina beach nourishment and project monitoring are reported in English units. Therefore, to facilitate comparison of quantities reported herein with documented amounts, English values are given precedence followed by their metric equivalents, as practicable. Considering the variability of survey coverage in time and

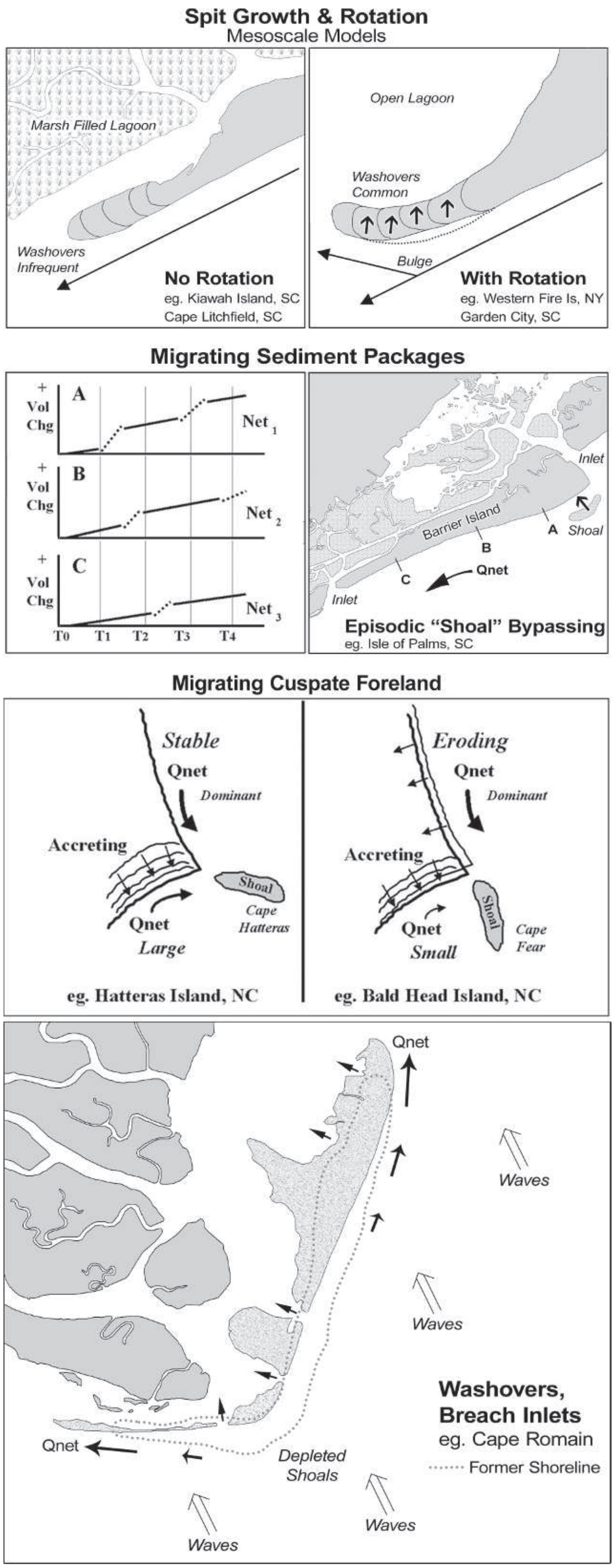

Figure 2. Example signatures of erosion. (Top) Spit growth with rotation leaves a bulge (salient), which becomes a focus of erosion. (Upper middle) Migrating sediment packages downcoast of episodic shoal-bypassing events.

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(Lower middle) Asymmetric convergent transport at cuspate forelands. (Bottom) Divergent transport at capes with depleted offshore shoals showing accelerated erosion as beaches go into "washover" mode. (After Kana, 1995, 2011)

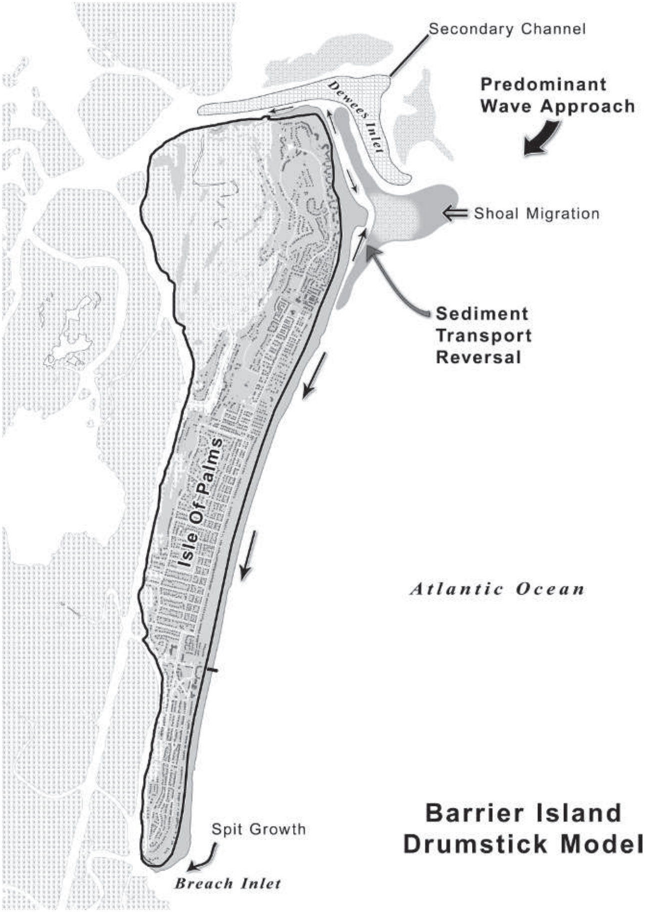

Figure 3. Drumstick barrier island model (after Hayes, 1979) of Isle of Palms, a mesotidal mixed-energy setting with large ebb-tidal deltas feeding the downcoast beach via the process of shoal bypassing. Image shows net transport into the lee of the migrating shoal. Upon attachment, net transport tends to spread away from the attachment point.

space, numerous approximations are necessary for a state-wide inventory of beach conditions. The goal is to provide realistic quantity estimates at decadal scales to place the overall changes in context and identify the most important erosion factors at each site.

Depth of Closure (DOC) Estimates

As an example of the expansion of the beach survey database over the past three decades, the number of lines surveyed along Myrtle Beach (9 mi, ~15 km) has increased from 36 wading depth profiles (Kana and Svetlichny, 1982) to >100 profiles extending 2500 ft (~750 m) offshore to a depth of 25 ft (~7.5 m). This has allowed better estimates of the seaward limit of active

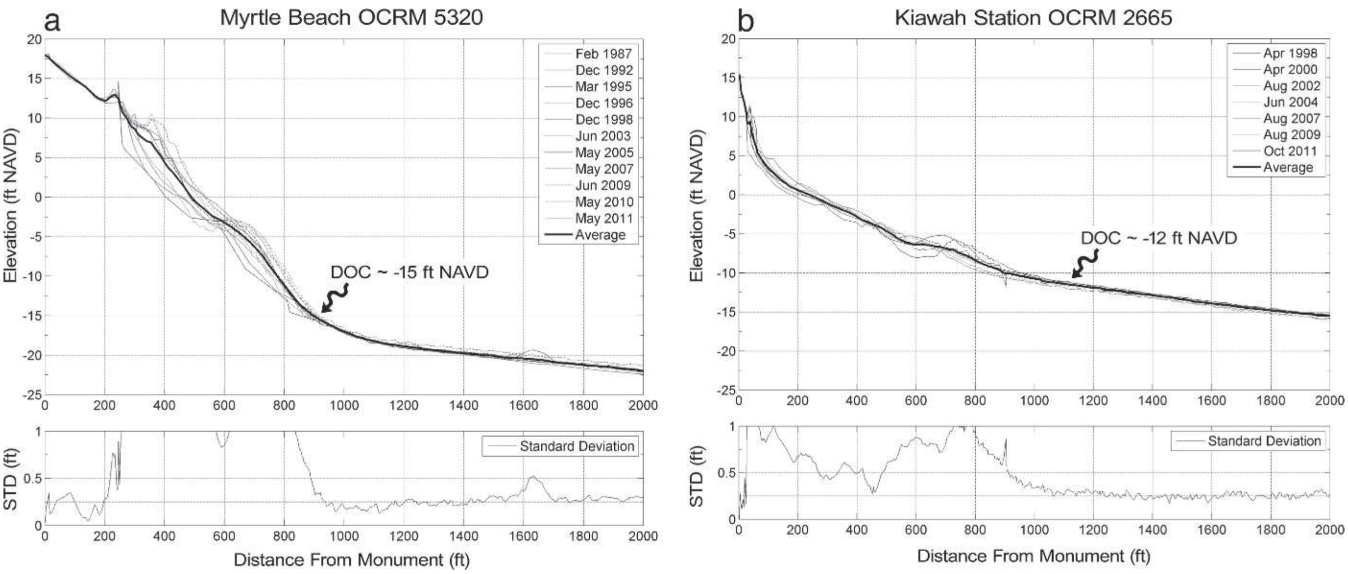

Figure 4. Comparative profiles for Myrtle Beach and Kiawah Island and standard deviation of change indicating DOC at ~15 ft (~4.6 m) NAVD and ~12 ft (~3.7 m) NAVD, respectively.

beach changes. Comparative profiles indicate that DOC at decadal scales along Myrtle Beach is approximately –15 ft (~4.5 m) NAVD[1] (Kana, Kaczkowski, and McKee, 2011).

At Kiawah Island, monitoring has expanded from 12 wading-depth lines covering 8 mi (~13 km) in 1980 (Sexton, Hayes, and Dinnel, 1981) to 87 deepwater lines since 2006. These data indicate the decadal DOC is around –10–12 ft (–3–3.6 m) NAVD (CSE, 2011a). DOC for Hunting Island (near the south end of the coast) is similarly estimated to be in the range –11–12 ft NAVD on the basis of two decades of monitoring (Traynum, Kana, and Simms, 2010). By comparison, DOC at Duck (North Carolina), 250 mi (410 km) north of Myrtle Beach, is estimated via comparative profiles to be much deeper, in the range 25–29 ft (7.6–8.8 m) NAVD (Birkemeier, 1985).

Shallow DOC in South Carolina reflects lower wave energy and a broader continental shelf than neighboring North Carolina. The common presence of surficial mud in shallow nearshore areas lends further support to the DOC estimates. Mud deposits are extensive off the South Carolina coast in water depths <20 ft (~6 m) NAVD (CSE, 2008a; Van Dolah *et al.,* 1993). On the basis of these results, it is reasonable to assume the principal zone of littoral sand volume change at decadal scales along the South Carolina coast is inside the –15 ft (~4.5 m) NAVD contour. Conveniently, this depth approximately equals –12 ft (~–4.2 m) mean lower low water (MLLW) in South Carolina (NOAA, 2008), a contour commonly illustrated on navigation charts. Figure 4 shows examples of comparative profiles used in evaluating DOC for South Carolina beaches. A continuous standard deviation of change approaching zero provides empirical evidence for DOC. Figure 5 illustrates a section of the central coast, highlighting the principal zone of littoral volume change at decadal scales. The key implication of this is that small-scale changes in bottom elevation seaward of the –15 ft (~–4.5 m) NAVD contour may be ignored without significantly biasing results.

Ebb-Dominant Inlets

As Figure 5 suggests, major ebb-tidal deltas are associated with many South Carolina inlets. These lobate sand bodies are estimated to contain >75% of the quality sand resources along the coast—much greater volumes than contained within the subaerial portions of barrier islands, including interior ridges (Sexton and Hayes, 1996).

Studies by Nummedal and Humphries (1978), FitzGerald (1984), and others show a strong tendency for South Carolina inlets to be ebb-dominant based on asymmetries of the tide at each entrance. This has important implications for beach changes because it means the budget of littoral sands is conserved with relatively little volume lost to the estuaries (Kana, 1995b). Sand circulates between ebb-tidal deltas and the adjacent beaches in complex patterns (FitzGerald, Nummedal, and Kana, 1976), but upon eroding from the beach into inlet channels, it is likely to be retained within the shoals of an ebb-tidal delta and remain within the active littoral zone (Kana, Hayter, and Work, 1999).

Sand exchange across major inlets tends to be episodic and takes the form of discrete "shoal bypassing" events (FitzGerald, 1984; Sexton and Hayes, 1982). Gaudiano and Kana (2001) presented empirical relationships between the volume and frequency of shoal bypassing and tidal prisms of nine South Carolina inlets; however, their estimates of bypassing volumes appear to be significantly lower than recent measurements for a number of events (CSE, 2011a, b). At present, the weakest link in studies of beach change along the South Carolina coast

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[1] NAVD – North American Vertical Datum of 1988, which is ~0.5 ft (~0.15 m) above local mean sea level (Source: National Oceanic and Atmospheric Administration National Ocean Service).

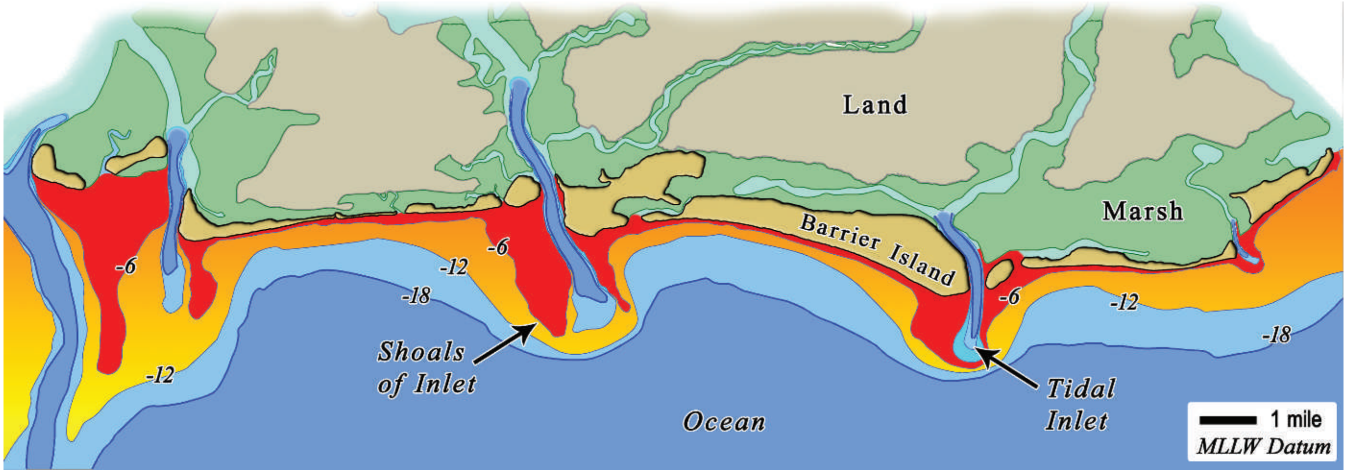

Figure 5. The principal sand bodies associated with decadal-scale beach and inlet changes along the South Carolina coast are inside the –12 ft (–3.7 m) MLLW contour ("red zone").

is the uncertainty in the timing and scales of bypassing events at inlets. CSE (2011b) has obtained high-resolution semiannual surveys of Dewees Inlet and its ebb-tidal delta since 2007 for purposes of tracking the initiation of a channel avulsion and computing the rate of growth and migration of a bypassing shoal (Figure 6). These data are providing further confirmation of the seaward limits of significant volume change for local sediment budgets.

Statewide Erosion Inventories

The first statewide beach erosion inventories were made by USACE (1971) as part of the National Shoreline Study. CRD researchers in the 1970s used historical charts, aerial photographs, and related measures of linear shoreline change to estimate 25-, 50-, and 100-year trends (*e.g.,* Hubbard *et al.,* 1977; Stephen *et al.,* 1975). Anders, Reed, and Meisburger (1990) published the most detailed database to date. Efforts continue today (*e.g.,* Barnhardt, 2009) to improve the resolution and obtain datum-based shorelines (List and Farris, 1999) using light detection and ranging (LIDAR) technology and other remote sensing. These data are used by the state to publish official erosion rates, and in a number of localities, linear measures of beach change are all that is available.

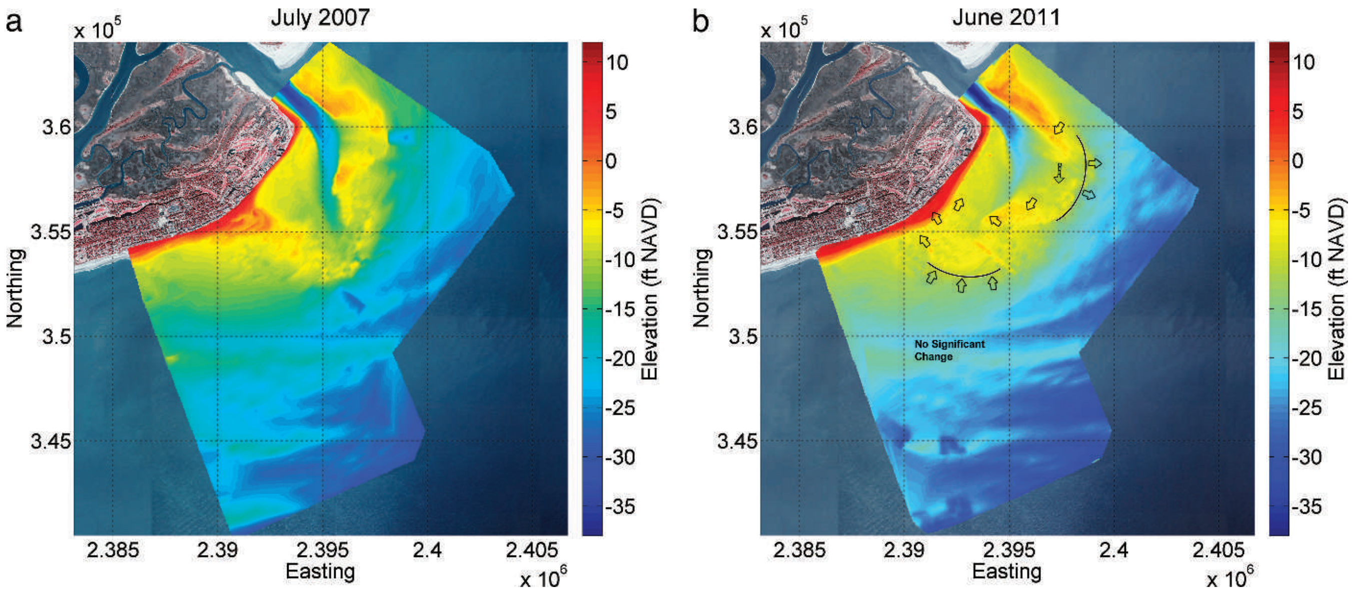

Figure 6. Yearly bathymetric surveys of Dewees Inlet (2007 to present) document channel avulsions, net sand transport (arrows), and volumes associated with shoal-bypassing events (from CSE, 2011).

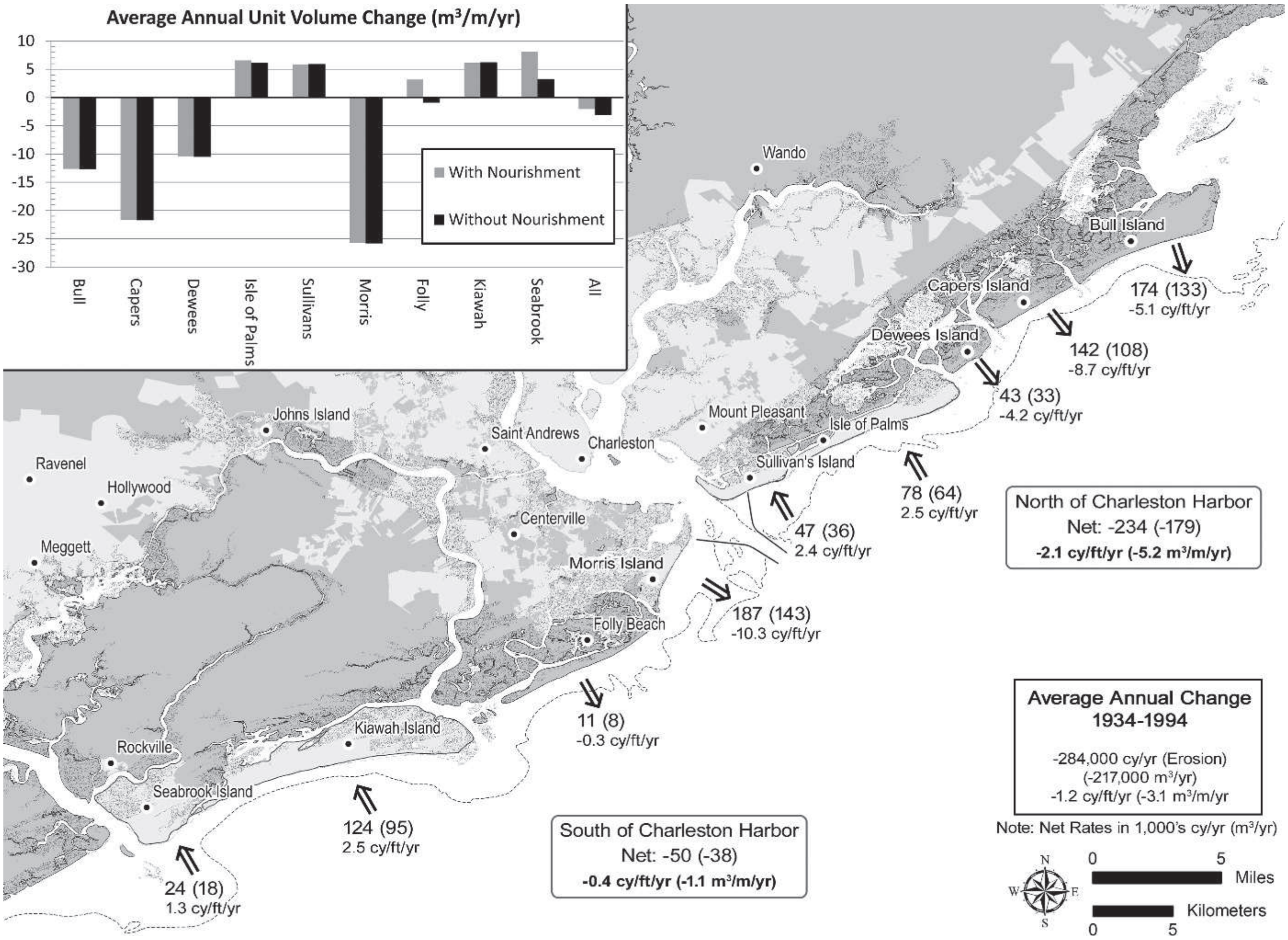

Figure 7. Average annual beach volume changes (1934–1994) for central South Carolina extrapolated from linear shoreline changes factoring out nourishment (units: yd^3/y [m^3/y] ×1000). Offshore-directed arrows are erosion (–). (After Kana and Gaudiano, 2001)

Kana and Gaudiano (2001) extrapolated linear shoreline changes (1934–1994 and various decadal periods) to volumetric measures using a defined DOC for nine central South Carolina barrier islands encompassing ~43 mi (~70 km). The results provided estimates of beach gains and losses and demonstrated that regional net volume changes for these islands (284,000 yd^3/y; 217,000 m^3/y) are relatively low, whereas results for individual islands are highly variable (Figure 7). Gayes (2003) and Barnhardt (2009) similarly reported net average annual volume changes of only ~130,000 yd^3/y (100,000 m^3/y) (accretion) along South Carolina's northeastern coast encompassing ~45 mi (~70 km) of developed shoreline.

In both cases, the net regional volume change reduces to magnitudes of 0.5–1.2 yd^3/ft per year (equivalent to about 1–3 m^3/m per year) with some decadal periods yielding net accretion and others net erosion. The relatively low magnitudes involved (on a regional basis) and alternating signs (+ accretion, – erosion), depending on the time period selected, probably reflect a normal range of error in the underlying data and extrapolations rather than decadal weather and wave climate variations. Importantly, regional results suggest littoral sands are being recycled within many beach inlet systems of South Carolina rather than lost at high rates to lagoons or downcoast areas.

Major Anthropogenic Impacts

There have been five principal types of anthropogenic impacts to South Carolina beach volumes in the past century:

(1) Major harbor jetties (4)—Charleston Entrance (*ca*. 1895), Winyah Bay (ca. 1898), Murrells Inlet (1977), Little River Inlet (1980)—Winyah Bay jetties are situated 10 mi (~16 km) south of the nearest development. The other three jetty systems are flanked by developed beaches. Each jetty incorporates a weir to allow sand impoundment in an interior deposition basin and to facilitate maintenance dredging.

(2) Seawalls (including low bulkheads and revetments)—The Office of Ocean and Coastal Resources Management (OCRM, 2010) estimates that 933 out of 3850 (24%) beachfront habitable structures are fronted by some type of shore-parallel erosion

control structure. An unknown but significant proportion of these structures is presently buried. On the basis that ~50% of the beachfront is undeveloped, it is likely that less than ~15% (~28 mi, ~46 km) has shoreline armoring. Nearly all seawalls were constructed between the 1950s (partly in response to erosion associated with Hurricane *Hazel*, the Grand Strand storm of record in 1954) and the early 1980s. New seawalls were banned in South Carolina with passage of the Beach Management Act in 1988 (OCRM, 2010). The present distribution of exposed seawalls in the active beach zone will be discussed later in the paper for a number of shoreline segments.

(3) Groins—South Carolina has an estimated 165 groins (OCRM, 2010), with >75% concentrated along four barrier islands (north to south): Pawleys Island (24), Folly Beach (42), Edisto Beach (34), and Hilton Head Island (25). These four groin fields stabilize ~15 mi (25 km) of ocean coast—about 8% of all South Carolina beaches. Typical groin spacing is 600 ft (~180 m). Most groins were constructed in the 1950s and 1960s, and originally consisted of pile-supported timber sheeting. As the wood deteriorated and functionality declined, quarry stone was added, followed by grouting in some cases to create less permeable, monolithic structures (Kana, White, McKee, 2004). Terminal groins stabilize certain shorelines near inlets to retain sand along the ocean beach and, in some cases, prevent the downcoast migration of channels, including Midway Inlet (Pawleys Island), Pawleys Inlet (Debidue Island), Dewees Inlet (Isle of Palms), Breach Inlet (Sullivan's Island), Lighthouse Inlet (Folly Beach), and Port Royal Sound (Hilton Head Island). An estimated 25% of the groins are completely buried, and another 15% are barely exposed or have deteriorated to the point of being nonfunctional at present.

(4) Inlet dredging—The major navigation channel dredging is concentrated at the four jettied inlets. Jetty lengths and associated channel depths relative to MLLW (Charleston Entrance at 47 ft [14.3 m], Winyah Bay Entrance at 27 ft [8.2 m], Little River Inlet at 12 ft [3.7 m], and Murrells Inlet at 10 ft [3.0 m]) generally preclude natural bypassing at those locations. Folly River (mouth of Stono Inlet) and Port Royal Sound (Hilton Head Island) are the only other localities where significant channel dredging has occurred in the past century (USACE, unpublished project records).

(5) Beach nourishment—A total of 44.1 million yd^3 (~33.7 million m^3) of nourishment material from external sources have been placed along 62.6 discrete miles (102.7 km) of beach between 1954 and 2010 (Kana, 2012). Since 1979, 39.4 million yd^3 (30.1 million m^3) have been placed (Table 1). More than 80% of the nourishment has involved four localities: Grand Strand beaches (Little River Inlet to Murrells Inlet ~35 mi, or ~57.4 km), Folly Beach (5.9 mi, 9.6 km), Hunting Island (3.0 mi, 4.9 km), and Hilton Head Island (9.3 mi, 15.2 km).[2] These four areas represent ~28% of the South Carolina ocean coast. Figure 8 shows the nourishment volumes by decade, with >45% of the volume placed during the 1990s. It can be shown that 1 yd^3 yields ~1 ft^2 of beach area (CERC, 1984) along many coasts. (The metric equivalent is 10 m^3 yields ~1 m^2 of beach area.) This assumes a dry-beach elevation of ~7 ft (~2 m) and a closure depth around 20 ft (~6 m) relative to mean tide level. Along South Carolina beaches where DOC is seen to be shallower, the ratio of beach area to volume-added is incrementally greater by factors ranging from ~1.2 (Myrtle Beach) to 1.6 (Hilton Head Island). Thus, beach nourishment activities along the Grand Strand (~13.4 million yd^3, 10.2 million m^3) have added the equivalent of ~16 million ft^2 (~370 acres, 150 ha). Along Hilton Head Island, where the ratio is higher, ~11 million yd^3 (8.4 million m^3) have added ~17.5 million ft^2 (~400 acres, ~160 ha) since 1969. Obviously, beach area additions from nourishment are offset to varying degrees by erosion of the fill. The effect of nourishment on the observed beach changes is discussed later in the paper for each shoreline segment.

Other anthropogenic effects that are considered to have played a minor or negligible role in the decadal-scale beach changes include ~11 ocean piers, numerous storm water outfalls, short-lived emergency sand bags, and a small number of pile-supported buildings encroaching at various times on the active beach.

SEA LEVEL RISE

Long-term tide gauge records exist for Charleston Harbor, and raw sea-level data are archived with the Permanent Service for Mean Sea Level housed within the National Oceanography Centre in Liverpool (U.K.). Based on these data (1920–2012 period), the century trend for the central South Carolina coast is a mean sea level rise (SLR) averaging ~0.12 in/y (3.12 mm/y). This is equivalent to 1.02 ft/century (0.31 m/century). During the period of interest herein (~1980–2010), local SLR has totaled 3.46 in (~88 mm) in Charleston Harbor (Table 2).

Shoreline change in the presence of SLR without consideration of longshore and cross-shore sediment transport is related to the slope of the foreshore (Bruun, 1962; Hands, 1981). The range of equilibrium foreshore slopes along South Carolina beaches is roughly 1 on 15 (Edisto Beach) to 1 on 40 (Hilton Head Island), with a majority of beaches around 1 on 25 (Brown, 1977). During the period 1980–2010, the observed SLR (assumed here to be 3.46 in [~88 mm] statewide) potentially accounts for inundation (landward transgression of the mean tide level along the beach) in the range of 4.1–11.5 ft (~1.3–3.5 m) for the given beach slopes.

On an annualized basis, the shoreline change due to local SLR is in the range 0.14–0.38 ft/y (0.044–0.117 m/y). Applied over the ~100 mi (~165 km) of developed beaches in the state, average SLR inundation yields potential beach area loss over 30 years totaling roughly 4 million ft^2 (~100 acres, ~40 ha). As demonstrated in the previous section, 4 million ft^2 of beach loss equates to roughly 3 million yd^3 of profile volume loss (~100,000 yd^3/y over 30 years). (The metric equivalents are 0.4 million m^2, 2.3 million m^3, and 75,000 m^3/y, respectively.) On an annual unit volume basis, this equates to losses of ~0.2 yd^3/ft per year (~0.5 m^3/m per year). Considering that most South Carolina beaches experience much greater magnitude changes from year to year (OCRM, 2010), it is reasonable to conclude that SLR is a minor factor in the observed beach volume changes.

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[2] Lengths reference placement limits, not island lengths.

Table 1. *South Carolina beach nourishment events by locality (north–south) ~1980–2010. Shore lengths are maximum extents of all projects by locality. Beach area to volume ratio is based on estimated local DOC. (Data sources—project records of USACE–Charleston District, SCDHEC-OCRM, Coastal Science & Engineering Inc., Olsen Associates, and Applied Technology & Management; Kana 2012).*

Segment	Locality (No. of Nour. Events)	Shore Length (ft)	By Segment (%)	Nour. Vol. (yd^3)	Beach Area to Volume Ratio	Equivalent Area (ft^2)	Equivalent Area (acres)	Unit Nour. Vol. (yd^3/ft)	Annualized Unit Vol. (yd^3/ft per year)
1	Waties Island (1)	6500	3.5	513,000	1.2	615,600	14.1	78.9	2.6
	North Myrtle Beach (3)	45,400	24.6	3,902,549	1.2	4,683,059	107.5	86.0	2.9
	Arcadian Shores (2)	6400	3.5	777,574	1.2	933,089	21.4	121.5	4.0
	Myrtle Beach (4)	48,780	26.4	4,997,201	1.2	5,996,641	137.7	102.4	3.4
	Garden City–Surfside (5)	40,650	22.0	3,242,124	1.2	3,890,549	89.3	79.8	2.7
	Unnourished areas	*37,070*	*20.1*	—	1.2	—			—
	Grand Strand total (15)	**184,800**	**100.0**	**13,432,448**	**1.2**	**16,118,938**	**370.0**	**72.7**	2.4
2	Huntington Beach (3)	10,000	7.6	1,346,176	1.3	1,750,029	40.2	134.6	4.5
	Pawleys Island (2)	16,200	12.3	490,000	1.3	637,000	14.6	30.2	1.0
	Debidue Beach (3)	8500	6.4	1,044,079	1.3	1,357,303	31.2	122.8	4.1
	Unnourished areas	*97,300*	*73.7*	—	1.3	—			—
	Total (8)	**132,000**	**100.0**	**2,880,255**	**1.3**	**3,744,332**	**86.0**	**21.8**	0.7
3	*Unnourished areas*	*158,400*	*100.0*	—	1.3	—	—	—	—
4	Isle of Palms (2)	10,200	*9.2*	1,283,895	1.6	2,054,232	47.2	125.9	4.2
	Unnourished areas	*100,680*	*90.8*	—	1.5	—	—	—	—
	Total (2)	**110,880**	***100.0***	**1,283,895**	**1.5**	**1,925,843**	**44.2**	**11.6**	0.4
5	Folly Beach (3)	28,880	*23.8*	5,577,200	1.5	8,365,800	192.1	193.1	6.4
	Folly Beach Park (11)	2000	*1.6*	707,095	1.5	1,060,643	24.3	353.5	11.8
	Seabrook Island (1)	5850	*4.8*	684,474	1.2	821,369	18.9	117.0	3.9
	Unnourished areas	*84,710*	*69.8*	—	1.5	—	—	—	—
	Total (15)	**121,440**	***100.0***	**6,968,769**	**1.5**	**10,453,154**	**240.0**	**57.4**	1.9
6	Edisto Beach (3)	18,258	*13.8*	1,026,061	1.4	1,436,485	33.0	56.2	1.9
	Hunting Island (5)	15,700	*11.9*	3,131,681	1.5	4,697,522	107.8	199.5	6.6
	Unnourished areas	*98,042*	*74.3*	—	1.5	—	—	—	—
	Total (8)	**132,000**	***100.0***	**4,157,742**	**1.5**	**6,236,613**	**143.2**	**31.5**	1.0
7	Hilton Head Island (4)	45,500	30.8	8,995,900	1.6	14,393,440	330.4	197.7	6.6
	Hilton Head–Sea Pines (1)	3400	2.3	245,000	1.6	392,000	9.0	72.1	2.4
	Daufuskie (1)	18,500	12.5	1,410,000	1.6	2,256,000	51.8	76.2	2.5
	Unnourished areas	*80,440*	*54.4*	—	1.6	—	—	—	—
	Total (6)	**147,840**	**100.0**	**10,650,900**	**1.6**	**17,041,440**	**391.2**	**72.0**	2.4
All	Nourishment events (54)	330,718	33.5	39,374,009	1.4	55,520,318	1274.6	119.1	4.0
	Unnourished areas	656,642	66.5	—		—	—	—	—
	State total length (ft)	**987,360**	**100.0**	**39,374,009**	**1.4**	**55,520,318**	**1274.6**	**39.9**	**1.3**

Nour. = nourishment, Vol. = volume.

METHODOLOGY AND DATA PRESENTATION

Statewide volume change data are not available for decadal periods. However, certain site-specific measurements span long periods and can be combined with linear shoreline change data, geomorphic indicators of net sand transport, and historical photos to estimate volume change and assess the beach condition. In the following sections, each segment of the South Carolina coast is described in terms of its primary sand transport pathways, beach nourishment, measured volume change rate (as available) and related evidence of erosion or accretion. Key events such as record storms are referenced.

Decadal databases, available for certain sites, are used to quantify and illustrate certain signatures of beach volume change. Unit volume changes are reported to the extent possible for each area to facilitate comparisons. Applicable nourishment volumes are given as aggregate quantities so as to provide a convenient check on documented amounts, which are typically reported in cubic yards. Fill densities (average volume

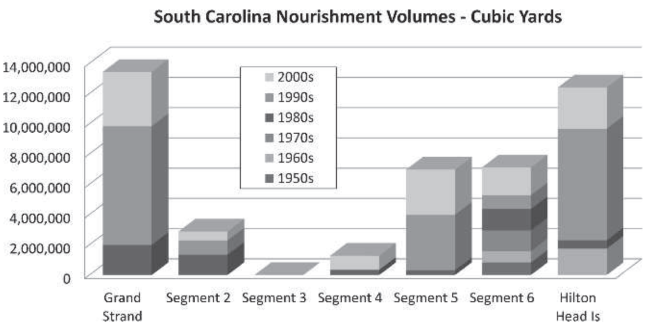

Figure 8. South Carolina beach nourishment volumes by decade and shoreline segment. See Table 1.

Table 2. *Rates of mean sea level (MSL) rise in various decadal periods for Charleston Harbor based on archived monthly mean water levels (data source: National Oceanography Centre, Liverpool, U.K.).*

Period	MSL (mm/y)
1920–2012	3.12
1950–2012	2.88
1980–2012	2.94
1990–2012	1.63
2000–2012	3.55

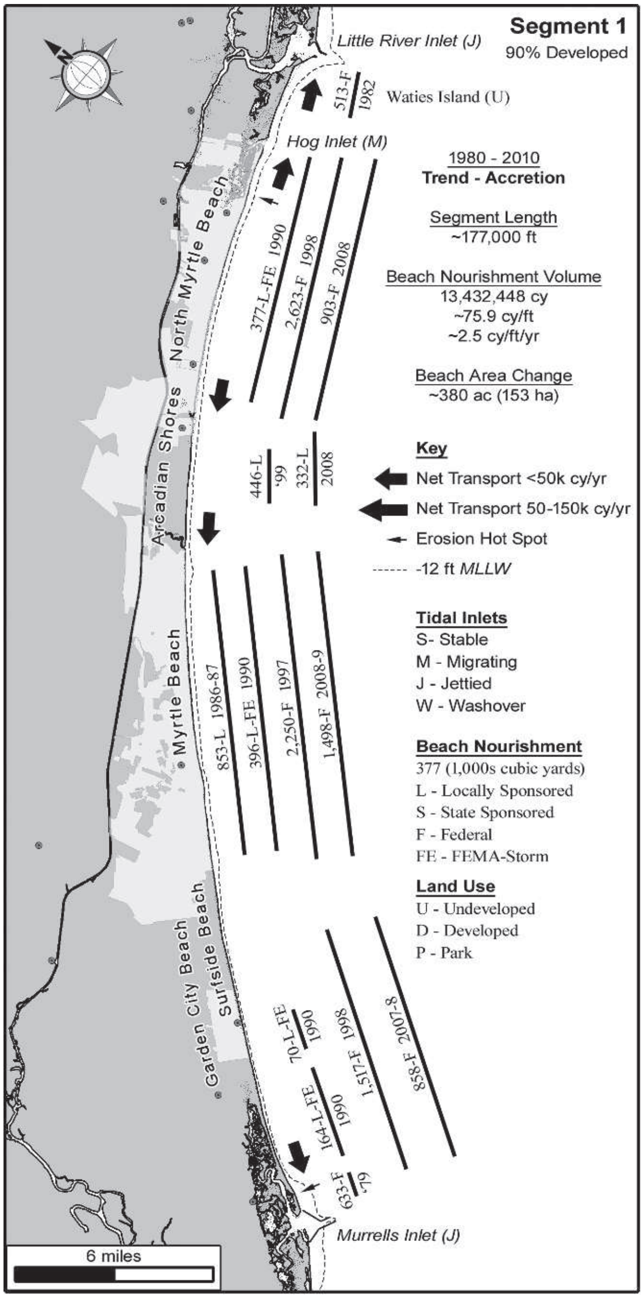

Figure 9. Segment 1—Beach condition changes, principal sand transport directions, and beach nourishment events along the Grand Strand (1980–2010).

per unit beach length) are based on the maximum project length (multiple nourishments) at a site unless otherwise noted.

Qualitative references to low, moderate, or high rates of change (per year) should be interpreted as <2 yd^3/ft (5 m^3/m), 2–6 yd^3/ft (5–15 m^3/m), and >6 yd^3/ft (15 m^3/m), respectively. For additional information on volume calculation methods utilized for many South Carolina beaches, see Bodge, Olsen, and Creed (1993); Gayes *et al*. (2001); Kana (1993); McCoy *et al*. (2010); and Olsen Associates (1999).

Seven shoreline segments are referenced herein (see Figure 1):

(1) Little River Inlet to Murrells Inlet–strand resort beach–the "Grand Strand"
(2) Huntington Beach to North Island–barrier island–strand beach
(3) Winyah Bay to Bulls Bay–wilderness barrier islands–cape foreland and Santee River delta system
(4) Bull Island to Charleston Harbor–beach-ridge barrier islands (5)
(5) Morris Island to North Edisto River Inlet–beach-ridge barrier islands (4)
(6) Botany Bay Island to Fripp Island–beach ridge and washover barrier islands and St. Helena Sound
(7) Pritchards Island to Savannah River Entrance–beach ridge and washover barrier islands and Port Royal Sound

Hayes and Michel (2008) provide a comprehensive description of the South Carolina geologic setting, long-term barrier island evolution, inlet history, and coastal ecology.

The general azimuth of the coast is NE–SW, parallel to the two principal wind directions; however, local shoreline orientations range from N–S to E–W with implications for net sediment transport directions. Net transport is generally to the SW, but numerous drift reversals are associated with wave transformation and sheltering around ebb-tidal deltas and harbor entrances. For information on wave climatology, see Volugaris *et al*. (2008).

Beach Changes ~1980–2010

Segment 1—Little River to Murrells Inlet

The northernmost segment is a densely developed, ~35-mi-long (~57.4-km) arcuate strand shoreline with one intermediate tidal inlet (Hog Inlet) 1.2 mi (2 km) from the northern boundary (Figure 9). The Grand Strand is characterized by low erosion rates and low net longshore transport. Wind and wave energy are bimodal, with northerly components slightly dominant. Geomorphic indicators (spit growth) show net transport is NE at Hog Inlet for the 1980–2010 period, during which time the Little River jetties were in place. Minor swashes (inlets draining interior tidal wetlands) between North Myrtle Beach and Myrtle Beach show net southerly deflection, but transport rates are estimated to be well below 50,000 yd^3/y (~38,000 m^3/y) given the general stability of the segment and the relative uniformity of volume changes over the length of the strand.

Spit growth and minor shoaling in Murrells Inlet confirm southerly transport prevails at the south end of the Grand Strand. However, net longshore transport is low given the lack of maintenance dredging in the channel since 1988 (USACE, unpublished records). A former inlet position in the early 1900s ~0.6 mi (1 km) updrift of present Murrells Inlet left a bulge in the shoreline—"salient"—associated with an abandoned ebb-tidal delta. This area experienced focused erosion as the delta shoals were depleted (Kana, 1995a) and led to construction in the 1960s of four groins and seawalls to stabilize the "erosion

Figure 10. Murrells Inlet and Garden City looking north in 1987. Collapsed shoals of a former inlet from the early 1900s produced a salient (arrow) which has been a focal point of erosion and shore protection measures during the past 50 years.

hot spot" (Figure 10). The Murrells Inlet jetties further stabilized "Garden City" spit in 1977 (Douglass, 1987).

By 1980, nearly all of the Grand Strand was intensively developed. (Waties Island is a private conservation area with no development.) Seawalls were in place along ~50% of the reach by 1980, and a majority of these localities lacked a dry-sand beach at the time.

Fifteen beach nourishment events have occurred since ~1980, with a total of ~13.4 million yd^3(10.2 million m^3) added from external sources (see Table 1). The bulk of the projects are associated with the 50-year USACE beach nourishment and hurricane protection plan (USACE, 1993) and early disposal projects associated with jetty construction at Little River Inlet and Murrells Inlet (Chasten, 1992; Douglass, 1987). There has been no artificial bypassing at Little River Inlet since 1982 and only one event (1988) at Murrells Inlet, lending further support to the observation of low net sand transport rates along the Grand Strand. The average nourishment density for the entire reach has been ~72.5 yd^3/ft (~181 m^3/m) over the 30-year period of interest.

Myrtle Beach, a 9-mi (14.7-km) reach in the central Grand Strand, offers the most detailed database. This beach has been nourished four times (see Figure 9) and received 5.0 million yd^3 (3.82 million m^3), which is an average fill density of ~105 yd^3/ft (~263 m^3/m). Figure 11 shows the average unit volume to low-tide wading depth for key dates back to Hurricane *Hazel* (1954), the storm of record. The results show gains from nourishment and losses between nourishment events averaging ~0.65 yd^3/ft per year (~1.63 m^3/m per year). The net change since ~1980 is an average gain of ~60 yd^3/ft (150 m^3/m). Kana, Katmarian, and McKee (1997) showed that the volume changes along the beach to low-tide wading depth are ~60% of the net volume change to the estimated DOC at the site. Therefore, the decadal background loss rate along Myrtle Beach is estimated to be ~1.15 yd^3/ft per year (~2.9 m^3/m per year) (Kana, Kaczkowski, and McKee, 2011). SLR is assumed to account for 0.2 yd^3/ft per year (0.5 m^3/m per year) or ~15%–20% of the background loss rate since 1980. The balance of losses is attributed to longshore advection into adjacent unnourished sections of the Grand Strand (see Figure 9).

Figure 12 illustrates the ~30-year change at one locality along Myrtle Beach. Although the conditions in Figure 12 are representative of most of the Grand Strand, several erosion hot spots persist, including "Cherry Grove" (North Myrtle Beach) and portions of Garden City, both of which are sites of former inlets. Nourishment has buried nearly all seawalls, incorporating a vegetated berm along the back beach. The principal storms of the past 30 years were Hurricane *Hugo* (September 1989) and the March 1993 northeaster (Kana, Katmarian, and McKee, 1997). The overall condition of Grand Strand beaches was better in 2010 than 1980, with additional beach/dune area.

London *et al*. (2009), utilizing comparative aerial imagery to calculate "beachfront area" changes, reported a net gain of

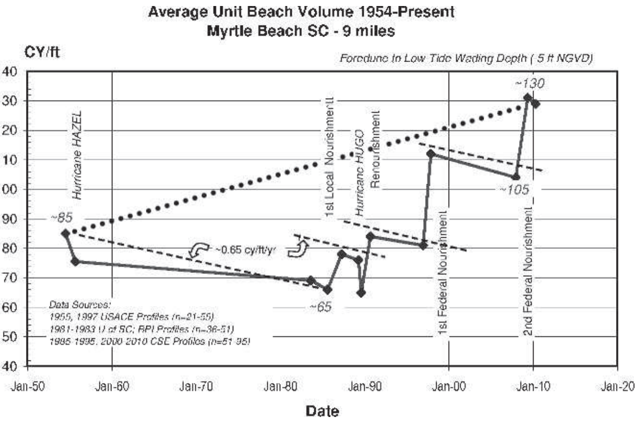

Figure 11. Average unit volume changes along Myrtle Beach to –5 ft NGVD (~6 ft NAVD) for key dates showing the background erosion losses (~0.65 yd^3/ft per year, ~1.6 m^3/m per year) combined with nourishment additions, yielding a net long-term growth of the beach. (NGVD is the National Geodetic Vertical Datum of 1929, which is ~0.98 ft below NAVD along the South Carolina coast.)

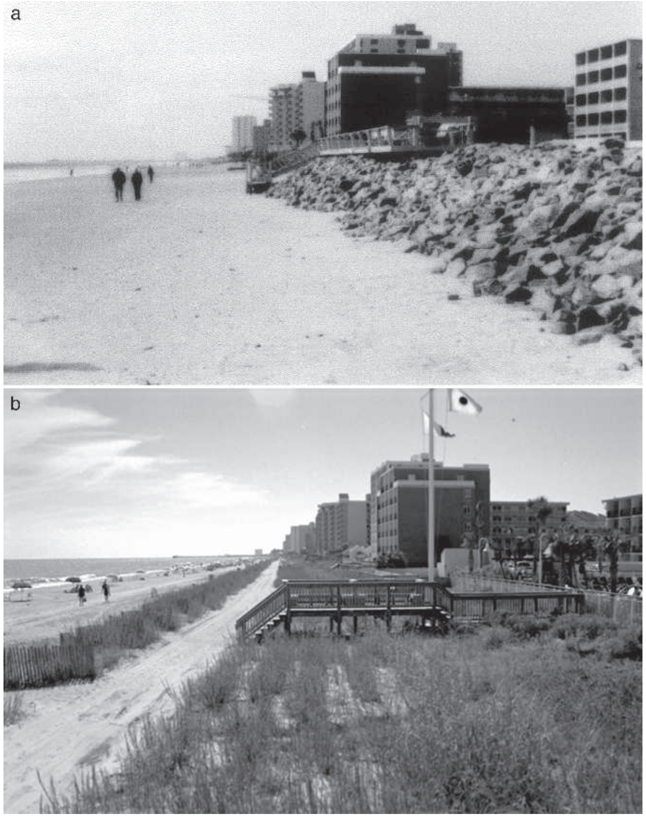

Figure 12. Conditions at 17th Avenue South (Myrtle Beach) at low tide in 1985 (a) and high tide in 2001 (b). There was no high-tide beach in 1985.

~286.8 acres (~115 ha) of beach area in Segment 1 (Grand Strand) between 1987 and 2006. Federal nourishment in 2007–2008 placed an additional ~3.6 million yd^3 (2.7 million m^3), which is the equivalent of ~100 acres (40 ha) more beach area. Combining these estimates yields an average change in beach width (structure setback) of ~90 ft (27.5 m) for the Grand Strand for the period 1980–2010. Although this has not been verified independently, empirical evidence suggests it is a realistic approximation, as the photos in Figure 12 suggest.

Segment 2—Huntington Beach to North Island

Segment 2 is a 25-mi-long (41-km) arcuate strand shoreline that includes two barrier islands (Pawleys Island and North Island) and mainland-attached barrier spits (Huntington Beach, Cape Litchfield, and Debidue Island) (Figure 13). It is anchored at each end by jetties and is ~50% developed. Litchfield Beach at the north end of the segment is one of the most stable sections of coast, showing little change over the past century, even in the aftermath of Hurricane *Hugo* (Anders, Reed, and Meisburger, 1990; Stauble *et al.,* 1990).

Pawleys Island, a 3.5-mi-long (5.7-km) narrow, beach-ridge barrier island, is bounded by shallow, migratory inlets confirming net southerly transport. Terminal groins at the north end of Pawleys Island and Debidue Beach limit the southward excursion of Midway Inlet and Pawleys Inlet, respectively. Ebb-tidal delta volumes are small in each case (an order of 1.3 million yd^3, 1 million m^3), and the channels are wadeable at low tide. Sand bypassing freely occurs (Gaudiano and Kana, 2001). Like the Grand Strand, century erosion rates along Pawleys Island are low (Hubbard *et al.,* 1977), but a field of groins was constructed in the 1950s to further stabilize the beach. The 200-ft-wide (60-m) spit at the south end is the only developed segment of the South Carolina coast to breach during a hurricane in the past 50 years. A channel was cut by Hurricane *Hugo* and was closed artificially soon after the storm.

Debidue Beach receives sand from Pawleys Island and shows a signature of moderate accretion at the north end and high erosion at the south end. North Inlet is a large, positionally stable inlet with an extensive ebb-tidal delta and small flood-tidal delta (Nummedal and Humphries, 1978). A former inlet (*ca.* 1900s) discharged ~1.1 mi (1.8 km) updrift of present-day North Inlet (Zarillo, Ward, and Hayes, 1985). Upon abandonment (probably in the 1920s), its delta shoals left a salient which has been a focal point of erosion much like the south end of Garden City Beach (see Figures 2, upper, and 10). Long-term erosion rates in the area of the abandoned inlet are upward of 15 ft/y (~15 m/y). Decadal volume changes (CSE Baird, 1999) indicate the northern one-third of Debidue Beach has been accreting at ~2.5 yd^3/ft per year (6.3 m^3/m per year), whereas

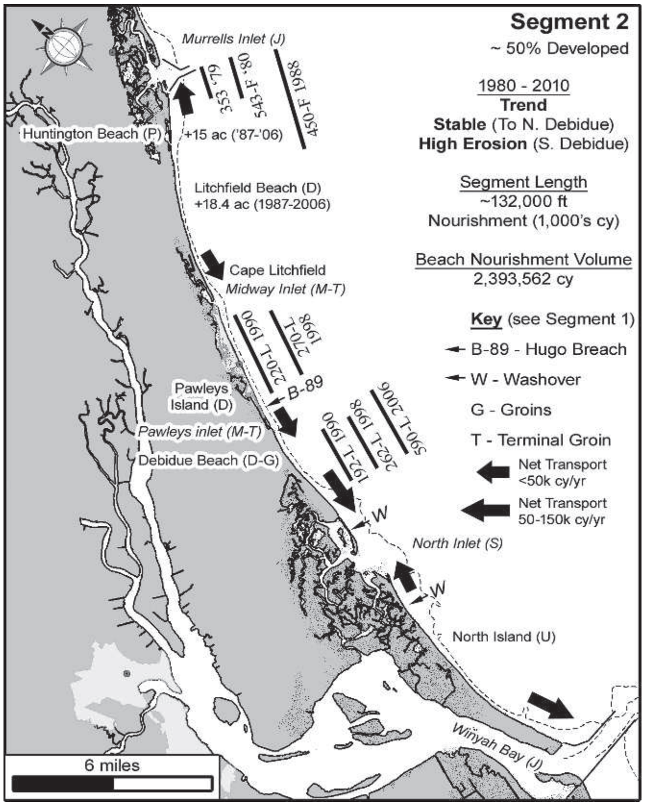

Figure 13. Segment 2—Beach condition changes, principal sand transport pathways, and beach nourishment events (1980–2010).

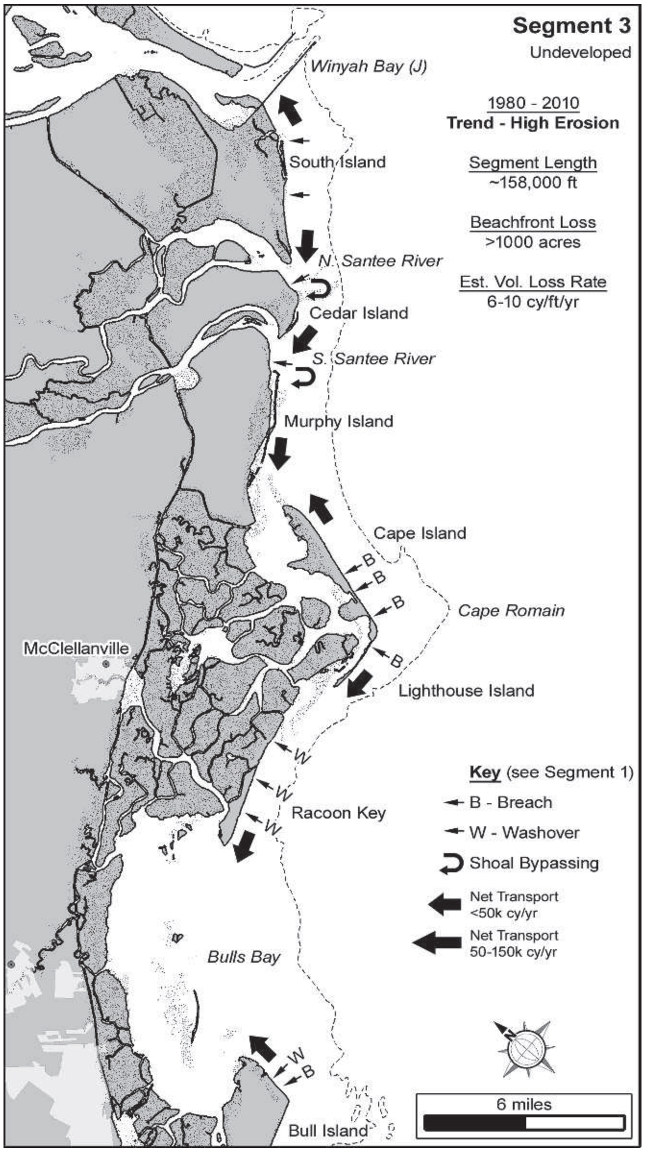

Figure 14. Segment 3—Beach condition changes, principal sand transport pathways, and breach inlet formation (1980–2010).

the salient at the south end has been losing $\sim$8–10 yd^3/ft per year ($\sim$20–25 m^3/m per year). The transition zone from accretion to erosion splits a developed portion of the beach. Various shore protection measures have been implemented, including two downcoast groins (1969), which deteriorated by 1980 and are now nonfunctional; construction of a 4500-ft-long ($\sim$1,375-m) timber bulkhead in 1981; and beach nourishment from external sources in three events totaling 1.04 million yd^3 ($\sim$798,200 m^3).

The remainder of the segment consists of a 7.6-mi-long (12.5-km) arcuate beach ridge barrier island (North Island) with marked evidence of drift reversals at the north end in the lee of North Inlet and a stable fillet at the south end (Winyah Bay jetty). The central section of the island is stable, whereas an $\sim$1-mi-long ($\sim$1.6-km) section 1.5 mi ($\sim$2.5 km) downdrift of North Inlet is a focal point of erosion. The signature of erosion for the erosion hot spot indicates net losses are due to a combination of divergent transport to the north (updrift), to the south (downdrift), and into the marsh via overwash during the past 30 years.

Beach nourishment (disposal of navigation channel sediment) was placed along Huntington Beach in three events (1979–1988), adding 1.35 million yd^3 (1.03 million m^3) in connection with Murrells Inlet construction and maintenance (Douglass, 1987). Since then, there has been no bypassing, and the beaches to the south have remained stable. Nourishment at Pawleys Island has taken the form of recycling sand by land-based equipment from the accretion zones and channel shoals at either end of the island and placing it within the field of groins (1990 after *Hugo* and 1998 in connection with groin repairs; Kana, White, and McKee, 2004).

The overall condition of the shoreline segment has remained essentially unchanged since 1980 from Huntington Beach to north Debidue Beach. Foredunes along Litchfield Beach and North Debidue Beach remain among the highest in the state at >20 ft NAVD ($\sim$6 m NAVD). The south end of Debidue Beach has had one of the highest volumetric loss rates along a developed section of South Carolina despite three nourishment events (1990, 1998, 2006) that added a high density of 123.2 yd^3/ft ($\sim$308 m^3/m) along 1.6 mi (2.6 km). A bulkhead at the south end of the development remains an erosion hot spot because nourishment sand is drawn off rapidly by high erosion in the salient to the south.

Segment 3—Winyah Bay to Bulls Bay

Segment 3 is an undeveloped, 30-mi-long (49.2-km) delta and cape foreland coast (Figure 14) with six major inlets, including the North and South Santee Rivers, four minor inlets, highly transgressive Cape Romain (one of the Carolina capes along with Hatteras, Lookout, and Fear), and Bulls Bay, the largest embayment of open water along the coast ($\sim$8 × 4 mi, 13 × 6.5 km).

No volumetric erosion data are available for this part of the coast given its restricted access and lack of surveys. The authors used historical aerial photography from various sources (including South Carolina Department of Natural Resources, CSE, and Google Earth) to estimate rates of shoreline change and Hayes and Michel (2008) to assess generally conditions in Segment 3. Fully 80% of the ocean beaches are transgressive washover barriers, with the primary accretion zones limited to recurved spits on the northern sides of the two Santee River inlets and the ends of Cape Island and Lighthouse Island.

For some decades before the early 1980s, Cape Island and Lighthouse Island were joined, forming a contiguous cuspate foreland in the shape of an arrowhead. Net sand transport is north along the northern arm and west along the "south" half of the Lighthouse Island arm of the cape (see Figure 14). Between 1989 and 2010, Cape Island retreated >40 ft/y ($\sim$12 m/y) and extended north >2800 ft ($\sim$850 m). The net transport rate based on spit accretion is on the order of $\sim$40,000 yd^3/y ($\sim$30,000 m^3/y) over the past couple of decades. With a

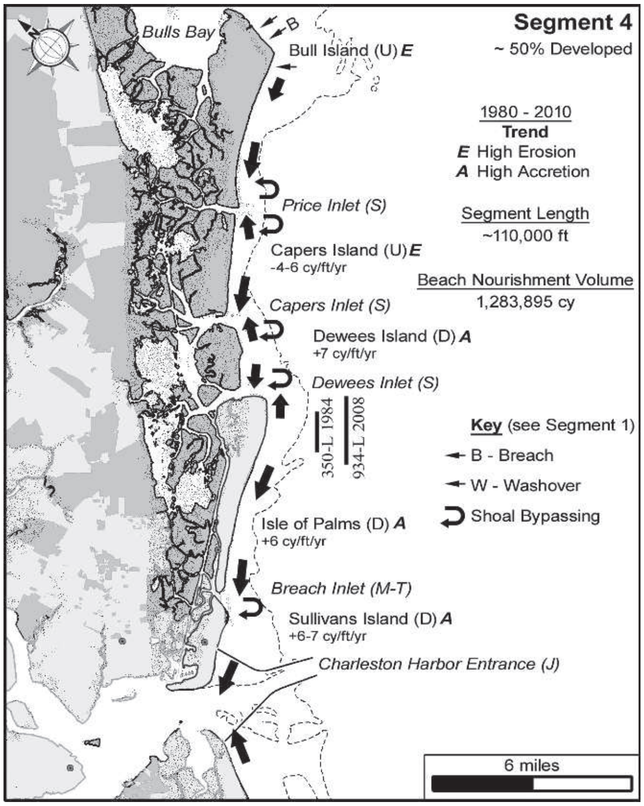

Figure 15. Segment 4—Beach condition changes, principal sand transport pathways, and shoal-bypassing areas (1980–2010).

divergence of sand transport away from the cape and little new sand entering the system from offshore (Ruby, 1981), Cape Romain is disintegrating.

Recent aerial imagery indicates that, around 2010, there were at least four breach inlets into the interior lagoon and extensive outcrops of marsh mud along the intertidal zone of Cape Island. Beaches consist of a thin lens of sand (or shelly sands in some areas) overwashing tidal marsh. Lack of new sand combined with exposure of underlying mud deposits exacerbates erosion in two ways. First, erosion accelerates once a beach goes into washover mode because some portion of the littoral volume is lost to the lagoon (see Figure 2). Second, the sediments that become exposed on the retreating beach consist of high percentages of mud. Continual winnowing of fine-grained material further undermines the profile, increasing the rate of shoreline recession and volume loss.

Some beaches in this shoreline segment (*e.g.,* Raccoon Key) are largely composed of *Crassostrea virginica* (common oyster) shells left as a lag deposit after winnowing of marsh muds. High erosion in the Cape Romain area has also adversely affected sea turtle nesting, forcing conservation officials to relocate sea turtle eggs to higher ground for incubation and release (source: South Carolina Department of Natural Resources, unpublished data).

Land loss in the Winyah Bay to Bulls Bay segment is estimated to be >1000 acres (>400 ha) since 1980 (London *et al.,* 2009; this study). This equates to average annual shoreline recession of roughly 10 ft/y (3 m/y). An equivalent volume loss rate is ∼8 yd^3/ft per year (∼20 m^3/m per year) over the past three decades. See Kjerfve and Magill (1990) and Hayes and Michel (2008) for a summary of anthropogenic impacts on the Santee River system and its sediment supply over the past century.

Segment 4—Bull Island to Charleston Harbor

Segment 4 is a 21-mi-long (34.4-km) barrier island reach with five beach-ridge barrier islands, three naturally stable inlets (drowned coastal plain paleochannels at Price, Capers, and Dewees), and one migrating shallow inlet (Breach Inlet) anchored downcoast by groins (Figure 15). This segment includes two of the best examples of drumstick barrier islands in the world (Bulls Island and Isle of Palms, see Figure 3). Sand supply has been plentiful along this segment, with each island exhibiting multiple interior ridges heavily vegetated with climax forest species, confirming century trends of accretion; 50% of the segment is developed.

The stable inlets are ebb-dominant and maintain large ebb-tidal deltas containing ∼6–16 million yd^3 (∼4.5–12.0 million m^3) (FitzGerald, 1984; Gaudiano and Kana, 2001). Wave sheltering by the deltas and episodic bypassing have led to the drumstick shape, large downcoast offsets of the strandline, and sediment transport reversals in the lee of each delta. As Figure 7 illustrates, Bull Island and Capers Island (both undeveloped) have been net exporters of sand from the beach for various decades since 1934. During one decade spanning 1983–1994, the two islands lost ∼265,000 yd^3/y (∼202,000 m^3/y), which equates to ∼5.2 yd^3/ft per year (∼13 m^3/m per year) (Kana and Gaudiano, 2001).

Dewees Island (∼1.9 mi long, 3.1 km) had one of the highest erosion rates along the South Carolina coast over the past century (Stephen *et al.,* 1975). Shoreline recession through the late 1970s was upward of 20 ft/y (∼6 m/y). Since 1980, Dewees Island has gained 200–450 ft (∼60–135 m) of beach and dunes. Average annual accretion has been roughly 10 ft/y (∼3 m/y), which equates to ∼6.7 yd^3/ft per year (∼16.7 m^3/m per year). Virtually the entire oceanfront is sheltered by the ebb-tidal delta shoals of Capers Inlet and Dewees Inlet, so DOC at yearly to decadal scales is shallow. High erosion rates before 1980 were likely due to lack of sand bypassing from Capers Inlet. Several bypassing events since 1980 appear to have been responsible for the 30-year accretion trend. London *et al.* (2009) reported 93.7 acres (37.5 ha) added along the oceanfront between 1987 and 2006.

Isle of Palms (on which the drumstick barrier island diagram of Figure 3 is based) has experienced shoal-bypassing events at 6.6 (±2.1)-year intervals (1944–1997) (Gaudiano and Kana, 2001). Recent events have been more frequent and have involved up to 500,000 yd^3 (∼380,000 m^3) (CSE, 2011b). These natural additions have created a characteristic salient near the downcoast terminus of the ebb-tidal delta about 1 mi (1.6 km) from the Dewees Inlet channel entrance. Kana and Gaudiano (2001) showed the upcoast end of Isle of Palms has experienced net losses of ∼20,000–30,000 yd^3/y (∼15,000–27,000 m^3/y),

Figure 16. Shoreline change along Sullivan's Island 1941–2008 superimposed on a 2008 image (courtesy South Carolina Department of Natural Resources).

whereas the island overall has accreted by ~200,000 yd^3/y (~150,000 m^3/y) in recent decades.

Two nourishment projects involving external sand have been completed within Segment 4 since 1980. A total of 350,000 yd^3 (268,000 m^3) (1984) and 934,000 yd^3 (~714,000 m^3) (2008) were placed along the bulbous updrift shoreline of Isle of Palms near Dewees Inlet. Postproject surveys show that ~75% of these additions spread westward to downcoast areas and ~25% shifted north along the inlet shoreline to be recycled back to the Dewees Inlet ebb-tidal delta (CSE, 2011b; Kana, Hayter, and Work, 1999). Natural bypassing volumes combined with nourishment have resulted in ~200 ft (60 m) of accretion and burial of seawalls that had become exposed in the 1980s. The estimated average annual unit volume gain along Isle of Palms has been ~6 yd^3/ft per year (15 m^3/m per year).

The healthy sand supply along Isle of Palms and net longshore transport into the Charleston Entrance Bight have produced frequent, large-scale, shoal bypassing across Breach Inlet (Gaudiano and Kana, 2001). The net result along Sullivan's Island has been decades of accretion along the ~3-mi-long (5-km) oceanfront. The easternmost ~0.6-mi (1-km) beach length on the downcoast side of Breach Inlet is armored and stabilized by six short groins to prevent further channel migration. The updrift spit overextends the entrance and periodically breaches, triggering a shoal-bypassing event. Since the 1940s, the Sullivan's Island oceanfront has accreted upward of 2000 ft (600 m) (Figure 16). Accretion extends well past the Charleston jetty weir, which enters the beach around the middle of the island. CSE, Sabine & Waters, and Dewberry (2010) estimated that between 1941 and 2008, the oceanfront gained 8.4 million yd^3 (~6.4 million m^3), which averages ~10 yd^3/ft per year (25 m^3/m per year). The estimated "30-year" volumetric accretion rate (1983–2009) along Sullivan's Island oceanfront is 6.4 yd^3/ft per year (16.0 m^3/m per year). The downcoast 0.5-mi (0.8-km) segment of Sullivan's Island fronting Charleston Harbor is armored and stabilized by groins and a quarry stone "zigzag" breakwater.

Segment 5—Morris Island to North Edisto River Inlet

Segment 5 is a 23-mi-long (37.7-km) barrier island reach with four beach ridge barriers, two naturally stable inlets (Lighthouse and Stono), and one migratory inlet (Captain Sams) (Figure 17). The northernmost island, Morris Island, is the terminus of the south jetty at the Charleston Harbor Entrance. Net longshore transport diverges north and south from the center of Morris Island. Before jetty construction, entrance shoals off Sullivan's Island tended to overextend to the south and deflect the Charleston channel. Periodic breaches of the shoals likely initiated natural bypassing to Morris Island and Folly Beach. This process stopped with construction of the jetties and the maintenance and deepening of Charleston Harbor (FitzGerald, 1988; Hansen *et al.,* 1987). While

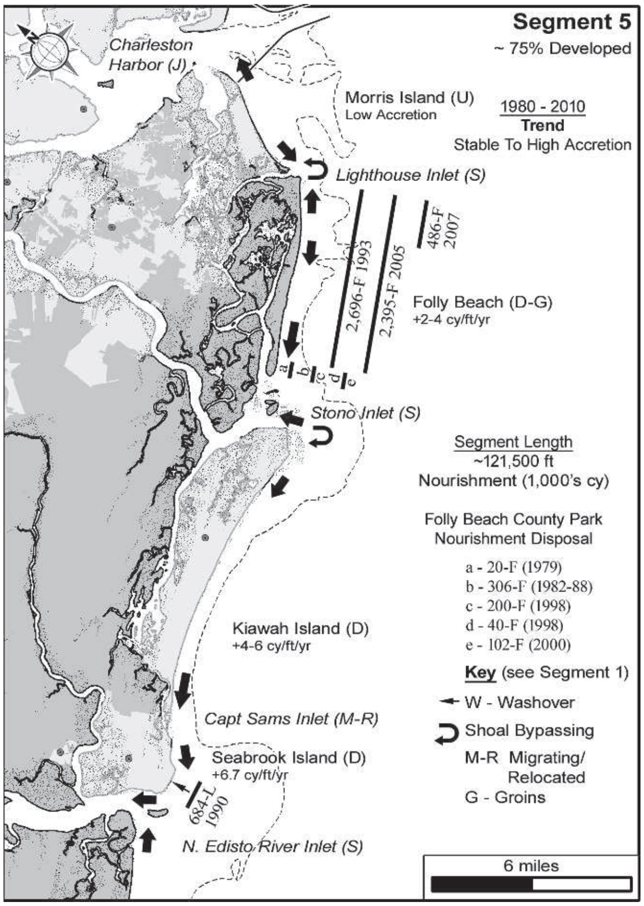

Figure 17. Segment 5—Beach condition changes, principal sand transport pathways, and beach nourishment events (1980–2010).

undeveloped Morris Island became an active dredge disposal site in the 1930s, erosion of >25 ft/y (7.6 m/y) (Stephen *et al.,* 1975) along the southern end near Lighthouse Inlet left the Morris Island lighthouse over 1500 ft (~450 m) offshore by the 1970s. Since 1980, the center of Morris Island has eroded at ~8 ft/y (~2.4 m/y), while the ends have accreted by ~50,000 yd^3/y (~40,000 m^3/y) (see Figure 7). Recent shoal buildup around the Morris Island lighthouse suggests there have been sand inputs associated with bypassing events from Lighthouse Inlet and Folly Beach.

The remaining barrier islands in the segment are developed and exhibit accretion during the past three decades. The buildup at Folly Beach is due to groins constructed in the 1940s–1950s in response to erosion and nourishment events since 1980 totaling 5.63 million yd^3 (4.31 million m^3) (Figure 17). Most of Folly Beach (5.85 mi long, 9.6 km) is armored with seawalls, accounting for minor shoreline change in the past 60 years (Kana and Gaudiano, 2001). A 50-year federal nourishment project was initiated in 1993 (Ebersole, Neilans, and Dowd, 1996; Edge *et al.,* 1995), with a second event in 2005. Post-Hurricane *Ophelia* (2005) nourishment was placed in 2007 along the "washout"—a salient associated with the former terminus of the Charleston Entrance ebb-tidal delta. Sediment transport diverges at the salient and shifts sand north and south from that point as evidenced by fillet geometry around exposed groins at the ends of the island.

A measure of improvement in beach condition along Folly Beach is the number of groins presently exposed compared with the 1980s. Out of 43 groins reported for the island (OCRM, 2010), ~38 were exposed in 1989 (before most nourishment) and ~25 were exposed in 2012. Volume change data for intermediate time periods combined with nourishment density and geomorphic evidence indicate Folly Beach has received an average of 6 yd^3/ft per year (15 m^3/m per year) since 1980 and has an estimated loss (and net gain) rate of ~3 yd^3/ft per year (7.5 m^3/m per year). London *et al*. (2009) reported a gain in beach area of 77.6 acres (31.0 ha) for the period ~1987–2006, which encompasses major nourishment events in 1993 and 2005. This equates to average unit volume gains of ~4.6 yd^3/ft per year (~11.5 m^3/m per year) over 19 years as a check on the 30-year approximation.

Kiawah Island and Seabrook Island are highly accretional beach ridge barrier islands with a well-documented shoreline history (Hayes, 1977; Hayes, Kana, and Barwis, 1980). The primary source of sand has been shoal-bypassing events from Stono Inlet (CSE, 2011a; Gaudiano and Kana, 2001). Between 1990 and 2005, two events added ~5 million yd^3 (3.8 million m^3) at the eastern end of Kiawah and created an ~3-mi-long (~5-km) barrier beach-lagoon system, which advanced the shoreline >1500 ft (450 m) (Kana, Traynum, and Jordan, 2011). The increase in profile volume density to approximate DOC between 1999 and 2008 at one station alone was 473.4 yd^3/ft (1,183.4 m^3/m). Between August 1983 and April 1999, Kiawah Island's 7.6-mi-long (12.5-km) oceanfront (excluding the east end) gained 1.7 yd^3/ft per year (4.25 m^3/m per year) to low-tide wading depth (CSE, 1999). Combining the major shoal-bypassing volumes at Stono Inlet between 1990 and 2005 and extrapolating to DOC yields an estimated average annual gain of ~5 yd^3/ft per year (~12.5 m^3/m per year). This totals ~7.6 million yd^3 (~5.8 million m^3), which is equivalent to ~11.5 million ft^2 (~264 acres, ~105 ha) of beach area along Kiawah Island. London *et al*. (2009) estimated Kiawah gained 196.8 acres (78.7 ha) between 1987 and 2006.

Net longshore transport is westerly and approaches ~120,000 yd^3/y (~90,000 m^3/y) along Kiawah spit (Kana and Mason, 1988). This transport accounts for spit growth and inlet encroachment into Seabrook Island. Since 1980, Captain Sams Inlet has been relocated twice to its 1963 position (1983 and 1996). This has forced shoal-bypassing events, which have added ~2 million yd^3 (1.5 million m^3) to Seabrook Island (CSE, 2011c). In 1980, ~9000 ft (2750 m) of Seabrook (~70% of the beach) was armored with seawalls and lacked a dry-sand beach in those areas. In 2010, ~2000 ft (~610 m) lacked a dry-sand beach. Average annual beach volume gains along Seabrook Island since 1980 are ~6.7 yd^3/ft per year (16.7 m^3/m per year) (CSE, 2008b). These averages incorporate the volume gained from inlet relocation and one nourishment project from an external source (1990) which placed 684,500 yd^3 (~523,300 m^3) along an encroaching channel of North Edisto River Inlet. London *et al*. (2009) reported 94.6 acres (37.8 ha) of added beach area between 1987 and 2006.

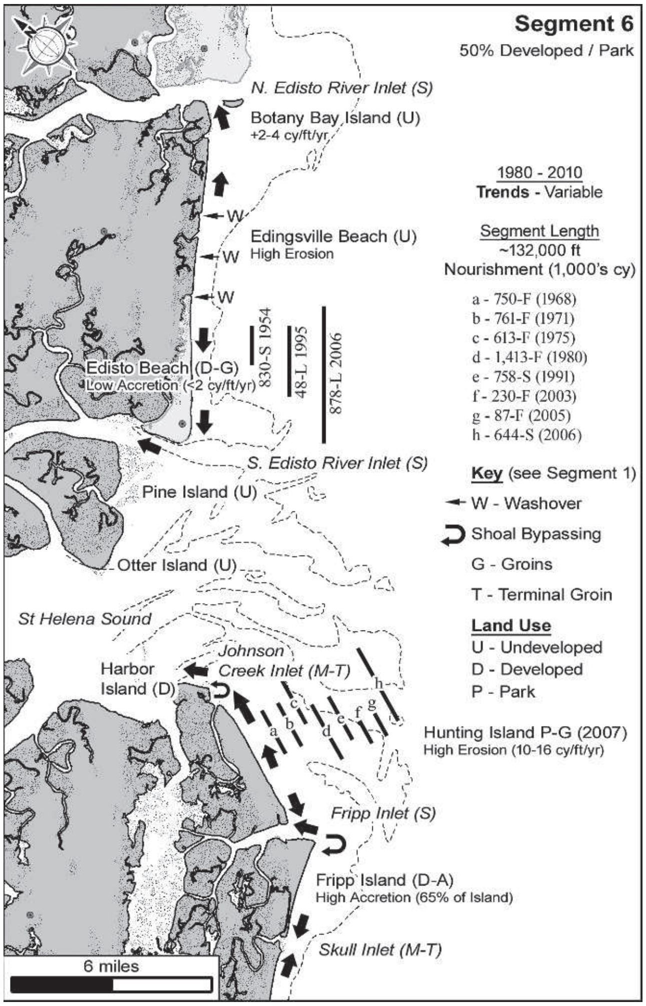

Figure 18. Segment 6—Beach condition changes, principal sand transport pathways, and beach nourishment events (1980–2010).

Segment 6—Botany Bay Island to Fripp Island

Segment 6 is a 25-mi-long (41-km) reach with five beach ridge barrier islands (Botany Bay, Edisto, Harbor, Hunting, Fripp), one naturally stable inlet (Fripp), and the largest sound along the South Carolina coast (St. Helena) (Figure 18). This segment includes a 7-mi-long (11.5-km) transgressive, washover barrier section (Edingsville Beach). Approximately 33% of the coast is developed, and 15% is accessible public park land.

St. Helena Sound and its offshore shoals dominate this part of the South Carolina coast. Smaller inlets and their associated ebb-tidal deltas are nested within the ebb-tidal delta of the sound.

The northern barrier island complex of Botany Bay Island, Edingsville Beach, and Edisto Beach is bounded by the North and South Edisto River Inlets, both of which have ebb deltas containing on the order of 150 million yd^3 (~120 million m^3) (Imperato, Sexton, and Hayes, 1988). Sheltering by each delta and wave refraction into the Edingsville embayment drive sand away from the center of the reach. Shoreline retreat along Edingsville Beach is >15 ft/y (4.6 m/y) (SCCC-OCRM, 1991–2010). This transgressive barrier segment is washing into a mature salt marsh, leaving exposed mud and shell deposits along the intertidal beach. Winnowing of mud concentrates coarse shell material, which comprises the principal sediment source to beaches at the ends of the reach (CSE, 2011d).

Edisto Beach is anchored by groins that reduce erosion losses along the oceanfront (Kana, White, and McKee, 2004; USACE, 1965). Three nourishment projects have been completed, including the first-ever in South Carolina (1954). The 1954 project involved direct excavation of marsh deposits and placement along a 1-mi (1.6-km) section where the oceanfront access road was being encroached by the surf zone (see Figure 18). Groins were installed to retain nourishment (Kana, White, and McKee, 2004; USACE, 1965). This project likely increased the shell content along Edisto Beach by pumping oyster shells from the marsh.

Projects in 1995 and 2006 utilizing sands from an ebb-tidal delta added 1.03 million yd^3 (784,400 m^3) and advanced the shoreline ~70 ft (~21 m). Volume losses before 2006 were relatively low because the groins were fully exposed and functional, albeit leaving no setbacks or protection for much of the development. Erosion losses since 2006, when all groins were buried after nourishment, more closely reflect conditions in the absence of sand-retaining structures. The upcoast 11,828 ft (3.6 km) of oceanfront has eroded at ~2.83 yd^3/ft per year (~7.1 m^3/m per year) since 2006, whereas the downcoast area (16,543 ft, 5.04 km), including the exposed beach along the sound, has accreted at a comparable rate of 1.69 yd^3/ft per year (4.23 m^3/m per year). Surveys show a near balance of volume gains and losses after nourishment over the length of Edisto Beach (CSE, 2011d). A similar balance of gains and losses before nourishment (CSE, 2003) and ground observations suggest the nourishment volumes account for nearly all the changes in the past few decades.

Fripp Island, Hunting Island, and Harbor Island mark the entrance on the south side of St. Helena Sound. Net sediment transport is toward the St. Helena Sound embayment for each island, with local drift reversals at the south ends of Hunting Island and Fripp Island. Harbor Island is composed of sands derived from the north spit of Hunting Island, which was originally a 1.3-mi-long (2.1-km) reach that separated from Hunting Island in the early 20th century with the breach of Johnson Creek Inlet (CSE Baird, 1998; Traynum, Kana, and Simms, 2010). Sand bypasses the inlet from Hunting Island to Harbor Island by way of the Johnson Creek ebb-tidal delta, which contains ~5 million yd^3 (3.8 million m^3). Harbor Island's erosion signature is distinct, with high rates of accretion over the past 30 years along the southern half and low erosion along the northern half of the island.

Hunting Island has one of the highest erosion rates in South Carolina at upward of 25 yd^3/ft per year (~62.5 m^3/m per year) (CSE Baird, 1998) after factoring out the effect of nourishment. A principal factor accounting for high erosion is wave refraction/diffraction through offshore shoals. Arcuate wave fronts break along a convex shoreline that remains out of equilibrium with incident waves, leading to rapid spreading of sand from the middle of the island. Sand transport is

Figure 19. Fripp Island looking southwest at low tide on 31 May 2008 showing natural accretion associated with a major inlet shoal-bypassing event. Dashed line marks the 1990 shoreline/seawall.

dominantly north because of the added effect of strong, flood-tidal flows into St Helena Sound (CSE Baird, 1998, Stapor and May, 1981; USACE, 1964). Eight nourishment events between 1968 and 2006—totaling 5.25 million yd^3 (~4.01 million m^3)—failed to keep pace with erosion, forcing abandonment and relocation of state park facilities. In 2007, six groins—spaced ~1200 ft (365 m)—were placed at three recreational access points along the island to create safe swimming areas free of submerged stumps and debris. The groins have retained sand, allowing limited formation of a dune ridge over a 5-year period. Remaining areas between the groin clusters continue to erode. The southern end of Hunting Island (not stabilized by groins) remains one of the most erosional sites along the South Carolina coast. Net annual sand volume losses island-wide since 1991 have been in the range of 10–16 yd^3/ft per year (25–40 m^3/m per year) (Traynum, Kana, and Simms, 2010).

Fripp Island, a 3-mi-long (5-km) drumstick barrier island, is sheltered from northeasters by the shoals of Fripp Inlet. During the early history of development in the 1970s through the mid-1980s, most of the island became armored by seawalls. The prominent downdrift offset of Fripp Island exposed the inlet shoreline to northeasters. During the past 30 years, the Fripp Inlet shoals have overextended and deflected the main channel to the southwest. A major shoal-bypassing event occurred in the late 1990s, adding upward of 3 million yd^3 (2.3 million m^3) to the center of the island (CSE, 2010b) (Figure 19). This sand has spread toward the ends of the island and has resulted in burial of nearly 2 mi (3.3 km) of seawall. By comparison, in 1990, there was only ~0.5 mi (0.8 km) of dry-sand beach along Fripp Island (CSE, 1990). The Fripp Inlet shoreline of Fripp Island has been scoured by the inlet with depths at the toe of the seawall reaching as much as 45 ft (13.7 m) (CSE, 2012). Ebb-dominant flows in the channel (Hubbard, 1977) and a lack of intertidal beach preclude natural shoreline restoration along Fripp Inlet by way of sand moving around the eastern end of the island (the normal pathway for wave-generated transport in the lee of the ebb-tidal delta). London *et al*. (2009) reported Fripp Island gained 70.8 acres (28.3 ha) of beach area between 1987 and 2006, which is equivalent to ~7 yd^3/ft per year (~17.5 m^3/m per year) apportioned over the ~3-mi (~4.8-km) oceanfront.

Section 7—Prichards Island to Savannah River Entrance

Segment 7 is a 28-mi-long (45.9-km) barrier island section with four beach ridge barrier islands (Pritchards, Bay Point, Hilton Head, Daufuskie), two major sound entrances (Port Royal and Calibogue), and several unstable migrating inlets and wash-over barrier segments (Figure 20). Fifty percent of the shoreline is developed, with Hilton Head Island comprising the major resort center along the southern part of the state.

Sparsely developed barrier islands (accessible by boat) updrift of Port Royal Sound (Pritchards, Capers, Bay Point) exhibit net transport into the bight of the sound with small ebb-tidal deltas nested within the Port Royal delta. The southern limit of Port Royal ebb shoals ("Gaskin Banks") terminates off the middle of Hilton Head Island. The breakwater effect of Gaskin Banks accounts for the broad salient in the Hilton Head Island shoreline, centered along Palmetto Dunes Plantation about 6 mi (9.8 km) from the entrance to Port Royal Sound (CSE, 1986).

Studies show no large-scale shoal-bypassing events into the middle of Hilton Head Island over the past ~50 years (CSE, 1986; USACE, 1974), probably from a combination of factors, including the offshore distance of the Gaskin Bank shoal (>2 mi, 3.3 km) and the relatively low wave energy along this section of coast in the lee of the Port Royal Sound ebb-tidal delta. As a result, the principal erosion signature has been dispersion and transport of sand from the salient to each end of the island. The southern spit (Sea Pines Plantation) has generally accumulated sand over the past 30 years, with one nourishment project in 1999 (245,000 yd^3, 187,300 m^3) to address an erosion hot spot (Olsen Associates, 2005). Five nourishment events since 1969 along the Hilton Head Island oceanfront have added 10.6 million yd^3 (8.1 million m^3) along ~8.62 mi (14.1 km) to counter sand losses from the center of the island. Omitting the 1969 project, the average fill density to the nourished section of the oceanfront since 1980 has been ~198 yd^3/ft (~495 m^3/m) (see Table 1; source: Olsen Associates, unpublished). As Figure 20 shows, renourishment has occurred at 7-year to 10-year intervals along the center of Hilton Head Island.

The Port Royal Sound shoreline has experienced local erosion hot spots associated with shoal-bypassing events from "Joiner Banks," an inshore shoal ("trailing ebb spit"; Hayes, 1980) at the mouth of Port Royal Sound that periodically attaches (Olsen Associates, 2005). Groins and nourishment have been used to maintain the eastern end of Hilton Head Island (Port Royal Plantation). London *et al*. (2009) reported that Hilton Head Island gained 151.7 acres (60.7 ha) of beach area between

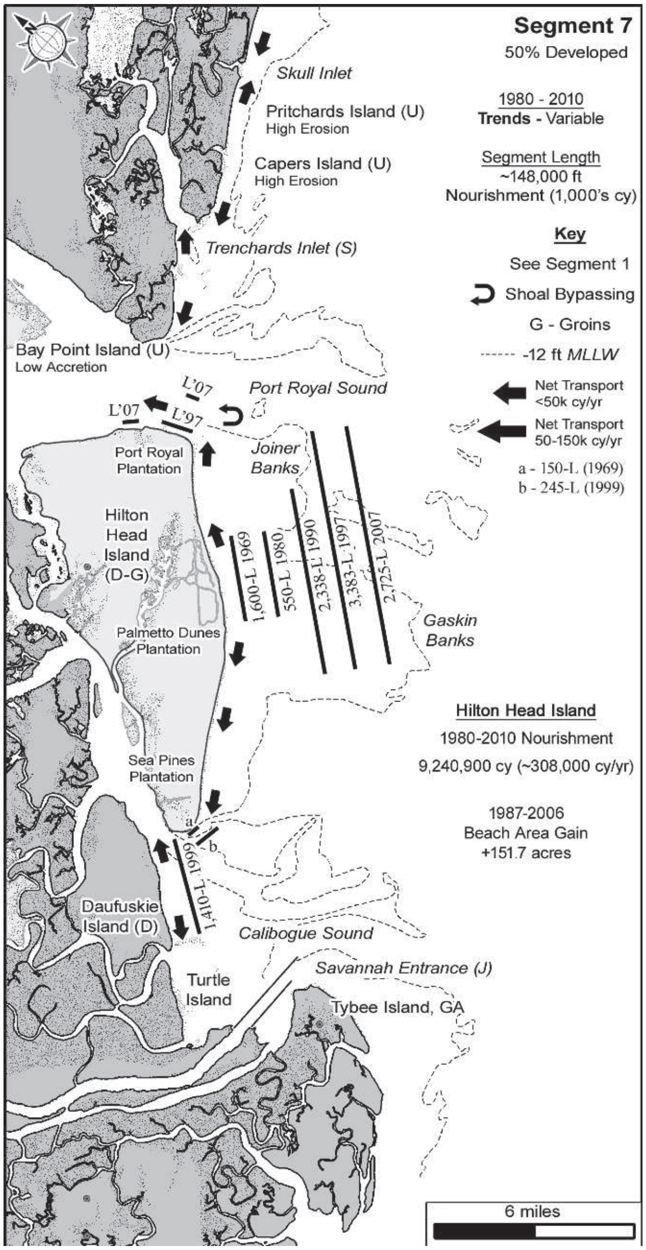

Figure 20. Segment 7—Beach condition changes, principal sand transport pathways, and beach nourishment events (1980–2010).

1987 and 2006, which is equivalent to ~4.2 million yd^3 (~3.16 million m^3) in this setting. Of the reported 25 groins installed along Hilton Head Island, only seven were visible in 2010. The rate of nourishment over the past 30 years appears to have been roughly twice the underlying erosion rate, leaving Hilton Head Island with significantly more beach/dune area in 2010.

Daufuskie Island is a "sea island" barrier encompassing a Pleistocene remnant core and Holocene ridges (Hayes and Michel, 2008). Fully in the lee of Calibogue Sound shoals, 3 mi (5 km) of its length consists of exposed beaches, and the balance is a sheltered estuarine shore. Sand transport diverges from the center of the island (Melrose Plantation) with active spit growth to the NE and SW (Bloody Point). Erosion dominates along the oceanfront, with average shoreline recession (1941–1988) of ~6.5 ft/y (2.0 m/y) (Jones *et al.,* 1988). One nourishment project has been implemented during the past 30 years (1998–1999; 1,410,000 yd^3, 1.078 million m^3) (Applied Technology & Management, unpublished data). A timber bulkhead was constructed along Melrose Plantation in 1985, and a terminal groin was constructed in 2002 at Bloody Point.

In 1984, roughly 80% of the Daufuskie Island oceanfront exhibited erosion stress with outcrops of underlying semi-lithified mudstone of likely Pleistocene age exposed across the intertidal beach, continuous erosional escarpments along the center of the island, and dead trees in place in the surf zone (RPI, 1984). Aerial imagery for 2010 shows ~20% of the oceanfront (bulkheaded section) lacks a dry beach, whereas the remaining beachfront includes expanded recreational area. London *et al*. (2009) reported a net increase in beach area totaling 14.3 acres (5.7 ha) between 1987 and 2006. Nourishment inputs (averaging ~76.2 yd^3/ft, 190.5 m^3/m) would be expected to yield ~50 acres (20 ha) in this setting. Therefore, the 1999 nourishment project partially offset erosion losses for at least one decade.

The southernmost South Carolina beach is Turtle Island, a remnant washover barrier on the north side of Savannah Entrance Channel.

SUMMARY AND CONCLUSIONS

Three decades of beach monitoring along the South Carolina coast (1980–2010) indicate nearly all developed beaches have gained volume and area either via natural accretion or artificial nourishment. The most rapidly eroding sections of coast tend to be wilderness beaches, such as Cape Romain or Edingsville Beach (which are only accessible by boat) or public parks such as Hunting Island or Folly spit.

The South Carolina coast is highly compartmented, with numerous tidal inlets and ebb-tidal deltas serving as underwater headlands. Sand resources tend to be conserved between inlets and adjacent beaches in the segments of coast that are healthy and experience a balanced beach cycle of onshore–offshore transport. Along eroding wilderness beaches, washovers are common and draw off sand from the active littoral zone. Wave sheltering by large ebb-tidal deltas has produced numerous drift reversals and has led to complexity in shoreline morphology, including numerous salients in the lee of offshore shoals and spits built into embayments. Shoal bypassing is a dominant process along much of the coast, accounting for healthy natural growth of many beaches, such as Isle of Palms, Sullivan's Island, and Kiawah Island.

Between 1980 and 2010, 39.4 million yd^3 (~30.1 million m^3) from external sources added roughly 55.5 million ft^2 (~1,275 acres, ~510 ha) of beachfront along 62.6 mi (102.6 km). This is an average of ~168 ft (~51 m) of beach width within the nourished reaches. A majority of the volume was placed at four localities: Grand Strand (North Myrtle Beach, Myrtle Beach, Surfside Beach, Garden City Beach), Folly Beach, Hunting Island, and Hilton Head Island. All but Hunting Island had wider beaches in 2010 compared with 1980.

The rate of nourishment along the Grand Strand (Segment 1) greatly exceeded the background erosion rate, leaving beaches about 90 ft (~27.4 m) wider in 2010. At Hilton Head Island, where historical erosion has been 5–10 times greater than the Grand Strand, nourishment has exceeded sand losses, adding 75–125 ft (22.8–38.1 m) of new beach width. Nourishment has also exceeded erosion losses along Huntington Beach State Park, the eastern end of Isle of Palms, Folly Beach, most of Seabrook Island, most of Edisto Beach (past decade), and ~80% of Daufuskie Island (past decade). Sites where nourishment has not kept pace with sand losses include south Debidue Island, Folly Beach County Park, Hunting Island State Park (except limited swimming areas now protected by groins), and the bulkheaded section of Daufuskie Island. In all of these cases (~7 mi, 11.5 km), the background erosion rate is high (order of ~6 yd^3/ft per year, ~4.6 m^3/m per year or higher). Sand tends to be drawn off the beach into the adjacent inlet at accelerated rates.[3]

Local SLR is reported to be 3.46 in (88 mm) for the period 1980–2010. Inundation from SLR represents a beachfront area loss of ~4 million ft^2 (roughly 100 acres, ~40 ha) applied over ~100 mi (~161 km) of developed coastline. This reduces to about 7.5 ft (2.3 m) of beach recession over the 30-year period of interest. It can be concluded from this that SLR is not a dominant factor in the observed beach changes.

Hurricane *Hugo* (1989) was the only major hurricane to impact the South Carolina coast between 1980 and 2010. It produced one breach of developed land (south end of Pawleys Island) and short-term recession of the vegetation line. By summer 1990, affected beaches along the Grand Strand had recovered naturally or had been renourished. Litchfield Beach fully recovered in ~2 years without new inputs of nourishment after *Hugo*, which points to the general stability of that beach, particularly its ability to recover naturally after a major storm. The conclusion here is that major storms have not been the principal cause of erosion at decadal scales along the South Carolina coast.

The beaches with the highest recession rates over the past 30 years tend to be washover barrier islands and unstable sand spits backed by open lagoons or marsh. The wilderness areas of Edingsville Beach and Cape Romain are sand-starved beaches rolling over the interior marsh or lagoon. High losses (upward of 40 ft/y [12.2 m/y] recession at some localities) are due to several factors: longshore transport drawing off sand from the center of each island toward the adjacent inlets, losses to the marsh/lagoon via washovers and breach inlets, and accelerated losses by dispersion of muddy marsh deposits, which become exposed along the receding beach. The only "developed" beaches in this condition at present are Folly Beach County Park, a 3000-ft spit at the south end of Folly Beach, and the "cabin road" area at the south end of Hunting Island State Park.

Beaches that have the highest accretion rates tend to be those receiving natural inputs of sand via "shoal bypassing"—the episodic release of bars from large ebb-tidal deltas. Frequent events at Capers Inlet (Dewees Island), Dewees Inlet (Isle of Palms), Breach Inlet (Sullivan's Island), Stono Inlet (Kiawah Island), Captain Sams Inlet (Seabrook Island), Johnson Creek Inlet (Harbor Island), and Fripp Inlet (Fripp Island) have produced moderate to high (*i.e.* 4–7 yd^3/ft per year; 10–17.5 m^3/m per year) accretion along the receiving islands. It is likely the volume bypassed from ebb-tidal deltas to developed beaches in South Carolina between 1980 and 2010 is comparable to the volume of nourishment. Two bypassing events at Kiawah alone (1990–2005) added ~5 million yd^3 (~3.8 million m^3), a volume equaling four nourishment events along the City of Myrtle Beach (1986–2009). Ebb dominance of many South Carolina inlets plays an important role in preserving littoral sand budgets, limiting losses to lagoons and increasing the rate of sand exchange between ebb-tidal deltas and the adjacent beaches.

By any objective measure, the condition of South Carolina's developed beaches in 2010 was better than 1980 because of beach nourishment and episodic shoal bypassing. By comparison, the majority of the state's wilderness beaches have eroded during the past 30 years. Barrier islands that are receding rapidly in South Carolina, such as Raccoon Key (Segment 3) or Edingsville Beach (Segment 6), do not appear to be maintaining the same profile or beach character. Instead, these formerly sandy beaches are being converted to a thin veneer of shelly sands perched on mud outcrops. Relict marsh deposits and back-barrier tidal creeks, encroached by the migrating barrier, are the source of the mud and shells. Erosion, combined with a change in the sediment quality of the beach, has affected turtle nesting habitat, forcing relocations of nests according to state wildlife officials. In a bit of serendipity for beachgoers and property owners, developed beaches of South Carolina tend to have the healthiest sand budgets through natural as well as artificial means, whereas undeveloped beaches, in general, tend to have the least healthy sand supplies over the past three decades.

ACKNOWLEDGMENTS

This paper draws from numerous shoreline erosion assessments by the Coastal Research Division–University of South Carolina, Research Planning Institute Inc., Coastal Science & Engineering Inc., U.S. Army Corps of Engineers–Charleston District, and South Carolina Department of Health & Environmental Control (SCDHEC)–Office of Ocean & Coastal Resource Management. The authors thank numerous municipalities and property owners associations for support of sustained monitoring efforts, particularly the cities of Myrtle Beach and Isle of Palms; the towns of Kiawah Island, Edisto Beach, and Hilton Head Island (c/o Olsen Associates); South Carolina Department of Parks Recreation & Tourism (Hunting Island); and the Seabrook Island Property Owners Association. Portions of this study were funded by the South Carolina Sea Grant Consortium under grant 265-1e4–South Carolina Coastal Erosion Study and grant R/CP-10–Meso-

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[3] Many South Carolina ebb-tidal deltas contain 10^7 to 10^8 yd^3 (Sexton and Hayes, 1996). Sand losses to the inlets from adjacent beach segments, by comparison, are on the order of 10^4 yd^3/y to 10^5 yd^3/y, a typical range for net longshore transport. Such large differences in magnitude, combined with imprecision of inlet shoal surveys, make it difficult to detect net growth or decline of ebb-tidal delta volumes at decadal scales and relate these changes to sand losses or gains along adjacent beaches.

scale Modeling of Sediment Transport and Morphologic Changes at Tidal Inlets.

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