QUANTITATIVE SHORELINE CHANGE ANALYSIS OF AN INLET-INFLUENCED TRANSGRESSIVE BARRIER SYSTEM: FIGURE EIGHT ISLAND, NORTH CAROLINA

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ABSTRACT

GIS-based analyses of NOS T-sheet maps, aerial photographs, LIDAR, and RTK GPS shoreline data spanning the time period from 1857 to 2003 were conducted to quantify shoreline rate-of-change values for Figure Eight Island, North Carolina. Four zones (I, II, III, & IV) were delineated along the island to summarize variations of shoreline change trends in response inlets, storms, and anthropogenic activity. Long-term mean annual erosion rates prior to island development ranged between -4.4 to -0.8 ft/yr (±0.39 ft/yr) along zones I through III, which account for the approximately 90% of the island's shoreline, and +5.6 ft/yr (±0.96 ft/yr) along Zone IV. Subsequent to development in 1966, shoreline change rates ranged between -1.7 to +5.8 ft/yr (±0.84 ft/yr) along zones I through IV. The overall long-term mean annual erosion rate during the period from 1857 to 2003 ranged between -1.8 to -0.4 ft/yr (±0.24 ft/yr), along zones I through III, and +2.1 ft/yr (±0.36 ft/yr) along Zone IV between 1927 and 2003. Zones I and IV, adjacent to Mason Inlet and Rich Inlet respectively, are dominated by inlet processes associated with movements of the ebb channel and changes in ebb-tidal delta symmetry. Zone II is mainly impacted by a mixture of storms, tides, longshore transport, and some inlet processes. Longshore transport reversals, associated with wave refraction downdrift of Rich Inlet's ebb delta inflection point, influence Zone III. Thorough shoreline and inlet management plans are critical for mitigation against imminent beach erosion. Innovative alternatives such as ebb shoal mining might provide needed beach nourishment material, as sand resources in the offshore and backbarrier are limited. However, detailed studies are needed to establish both short- and long-term impacts of human activities on shoreline morphology.

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INTRODUCTION

Long-term shoreline erosion and limited sand resources characterize the vast majority of barrier islands along southeastern North Carolina. Most of these islands are sites of extensive areas of residential and commercial development and are experiencing increasing pressures for further development. Long-term sea-level rise and storms also pose a threat these coastal areas, especially heavily developed portions where loss of property due to shoreline retreat is imminent. As the threat of damage to development from shoreline retreat intensifies, so does the desire of property owners to combat erosion by artificially stabilizing the oceanfront shoreline.

Historically, management policies dealing with coastal erosion set forth by the North Carolina Division of Coastal Management (NCDCM) have been recognized as being some of the most stringent and restrictive in the United States. However, these policies are becoming even more restrictive as available sand resources are depleted and the use of other potential borrow-sources is prohibited by environmental regulations. Hence, developed barrier islands of North Carolina are running out of shoreline stabilization options and analyses of shoreline change and coastal erosion hazards for the development of new mitigation strategies based on sound scientific reasoning is needed. Assessments of coastal hazards, such as tidal inlets and storms, along with anthropogenic effects on shoreline erosion are critical in determining what activities are likely to promote an increase or decrease in erosion. Figure Eight Island (Figure 1) is an exemplary site that typifies the need for these studies because the barrier is densely developed and located between two active tidal inlets, and located in an area frequently impacted by storms.

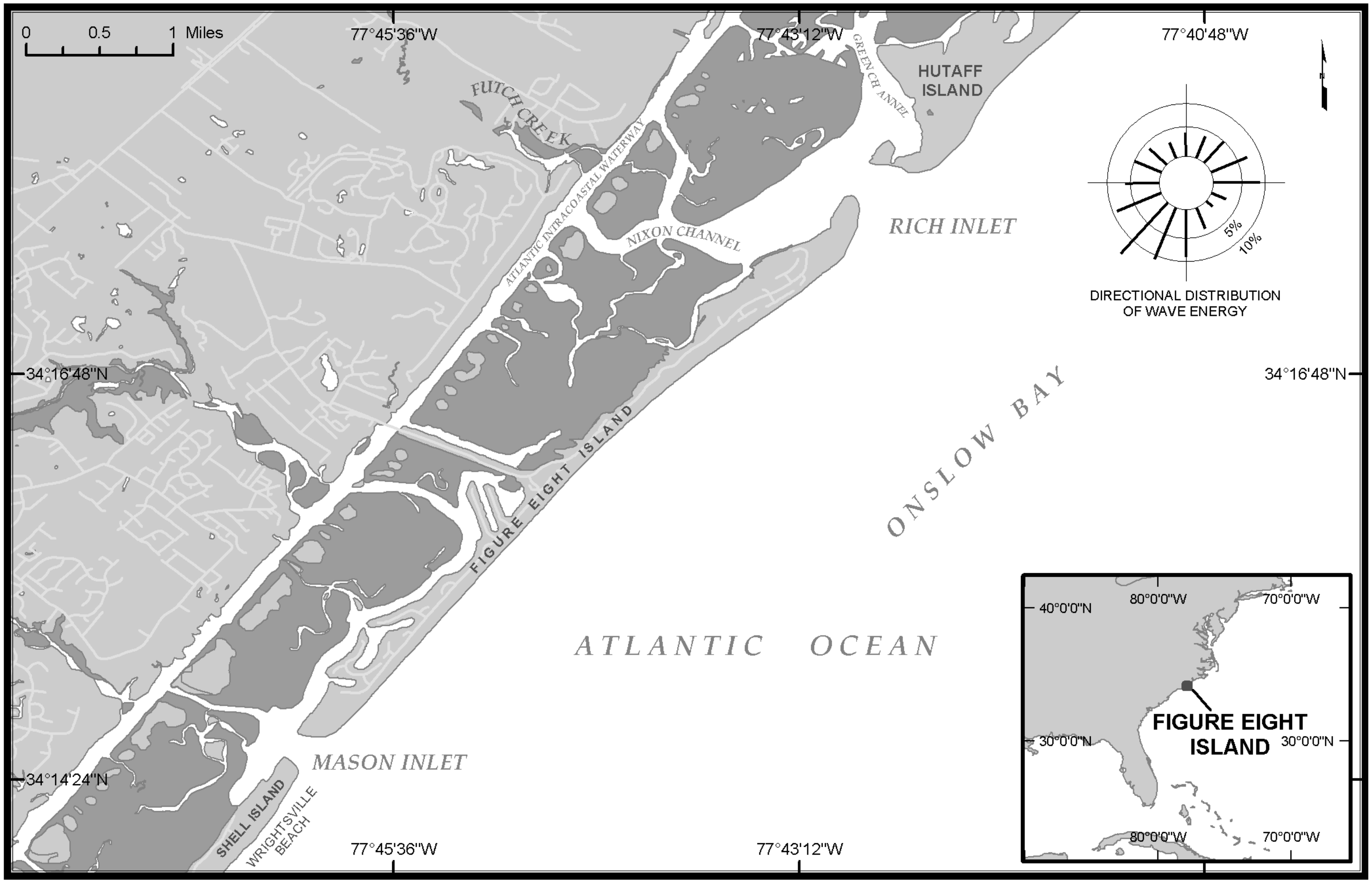

Figure 1. Location map of Figure Eight Island, North Carolina.

The primary goal of this research was to quantify shoreline changes through the collection of historical shoreline data and to delineate both spatial and temporal trends of shoreline change using state-of-the-art GIS mapping and analysis techniques. Fortunately, numerous historical survey maps and aerial photographic records exist of the island, spanning a large temporal scale, which provided a more comprehensive and robust dataset (Figure 2). Historically, generic terms such as shoreline, strandline, water line, and coastline have been used to identify a land-water interface (JOHNSON, 1919). For purposes of this study, the term "shoreline" refers to the high-water line (HWL) or swash terminus located on the beach following a high tide (DOLAN *et al*., 1978, 1980, 1991; PAJAK and LEATHERMAN, 2002). Except where noted, the units of measure for the study are presented in the English customary system, as opposed to International System units. The English customary system has been commonly used in a large number of publications regarding coastal North Carolina. Examples of common shoreline and inlet features are provided in Appendix A, labeled on aerial and ground photographs.

Previous Work

Few studies exist that quantify long-term shoreline change rates for Figure Eight Island and those that do, are older studies that lack the accuracy afforded by recent technological advances of geographic information systems (GIS) and digital shoreline mapping programs. A report published by WAHLS in 1973 attempted to quantify both short and long-term erosion rates using historical aerial photographs of the entire North Carolina coast. Maps published by the NCDCM (BENTON *et al*., 1997) estimated long-term average annual shoreline change rates for the North Carolina coast over a 50-year period through 1992.

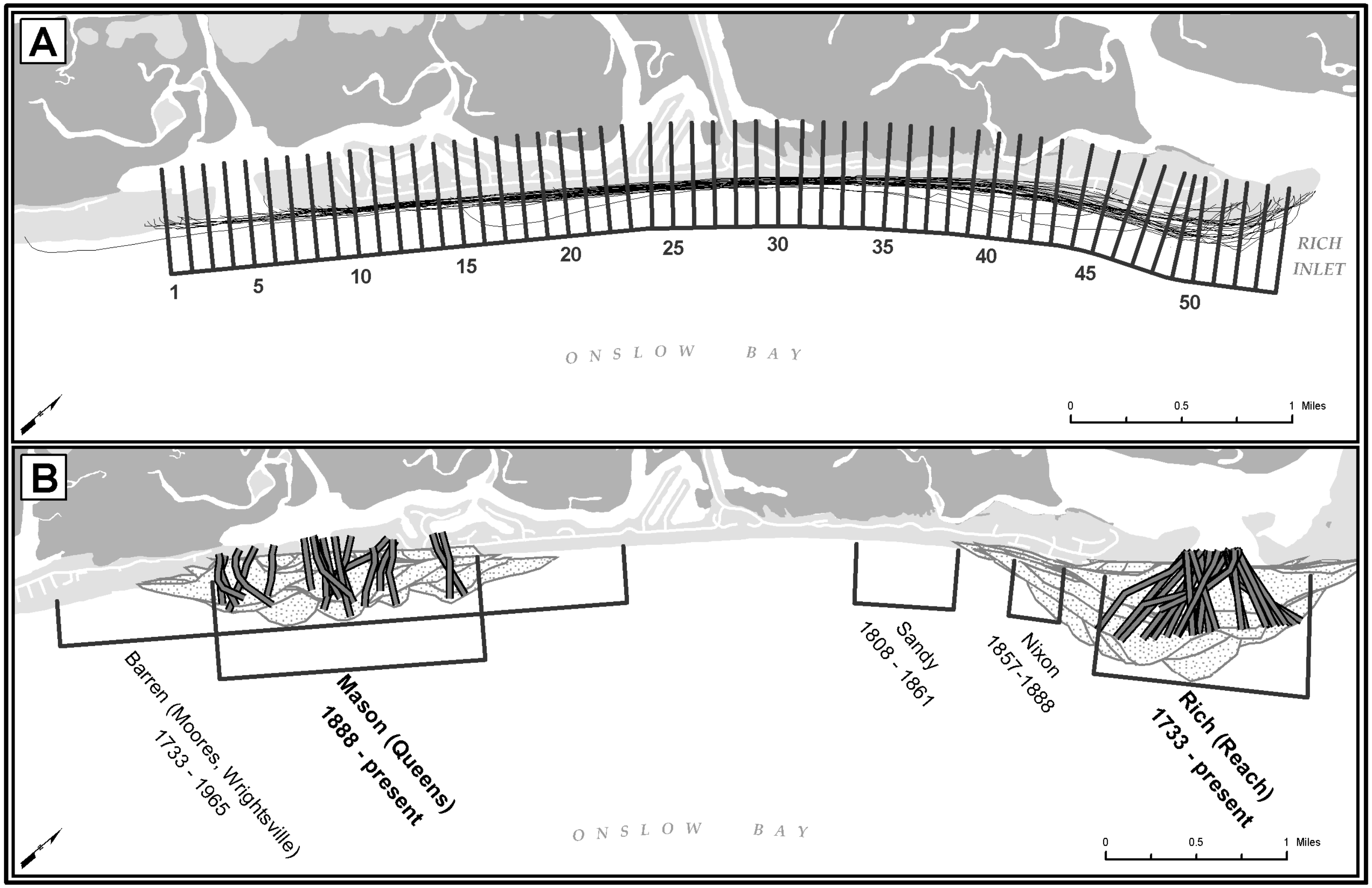

Figure 2. (a) Historical shoreline positions (1857 to 2003) and shoreline change transects. (b) Map depicting inlet migration corridors of historical inlets (1733 to 2003) and the positions of historical ebb channels and ebb deltas of Mason and Rich Inlets (1938 to 2003). Notice that historical inlets have impacted nearly all of Figure Eight Island. Inlet corridors were modified from BROOKS (1988).

Recently, the NCDCM (2003) has updated the maps to include shoreline positions extracted from highly controlled 1998 digital orthophotographs. Their study was conducted using advanced photogrammetric techniques and computer software to attain only two digital shorelines per barrier island, which was fewer than the number used in the study conducted by WAHLS (1973). However, although WAHLS utilized 5 to 10 historical shorelines, the data are suspect along Figure Eight Island because the analyses were performed under severe technological limitations.

Studies of inlet-influenced shoreline changes include those of BROOKS (1988), CLEARY (1996), JOHNSEN *et al*. (1999), JACKSON and CLEARY (2003), and JACKSON *et al.* (2004). BROOKS (1988) mainly investigated the morphologic characteristics of both Rich and Mason Inlets while CLEARY (1996) and JOHNSEN *et al*. (1999) determined mechanisms within inlet systems that influence erosion along adjacent shorelines for select barrier islands located along Onlsow Bay. Studies conducted by JACKSON and CLEARY (2003) and JACKSON *et al.* (2004) related oceanfront shoreline change along Figure Eight and Hutaff Islands to Rich Inlet morphodynamics. A pictorial atlas of North Carolina inlets (CLEARY and MARDEN, 1999) provides a summary of the influence of inlets on adjacent shorelines along North Carolina including those within the study area. The potential management concerns associated with the use of inlet related sand resources for nourishment purposes are described by CLEARY (2002).

These studies provided a general framework for the interpretation of both Rich and Mason Inlet's influence on shoreline change. However, because these studies were limited by available technology, a more quantitative approach using integrated GIS-based data of the barrier/inlet system was undertaken by this study to improve accuracy and aid in determining the zone of influence of bordering inlets.

REGIONAL SETTING

North Carolina's coast lies along the northern flank of the Georgia Bight, which extends a distance of approximately 750 miles between Cape Canaveral, Florida and Cape Hatteras, North Carolina. Southeastern North Carolina's coast is classified as a wave-dominated, low mesotidal barrier coast with mixed energy environments (HAYES, 1979, 1994; DAVIS and HAYES, 1984). Figure Eight Island, located approximately 35 miles north of Cape Fear, is a transgressive barrier island about 4.8 miles long (Figure 1). The island is bordered by a locationally stable inlet, Rich Inlet, to the north and a migrating inlet, Mason Inlet, to the south (BROOKS, 1988) (Figures 1 & 2b).

Offshore

Onslow Bay, situated between Cape Fear and Cape Lookout, borders nearly half of North Carolina's 320-mile long shoreline. The embayment is located along the northeastern limb of the Cape Fear Arch and is comprised of post-Triassic strata overlain with thin veneers of modern sediments (DALL and HARRIS, 1892; CLEARY and PILKEY, 1968; HINE and RIGGS, 1986; CLEARY, 1996). Oligocene siltstone units comprise the bulk of the exposed hardbottoms, along with small outcrops of an Oligocene limestone, located 1 to 5 miles offshore of Figure Eight Island (CLEARY, 2002) (Figure 3). In this region, generally at depths greater than -30 ft, sediment thickness ranges from about 1 to 3 ft and is composed mainly of calcareous-rich quartz sands and silts resulting from the weathering of the Oligocene units (Figure 3). Paleo-channels in the offshore typically trend northwest to southeast and are mud-filled (CLEARY, 2002). Relatively

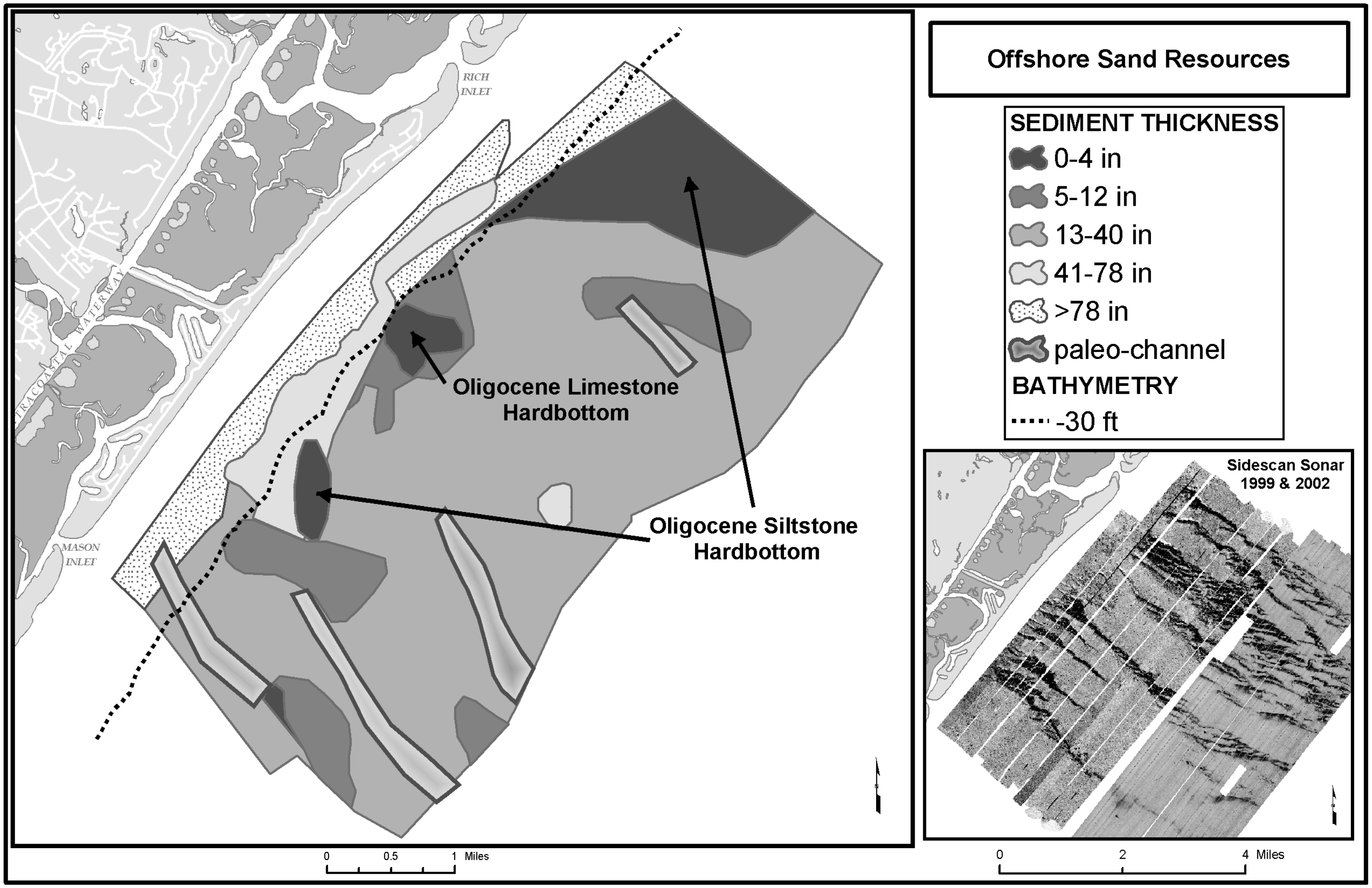

Figure 3. Map of shoreface sand resources and sidescan sonar mosaics from surveys conducted in 1999 and 2002. The majority of sediment in the offshore is muddy in nature and not viable as beach nourishment material. Figure is modified from Cleary (2002).

coarse-grained sands and gravels are scattered about the shoreface (Figure 3). Consequently, beach quality sands for nourishment projects exist only in small patchy areas and reinforce the contention that the offshore is sand-starved.

Coastal Setting

The tides in this area are mixed semidiurnal. The mean tide range is 4.2 ft with a mean spring tide level at 4.7 ft (National Ocean Service, 2003). The projected long-term sea level rise for this area based on tidal data from 1935 to 1999 is 2.22 mm/yr or 0.73 ft/century (National Ocean Service 2001). In a report for the U.S. Army Corps of Engineers (USACOE), JARRETT (1977) reported an average wave height for the region of 2.6 ft with a period of about 7.9 seconds.

Southerly longshore sediment transport, associated with northeasterly winds, is predominant over large temporal (decades or longer) and spatial scales (BYRNES and HILAND, 1995). However, seasonal variations occur due to differences in winter and summer wave regimes, which can result in local reversals. Furthermore, longshore transport is routinely affected by tropical and extratropical weather patterns and inlet processes. In a study conducted along nearby Wrightsville Beach the USACOE (1982) estimated the gross littoral transport to be 1,095,000 yd^3/yr (843,150 m^3/yr) with a net southerly component of 769,000 yd^3/yr (592,130 m^3/yr).

Inlets

Tidal inlets in southeastern North Carolina are primarily wave-influenced transitional systems (HAYES, 1994). Sand bodies tend to be concentrated within the inlet throat, although many systems display well-developed ebb-tidal deltas (CLEARY, 2002). OERTEL (1972) and HAYES (1980) described the morphology of tidal inlets, the associated sand bodies and the processes responsible for their development. Previous work has shown that slight changes in the symmetry of ebb-tidal deltas can have a profound effect on adjacent barrier island shorelines (FITZGERALD and HAYES, 1980; FITZGERALD, 1988; CLEARY, 1996; CLEARY *et al.,* 2000). Ebb delta morphology affects the refraction of waves and promotes local reversals of sediment transport leading to buildup on the downdrift shoulder or inlet-facing shoreline (HAYES, 1980; FITZGERALD, 1988). Such reversals of sediment transport, coupled with bar welding events, play an integral role in the accretion of the adjacent oceanfront shorelines (FITZGERALD, 1988; JACKSON and CLEARY, 2003).

In the southwestern portion of Onlsow Bay, 6 of North Carolina's 20 inlets border developed barrier islands that comprise the bay's shoreline. The stability of the location of these diverse inlets ranges from highly unstable migratory systems, such as Mason Inlet, to artificially stabilized inlets such as Masonboro Inlet. Despite the stability of an inlet's location, all inlets have the capacity to promote significant oceanfront changes. These changes are mainly due to complex linkages between the movements of the ebb channel, symmetry of the ebb-tidal delta, and migration of swash bars. Cyclical oceanfront shoreline erosion resulting from these active inlet hazard regions is becoming an increasing concern of coastal communities located within these areas.

Since the early 1700s, a number of historical inlets have influenced shoreline change along Figure Eight Island's oceanfront (BROOKS, 1988) (Figure 2b). Between 1733 and 1888, Moores Inlet bordered the southern end of the island and migrated in a southwesterly direction prior to the opening of Mason Inlet in 1888 (Figure 2b). Once Mason Inlet opened, Moores Inlet was located at the southern end of Shell Island and no longer directly influenced shoreline change along Figure Eight Island. The end result of the opening of Mason Inlet was a substantial reduction of the length of Figure Eight Island's shoreline. Moores Inlet was subsequently closed in 1965 and Shell Island became contiguous with Wrightsville Beach and Mason Inlet continued to migrate to the southwest. Sandy and Nixon Inlets were open for a relatively short period of time near the northern end of the island during the 1800s and migrated less than 0.5 miles (Figure 2b) during that period. The largest of the historical inlets, Rich Inlet, has remained a fairly stable feature since 1733. Presently, both Mason Inlet and Rich Inlet now border Figure Eight Island and are areas where severe cyclical oceanfront erosion is a primary management concern.

Rich Inlet forms the northern boundary of the island and drains an expansive estuary filled with tidal marsh where two large tidal creeks, Nixon and Green Channels, connect the inlet to the Atlantic Intracoastal Waterway (AIWW). Its ultimate origin is likely related to the ancestral channel of Futch Creek that presumably controlled the location of the paleo-inlet as sea level rose during the past several thousand years (CLEARY, 2002). The inlet's stability is enhanced by the large drainage area, which includes portions of the lagoon and Futch Creek estuary. As a result, it has been a relatively stable feature for the past century. The contemporary movement of the ebb channel has been confined to a ~ 1,600 ft wide pathway. The ebb-tidal delta rests on Oligocene siltstone that crops out along the ebb delta's outer margin forming hardbottoms in water depths of -30 ft (CLEARY, 2000).

Rich inlet is one of the larger inlets in southeastern North Carolina. The inlet minimum width (IMW) reached a maximum of 2,670 ft in October 1989 and a minimum of 920 ft in February 2001 (CLEARY, 2002). The average IMW since 1938 was ~ 1,900 ft. Data collected from an Acoustic Doppler Current Profiler (ADCP) survey conducted in October 2002 determined the average tidal prism to be ~645 x 10^6 ft^3 (KNIERIM, 2003) based on a average recorded spring tidal range of 4.27 ft. It is estimated that the ebb-tidal delta contains ~9.5 x 10^6 yd^3 of sediment to a depth of approximately -30 ft.

Mason Inlet, fed by Mason Creek and Banks Channel, is located at the southern end of the island and is a migrating inlet that has been artificially stabilized and maintained for navigational purposes. The inlet's movement since the early 1900's was mainly to the southwest along a one-mile pathway (BROOKS, 1988; CLEARY and MARDEN, 1999; JOHNSEN *et al.*, 1999; CLEARY and FITZGERALD, 2003). In March 2002, the inlet was relocated about 3,000 ft north from a position about 50 ft north of the Shell Island Resort to its current position. It is a fairly small inlet in comparison to Rich Inlet with average depths ranging from 10 to 15 ft and a minimum width of about 340 ft (CLEARY and FITZGERALD, 2003). In early September 2003, a tidal prism of approximately ~211 x 10^6 ft^3 and an estimated ebb tidal delta volume of ~2.4 x 10^6 yd^3 was obtained from an ADCP survey during a flood tide; equivalent to a spring tidal range based on one year of tide gage data (JOHN WELSH, *pers. comm.*).

Storms

Since 1806, nearly 60 hurricanes have made landfall along the North Carolina shore; 16 of which made landfall along the Cape Fear region from Bald Head Island to Topsail Island vicinity (Figure 4). Hurricane Hazel, a Category 4 storm on the Saffir-Simpson scale, made landfall in 1954 near the North Carolina and South Carolina border and is arguably the most destructive storm to impact the Cape Fear region. Between 1955 and

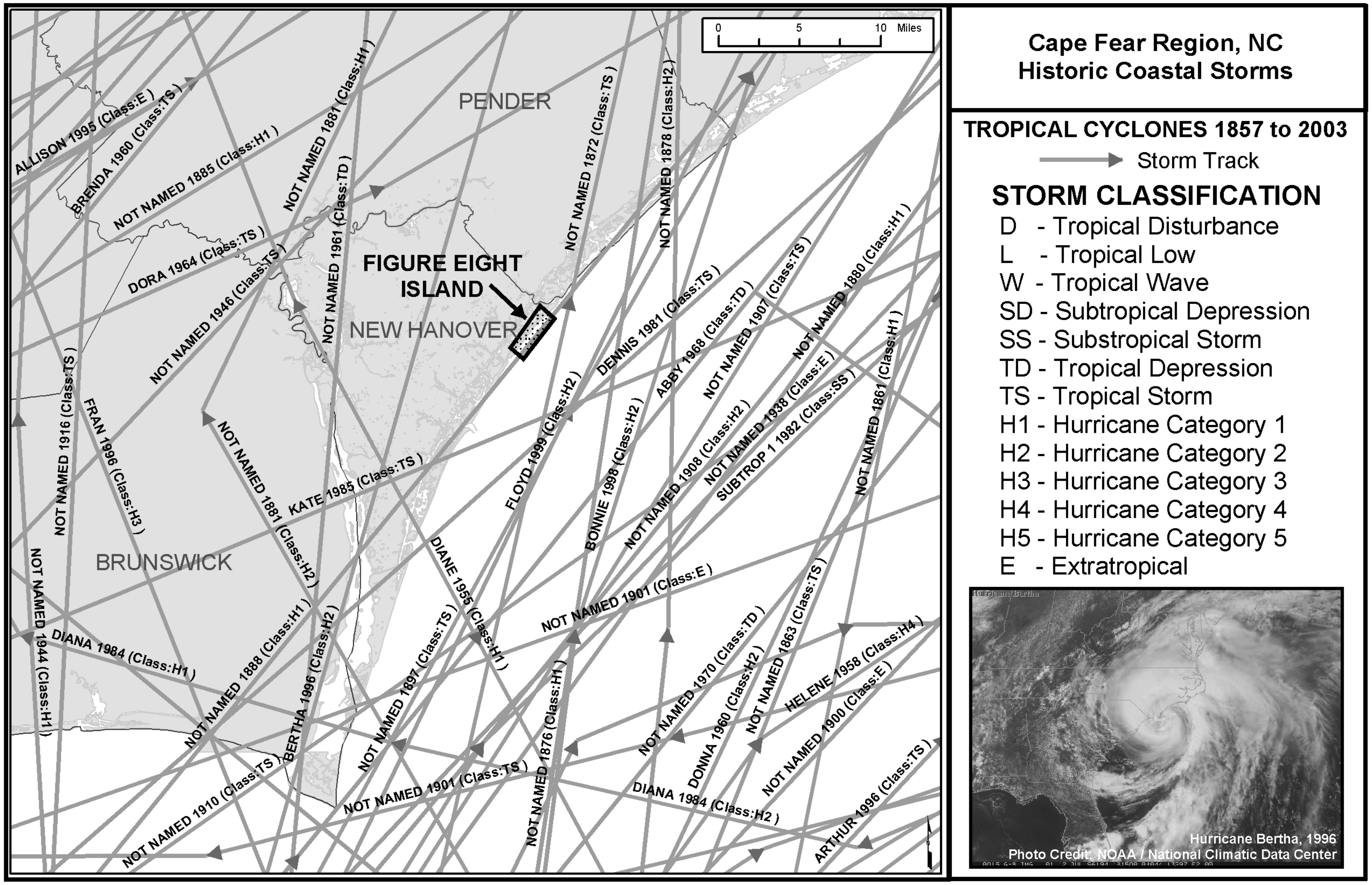

Figure 4. Major tropical systems affecting southwestern Onlsow Bay and Cape Fear Region from 1857 to 2003. (Source: NOAA)

1996, the region remained unaffected by a Category 3 or higher storm until Hurricane Fran made landfall in 1996. During the period from July 1996 through September 1999, four hurricanes (Bertha, Fran, Bonnie, and Floyd) ranging in scale from a Category 2 to 3 storm, made landfall within the region and caused substantial impacts to both beaches and property (HUDGINS, 2000; BARNES, 2001). However, it should be noted that impacts experienced along the shoreline were not only limited to land-falling storms but also included over 70 tropical systems passing offshore since 1870. Furthermore, extra-tropical storms or nor'easters have impacted the region causing substantial storm surge and heavy surf (HUDGINS, 2000; BARNES, 2001). Two notable extra-tropical systems, the Ash Wednesday storm of 1962 and February 1998 nor'easter, caused considerable shoreline erosion and property damage along coastal North Carolina.

Engineering Projects

Both long and short-term trends of shoreline erosion are often obscured by coastal engineering projects because the shoreline position is either stabilized or displaced seaward. At least 11 beach nourishment projects have taken place at various sites on the island since January 1972 to combat shoreline erosion (Figure 5). A summary of historical permits is provided in Appendix B. Nourishment activities have increased since the mid to late 1990's due an increase in tropical cyclone activity and the migration of Mason Inlet. Combined, these projects have utilized an estimated total volume just over 3×10^6 yd^3 of beachfill sand. The island is experiencing an increasing need for sand for erosion-prone shoreline segments along the northern and southern portion of the island. The majority of nourishment projects along the island have only utilized about 200,000 to 300,000 yd^3 of sand per project. Even though estimates suggested that

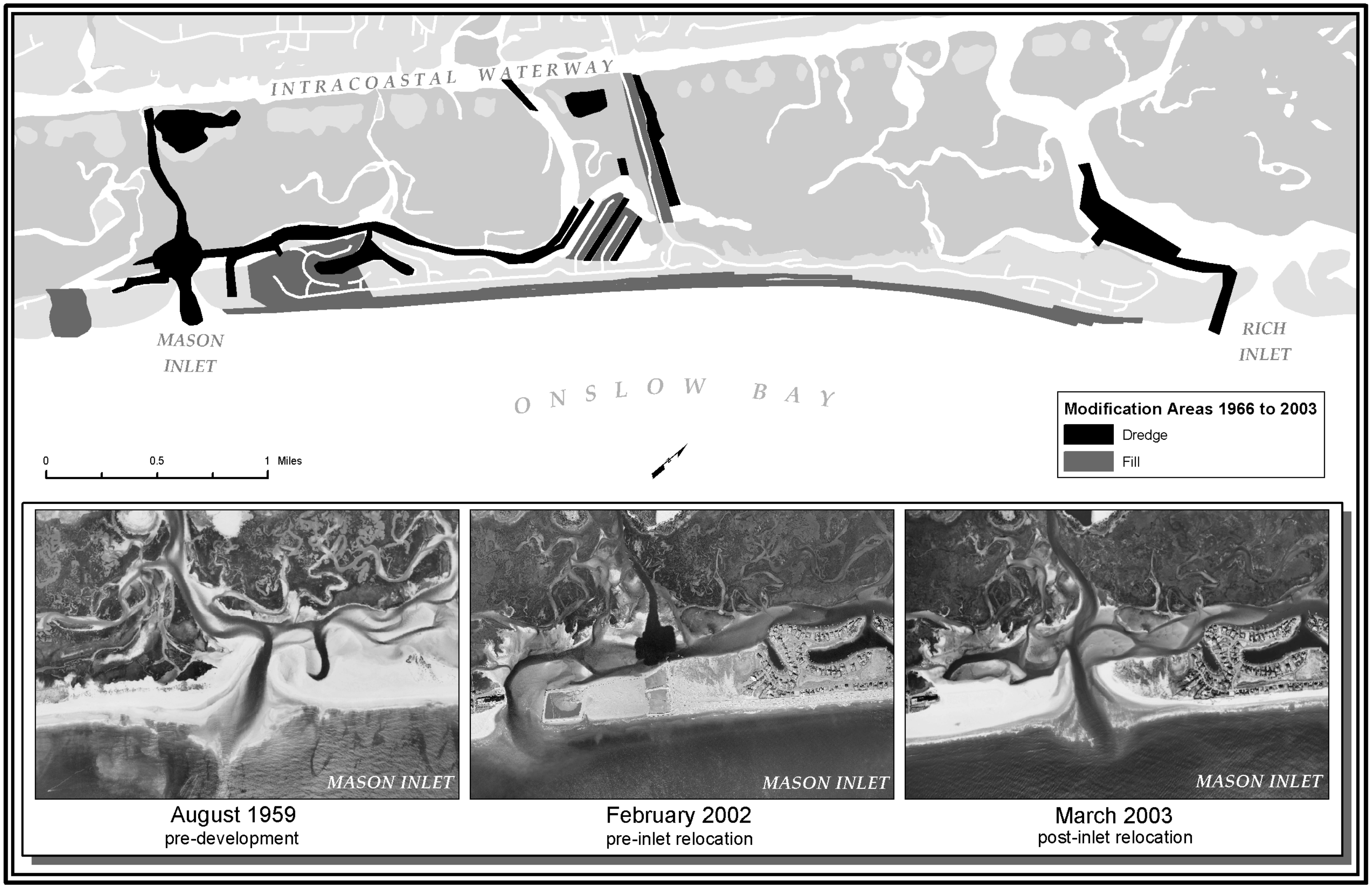

Figure 5. Areas affected by dredge and fill activities. Aerial photographs illustrate changes associated with island development and the recent relocation of Mason Inlet in 2002. The aerial photographs share identical spatial extents and scales.

island-wide beach nourishment projects should require about 4 to 5 x 10^6 yd^3 of sand to construct a berm with a width of ~150 ft, most projects have only utilized volumes of beachfill far less than 1 x 10^6 yd^3 of sand. This is partly due to regulatory policies and the availability of sand resources.

To date, property owners on Figure Eight Island have not been permitted to use hard structures for the prevention of oceanfront beach erosion. North Carolina's Administrative Code Title 15A, Chapter 7, Sections 07H.0308 and 07M.0200 (15A NCAC 07H .0308 and 15A NCAC 07H .0200) strictly prohibits the use of hard structures on oceanfront beaches, but, allows for the temporary emplacement of sandbags and permits beach scraping projects as long as they are based on sound engineering principles. Although several beach scraping activities took place during the 1980s, a major beach-bulldozing project took place shortly after Hurricane Fran in 1996 to refurbish the foredune system and restore the beach. Sandbags were placed along the northern 3000 ft stretch of shoreline fronting homes in 2000 after a shift in Rich Inlet's ebb channel promoted beach erosion in that area. Homeowners obtained a variance from the N.C. Coastal Resources Commission (NCCRC) and NCDCM in July 2003 to place additional sandbags on top of existing bags to increase elevation and protect against waves overtopping the bags.

Numerous dredging activities have taken place in inlet feeder channels and dredge-material islands along the AIWW for navigational purposes, beach nourishment, dune building, and island fill projects. The dredge-material islands behind Figure Eight Island were the result of dredging of the AIWW by the USACOE during the late 1920s. Initial dredge and fill activities on Figure Eight Island occurred during the mid-1960s when the island was being modified for development and infrastructure was being built. The causeway road was constructed over fill material placed in the backbarrier marsh while an expansive dune field and finger canals were constructed on southern end of the island. In 2001 and 2002, approximately 790,000 yd^3 of material was dredged from backbarrier marsh channels and southern spit to accommodate the relocation of Mason Inlet (Figure 5). Some of the sand was later used as fill material for the old inlet location and as beach nourishment material for the oceanfront.

METHODOLOGY

Historical records pertaining to natural physical processes, geologic features, and anthropogenic activities, such as those discussed above, are vital to the complete understanding of the evolution of a shoreline. Since the development of Figure Eight Island in the late 1960s, increasing advancements of technologies have afforded the capability to compile historical data of various types for rapid comparison both spatially and temporally, with a higher degree of accuracy. In the current study, a robust GIS database was created from historical shoreline data spanning nearly 150 years to quantify shoreline change, investigate long and short-term trends, and to ascertain both natural and anthropogenic influences. Shoreline change trends were obtained from analyses of three primary eras representing the development of the island: 1857 to 1966 (pre-development), 1966 to 2003 (development), and 1857 to 2003 (net).

Shoreline and Inlet Database

In order to establish the database, a series of historical near-vertical and vertical aerial photographs, orthophotographs, light detection and ranging (LIDAR) data, and National Ocean Service (NOS) T-sheets from various years were selected from collections archived at the USACOE' Wilmington District facility, North Carolina Department of Environment and Natural Resources (NCDENR), North Carolina Department of Transportation (NCDOT), NOAA Coastal Services Center, and consulting firms (Table 1). Ground control points from 1998 NCDENR digital orthophotos of the North Carolina coast and RTK GPS surveys were used during the map and image registration process. During the digitization process, the high-water line (HWL) was selected as the primary indicator of shoreline position (DOLAN *et al*., 1978, 1980, 1991; PAJAK and LEATHERMAN, 2002).

In the database, coverages of historical shorelines illustrate the open-ocean side of each barrier island and the ends that face inlets (Figure 2a). Consequently, some barrier islands do not have shoreline data for certain years due to gaps in available historical maps, aerial photography, and LIDAR coverages. Furthermore, because the island's length changed throughout time, some shorelines coverages did not contain all of the transect locations referenced in the study (Table 1, Figure 2a).

NOS T-Sheets

The earliest maps depicting reasonably accurate shoreline positions can be found on coastal survey maps from NOS, formally known as the United States Coast and Geodetic Survey topographic sheets (SHALOWITZ, 1964). These topographic sheets of the U.S. coastline, commonly referred to as T-sheets, were carefully constructed from plane-table surveys based on the position of the high-water line and not the mean high-water line as reported on the maps (SHALOWITZ, 1964). T-sheets have been admitted as evidence in courts and have been repeatedly upheld as accurate maps of shoreline position (SHALOWITZ, 1964). NOS T-sheets were digitized using a Calcomp™ digitizing tablet

Table 1. Shoreline data sources, associated agencies, and transect coverages.

Year	Source	Agency	Scale	Transects
1857 (-)	T-sheet 617 HWL	National Ocean Service	1:10,000	1 to 45
1880 (-)	T-sheet 1456 HWL	National Ocean Service	1:40,000	20 to 45
1888 (-)	T-sheet 617R HWL	National Ocean Service	1:10,000	15 to 46
1927 (Sep)	T-sheet 4249 HWL	National Ocean Service	1:20,000	17 to 53
1934 (Jan)	T-sheet 5043 HWL	National Ocean Service	1:20,000	15 to 53
1938 (May)	aerial photo HWL	U.S. Department of Agriculture	1:12,000	13 to 54
1945 (Jan)	aerial photo HWL	National Ocean Service	1:20,000	14 to 51
1949 (Nov)	aerial photo HWL	National Archives and Records	1:20,000	12 to 51
1956 (Mar)	aerial photo HWL	National Ocean Service	1:12,000	10 to 51
1959 (Aug)	aerial photo HWL	National Ocean Service	1:12,000	9 to 52
1966 (Mar)	aerial photo HWL	U.S. Army Corps of Engineers	1:12,000	9 to 51
1972 (Oct)	T-sheet 00700 HWL	National Ocean Service	1:10,000	8 to 45
1974 (Dec)	aerial photo HWL	NC Department of Transportation	1:12,000	9 to 51
1980 (Jul)	aerial photo HWL	U.S. Army Corps of Engineers	1:12,000	7 to 51
1984 (Sep)	aerial photo HWL	National Ocean Service	1:40,000	8 to 50
1989 (Oct)	aerial photo HWL	U.S. Army Corps of Engineers	1:12,000	6 to 51
1993 (Mar)	orthophoto HWL	U.S. Geological Survey	1:12,000	4 to 54
1996 (Aug)	aerial photo HWL	U.S. Army Corps of Engineers	1:12,000	3 to 54
1996 (Oct)	LIDAR	NOAA	-	1 to 53
1997 (Sep)	LIDAR	NOAA	-	1 to 52
1998 (Feb)	orthophoto HWL	New Hanover County	1:12,000	2 to 53
1998 (Jun)	orthophoto HWL	NCDENR	1:12,000	1 to 53
1998 (Sep)	LIDAR	NOAA	-	1 to 53
1999 (Sep)	LIDAR	NOAA	-	1 to 53
2000 (Aug)	LIDAR	NOAA	-	2 to 53
2002 (Feb)	orthophoto HWL	New Hanover County	1:12,000	1 to 54
2002 (May)	aerial photo HWL	U.S. Army Corps of Engineers	1:12,000	7 to 54
2003 (Jan)	orthophoto HWL	Gahagan & Bryant Associates	1:12,000	8 to 54
2003 (Mar)	aerial photo HWL	U.S. Army Corps of Engineers	1:12,000	8 to 54
2003 (May)	orthophoto HWL	Gahagan & Bryant Associates	1:12,000	7 to 54
2003 (Aug)	RTK GPS HWL	Trimble 5700 RTK GPS Survey	-	6 to 53

and ArcView™ GIS v.3.2a software. Once the map was registered, the HWL was digitized into an ArcView polyline shapefile and attributed. Digital shorelines of vectorized NOS T-sheets from 1934 and 1972 were also obtained from NOAA.

Aerial Photography

Aerial photographs were selected that provided the most complete coverage of oceanfront and inlet-facing shorelines. In some instances, island-wide coverage could not be obtained due to the limited area of flight paths during a particular year. Onscreen digitization of aerial photographs involved scanning and photorectification using an EPSON® Perfection® 1650 scanner and ERDAS Imagine® 8.6 photogrammetric software. Once an image was rectified and exported as a georeferenced TIFF file, the HWL, ebb channels, and ebb deltas were digitized in ArcView™ at a scale of 1:1,000 or greater as a polyline shapefile for the specified date of the photograph. Digital orthophotographs were also digitized using this method.

LIDAR

The LIDAR dataset was downloaded via the Internet from the NOAA Coastal Service Center's website in ESRI® Shapefile™ format. Once the data were downloaded, they were viewed in ArcView™ for any discrepancies or errors. The 0, 2, and 4-ft contours were selected and exported to separate shapefiles and imported into ArcInfo™ v.8.2. Numerous contours, adjacent to primary shoreline contours, demarking small beach features were removed in order that the shoreline change analysis program work properly. Otherwise, the program would identify those secondary features as the shoreline and base calculations off of those points rather than the actual shoreline. The 4-ft contour was ultimately used as the primary shoreline indicator because it best approximated the HWL. New shoreline coverages were built in ArcInfo™, utilizing both the CLEAN and GENERALIZE commands, and re-exported as ESRI® shapefiles for shoreline change analyses in ArcView™.

Real-time Kinematic GPS

Field surveys of the HWL were conducted using a Trimble® 5700 Real-time kinematic (RTK) GPS system. The system allows for precise measurements of points Earth's surface that can be referenced to a number of horizontal coordinate systems and vertical datums. The HWL was mapped both by walking and riding an all-terrain vehicle over the HWL taking measurements every 3 feet. Point data derived from the surveys were extracted from the GPS, imported into ArcView™, and converted into a polyline shapefiles.

Shoreline Position Error

Shoreline position errors are expected to occur due to a combination of "built in" errors in digitization techniques, photo/map quality, and human ability (ANDERS and BYRNES, 1991; CROWELL *et al*., 1991; DOLAN *et al*., 1980: DOUGLAS and CROWELL, 2000; MOORE, 2000; DANFORTH and THIELER, 1992a & b; and THIELER and DANFORTH, 1994a & b). Because all shoreline positions have some degree of inaccuracy, such errors should be reported so that rate-of-change calculations may be interpreted and used judiciously. Table 2 provides a summary of worst-case shoreline position errors associated with various shoreline data sources.

In order to aid in the estimation of the position error of a shoreline, the root-mean-square error (RMSE) equation is calculated by comparing predicted points from a registered map or aerial photo against the actual points referenced on a highly controlled basemap or orthophoto. Residuals (R) are calculated by subtracting the actual values from the predicted values for both x and y coordinate pairs. Once residuals for at least three coordinate pairs are calculated, RMSE is:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(R_{x_i}^{\;2} + R_{y_i}^{\;2}\right)} \tag{1}$$

Error reduction and quality control of digitized aerial photography were accomplished by recalculation of RMSE values from randomly selected points across registered aerial photographs using the 1998 orthophotos as a standard. During the georeferencing process, a target RMSE value of less than 15 ft was sought per photo and easily obtained from higher quality controlled imagery. Older imagery from the 1930s to 1960s generally contained more distortion and produced higher RMSE values because of stretching, shrinking, and warping of the photographic paper or medium. Such images and their RMSE values were noted in the GIS database. Unfortunately, due to limited technology, NOS T-Sheets often contain elevated RMSE values (ANDERS and BYRNES, 1991). Studies have proposed worst-case error estimates of up to ~28 ft for T-sheets shoreline positions to estimate mapping inaccuracies (CROWELL *et al*., 1991). Nevertheless, subsequent error analyses conducted by the same authors of several case studies show the level of error is likely far less than the worst-case estimate (CROWELL *et al*., 1991).

RMSE calculations obtained during the rectification of maps and aerial photos do not necessary account for all errors in the position of a shoreline. Studies have also shown that a number of factors such as map or photo scale, line-width of a plotted shoreline on a map, and interpretation of the high-water line also limit shoreline accuracy (DOLAN *et*

Table 2. Summary of estimated worst-case shoreline position errors.

Potential Error Source	Scale	Error (ft)	Reference
	HWL Displacement		
medium-sized sand beach with a slope 3º to 6º (Atlantic Coast)[A]	1:1	7	DOLAN et al., 1980
storms (Atlantic Coast)[B]	1:1	100	MOORE, 2000
	Maps and Aerial Photography		
NOS T-sheets (1844-1880)[C]	1:10,000	29	CROWELL et al., 1991
NOS T-sheets (1880-1930)[D]	1:10,000	28	CROWELL et al., 1991
NOS T-sheets (from aerials)[E]	1:10,000	20	CROWELL et al., 1991
USGS Quadrangles[F]	1:24,000	40	National Map Accuracy Standards
aerial photography[G]	1:10,000	25	CROWELL et al., 1991
	GPS and LIDAR Surveys[1]		
RTK GPS[H]	1:1	3	-
LIDAR[I]	-	3	-
	Shoreline Position Measurement		
digitizer error[J]	1:10,000	16	ANDERS and BYRNES, 1991
operator error[K]	1:10,000	8	CROWELL et al., 1991

Era[2]	Elapsed Time (years)	Error Source	Annualized Shoreline Position Error (± ft/yr)[3]
1857 to 1966	109.28	A, C, G, J, K	0.39
1927 to 1966	38.50	A, E, G, J, K	0.96
1966 to 2003	37.45	A, G, H, J, K	0.84
1857 to 2003	146.73	A, C, H, J, K	0.24
1927 to 2003	75.95	A, E, H, J, K	0.36

[1]Based on estimates from the current study.
[2]Primary time periods selected in this study to estimate long and short-term shoreline change rates.
[3]Annualized shoreline position error calculation is provided in Appendix C.

al., 1980; CROWELL *et al*., 1991; MOORE, 2000; THIELER and DANFORTH, 1994 a & b). Field interpretations of HWL during RTK-GPS surveys were not without error. The curvilinear nature of the swash terminus along with heavy mineral lags and newly deposited wind-blown sand distorted the location of the HWL in certain places (Appendix A). Hence, along some places of the mapped shoreline an error of 1 to 3 ft existed in the vectorized point data. In the current study, total position error estimates ranged 15 to 20 ft for shorelines mapped from aerial photography, 20 to 28 ft for T-sheets, and 1 to 3 ft for RTK surveys (Table 2).

Measurement of Shoreline and Inlet-Related Changes

To date, a standardized method of calculating shoreline change and rate statistics has yet to be adopted collectively by government, public, and private institutions. Fortunately, tools currently available such as the Digital Shoreline Analysis System (DSAS) (THIELER and DANFORTH 1992a & b; THIELER *et al*., 2003) provide thorough calculations of shoreline change rates and are becoming increasingly integrated with GIS. An extension for ArcView™ called SCARPS (Simple Change Analysis of Retreating and Prograding Systems) was developed by the author and used as the primary method of calculating shoreline position changes and rates.

All digital shoreline files were projected to North Carolina state plane projection (4901), NAD 1983 datum, GRS 1980 spheroid, and feet map units prior to analysis. Shoreline change was calculated by measuring the position differences of the HWL between each historical shoreline within the GIS. Given that LIDAR shorelines are not HWL positions, separate analyses were conducted to include LIDAR shorelines while other analyses concentrated solely on shorelines sharing a common datum. For each analysis, shoreline change transects were cast shore normal from a baseline and spaced at 50-ft intervals from each other during analyses. However, results presented here are from shoreline change analyses with a spacing of 500 ft between each transect (Figure 2a). These analyses were comparable to those utilizing 50-ft spacing between transects and were easier to display in maps and graphs. Shoreline rate-of-change models and statistics were computed using calculation methods summarized in Table 3. A detailed explanation of each shoreline change calculation is provided in Appendix C. The end-point rate (EPR) and "least-squares fit" linear regression rate (LRR) calculation, widely used by state and local agencies (National Research Council, 1990), were the primary models used to estimate both long-term and short-term shoreline change rates for the current study. Even though shoreline change is not necessarily a linear process, especially adjacent to inlets, these models provide the best approximation of annual change rates (CROWELL *et al*., 1991). Baselines were also erected from across both inlets, from Figure Eight Island to the adjacent barrier island, for measurements of the ebb channel orientation, channel midpoint position, inlet width, and ebb delta change.

In order to verify the accuracy of the results, the DSAS extension for ArcView GIS was used to generate erosion and accretion rates along the same transects constructed by SCARPS. Manual measurements of shoreline change were made onscreen within the GIS to verify the values obtained from both programs to further assure the quality of the results. Utilizing values obtained from each shoreline change rate method, SCARPS was also used to forecast future shoreline positions by erecting a new shoreline for a chosen number of years into the future.

Table 3. Comparison of shoreline change calculations.

Calculation	Advantage	Disadvantage	GIS Procedure	Reference
end-point rate (EPR)	requires only two shorelines; summation of all shoreline influences	neglects data between oldest and youngest shoreline	SCARPS, DSAS	DOLAN *et al*., 1991; APPENDIX C
linear regression rate (LRR)	utilizes all shoreline data, widely accepted computational method	affected by outliers; tends to underestimate rates	SCARPS, DSAS	DOLAN et al., 1991; APPENDIX C
average of end-point rates (AER)	provides comparable long-term rates to EPR and LRR	tends to overestimate short-term rates	SCARPS	APPENDIX C
average of rates (AOR)	incorporates shoreline position errors; attempts to remove shoreline data with higher postion errors	no computational norm for the minimum time span equation; produces highely varied rates when compared to LRR and EPR	DSAS	FOSTER and SAVAGE, 1989; DOLAN et al., 1991
jackknife rate (JKK)	less susceptible to outlier effects than LRR; purely computational method	involves numerous computations, requires many shorelines	DSAS	DOLAN *et al*., 1991
average of eras rates (AOE)	provides an overall average for all combined eras	not a common method of generating rates	DSAS	THIELER *et al*., 2003
standard devation of rates (SOR)	measures the variability of rates about the mean for all eras	does not provide a rate calculation	DSAS	THIELER *et al*., 2003
variance of rates (VOR)	employs a common statistical computation	does not provide a rate calculation	DSAS	THIELER *et al*., 2003
standard devation of changes (SDC)	provides a measure of shoreline position fluctuation; incorporates shoreline change measured between each data point to the oldest shoreline in the dataset	does not provide a rate calculation	SCARPS	APPENDIX C
average zone change (AZC)	summarizes the average shoreline change along a shoreline segment; aids in characterizing shoreline response to various influences	dependent on subjective interpretation of zone location; the location of a zone might move over time	manual	APPENDIX C
average zone rates (AZR)	determines average shoreline change rates along a shoreline segment; assigns a single rate to an entire shoreline segment	dependent on subjective interpretation of zone location; the location of a zone might move over time	manual	APPENDIX C

Delineation of Shoreline Change Zones

Although many factors influence shoreline change on an island-wide scale, it can be expected that the magnitude of accretion or erosion can increase or decrease near an inlet over a relatively short time period. A study conducted by FENSTER and DOLAN (1996) attempted to statistically assess the spatial extent of inlet impacts on adjacent shorelines. Based on data from a portion of the Outer Banks of North Carolina and the Virginia coast, their study concluded that inlets might influence shoreline change trends in a zone up to eight miles along a barrier island (FENSTER and DOLAN, 1996).

In the current study, it was hypothesized that a barrier island would have a least three basic shoreline change zones; two of which are primarily inlet-influenced and one of which is a transition zone of variable length. A shoreline change zone is defined as a segment of the shoreline displaying an overall difference in magnitude of erosion or accretion from adjacent reaches due to one primary influencing factor, such as an inlet, or combination of factors. Identifying these zones is critical because they provide a better understanding of the evolution of the barrier island's shoreline in response to various influences. The study attempted to combine both qualitative and quantitative methods to delineate these areas. In order to assist with the delineation of shoreline segments, ArcGIS™ GeoStatistical Analyst™ surface maps of cumulative shoreline change for all dates in the dataset were used to identify patterns along the island through time. Each plot was compared with maps of historical shoreline, inlet ebb-channels, and ebb delta positions (Figure 2b) to determine which transects were directly affected by inlet processes. Standard deviation of shoreline position change and rate-of-change statistics were also used to assist with grouping transects into zones. Identification of re-curved spits, scarps, overwash fans, sand dunes, and peat exposures on aerial photography provided another dimension to the analyses.

RESULTS

Shorelines are dynamic features in a constant state of change. CAMFIELD and MORANG (1996) suggested that at least 10 years of continuous shoreline data are needed to interpret short-term trends and at least 50 years of data are needed for deciphering long-term trends. Factors influencing shoreline change such as sea-level rise, geologic framework, coastal storms, and inlets, work in concert with one another but vary both spatially and temporally. Although the dataset for Figure Eight Island provided only snapshots in time of shoreline position, each shoreline represented the cumulative effects of all factors influencing change. Unfortunately, no established methods exist that are able to statistically relate the geologic framework, which is thought to influence change (RIGGS *et al.*, 1995; CLEARY *et al.*, 1999), or other factors to long-term erosion (HONEYCUTT *et al*., 2002). Therefore, only apparent shoreline change trends and influences may be ascertained from statistical analyses of the dataset and visual inspections of aerial photographs.

This study focused on two major aspects of shoreline change along Figure Eight Island, island-wide and zone-wide, to facilitate the determination of trends. The results from island-wide shoreline change analyses are presented in Table 4 and from zone-wide analyses in Table 5. Shoreline change rates along each transect for the 1857 to 1966 (pre-development), 1966 to 2003 (development), and 1857 to 2003 (net) eras are summarized in Table 4. Zone-wide analyses focused primarily on relating shoreline change trends of island-wide analyses to inlet morphodynamics, storms, and anthropogenic activity. All shoreline change rates reported below, unless otherwise noted, are in terms of the EPR calculation method. Furthermore, the term “average” is used to refer to the arithmetic mean. Shoreline change maps depicting graphs of EPR, LRR, AER, and standard deviation calculations, along with the ranges between eras, are provided in Appendix D.

Island-wide Shoreline Change

1857 to 1966 (pre-development)

The earliest known record of Figure Eight Island can be traced to the original royal land grant to James Moore in 1762 (NADEAU, 1998). Local people often referred to the island as “The Banks” or “Foy Island” prior to being officially dubbed “Figure Eight Island” during the early stages of development in the 1960s (NADEAU, 1998). The first detailed map of the island’s shoreline is a NOS T-sheet from 1857 (Figure 6). Nixon Inlet is depicted on the T-sheet at a location of about one mile south of present day Rich Inlet (Figure 6). During that time, a middle-ground shoal separated Nixon Inlet from Rich Inlet. Subsequent to Nixon Inlet’s closure in 1888, the middle-ground shoal became incorporated into Figure Eight Island, which added about 4,000 ft to the length of the shoreline at the northern end of the island (Figure 6). Throughout the period from 1857 to 1888, the shoreline accreted an average of +170 ft at a rate of approximately +5.5 ft/yr. During this time, the length of the island was considerably reduced from 4.9 miles to its shortest known length of 2.9 miles following the opening of Mason Inlet in 1888 (Figures 2 & 6). Between 1888 and 1934, subsequent to Nixon Inlet’s closing, the island’s length increased to 3.7 miles as the northern middle-ground shoal attached to the barrier (Figure 6). Unlike the previous time period, the shoreline retreated an average of -455 ft along

Table 4. Summary of shoreline change end-point rates (EPR), linear regression rates (LRR), and average of end-point rates (AER) for each transect.

Transect	Pre-development (ft/yr)				Development (ft/yr)				Net (ft/yr)		
	Era	EPR	LRR	AER	Era	EPR	LRR	AER	EPR	LRR	AER
1	1857 to -	-	-	-	1996 to 2002	1.0	14.7	-26.8	-2.1	-2.3	-2.4
2	1857 to -	-	-	-	1996 to 2002	-23.3	-11.4	-50.1	-2.1	-1.8	-1.8
3	1857 to -	-	-	-	1996 to 2002	5.6	-1.2	97.6	-1.6	-1.5	-1.5
4	1857 to -	-	-	-	1993 to 2002	7.7	7.6	18.6	-1.6	-1.5	-1.5
5	1857 to -	-	-	-	1993 to 2002	6.1	5.7	8.5	-1.0	-1.1	-1.1
6	1857 to -	-	-	-	1989 to 2003	-9.6	-1.9	6.9	-2.3	-1.1	-1.1
7	1857 to -	-	-	-	1980 to 2003	2.0	0.1	2.9	-1.1	-1.2	-1.2
8	1857 to -	-	-	-	1972 to 2003	2.3	0.8	7.0	-1.6	-1.1	-1.3
9	1857 to 1966	-0.9	-1.6	-1.7	1966 to 2003	-3.6	-2.4	-1.9	-1.6	-1.1	-1.2
10	1857 to 1966	-0.3	-1.2	-1.3	1966 to 2003	-4.2	-2.4	-4.7	-1.3	-1.1	-1.2
11	1857 to 1966	-0.5	-1.0	-1.1	1966 to 2003	-3.3	-1.1	-4.3	-1.2	-1.0	-1.1
12	1857 to 1966	-0.8	-1.1	-1.1	1966 to 2003	-1.8	0.2	-2.6	-1.0	-0.8	-1.1
13	1857 to 1966	-1.0	-0.9	-0.9	1966 to 2003	-1.2	0.9	-1.6	-1.0	-0.9	-1.0
14	1857 to 1966	-1.1	-1.0	-0.7	1966 to 2003	-0.1	1.5	-1.0	-0.8	-0.9	-0.9
15	1857 to 1966	-1.0	-0.4	-0.9	1966 to 2003	-0.1	1.5	-0.7	-0.8	-0.7	-0.9
16	1857 to 1966	-1.0	-2.7	1.7	1966 to 2003	0.8	1.6	-0.6	-0.5	-2.2	-0.1
17	1857 to 1966	-1.2	-3.4	1.7	1966 to 2003	1.6	1.9	-0.1	-0.5	-2.5	-0.1
18	1857 to 1966	-1.7	-3.7	1.3	1966 to 2003	2.8	2.5	1.2	-0.5	-2.4	-0.4
19	1857 to 1966	-2.0	-3.6	0.8	1966 to 2003	3.7	3.2	2.5	-0.6	-2.2	-0.5
20	1857 to 1966	-2.1	-2.2	0.1	1966 to 2003	4.7	3.4	4.0	-0.4	-1.4	-0.6
21	1857 to 1966	-1.8	-1.5	-0.3	1966 to 2003	3.8	2.4	3.0	-0.4	-1.2	-0.7
22	1857 to 1966	-1.5	-1.4	-0.4	1966 to 2003	3.0	2.4	1.5	-0.4	-1.1	-0.8
23	1857 to 1966	-1.3	-1.0	-0.8	1966 to 2003	1.8	1.9	0.4	-0.5	-0.9	-0.9
24	1857 to 1966	-1.0	-0.8	-1.0	1966 to 2003	1.8	1.7	-0.5	-0.3	-0.7	-0.9
25	1857 to 1966	-1.1	-0.8	-1.3	1966 to 2003	2.6	1.9	-0.2	-0.2	-0.6	-1.0
26	1857 to 1966	-1.2	-0.5	-1.5	1966 to 2003	3.1	2.3	0.3	-0.1	-0.4	-1.0
27	1857 to 1966	-1.4	-0.5	-1.9	1966 to 2003	3.5	2.9	1.0	-0.2	-0.3	-1.2
28	1857 to 1966	-1.2	-0.4	-1.4	1966 to 2003	3.9	3.1	1.7	0.1	-0.1	-0.9
29	1857 to 1966	-1.6	-0.8	-1.9	1966 to 2003	3.6	3.2	1.4	-0.3	-0.3	-1.3
30	1857 to 1966	-1.8	-1.1	-2.1	1966 to 2003	3.6	3.4	1.8	-0.4	-0.4	-1.4
31	1857 to 1966	-1.8	-1.0	-1.8	1966 to 2003	4.2	3.4	2.3	-0.3	-0.4	-1.2
32	1857 to 1966	-2.1	-1.3	-2.3	1966 to 2003	4.3	3.4	2.6	-0.5	-0.4	-1.5
33	1857 to 1966	-2.6	-1.9	-3.1	1966 to 2003	4.3	3.7	2.3	-0.9	-0.7	-2.1
34	1857 to 1966	-2.9	-2.3	-3.3	1966 to 2003	4.7	4.6	2.3	-1.0	-0.7	-2.3
35	1857 to 1966	-3.3	-2.7	-3.8	1966 to 2003	5.4	5.0	3.4	-1.1	-0.7	-2.5
36	1857 to 1966	-4.1	-3.5	-4.6	1966 to 2003	5.7	4.9	4.3	-1.6	-1.0	-3.1
37	1857 to 1966	-4.7	-4.3	-5.0	1966 to 2003	6.5	5.7	5.2	-1.8	-1.3	-3.5
38	1857 to 1966	-3.9	-4.4	-3.1	1966 to 2003	6.8	5.9	5.8	-1.2	-1.2	-2.3
39	1857 to 1966	-5.3	-5.9	-5.4	1966 to 2003	6.9	6.1	6.3	-2.2	-1.6	-3.8
40	1857 to 1966	-6.5	-6.8	-7.3	1966 Era 2003	7.0	6.0	6.9	-3.0	-1.8	-5.0
41	1857 to 1966	-6.3	-6.9	-7.0	1966 to 2003	6.8	6.2	7.5	-3.0	-1.6	-4.7
42	1857 to 1966	-6.0	-7.2	-6.6	1966 to 2003	7.0	5.9	8.6	-2.7	-1.3	-4.4
43	1857 to 1966	-5.4	-6.8	-5.8	1966 to 2003	6.0	5.0	8.7	-2.5	-1.0	-3.7
44	1857 to 1966	-4.4	-6.0	-4.7	1966 to 2003	4.7	3.6	9.4	-2.1	-0.4	-2.8
45	1857 to 1966	0.9	-1.6	1.9	1966 to 2003	1.5	0.7	6.8	1.1	1.5	1.8
46	1888 to 1966	-6.2	-5.0	-11.2	1966 to 2003	-0.6	-0.6	4.3	-4.3	1.2	-5.8
47	1927 to 1966	8.2	9.8	8.2	1966 to 2003	-2.4	-2.6	2.8	2.9	4.0	6.3
48	1927 to 1966	8.3	11.3	2.9	1966 to 2003	-5.8	-6.6	0.3	1.4	3.3	4.1
49	1927 to 1966	9.3	12.1	2.7	1966 to 2003	-6.8	-8.4	-1.7	1.4	3.0	3.8
50	1927 to 1966	6.3	8.2	2.3	1966 to 2003	-3.6	-2.3	-0.6	1.4	3.1	3.1
51	1927 to 1966	-6.6	-2.4	0.6	1966 to 2003	10.2	10.3	16.2	1.6	4.4	2.5
52	1927 to 1959	11.5	11.0	20.2	1993 to 2003	-28.3	-53.4	-2.8	1.5	1.5	7.2
53	1927 to 1938	63.8	59.5	34.2	1993 to 2003	-46.0	-36.8	-34.9	0.9	0.9	8.1
54	1938 to -	-	-	-	1993 to 2003	-44.9	-27.9	-56.7	-4.3	-3.4	-2.6

Table 5. Summary of zone-wide shoreline changes and rates.

ERA*		SHORELINE CHANGE (ft)				SHORELINE CHANGE EPR (ft/yr)			
		Zone I	Zone II	Zone III	Zone IV	Zone I	Zone II	Zone III	Zone IV
	Transects:	9 to 16	17 to 34	35 to 45	46 to 51	9 to 16	17 to 34	35 to 45	46 to 51
		Pre-development Era							
1857/01/01 to 1966/03/18		-88.9	-184.4	-485.2	-	-0.8	-1.7	-4.4	-
1927/09/27 to 1966/03/18		-	-	-	213.8	-	-	-	5.6
		Development Era							
1966/03/18 to 2003/08/22		-63.2	126.5	218.5	-56.1	-1.7	3.4	5.8	-1.5
		Net							
1857/01/01 to 2003/08/22		-152.1	-57.9	-266.7	-	-1.0	-0.4	-1.8	-
1927/09/27 to 2003/08/22		-	-	-	157.7	-	-	-	2.1
		Aerial Photography							
1938/05/17 to 1945/01/23		-72.7	-12.0	-33.8	-275.4	-10.9	-1.8	-5.0	-41.1
1945/01/23 to 1949/11/15		31.7	-22.2	-12.3	79.8	6.6	-4.6	-2.6	16.6
1949/11/15 to 1956/03/25		-83.3	-38.2	33.8	323.2	-13.1	-6.0	5.3	50.8
1956/03/25 to 1959/08/16		-37.0	-50.7	-36.4	107.0	-10.9	-14.9	-10.7	31.5
1959/08/16 to 1966/03/18		68.4	-17.1	-34.1	-155.9	10.4	-2.6	-5.2	-23.6
1966/03/18 to 1974/12/01		-49.1	-18.7	79.6	81.6	-5.6	-2.1	9.1	9.4
1974/12/01 to 1980/07/21		-22.3	27.8	72.5	93.5	-4.0	4.9	12.9	16.6
1980/07/21 to 1984/09/15		-26.1	-39.1	-106.3	-214.9	-6.3	-9.4	-25.6	-51.7
1984/09/15 to 1989/10/05		-6.5	-11.3	43.2	54.3	-1.3	-2.2	8.5	10.7
1989/10/05 to 1993/03/06		9.6	37.7	17.3	123.0	2.8	11.0	5.1	36.0
1993/03/06 to 1996/08/09		1.1	1.6	18.7	48.6	0.3	0.5	5.5	14.2
1996/08/09 to 1998/02/17		-12.7	-39.9	-14.7	-86.5	-8.3	-26.1	-9.6	-56.7
1998/02/17 to 1998/06/19		64.4	92.6	111.2	71.8	192.8	277.2	332.8	214.9
1998/06/19 to 2002/02/20		52.4	52.4	1.3	-269.4	14.3	14.2	0.4	-73.3
2002/02/20 to 2002/05/16		-37.0	6.1	-14.2	-16.6	-158.9	26.1	-60.9	-71.1
2002/05/16 to 2003/01/15		-34.0	-7.2	-3.8	-16.4	-50.8	-10.8	-5.7	-24.5
2003/01/15 to 2003/03/10		24.9	-19.3	-17.3	-13.2	168.2	-130.4	-116.9	-89.5
2003/03/10 to 2003/05/11		-27.7	-2.8	-1.4	15.8	-162.9	-16.6	-8.4	93.0

*date format = yyyy/mm/dd

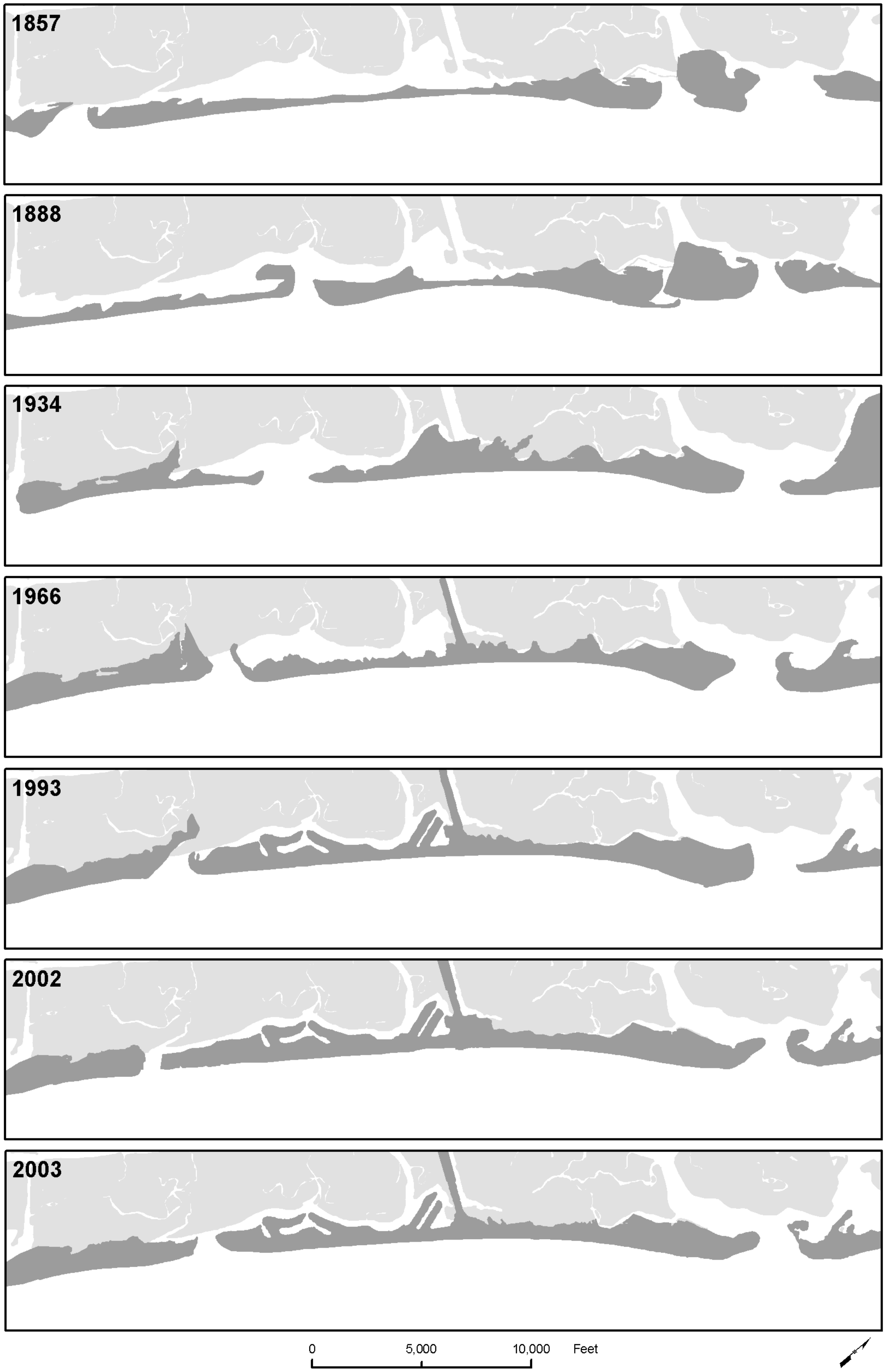

Figure 6. Shoreline morphology of Figure Eight Island from 1857 to 2003.

the island at rate of approximately -9.9 ft/yr. During the period from 1934 to 1966, about two-thirds of the island continued to experience shoreline erosion. Along transects 15 through 37, erosion rates ranged between -0.1 and -5.1 ft/yr. The northern portion of the island experienced net accretion ranging from +0.3 to 12.1 ft/yr along transects 38 through 51.

Overall, estimated shoreline change EPRs, LRRs, and AERs for the pre-development era, spanning the period from 1857 to 1966, ranged from -0.9 to -6.5 ft/yr along transects 9 through 46 and gradually increased in magnitude from the southern to northern portion of the shoreline segment (Figure 7 & Table 4). Substantial deviations in shoreline change rates occurred near Rich Inlet along transects 46 to 53 (Figure 7). In this region, the shoreline accreted at rates between +0.9 and +63.8 ft/yr during the period from 1927 to 1966 (Table 4).

1966 to 2003 (development)

Since 1966, some form of anthropogenic activity such as beach scraping or beach nourishment has altered nearly all of the island's oceanfront shoreline. Between 1966 and 1993, the southern half of the island experienced net erosion along transects 9 through 27. The average shoreline change along this region was -55 ft at a rate of -2.0 ft/yr. Conversely, the northern portion of the island accreted an average of +103 ft at rate of +3.8 ft/yr along transects 28 to 54. Since 1993, several beach renourishment projects occurred along either a portion of, or the entire length of the island's shoreline. As a result, during the period from 1993 to 2002, the shoreline along transects 4 through 45 accreted an average of +101 ft at a rate of +11.3 ft/yr. However, along transects 46 to 54, near Rich Inlet, the shoreline lost an average of -246 ft at an EPR of -27.5 ft/yr. Between

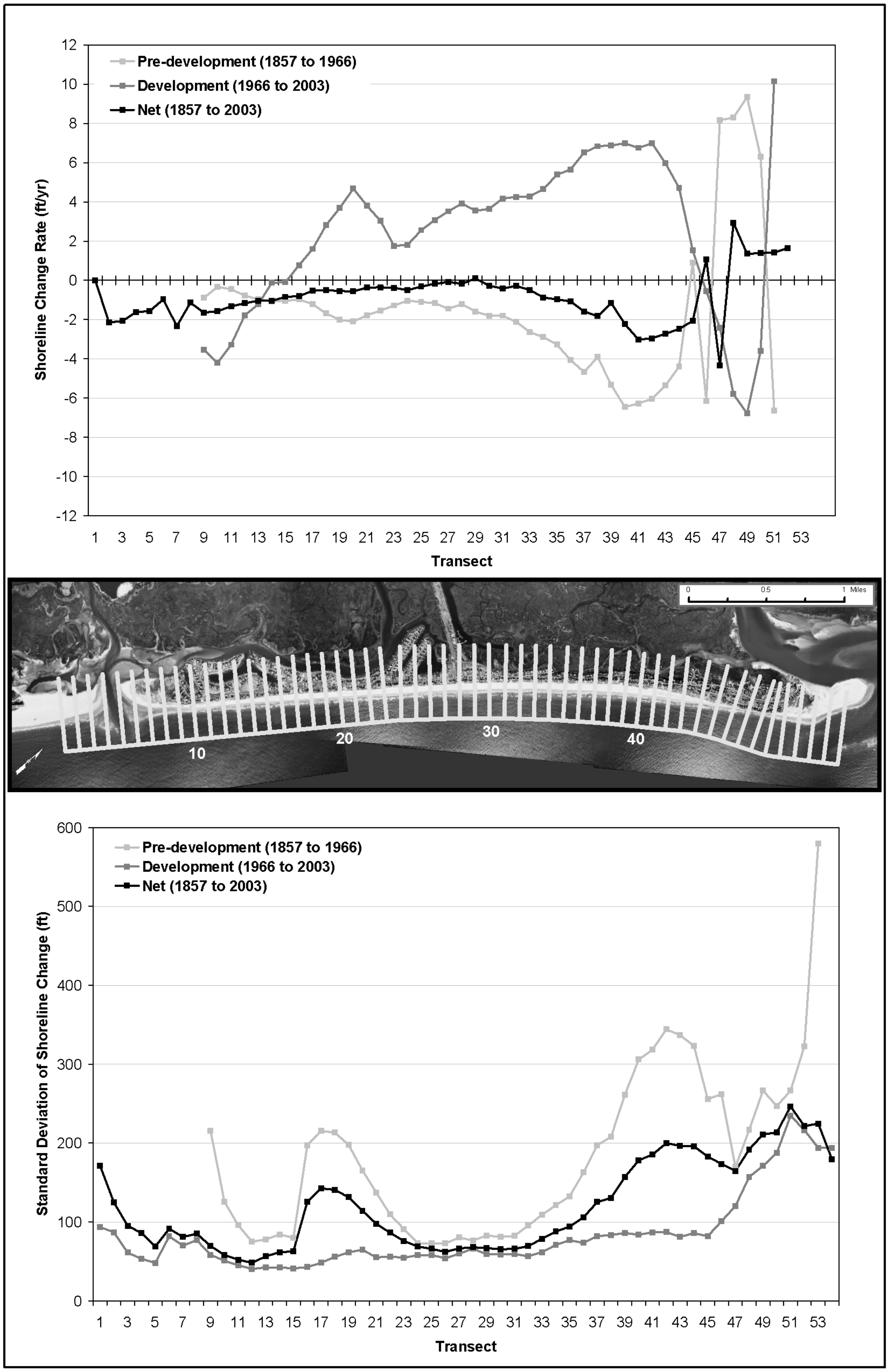

Figure 7. Standard deviation and shoreline change rates for the time periods 1857 to 1966, 1966 and 2003, and 1857 to 2003. Map of transect locations used to calculate shoreline change statistics.

February 2002 and March 2003, the average shoreline change along the entire island was -37 ft.

Throughout the entire development era, along the central portion of the island, net shoreline change rates ranged from +0.8 to +7.0 ft/yr between transect 16 and 45 (Figure 7 & Table 4). The shoreline position appeared to fluctuate more along transects closer to Rich and Mason Inlets than the central portion of the island as depicted in the graph of standard deviation in Figure 7. The average shoreline change rates along transects 1 through 16 were -1.5 ft/yr and -14.1 ft/yr along transects 46 to 54. In contrast, shoreline change rates did not fluctuate as much along transects 17 through 45 along the central portion of the island. During the development era, rates averaged approximately +3.4 ft/yr along this area (Figure 7).

1857 to 2003 (net)

Shoreline change rates computed for each transect varied along the island at each transect for the entire study period (Table 4). Long-term erosion rates varied from -0.1 to -4.3 ft/yr for over 80 percent of the island while the northernmost 10 transects, adjacent to Rich Inlet, ranged from -4.3 to +2.9 ft/yr (Table 4). Furthermore, the standard deviation of shoreline change increased along transects from the central portion of the island, at transect 28, outward towards the inlets (Figure 7).

Zone-wide Shoreline Change

Inspections of the dataset suggest that Figure Eight Island's shoreline can be divided into four zones based on shoreline change trends depicted in Figure 8 and 9. The location of each zone was primarily based on coast-wide trends depicted in an interpolated surface map of cumulative shoreline change throughout the 1857 to 2003 period (Figure 8).

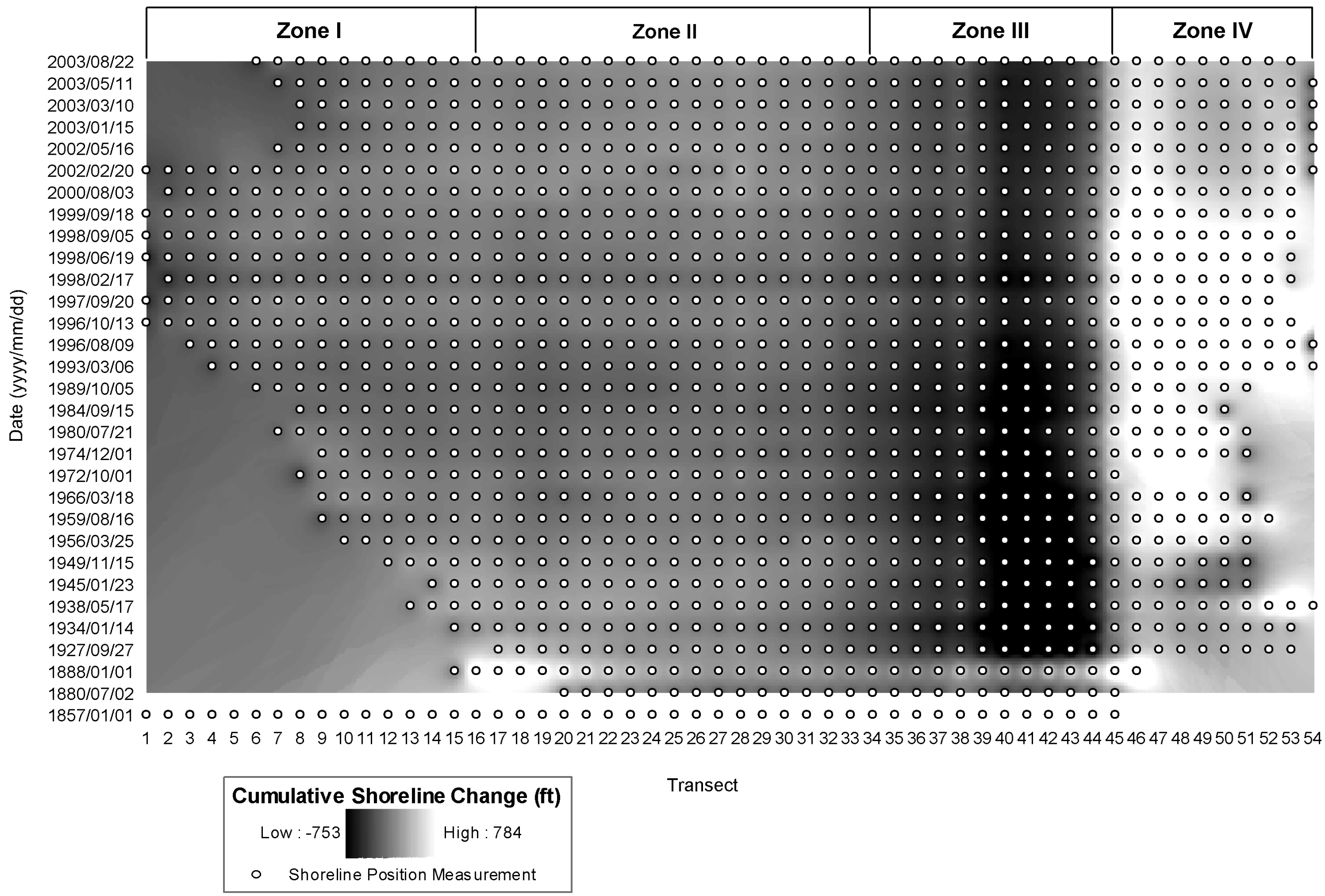

Figure 8. Interpolated surface map of cumulative shoreline change from 1857 to 2003 for each transect.

Additionally, both pre- and development era EPRs and standard deviations graphs of shoreline change aided with the determination of each zone's location (Figure 7). The surface map facilitated the visualization of cumulative changes occurring along each transect throughout the period from 1857 to 2003 (Figure 8). Moreover, the surface map assisted with ascertaining both spatial and temporal trends when it was used in conjunction with plots of historical shoreline change regions in Figures 9b and 9c. Figure 9a depicts the location of each zone and their respective transects for the island's 2003 shoreline configuration. Shoreline change rates for each of the four zones described in the following sections are given in terms of the EPR calculation method.

Zone I

Transects 9 through 16 are located within Zone I, which extends approximately one mile northeast of Mason Inlet (Figure 9a). The zone is located in the historical migration corridor of old Moore's Inlet and present-day Mason Inlet respectively (Figure 2b). Following the relocation of Mason Inlet in March 2002, transects 1 through 8 were no longer situated on the oceanfront of Figure Eight Island. Throughout the time period from 1857 to 2003 the average shoreline erosion rate for the zone was about -1.0 ft/yr (Table 5). Prior to island development, the average erosion rate was approximately -0.8 ft/yr while the development era's rate was nearly -1.7 ft/yr (Table 5).

Two notable periods of net shoreline accretion occurred from 1945 to 1949 and from 1959 to 1966. The zone's shoreline experienced a net gain of +32 ft and +68 ft respectively preceding development of the island (Table 5). In spite of several nourishment and beach scraping projects that took place between 1966 and 2003, net

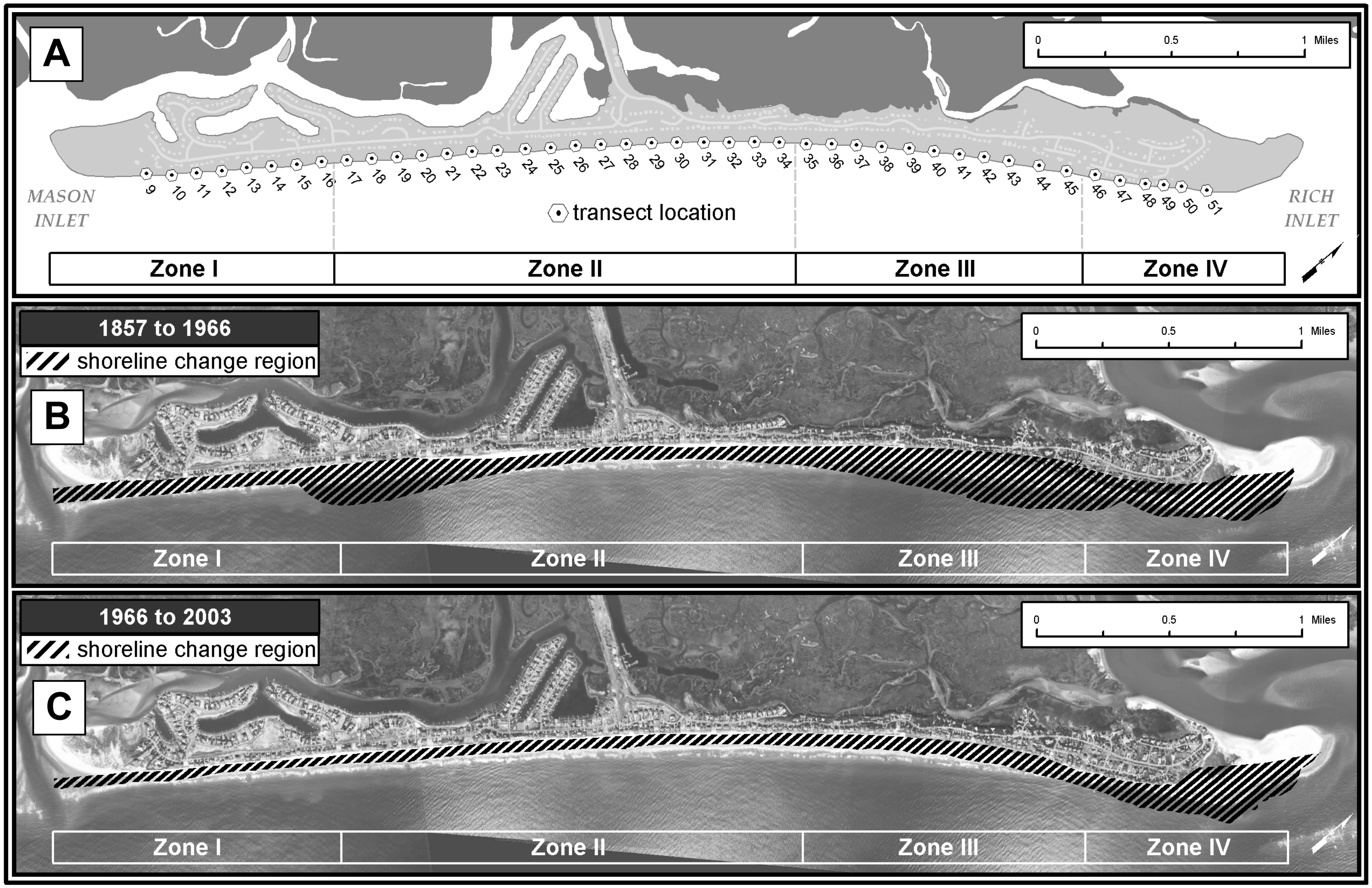

Figure 9. (a) Location of shoreline change zones and their respective transects for the island's shoreline configuration as of 2003, and, regions of historical shoreline position fluctuation during the time periods from (b)1857 to 1966 (pre-development era) and from 1966 to 2003 (development era).

erosion characterized the zone. Each attempt to stabilize the shoreline was short-lived as the zone continued to erode following beach restoration.

Zone II

Zone II spans nearly 35 % of the length of the island's oceanfront shoreline and is comprised of transects 17 through 34 (Figure 9a). Based on the distribution of physiographic elements imaged on aerial photographs between 1938 and 2003, Zone II was generally topographically lower and narrower than neighboring zones. Topographic features indicative of coastal storm impacts and shoreline erosion, such as overwash fans, scarps, and dune breaches occurred at a higher frequency along Zone II than in neighboring zones.

Subsequent to storms during period between 1954 (Hurricane Hazel) and 1962 (Ash Wednesday storm), Zone II exhibited numerous overwash terraces and fans along nearly 90 percent of the zone. The recovery of the foredune system that was severely breached during the Ash Wednesday storm of 1962 was later hampered by island development in 1966. Shoreline recession along Zone II averaged approximately -140 ft at a rate of about -5.0 ft/yr during the period between 1938 and 1966. Prior to 1938, the shoreline had only retreated an average of approximately -44 ft at a rate of -0.5 ft/yr from the 1857 shoreline position.

During period from 1966 to 1989, Zone II's shoreline lost an average of -41 ft at a rate of -1.8 ft/yr. Conversely, between 1989 and 1993, the zone accreted approximately +38 ft (Table 5). Shoreline accretion along the zone is likely attributable to a major beach nourishment project that occurred in February 1993. Between March 1993 and February 1998, the zone experienced net erosion of approximately -38 ft. During this time period, a foredune system fronting oceanfront homes was completely destroyed with the landfall of Hurricanes Bertha and Fran in 1996. Despite a beach nourishment project in March 1998, the island continued to experience severe storm impacts. In the aftermath of Hurricane Bonnie in August 1998 and Hurricane Floyd in September 1999, overwash and shoreline erosion characterized the entire zone.

Similar to Zone I, increased shoreline accretion along Zone II followed beach nourishment projects that occurred immediately prior to the March 1993, June 1998, and February 2002 aerial photographs (Table 5). Prior to island development and beach nourishment projects, the long-term average erosion rate was approximately -1.7 ft/yr during the period from 1857 to 1966 (Table 5). Furthermore, the shoreline's position fluctuated naturally in response to coastal storms and inlets, as opposed to being confined within a smaller corridor by beach nourishment projects during the development era (Figure 9b & c). Although the shoreline appeared to accrete during the development era at a rate of +3.4 ft/yr, overall, from 1857 to 2003, the average long-term erosion rate was approximately -0.4 ft/yr (Table 5).

Zone III

Zone III is comprised of transects 35 through 45 (Figure 9a) and located within an area historically impacted by inlets (Figure 2b). Zone III also is located within a region typically downdrift from a point of inflection where Rich Inlet's ebb delta converges tangentially to the oceanfront shoreline. Historical inflection points of Rich Inlet's ebb delta complex located along Figure Eight Island's shoreline have been confined within a corridor of about 1000 ft in length. This narrow segment forms the changing boundary that separates Zone III from Zone IV. Historically, shoreline positions within Zone III have fluctuated due to the position and orientation of Rich Inlet's ebb channel and the amount of bar-welding activity (JACKSON and CLEARY, 2003; JACKSON *et al.*, 2004). The zone also represents a transition region where the shoreline shape shifts from nearly linear, along the southerly portion of the zone, to more concave along the northern section (Figure 9a).

During the pre-development era from 1857 to 1966, the shoreline retreated an average of -485 ft at a rate of approximately -4.4 ft/yr. Throughout this time period, the region of shoreline fluctuation was far greater along Zone III than during the development era (Figure 9b & c). During the development era, the zone experienced net shoreline accretion of about +218 ft at a rate of +5.8 ft/yr (Table 5). However, shoreline erosion ranging between -15 ft and -106 ft occurred following Hurricane Diana in 1984 and hurricanes throughout the mid to late 1990s. Consequently, the shoreline was nourished three times during the period between 1993 and 2000 to mitigate erosion caused by these storms. During the period between August 2000 and March 2003, following a major realignment of Rich Inlet's ebb channel, the shoreline along Zone III retreated an average of -68.2 ft before erosion rates began to decrease by May 2003 (JACKSON and CLEARY, 2003; JACKSON *et al.*, 2004). Although net accretion occurred during the development era, the overall long-term average erosion rate throughout the time period from 1857 to 2003 was approximately -1.8 ft/yr (Table 5).

Zone IV

Zone IV includes the shoreline segment between transects 46 through 51, located adjacent to Rich Inlet (Figure 9a). The zone also includes the former inlet zone of Nixon Inlet (Figure 2b) and the attached middle-ground shoal shown in the 1857 and 1888 illustrations in Figure 6. Throughout the pre-development era spanning 1927 to 1966, the shoreline accreted an average of +213.8 ft at a rate of approximately +5.6 ft/yr (Table 5). Net accretion also characterized the zone throughout most of the development era until 1996. Between 1966 and 1996, the shoreline accreted an average of +326.8 ft at a rate of +10.7 ft/yr (Table 5). However, following the increased storm period of the late-1990s and reconfiguration of Rich Inlet's ebb-channel, the shoreline eroded an average of -382.9 ft at a rate of -55.8 ft/yr. Between October 2000 and March 2003, erosion rates along the zone increased following a major shift that occurred in the orientation of Rich Inlet's ebb channel (JACKSON and CLEARY, 2003; JACKSON *et al.*, 2004). Consequently, sandbags were emplaced along 12 homes to protect them from potential damage caused by further shoreline erosion. Despite the recent period of increased erosion, the shoreline along Zone IV has accreted an average of +157.7 ft at a rate of +2.1 ft/yr throughout the time period from 1927 to 2003 (Table 5).

Inlet Changes

Based on the aforementioned previous studies of inlet influence on adjacent oceanfront change, the migration and orientation characteristics of the inlet's ebb channel, along with the spatial extent of the ebb delta, were quantified for comparison with shoreline change trends. Table 6 provides a summary of ebb channel and ebb delta properties for both Mason and Rich Inlets based on measurements from aerial photographs spanning the time period from 1938 to 2003.

The study suggests that Mason Inlet directly affects a shoreline segment approximately 1-mile in length along the southern-most portion Figure Eight Island. During the period from May 1938 to February 2002, the ebb channel of Mason Inlet

Table 6. Mason and Rich Inlet's historical ebb channel and ebb delta properties.

MASON INLET					
Date	Ebb channel	Ebb channel migration (from preceding date)			Ebb delta
	azimuth	distance (ft)	rate (ft/yr)	direction	area (ft^2)
May-1938	102	-	-	-	4,982,863
Jan-1945	123	204	30	NE	2,652,397
Nov-1949	146	1866	388	SW	4,691,525
Mar-1956	127	227	36	NE	3,939,676
Aug-1959	150	1394	411	SW	4,139,319
Mar-1966	138	877	133	NE	4,292,466
Dec-1974	114	1047	120	SW	4,560,754
Jul-1980	118	33	6	SW	4,661,580
Sep-1984	121	904	218	SW	3,447,391
Oct-1989	138	1038	205	SW	5,221,332
Mar-1993	153	782	229	SW	4,997,240
Aug-1996	100	275	80	SW	3,430,686
Feb-1998	133	469	308	SW	2,519,368
Jun-1998	100	53	159	SW	3,434,358
Feb-2002	111	66	18	NE	3,806,128
May-2002	117	3154	relocation	NE	2,473,199
Jan-2003	118	145	217	SW	2,959,583
Mar-2003	107	31	206	SW	3,080,377
May-2003	97	84	493	SW	3,388,857

RICH INLET					
Date	Ebb channel	Ebb channel migration (from preceding date)			Ebb delta
	azimuth	distance (ft)	rate (ft/yr)	direction	area (ft^2)
May-1938	126	-	-	-	9,604,163
Jan-1945	138	716	105	NE	10,484,095
Nov-1949	180	580	120	SW	11,953,121
Mar-1956	152	45	7	SW	12,147,217
Aug-1959	140	625	184	NE	13,678,610
Mar-1966	172	295	45	SW	11,391,023
Dec-1974	170	399	46	SW	9,814,976
Jul-1980	112	175	31	NE	8,762,715
Sep-1984	123	238	57	NE	7,030,754
Oct-1989	156	202	40	NE	12,903,317
Mar-1993	162	306	89	SW	12,614,589
Aug-1996	103	1056	308	NE	9,674,780
Feb-1998	106	6	4	NE	7,362,296
Jun-1998	104	141	422	NE	-
Feb-2002	156	588	160	SW	-
May-2002	161	308	1322	NE	9,399,350
Jan-2003	182	-	-	-	-
Mar-2003	190	294	360	NE	8,020,467
May-2003	-	-	-	-	-

migrated in a southwesterly direction a net distance of 6,458 ft at an average rate of approximately 101 ft/yr. Between 1938 and 1974, the ebb channel migrated a net distance of nearly 3,000 ft to the southwest after reversing migration directions three times (Table 6). Movement of the inlet to the southwest during the periods from 1945 to 1949 and from 1956 to 1959 occurred at rates of nearly 400 ft/yr (Table 6). The position of the ebb channel remained relatively stable from 1974 to 1980, where it only moved about 33 ft to the southwest. Between July 1980 and February 2002, prior to the relocation project, the ebb channel migrated predominantly in the southwesterly direction a net distance of about 3,425 ft. Following relocation in 2002, the ebb channel shifted to the southwest a net distance of 260 ft during the period between May 2002 and May 2003.

The orientation of the ebb channel as it passes through the outer ebb delta can have profound effects on shoreline change by promoting or limiting sand-bypassing within the inlet system to adjacent beaches. During the period from 1938 to 2003, the orientation of the Mason Inlet's ebb channel across the outer bar fluctuated between 97º and 153º (Figure 10a). In 1938, the ebb channel's orientation was 102º and by 1949, the channel had reoriented to approximately 146º (Table 6). During this time, a large flood channel oriented at about 184º was nested against the downdrift shoulder or inlet-facing shoreline of Shell Island. Following this time period, the adjacent Figure Eight shoreline experienced net erosion along the southern third of the island. Subsequent to the landfall of Hurricane Fran in September 1996, the ebb channel's orientation was about 100º (Figure 10a). Between September 1997 and February 1998, the azimuth of the ebb channel approximated 133º and a major marginal flood channel became nested on the

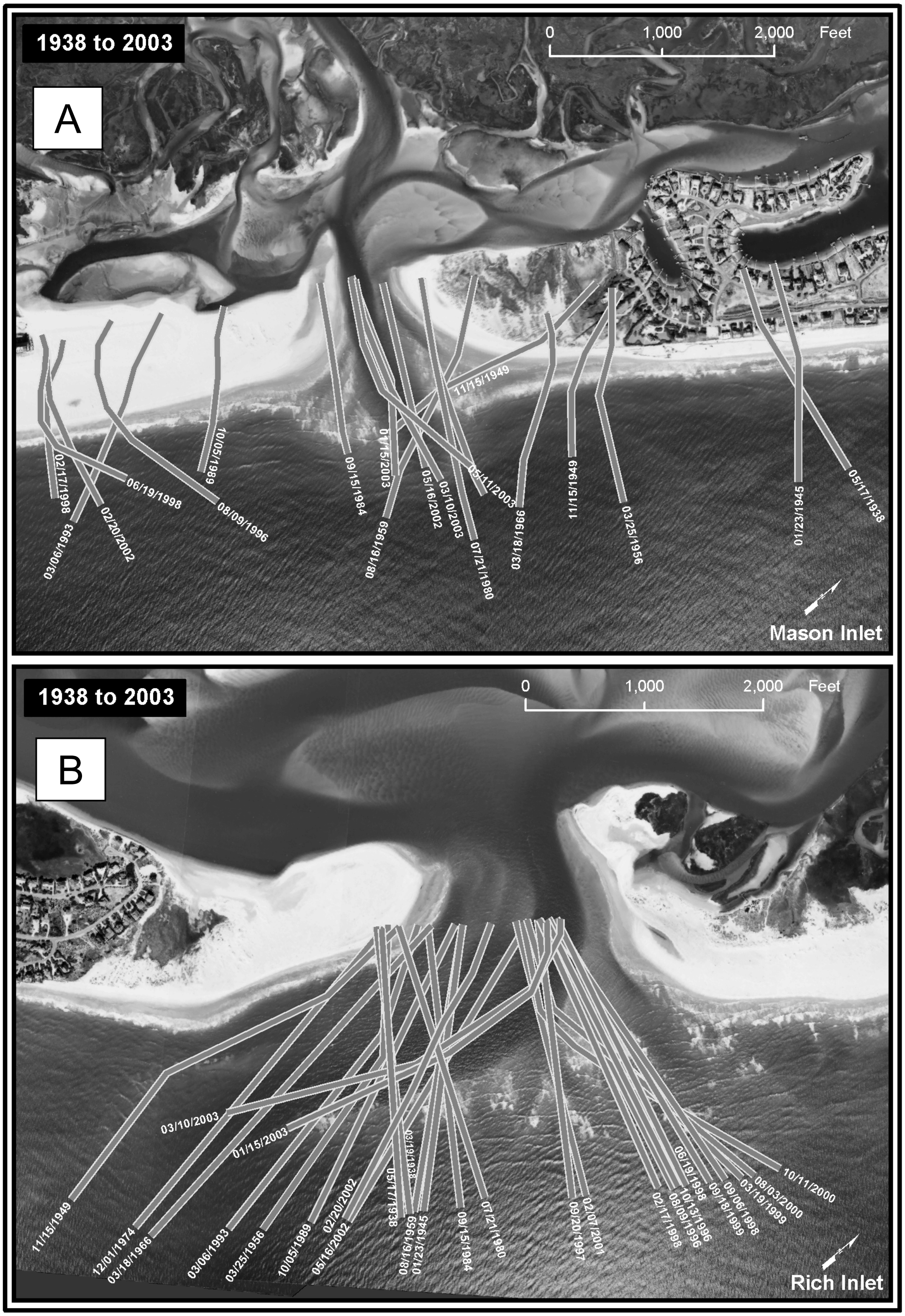

Figure 10. Historical ebb channel positions for (a) Mason Inlet and (b) Rich Inlet based on aerial photograph measurements during the period 1938 to 2003.

updrift Figure Eight Island shoulder. Subsequently, during the period between February 1998 and June 1998, the ebb channel returned to an orientation of about 100º (Table 6). Prior to inlet relocation in March 2002 the channel was oriented in a more southeasterly direction to 111º (Table 6). The channel was artificially aligned to a nearly shore-normal azimuth of approximately 116º during the inlet relocation project but subsequently reoriented to about 97º by May 2003 (Table 6).

Unlike Mason Inlet, Rich Inlet has remained a relatively stable feature since 1938 given that the inlet's ebb channel has been confined to a ~ 1600 ft corridor. Throughout the period from 1938 to 2003, the orientation of the ebb channel across the outer bar fluctuated between 83º and 181º (Figure 10b). Between 1938 and 1993, the ebb channel was oriented predominantly in a southeasterly direction between 112º and 181º before realigning to a more easterly orientation of 103º in 1996 (Table 6). Moreover, the positions of the ebb channel promoted accretion along the Figure Eight Island margin of the inlet. During the period from 1993 to 1996, the ebb channel migrated rapidly toward the northeast a distance of 1,056 ft at a rate of 308 ft/yr (Table 6). Between August 1996 and February 1998, the ebb channel moved northward a net distance of 147 ft before reversing its migration direction in June 1998 and began tracking southwest (Table 6). Between June 1998 and February 2002 the ebb channel migrated a distance of 588 ft to the southwest at a rate of at 160 ft/yr.

While the ebb channel tracked to the northeast between March 1993 and February 1998, the northern spit of Figure Eight Island elongated, dramatically reducing the inlet's minimum width. Although the migration direction changed to the southeast in June 1998, the orientation of the ebb channel continued to be deflected to a northeasterly direction before reaching an alignment maximum of 83º in October 2000. A breach of the ebb-tidal delta occurred in the latter part of 2000 that resulted in a shore-normal shift of the ebb channel. The migration direction of the ebb channel reversed again in 2001 and began tracking to the northeast at 41.7 ft/yr. In December 2003 the outer bar portion of the ebb channel continued to shift to the southeast toward Figure Eight Island following its initial deflection of 115º in February 2001. During the period from 1993 to 2003, the complex interplay between the position and orientation of the ebb channel favored accretion along the southern 1-mile portion of Hutaff Island's oceanfront (Figure 1) and erosion along Zone IV of Figure Eight Island. During this time, the Hutaff Island shoreline segment accreted an average of +240.2 ft while Zone IV's shoreline retreated an average of -236.1 ft.

DISCUSSION

Shoreline Change Trends and Influences

Shoreline change along Figure Eight Island's oceanfront is anything but uniform in nature. Substantial variations of shoreline change rates along each transect, especially within close proximity to an inlet, support this contention (Figure 7). Typically, seasonal fluctuations of shoreline position along the island are to be expected due to changes in wind and wave climate regimes. However, the data indicate that the extent of shoreline movement increased markedly following the onset of changes in inlet morphology, storm activity, and beach nourishment projects. The frequency and magnitude of these influences play an integral role in the evolution of the shoreline along the entirety of the barrier and along specific segments of the oceanfront. Consequently, it is difficult to assign a single erosion rate to characterize the magnitude of shoreline change for the entire island. Therefore, Zones I through IV best characterize oceanfront segments where the variations of spatial and temporal shoreline change trends result from specific influences, such as inlets (Figure 11). However, the boundaries between each zone are not fixed and changed as the island's length changed through time (Figure 6).

Throughout the 1857 to 2003 era, the rate of shoreline erosion along Zone II was less than adjacent zones I and III based on the EPR calculation method (Figure 11a). Average shoreline change along Zone I and III during this time period was almost 3 to 5 times greater than that recorded along Zone II (Figure 11a). Although Zone I through III had erosion rates ranging from -0.4 to -1.8 ft/yr during this time period, Zone IV had an overall accretion rate of approximately +2.1 ft/yr (Figure 11b). Shoreline erosion rates along the island for the 107-year time period prior to development were typically greater than the development era's rates spanning a 37-year period, with the exception of Zone IV. While Zone I through III eroded during the pre-development era, Zone IV accreted. The opposite occurred during the development era when Zone IV eroded at a average rate of approximately -1.5 ft/yr. Shoreline erosion prior to island development ranged from approximately -0.8 to -4.4 ft/yr along zones I through III (Figure 11b). However, Figures 7, 9, and 11b suggest a retardation of erosion rates or an increase of accretion rates for most of the island during the development era, with the exception of transects within Zone IV.

Earlier island-wide shoreline change rates calculated by WAHLS (1973) suggested that Figure Eight Island had increasing rates of accretion during eras prior to 1966 (Figure 12a). However, data from the current study suggest that the opposite occurred during those pre-development eras, where average island-wide erosion rates increased

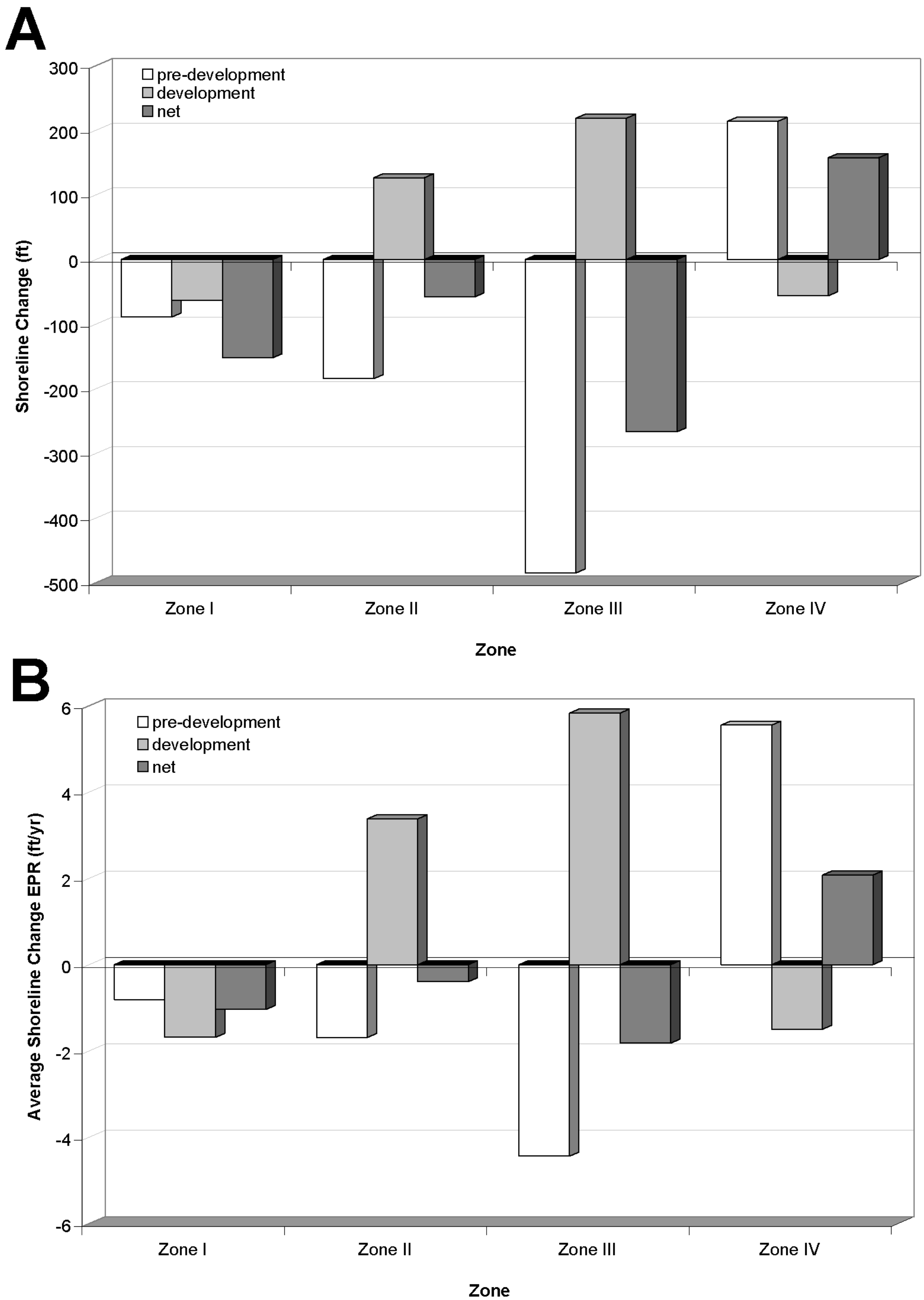

Figure 11. Summaries of average (a) shoreline change and (b) end-point rates for each zone spanning pre-development, development, and net eras.

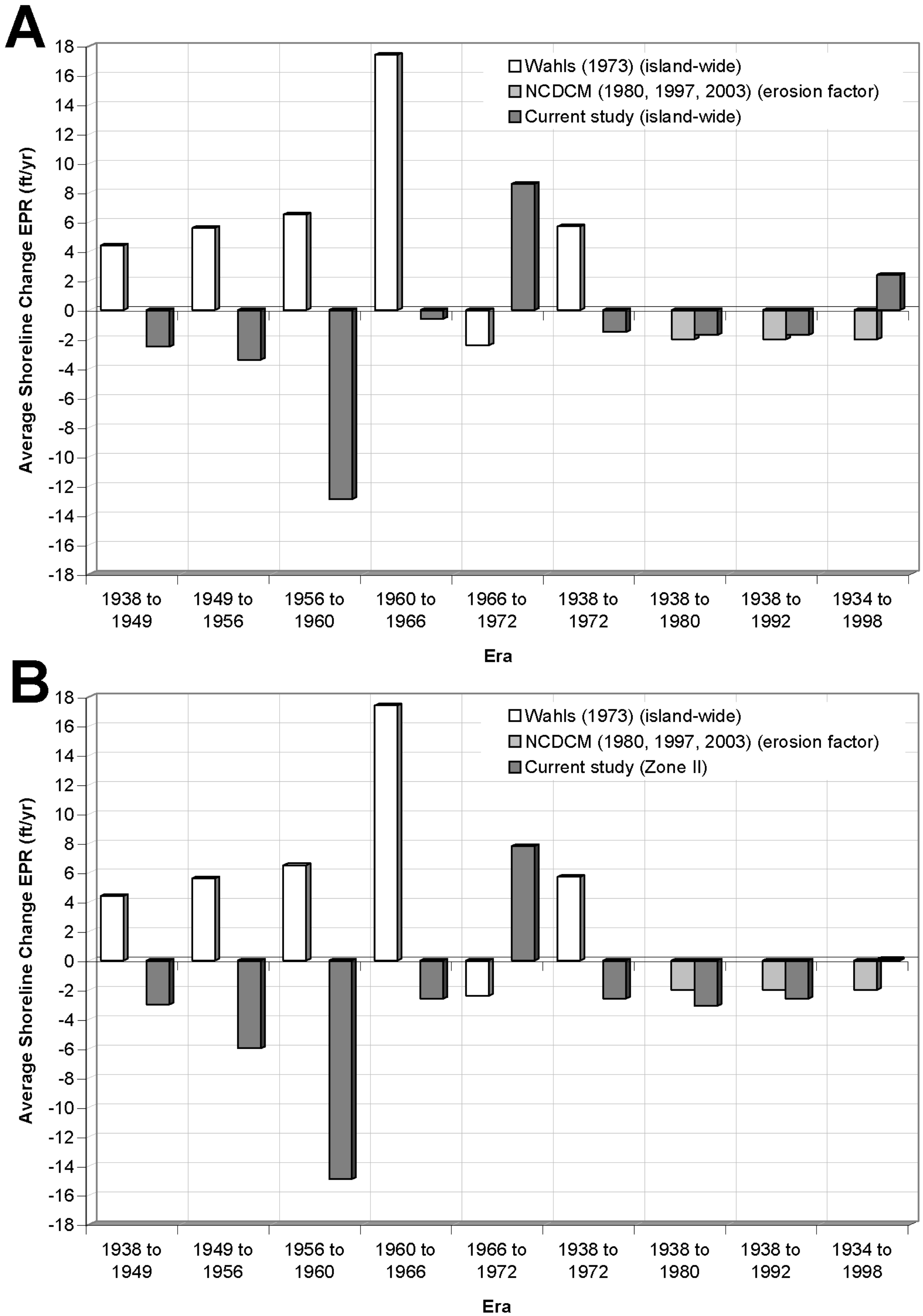

Figure 12. Comparison of shoreline change rates from previous studies against (a) island-wide and (b) Zone II rates from the current study.

from about -2.5 to -12.9 ft/yr between 1938 and 1966 (Figure 12a). Average zone-wide shoreline erosion rates along Zone II, the more stable portion of the island, also increased from -3 to -14.9 ft/yr (Figure 12b). Although the NCDCM's erosion setback factor of -2 ft/yr remained constant for each long-term era calculated from the 1930s to 1980, 1992, and 1998, data from the current study suggest erosion rates in fact decreased and that accretion increased between 1980 and 1998 during the development era (Figures 12a & b).

The increase in accretion rates alluding to natural buildup since island development is attributable to multiple beach nourishment and dredge/fill projects that mask the actual trend of increased erosion. For example, the shoreline advanced seaward along the entire length of the island between +64 ft and +111 ft from February 1998 to June 1998 following a beach nourishment project (Table 5). The amount and rate of shoreline advance far exceeded any natural accretion event recorded during previous time periods for the entire island. Furthermore, nourishment projects have maintained the shoreline position within a smaller corridor (Figure 9c). As a result, a lower standard deviation of change occurred along each transect during the development era when compared to that of the pre-development era trend (Figure 7).

Undoubtedly, natural cycles of shoreline erosion and accretion have been disrupted by the artificial seaward displacement of the high-water line seaward during nourishment projects. Short-term rate calculations following beach nourishment projects, along zones I through III from May 2002 to May 2003, revealed the shoreline experienced rates of erosion in excess of -30 ft/yr, which were much higher in magnitude than rates computed for comparable time periods. By August 2003, the erosion rates decreased as the beach system attempted to attain a pre-nourishment, pre-development "equilibrium." Unfortunately, it is highly doubtful that such equilibrium will ever be achieved because erosion control projects have attempted to stabilize the shoreline seaward of development.

The disruption of natural shoreline processes caused by erosion control projects ultimately impedes barrier island migration. Landward migration of the barrier island is almost certainly inevitable given that net erosion occurred throughout the pre-development era, natural accretion along the entire shoreline rarely took place between 1857 and 2003, and the long-term sea level is projected to rise 0.73 ft/century (National Ocean Service, 2001) throughout the study area. Therefore, it is reasonable to assume that the shoreline of Figure Eight Island is likely to continue to experience erosion unless some form of soft or hard stabilization is implemented.

Along the southern portion of the island, Mason Inlet clearly has a substantial influence over rates of erosion and accretion along Zone I. Strong correlations can be made between the migration of the ebb channel to the amount of shoreline retreat and advance along Zone I and partially in Zone II. However, what is unclear is how the variation of ebb channel orientation has played a role in changes along the oceanfront. Representative aerial photographs in Figure 13 illustrate the apparent relationship of ebb-channel orientation and position to adjacent shoreline change for Mason Inlet. While southwesterly migration rates have been highly variable since 1938, the ebb channel briefly displayed on occasion the ability to reverse migration directions and track to the northeast (Table 6). Figure 14a illustrates that although the ebb-channel reversed migration directions multiple times, the entire inlet system only migrated to the northeast

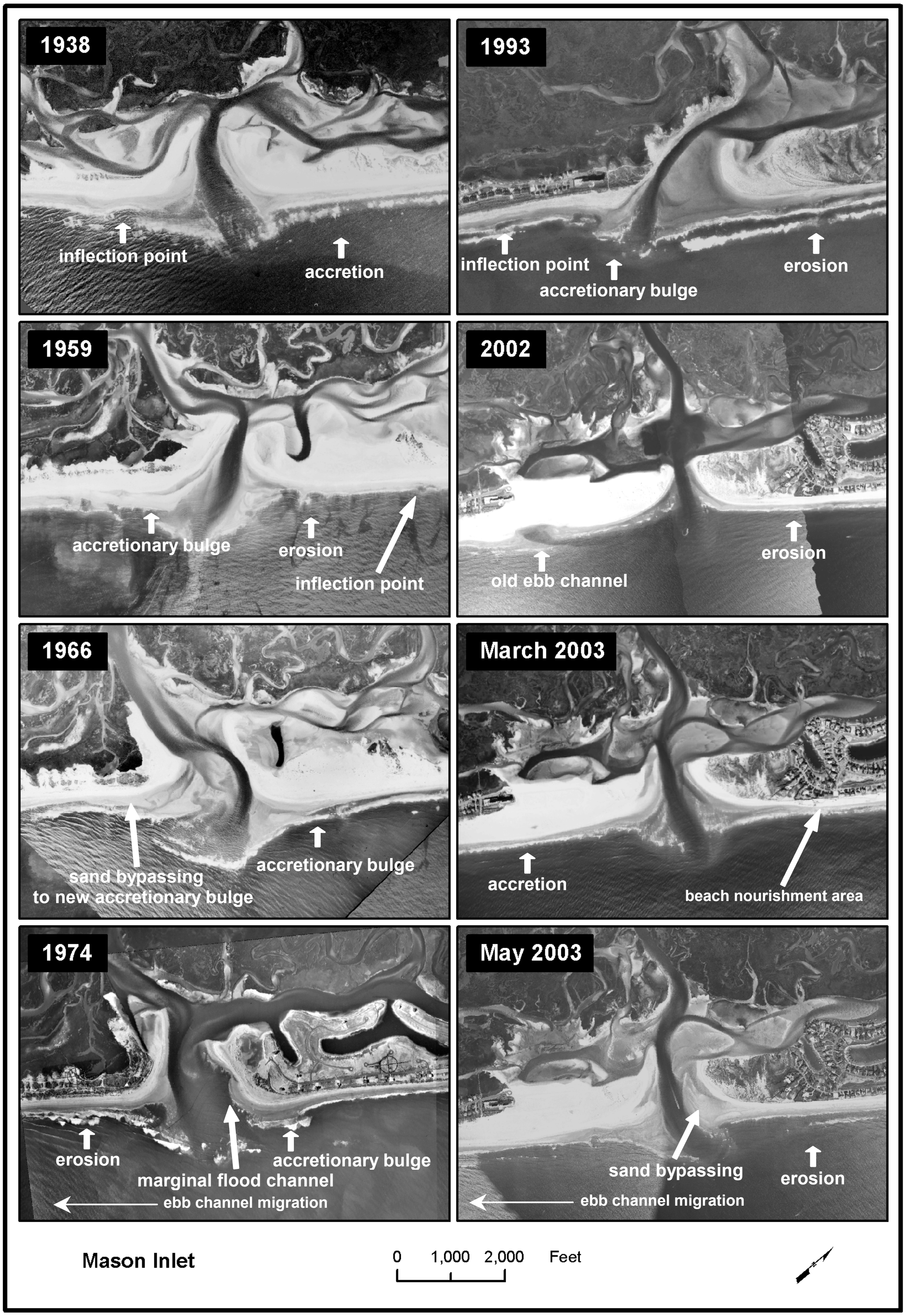

Figure 13. Representative aerial photographs illustrating ebb tidal delta dynamics of Mason Inlet.

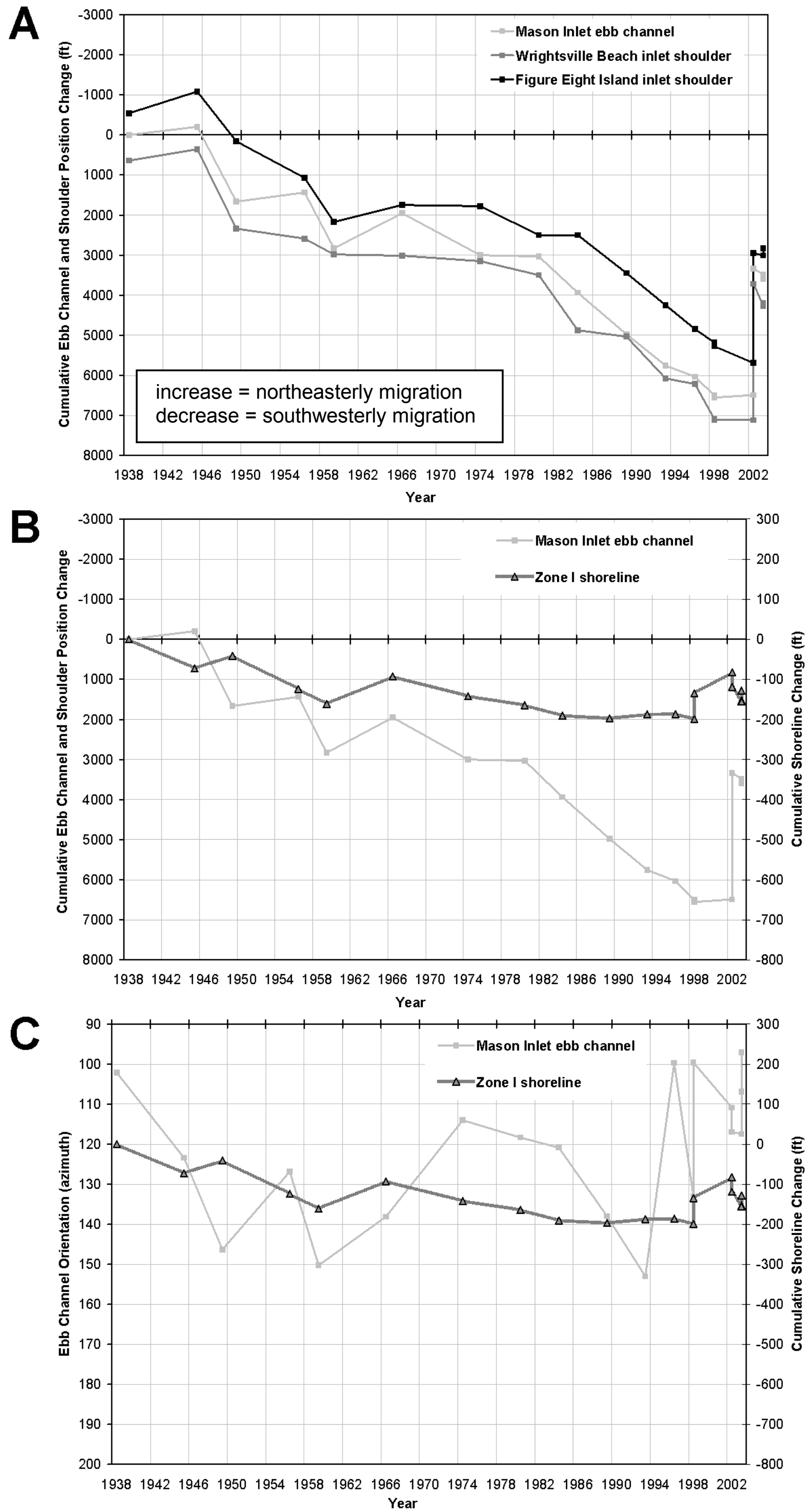

Figure 14. Comparison of (a) cumulative inlet migration of Mason Inlet's ebb channel and adjacent shoulders, and, apparent relationships between shoreline change along Zone I and ebb channel (b) migration and (c) orientation.

one time between 1938 and 2003. Inspection of the 1966 aerial photo in Figure 13 illustrates the ebb channel located northeast of the 1959 position and a large accretionary bulge along Figure Eight Island's oceanfront. Conversely, the 1993 photo depicts erosion along Figure Eight Island's oceanfront following the migration of the ebb channel to the southwest (Figure 13). A plot of the cumulative ebb channel migration and cumulative shoreline change along Zone I in Figure 14b illustrates that oceanfront erosion along Zone I usually increased as the ebb channel moved toward the southwest between 1938 and 2002. The rate of oceanfront erosion appeared to also increase as the rate of migration increased, especially between 1966 and 1998 (Figure 14b). Furthermore, the largest increases in migration rates and shoreline erosion that occurred during periods between 1955 and 1959 and from 1996 to 1998 could be related to storm activity (Figure 14b).

A cursory inspection of the data suggests that accretionary bulges typically occur along Zone I when the ebb channel orientation realigned from a southerly to a more easterly orientation between 97º and 127º. Aerial photographs from 1938, 1966, and 1974 in Figure 13 show the formation of accretionary bulges along Figure Eight Island's oceanfront along Zone I. Shoreline erosion that occurred from 1959 and 1993 appeared to result following the reorientation of the ebb channel from an easterly to a more southerly orientation between 127º and 153º (Figure 13). However, inspection of Figure 14c demonstrates that there is no clear correlation between shoreline change and ebb channel orientation. During periods of increased rates of ebb channel migration to the southwest and southeasterly orientations, the width from the oceanfront to the sound-side of the spit decreased considerably. Between the early 1960s and the late 1970s, the spit often appeared bulbous along Zone I during periods of when inlet migration rates were less than 150 ft/yr and the ebb channel's orientation was approximately 120º. However, as the inlet began to migrate at a higher rate to the southwest during the 1980s and 1990s, the spit was relatively narrow. Therefore, it is hypothesized that given the inlet's relatively small size, the system's ability to accrete sand along the updrift oceanfront is greatly reduced as inlet migration rates increase, even if the ebb channel is in an optimum orientation of about 120º. All other influences aside, the maximum potential of accretion along Zone I might be attained if the optimum channel orientation is reached during a period when southwesterly inlet migration rates are less than 150 ft/yr.

Pre-development erosion rates along Zone II might provide the best indication of the island's overall long-term shoreline change trend because it appears to represent the cumulative effects of all natural influences, including both inlets. Throughout Zone II it is likely that both Mason Inlet and Rich Inlet exert an influence over the magnitude of shoreline change, however, other factors such as storms tend to have more profound effects. Episodic events leading to a large amount of accretion along Zone I and IV due to changes in inlet morphology rarely occur in Zone II. Given its location and topographic characteristics, the Zone II is heavily impacted by coastal storms resulting in overwash and is best described as a chronic erosion zone. Prior to development, overwash from storm events lead to substantial amounts of erosion and often enhanced the curvature of the shoreline along Zone II. Erosion along the zone increased considerably from 1996 to 1999 following the landfall of four tropical systems within the area. Not since the 1950s and early 1960s had the island been affected by such a number of major storms within a period of 7 years or less. Despite beach nourishment projects that took place during the 1990s, the area continued to erode. Historically, the erosion along Zone I and II was exacerbated as the shoreline tended to straighten over time and become more linear due to Mason Inlet's migration. Hence, the accretionary bulges that occurred along the oceanfront usually dictated the curvature of Figure Eight Island's shoreline. Accretionary bulges related to Rich Inlet were usually far greater in size that those updrift of Mason Inlet. The realignment of the updrift trailing shoreline along zones I and II, due to a combination of inlet migration and the erosion of the accretionary bulge created along Zone I, has contributed to the preferred near-linear shoreline shape of the southern portion of the island.

In a similar scenario described for Zone I, aerial photographic data suggests a direct relationship between the ebb channel orientation and position and oceanfront shoreline change along Zone IV downdrift of Rich Inlet (Figure 15). Previous studies suggested that ebb delta breaching events reposition and realign the ebb channel and initiate reversals in shoreline change patterns along Zone IV. However, unlike Mason Inlet, Rich Inlet's ebb channel orientation appears to play a much stronger role in oceanfront shoreline change given the large size of the inlet (Figure 16). A comparison of cumulative ebb channel migration and cumulative shoreline change along Zone IV (Figure 16b) suggests oceanfront erosion along the zone generally increased as migration continued to the northeast from the 1938 position. Figure 16c illustrates a possible linkage between accretion along Zone IV and ebb channel orientations between 140º and 170º. Comparison of Figures 16b and 16c illustrates that the shoreline along Zone IV accreted more sand when the ebb channel was oriented between 140º and 170º and its

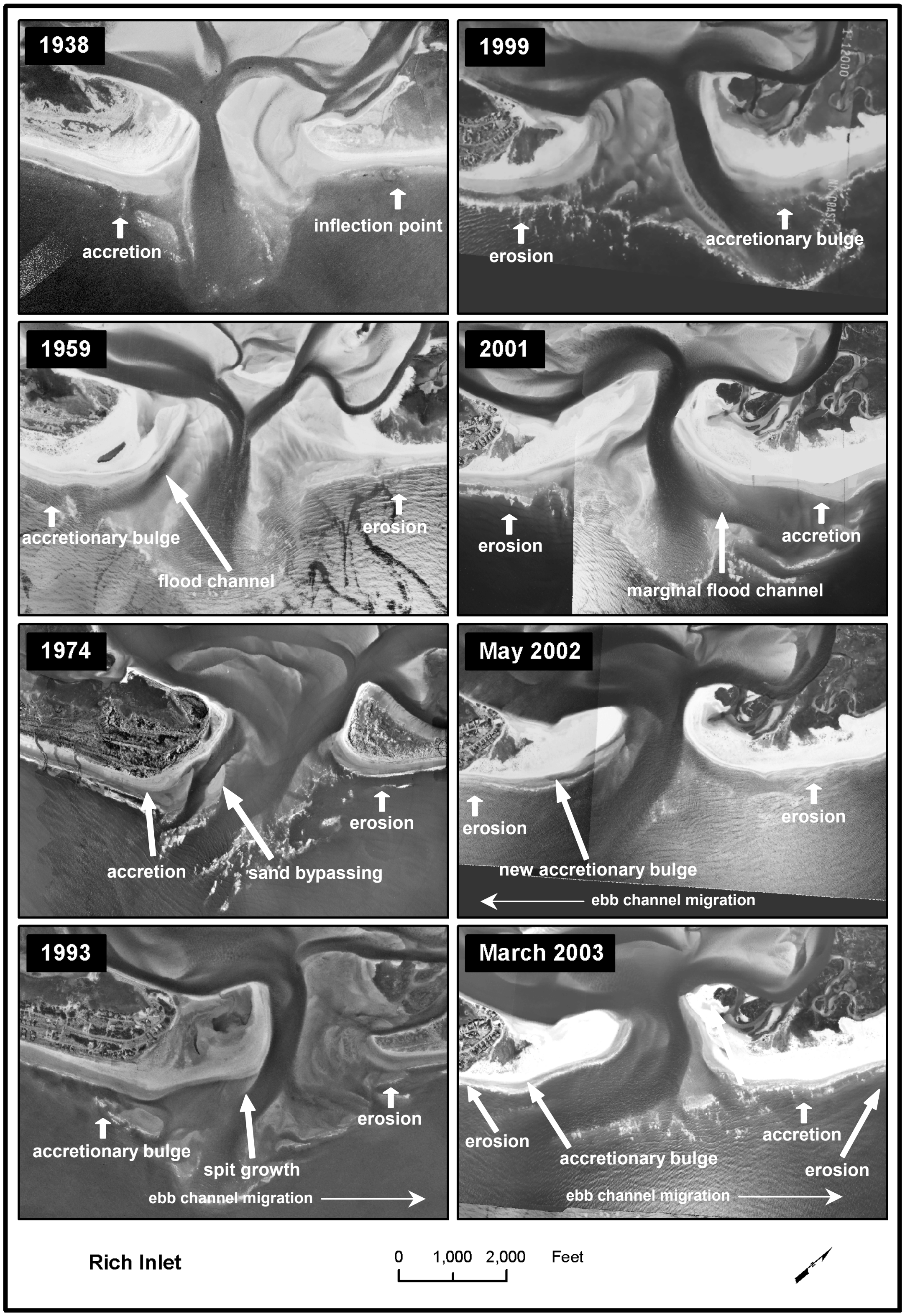

Figure 15. Representative aerial photographs illustrating ebb tidal delta dynamics of Rich Inlet.

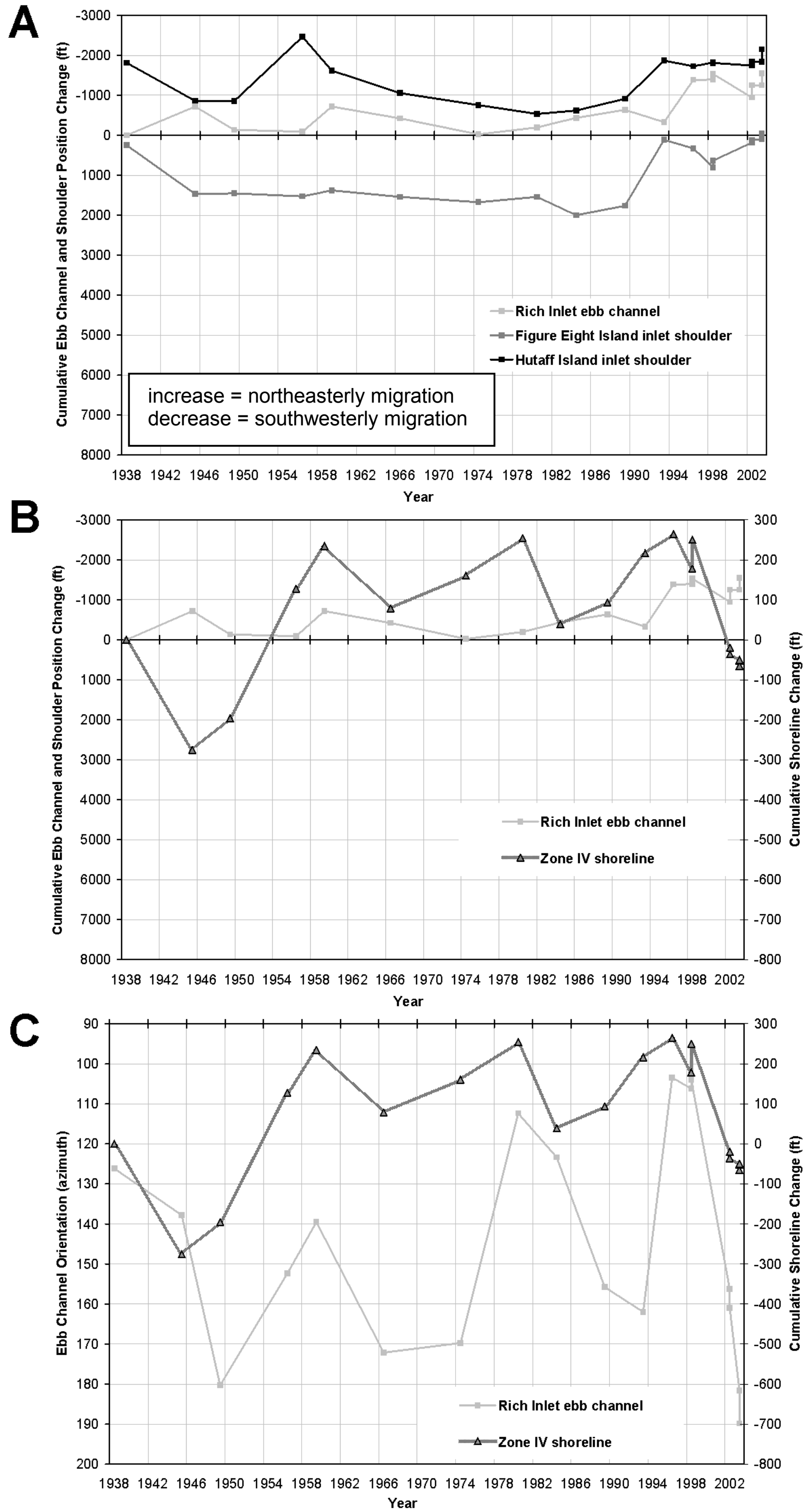

Figure 16. Comparison of (a) cumulative inlet migration of Rich Inlet's ebb channel and adjacent shoulders, and, apparent relationships between shoreline change along Zone IV and ebb channel (b) migration and (c) orientation.

position approximated the 1938 location. Ebb channels with similar positions and orientations depicted on aerial photographs from 1938 and 1959 illustrate accretion along Figure Eight Island's oceanfront (Figure 15). Between 1993 and 2003, the northeasterly migration of the ebb channel exacerbated erosion along Zone IV and likely promoted the elongation of the northern spit (Figure 15). Due to the elongation of the spit to the northeast, the accretionary bulge has been pushed just north of the developed area and has slowed the retreat of the shoreline until the ebb channel can track farther south (Figure 15). Therefore, the optimum channel orientation needed to promote accretion along Zone IV is estimated to be about 145°. Additionally, the preferred ebb channel position should approximate the location of the ebb channel imaged on the 1938 aerial photograph (Figure 15).

Currently, sandbags that were emplaced along oceanfront homes within Zone IV continue to fail during increased water levels in minor storms and unusually high spring tides. Due to N.C. State regulations the sand bags must meet certain height specifications and must be removed by 2008. If the requests for future variances to keep the sandbags in place are denied, then the only solution will involve channel relocation. It is likely that such relocation efforts will be confronted with many environmental and regulatory issues. A rapid reconfiguration of the ebb channel and ebb-tidal delta must occur in order to afford the degree of natural protection needed for the homes fronted by the narrow wall of failing sandbags.

Adjacent to Zone IV, Zone III has experienced substantial erosion since 1966. The shoreline along Zone III represents transition area between zones II and IV, where longshore transport and wave processes influenced by Rich Inlet exacerbate erosion.

Consequently, throughout the period from 1927 to 2003, Zone III tended to maintain a more concave shape (Figure 9). Therefore, it is reasonable to assume that the contrast in shoreline shape between Zone III and IV results from inlet-related processes, thus leading to differing magnitudes of change. The shoreline along both Zone III and IV should be considered erosion hotspots due to their capacity to experience erosion events not only of high magnitude, but also frequency.

Based on the aforementioned trends for each zone and the configurations of each inlet's ebb channel, five short-term shoreline change scenarios are proposed for each zone along the island (Figure 17). Although Zone II is depicted where net erosion is occurring throughout each scenario, the zone likely experiences periodic accretion when adjacent zones III and IV are accreting. Scenario A depicts the optimum conditions for the island's shoreline to maintain its position or prograde. During the scenario, both inlets' ebb channels are stable and have shore-normal alignments. The island's worst-case scenario for shoreline erosion, Scenario E, occurs when each inlet's ebb channel is aligned in opposite directions as the inlets diverge. Sand is ultimately bypassed to the adjacent barrier islands rather than Figure Eight Island. Scenarios B, C, and D are variations of A and E. The island's configuration was closest to that of Scenario A during the period from 1934 to 1938 and was predominately configured to that illustrated Scenario B during several time periods prior to 1974. During the period from 1974 to 1996, the island's configuration was often similar to Scenario C and comparable to Scenario D between 1996 and 2002. In 2003, Rich Inlet's configuration was similar to that depicted in Scenario C, while Mason Inlet post-relocation configuration was comparable to that illustrated in Scenario A.

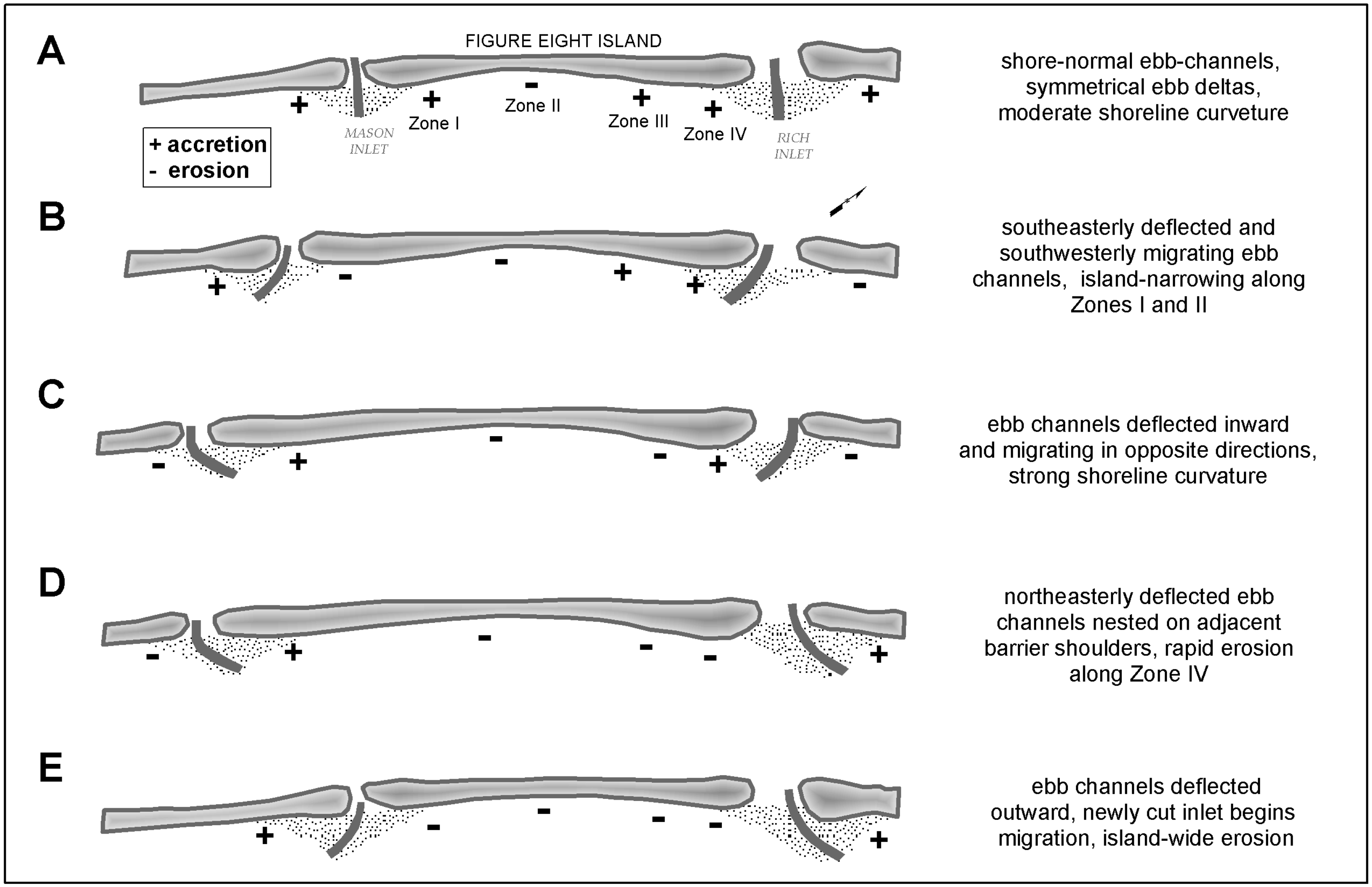

Figure 17. Conceptual shoreline change scenarios for Figure Eight Island based on the position and orientation of the ebb channel within each inlet system.

Shoreline Forecasting and Caveats

A number of state coastal management agencies use both EPR and LRR models to forecast future shoreline positions to assist with delineating setback lines and estimating beach nourishment needs. Currently, setbacks along Figure Eight Island's oceanfront are based on the NCDCM (2003) estimated average annual erosion rate setback factor of -2 ft/yr along the length of the island (Figure 12). The NCDCM's setback factor is based on trends ascertained from shoreline change rates, spanning a 54-year period from approximately 1934 to 1998, which are calculated using the EPR model. However, maps published by the NCDCM (2003) explicitly state that information presented on the maps is not "predictive" and "does not reflect the short-term erosion caused by storms".

Utilizing EPR rates calculated at each transect for the periods spanning 1857 to 1966 and 1857 to 2003, forecasted shoreline positions based on a 25-year projection were plotted for the year 2028 (Figure 18). The purpose of using rates from the 1857 to 1966 era was to forecast a shoreline based on data from pre-development conditions (Figure 18). The position of the predicted shoreline based on this era is mostly landward of the houses along the oceanfront, except along Zone IV. The prediction along Zone IV is problematic given the fluctuation of rates in that area. Although there appears to be no imminent threat to homes based on the 1857 to 2003 forecast, a number of problems exist based on the assumptions of the EPR and LRR rate models used for the predictions.

Perhaps the most unfavorable assumption that undermines the forecast is that the barrier island's shoreline is changing at a constant rate at each transect. The assumption is weak because Figure Eight Island's shoreline is constantly subjected to natural and unnatural processes that influence shoreline change rates (Figures 11 & 12). Since 1966,

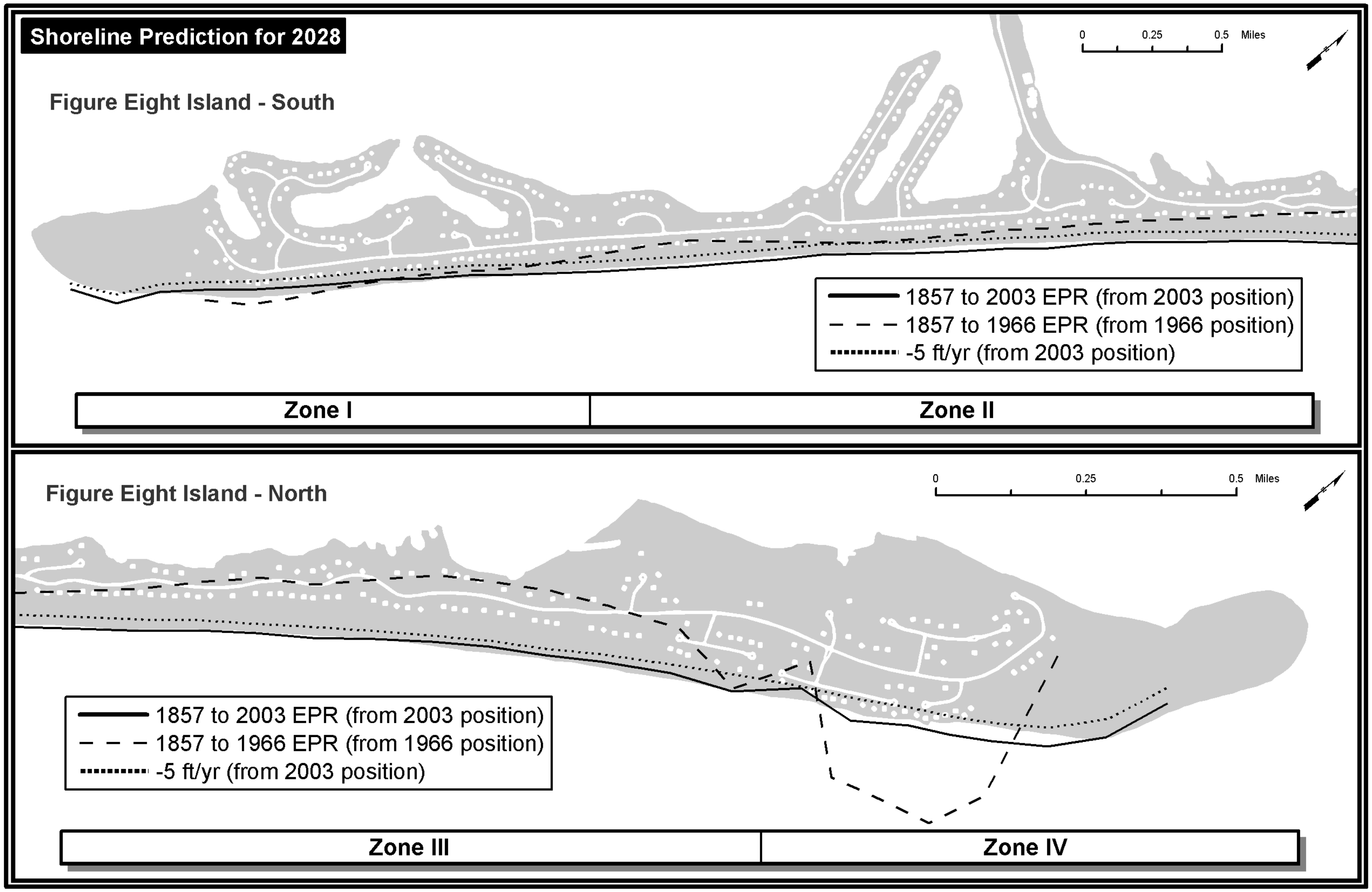

Figure 18. Predicted shoreline positions based on the EPR model for the year 2028. A predicted shoreline based on a -5 ft/yr erosion rate is depicted for reference.

man has placed numerous homes and paved structures on the island that tend to impede natural barrier shoreline processes, resulting in little change of shoreline shape. Additionally, since the early 1980s, beach nourishment projects have also contributed to the alteration of the shoreline's morphology. Erosion and accretion rates were inflated along the island following beach nourishment projects and add noise to long-term shoreline change statistics (Table 5). Therefore, any setback factor or forecast of shoreline position based on development era data is weakened by potentially noisy rates. Hence, the NCDCM should consider pre-development shoreline change trends in conjunction with development trends, using multiple shorelines instead of only two when determining setback factors.

Regardless of the reliability of predicted shorelines or setback factors, natural processes continue to promote shoreline retreat and ultimately bring about a serious dilemma for property owners on the island: either relocate their homes or stand their ground on a barrier shoreline that continually erodes. Consequently, the need for future nourishment projects will likely increase and further complicate the interpretation of shoreline change trends.

Future Implications of Shoreline Retreat

Because Figure Eight Island's shoreline may also be affected by the morphodynamics of adjacent barrier islands and substantial portions of the offshore and backbarrier, it is uncertain how much influence those areas will have in the future as they continue to endure changes induced by man and nature. Unfortunately such changes often appear subtle in the short-term and their capacity to promote major long-term shoreline changes are often underestimated. One such long-term change that might impact the island may result from the shoreline retreat of adjacent Hutaff Island. As both Figure Eight Island and nearby Wrightsville Beach are artificially stabilized and virtually held in place, Hutaff Island remains in an unstabilized, undeveloped state subject to shore processes promoting considerable barrier island retreat. Through time, as Hutaff Island retreats, the northern portion of Figure Eight Island will likely become further exposed to increased wave attack and erosion. The possibility of such events raises an important question: should all or portions of Hutaff Island beaches be nourished to attain a more favorable shoreline shape to attempt to minimize impacts to systems downdrift of the barrier? It is highly unlikely that this will ever be considered.

Like most barriers in southeastern Onslow Bay, Figure Eight Island is a sand-starved island with an urgent need to mitigate shoreline erosion. Little sand resources exist offshore while sediment dredging in backbarrier channels and spoil islands is becoming increasingly limited by environmental restrictions (CLEARY, 2002). Ultimately it will become more difficult to use beach nourishment as a viable option for shoreline stabilization unless potential sand resources, such as ebb delta shoals, and "innovative structures" are explored.

Mining of Rich Inlet's ebb tidal delta might prove to be the best option for obtaining beach quality sand for nourishment of the island's eroding beaches. A study conducted by CIALONE and STAUBLE (1998) investigated the impacts of eight ebb-shoal mining projects in Florida, New Jersey, and New York and concluded that the stability of some adjacent oceanfront shorelines increased. However, the downsides are the potential impacts such projects might have to marine habitats and other coastal environments. The study suggested that additional analyses are needed to assess the long-term impacts on the barrier island-inlet system.

Historically, homeowners on Figure Eight Island have been poised to combat shoreline erosion through whatever means permissible by state laws. Development of a well-constructed shoreline and inlet management plan is needed to bridge the gap between science and policy so that newer, more innovative solutions may be sought. Regardless, as shoreline retreat becomes an increasing threat to many coastal communities, researchers continually push to gain a better understanding of the inlet/barrier linkage.

CONCLUSIONS

Figure Eight Island is experiencing net long-term erosion. Compartmentalizing the island into four zones provides a means of summarizing the variation of rates of shoreline change. Long-term average annual erosion rates based on pre-development conditions ranged between -4.4 to -0.8 ft/yr along Zones I through III, which account for the approximately 90 percent of the island's shoreline, and +5.6 ft/yr along Zone IV. Subsequent to development in 1966, rates ranged between -1.7 to +5.8 ft/yr along Zones I through IV. The overall long-term average annual erosion rate during the period from 1857 to 2003 ranged between -1.8 to -0.4 ft/yr, along Zones I through III, and +2.1 ft/yr along Zone IV between 1927 and 2003.

Two Zones, I and IV, are dominated by inlet processes. Oscillations of both ebb channel position and orientation of both Rich Inlet and Mason Inlet have a profound impact on shoreline change of the entire island. Optimum channel orientations to promote oceanfront accretion in these zones are ~120° for Mason Inlet and ~145° for

Rich Inlet respectively. The ideal scenario for accretion along Zone I might occur if the optimum orientation of Mason Inlet's ebb channel is attained and inlet migration rates are less than 150 ft/yr to the southwest. The potential for accretion along Zone IV increases as the position of Rich Inlet's ebb channel approximates the 1938 position. Zone II is slightly inlet-influenced but is heavily influenced by a combination of incident waves, longshore transport, and storms. Longshore transport and wave processes, affected by the immediate updrift position of Rich Inlet's ebb delta, influences shoreline change along Zone III. Zones III and IV are erosion hotpots where most of the oceanfront development is located either inside, or within close proximity to, a region of historical shoreline fluctuation.

Shoreline change rates and trends along the island during the development era suggest that anthropogenic impacts on natural processes have lead to the reconfiguration of shoreline shape and system-wide changes. Since 1966, the southern two-thirds of island's oceanfront shoreline has experienced a reduction in shoreline curvature. The data indicate that erosion rates increase rapidly immediately following beach nourishment projects and gradually decrease over time. Additionally, frequent beach nourishment projects add noise to shoreline change rate calculations by artificially displacing the shoreline seaward, thus yielding accretion rates that mask long-term erosion trends.

A detailed shoreline and inlet management plan is needed to mitigate the impending beach erosion. Though controversial, options such as channel relocation or ebb shoal mining might prove beneficial in counteracting erosion as sand resources in the offshore and backbarrier are limited. Further detailed studies are needed to determine the both the short- and long-term impacts of human activities on shoreline erosion and changes within the inlet-barrier island system.

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APPENDIX A. SHORELINE AND INLET TERMINOLOGY (FIGURE A1)

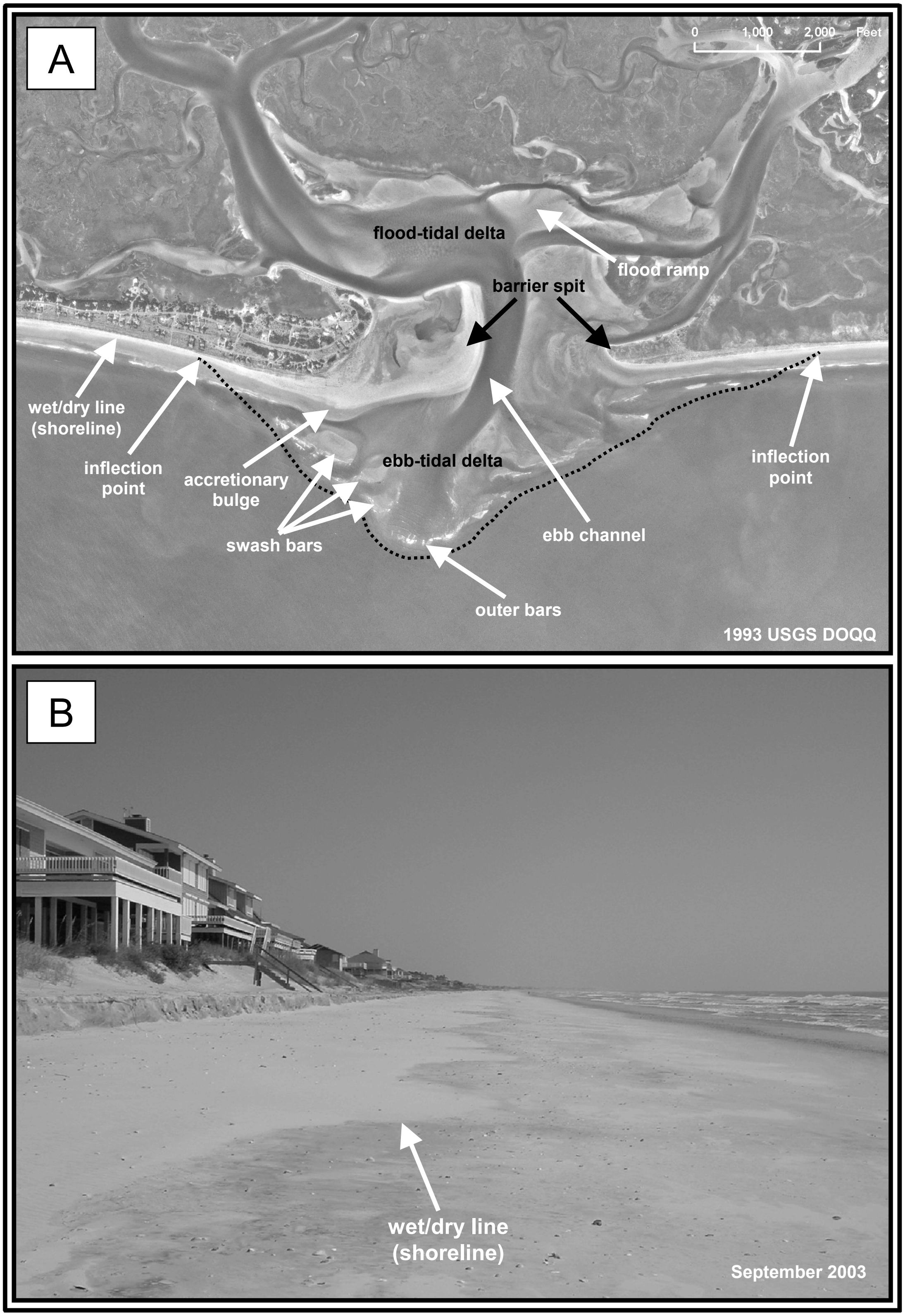

Figure A1. (a) Vertical aerial photograph of Rich Inlet labeled with shore and inlet terminology used in this manuscript. (b) Field interpretation of a high water line left from the proceeding high tide.

APPENDIX B. PAST DREDGE AND FILL ACTIVITIES.

Table B1. Historical permits for shoreline and island maintenance projects.

Permit	Issued	Agency	Type	Region	Dredge (yd^3)	Fill (yd^3)
59-64 & 65-03	10/13/1964	USACOE	dredge and fill	causway road	350,000	350,000
12-66	04/19/1966	USACOE	dredge and fill	finger canals	300,000	300,000
5-69	01/28/1969	USACOE	dredge and fill	south end	1,000,000	1,000,000
unknown	01/18/1972	USACOE	dredge and nourishment	middle island	-	-
unknown	06/15/1972	USACOE	dredge/fill	backbarrier causway	-	-
unknown	06/25/1977	USACOE	dredge/fill & bulkhead	backbarrier Mason Inlet	13,000	13,000
unknown	01/01/1979	USACOE	navigation	Rich Inlet	-	-
89-83	06/30/1983	CAMA	dredge and nourishment	Rich Inlet and north end	90,000	90,000
11-85	03/21/1985	CAMA	dredge and nourishment	south end	46,300	46,300
23-86	01/01/1986	CAMA	dredge and nourishment	southern half	250,000	250,000
87-XX-SP	01/11/1987	CAMA	bulldozing	southern half	-	-
87-XX	03/18/1987	CAMA	bulldozing	southern half	-	-
87-90	04/13/1987	CAMA	bulldozing	southern	-	-
2-90	01/04/1990	CAMA	bulldozing	island-wide	-	-
26-92	11/25/1992	CAMA	dredge and nourishment	southern half	343,000	343,000
21-93 & 46-94	02/16/1993	CAMA	dredge and nourishment	Rich Inlet and north end	274,000	274,000
2-90 Renewal	12/13/1994	CAMA	bulldozing	island-wide	-	-
2-90 Renewal	11/04/1996	CAMA	bulldozing	island-wide	-	-
29-98	03/02/1998	CAMA	dredge and nourishment	island-wide	450,000	450,000
17999-d	09/01/1998	CAMA	emergency berm	southern half	-	-
12-99	01/29/1999	CAMA	dredge and nourishment	island-wide	785,000	785,000
unknown	01/01/2000	CAMA	sandbags	north end	-	-
22646-d	03/17/2000	CAMA	dune building	north end	-	-
exemption	09/19/2000	CAMA	bulldozing	north end	-	-
exemption	10/05/2000	CAMA	bulldozing	north end	-	-
exemption	11/03/2000	CAMA	bulldozing	north end	-	-
exemption	11/03/2000	CAMA	bulldozing	north end	-	-
28371-j	11/16/2001	CAMA	bulldozing	south end	-	-
27465-d	11/26/2001	CAMA	sandbags	north end	-	-
27464-d	11/26/2001	CAMA	sandbags	north end	-	-
151-01	11/28/2001	CAMA	dredge and fill	Mason Inlet and southern half	790,000	790,000
unknown	01/15/2003	CAMA	dredge and nourishment	south end	80,000	50,000
unknown	03/10/2003	CAMA	dredge and nourishment	south end	80,000	50,000
unknown	09/17/2003	CAMA	additional sandbags	north end	-	30,000

APPENDIX C. CALCULATION OF SHORELINE CHANGE AND STATISTICS.

Shoreline change (SC) is calculated by subtracting the shoreline position of an older date from a younger shoreline position. In the current study, shoreline change and rate statistics were calculated for transects generated shore normal from a baseline every 150 and 500 ft. Given N shoreline samples, numbered in order from oldest to youngest date and Y to denote shoreline position, the SC is:

$$SC = Y_N - Y_1 \tag{2}$$

The EPR rate method is calculated by dividing the shoreline change of two shorelines by the elapsed time between them to yield a distance-per-time rate. Therefore, the shoreline change rate yielded by the EPR method is the slope of the line between two points. Using X to denote the date of a shoreline, the EPR is:

$$EPR = \frac{Y_N - Y_1}{X_N - X_1} \tag{3}$$

Unlike the EPR method, the LRR model utilizes all shoreline positions instead of only two. The rate calculated by the LRR method is the slope of the line that is the least-squares distance to the actual shoreline points. The equation is:

$$LRR = \frac{\sigma_{XY}}{\sigma_{XX}} \tag{4}$$

Where σ_{XY} is the sample covariance between dates (X) and their corresponding shoreline position (Y), and, σ_{XX} is the variance of the date sample.

Mean shoreline change ($\overline{SC}$) and mean EPR (AER) where calculated utilizing the following equations:

$$\overline{SC} = \frac{1}{N}\sum_{i=1}^{N} SC_i \tag{5}$$

$$AER = \frac{1}{N} \sum_{i=1}^{N} EPRi \tag{6}$$

Where SCi is the calculated change in shoreline position between eras and EPR_i is the calculated EPR for each shoreline (Y_N), utilizing the oldest date in the dataset as Y_1.

Standard deviation of shoreline change (SDC) provides a measure of shoreline position variability about the mean position of shoreline change. The calculation can be used to quantify the fluctuation shoreline positions and aid in the delineation of segments under a particular influence or multiple influences. The SDC is:

$$SDC = \sqrt{\frac{1}{N} \sum_{i=1}^{N} \left(SC_i - \overline{SC}\right)^2} \tag{7}$$

To best summarize the nature of shoreline behavior along the island, the shoreline was divided into zones displaying differing characteristics and trends. For example, numerous studies have shown that portions of a barrier island's shoreline that are artificially stabilized are likely to exhibit shoreline change patterns vastly different that adjacent unstabilized beaches. Calculations of average zone shoreline change (AZC) and average zone rates-of-change (AZR) aid in characterizing the overall behavior of a shoreline area. Given N transects for a zone, the AZC is:

$$AZC = \frac{1}{N} \sum_{i=1}^{N} TCi \tag{8}$$

Where TC_i is the calculated shoreline change (SC) between dates. The AZR is:

$$AZR = \frac{1}{N} \sum_{i=1}^{N} TRi \tag{9}$$

Where TR_i is the calculated EPR for between dates.

Once the potential shoreline position errors (E_{sp}) of any two shorelines are known, the annualized shoreline position error (rate-of-change error) between the shorelines can be approximated. The calculation is simply the square root of sum of each shoreline potential error squared, divided by the elapsed time between their dates. Therefore, given N shoreline samples, numbered in order from oldest to youngest date, the estimation of shoreline change rate error (SCRE) is:

$$SCRE = \frac{\sqrt{{E_{sp1}}^2 + {E_{sp2}}^2 + {E_{sp3}}^2 \ldots + {E_{spn}}^2}}{X_N - X_1} \tag{10}$$

Where Y is the RMSE of the shoreline position and X is the date of the shoreline.

APPENDIX D. SHORELINE CHANGE MAPS. (FIGURES C1 THROUGH C4)

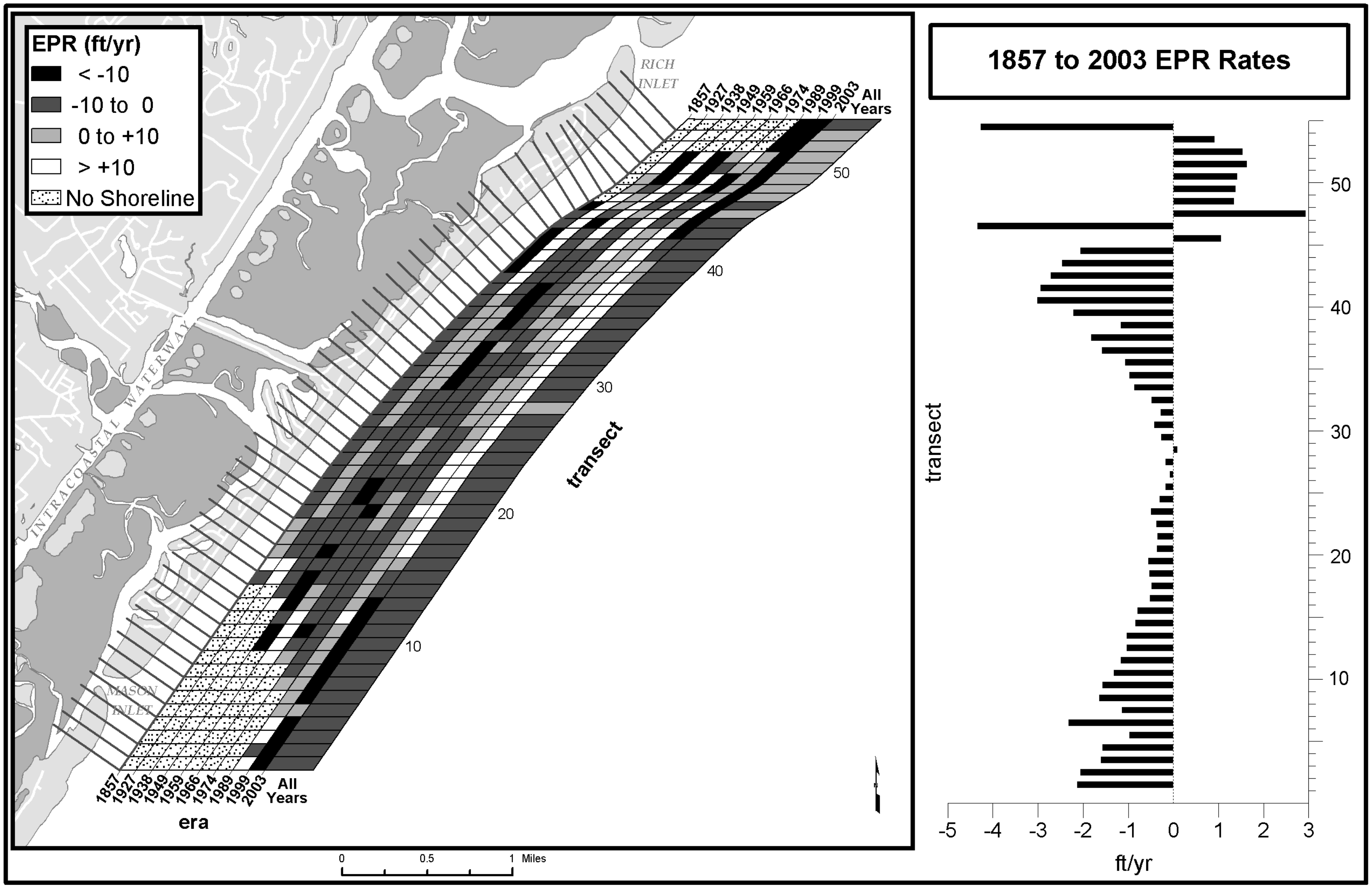

Figure C1. Map depicting shoreline change rates based on the EPR model.

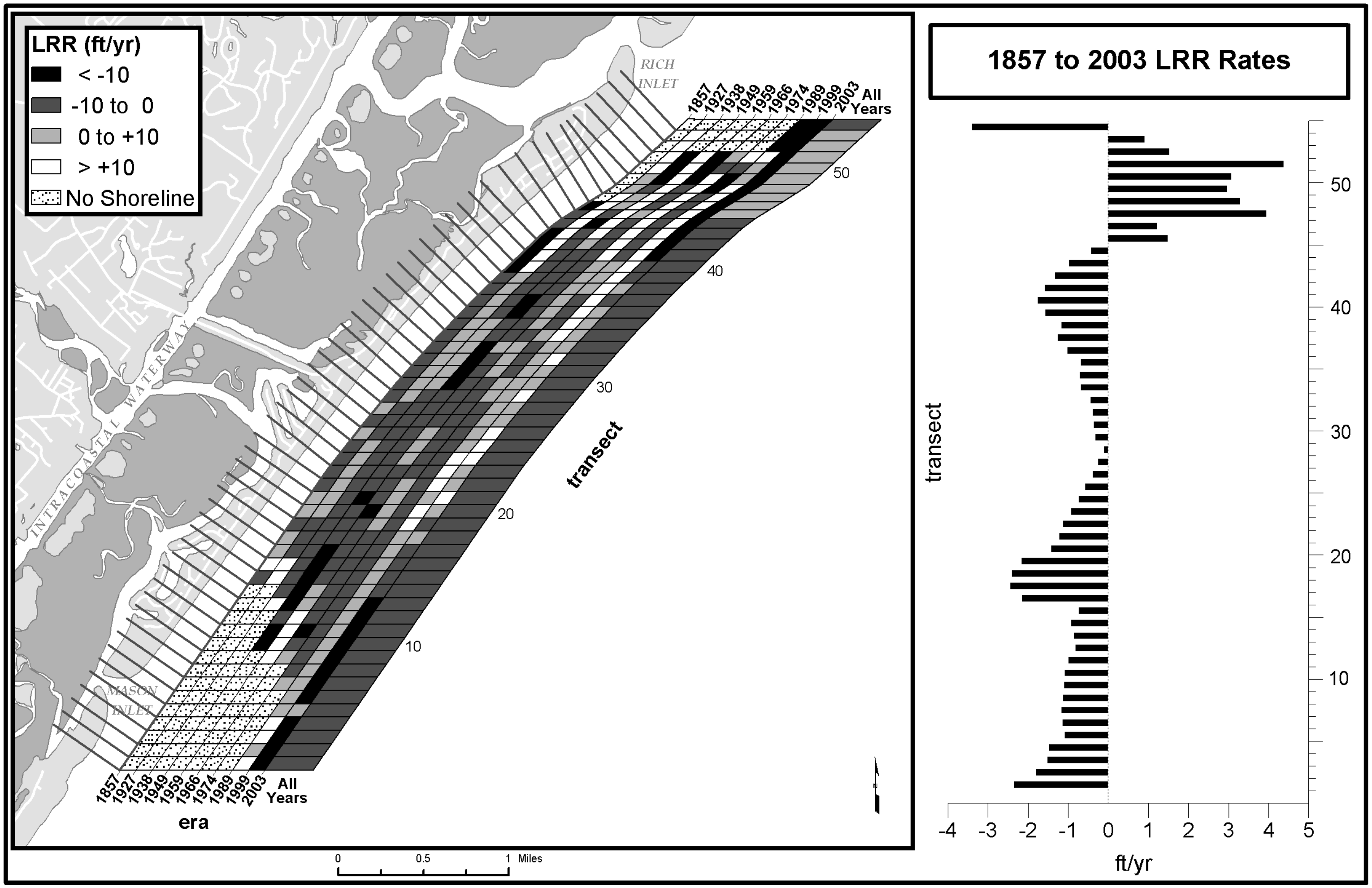

Figure C2. Map depicting shoreline change rates based on the LRR model.

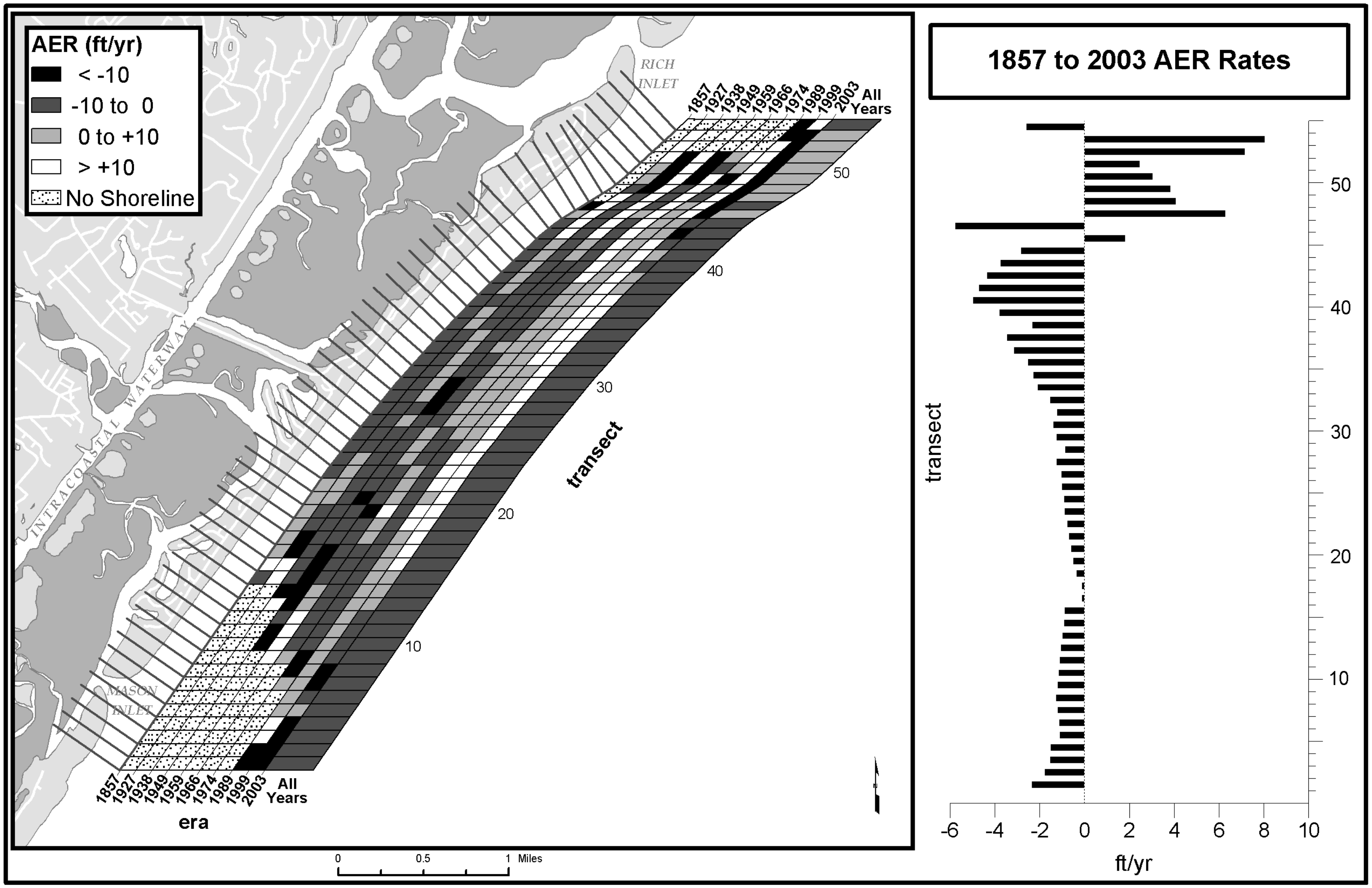

Figure C3. Map depicting shoreline change rates based on the AER model.

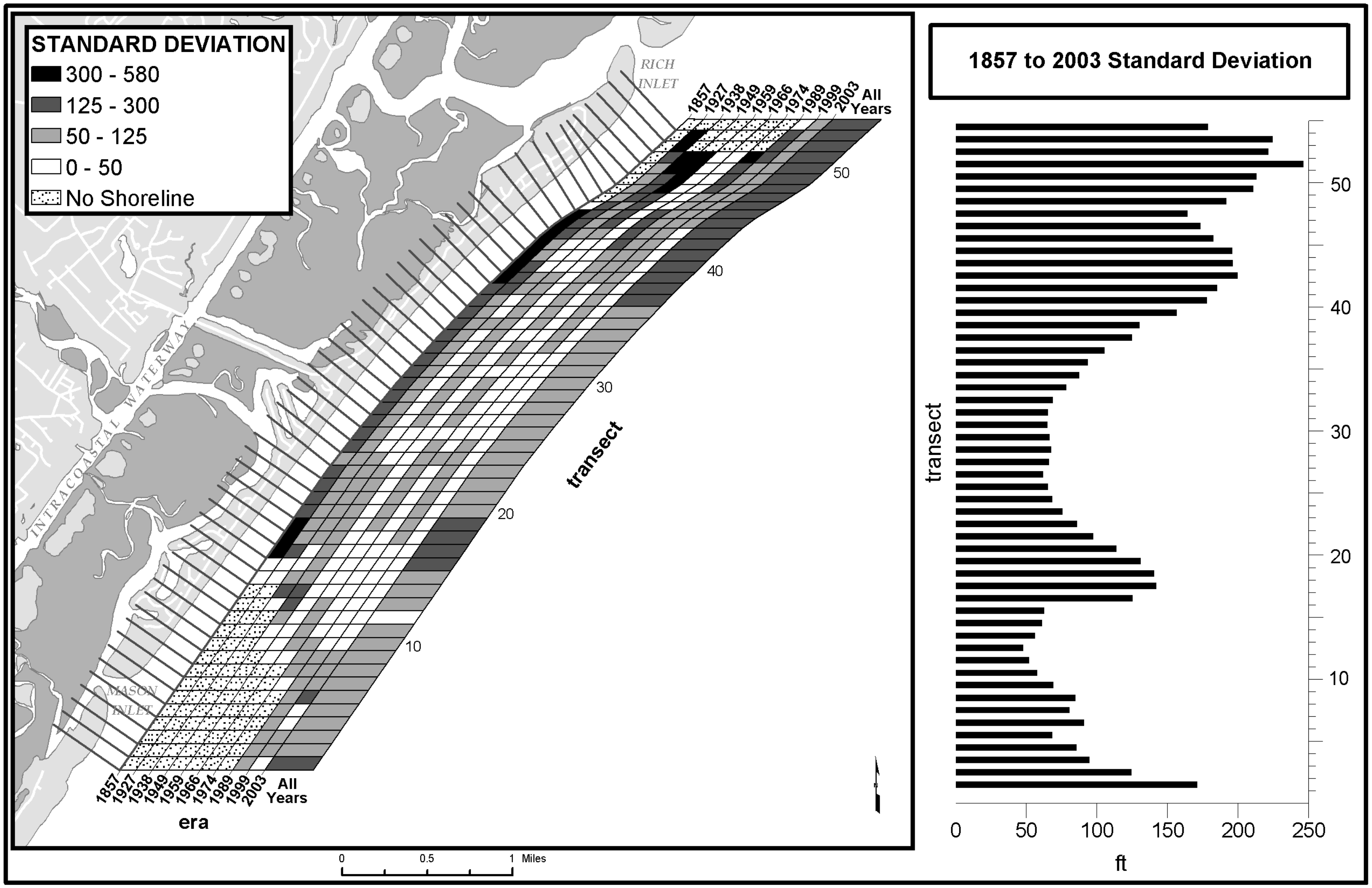

Figure C4. Map depicting the standard deviation of shoreline change.