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Author: Cleary, William J.

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Variations in Inlet Behavior and Shoreface Sand Resources: Factors Controlling Management Decisions, Figure Eight Island, NC, USA

William J. Cleary

Center for Marine Science, University of North Carolina at Wilmington,
1Marvin K. Moss Lane, Wilmington,
North Carolina, 28409, USA,
Clearyw@uncwil.edu

ABSTRACT

Although beach nourishment is considered the only viable option for maintaining oceanfront beaches, the prohibition of large-scale mining of mainland sites and estuarine channels has made it difficult for communities with severe erosion problems to plan mitigation. Figure Eight Island, North Carolina, is an example of a community where erosion during the past decade has increased dramatically due to the combined effects of the bordering inlets and the impacts of recent hurricanes. The chronic erosion has prompted a system wide investigation aimed at inventorying the offshore sand resources for long-term management of the oceanfront beach. The contrasting behavior patterns of Rich and Masons Inlets, which form the island's northern and southern boundaries respectively, have influenced historic shoreline change patterns. Although Rich Inlet has been relatively stable, the ebb channel has shifted repeatedly; and as a consequence, reconfiguration of the expansive ebb delta has led to severe erosion along a 2 km reach downdrift of the inlet. Mason Inlet is a small migrating system whose soundside channels have shoaled since the mid 1990's, resulting in a dramatically reduced tidal prism and increased migration rates that exceeded 140m y^{-1}. Migration and consequent realignment of the trailing barrier resulted in oceanfront erosion that extended for 3 km updrift. Relocation of the inlet is planned for early 2002. Less than 10% of the 4.0 million m^3 needed for nourishment will be available as a result of the relocation efforts.

Although the shoreface has been viewed as a potential borrow source, data indicate it has a low potential for providing significant volumes of quality sand. The lack of shoreface sand resources and the minor amount available from future dredging activities at Mason Inlet strengthens the need for developing a sound sand management strategy for Rich Inlet for long-term maintenance of the oceanfront.

ADDITIONALINDEXWORDS: *Beach nourishment, ebb-tidal delta, inlet migration, inlet relocation, shoreline change*

INTRODUCTION

Much of the shoreline in southeastern North Carolina is situated within chronic erosion zones. During the past six years the erosion has been greatly exacerbated by four landfalling hurricanes. As a result all coastal communities are attempting to formulate long-term erosion and storm damage reduction plans. Most of these coastal communities are seeking assistance from both local and federal agencies. The focus of these management plans is the availability of sufficient quantities of high-quality beach compatible material for the initial construction and subsequent re-nourishment of beachfill projects. Currently the State of North Carolina has an extremely restrictive shoreline stabilization policy that includes a ban on the construction of shoreline hardening structures. Other than the relocation of erosion-threatened homes, the only viable option available to the community is beach nourishment for maintaining the eroding oceanfront beach; however many communities are facing critical shortages of sand for nourishment purposes. The shortages stem from the general lack of sand in the local system and the severe environmental restrictions in place.

Figure Eight Island, the subject of this paper, is a private community that is not requesting government assistance and the use of public funds for erosion mitigation (Fig. 1). As a consequence, the island is an exemplary site for studying a variety of management issues not influenced by the availability and conditions associated with the use of tax dollars. The island is a prime example of community that has experienced rapid development and increased land values since the mid 1970's. The driving factor behind development was and continues to be the presence of an oceanfront beach. Therefore, preservation of this eroding feature is of the utmost concern to the community. The chronic long-term and inlet-induced erosion, coupled with

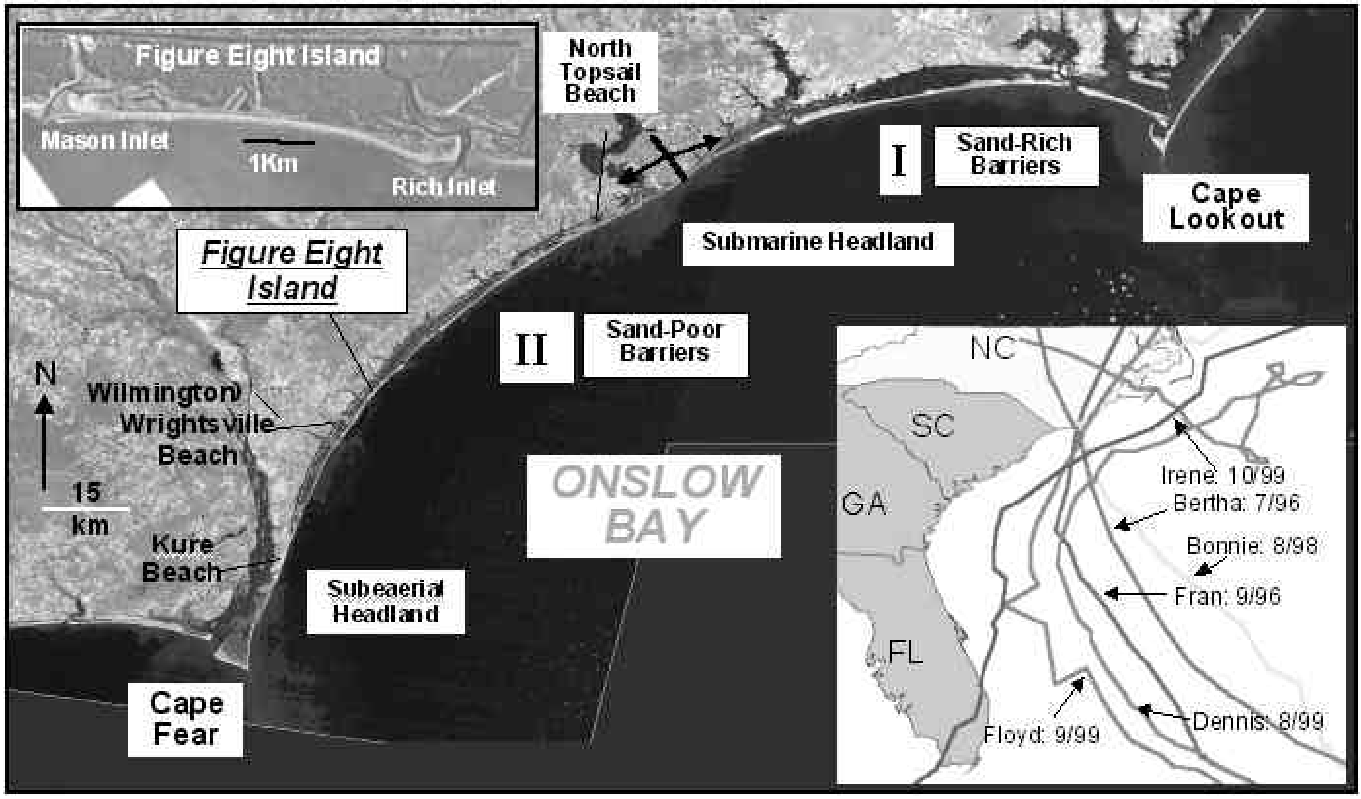

Figure 1. Location map illustrating hurricane tracks.

the effects of the recent hurricanes, has prompted the community to undertake a reassessment of the availability of sand resources for nourishment. As a consequence of the prohibition of the large-scale mining of mainland sites and estuarine channels, the island has focused on the availability of sand resources on the shoreface and within the adjacent tidal inlet systems. Currently the island is developing a detailed long-term management plan that includes the identification of hazard zones and the assessment of potential sand resources that could be targeted in the future for beach nourishment. This paper provides an overview of a number of ongoing and completed studies that form the basis for the formulation of the island's management strategy. The focus of the overview is the impact of the tidal inlets. Critical to the development of the management strategy is an understanding of the influence of the inlets on shoreline erosion and the role they will play in dictating the maintenance of the oceanfront beach.

GEOLOGIC SETTING OF FIGURE EIGHT ISLAND

The configuration of the North Carolina coastline reflects major differences in the underlying geological framework. Cape Lookout separates the North Carolina coastal system into two large-scale coastal provinces, each with distinctive types of headlands, barrier islands, spits, and estuaries (RIGGS *et al*., 1995). Figure Eight Island is located within the southern province that extends from Cape Lookout to Sunset Beach, NC. Upper Cretaceous through to Pliocene age units associated with the Carolina Platform underlie the region. This structural platform has risen incrementally over geologic time causing the units to be truncated by the landward migrating shoreface system during oscillations of sea level (RIGGS *et al*., 1995). Consequently, an erosional topography exists with exposures of the rock units on the shoreface.

Figure Eight Island is situated in southwestern Onslow Bay, a broad, shallow, high-energy shelf sector (Fig. 1). Modern sediment accumulation in this region of Onslow Bay is negligible (CLEARY and PILKEY, 1968; CLEARY and THAYER, 1973; CROWSON, 1980; RIGGS *et al.*, 1995; JOHNSTON, 1998; MARCY and CLEARY, 1998).

The island is a 9 km-long transgressive barrier situated along the high energy flank of Cape Fear that is frequently impacted by both tropical and extra-tropical storms. The private residential, island is bordered by Rich Inlet, at the northern end of the barrier, and Mason Inlet, at the barrier's southern margin (Fig.1). The U.S. Army Corps of Engineers (JARRETT, 1977) published average wave height and wave period for the region were 0.79 m (2.6 ft) and 7.9 s. The dominant direction of wave approach is from the northeast and east accounting for approximately 64 % of the wave energy impinging on the coast. The USACE (1982) have estimated that the gross littoral transport for nearby Wrightsville Beach is 843,150 m^3 y^{-1} with a net southerly component of 592,130 m^3 y^{-1}.

Development of the island began in the late 1960's when a causeway was constructed across the 1.8 km wide lagoon along the central portion of the island. Between 1967 and 1972 approximately 1.0 million m^3 of material was dredged from the lagoon along the southwestern portion of the island for the construction of a series of finger canals and connecting waterways. Much of this material was placed on the upland areas along the southern portion of the island to increase its elevation for construction purposes. A variety of small scale erosion mitigation efforts were undertaken in the 1980's at both the northern and southern portions of the island in an effort to offset the inlet induced erosion. Aside from beach bulldozing efforts, mitigation included placement of experimental sand-filled tubes along a 725 m long section updrift of Mason Inlet in 1985 and placement of dredge material, excavated from interior channels, along the northernmost section of the island downdrift of Rich Inlet (1981- 85). In 1993 approximately 260,000 m^3 of sand was placed along the southern half of the island in an attempt to nourish the updrift shoreline segment influenced by Mason Inlet.

Prior to 1996 the island had not experienced the impacts of a major landfalling hurricane since 1959. In the summer of 1996, during a seven-week period of time, Hurricane Bertha, a Category I storm, and Hurricane Fran, a strong Category III storm, made landfall in the immediate area (Fig. 1). Elevated water levels exceeded the hundred-year flood level during Hurricane Fran, resulting in the complete erosion of the nourished beach and dunes. Inundation also resulted in the development of extensive washover topography. Scores of homes along the southern portion of the island were damaged and several were destroyed.

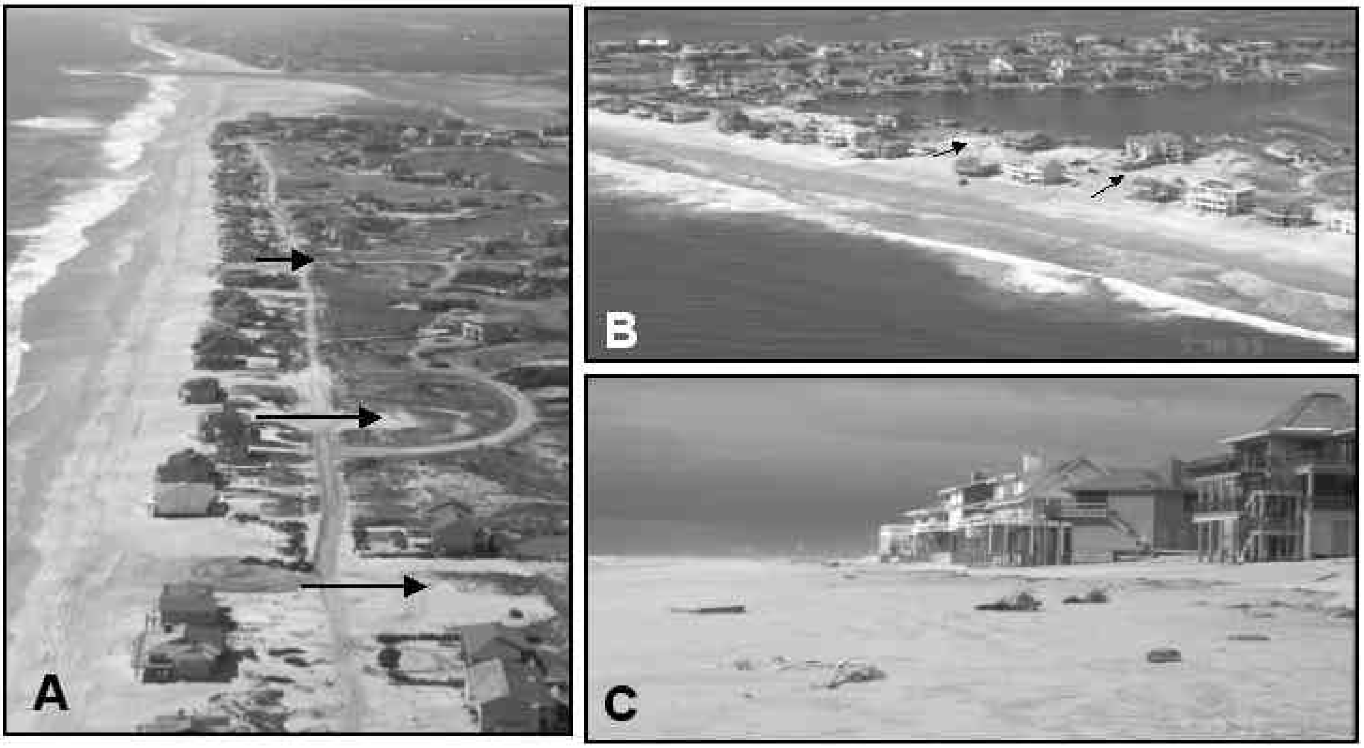

Figure 2. Aerial photographs (9/19/99) of Hurricane Floyd impacts on Figure Eight Island. A. South view of island. Wrightsville Beach and Mason Inlet are located at top of photograph. Almost all of the dunes along the island were destroyed. B. Landward view along the south central part of barrier. Extensive washover fans developed in this area of the island. Bulldozer (center of view) is scraping sand for dune rebuilding efforts. C. South view of flattened profile and former location of dune line. Note position of wrack line and lack of fronting dunes.

In order to mitigate the impact of Hurricane Fran, an additional 312,000 m^3 of sand was dredged from a navigation channel and placed along portions of the northern and central sections of the island. In August 1998, Hurricane Bonnie, a Category II/III storm, made landfall in the area, causing erosion of the beach and the restored dune line. The beach and dunes along the island's southern section were rebuilt in April 1999, with 300,000m^3 of material excavated from a dredge material island along the AIWW. In September 1999, Hurricane Floyd made landfall at Cape Fear and tracked north along the coast. Numerous homes were damaged and all of the restored dunes were destroyed leading to the formation of extensive washover fans (Fig. 2). The most recent beach renourishment in February 2001, involved the excavation of the previously dredged navigation channel and the placement of 273,000 m^3 of material along the northern half of the island. Approximately half of this material remains in place as of December 2001.

MASON INLET

Information pertaining to inlet and oceanfront shoreline changes was derived from a variety of sources including BROOKS (1988), JOHNSEN *et al*. (1999) and an ongoing unpublished investigation of the Mason Inlet system. The later study forms the basis for a portion of the management strategy for Figure Eight Island's long term development. The aforementioned study was based on an analysis of digitized aerial photographs representative of the period between 1938 and 2001. Oceanfront shoreline change and inlet migration and system change data were derived from measurements made along a series of photogrammetric transects established on Digital Orthophotographic Quadrangles (DOQ).

General Setting

Mason Inlet is a small SW migrating system that separates Figure Eight Island to the northeast from Shell Island (the northern 5 km of Wrightsville Beach) to the southwest (Figs. 1, 3). Geomorphic evidence indicative of extensive former inlet activity can be found within the marsh-filled lagoon where a series of narrow, elongated shrub dominated marsh islands occur (CLEARY *et al.*, 1976). Historic map and core data support the geomorphic data (CLEARY and HOSIER 1979).

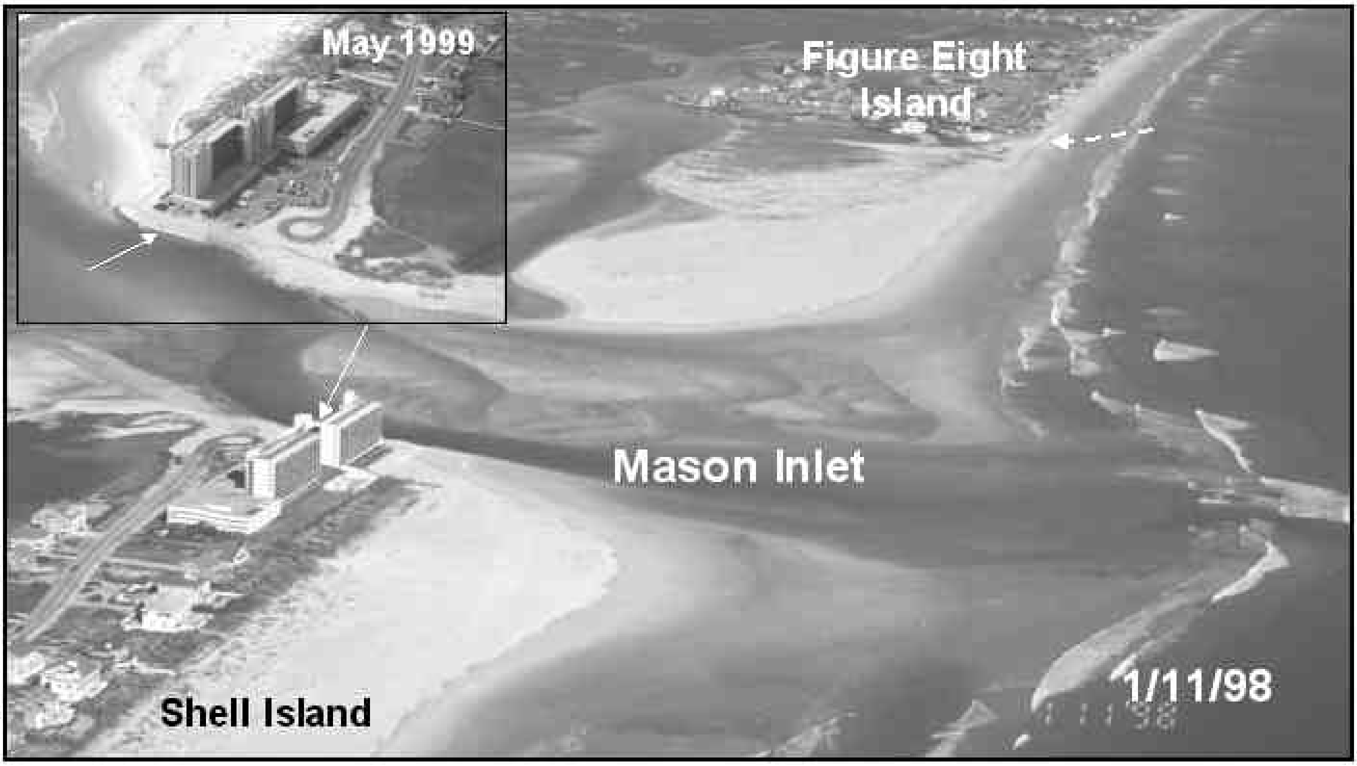

Figure 3. North view (1/11/98) of Mason Inlet and adjacent Figure Eight Island and Wrightsville Beach. Insert (5/99) shows oversize sand bags at base of threatened Shell Island Resort. Note clogged interior channels and position of ebb channel.

Contemporary Inlet Characteristics

The inlet is characterized by a relatively small, minimum inlet width with a mean value of approximately 200 m for the past 60 years. No historic bathymetric surveys exist of the inlet and ebb tidal delta. Recent bathymetric surveys in 1995 indicated the ebb channel thalweg reached a maximum depth of 3.0 m. Field surveys have shown that the thalweg has deepened to 5.0 m after the placement of a series of large sandbags in 1997, along the Shell Island Resort, on the inlet's eroding south shoulder (APPLIED TECHNOLOGY MANAGEMENT, 2000).

A tidal prism of 1.9 x 10^6 m^3 was calculated following the method of JARRETT (1977) using data from the 1995 partial survey of the inlet throat. Recent collected ADCP data indicated the tidal prism has decreased to approximately 0.65 x 10^6 m^3. Currently the ebb tidal delta is estimated to contain less than 300,000 m^3 of material. A comparison of aerial photographs from 1986 and 2001 indicate the extent of the delta has decreased markedly during the past 15 years. Aerial photographs (Fig. 4) also show a dramatic infilling of the lagoon and the soundside access channels that connect the inlet to the Atlantic Intracoastal Waterway (AIWW).

Data indicate the ebb channel orientation, both within the throat and across the ebb delta platform, have changed significantly from 1938 to 2001. BROOKS (1988) and CLEARY (1996) demonstrated that the orientation of the outer bar channel dictates the ebb delta shape, and triggers minor phases of erosion and accretion along the shoulders depending upon the asymmetry of the ebb tidal delta. Orientation of the ebb channel across the ebb platform has ranged from 69° to 178° (ENE-NE). There have been numerous cycles of ebb channel deflection and ebb delta breaching and channel reorientation since 1938. The duration of the cycles have varied from 1-7 years. Because the ebb shoals are of limited extent, the more recent cycles are of shorter duration. During ebb delta breaching events, sand bar complexes that are bypassed updrift weld onto the Figure Eight Island shoulder. The swash bar packets migrate into the inlet throat ultimately extending the lengthening spit that comprises the Figure Eight Island shoulder. Historically this bypassing scenario has promoted an increase in the migration rate as the updrift shoreline accreted and extended further to the southwest (BROOKS, 1988; CLEARY, 1996; JOHNSEN *et al*., 1999).

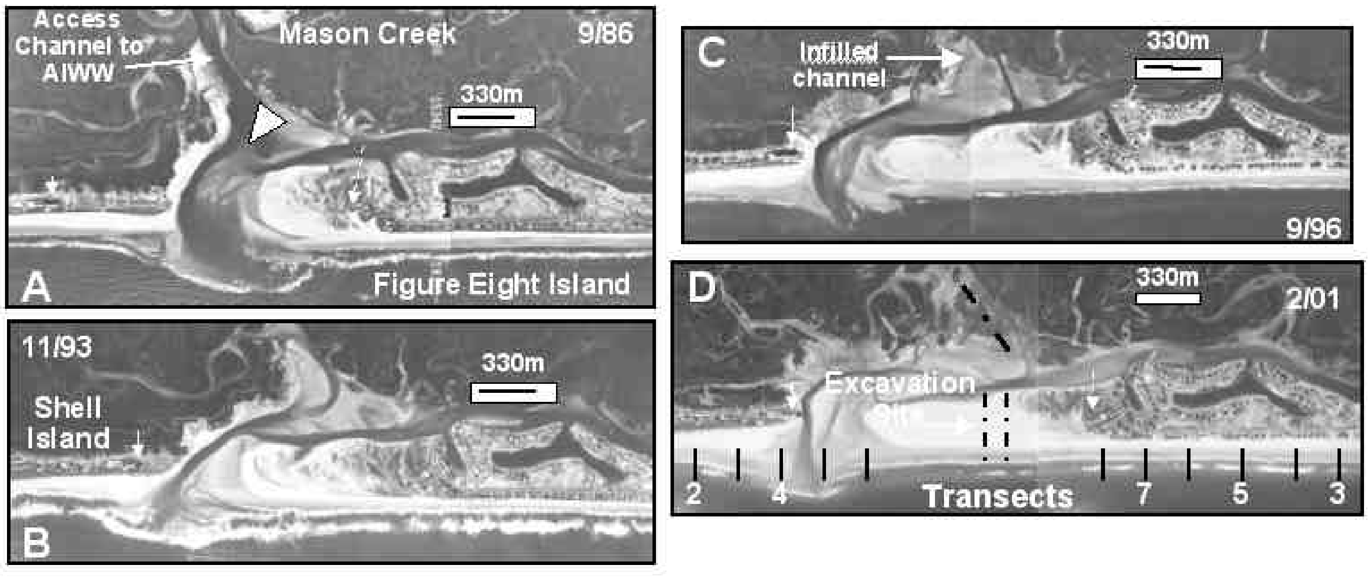

Figure 4. Aerial photographs (9/86 – 2/01) depicting historic changes in Mason Inlet system. A. Photograph (9/86) depicts conditions shortly after construction of Shell Island Resort. Note position of flood ramp (triangle) and AIWWaccess channel. B. Photograph (11/93) depicts rapid deterioration of soundside channels that resulted in a significant decrease in the tidal prism and a corresponding change in migration rates and size of the ebb delta. C. Post Hurricane Fran view (9/96) of inlet depicting infilled interior channels and position of inlet prior to placement of sand bags. D. Photograph (2/01) depicts clogged channels, proposed site for relocation of inlet and transects used for determining oceanfront changes.

Inlet Migration and Shoulder Changes

Previous studies (BROOKS, 1988; CLEARY and MARDEN, 1999; JOHNSEN *et al*., 1999) documented that shoulder migration rates have not been consistent through time. The rate of southerly migration has varied and there have been minor short-term reversals in the direction of migration due to expansion of the inlet and deflection and reorientation of the various segments of the ebb channel. The inlet migrated 1085 m between 1974 and 1996, prior to the placement of the oversized sandbags (Fig. 3). Migration rates for the above period average 50 m y^{-1} (22-year average). Short term rates since 1993 approached 100 m yr^{-1}.

Between 1974 and 1980 the updrift Figure Eight Island shoulder extended a distance of 238 m to the southwest, while the downdrift Shell Island shoulder eroded 117 m. A reversal in the differential movement occurred during the subsequent period between 1980 and 1985 when the updrift shoulder migrated only 156 m, while the downdrift shoreline eroded 245 m. Between 1985 and 1990 both shoulders migrated approximately 217 m to the southwest. A dramatic increase in the movement of both shoulders occurred between 1990 and 1996 when the updrift shoulder moved 410 m and the downdrift shoulder eroded 317 m. Between 1974 and 1996 the Figure Eight Island shoulder moved 120 m more than the south shoulder. During this time period, the throat section infilled and narrowed before deepening as a result of the "hardening" of the south shoulder in 1997.

The movement of the ebb channel midpoint within the throat has been as variable as the shoulder changes. Between 1974 and 1980 the channel midpoint migrated only 78 m. Migration of the channel increased during the subsequent five years (1980-1985) when the channel moved 341 m to the southwest. During this time interval the flood ramp steadily encroached on the primary access channel initiating a shoaling phase. Migration rates during the interval 1974 to 1985 increased from 1.1 m per month to 5.6 m per month. Between 1985 and 1990 the midpoint migrated to the southwest a distance of 245 m at rates of 4.1 m per month. From 1990 to 1996 the channel migrated

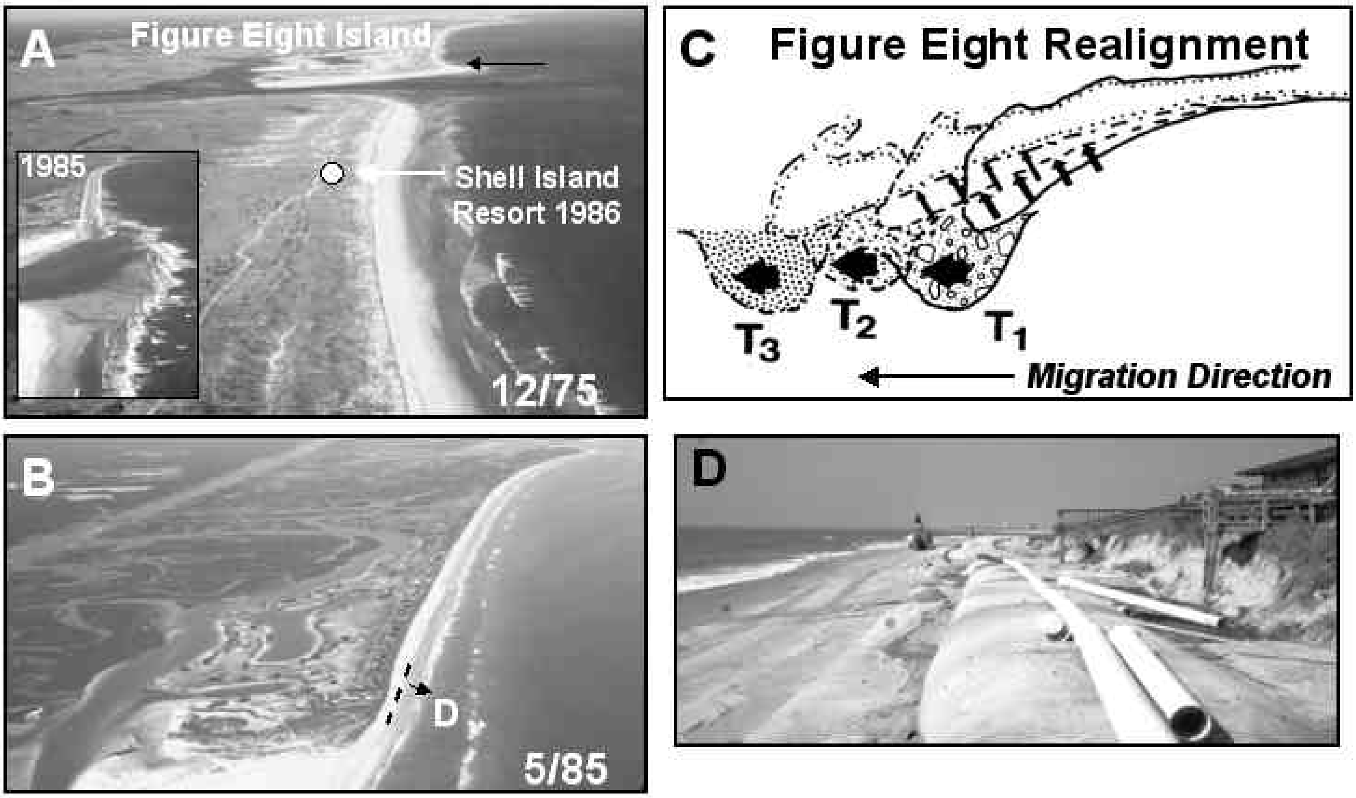

Figure 5. Impact of Mason Inlet migration and realignment of Figure Eight Island. A. North view of Shell Island, Mason Inlet and Figure Eight Island (12/75). Dot depicts location of Shell Island Resort and approximate 2001 position of inlet. Note large shoreline protuberance on updrift oceanfront, general curvature of barrier and wide dune and beach. B. May 1985 view of updrift oceanfront. Dashed line depicts location of Longard tubes emplaced in April/May 1985. C. Cartoon illustrating realignment of trailing (updrift) barrier as migration occurs. D. Longard tubes were placed (5/85) along a 600 m section of the eroding oceanfront in an attempt to mitigate impacts of inlet migration. By September 1985 most of the tubes failed.

363 m at a slightly higher average migration rates of 5.0 m per month. Prior to the placement of the sand bags on the south shoulder the monthly average migration rates were approximately 7.0 m per month.

Since 1990 the rates of channel and shoulder migration have more than doubled. The dramatic increase reflects the drastic reduction of the inlet's tidal exchange capacity and the concomitant increase in the relative importance of the littoral processes. The encroachment of the flood ramp upon access channel began in the early to mid 1980's (Fig. 4 A-D). With continued inlet migration, the expanding flood tidal delta and the main soundside channel were eventually juxtaposed (CLEARY and MARDEN, 1999; JOHNSEN *et al*., 1999). Since the early 1990's when the migration rates steadily increased, there has been a rapid shoaling of the lagoon channels as the flood delta overstepped and infilled the main feeder channel.

Inlet Induced Oceanfront Shoreline Changes

The southwesterly migration of the inlet not only impacts the shape of the shoreline along the throat, but it also alters the planform (Fig. 5 A - C) of the adjacent oceanfront shorelines (CLEARY, 1996; CLEARY and MARDEN, 1999; JOHNSEN *et al*., 1999). Measurements made along photogrammetric transects (Fig. 4 D), established along the migration pathway, indicate that concurrent with migration, the updrift Figure Eight Island shoulder experienced erosion, while the oceanfront along Wrightsville Beach accreted.

Since 1974 102 m of shoreline retreat has occurred along the updrift Figure Eight Island shoreline in vicinity of transect 4 (Fig. 4 D). In order to mitigate the onset of erosion during the early phases (1983 - 85) of the realignment of the trailing barrier, a series of sand bags were to be placed along a 600 m-long stretch of the Figure Eight Island shoreline to prevent further land loss (Fig. 5 B-D). A decade later, the entire southern half of the oceanfront was renourished with approximately 230,000 m^3 of sand dredged from the adjacent flood delta and interior channels. The complete destruction of fronting dunes and the massive overtopping during Hurricane Fran in September 1996, necessitated a second nourishment involving 257,000 m^3 of material that was removed from a large dredge material island along the AIWW.

In contrast to the net erosion on Figure Eight Island, the downdrift Wrightsville Beach shoreline prograded as much as 75 m during the 22-year period between 1974 and 1996 (Fig. 4). However, during this same time interval, the shoreline along the throat eroded 916 m due to the migration of the inlet. The net accretion along the Shell Island shoulder is related to the welding of swash bar complexes and sediment trapping within the lee of the linear channel margin bar that is commonly welded to the Shell Island shoulder (Figs. 4 A-C).

Management Issues

The inlet has been the focus of a variety of environmental and management issues since 1995 when the rapid erosion of the Shell Island shoreline threatened to undermine the Shell Island Resort. After unsuccessful attempts at hardening the inlet shoreline, the concerned parties obtained a variance from the state in September 1997 to place oversize sand bags along the base of the threatened structure. The variance allowed the bags to remain in place for a period of two years while efforts were made to formulate a plan for relocation of the inlet. The Mason Inlet Preservation Group, consisting of property owners potentially impacted by the migrating inlet, approached the local New Hanover County government in the fall of 1998 to enter the fray and act as a sponsor of the relocation efforts. The modification of the inlet has been the focus of considerable debate because of the environmentally sensitive nature of the issues and the perceived economic ramifications for the county. Nonetheless, an extension of the sand bag permit was obtained in December, 1999 that allowed the bags to remain in place for an additional year as work continued toward relocation. An assessment plan was agreed upon by the homeowners that would benefit from the inlet's relocation, and in August 1999 a permit was filed with the NC Division of Coastal Management.

The original modification plans involved the excavation of a new inlet corridor (640 x 152 x –3.0m NGVD) across Figure Eight Island, approximately 914 m north of the existing inlet. In order to assure the success of the project, the interior channels as well as Mason Creek, the clogged access channel that connects the interior to the AIWW, had to be dredged (Fig. 3, 5 B). A portion of the material from the dredging operations will be used to plug the existing inlet, and approximately 226,000 m^3 of the excavated material is to be placed along a 2590 m segment of Figure Eight Island. Subsequent to the review of a number of Environmental Assessment Reports by the state and federal agencies, a number of mitigation measures and plans for wetlands and threatened or protected species were incorporated into the design plans. A second extension of the sand bag permit was issued in late 2000 to allow the permitee to respond to comments by the various regulatory agencies. In November 2001 the US Army Corps of Engineers issued a conditional permit for the project that after much debate was accepted by the county. The current schedule calls for the inlet relocation project to begin in early January 2001, barring any litigation by opponents of the project.

RICH INLET

The description and interpretation of the contemporary and historic inlet and oceanfront changes is based on a unpublished study by CLEARY (2001) that compliments previous works of BROOKS (1988) and JOHNSEN *et al*. (1999). The most detailed and recent investigation (CLEARY, 2001) was based on an analysis of a total of 40 sets of historical aerial photographs that were analyzed for temporal and spatial changes in the inlet system.

Thirteen representative sets of aerial photographs dating between 1938 and 2001 were registered and digitized. In this study digitally geo-rectified aerial photographs, referred to as Digital Orthophotographic Quadrangles (DOQ) and Digital Orthophotographic Quarter Quadrangles (DOQQ), were used as base-maps. Several photogrammetric baselines were established and relative to these, a series of inlet parameters were measured. Changes in the oceanfront shoreline positions were measured along 19 transects oriented normal to a shore-parallel baseline that extended along the inlet's zone of influence.

General Setting

Rich Inlet is a relatively large inlet that separates Hutaff Island, a 9 km long undeveloped barrier to the northeast, from Figure Eight Island to the southwest (Figs. 1, 6, 7). The inlet drains an expansive marsh-filled lagoon where two large, relatively deep tidal creeks, Nixon and Green Channels, connect the inlet to the Atlantic Intra-Coastal Waterway (AIWW). Historic map and geomorphic data indicate the inlet has been a relatively stable feature over the past two centuries and has been confined to a 1.0 km wide zone. The large drainage area that includes portions of the bar-built lagoon and Pages Creek estuary enhances the inlet's stability. Underlying Tertiary rock units that rise within 5 m of the marsh surface probably dictate the extent of its migration pathway. Oligocene siltstone hardbottoms are common along the outer margin of the ebb-tidal delta in water depths of – 9.0 m (CLEARY, 2000).

Figure 6. Oblique north view (12/00) of Rich Inlet, Figure Eight Island and Hutaff Island. Rapid erosion of oceanfront stemmed from northeasterly migration and realignment of ebb channel. Ebb delta breaching occurred several months earlier setting the stage for a southerly migration of the channel. Insert shows the current condition (9/01) of the eroding oceanfront.

Inlet Characteristics

The inlet is a relatively large feature compared to other inlets within the region. The inlet's minimum width has varied considerably during the past seven decades from a maximum width of 815 m in October 1989 to a minimum width of 280 m in February 2001. The inlet's average minimum width since 1938 is approximately 600 m. Data from a series of recent Accoustic Doppler Current Profiler (ADCP) surveys in 2001 indicated that the depth of the throat segment of the ebb channel ranged from 5.4-11.9 m. The peak average velocity on a falling tide during spring tide conditions was 0.76 m sec. The maximum velocity measured in the thalweg was 2.6 m sec. ADCP data collected in October 2001 indicated the ebb tidal prism was 15.94 x 106 m^3. The ebb-tidal delta is estimated to contain 7-9 million m^3 of material to depths of 6 m.

Analyses of the photogrammetric data indicate that the orientation and position of the ebb channel have changed repeatedly over time and have dictated much of the shoreline change patterns over the past 60 years. Figure 8 illustrates some of the recent channel changes and the effects on the adjacent shorelines. Since 1938 the orientation of the outer bar channel has ranged from approximately 75° to 175°. Between 1938 to 1993, the channel was commonly aligned in a south-southeasterly to southeasterly orientation (130-175o). The channel orientation began to change in 1994 toward a more easterly alignment. In the summer of 2000 the channel assumed its most NE alignment (75o) since 1938. By December 2000 the outer portion of the ebb channel had been repositioned and realigned in a shore normal fashion (Fig. 6). An October 2001 overflight indicated the new channel was better defined and was flanked to the northeast by an expanding marginal flood channel (CLEARY, 2001).

Dramatic changes have also occurred in the direction and rates of inlet movement (Fig. 9). During the period 1938 to 1945 the inlet moved 226 m in a northeasterly direction. Over the next 36 years, between 1945 and 1981, the channel reversed direction and moved 280 m to the southwest. In 1981 the inlet began to migrate to the northeast, and by 1986 had migrated 174 m at average rates of 35 m y^{-1}. Over the next seven years the rate of movement decreased and averaged only 2.6 m y^{-1}. Since 1993 the channel migrated relatively rapidly (30-70 m y^{-1}) to the NE a distance of 323 m. Additionally, in mid 1999 the channel was located approximately 520 m northeast of its 1938 position (Fig. 8). In late summer of 2000, the ebb channel reversed its northeasterly direction of migration and moved approximately 70 m to the southwest. The change in the channel position was triggered by the reorientation of the outer bar channel from 70° in August 2000 to 135° in December 2000.

Oceanfront Shoreline Change

Figures 10 and 11 illustrate that there were dramatic differences in the shoreline change patterns along the Figure Eight Island and Hutaff Island oceanfronts between 1938 and 2001. Since 1938 the net erosion along the updrift oceanfront on Hutaff Island ranged from 12-123 m. In contrast to the severe erosion along Hutaff Island, net accretion (Figs. 7, 10, 11) occurred along Figure Eight Island. Accretion along this oceanfront ranged from 10-68 m. This 2 km long historic accretion zone is a direct by-product of the relative stability of the inlet (Fig. 7).

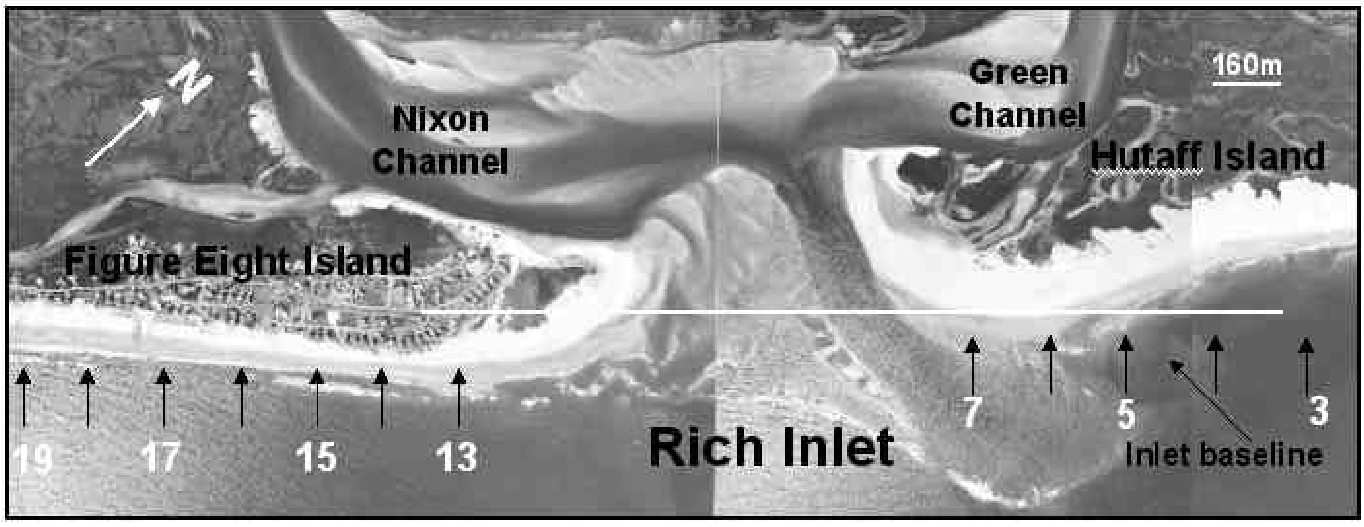

Figure 7. Aerial Photograph (3/99) depicting Rich Inlet and locations of transects used for measuring oceanfront and inlet changes. Note position and orientation of ebb channel. Compare with Figure 6.

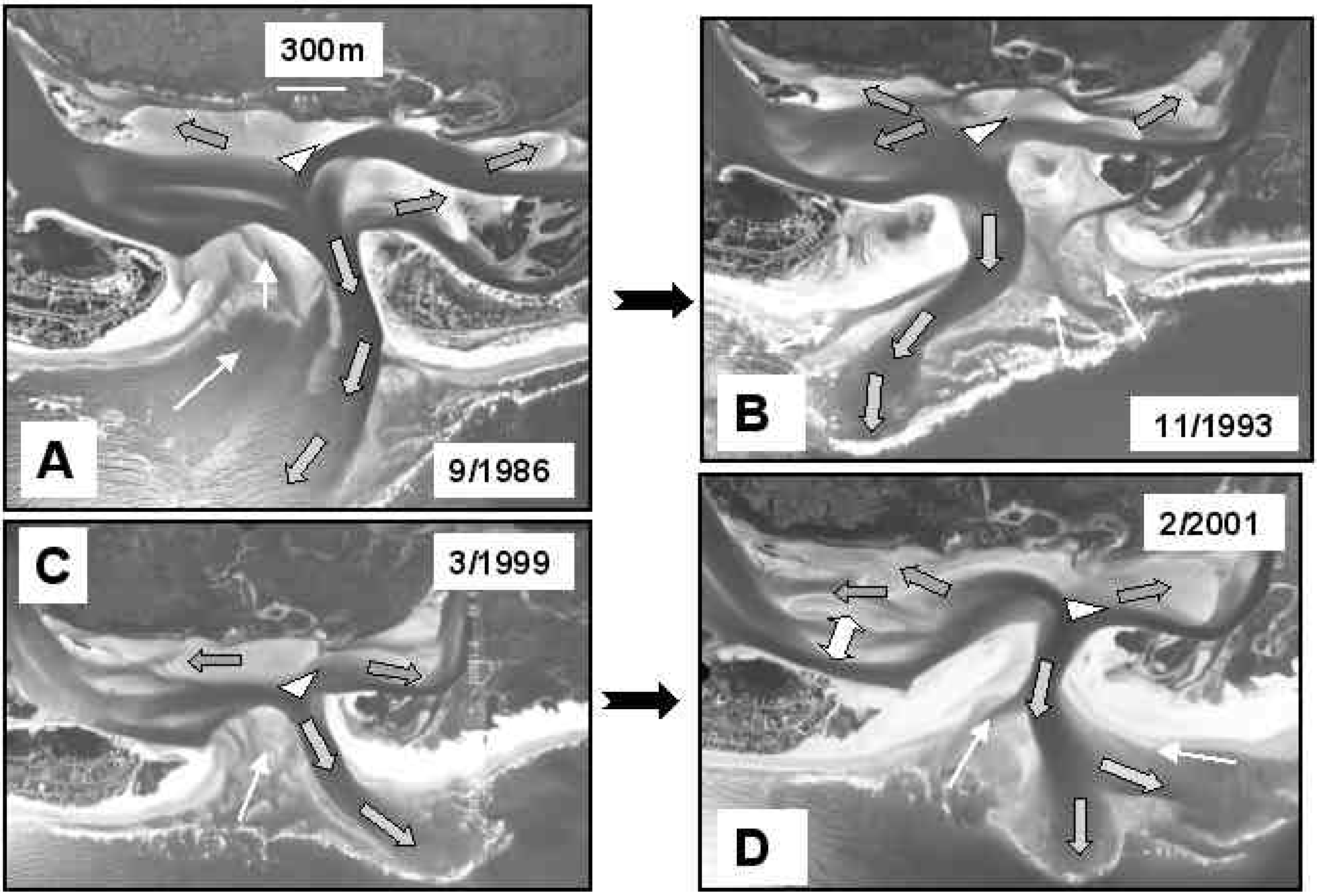

Figure 8. Aerial photographs illustrating Rich Inlet changes (9/96–2/01). A. Photograph depicts initial growth of incipient spit and wide flood channel flanking SE oriented ebb channel. B. Inlet morphology in November 1993 consists of an ebb channel strongly skewed toward Figure Eight Island and a wide updrift marginal flood channel. Note erosion on Hutaff Island and buildup on downdrift oceanfront. C. Photograph (3/99) depicts change in ebb channel orientation and position. Configuration results in erosion on downdrift oceanfront and accretion on updrift barrier. D. Photograph depicts reoriented ebb channel after September 2000 ebb delta breaching event. Note narrowing of throat and due to infilled downdrift flood channel and corresponding spit growth.

The shoreline changes along Figure Eight Island between 1990 and 2001 are depicted in Figure 10. The shoreline change patterns were very erratic between 1990 and 1993 (Figs. 7, 10). Shoreline changes during the subsequent three years (1996 to 1999) reflect the impact of Hurricane Fran and renourishment of the beach. The rapid movement of the ebb channel to the northeast between 1996 and 2001, coupled with the ebb channel's reorientation, promoted an increase in recession. Net oceanfront erosion ranged from 36-84 m. The majority of the severe erosion along the oceanfront occurred between 1998 and 2001.

Since 1990 Hutaff Island shoreline has experienced a net loss of oceanfront (Figs. 7, 11). Figure 11 illustrates that the shoreline erosion ranged from 1-94 m. The majority of the recession occurred during a period of time when the ebb channel was aligned along the Figure Eight Island shoulder. During the period from 1993-2001, net accretion characterized the shoreline (Figs. 7, 8, 11). The buildup of the Hutaff Island oceanfront reflected the northeasterly movement and realignment of the ebb channel.

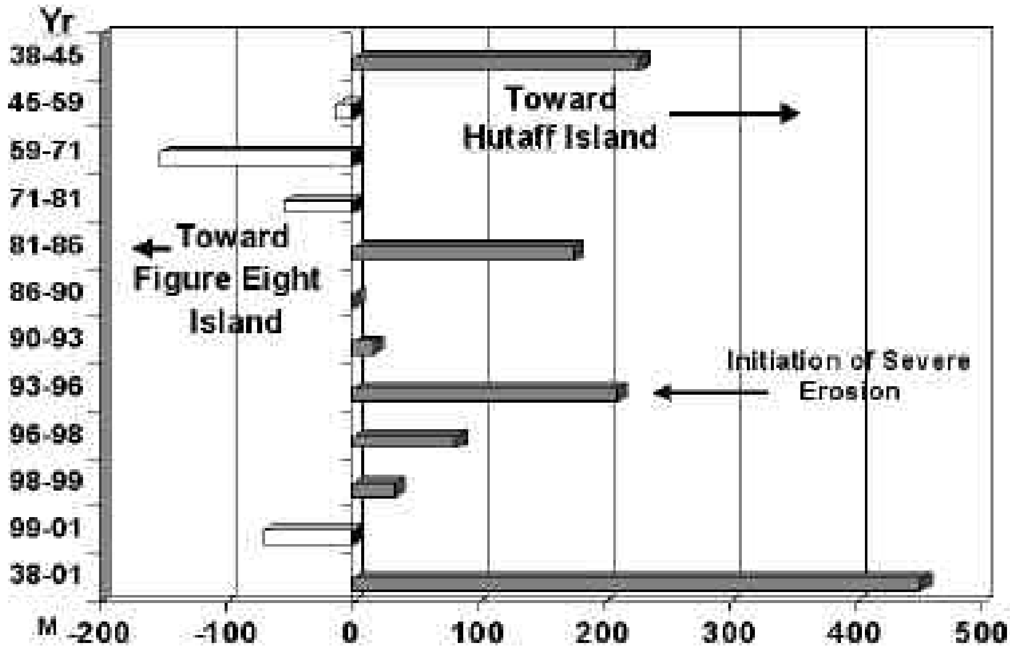

Figure 9. Bar graph depicting migration of Rich Inlet ebb channel mid-point since 1938.

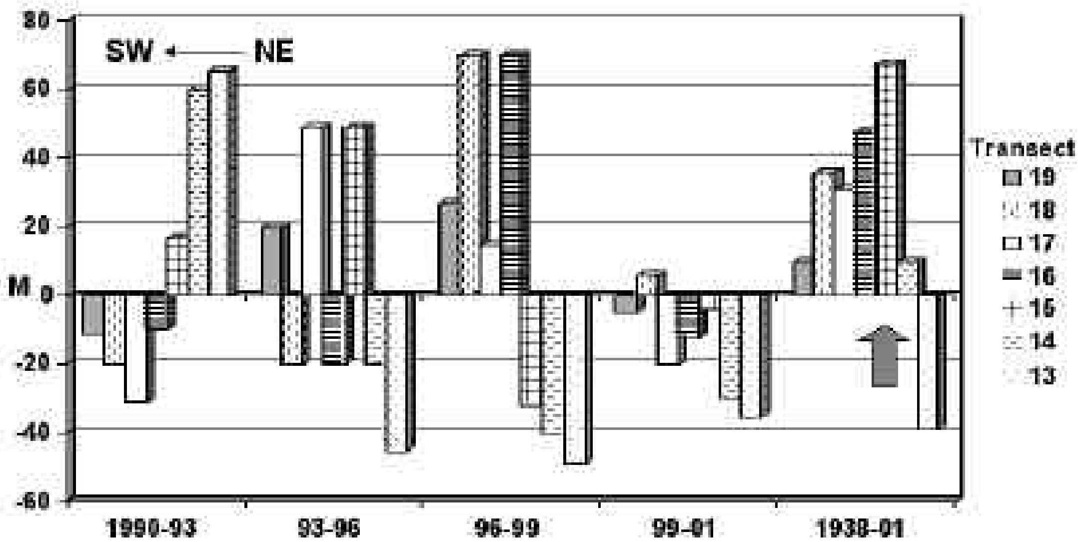

Figure 10. Graph depicting recent oceanfront shoreline changes (1999-2001) along Figure Eight Island and historic changes between 1938-2001. See Figure 7 for transect locations.

Ebb Channel Deflection and Shoreline Changes

Changes in the orientation and position of the outer bar channel, have played a defining role in oceanfront shoreline change (Fig. 8). Although erosion did occur along some areas of the northern end of Figure Eight Island during the period between 1971 and 1981, this ten-year interval was characterized as an accretionary episode. During this period, the ebb channel was migrating to the southwest and was generally skewed toward Figure Eight Island. The ebb channel assumed its southwesterly most position during the early 1980's.

A severe, but localized, erosion episode occurred in the early to mid-1980's (1981 to 1984) along the extreme northern portion of the Figure Eight Island oceanfront and inlet shorelines. In March 1981 the ebb channel was located adjacent to Hutaff Island and was separated from Figure Eight Island by an extremely wide marginal flood channel on the southwestern margin of the inlet. A newly formed ebb channel realigned itself in an east-southeast orientation that promoted the encroachment of the marginal flood channel onto Figure Eight Island between 1982 and 1984 and initiated a period of rapid erosion.

The erosion scenario was very complicated due to the continuously changing configuration of the ebb and marginal flood channels. The large scale channel reconfigurations and realignments prompted large sand bar complexes on the ebb delta to migrate into the Figure Eight Island marginal flood channel and eventually the estuary. During the migration and welding of the swash bar packets onto the shoreline, small-scale erosion events occurred in the lee of the sand bars due to secondary wave refraction around individual sand bar complexes. Erosion of the shoreline bordering the marginal flood channel was rapid and short-lived, and rates as high as 1.0 m per day for a six-week period were recorded. During the height of the erosion episode in 1984, the inlet shoreline eroded an average of 35 m.

During the time interval 1986 to 1993, the ebb channel remained in approximately the same position and orientation (Fig. 8). The expansive downdrift flood channel continued to infill as large volumes of sand were transported into the inlet throat. The incipient spit complex that initially formed in early 1985 was completely emergent after 1990. Consequently, progradation of the inlet shoreline in some areas was as much as 350 m (Fig. 8). By 1993 the expanding northern marginal flood channel led to further deflection of the ebb channel and a southerly channel alignment. The 1993 configuration of the inlet system consisted of a strong, south-southeasterly skewed ebb channel that was flanked by a very narrow flood channel on the Figure Eight Island shoulder and a wide updrift flood channel on the Hutaff Island margin. This morphology provided a scenario favorable for ebb delta breaching and channel reorientation. The breaching event probably occurred sometime in the later part of 1995. Alternatively the realignment of the ebb channel to more easterly orientation may have occurred through a continuous deflection of the ebb channel.

Regardless of the mechanism that initiated the channel movement, a period of severe erosion ensued for much of the northern 2 km of the island. Between 1993 and 1999, the ebb channel migrated approximately 325 m in a northeasterly direction (Fig. 9) Reorientation of the outer bar channel occurred concurrently with the northeasterly movement of the channel. In 1999, the ebb channel was located in its most northeasterly position (Fig. 7). The channel's movement to the northeast coincided with a change in the orientation of the outer bar channel from 155° to 75°.

The consequences of this complex northeasterly movement for the Figure Eight Island oceanfront were twofold: first and foremost, the large swash bar complexes no longer nourished the developed segment of the shoreline; secondly, the highly asymmetric ebb-tidal delta no longer afforded protection to the northern end from wave attack (Fig. 8). As the ebb channel migrated further to the NE, the outer channel segment reoriented, causing the location of bar attachments to shift away from the developed portion of the island. As channel migration occurred, the entire offshore shoal complex was continuously reconfigured. The impact of the reconfiguration of the ebb delta is apparent upon inspection of Figures 10 and 11. During the late 1990's, when erosion reached a critical point, the ebb delta afforded little or no protection for the oceanfront and consequently no inlet-related nourishment of the beach occurred. Erosion along the oceanfront between transects 13-15 exceeded 80 m (Fig. 10). Erosion of the recently renourished northern segment of the beach will likely continue until a more southerly shift of the ebb channel and shoals occur.

In contrast to the above erosion scenario, the Hutaff Island oceanfront during this period experienced a general buildup even though it was the landfall site for Hurricane Bertha. Figure 11 illustrates that the shoreline change pattern was altered appreciably after 1993. Erosion dominated the oceanfront between 1990 and 1993 when the channel was located closer to Figure Eight Island and aligned in a southeasterly orientation. The average erosion rates for the 1.5km long shoreline segment updrift of the inlet was 36 m y^{-1}. As ebb channel migration and realignment occurred in 1994, accretion became the norm along Hutaff Island. Between 1996 and 1999 as the inlet tracked to the northeast, the oceanfront accreted by as much as 60 m. Since March 1999, the shoreline has prograded an average of 36 m.

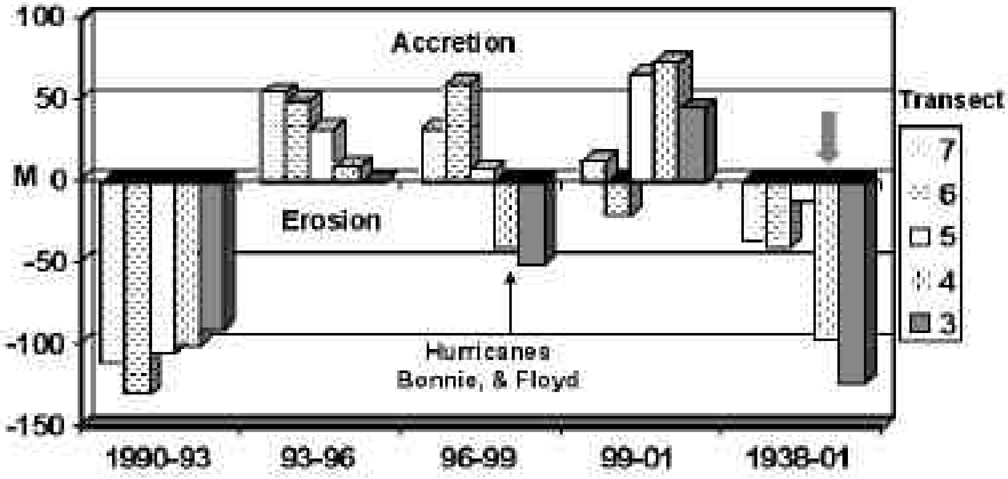

Figure 11. Graph depicting recent oceanfront shoreline changes (1999- 2001) along Hutaff Island and historic changes between 1938-2001. See Figure 7 for transect locations.

Inlet Sand Resources and Management Issues

Beach renourishment projects along the northern portion of the island have relied on the excavation of a "navigation channel" within Nixon Channel that has repeatedly infilled due to the expansion of the adjacent flood tidal delta. The volume of sand transported through Nixon Channel to the AIWW is estimated at 35,000 m^3 yr^{-1}. Although the state advocates nourishment as the preferred means of maintaining the oceanfront beach and although a significant volume of sand is contained within the flood tidal delta and interior channels, it has become extremely difficult, if not impossible, to obtain large volumes of material from estuarine waters. The prohibition of future large-scale mining efforts that involves periodic dredging of choked navigation channels precludes the use of these areas for future renourishment efforts. As a consequence, the island’s governing body has initiated efforts directed at developing a management strategy for the ebb tidal delta and throat segment of Rich Inlet. Any modification of this inlet system for beach renourishment purposes will be met with stiff resistance by regulatory agencies. Nonetheless efforts are continuing because the inlet and its associated shoals represent the only viable target site for large volumes of renewal sand resources.

The first step in this effort included the determination of the extent and nature of the inlet’s influence on the adjacent shorelines. The key to this understanding was the relationship between the ebb channel position and orientation and the shoreline change patterns on both Figure Eight and Hutaff Islands. The channel’s position and alignment are critical factors in the determination of the timing and extent of dredging operations. The most felicitous ebb channel position and orientation involves a configuration where the ebb channel is aligned in a shore normal fashion and positioned approximately 800 m southwest of its current position.

Data indicate that the ebb channel has begun to track in a southerly direction; and as a result a reversal in the shoreline change patterns it will probably occur as the barrier planforms are altered accordingly. The continual repositioning of the ebb shoals to more favorable southwesterly locations will have an increasing positive impact on the Figure Eight Island shoreline. It is difficult to predict what time span is involved in the migration of the ebb channel along the 800 m long pathway to its optimum position. It may be as much as a decade or more, but there is a high probability that a breach across the narrow, low-relief spit will shorten the time lag considerably (Figs. 6, 8 D).

Although the details of the inlet management plan being developed are far from complete, they focus on a scenario where the ebb channel is deepened from the throat to the outer bar and realigned in a shore normal fashion. Channel dredging would yield approximately 1.0-1.5 million m^3 or more of material, depending upon the footprint of the excavation and the morphology of the outer bar. A number of other supporting investigations is underway, including a hydrographic study of the inlet system, that will provide additional environmental information.

SHOREFACE SAND RESOURCES

Investigations of the offshore areas of other nearby beaches such as North Topsail Beach, Wrightsville Beach, and Kure Beach/ Fort Fisher showed the shoreface to be very complex (Fig. 1). These investigations indicated that each shoreface sector was unique, and each could differ significantly from the immediately adjacent areas in terms of the underlying geologic controls. The sand resource potential of the aforementioned areas was also shown to vary from site to site. JOHNSTON (1998) and CLEARY *et al*. (1999) indicated the offshore areas of North Topsail Beach had no potential for sand resources. Data from investigations by THIELER *et al*. (1997, 1998) suggest the middle and outer portion of the shoreface off nearby Wrightsville Beach was only a marginal prospect for beachfill sand. The studies by MEISBURGER (1977, 1979), USACE (1993), SNYDER *et al*. (1994), and MARCY and CLEARY (1998) of the Carolina Beach to Fort Fisher shoreface indicated the offshore areas of this headland shoreline segment contained significant deposits of high quality sand. The assessment of the shoreface sand resource potential off Figure Eight Island was based on a report by CLEARY (2000). The aformentioned investigation was based an analysis of a suite of 62 vibracores and 55 SCUBA based diving surveys that were integrated with seismic and sidescan sonargraph surveys.

Figure Eight Island Shoreface Sediments and Sand Resource Potential

The Figure Eight Island shoreface is characterized by relatively gentle gradients with no major rock ledges present seaward to a distance of 4.5 km. Minor undulations in the seafloor morphology are related to the presence of a series shore-normal to shore-oblique features resembling ripple scour depressions. Data from diver surveys indicated that the floors of the depressions are mantled by coarse sediments that range from cobble sized lithoclasts to medium, sand sized shell hash. Several areas of the shoreface are dominated by very low relief (<0.50 m) hardbottoms. The hardbottom areas are composed of well-indurated Oligocene sandy limestones and poorly consolidated Oligocene siltstones. Limestones hardbottoms are restricted to the nearshore area in the center section of the island approximately 2.0 km southwest of Rich Inlet. Other hardbottom areas, composed of Oligocene siltstone (HO), occur in an area immediately seaward of Rich and Mason Inlets (Fig. 12).

The shoreface is characterized by a relatively thin veneer (0.1-2.5 m) of modern and palimpsest sediments resting disconformably on Oligocene strata. The complex surface sediment mosaic originates from the reworking of the underlying strata and sediments during shoreface migration and periodically during major storms. Core data suggests that in areas where the sediment thickness is less than 30 cm, the underlying rock units are periodically exposed and subsequently reburied. Many of the cores recovered contained graded sequences overlying the Oligocene siltstone that is extensively bored. The bores frequently contain the intact bivalve and are often infilled with material that is lithologically different than the overlying mobile sediment.

Vibracore data (Fig. 12) indicate that the shoreface veneer consists of variable thick sequences of shelly, fine quartz sand with differing amounts of silt and mud intercalated with clean and muddy sandy shell hash and carbonate gravels. The majority of the shoreface sediment cover is generally less than 100 cm in thickness (Fig. 12). Thickness of the modern sediment package ranges from less than 1 cm in hardbottom areas to more than 2.5 m in muddy backfilled paleo-channels.

Clean sand units are widespread but they are seldom greater than 50 cm in thickness. At many sites the clean sand units are often absent, and in many locations muddy sand comprises the entire sediment sequence. Often the mud rich units are interbedded with 12-30 cm thick layers of shell hash and gravels. These data indicate that the thin, often muddy, nature of the sediments and the presence of environmentally sensitive hardbottoms preclude the use of the shoreface as a potential borrow area for nourishment quality sand.

OVERVIEW

Recent beach rebuilding efforts have been limited to relatively small-scale projects involving the piecemeal placement of several hundred thousand cubic meters of material along erosion hot spots. The relocation of Mason Inlet in early 2002 will initially provide 425,000 m^3 of compatible material for beach nourishment purposes along the southern portion of Figure Eight Island. This one-time placement represents approximately 17% of the volume needed for a single cycle, island wide nourishment project. It is estimated that post-relocation maintenance dredging of the new inlet will provide as much as 35,000 $m^3\ y^{-1}$ over a three-year cycle. Routine maintenance dredging of the confluence of the access channel (Mason Creek) and the

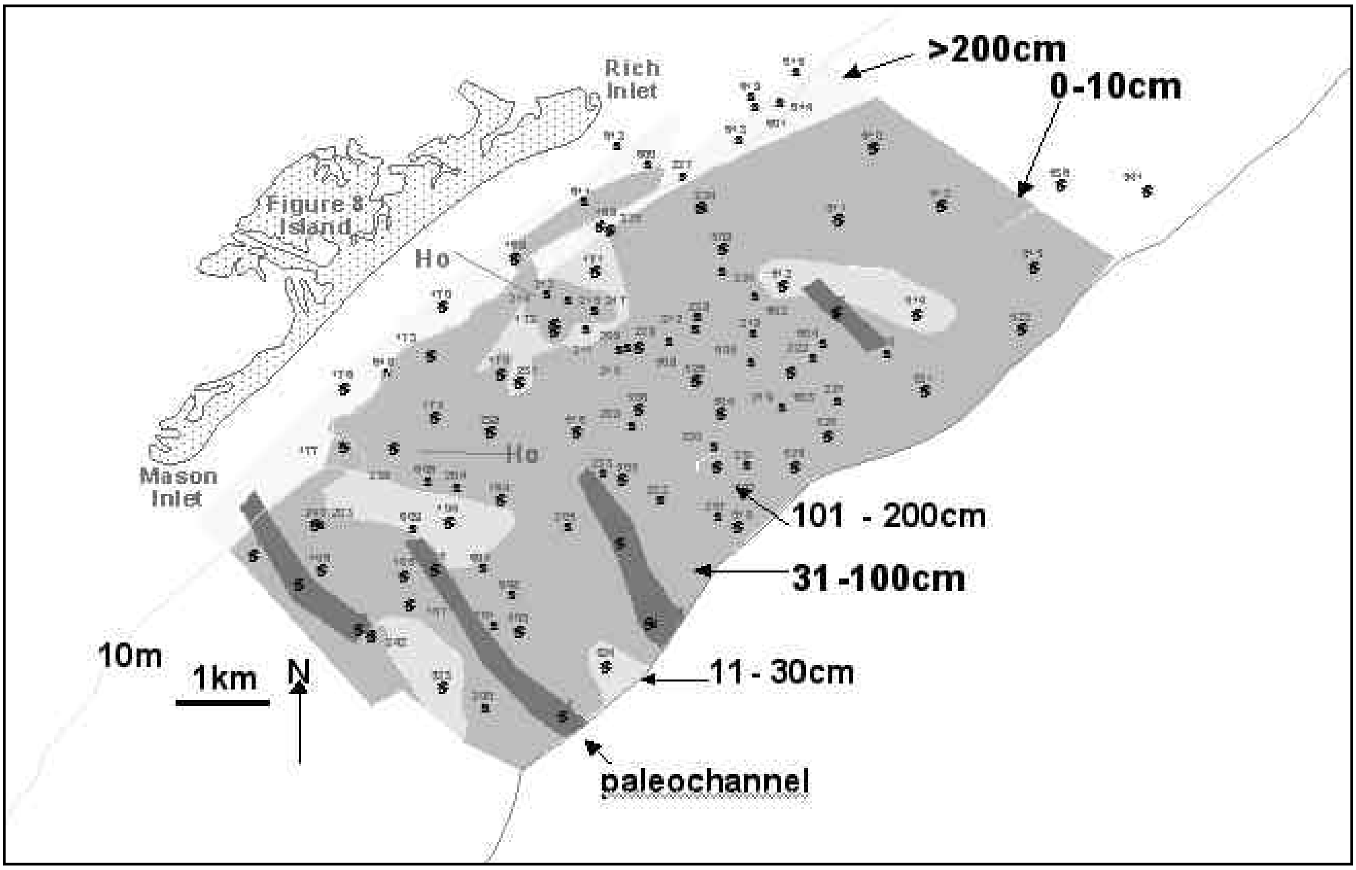

Figure 12. Map of shoreface sediment thickness. Thickness of surficial sediments was determined through a compilation of vibracore data and diver mapping surveys. The thin muddy nature of sediment sequence and the presence of hardbottoms (Ho) composed of Oligocene limestones and siltstones precludes the use of the shoreface as borrow source.

AIWW will be required periodically after the newly relocated inlet reaches equilibrium. It is estimated that as much as 69,000 m^3 yr^{-1} of additional material will also be available for renourishment purposes on the island when maintenance dredging commences.

It is highly unlikely that navigation improvements within Nixon Channel at the north end of the island in the near future will provide any substantial volume of material for beachfill projects. The lack of a significant borrow source within the interior channels of Rich Inlet, coupled with the lack of potential target sites on the shoreface, only strengthens the contention that the long-term maintenance of the oceanfront beach is tied to the utilization of sand contained within the outer bar of Rich Inlet. The initial modification of this system (throat and outer bar) could provide more than 50 % of the one-time nourishment needs for the island. The development of a sound sand management strategy for the inlet and adjacent barriers is crucial for the identification of potential problems and future mitigation of any negative impact associated with the inlet's modification. It is beyond the scope of this paper to expound upon potential mitigation scenarios except to mention that unlike most publicly financed projects, the financial resources are available to remedy adverse environmental impacts that can be identified prior to or subsequent to channel/shoal modification.

Since abandonment and not relocation is the option for the great majority of homes on the island, the denial of a permit for inlet modification by regulatory agencies would set the stage for wholesale use of a variety of "innovative" erosion control devices. Most of the other 13 coastal communities in southeastern North Carolina are faced with sand shortages because of the paucity of shoreface sand resources and the restrictive nature of the state's regulatory policy regarding mining of sand within estuarine waters. Unless the restrictive regulations regarding beach nourishment are relaxed, the next major storm event will set in motion a groundswell movement for implementation of shoreline hardening devices that are currently banned by the state.

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