Beach Changes Along Eastern Bogue Banks, North Carolina, Resulting from the 1996 Hurricane Season

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ABSTRACT


Thirteen permanent beach transects established prior to the 1996 hurricane season were used to evaluate the effects of two hurricanes on erosion and accretion rates along eastern Bogue Banks, North Carolina. Monthly monitoring for nearly two years showed that erosion patterns exhibited considerable variability and were highly influenced by the hurricanes. Whereas severely eroded sections of beach, up to 20.4 m (65.8 m^2/yr), had not recovered 1.5 yr after the hurricanes, the areas that accreted immediately following the two storms, up to 17.7 m (12.6 m^2/yr), remained stable. Application of a numerical model, REF/DIF in v. 2.51, was used to test the effects of offshore bathymetry on beach response to the hurricanes. Model results showed that predicted gradients in longshore current velocities correlated well with erosion rates during the two storms.

ADDITIONAL INDEX WORDS: Beach erosion, hurricanes, longshore currents.

INTRODUCTION

Tropical storms have long been known to cause coastal erosion and destruction of beachfront property as a result of increased wave heights, storm surge, and high winds. The extremely intense hurricane that made landfall at Galveston, TX in 1900 killed 6,000 people (NOAA, 1977), and Hurricane Hugo which hit Charleston, SC in 1989 (Category IV) caused over $4 billion in damage and beach erosion as far as 180 km north and 50 km south of the eye (DAVIDSON et al., 1990 and FINKL and PILKEY, 1991). While category V hurricanes account for less than one percent of Atlantic Coast hurricanes (BARNES, 1995), a particularly damaging category V storm, Hurricane Camille, made landfall on the Gulf Coast near Biloxi, MS in 1969 with winds in excess of 280 km/hr and a storm surge over 7.5 m (BARNES, 1995). Although no category V storms have made landfall in North Carolina, the state has a long and intense hurricane history. Scientific understanding of the response of the coast, especially during storms, remains incomplete and is the focus of this paper.

During the summer of 1996, two hurricanes made landfall in the southeastern part of North Carolina (Figure 1). Hurricane Bertha (category II) made land fall near Wilmington, NC on July 12, 1996. Storm surge recorded at Beaufort, NC (approximately 120 km to the northeast) was 0.85 m (2.8 ft) (web site statistics, National Hurricane Center). Hurricane Fran (category III) made landfall on September 12, 1996 near Cape Fear, NC. Storm surge recorded at Beaufort, NC (approximately 160 km to the northeast) was 1.65 m (5.4 ft) (web site statistics, National Hurricane Center). The catastrophic damage and losses of beachfront property during this single hurricane season highlight and intensify the need for a better scientific understanding of how to respond to the increasing challenge of beachfront erosion.

Beach profiles that we had established prior to both storms provided a unique opportunity to study the effects of back-to-back hurricanes in a single season and to monitor post-storm recovery. Objectives of the research were to 1) document the erosion and recovery of eastern Bogue Banks, NC during and following the two hurricanes using these established beach transects, and 2) elucidate the underlying causes of the variability in accretion and erosion rates using a numerical model which simulated the patterns of wave refraction/diffraction and calculated the nearshore currents.

COASTAL SETTING

Bogue Banks is a moderately developed barrier island (45 km long; 600 m average width) located along the central North Carolina coast in the northern portion of Onslow Bay between Cape Lookout and Cape Fear (Figure 1). It has been characterized as a beach-ridge dominated and inlet-modified barrier island that is relatively wide at each end and narrow in the middle (MOSLOW and HERON, 1994). The depositional history of Bogue Banks differs from the more common transgressive, storm-dominated barrier islands of the Outer Banks. During early Holocene, rapid sea level rise apparently caused Bogue Banks to transgress until about 4,000 years ago, at which time the island began to prograde seaward in response to a large sediment supply and lower rate of sea level rise. According to PILKEY et al. (1975) and STEELE et al. (1980), Bogue Banks has now returned to an erosional stage, most likely from reductions in sediment supply.

Borehole data from STEELE (1980) confirm that Bogue
Banks has in fact gone through a retrogradational phase. Coarsening-upward foreshore-shoreface sequences are laterally extensive along Bogue Banks except at the eastern and western ends which are characterized by fining-upward inlet fill deposits (Steele, 1980). In addition, Tertiary deposits crop out on much of the sea floor seaward of Bogue Banks, and a thin (1–3 m) Pleistocene sequence unconformably overlies these deposits near the inner continental shelf (Hine and Snyder, 1984). The shoreface is generally the concave upward surface that extends from the surf zone to the point where the slope becomes the same as the inner continental shelf. Offshore of Bogue Banks, the shoreface extends to approximately 12 m depth and is only 800 m wide. It consists of a basal Pleistocene sequence overlain by Holocene transgressive lagoonal deposits and regressive shoreface sands (Hine and Snyder, 1984). In addition, approximately 33 percent of the inner shelf consists of buried channel deposits (Hine and Snyder, 1984).

Bogue Banks is situated in a microtidal environment with a mean tidal range of 0.89 m (Heron et al., 1984). While the
tidal range is relatively low, tidal processes play an important role in transporting fine and coarse-grained sediment in the vicinity of Beaufort Inlet where tidal currents have been measured in excess of 115 cm/s (Sarle, 1977). However, the most significant coastal processes that affect sedimentation along Bogue Banks are waves, especially storm waves.

Mean annual wave height for the Outer Banks of North Carolina is 1.7 m with wave heights exceeding 2.0 m approximately 30% of the year (Nummedal, et al., 1977). Bogue Banks receives about 50% less wave energy at the shoreline than adjacent Core Banks, located north of Cape Lookout (Figure 1), due to a sheltering effect caused by its shoreline orientation (Heron, et al., 1984). Thus, the estimated longshore sediment transport rate along Bogue Banks is perhaps an order of magnitude less than that on Core Banks (500,000 m³/yr to the south; USACE, 1990; McNinch and Wells, 1999). In terms of storm impact, 150 recorded hurricanes have made landfall on the North Carolina coast since 1585 (Heron, et al., 1984), and an average of 1.64 hurricanes affect the Outer Banks each year (Crutcher and Quayle, 1974).

Beaufort Inlet, located at the eastern end of Bogue Banks, has been modified by channel alignment and dredging since 1911. A total of approximately 5 million m³ of sediment was used as replenishment material (from disposal projects) at eastern Bogue Banks in 1986 and 1994. Dredge spoil from the inner channel of the inlet is pumped to the beaches at eastern Bogue Banks when the storage site at Brandt Island is filled (Figure 1). Dredge spoil from the outer channel has historically been placed in offshore disposal areas and recently been used to construct a nearshore berm. Figure 1 shows locations of channels and the disposal areas that are maintained as part of the Morehead City Harbor Project (MHCHP), and further detail about the MHCHP is given in Roessler (1998).

**METHODS**

**Beach Profile Monitoring**

Thirteen beach profiles were measured using a Topcon AT-2 Autolevel and telescoping rod from a backshore baseline established by the U.S. Army Corps of Engineers (USACE) to approximately 1 m below MLLW (Figure 2). Readings were recorded along each transect approximately every 10 m or at any significant slope change, and vertical measurements were recorded to the nearest one centimeter. Eight of the stations, located at Fort Macon State Park and Atlantic Beach, were established between 1958 and 1986 by the USACE; the remaining five stations, located at Pine Knoll Shores, were established in 1995 as part of an unrelated project. The profiles were measured monthly over a two year period and, when possible, before and after major storm events. Spacing between profiles was approximately 1 km, and local fishing piers are shown as reference points. Reference elevations for the profiles located at Fort Macon State Park and Atlantic Beach were corrected to MLLW as determined from National Ocean Survey (NOS) benchmarks located at Atlantic Beach (Roessler, 1998). The survey data were entered into a computer program, referred to as the Interactive Survey Reduction Program (ISRP), which was developed by the USACE to calculate volume changes in sediment (Birkemeier, 1984).

**Numerical Model**

The numerical model REF/DIF 1, Version 2.51, which simulates the behavior of monochromatic waves over an irregular bathymetry (Kirby and Dalrymple, 1994), was used to test the hypothesis that offshore bathymetry caused nearby sections of beach to respond differently to Hurricanes Bertha and Fran. The model was used to predict breaking wave heights and angles along eastern Bogue Banks, from which longshore currents were calculated to quantify the effects of the hurricanes on shoreline change at Bogue Banks.

REF/DIF 1 is a finite-difference model that predicts wave refraction and diffraction explicitly on the basis of a model grid. Published NOAA and NOS charts along with USACE bathymetric data from the ebb tidal delta of Beaufort Inlet were digitized to produce a 22 × 22 km grid. The model grid consisted of an offshore grid with spacing of 100 m in both the longshore and cross-shore direction, and a nearshore grid within 3.5 km of the shoreline with 100 m grid spacing in the longshore direction and 10 m in the cross-shore direction (Figure 3).

Offshore wave data were obtained from the Atlantic Coast Hindcast, Phase II Wave Information Study compiled by the Waterways Experiment Station (Brooks and Brandon, 2001).
The data included wave height, period, and direction computed for an 18-year period from 1976 using a numerical hindcast method. The Waterways Experiment Station also provided hindcast data for Hurricanes Bertha and Fran for this study. Hindcast data were from a location 22 km offshore at a water depth of 20 m (34.50N, 76.75W) (Brooks and Brandon, 1995).

Breaking wave heights and angles predicted from the model were then used to calculate the longshore current velocity from an equation developed by Komar (1975). Cross-shore currents, such as rip currents and undertow, which were not considered in this study, can be important during storms. A weighted average of the breaker height and angle was used to produce a smooth plot of longshore current velocities from the following equation.

\[
V = 2.7u_m \sin \theta_b \cos \theta_b - 1.414\pi/C_f \gamma_b (1 + 3\gamma_b/8 + \cos \theta_b^2(\gamma_b/4)u_m(\delta H_r/\delta y) \tag{1}
\]

where: \( u_m \) = maximum horizontal orbital velocity; \( \theta_b \) = wave angle at breaking; \( H_b \) = wave height at breaking; \( \gamma_b \) = \( H/h \) at wave breaking (where \( h \) is water depth); \( C_f \) = coefficient of friction.

Equation (1) provides an empirical solution for longshore current velocity at the mid-surf position. Although the equation is appropriate because it combines the effects of oblique wave approach and longshore variability in breaking wave heights, it is limited in its application for two reasons. First, although useful for predicting longshore current velocities at the mid-surf location, the equation ignores effects of any cross-shore variations that may be present. Second, the equation requires assumptions to be made concerning the coefficient of friction (\( C_f \)), which is important to sediment transport (Thornton and Guza, 1986).

RESULTS

Barrier Island Dynamics

Eastern Bogue Banks was highly influenced by Hurricanes Bertha and Fran. Figure 4 shows the volumetric changes in sediment above MLLW for July (Post-Bertha) and September 1996 (Post-Fran), September 1997, and April 1998. Volume changes were calculated by comparing the survey data to a baseline profile measured in May 1996 for Pine Knoll Shores (Profiles 1–5) and June 1996 for Atlantic Beach and Fort Macon (Profiles 6–13), and thus represent cumulative effects. Linear erosion and accretion rates, based on changes in the location of the primary dune toe, or in the berm crest for profiles that were replenished, correlate reasonably well with the volumetric erosion rates (Roessler, 1998).

Whereas some areas eroded severely, other stretches of beach locally accreted. Fort Macon State Park (Profile 12), the central portion of Atlantic Beach (Profiles 7 and 8), and parts of Pine Knoll Shores (Profile 3) showed very high rates of erosion during the hurricanes, while other regions of Atlantic Beach (Profiles 6 and 11) and Pine Knoll Shores (Profiles 4 and 5) showed very little erosion and sometimes accretion. One year after Hurricane Fran (September 1997) much of the beach had not recovered. In fact, erosion had intensified in areas which suffered the worst erosion during
the hurricanes, while the profiles that showed accretion or very little erosion during the hurricanes continued to build.

**REF/DIF Numerical Model**

Offshore bathymetry clearly plays an important role in forcing longshore currents, causing adjacent sections of beach to respond differently to fairweather conditions, but more importantly to storm events. The motivation for using the combined wave refraction/diffraction model (REF/DIF 1 v. 2.51) was to test how offshore bathymetry caused nearby sections of beach to respond differently during Hurricanes Bertha and Fran. Input wave conditions (wave height, direction, and period) based on wave hindcast data were 6.5 m, 158° TN (true north), and 10 s for Hurricane Bertha and 7.6 m, 137° TN, and 10 s for Hurricane Fran. Figure 5 shows that the erosion and accretion that took place during Hurricanes Bertha and Fran varied widely across the study area. The erosion rates were calculated from changes in profiles measured between May 8 or June 6–13, 1996 and July 25–30, 1996 for Hurricane Bertha and between August 22–29, 1996 and September 13–17, 1996 for Hurricane Fran.

Breaking wave heights and angles during Hurricanes Bertha and Fran are shown in Figure 6 from model results using a wave breaking coefficient of 0.78. The overall pattern of breaking wave height was similar for the two hurricanes with wave heights generally decreasing to the east towards Beaufort Inlet. However, wave heights differed slightly in the western portion of the study area and decreased more sharply near the inlet during Hurricane Bertha. Waves approached Bogue Banks from the southeast during both hurricanes, but had a more oblique angle to the shoreline during Hurricane Fran. Breaking wave angle (orthogonal direction relative to TN; negative is to the west and positive to the east) was nearly constant in the western portion of the study area and became less negative, and in some cases positive, near the inlet.

Model runs show that the ebb tidal delta and offshore disposal area (Figure 3) played significant roles in nearshore processes. During both hurricanes, waves broke and refracted around the ebb tidal delta and the offshore disposal area which caused wave heights to decrease along the shoreline and wave angles to become less negative in the eastern portion of the study area.

Predicted longshore current velocities were plotted against erosion and accretion rates to determine the effects of offshore bathymetry on wave refraction and diffraction and to determine if gradients in longshore current velocities could be correlated with the observed patterns (Figure 7). Gradients in transport that result from changes in velocity are probably responsible for deposition and erosion. Therefore, erosion is expected to occur when current velocities increase and accretion to occur when current velocities decrease.

Fairweather waves that approach Bogue Banks from the southeast (H = 1.25 m, D = 120 TN, T = 7 s) and the southwest (H = 1.2 m, D = 205 TN, T = 6 s) were also examined. Similar to wave data for the two hurricanes, breaking wave height for fairweather waves from the southeast and south-

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Figure 4. Measured volumetric erosion rates above MLLW for period May 1996 to January 1998.

Distance (km)

![Graph showing measured volumetric erosion rates above MLLW for period May 1996 to January 1998.](image-url)
Beach Changes Along Eastern Bogue Banks

Figure 5. Measured erosion rates following Hurricanes Bertha and Fran.

DISCUSSION

Beach profile data collected during this study, together with archived historical data provided by the USACE, indicate that Bogue Banks is generally eroding and that the 1996 hurricane season significantly accelerated the overall erosion rate. Figure 7 combines on the same plots the predicted longshore current velocities, erosion and accretion rates following Hurricanes Bertha and Fran, and the location of replenishment material. Replenishment material appeared to have a significant effect on erosion rates. The sediment disposed at eastern Bogue Banks was derived from dredge spoil from the inner channel of Beaufort Inlet. This material consisted of a relatively high percentage of fine-grained sediment which was mainly placed above MLLW thus creating an unnatural, steep beach slope which was especially susceptible to subsequent erosion. Although much of the sediment from the 1986 and 1994 disposal projects still remains on the beach, the sections of beach that were replenished experienced extremely high erosion following the 1996 hurricane season.

The model predicts a divergence in longshore currents at eastern Atlantic Beach in the vicinity of Profile 11 during Hurricane Bertha (11 km). Profile measurements before and after Bertha showed that Profile 10 and Profile 11, which were located directly west and east of the predicted divergence, underwent slight accretion. This region of the study area was highly sensitive to the location of the replenishment material. Profile 11, which was not replenished in 1986 or 1994, may have gained sediment from transport of 1986 replenishment material to the east. Farther east, as the longshore current velocity increased, the beach displayed severe erosion. However, when the longshore current velocity decreased near Beaufort Inlet, the erosion rate continued to increase. This was likely due to a combined effect of inlet processes, potentially increasing cross-shore transport, and the large amount of sediment disposed in this area which created an abnormally steep beach with relatively large amounts of fine-grained material. Similar to Profile 11, Profile 10 accreted slightly, which could be attributed to replenishment material being transported to the west and deposited when the longshore current velocity decreased. Although the model predicted convergence of longshore currents in the vicinity of Profile 9, the erosion during Hurricane Bertha was probably again a result of an abnormally steep profile created by the
1986 replenishment project and loss of fine-grained replenishment material to the offshore.

A divergence in longshore currents was predicted near Profile 7 (6 km) during Hurricane Bertha and, as expected, the beach eroded severely. Longshore current velocities increased west of Profile 7 and the beach here also eroded. However, as the current velocity decreased, the beach accreted from Profile 6 to eastern Pine Knoll Shores. Accretion in this section of the study area can be explained by the large amount of replenishment sediment transported to the west, the overall direction of net littoral transport. When the longshore current velocity increased again at Pine Knoll Shores near Profile 3, the beach eroded rapidly.

The interaction of longshore current velocities and replenishment sediment was similar during Hurricane Fran. A divergence in longshore currents was predicted just west of Profile 10 which displayed erosion. Similar to conditions during Hurricane Bertha, the predicted longshore current veloc-

Figure 6. REF/DIF predictions of breaking wave heights and angles for Hurricanes Bertha and Fran.
Figure 7. Calculated longshore current velocities and measured erosion rates for Hurricanes Bertha and Fran, including location of sediment disposal on the beach.

Erosion (+) and accretion (-) (m³/m)

Distance (km)

Bertha

Fran

Predicted Longshore Current Vel. (m/s)

Erosion (+) and accretion (-) (m³/m)

Distance (km)

Figure 7. Calculated longshore current velocities and measured erosion rates for Hurricanes Bertha and Fran, including location of sediment disposal on the beach.
when combined with the 1986 and 1994 replenishment locations, correlated well with measured erosion rates. The variability in erosion rates following the 1996 hurricane season was similar to that displayed in the long-term rates calculated by the North Carolina Division of Coastal Management (NCDCM), which were based on shoreline changes in aerial photographs over the past 50 years (Figure 10). Clearly it would not be reasonable to attempt to correlate long-term erosion rates with wave refraction/diffraction model results because of the variability in wave climates over long periods (e.g., swell versus storm events and directional variability). However, it is significant that, although the short-term erosion rates measured in this study were much greater than the long-term rates, the same processes that appeared to control these short-term rates have been present over at least the past 50 years. Since the frequency of tropical storms and hurricanes is anticipated to increase during the next decade (Gray, 1990; Landsea, et al., 1992), it is not only important
Figure 9. Calculated longshore current velocities for fairweather waves from the southeast and southwest.

to document erosion following large storms, but to understand the physical processes that influence these erosion rates. Survey data and REF/DIF results from this study confirmed that offshore bathymetry, and channel dredging and disposal of dredge spoil associated with the MHCHP, played an important role in forcing longshore currents during Hurricanes Bertha and Fran, thereby influencing erosion rates at eastern Bogue Banks.

CONCLUSIONS

Beach profile data and the application of a combined wave refraction/diffraction model indicated that offshore bathymetry significantly impacted the nearshore wave height, wave angle, and forcing of nearshore currents during Hurricanes Bertha and Fran, which in turn influenced erosion rates on eastern Bogue Banks, NC. Specifically, the following conclusions can be drawn from this study:

1) During a two-year period from June 1996 to April 1998, sections of the beach along eastern Bogue Banks eroded severely while other locations were relatively stable. Survey results indicated that there were three areas of consistently high erosion which included eastern Pine Knoll Shores (Profile 3), western Atlantic Beach (Profile 7), and Fort Macon State Park (Profile 12); other sections of beach were relatively stable, including eastern Pine Knoll Shores and western Atlantic Beach (Profiles 5 and 6), and central Atlantic Beach (Profile 9).

2) Erosion and accretion rates were highly influenced by Hurricanes Bertha and Fran. Erosion rates were higher during the 2-yr period of this study than the historical rates, and much of this erosion was the result of the two hurricanes. In fact, the areas that suffered the greatest erosion rates during the two storms recovered less (in some cases continued to erode) following the back-to-back events, thus suggesting that these areas may be long-term erosion hot spots. However, not all sections of the study area eroded during these two storms. During Hurricane Bertha, sections of beach in eastern Pine Knoll Shores and western Atlantic Beach (Profiles 4, 5, and 6) and eastern Atlantic Beach (Profiles 10 and 11) gained sediment. In addition, parts of Pine Knoll Shores (Profiles 1 and 4) gained sediment during Hurricane Fran.

3) Linear and volumetric erosion rates measured during this study were higher than long-term NCDCM rates but exhibited similar patterns. Processes that influenced erosion and accretion patterns during this study period have also likely been operating over at least the past 50 years (Roessler, 1998). This observation suggests that erosion will likely increase in the sections of beach that severely eroded during this study.

4) Predicted longshore currents during Hurricanes Bertha and Fran correlated well with measured erosion and accretion rates. During the two-year study, Hurricanes Bertha and Fran had the greatest effect on erosion and accretion rates. Although cross-shore currents were not evaluated and could be important, it appears that gradients in longshore current velocity during the two hurricanes exert considerable control over erosion and accretion rates.

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