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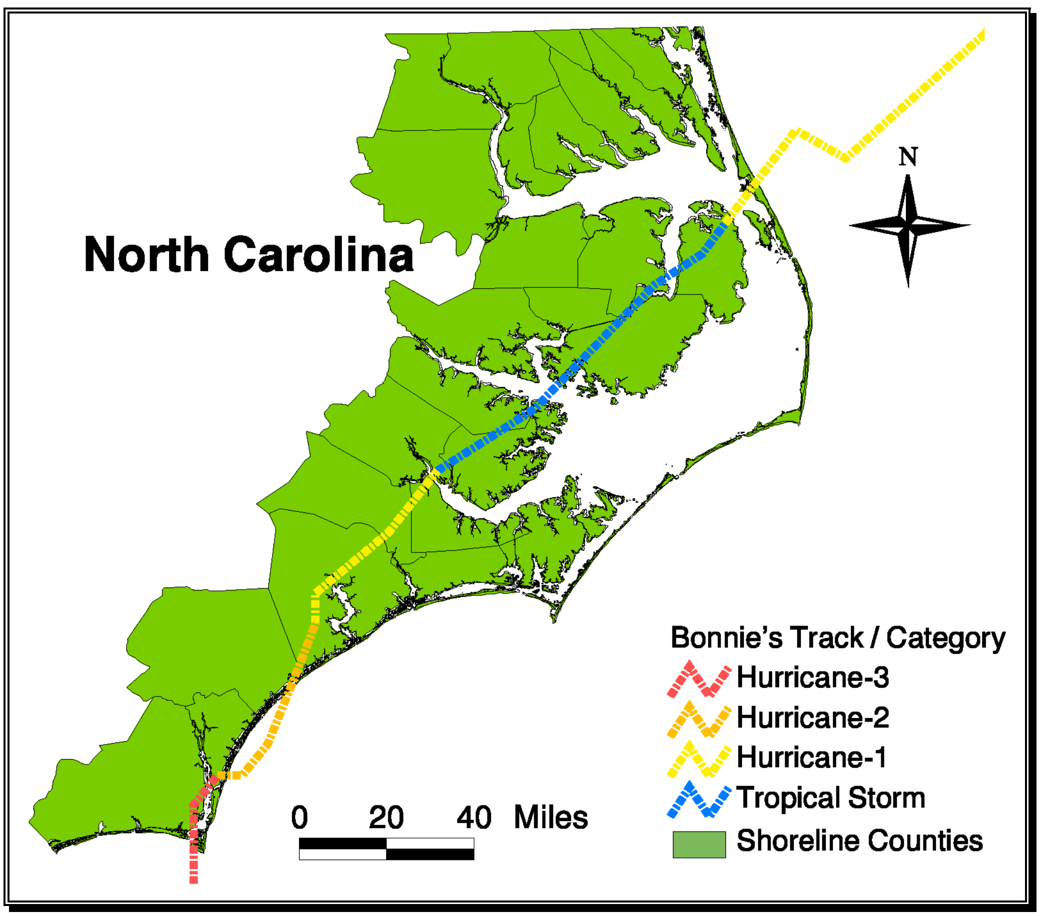
CSC Technical Report: NOAA/CSC/99031-PUB July 1999

AN EVALUATION OF HURRICANE-INDUCED EROSION ALONG THE NORTH CAROLINA COAST USING AIRBORNE LIDAR SURVEYS



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ABSTRACT

Two airborne light detection and ranging (LIDAR) beach surveys of the North Carolina coast are used to assess the hurricane-induced impacts from Hurricane Bonnie. The baseline survey was conducted over North Carolina in fall of 1997, and a second survey was conducted in fall of 1998, within days of Bonnie's landfall. The very high density and accuracy of elevation measurements allows regional-scale beach volume calculations at an accuracy unavailable using traditional beach profiling survey methods. Geographic information system software is used to determine volumetric change of the dry beach for all North Carolina barrier beaches. From volumetric change calculations, the volume of sediment gain or loss by unit area and unit length of the beach are determined for each beach.

The northern barrier island beaches show greater average sediment loss over the length of the beach than the beaches in the middle and southern sections of the coast. The northern beaches generally show long erosional sections of beach and dunes with smaller pockets of accretion. Overwash, when observed, is minor. Beaches in the central coast show a different response: alternating patterns of erosion and accretion with relatively little net sediment volume change. The areas of erosion are less severe than on northern beaches. More overwash is apparent, but generally it is limited, with the exception west of Cape Lookout where sediment was deposited on the barrier flats. The southern beaches exhibited a mixture of sediment gain and loss. Much of the gain can be attributed to a major beach renourishment project. Those beaches not renourished, however, have higher average losses of sediment over the length of the beach than the central section of coast. Complete islands and large sections of beaches were completely overwashed, significantly changing the beach morphology, but having a low impact on the total sediment volume.

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AN EVALUATION OF HURRICANE-INDUCED EROSION ALONG THE NORTH CAROLINA COAST USING AIRBORNE LIDAR SURVEYS

1.0 INTRODUCTION

This introductory section provides a brief overview of the Airborne LIDAR Assessment Coastal Erosion (ALACE) Project out of which this report originated and provides some background on Hurricane Bonnie and the North Carolina coastline.

1.1 Airborne LIDAR Assessment of Coastal Erosion Project

The ALACE project is a partnership between the National Oceanic and Atmospheric Administration (NOAA) Coastal Services Center (CSC), the National Aeronautics and Space Administration (NASA) Wallops Flight Facility (WFF), and the U.S. Geological Survey (USGS) Center for Coastal Geology. The project's goal is to develop and demonstrate aircraft laser altimetry mapping as a source of highly accurate, cost-effective information on coastal topography, erosion, and shoreline position. In working toward this goal, NOAA, NASA, and USGS have conducted several mapping missions along stretches of U.S. coastal beaches using the NASA developed laser mapping instrument, Airborne Topographic Mapper (ATM), flown aboard a NOAA Twin Otter aircraft.

The ALACE project conducted laser beach surveys along sections of the U.S. coastline during 1996, 1997, and 1998. All North Carolina beaches were surveyed during each of the 1997 and 1998 surveys. The 1997 survey was conducted over six days between September 16th and September 29th. The 1998 beach survey was conducted within six days after Hurricane Bonnie's landfall on the North Carolina coast to measure beach changes resulting from the hurricane. The survey began September 1st and ended September 7th, two days behind schedule due to rain and low clouds associated with Tropical Storm Earl.

The very high density of elevation measurements for laser beach surveys, approximately one measurement every few square meters, provides a unique ability to determine the sand volume on a beach with an accuracy far greater than previous methods utilizing beach profiles. Determining sand volume from beach profiles required an assumption of a linear along shore gradient in the change detected between adjacent profiles (Oertel, *et al.*, 1989). LIDAR data does not require this assumption.

1.2 Hurricane Bonnie

Since the fall of 1996, the North Carolina coast has been impacted by three hurricanes, all making landfall just east of the border between North Carolina and South Carolina and west of Cape Fear. Two hurricanes, Bertha and Fran, struck the coast in the fall 1996. No hurricanes impacted the North Carolina coast during 1997, providing a period for beach recovery, both natural and artificial. The most recent hurricane, Bonnie, came ashore as a category 3 storm on August 26, 1998 (Figures 1 and 2). The 400-mile wide storm stalled near Wilmington, North Carolina for an hour, jogged east off the coast with the eye passing over the south end of Masonboro Island, then returned to a northwest track moving inland again across the south end of Topsail Beach. Bonnie maintained a roughly northwest track, losing intensity until reentering the Atlantic ocean as a category 1 storm near Kitty Hawk.

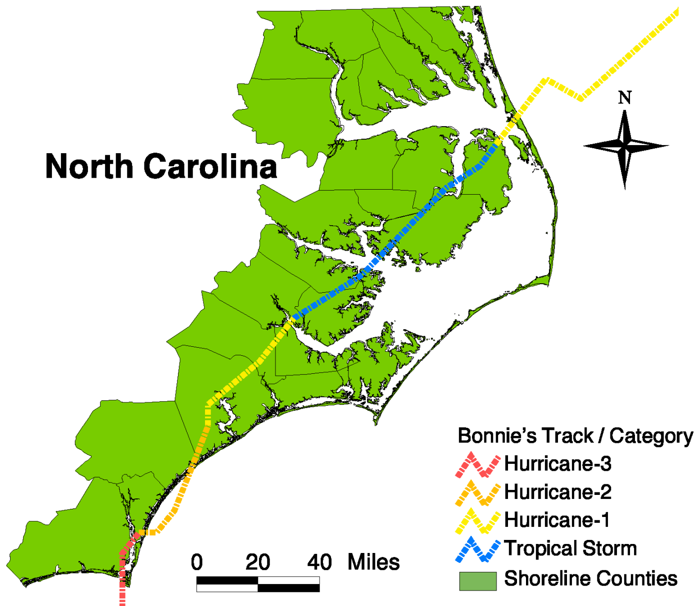

Figure 1. Map showing the path of Hurricane Bonnie over North Carolina. The color-coded line indicates Bonnie's category as defined by the Saffir/Simpson Hurricane Scale (Simpson, 1974).

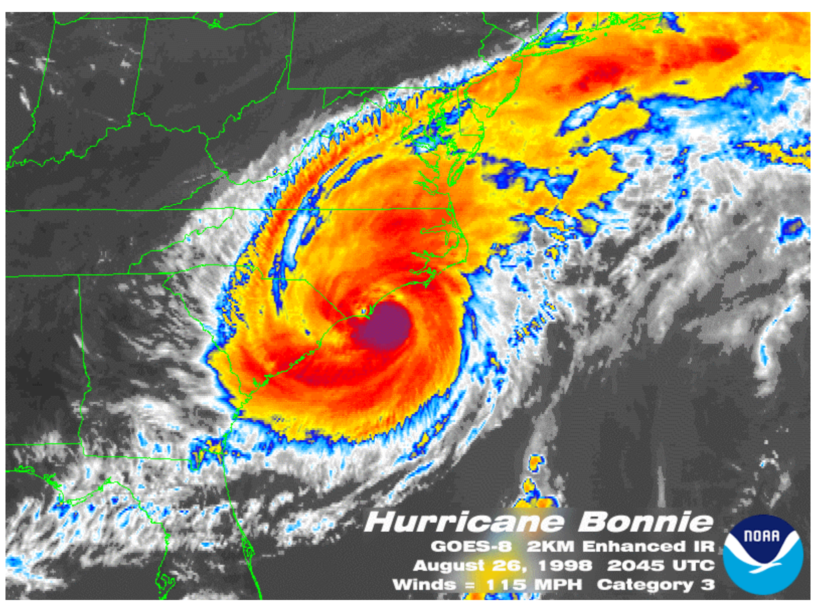

Figure 2. Colorized infrared satellite image of Hurricane Bonnie approaching the North Carolina coast on August 26, 1998 (www.ncdc.noaa.gov/ol/reports/bonnie/bonnie.html).

1.3 North Carolina's Barrier Islands

The 300 miles of North Carolina coast are fronted by 21 long narrow barrier islands separated by inlets (Figure 3). The islands are generally sandy with low vegetation and low vertical relief. The coast is dominated by three cuspate forelands, Cape Fear, Cape Lookout, and Cape Hatteras. The islands from Cape Lookout north are backed by several sounds, separating the islands from the mainland by as much as 30 miles. There are small regions of development, but a majority of the land is federally controlled and within designated Coastal Barrier Resources Act (COBRA) zones. The federally controlled coast is composed of the Cape Lookout National Seashore, Cape Hatteras National Seashore and the Pea Island National Wildlife Refuge. North Carolina's southern barrier islands are shorter in length and more developed than the northern coast The islands are typically separated from the mainland by narrow bands of salt marshes.

As a whole, the barrier islands are primarily microtidal, (i. e. have a tidal range less than six feet) transgressive barriers with the exception of Bogue and Shackleford Banks, which are microtidal regressive barriers. The low tidal range results in a wave-dominated coastline, therefore, wave-generating storm events are major factors defining and changing the coastal morphology of the barrier islands (Leatherman, 1988). The shoreline orientation changes from west-to-east trending in the south, through southwest-to-northeast trending in the central section, to southeast to northwest trending in the north. This varied orientation results in wind and waves from a single hurricane impacting sections of the coastline differently.

2.0 OBJECTIVES

The objectives of this report are 1) to evaluate hurricane-induced beach change along the entire North Carolina coast using laser beach mapping, and 2) to determine the volumetric change in sand above the low-tide line from September 1997 to September 1998, immediately after hurricane Bonnie's passage across North Carolina.

3.0 METHODS

The following section describes the methods for the collection of light detection and ranging (LIDAR) beach topography and the methods applied in the analysis of beach change.

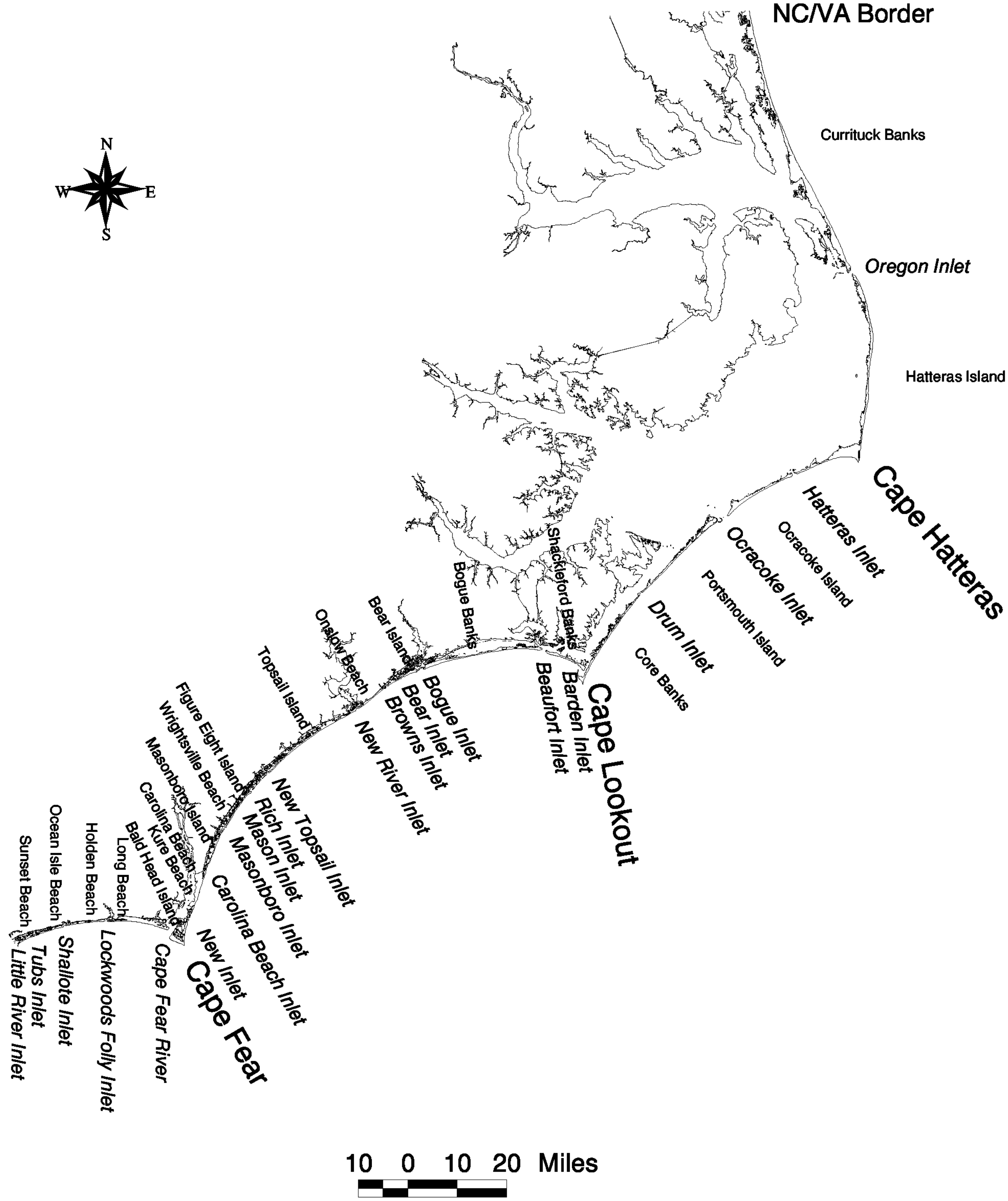

Figure 3. Map showing the location of inlets and barrier islands along the North Carolina coast.

3.1 LIDAR Data Collection

3.1.1 North Carolina Laser Beach Surveys

Elevation measurements were collected along North Carolina beaches during September 1997 and 1998 using the Airborne Topographic Mapper II (ATM) (Krabill, *et al.*, in print) (Figure 4). The ATM is a scanning pulsed laser ranging system mounted onboard a NOAA aircraft, and is used to measure ground elevation and coastal topography. The system uses a high frequency laser directed at the earth's surface through an opening in the bottom of the aircraft's fuselage. The laser system records the time difference between emission of the laser beam and the reception of the reflected laser signal in the aircraft while associated systems are simultaneously recording the aircraft's position and orientation. The plane travels over the beach at approximately 135 miles per hour (60 meters per second) while surveying from the low-water line to at least the landward base of the sand dunes. The ATM, developed by NASA WFF in Virginia, measures ground elevation with a vertical resolution of 15 centimeters (Meredith, *et al.*, 1998) and a horizontal accuracy within 0.8 meters assuming a survey altitude of 700 meters.

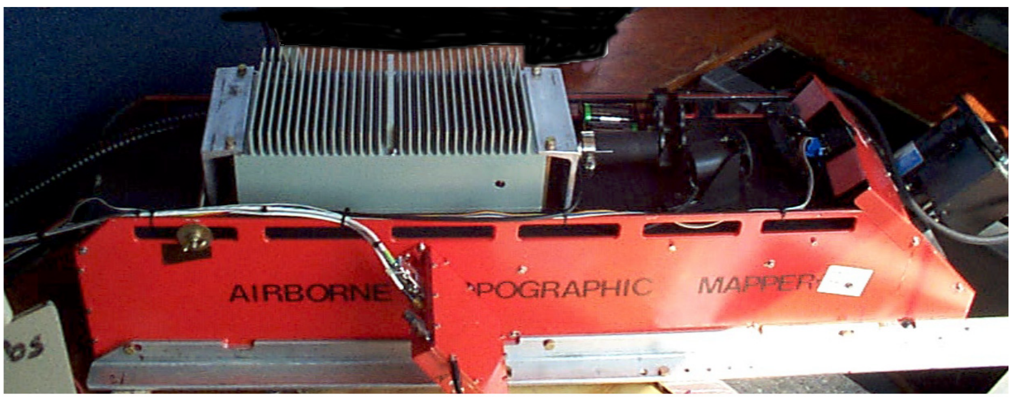

Figure 4. Airborne Topographic Mapper II.

3.1.2 Data Processing, Extraction, and Conversion

After receiving the mission-post-processed data from NASA WFF, the data were filtered to remove extreme elevations above and below the ground surface. The data were then loaded into a database to allow subsetting, datum conversion, reprojection, and gridding. These processes were performed using the Web-based system LIDAR Data Retrieval Tool (LDART), which was created by the Center for storing and distributing ALACE beach survey data.

The North Carolina coast was divided into 24 rectangular tiles (Figure 5), each tile covering approximately 13 miles (22 kilometers) of coastline. LDART was used to extract the data for each of the tiles. The LDART system performed the following processing on the original point data to produce the 24 binary raster grids for both the 1997 and 1998 survey:

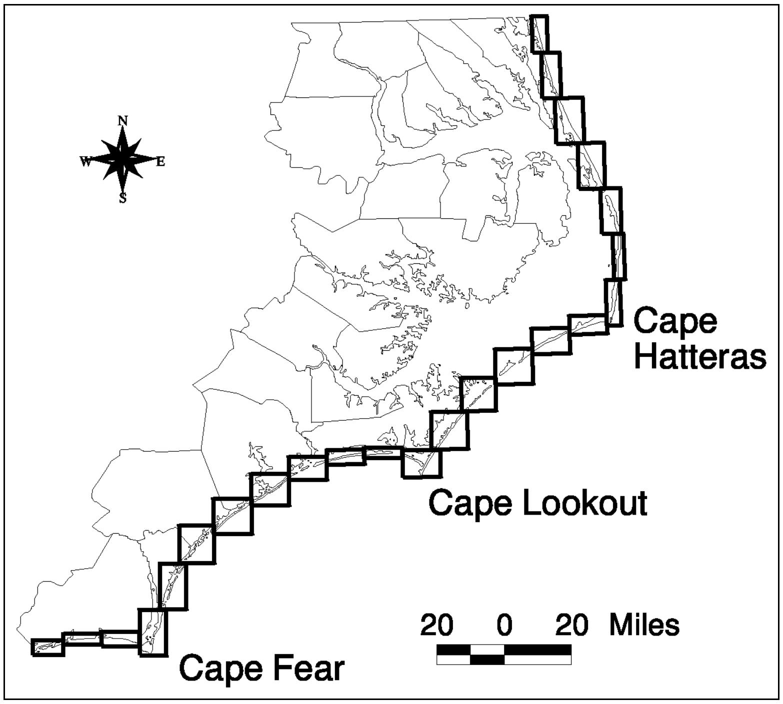

Figure 5. Map showing the rectangular tiles defining extent of 24 data grids for each of the 1997 and 1998 LIDAR surveys.

- All point data within the bounds of a tile were extracted. The same tile bounds were used for both survey years to create coincident grids.
- Point data were converted from International Terrestrial Reference Frame of 1994 (ITRF94) referencing the World Geodetic System of 1984 (WGS84) ellipsoid to the North American Datum of 1983 (NAD83) referencing the Geodetic Reference System of 1980 (GRS80).
- Vertical elevations were converted from GRS80 ellipsoid referenced elevations in meters to National Geodetic Vertical Datum of 1929 (NGVD29) elevations in feet.
- Point data were interpolated into binary raster grids with a 15-foot cell-size. Inverse distance weighted (IDW) interpolation was employed using the six nearest neighbor points within a 25-foot search radius.
- After creation of the binary raster grids, the grids were projected from geographic coordinates to North Carolina Stateplane x,y coordinates in feet and then imported into an ArcView® Geographic Information Systems software project.

3.2 Data Analysis Methods

Determination of the volumetric change in beaches between inlets for the entire North Carolina coast involved the following steps:

1. Delineation of the beach between inlets.
   For purposes of calculating volumetric change in the dry beach, the beach was defined as the region between the land/water interface and the back dune system or any substantial human development. The landward boundary was extended to included the barrier flat on islands of low elevation, to capture sediment deposition from overwash. The landward boundary was drawn to exclude measurements over high vegetation, where elevation variability increases due to variable penetration of laser pulses over vegetation. The ATM laser does not penetrate the water, but measures the water surface elevation when scanning over water; therefore, the shoreward definition of the beach excluded measurements over water. If these data were included, they would give erroneous volumetric results due to changing water levels between flights.

   Using ArcView®, a polygon was digitized around the beach using the elevation grids for the 1997 and 1998 surveys and knowledge of the water level at the time of each survey. The water level values were obtained through the examination of shore-normal profiles generated at several points along the beach. For beaches exhibiting erosion or accretion between the 1997 and 1998 surveys, the seaward land/water boundary was used. This criterion resulted in the inclusion of measurements over the water for the more landward shoreline, but it was important to detect and measure this change (accretion/erosion) even though the quantification of the volume of change may be an under- or overestimate.

   Beach length was determined by using ArcView® to approximate the length of ocean-facing shoreline. The total beach length calculated for North Carolina was 314 miles (553,486 yards) and beach area for the analysis was 67,611,707 square yards. These measurements are valid for this analysis only and are not the standard definitions of beach length or area.

2. Differencing 1997 and 1998 elevation grids.
   ArcView®'s Map Calculator function was used to create new difference grids by subtracting the coincident 1997 elevation grids from the 1998 grids. These difference grids were then clipped, using the beach delineation polygons, to include only data from cells within the defined beach region. The clipped difference grids indicate beach elevation change from 1997 to 1998.

3. Calculate volumetric change and area of gain and loss between years.
   An Avenue™ script was developed to calculate the volume and area of sand gain and loss for a difference grid. The script was run on each of the difference grids to produce sand gain and loss totals for each section of beach between inlets for all of North Carolina.

4.0 RESULTS AND DISCUSSION

The results of the volumetric beach change analysis for the North Carolina coast are presented in Figure 6–13. Appendix A contains a table summarizing the results of the volumetric analysis for each beach. We are unable to determine the change in sand volume on the barrier islands that is due strictly to Hurricane Bonnie because the pre-Bonnie survey took place almost one year prior to the post-Bonnie survey, which was conducted within days of the hurricane's passage. A confounding factor in assessing the beach change due to Bonnie was beach renourishment. Numerous beach renourishment projects were conducted along the North Carolina barrier islands and are discussed in detail below. With the exception of renourishment effects, we assume that the significant changes detected were produced primarily from Hurricane Bonnie. Analysis of ATM-based elevation change in a portion of this region between 1996 and 1997, a period with no hurricanes, did not show significant volumetric losses. Instead, increases in dune and beach elevation were observed, presumably as recovery occurred from previous hurricanes, Bertha and Fran, in 1996 (Jansen *et al.*, 1999); therefore, we feel the assumption that Hurricane Bonnie caused the majority of the 1997 to 1998 changes is reasonable. Below we discuss hurricane impacts from the regional perspective and then show observations of localized processes including renourishment, overwash and inlet closures.

Appendix B contains a collection of color plates showing elevation and elevation change maps generated from the LIDAR surveys. These plates provide images for each beach of the 1998 topography and the change in topography detected using the 1997 and 1998 LIDAR surveys. Patterns and magnitude of change may be identified from the change maps.

4.1 Regional Perspective

Of the 21 North Carolina beaches analyzed, 12 show a net loss in sand from the dry beach. Although this number is only slightly more than half the beaches/islands, these 12 beaches constitute more than 77 percent of the North Carolina barrier beach length. A common engineering unit for expressing beach change is volume change per unit length of beach. The color-coded map presented in Figure 6 shows the spatial distribution of beach volume changes per yard of beach for each beach section. The colored line categorizes the magnitude of this change. Darker greens indicate increased average sand gain and the darker reds indicate increased average sand loss per yard of beach. The general change pattern is large losses on northern beaches, small, mixed gains and losses on the central beaches, and larger gains and intermediate losses on the southern beaches.

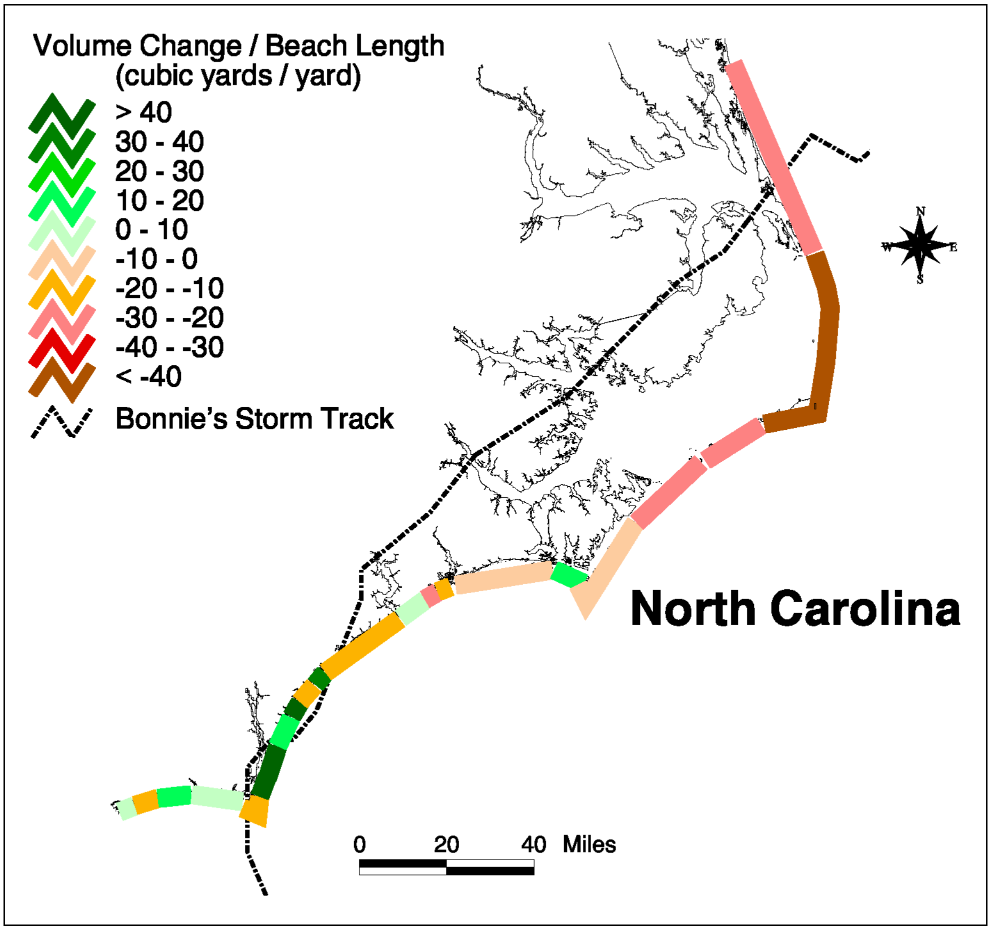

Figure 6. Color-coded map categorizing the average change in sand volume per yard of beach for each beach along the entire North Carolina coast. Dark green represents areas with the highest average gain in sand volume on the dry beach per yard of beach. Dark red represents segments with the highest average loss in sand volume per yard of beach.

The highest average sand losses per length occurs along the northern coast and generally show long erosional sections of beach and dunes with smaller pockets of accretion. The little overwash seen is minor. The central section of the coast has both gains and losses, and the magnitudes of change are generally the smallest observed along the coast. Patterns of erosion differ from those along northern beaches. The central section patterns are shorter, alternating areas of erosion and accretion with relatively little net sediment volume change. Erosion is less both areally and volumetrically than erosion to the north. More overwash is apparent, and is most significant west of Cape Lookout, where large sections of overwash penetrated to the barrier flats. The southern beaches exhibit a mixture of sediment gain and loss, with the highest average gains in sand volume per yard; however, most of these gains can be attributed to renourishment projects. Those beaches along the southern barrier islands east of Cape Fear that were not renourished experienced losses in sand volume that is intermediate between the central and northern sections. Complete islands and large sections of beaches were completely overwashed, significantly changing the beach morphology, but having a low impact on the total beach volume.

Details of the average sand gain or loss per yard for each beach are presented in Figure 7. The maximum average gain per yard (57.8 cubic yards / yard) is seen between Masonboro Inlet and Mason Inlet, a beach influenced by a major renourishment project. The minimum average gain per yard is observed between New River Inlet and Browns Inlet, (1.9 cubic yards / yard). The greatest average sand loss per yard (49.0 cubic yards / yard), almost twice the amount of any other beach, is on the beach between Hatteras Inlet and Oregon Inlet. The smallest average loss per yard (3.0 cubic yards / yard), is between Barden Inlet and Drum Inlet.

The net volume of sand loss/gain for each beach is shown in Figure 8. The maximum change in the net volume of sand for any beach is a loss of more than 4.6 million cubic yards between Hatteras Inlet and Oregon Inlet. The smallest net change is a gain of 25,377 cubic yards between New River Inlet and Browns Inlet. Those beaches that underwent major sand renourishment between the 1997 and 1998 surveys (Plates 6–8) all show a gain in the sand volume. Other beaches with gains in sand volume are those just west of Capes Fear (Plates 3 and 4) and Lookout (Plate 16), between Rich Inlet and New Topsail Inlet (Plate 10), and a minor increase occurs between New River Inlet and Browns Inlet (Plate 13).

Figure 9 shows the individual volume of gain and loss for each beach. The maximum loss in sand volume for a single beach is more than 5.5 million cubic yards between Hatteras and Oregon inlets and the minimum loss is just less than 80,000 cubic yards between Masonboro and Mason inlets. The maximum gain in sand volume for a single beach is 2.1 million cubic yards between New Inlet and Carolina Beach Inlet and the smallest gain is 129,000 cubic yards Browns Inlet and Bear Inlet.

Figure 10 gives the total beach area over which beach change was calculated. Differences in beach area primarily result from differences in beach length (i.e. there is little variation in beach width). The longest beaches are located along the northern section of the coast. The beaches along the southern half of the coastline are significantly shorter with the total area in most cases not exceeding 2 million square yards.

The graph in Figure 11 presents the average volume change over the entire beach area. As seen when analyzing volume change per beach length (Figures 6 and 7), the highest sand loss is observed along the northern beaches, while the smallest changes are seen along the middle barrier beaches and the southern beaches show the highest average gains. The maximum gain per square yard (0.48 cubic yards / square yard) is seen between Masonboro Inlet and Mason Inlet, a beach influenced by a major renourishment project. Between New River Inlet and Browns Inlet, the smallest average gain is observed (0.02 cubic yards / square yard). The greatest average sand loss (0.40 cubic yards / square yard), almost twice the loss of any other beach, is on the beach between Hatteras Inlet and Oregon Inlet. The smallest average loss, equal in magnitude to the smallest average gain, (0.02 cubic yards / square yard), is between Barden Inlet and Drum Inlet.

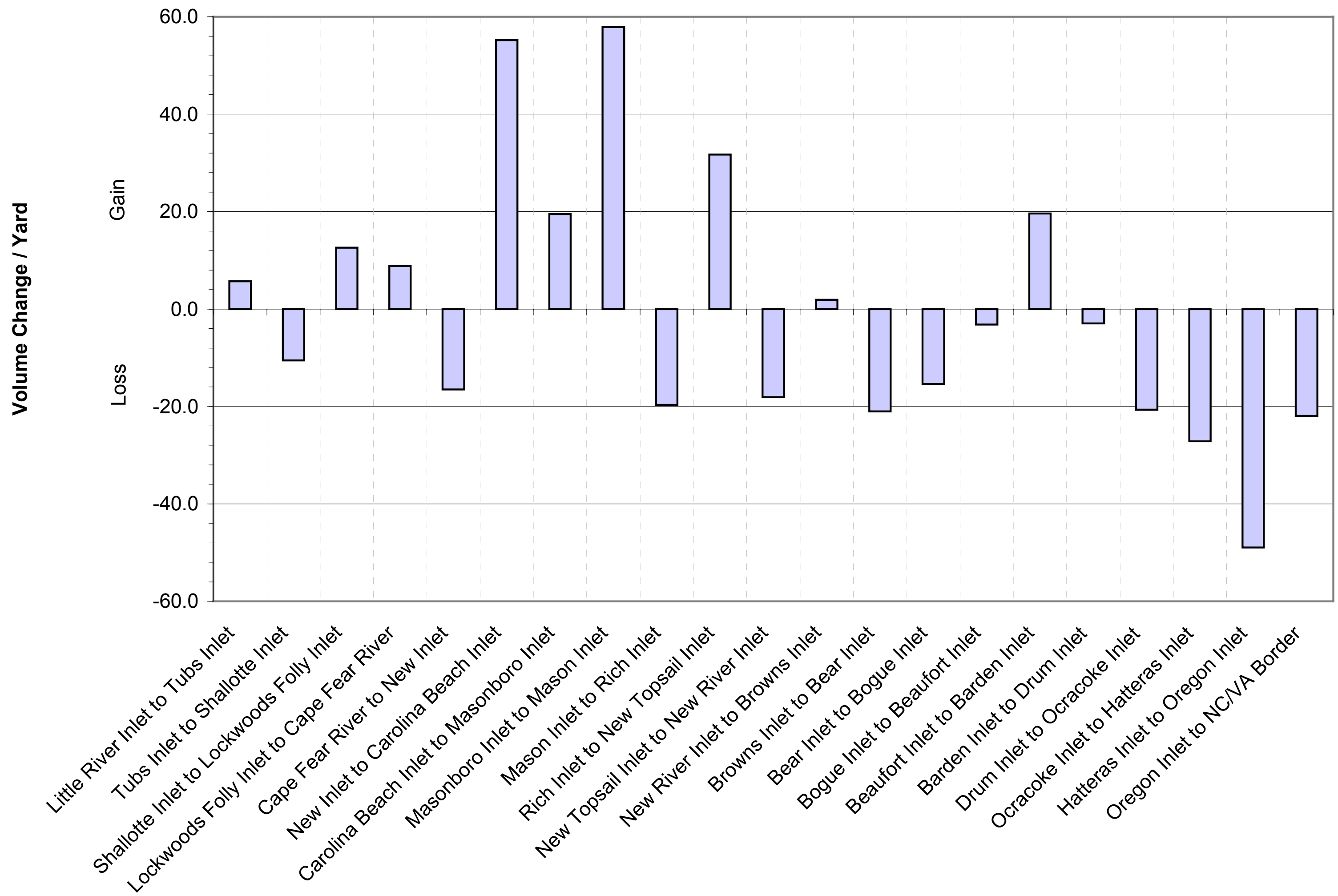

Figure 7. Graph showing the average sand gain or loss for every yard of beach for each section of beach between inlets. The inlet pairs are ordered from south (leftmost) to north. Negative values indicate loss and positive values indicate gain.

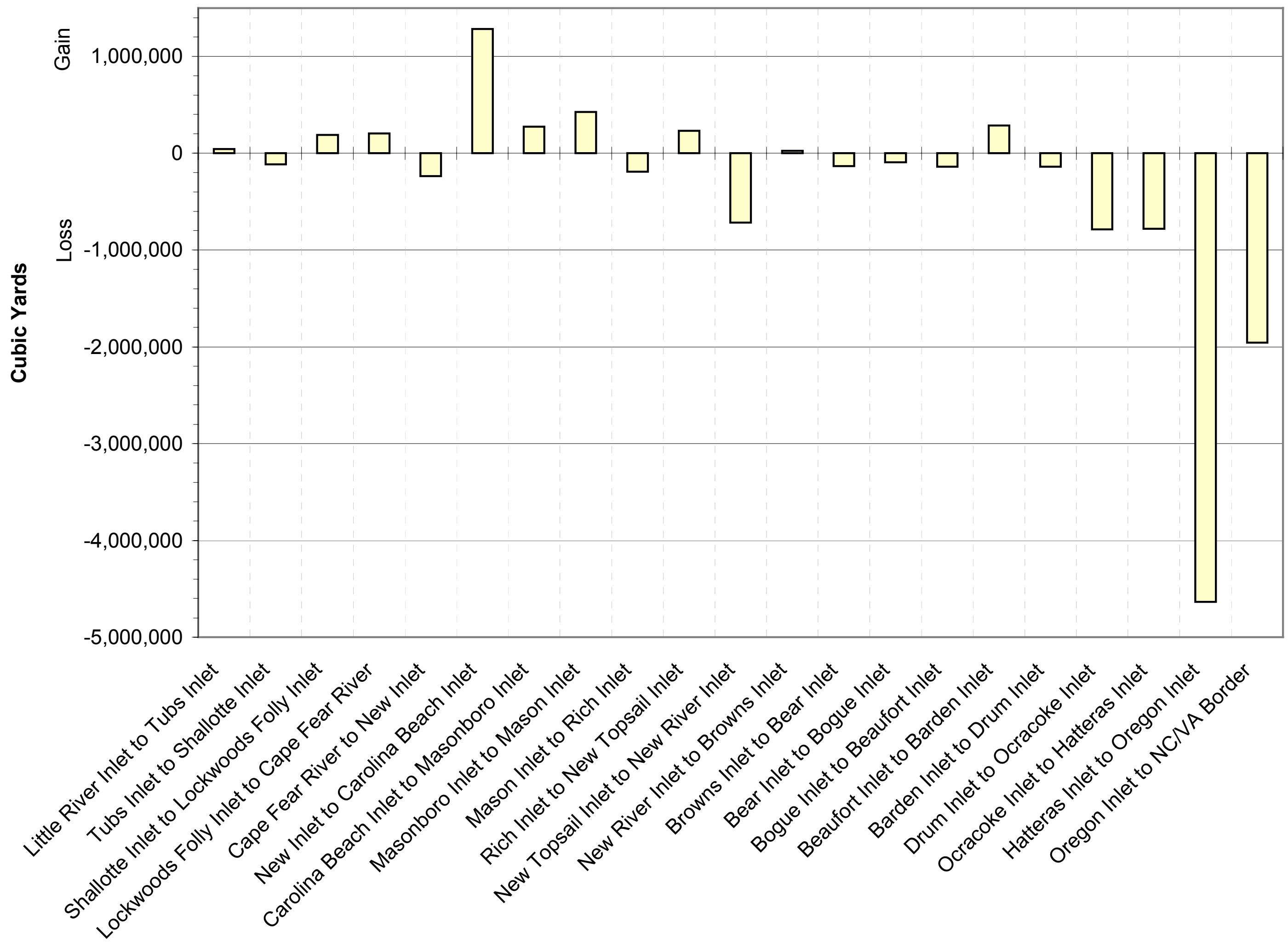

Figure 8. Graph showing the net change in sand volume on the dry beach for each section of beach between inlets. Positive values indicate a net gain of sand and negative values indicate a net loss. The inlet pairs are ordered from south (leftmost) to north.

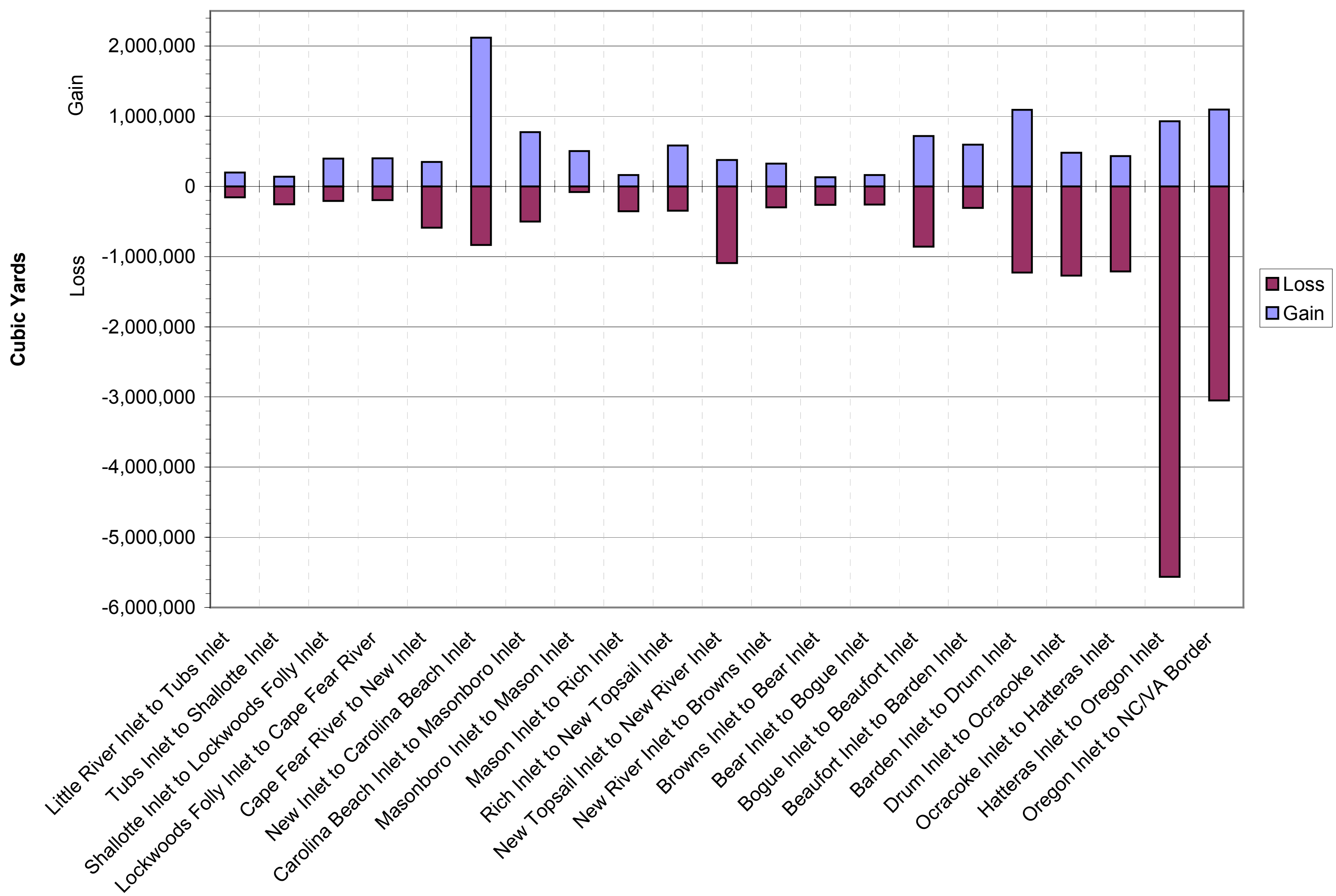

Figure 9. Graph showing the volume of sand gained and lost from the dry beach for each section of beach between inlets. Positive values indicate a gain of sand and negative values indicate a loss. The inlet pairs are ordered from south (leftmost) to north.

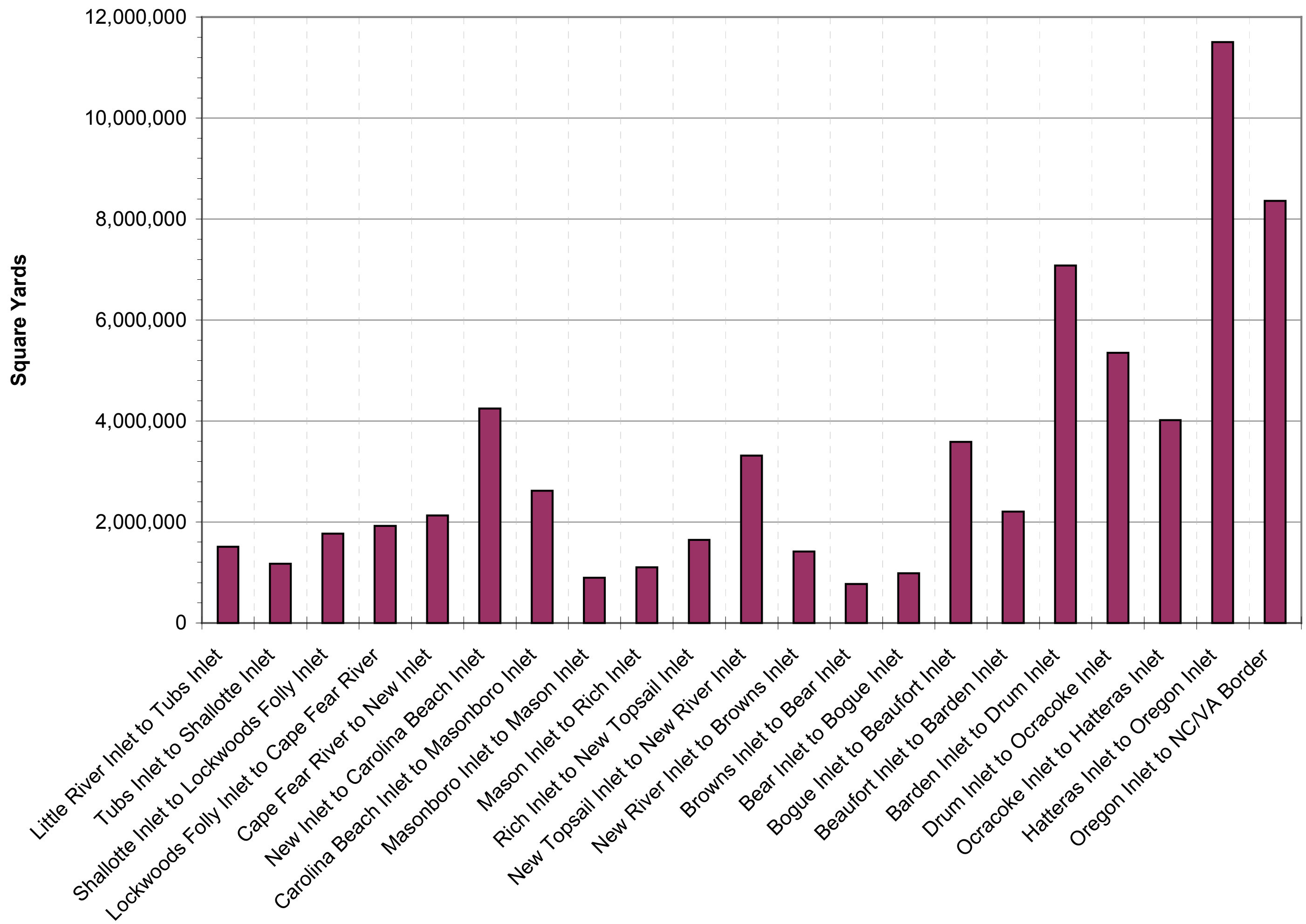

Figure 10. Graph showing the total area of the dry beach for each section of beach between inlets. The inlet pairs are ordered from south (leftmost) to north.

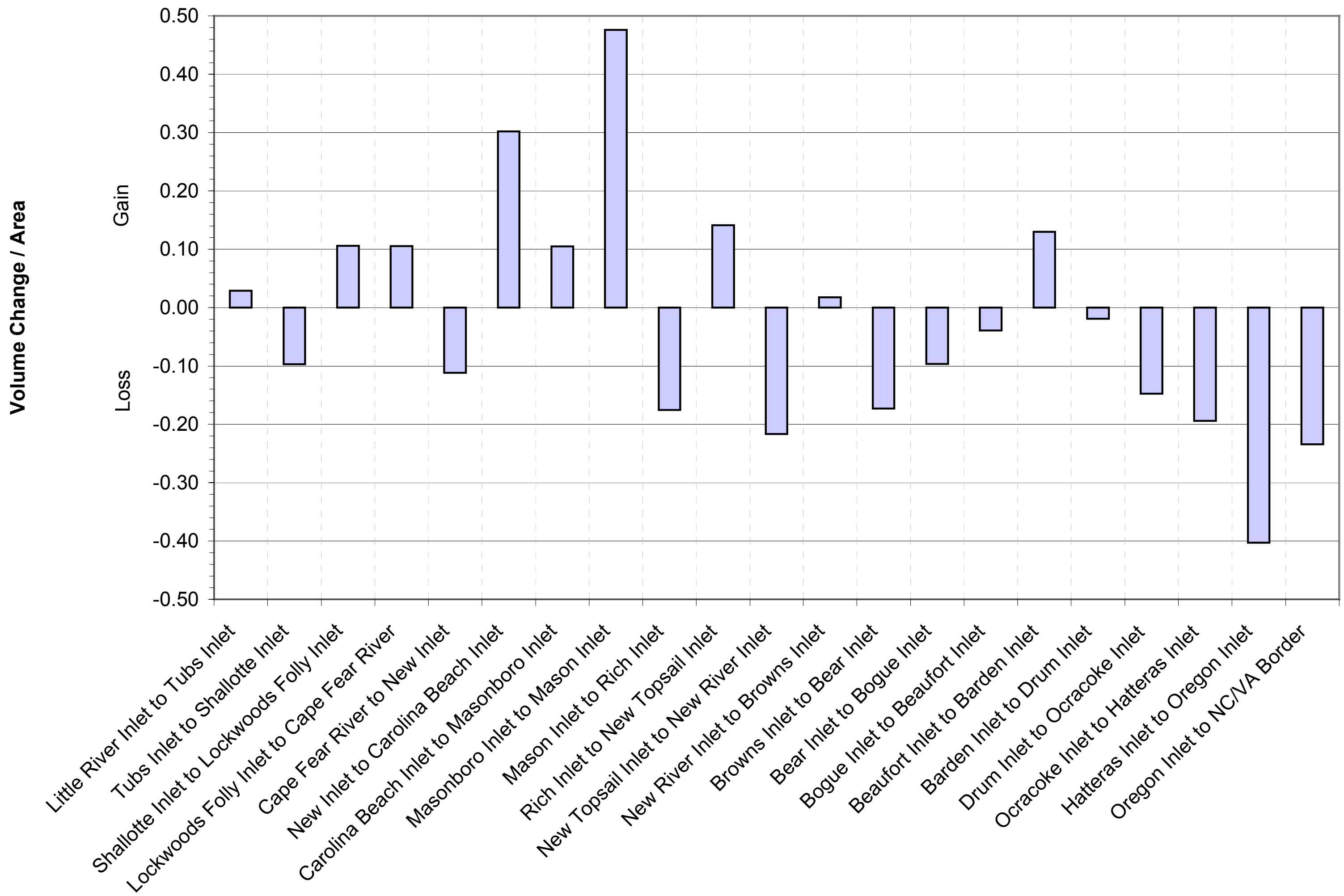

Figure 11. Graph showing the average volume of sand gain or loss every square yard of dry beach for each section of beach between inlets. The inlet pairs are ordered from south (leftmost) to north. Negative values indicate loss and positive values indicate gain.

4.2 Localized Observations

An advantage of the high spatial resolution data set is the ability to observe small-scale beach processes and details of hurricane impacts. Specific examples of renourishment, geomorphologic influences, overwash, and inlet closures are presented below.

4.2.1 Renourishment Influences

A significant confounding factor in assessing the beach change due to Hurricane Bonnie is beach renourishment. Numerous beach renourishment projects were conducted along the North Carolina barrier islands (Table 1). Four major (> 550,000 cubic yards) beach renourishment projects were conducted between the 1997 and 1998 surveys, Kure Beach, Carolina Beach, Masonboro Island, and Wrightsville Beach. The Kure Beach renourishment, started June 1997, was approximately halfway through completion when the September 1997 survey was conducted (Figure 12). Along with the four major projects, seven other smaller renourishment projects occurred, primarily along the southern barrier islands.

Coverage Extent	Renourishment Area	Est. Volume (y^3)	Comments
Shallotte Inlet to Lockwoods Folly Inlet	Holden Beach	50,000	trucked in for dune creation
	West side of Lockwoods Folly Inlet	<35,000	inlet maintenance
New Inlet to Carolina Beach Inlet	Kure Beach	3,380,000	major renourishment project
	Carolina Beach	1,200,000	major renourishment project
Carolina Beach Inlet to Masonboro Inlet	Northern end Masonboro Island	555,654	major sand bypass associated with Wrightsville project
Masonboro Inlet to Mason Inlet	Wrightsville Beach	1,116,573	major renourishment project
Mason Inlet to Rich Inlet	Southern end Figure Eight Island	400,000	
New Topsail Inlet to New River Inlet	Southern end Topsail Island	200,000	inlet maintenance
New River Inlet to Browns Inlet	Northern end Onslow Beach	42,484	maintenance dredge deposit
Bear Inlet to Bogue Inlet	Western end Bogue Banks	58,093	maintenance dredge deposit
Hatteras Inlet to Oregon Inlet	Avon	>25,000	maintenance dredge deposit

Table 1. Renourishment projects along the North Carolina barrier islands between 1997 and 1998.

The effects of a minor renourishment project can significantly influence the results of the volume analysis on beaches showing small overall volume changes. This effect is demonstrated in the renourishment project (42,484 cubic yards) conducted on the northern end of Onslow Beach between New River Inlet and Browns Inlet. The beach as a whole shows a net sand gain of 25,377 cubic yards; however, if the section of beach that received renourishment sand (northern end of Onslow Beach) is excluded from the volume calculation, the beach shows a net loss of 40,039 cubic yards.

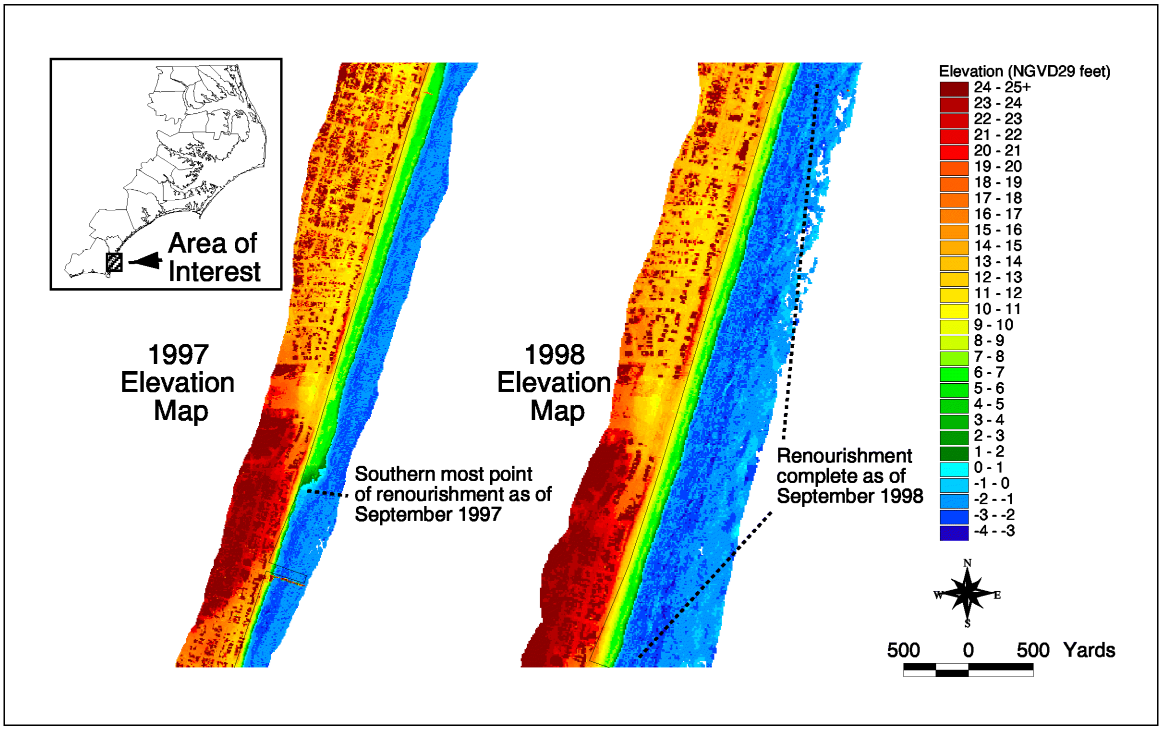

Figure 12. Color-coded elevation maps. The 1997 map shows the Kure Beach renourishment midway through completion at the time of the LIDAR survey. The 1998 map shows the completed project with the new wider beach extending southeward.

The highest average accretion per area and per beach length occurs on beaches that underwent major renourishment between the 1997 and 1998 surveys. Four major renourishment projects took place along North Carolina's southern beaches. The projects were located at Kure Beach, Carolina Beach (both located between New Inlet and Carolina Beach Inlet) (Plate 6), Wrightsville Beach (Plate 8), and the north end of Masonboro Island (Plate 7). Because of the separation in time of the LIDAR surveys, the direct impact of Hurricane Bonnie on the renourished beaches cannot be determined. Although the beaches all indicate an increase in sand volume from renourishment, sand loss due to Bonnie may also have occurred, but without data from post-renourishment surveys, no quantitative assessment can be made. Masonboro Island (Plate 7) provides an interesting view of the varied beach response for adjacent non-renourished and renourished beach sections. The island is undeveloped and low-lying. The northern inlet is stabilized with jetties to maintain a navigation channel. The sand-starved northern end of Masonboro Island is periodically renourished during inlet dredging operations to maintain the navigation channel and to provide an artificial sand-bypass mechanism. During the Spring of 1998, 800,000 cubic yards of sand were deposited on the northern end of Masonboro Island about a mile south of the inlet. The entire island was overwashed during Bonnie, moving the shoreline position landward; however, the overwash is significantly less along the wider renourished portion of the beach (Plate 7).

4.2.2 Cape Influences

Three beaches that were not renourished show significant accretion. They are the beaches just west of Capes Fear and Lookout (Plates 3, 4, and 16). For these beaches, the average gain per beach length ranges between 8.8 and 19.6 cubic yards per yard. These gains may result from the combination of the unique east-west coastline orientation and the large southward extension of the capes directly to the east. These hook-like features may have formed a trap for sediment and protected the shoreline from longshore currents. The higher average sediment gain (19.6 cubic yards per yard) seen on the beach just west of Cape Lookout may be attributable to the significant overwash observed, which is less apparent for the two beaches west of Cape Fear, as indicated by lower average volume gains (12.6 and 8.8 cubic yards per yard). A similar accretional pattern is not observed west of Cape Hatteras, where the shoreline orientation runs more northward and the Cape's southward extension is smaller than that of the other two capes.

Hatteras Island (Plate 20), situated between Hatteras Inlet and Oregon Inlet, has the highest average erosion per beach length, 49.0 cubic yards per yard of shoreline, nearly twice the average change per length seen on any other beach. The beaches immediately south (Plate 19) and north (Plate 21) of Hatteras Island show the next highest loss in sand volume per length, 27.2 cubic yards per yard and 22.0 cubic yards per yard, respectively. Between Hatteras Inlet and Oregon Inlet, there is a net loss of over 4.6 million cubic yards of sand from the beach. Erosional hotspots show vertical losses exceeding 20 feet Figure 13 and changes in volume equal to almost 100 cubic yards per yard of beach (Figure 14, black box). The cross-sectional profile shows a total elimination of the 20-foot dune and a retreat of the shoreline of 125 feet. Very little sand was deposited landward of the dune, only a 1- to 2-foot increase in beach elevation can be observed directly behind the dune. One must conclude most of the sediment moved into the offshore zone.

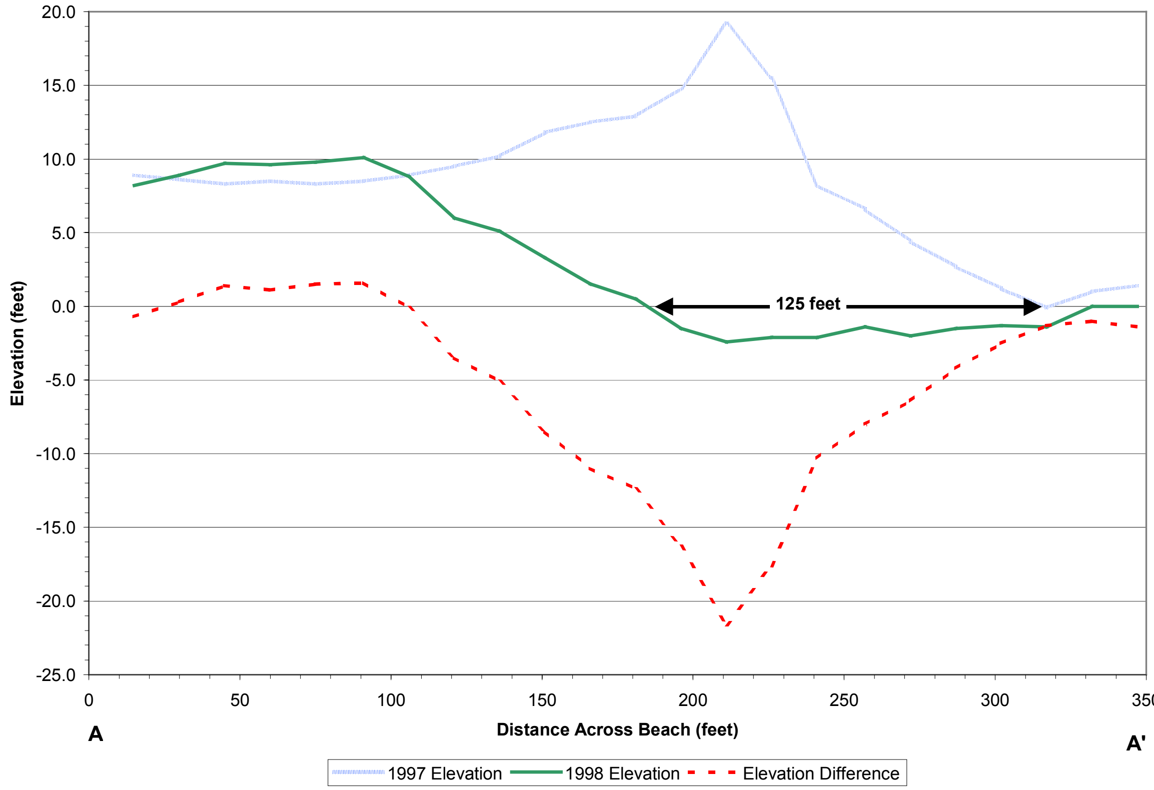

Figure 13. Shore-normal profile approximately 1.5 miles north of Cape Hatteras. Distance across the beach begins at the landward end of the profile (i.e., 0). The dashed line shows the actual change in elevation across the width of the beach. Negative elevation differences indicate a loss in elevation from 1997 to 1998.

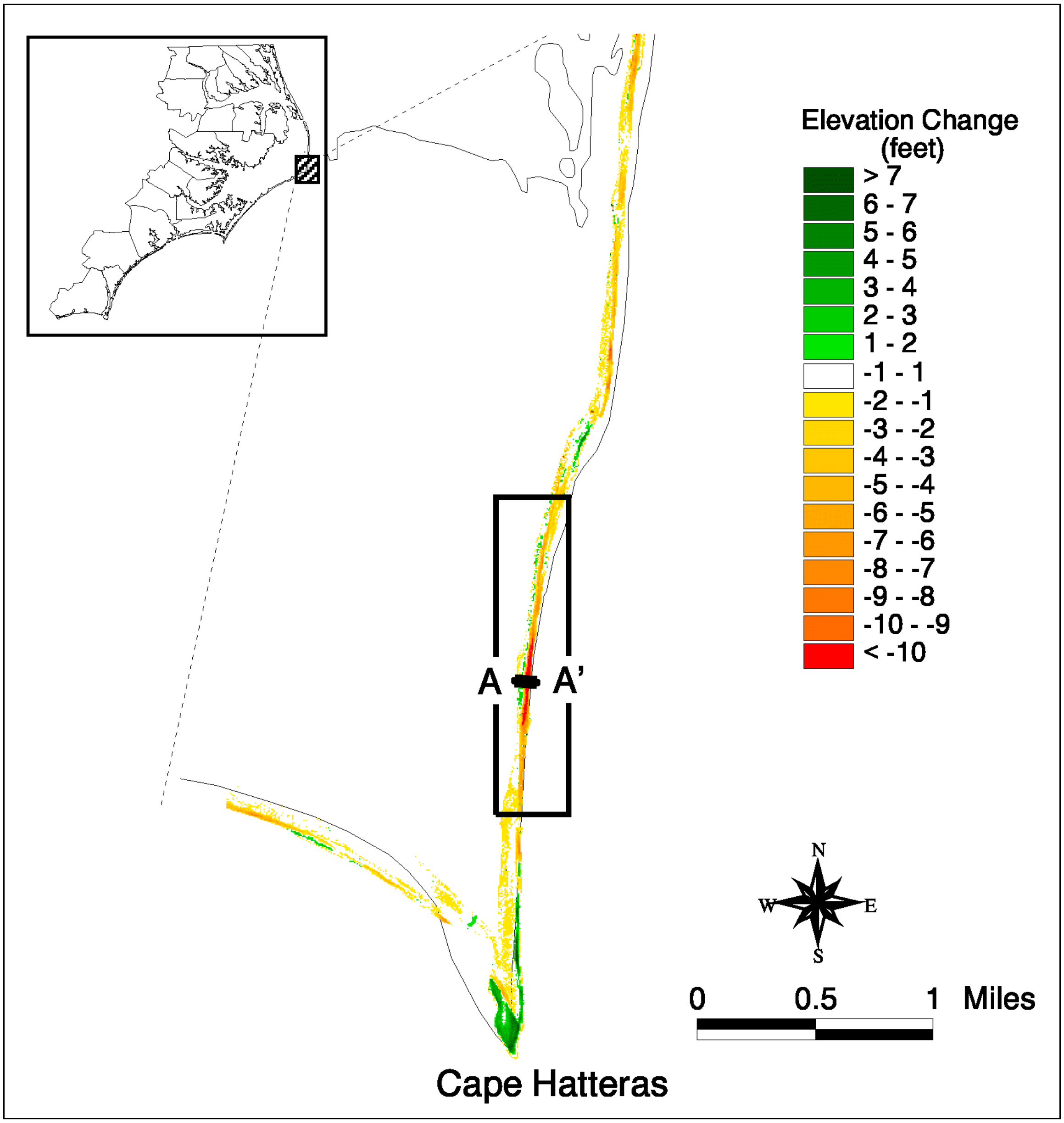

Figure 14. 1997 to 1998 elevation change map showing areas of severe erosion north of Cape Hatteras. Red indicates areas with the greatest elevation loss and dark green shows areas with the greatest gain in elevation. Only elevation changes exceeding 1 foot are shown. The bold black line (A-A') locates the shore-normal profile presented in Figure 13. The black rectangle delimits the area for which average volumetric loss discussed in text was calculated.

4.2.3 Overwash

The southern barrier islands have five large regions of complete sand overwash to the backside of the island. The central barrier islands had two regions of significant overwash (Figure 15). The southern areas include Cape Fear to New Inlet (Plate 5), a section of beach immediately north of New Inlet (Plate 6), a section of beach immediately south of Carolina Beach Inlet (Plate 6), Masonboro Island (Plate 7), and the beach between Rich Inlet and New Topsail Inlet (Plate 10). The two northern areas include the entire beach between Beaufort Inlet and Barden Inlet (Plate 16), and the beach west of Cape Lookout (Plate 17). The results of the overwash can be identified on the elevation change maps contained on the plates in Appendix B by the eroded beach (depicted in yellows and reds) and the sediment deposits (depicted in greens) penetrating toward the backside of the island. Overwash is less visible and extensive along the northern North Carolina barrier islands. The response along the northern islands appears to be driven more by longshore and offshore sediment transport, accounting for the higher average volumes of sand loss. The areas of overwash were delineated and the volumetric change for the overwashed regions calculated (Table 2). The volume gains may be conservative due the width of the laser survey, which do not always extend sufficiently inland to detect all washover deposits and due to the slightly different flight lines of the 1997 and 1998 surveys, that results in variable coverage over the survey's landward edge. All of the overwash areas indicate a net gain in sand volume. This gain occurs on the landward side of the beaches.

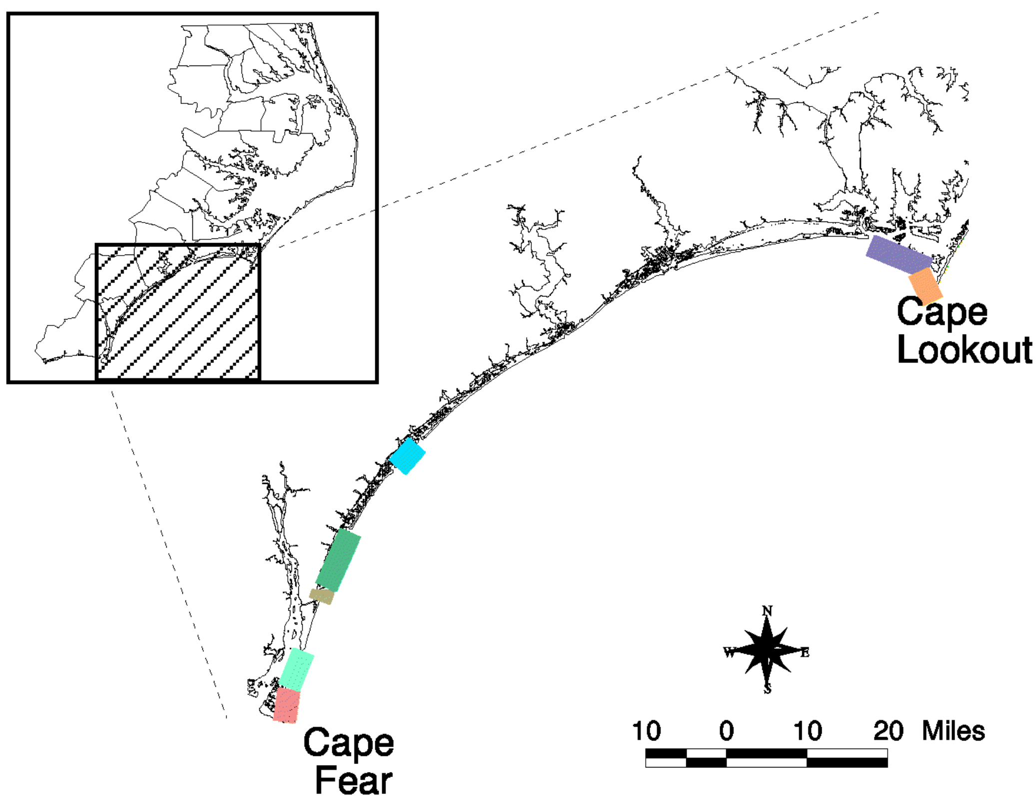

Figure 15. Map locating regions of significant overwash. The colored lines denote the different beach segments with overwash.

Location of Overwash	Volume (y3)			Area (y2)			Vol. Chg./ Yard
	Gain	Loss	Net Chg.	Gain	Loss	Total	
Cape Fear to New Inlet	361,598	307,026	54,572	1,305,630	625,557	1,931,187	7.9
North of New Inlet	618,111	451,081	167,030	1,453,960	736,813	2,190,773	18.9
South of Carolina Beach Inlet	183,308	119,631	63,677	455,517	202,505	658,022	22.5
Carolina Beach Inlet to Masonboro Inlet	525,628	500,106	25,522	1,266,810	1,114,760	2,381,570	2.1
Rich Inlet to New Topsail Inlet	581,963	349,426	232,537	1,088,120	559,668	1,647,788	33.5
Beaufort Inlet to Barden Inlet	595,834	308,999	286,835	1,621,220	582,905	2,204,125	20.2
Barden Inlet to Cape Lookout	408,560	157,685	250,875	924,897	228,077	1,152,974	40.1

Table 2. Volumetric gain and loss quantities for beach regions exhibiting major overwash.

Masonboro Island (Plate 7), located between Carolina Beach Inlet and Masonboro Inlet, provides an excellent example of a transgressive (landward moving) barrier island's response to a major storm event like Hurricane Bonnie. The color-coded elevation map created from the 1998 LIDAR survey is shown in Figure 16 for a small representative section of the island. As is typical with the sections of beach exhibiting overwash, the topography is low, usually not exceeding 10 feet NGVD29. The 1997 to 1998 elevation change map in Figure 16 shows significant loss along the ocean margin (depicted in reds and yellows) and washover deposits (depicted in greens) penetrating the marsh on the landward side of the low dune ridge. The change in the island's profile is shown in Figure 17. The location of the profile is visible as the bold black line on the 1998 elevation map in Figure 16. The shoreline retreated 55 feet and the vertical elevation was reduced by almost 1 foot. Although significant change in beach morphology is apparent, there is little change in the island's sediment volume (Table 2).

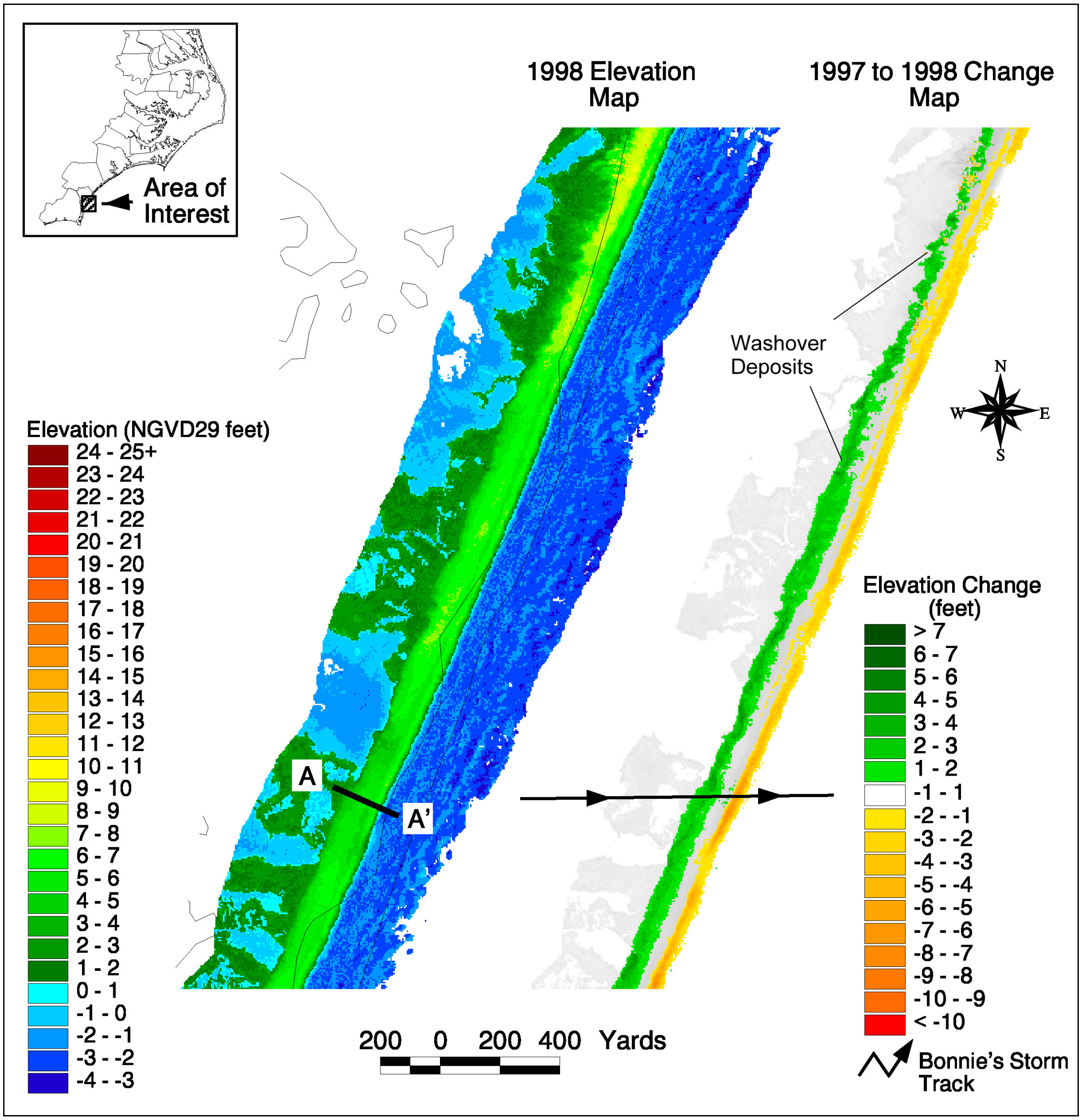

Figure 16. Example of overwashing on Masonboro Island. The 1998 elevation map is color-coded showing the highest elevations as dark red and lowest in dark blue. The change map depicts elevation change between the 1997 and 1998 surveys. Red indicates areas with the greatest elevation loss and dark green shows areas with the greatest gain in elevation. Only elevation change exceeding 1 foot is shown. The bold black line (A-A') on the 1998 elevation map locates the shore-normal profile presented in Figure 17. The path of Hurricane Bonnie is shown as a black arrow on the elevation change map as the eye of the storm makes a brief excursion back into the Atlantic.

Figure 17. Profile showing island overwash on Masonboro. Distance across the beach begins at the landward end of the profile (i.e., 0). The dashed line shows the actual change in elevation across the width of the beach. Negative elevation differences indicate a loss in elevation from 1997 to 1998.

4.2.4 Inlet Closures

Three inlets appearing in the 1997 laser surveys are shown to have completely closed by the 1998 survey (Figure 18). These inlets were located approximately 1 mile east of Little River Inlet at an historic inlet site (Plate 1), 1.5 miles south of New Topsail Inlet and known as Little Topsail Inlet (Plate 10), and 2 miles south of the northern end of Topsail Island (Plate 11b). The inlets were all located along the southern coast where Hurricane Bonnie impacted the coast longer and with the greatest intensity.

Individual elevation maps from 1997 and 1998 surveys and an elevation change map are shown in Figure 19 for Little Topsail Inlet. The change map indicates complete overwash of the northern section of the island by storm surge, which produced erosion on the beach and sediment deposition on the backside of the island. In the area of the former inlet, we see only deposition across the entire section of the island. The total volume of new sand deposited within the former inlet was approximately 47,382 cubic yards. The profiles in Figure 20 demonstrate the change in the island profile at the inlet and just south of the inlet.

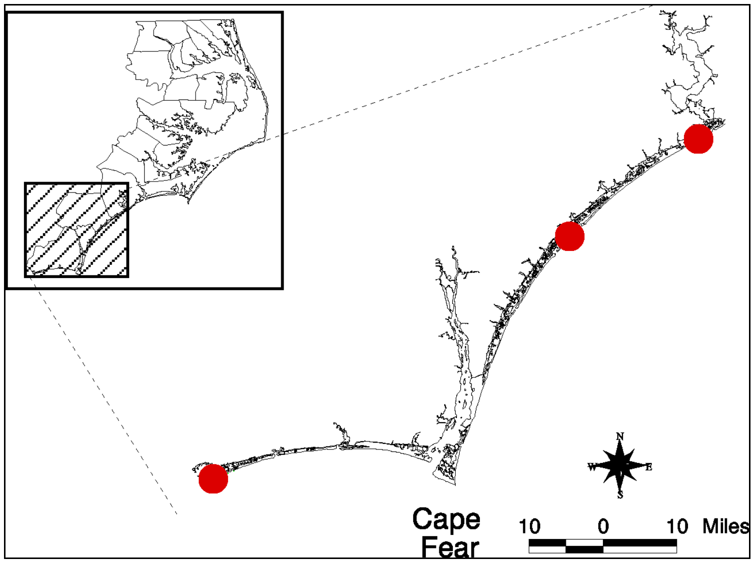

Figure 18. Map identifying locations of inlet closures (red dots) between 1997 and 1998 surveys.

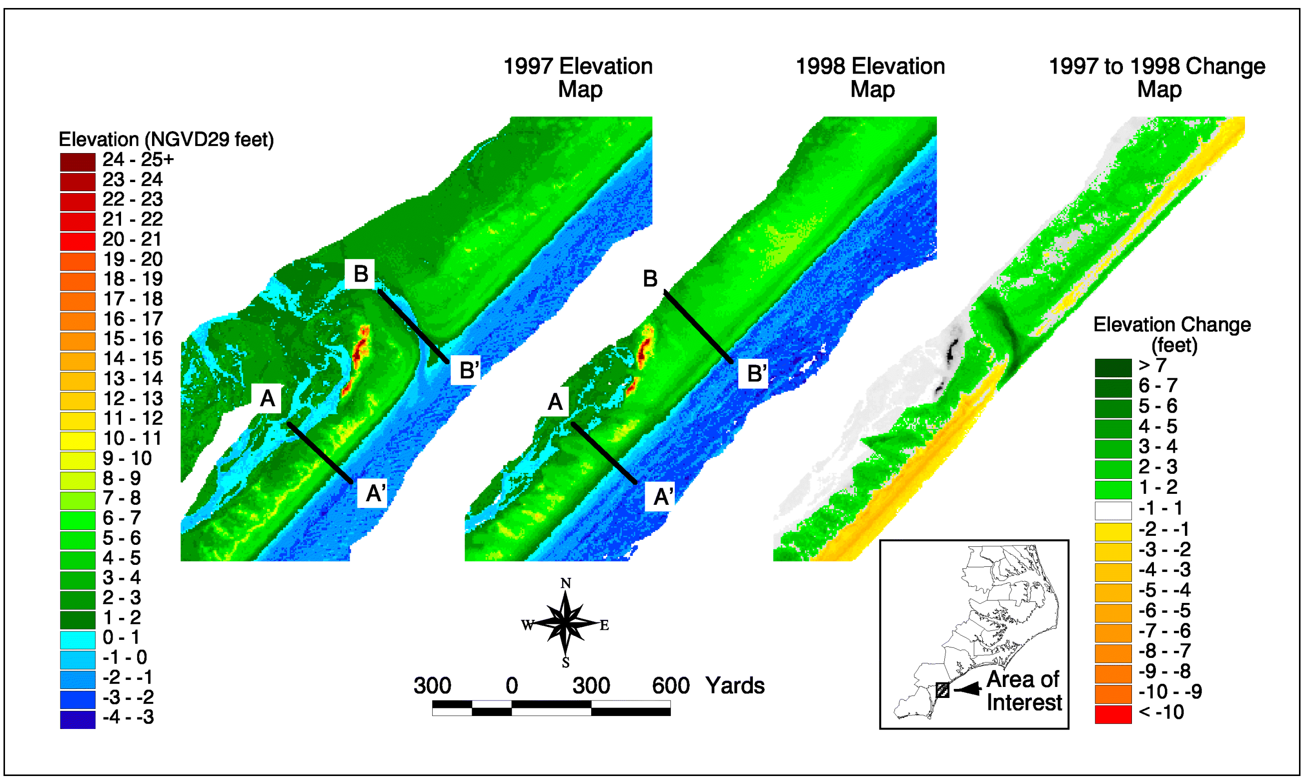

Figure 19. Example of inlet closure. This inlet was formerly known as Little Topsail Inlet and was located just south of New Topsail Inlet. The 1997 and 1998 elevation maps are color-coded depicting the highest elevations as dark red and lowest in dark blue. The change map depicts elevation change between the 1997 and 1998 surveys. Red indicates areas with the greatest elevation loss and dark green shows areas with the greatest gain in elevation. Only elevation change exceeding 1 foot is shown. The bold black lines (A-A' and B-B') on the elevation maps locate the shore-normal profile presented in Figure 20.

(a)

(b)

Figure 20. (a) Profile A-A' shows the beach response just south of the former Little Topsail Inlet. (b) Profile B-B' of island before and after the Little Topsail Inlet closure. Distance across the beach begins at the landward end of the profile (i.e., 0). The dashed line shows the actual change in elevation across the width of the beach. Negative elevation differences indicate a loss in elevation from 1997 to 1998.

5.0 CONCLUSIONS

Airborne laser topographic surveys can be used to extensively monitor beach dynamics and examine beach morphology on a regional scale with an accuracy previously unavailable with traditional monitoring techniques. Multi-temporal LIDAR beach surveys allow elevation change detection, dry beach volume calculations, and profile examination. The regional analysis of Hurricane Bonnie's impact to the North Carolina barrier islands using LIDAR surveys provides interesting insights into varied response of the beaches to a major storm event. Hurricane Bonnie's path up the coast, combined with the varying coastline orientation, produced different responses along the coast. Although reduced storm conditions would be expected as a result of increased distance from the storm's eye, the northern barrier island beaches show a greater average sediment loss over the length of the beach than the beaches in the middle and southern sections of the coast. The northern beaches generally show long erosional sections of beach and dunes with smaller pockets of accretion. The overwash seen was minor. Central beaches show a different response: little sediment volume change with a pattern of short alternating areas of erosion and accretion. The areas of erosion are less severe than to the north. More overwash is apparent, but generally it is limited. The southern beaches exhibit a mixture of sediment gain and loss. Much of the gain can be attributed to major beach renourishment projects; however, those beaches not renourished have higher average losses of sediment over the length of the beach than the middle section of coast. Complete islands and large sections of beaches were completely overwashed, significantly changing the beach morphology, but having a low impact on the total beach volume.

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7.0 APPENDIX A – BEACH SUMMARY TABLE

Summary of change by each beach section separated by inlets for the entire North Carolina coast. "*" denotes beaches that received additional sand from minor renourishment projects and "**" denotes beaches that received additional sand from major renourishment projects.

	Volume (y^3)			Area (y^2)			Vol. Chg. per	
Beach Extent	**Gain**	**Loss**	**Net Chg.**	**Gain**	**Loss**	**Total**	**Area (y^3/y^2)**	**Len (y^3/y)**
Little River Inlet to Tubs Inlet	199,166	155,821	43,345	758,750	752,221	1,510,971	0.03	5.7
Tubs Inlet to Shallotte Inlet	137,704	251,947	-114,243	442,024	736,271	1,178,295	-0.10	-10.6
*Shallotte Inlet to Lockwoods Folly Inlet	394,056	206,739	187,317	1,036,760	731,024	1,767,784	0.11	12.6
Lockwoods Folly Inlet to Cape Fear River	399,954	196,453	203,501	1,205,539	719,955	1,925,494	0.11	8.8
Cape Fear River to New Inlet	349,392	586,649	-237,257	1,110,520	1,018,220	2,128,740	-0.11	-16.5
**New Inlet to Carolina Beach Inlet	2,117,512	835,266	1,282,246	2,993,411	1,252,814	4,246,225	0.30	55.2
**Carolina Beach Inlet to Masonboro Inlet	774,030	500,106	273,924	1,503,020	1,114,760	2,617,780	0.10	19.5
**Masonboro Inlet to Mason Inlet	504,976	79,483	425,493	706,474	187,862	894,336	0.48	57.8
*Mason Inlet to Rich Inlet	163,366	356,396	-193,030	425,608	674,439	1,100,047	-0.18	-19.7
Rich Inlet to New Topsail Inlet	581,963	349,426	232,537	1,088,120	559,668	1,647,788	0.14	31.7
*New Topsail Inlet to New River Inlet	374,794	1,093,601	-718,807	1,154,657	2,163,251	3,317,908	-0.22	-18.1
*New River Inlet to Browns Inlet	324,167	298,790	25,377	895,175	520,817	1,415,992	0.02	1.9
Browns Inlet to Bear Inlet	129,232	262,742	-133,510	284,215	488,030	772,245	-0.17	-21.0
*Bear Inlet to Bogue Inlet	163,771	258,532	-94,761	470,784	511,694	982,478	-0.10	-15.4
Bogue Inlet to Beaufort Inlet	717,152	858,061	-140,909	2,001,127	1,586,630	3,587,757	-0.04	-3.2
Beaufort Inlet to Barden Inlet	595,834	308,999	286,835	1,621,220	582,905	2,204,125	0.13	19.6
Barden Inlet to Drum Inlet	1,090,642	1,227,952	-137,310	3,745,090	3,333,910	7,079,000	-0.02	-3.0
Drum Inlet to Ocracoke Inlet	480,772	1,269,324	-788,552	2,214,587	3,134,362	5,348,949	-0.15	-20.6
Ocracoke Inlet to Hatteras Inlet	432,760	1,212,338	-779,578	1,466,744	2,551,625	4,018,369	-0.19	-27.2
*Hatteras Inlet to Oregon Inlet	928,981	5,563,664	-4,634,683	2,505,787	9,000,526	11,506,313	-0.40	-49.0
Oregon Inlet to NC/VA Border	1,093,944	3,050,427	-1,956,483	3,026,550	5,334,561	8,361,111	-0.23	-22.0

8.0 APPENDIX B – ELEVATION AND CHANGE MAPS

The following section contains 1998 elevation maps and 1997 to 1998 elevation change maps derived from LIDAR surveys for all the beaches along the North Carolina coast. The 1998 elevation maps are color-coded to indicate elevation based on the "Elevations" legend. Reds indicate higher elevations and blues indicate elevations around mean-sealevel. The elevations are in feet and reference the 1929 National Geodetic Vertical Datum. The NOAA shoreline is overlaid on the elevation maps a spatial reference. The 1997 to 1998 change maps are color-coded, based on the "Elevation Change" legend, to indicate the elevation change in feet of the beach between the 1997 and 1998 LIDAR surveys. The darkest green colors indicate the greatest gain in elevation from 1997 to 1998 (accretion) and the darkest reds indicate the greatest loss in elevation (erosion). To highlight the major change features and patterns, minor changes in elevation (1 foot or less) are not shown. The elevation change information is overlaid on the 1998 greyscale elevation image.

Each map presents an island separated by two inlets (Figure 3). The islands are ordered from south to north. Islands spanning pages are divided into sections with section 1 beginning at the southern end of the island.

Beach Extent	Plate #
Little River Inlet to Tubs Inlet	1
Tubs Inlet to Shallotte Inlet	2
Shallotte Inlet to Lockwoods Folly Inlet	3
Lockwoods Folly Inlet to Cape Fear River	4
Cape Fear River to New Inlet	5
New Inlet to Carolina Beach Inlet	6
Carolina Beach Inlet to Masonboro Inlet	7
Masonboro Inlet to Mason Inlet	8
Mason Inlet to Rich Inlet	9
Rich Inlet to New Topsail Inlet	10
New Topsail Inlet to New River Inlet	11a, 11b
New River Inlet to Browns Inlet	12
Browns Inlet to Bear Inlet	13
Bear Inlet to Bogue Inlet	14
Bogue Inlet to Beaufort Inlet	15a, 15b
Beaufort Inlet to Barden Inlet	16
Barden Inlet to Drum Inlet	17a, 17b, 17c
Drum Inlet to Ocracoke Inlet	18a, 18b
Ocracoke Inlet to Hatteras Inlet	19a, 19b
Hatteras Inlet to Oregon Inlet	20a, 20b, 20c, 20d, 20e
Oregon Inlet to NC/VA Border	21a, 21b, 21c, 21d, 21e