

Stephen Alston White UTILIZING DEMS DERIVED FROM LIDAR DATA TO ANALYZE TOPOGRAPHY: A CASE STUDY OF NORTH CAROLINA BARRIER ISLANDS. (Under the direction of Dr. Yong Wang) Department of Geography, July 2002.

This research examined volumetric changes (erosion, deposition, and net-change) of the beachfront along a portion of the North Carolina coastline. Volumetric analyses were conducted in this area using pairs of highly spatially accurate and high spatial resolution digital elevation model (DEM) data derived from light detection and ranging (LIDAR) data acquired in 1997, 1998, 1999, and 2000. An approximately 71 km stretch of the southern North Carolina coastline, consisting of five barrier islands located between Topsail Island and Masonboro Island were studied. The majority of erosion along the lower beach face detected during the 97-98 and 98-99 intervals can be attributed to the impacts of hurricanes that directly affected the study area during these periods. Accretion and deposition predominated over most of the islands due to the lack of major storms and hurricanes during 99 and 00.

During 97-98, three islands had net-volumetric gain of sediment ranging from 121,983 m³ to 217,886 m³, but the other two islands experienced net loss of 179,159 m³ and 469,792 m³. Between 98-99, all islands had net loss, ranging from 134,554 m³ to 427,248 m³. From 1999 to 2000, all islands gained in volume, with a range of 30,059 m³ to 329,725 m³.

The statistical significance of volumetric net changes per unit area of beach between barrier islands, during different time periods was analyzed using ANOVA (Analysis of Variance). Barrier systems classified according to the nature of human intervention was also evaluated using ANOVA. The ANOVA test allows for an in depth

inquiry into the similarity or differences of spatial variations out of fifteen comparisons between each pairs of time interval on each island and out of thirty comparisons between islands at each time interval. The ANOVA also served useful in comparing and contrasting the spatial variations of volumetric net change per unit area of beach for coastline characterized as beach nourishment, dune nourishment, developed beach, and undeveloped beach at three time periods.

UTILIZING DEMS DERIVED FROM LIDAR DATA
TO ANALYZE TOPOGRAPHY: A CASE STUDY OF
NORTH CAROLINA BARRIER ISLANDS.

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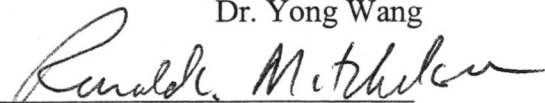
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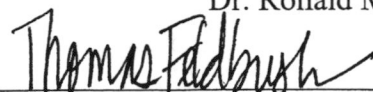
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TABLE OF CONTENTS

LIST OF FIGURES.....	vii
LIST OF TABLES.....	viii
CHAPTER 1. INTRODUCTION.....	1
CHAPTER 2. LITERATURE REVIEW.....	6
Barrier Islands.....	6
Remote Sensing and GIS in the Coastal Environment.....	11
LIDAR.....	13
Mapping Beach Morphology with Airborne Topographic Mapper.....	15
CHAPTER 3. ANALYTICAL APPROACHES.....	21
Study Area.....	21
Dataset.....	23
Data Derivation.....	25
Analysis.....	28
CHAPTER 4. RESULTS AND DISCUSSION.....	30
Spatial pattern of morphologic change.....	30
Volumetric changes of barrier islands of years 97-98, 98-99, 99-00.....	40
Normalized volumetric net changes per unit area.....	44
ANOVA Analysis.....	49
Test on means of each island at three consecutive yearly intervals.....	49
Test on means of all five islands together at each yearly interval.....	50
Comparison of coast based upon management practices	52
CHAPTER 5. CONCLUSION.....	58
BIBLIOGRAPHY.....	64

LIST OF FIGURES

1	Aerial imagery of barrier islands.....	7
2	Coastal man-made sand dunes along the Outer Banks.....	7
3	Aerial imagery of an overwash fan on Hatteras Island,.....	9
4	ATM II sensor and flights operation parameters.....	17
5	Map of study area.....	22
6	Visualization of Old Topsail Inlet.....	22
7	Hurricanes that directly affected the study area.....	24
8	Volumetric net change of AOIs at each yearly interval.....	31
9	Lower beach face erosion of 97-98 on Masonboro.....	32
10	Beach nourishment on Wrightsville Beach.....	32
11	Overwash fans on Masonboro Island in 1998.....	33
12	Dune destruction due to Hurricane Bonnie on Topsail.....	34
13	Lower beach face erosion of 98-99 on Figure Eight.....	36
14	Overwash fans on Masonboro Island in 1999.....	36
15	Dune nourishment on Figure Eight Island.....	37
16	Erosion of dune and lower beach face between 98-99 on Topsail.....	37
17	Deposition along the lower beach face on Masonboro during 99-00.....	39
18	Beach nourishment on Figure Eight Island.....	39
19	Volumetric changes of islands for 97-98, 98-99, 99-00.....	41
20	Volumetric net change per area of each AOI at each yearly interval.....	47

LIST OF TABLES

1	Dates of ATM flight surveys and hurricanes' landfall.....	23
2	Number of Area of Interest (AOI) used in volumetric analysis of island.....	26
3	Number of Area of Interest (AOI) designating management practices.....	27
4	Summary of AOIs experiencing erosion or deposition.....	35
5	Statistical summaries of net volumetric changes per area.....	46
6	<i>Post hoc</i> results of each island over three consecutive yearly intervals.....	50
7	<i>Post hoc</i> test results of ANOVA testing between islands during each yearly.....	51
8	Mean net change rates for management practice AOIs.....	53
9	<i>Post hoc</i> test result of ANOVA testing between management practices.....	55

CHAPTER 1

INTRODUCTION

The interaction of humankind with the natural coastal system has led to a great deal of concern for the geomorphic change and effective management of the coastal zone area (Carter 1989, Gares 1990, Nordstrom 1994). Approximately 53% of the current U.S. population resides largely within what is considered the coastal margin (Coastal 2000). The waters that surround and meet the coastal margin also provide very important breeding grounds for numerous marine species that offer a large percentage of the world's food supply. The current influx of people to, and development in, coastal areas emphasizes the need to provide a better understanding of their impacts on the environment and of changes that might be occurring. Some of the greatest impacts and changes involve the immediate coastal environment.

The immediate coastal environment may be defined as the narrow zone of interaction between land and ocean, which can consist of barrier islands. The islands are located on many coastlines where four factors are met: a rising sea level, a large amount of sand supply, a coastal plain of gentle slope, and a sufficient amount of wave energy required to move the sand (Pilkey et al. 1998). The islands are typically elongated narrow strips of sand, intersected by inlets that permit the flow of salt and fresh water into and out of the estuary located behind the islands (Pilkey et al. 1998). Barrier islands are dynamic because a complex intertwining system of processes, such as the wave action of water and aeolian processes acts upon them to shape and mold their form through time. Weather systems such as hurricanes, northeasters, and frontal boundaries are

acknowledged as significant events that can affect the form and topography of barrier islands (Dolan and Davis 1992, Inman and Dolan 1989). North Carolina's coastline, like other developed barrier island areas, is experiencing a battle with development and natural processes that affect the topography of the barrier islands. Particular portions of the North Carolina coastline have exhibited a loss of shoreline with rates of 5 to 12 m per year (Pilkey et al. 1998).

When studying morphologic or topographic changes on barrier islands, past researchers have been faced with the laborious task of surveying beaches in limited areal extents using widely spaced transects and profiles, or interpreting aerial photography. These limitations can lead to great misunderstanding and misrepresentation of certain morphological aspects such as erosion and deposition along a coastline. The widely spaced sampling and transect measurements used in past research is not of a comprehensive manner. These gaps found within the data can result in missing important aspects of morphologic change that are integral to understanding change and can possibly lead to inaccurate conclusions about the processes that cause the change. Differences in sediment transfer rates between natural and controlled barrier islands has been acknowledged (Dolan, 1973) but never confirmed through actual measurement of rates of volumetric change along the dynamic portions of these particular types of islands in a comprehensive manner.

Coastal topographic data can now be gathered within hours by an airborne light detection and ranging (LIDAR) data-gathering mission. LIDAR is a technology that uses a transmitted laser beam to depict the terrain of the earth (e.g., Krabill 1995, Wright

1997, Huising and Pereira 1998, Brinkman 2000, Hofton et al. 2000, Krabill 2000). Through a combined use of a laser transmitter with high repeating pulse frequency (RPF) and a high speed scanning system, very dense measurements of x, y, and z on the terrain surface by the laser beam are produced. Thus, the creation of an elevation data set with very fine spatial (x and y) resolution of up to 1.5 m, and fine vertical (z) resolution of 0.15 m or better becomes possible. The global positioning system (GPS) and inertial navigation system (INS) onboard the aircraft also allow accurate registration of the LIDAR data to ground surface.

Using 1996 and 1997 LIDAR data, Woolard (1999) investigated the effect of using the data to derive DEMs with different spatial resolutions on the representation of the topography of sand dunes and concluded that to accurately depict the topography of the dunes, the DEM's spatial resolution should be less than 5 m by 5 m. Meredith et al. (1999) evaluated hurricane-induced beach erosion between 1997 and 1998 along the entire North Carolina coastline using DEMs derived from LIDAR data at a resolution of about 5 m by 5 m. Their results showed a great potential to use the DEMs derived from LIDAR data to study certain morphological aspects such as deposition and erosion along a coastline at a large areal extent. However, their study only covered one time period, 1997-98, and the DEMs of a 5 m by 5 m spatial resolution used might be too coarse to accurately represent the topography of the beaches and dunes and to fully understand morphological changes of coastlines.

This research will use highly spatially accurate topographic data that allow for analysis of erosional and depositional patterns and volumetric net change over large

segments of barrier islands, which accurately depicts a more comprehensive change of a barrier island. Topographic changes between characterized sections of a barrier island based on the management practices that are allowed or dictated to occur need to be investigated for a better understanding of the spatial and quantitative relationships that exist.

This thesis reports recent progress on using DEMs derived from the LIDAR data to study the morphological/topographic changes on five barrier islands along the North Carolina coast. The work extends Meredith et al.'s (1999) approach by using DEMs at 1.5 m by 1.5 m resolution to analyze spatial patterns of deposition, erosion, and volumetric net change of the islands during periods of 1997-1998, 1998-1999, and 1999-2000. Means of net volume change per unit area (m^3/m^2) for AOIs (Area of Interest) in the study area were obtained and categorized by islands and by different beach management practices. The manner in which an island is managed is believed to significantly affect the rates of volumetric change. Mean net-volumetric changes per unit area of the AOIs for each island over three consecutive yearly intervals, of the AOIs for all islands within a single yearly interval over the three consecutive yearly intervals, and of the AOIs for each management practice are compared to determine the statistical significance of the variations through utilization of the ANOVA method, respectively.

The primary objective of this research is to utilize LIDAR data for examining barrier islands in a more detailed manner, while minimizing error found with in the derived DEMs. The major research questions that will be examined include: 1) Can DEMs derived from LIDAR and the method utilized in this research quantitatively

measure the spatial character of topographic change on these islands? 2) Are the spatial variations in net volumetric change per unit area similar from one barrier island to the next within a consistent time frame and are their variations similar from one time frame to the next? 3) And can we better understand the differing behaviors of more natural undeveloped barrier island sites from that of developed sites using LIDAR derived change analysis?

This thesis progresses with a brief overview of the dynamic nature of barrier islands and recent work using the tools of remote sensing and GIS to examine the coastal environment. Emphasis is directed towards the beaches and dunes where the greatest amount of storm-generated topographic change occurs. The study area is introduced next, followed by a description of the datasets used to investigate volumetric analysis and the analysis methodology. Results and discussions are presented based on the processing of DEMs derived from LIDAR. Concluding remarks and suggestions for future research will also be provided.

CHAPTER 2

LITERATURE REVIEW

Barrier Islands

The immediate coastal environment, defined as the narrow zone of interaction between land and ocean, is a very dynamic system. A number of processes, characterized by multiple feedback mechanisms, act upon this environment to shape and mold its form through time. Two of the greatest contributing factors in shaping the morphological forms of a coastal area include the wave action of water and aeolian processes. Forces of waves and wind are usually derived from particular atmospheric conditions. The formation of waves varies with the wind speed, the fetch, the duration of time the wind blows, and the water depth. Weather systems such as hurricanes, northeasters, and frontal boundaries can cause significant waves and wind that affect the form of the immediate coastal environment.

Barrier islands are just one of many morphologic landforms that may be present along the world's coastal shorelines. These islands are typically elongated narrow strips of sand that are intersected by inlets that permit the flow of salt and fresh water into and out of the estuary located behind the islands (Pilkey et al. 1998). An example of barrier islands along the North Carolina coastline is portrayed through aerial imagery capturing portions of Cape Lookout and Shackleford Island (Figure 1). Many distinct features can be found upon a barrier island such as a shoreface, dune field, overwash fans, grasslands, marshes, shrubs, maritime forest, and tidal flats. The shoreface and dune field are two main features that absorb a large proportion of the energy displaced by waves and wind.



Figure 1. Aerial imagery of Cape Lookout and Shackleford Island, both barrier islands located along the North Carolina coastline.



Figure 2. Coastal man-made sand dunes in Coquina Beach, Outer Banks, NC.

No two barrier islands are just alike; each island has its own special characteristics. Some islands may be characterized as overwash-dominated, other barriers have large natural dune fields; still other barriers have been heavily modified by human activities (Figure 2).

Barrier islands are involved in an ongoing process known as landward migration, (Leatherman 1979, Pilkey et al. 1998) a landward shift of the barrier island over time. Water and wind are contributing factors in moving the sand landward. This is the barrier island's response primarily to the rising sea level. The process of overwash has been recognized as an important mechanism responsible for the building of the barrier islands and for their landward migrations (Pierce 1969, Dolan et al. 1973). Overwash, dune migration, and tidal inlet movement contribute to barrier island migration, and these have been major topics of research (e.g., Pierce 1969, Armon 1979, Fisher and Simpson 1979, Kochel and Wampfler 1989). Overwash (Figure 3) occurs when a storm surge and the wave action combine to breach the dune line. Sediments, including sand and shells, are carried by flowing water through openings in the dune and are deposited in flat terraces or fans behind the dune line. Dunes on barrier islands vary drastically in relation to different spatial and temporal scales (Psuty 1992, Sherman 1995). Sediment grain size, the characteristics of the beach profiles, wind regime, wave activity, and vegetation are recognized as playing an important role in the function of dune formation and migration (Carter 1990).

When considering the dynamic morphological changes that occur on a barrier island, it is important to understand the presence of vegetation and its effects on the



Figure 3. Overwash fan located on Hatteras Island, NC.

changes (Hayden et al. 1995). The vegetation helps stabilize the sediment with its roots, providing protection from the effects of aeolian forces. The vegetation also caused deposition by trapping sediment blown by the wind.

Studies have examined rates of beach erosion and dune recession (Everts et al. 1983, Dekimpe et al. 1991, Dolan et al. 1991) and barrier island geomorphology and sediment budgets (Kochel et al. 1985, Inman and Dolan 1989). Other research has focused on the dynamics of the dune field (Gares et al. 1997, Andrews 1998). Aeolian transport has also been mentioned as a key factor in understanding barrier islands' morphology (Leatherman 1976, Leatherman and Zaremba 1987, Bauer et al. 1990, Gares et al. 1997, and Gares 1990).

Classifications and variations of barrier islands have also been studied (Dolan 1973, Inman and Dolan 1989, McBride 1995, Nordstrom 1994, Nordstrom 1995, McBride 1997, and Jackson et al. 2000). Dolan (1973) discussed the difference between a

natural barrier island and a controlled barrier island. The controlled barrier islands have undergone human modification such as massive dune construction, jetties, seawalls, and groin construction. In contrast, most natural barrier islands are better adapted to the steady state processes and extreme events when compared to controlled barrier islands (Dolan 1973). Energy dissipation and sediment transfer systems are different between these two types of barrier islands (Dolan 1973). Nordstrom (1995) examined how human intervention has affected and changed barrier island systems along the New Jersey coast. The construction of buildings, supporting infrastructure, jetty and shore protection structures such as seawalls to beach nourishment and dunes, dredging of inlets, and small effects such as alteration of wind flow by buildings and introduction of exotic species were cited (Nordstrom 1995) as prominent factors affecting a barrier island's dynamics. Jackson et al. (2000) classified Seven Mile Beach, New Jersey by the spatial and temporal changes that occurred on a developed barrier island from 1940 to 1987. Their classification system consisted of three variables representing the physical characteristics (subaerial beach width, dune zone width, distance from nearest inlet) and three key variables representing human alterations (number of buildings, number of shore-normal structures, and presence of shore parallel structures) that were measured from aerial photography. Three factors; geomorphic, inlet, and settlement factors were derived from the six variables using an extraction method of principal component analysis. Nordstrom (1994) discussed some of the aspects and implications of modeling human-altered geomorphic systems, which were recognized as an integral component of the landscape evolution. One of the alternative methodologies Nordstrom (1994) proposed for

examining the evolution of coastlines included the comparing and contrasting of a developed area against that of an undeveloped area that was assumed to have the same process controls.

McBride (1995, 1997) depicted regional variations in barrier islands through the use of National Ocean Service topographic sheets and aerial photography to document shoreline position from 1847 to 1991. The shore normal transects derived from these data provided the magnitude, direction, and rate of change along a barrier island system of the Mississippi River Delta. Barrier island coastlines were also classified in this study (McBride 1995) into eight geomorphic response-types; lateral movement, advance, dynamic equilibrium, retreat, in-place narrowing, landward rollover, breakup, and rotational instability, based upon megascale changes.

Remote Sensing and GIS in the Coastal Environment

With all the complex and dynamic processes that occur in the coastal environment, remote sensing and geographic information systems (GIS) are two tools that offer assistance in gaining insight into morphological changes occurring in the system. The primary contribution is to monitor and quantify the topographic changes, and these observations can lead to conclusions about the processes that caused the changes. The use of remote sensing and GIS within the coastal environment is very diverse with a multitude of applications and research efforts currently being undertaken. Successful applications have been undertaken in meteorology and oceanography, as well as over land areas. However, applications in the coastal zone defined as the region from the 200 m bathymetric contour out in the ocean up to the 200 m elevation height of land above

sea-level (Cracknell 1989, 1999), have been characterized as being more difficult and less successful (Eleveld 1996, Cracknell 1999). This difficulty is largely attributed to problems of scale and resolution. For example, using Landsat imagery and aerial photography, Dolan (1978) investigated the relationship between historical shoreline change and coastal orientation for a portion of the mid-Atlantic coastline. High correlations were found for the barrier island segments analyzed, but were not consistent from island to island. Wieneke (1991) expressed that coastal research required a high spatial resolution in conjunction with a high temporal resolution power to detect and study coastal landforms, processes, systems, patterns, and resources.

The dune field is a very dynamic system that stores and releases sediment through the interaction of various processes. This lead van der Wal (1996) to suggest that a finer resolution digital terrain model (DTM) would be helpful in the planning and engineering of a rolling dune system in the Netherlands. The PARALLEL model (van der Wal 1996) in which a DTM is a product, was designed to help quantify the morphometry of a foredune. Volumetric changes of dunes along the Outer Banks of North Carolina were analyzed by Andrews (1998) and Woolard (1999). Andrews (1998) surveyed a 150 m by 40 m portion of the dune line in the Coquina Beach vicinity to study the changes that occurred at a monthly interval for a period of one year. He developed a DEM for his study area for each monthly survey. The DEM was derived through interpolation of a set of height measurements and locations. The monthly DEMs were then imported into a GIS where erosion and depositional analysis was carried out.

Manual surveys, such as that used by Andrews (1998), can be very time-consuming, which limits the areal extent and scope of the study. The emergence of LIDAR surveys allows for a quick capture of highly accurate topographic data over large spatial extents. An overview of the LIDAR sensor and its operational and technological considerations is discussed next.

LIDAR

A LIDAR system operates on the basis that a range measurement can be derived from the time difference between a laser pulse sent from a transmitter and a back-scattered laser echo received by a receiver. LIDAR systems have been used in a large number of applications around the world (e.g., Krabill 1995, McLean and Freeman 1996, Mittenzwey 1997, Wright et al. 1997, Dubayah, 2000, Hwang et al. 2000, Krabill et al. 2000, Brock et al. 2002), however the development of suitable strategies for data collection and processing of LIDAR data still needs to be addressed (Huising and Pereira 1998). Careful details must be acknowledged and considered from the calibration and testing of the sensor before a data collection mission is flown, to the filtering and processing of the data afterwards.

An airborne LIDAR system is typically comprised of three essential parts, the LIDAR sensor, a Global Positioning System (GPS), and an Inertial Navigation System (INS). The GPS provides an accurate position of the sensor and the aircraft while in flight. The INS detects errors presented by the roll, yaw, and heading of the aircraft during data acquisition. Lasers with different wavelengths are used for various data acquisition. Using the GPS and INS, the location and range measurements made by the

transmission of lasers can be of high accuracy. This has allowed for data capture of surface height measurements of phenomena such as the ground surface, trees, dunes, waves, and man-made features (such as a building) (e.g., Krabill 1995, McLean and Freeman 1996, Mittenzwey 1997, Wright et al. 1997, Dubayah, 2000, Hwang et al. 2000, Krabill et al. 2000, Brock et al. 2002).

It should be noted that because an airborne LIDAR sensor can create (measure) height (elevation) at very high (spatial) resolution, multiple elevation values could be found within a resolution cell or pixel. An example of this multiple-z problem occurs, in an urban area where the laser system may produce measurements from the top of a building, along the middle side of the building, and the ground just beside the building. The capture of multiple z values can also occur in vegetated areas due to LIDAR measurements (echoes) from the top of tree canopy, branches, middle part of a tree trunk, or bottom part of the trunk. Thus, difficulties occur when trying to determine the source of the backscattered echoes. Attempts to extract meaningful ground surface topographic data from the LIDAR data can become a grueling and laborious task because extracting and removing the buildings and trees from the LIDAR data is not an easy job (Huising and Pereira 1998, Kraus and Pfeifer 1998). Filtering algorithms and automatic and manual extraction/deletion methods coupled with aerial photography and actual ground truthing have been used to aid the removal of the unwanted (above ground surface) features. Researchers are still searching for better/optimal solutions. For example, averaging all z values within a resolution cell was recommended for handling the multiple-z values on beach and dune areas (<http://www.csc.noaa.gov/crs/tcm/index.html>).

Satisfactory products have been derived using LIDAR sensors equipped with software that identifies and removes vegetation based on the percentage of shots that bounce back from the foliage. Also particular types of LIDAR sensors that can discriminate between the multiple returns of a single pulse and others have been tested, and could potentially resolve the multiple-z value issue (Stone 1999).

Mapping Beach Topography with Airborne Topographic Mapper

In 1995, NASA flew a survey using an Airborne Topographic Mapper (ATM) to measure beach topography in the northern portion of Assateague Island, Maryland. The National Park Service conducted a simultaneous ground survey where accuracy assessments of the LIDAR data were found to be within ± 15 cm (Krabill 2000). Other accuracy assessments of the ATM sensor were conducted at Duck Field Research Facility on the Outer Banks of North Carolina, as well as in comparison with five surveys conducted by four other researchers, all using state of the art techniques to acquire elevation measurements (Brock et al., 1999). The results of differences between surveys were of less than 10 cm in four cases, and of less than 15cm for the other survey (Brock et al. 1999). These results demonstrated the usefulness of using the ATM surveys to capture coastal topography that is as good or better than traditional methods (Brock et al., 1999). The ATM-II (Figure 4a) developed from the ATM consists of a spectra Physics TFR laser transmitter that is 7 ns wide, 250 micro-joule pulse at a frequency doubled wavelength of 523 nm in the green spectral region at a pulse rate of 2,000-10,000 Hertz (Krabill et al. 2000). The ATM-II was flown on a NOAA DeHavilland DHC-6 Twin Otter aircraft. The aircraft flies approximately 700 m above the surface at a speed of 60

m/s. The scanning pattern on the ground is of an elliptical manner with a swath width of approximately 300 m (Figure 4b). Approximately three thousand to five thousand spot elevations are collected per second as the aircraft flies over a beach (<http://www.csc.noaa.gov/crs/tcm/index.html>). Using differential kinematic GPS post-processing allows for determining the aircrafts trajectory to within 5 cm for accurate registration of LIDAR measurements to the ground surface (Krabill et al. 1987). Brock et al. (2000) expressed that the use of LIDAR point measurements in creating a 1-meter cell dimension does not introduce any real loss of accuracy in the horizontal positioning. In October of 1996 a joint effort between NASA and NOAA was initiated to provide an accurate baseline topographic survey of beaches on the east coast of the United States between Delaware and South Carolina (Wright et al. 1997). The survey of approximately 600 km of coastal beaches provided vertical elevation results with an accuracy of around ± 10 cm (Wright et al. 1997).

In response to the development of using airborne laser beach mapping technology, the Airborne LIDAR Assessment of Coastal Erosion (ALACE) Project emerged. It was a joint effort of NASA Wallops Flight Facility, Center for Coastal Geology of the USGS, and NOAA (<http://www.csc.noaa.gov/crs/tcm/index.html>). Its goal was to provide highly accurate topographic information primarily of the beach face and dune field. Since then shorelines have been mapped with this LIDAR system in a variety of locations along the eastern U.S. coastline, west coast beaches, and portions of the Great Lakes (<http://www.csc.noaa.gov/crs/tcm/index.html>).

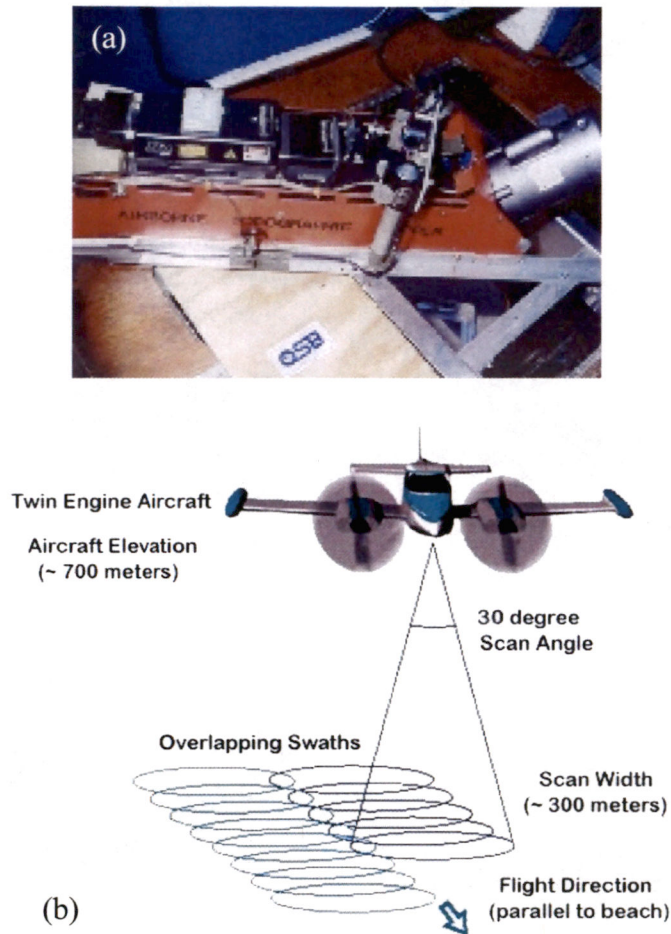


Figure 4. The ATM II sensor (a) and general LIDAR flight operation parameters (b).

The LIDAR data gathered through ALACE, is provided to NOAA's Coastal Services Center (NOAA/CSC). The NOAA/CSC archives, administers, and distributes the data to researchers, coastal managers, and the general public for the monitoring and studying of coastal beaches. LIDAR data is accessible on the Internet by a web-based application named as the LIDAR Data Retrieval Tool (LDART). LDART is an interface that allows for the distribution of the data in a variety of output formats such as ASCII

text, binary raster, geotiff, and contours. The output data, through LDART have been processed to level two of quality assurance/quality control (QA/QC) (<http://www.csc.noaa.gov/crs/tcm/index.html>). The level 2 outlier removal process involves plotting the level 1 data by latitude and elevation to define upper and lower elevations limits for valid measurements. The conversion of LIDAR data into products helps assist users in assessing the dynamic morphological changes that occurred along these coastlines.

Woolard (1999) used LIDAR data to derive DEMs for the coastal dunes on the Outer Banks of North Carolina. He analyzed the DEMs of the dune line at varying resolutions from 1 m by 1 m to 20 m by 20 m in differential study areas from 20,000 m² to 400,000 m². The use of directional statistics in calculating the mean standard deviation of the bi-directional angle of the slope and aspect characteristics of a DEM was implemented to provide a framework for understanding topographic complexity and variability. He found that to characterize coastal dunes in the Coquina Beach area and to analyze volumetric change of dunes accurately the spatial resolution of about 1 to 2 m was needed for the DEMs.

Sallenger et al. (1999) monitored coastal changes of Pacific west coast beaches in response to an El-Niño climatic cycle using beach morphological data gathered from LIDAR. LIDAR derived DEMs greatly enhanced the insight into the dynamic processes that occur in this particular coastal environment and over various spatial scales (Sallenger et al. 1999). Sallenger (1999) provided a storm impact scale that helps describe the processes and magnitude of changes that occur to barrier islands for particular storm

events. The coupling of calculated wave run-up and LIDAR data for examining the vertical dimensions of the coastline could assist in categorizing each type of four impact regimes. The scale was useful for analyzing storm impacts both along and between barrier islands of varying relief discriminating four impact regimes; swash regime, collision regime, overwash regime, and inundation regime. Brock (1999) compared surveys of airborne topographic data for Assateague Island, MD, Duck, NC, and the west coast. The study of high density and detailed surveys obtained through LIDAR technology demonstrates that seasonal changes in coastal morphology could be quantitatively calculated for the continental scale of North America (Brock 1999).

Meredith et al. (1999) evaluated hurricane-induced erosion between 1997 and 1998 along the entire North Carolina coastline utilizing DEM data derived from LIDAR data. They concluded that the northern barrier islands of North Carolina showed greater sediment loss than those of the middle and southern portions of the state (Meredith et al. 1999). In particular, northern islands show long erosional sections of beaches and dunes with small pockets of accretion, while the middle sections exhibit more of an alternating pattern of erosion and accretion with very little net volumetric change overall. The southern beaches' volumetric change was somewhat different due to substantial beach nourishment projects performed between 1997 and 1998 data acquisitions. Beaches exhibited an accretional state where beach nourishment was performed, whereas areas not nourished showed higher erosional results (Meredith et al. 1999).

It should be noted, however, that research using DEMs derived from LIDAR data has been limited because it is a fairly recent technology and it can potentially generate

huge volumes of data. Also data availability and temporal resolution are significant issues. Unless a data acquisition mission is flown immediately before and after a storm/hurricane event, no assumptions can be made about the impact of that event. The majority of LIDAR data presently available is not collected at this temporal resolution. The extent of the geographic study area and spatial resolution of DEMs are directly related to the resulting data file size. For instance for a given study area if the spatial resolution of the DEM data is reduced to one half, the file size is quadrupled. The available data storage that an image processing system possesses greatly affects the capabilities and amount of data that can be analyzed. All of these factors have affected the progress made in research using LIDAR data in the coastal environment.

CHAPTER 3

ANALYTICAL APPROACHES

Study Area

North Carolina's coastline is part of a unique coastal system, which is evident from the protruding barrier islands of the Outer Banks and the cusp shaped forms that are so prominent within the shoreline (Fig. 5). North Carolina's coast resides in what is considered a passive margin coastline or one that is tectonically inactive. The coastline can be subdivided into two distinct provinces, a northern and a southern. The two provinces can be delineated by drawing a line from approximately Kinston to Cape Lookout, North Carolina (Riggs et al. 1998). The barrier island systems within these two provinces vary greatly in relation to the underlying geologic framework (Riggs et al. 1998). Sediments in the southern province can be characterized with older harder rock units dating to the Upper Cretaceous and Pliocene with a 1.47 meter per kilometer average slope while the northern province is associated with much younger softer sediments from the Quaternary age which began approximately 1.7 million years ago with an average slope of 0.09 meter per kilometer (Riggs et al. 1998). Many differences can be found in relation to these two provinces such as wave energy, tidal amplitude, estuarine size, number of inlets, and length of islands (Riggs et al. 1998).

An approximately 71 km stretch of coastline consisting of five barrier islands is the study area. The islands (Figure 5) are oriented at about 45° off the north direction, with Topsail Island at the northern extent and Masonboro Island at the southern extent. Topsail Island, Figure Eight Island, and Wrightsville Beach are barrier islands that have

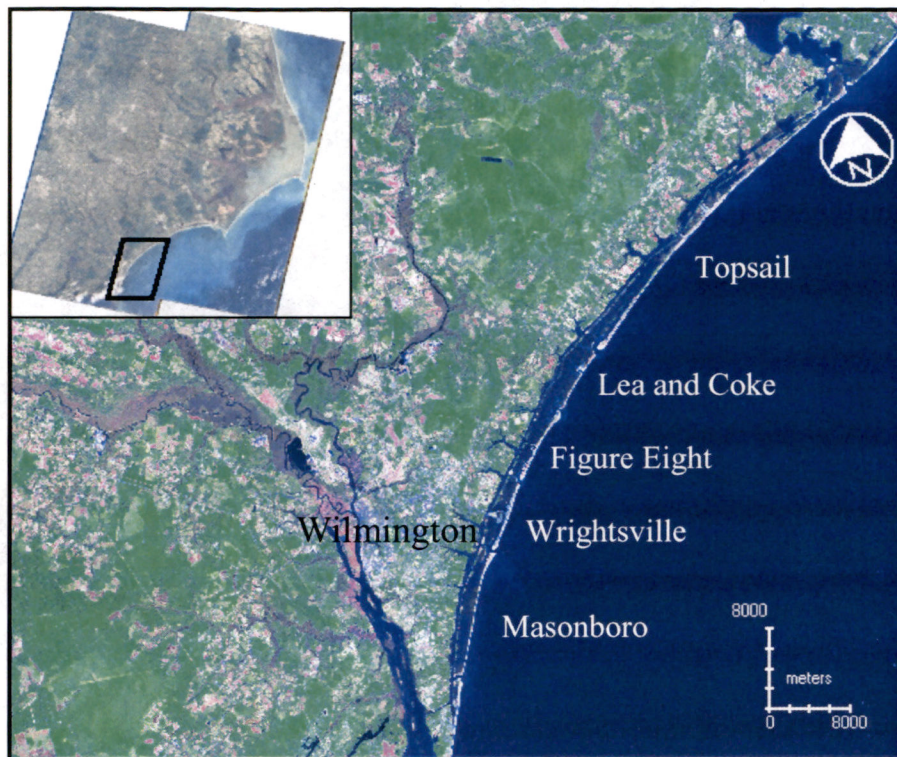


Figure 5. Study area consists of five barrier islands in the southern portion of the North Carolina coastline. The islands are near Wilmington, North Carolina. TM imagery is used as the background.



Figure 6. A digital visualization scene of the Old Topsail Inlet closure site (white arrow) produced by combining LIDAR derived DEMs (with a vertical exaggeration of 10) and USGS Color Infrared Digital Orthophoto Quarter Quads.

experienced rather dense development over the last few years. Lea Island, Coke Island, and Masonboro Island have been left in an almost natural state with overwash dominating a large majority of these barrier islands. In this study, because Old Topsail Inlet closed up (Fig. 6) between 1997 and 1998, original Lea Island and Coke Island, are considered as one island, Lea and Coke Island.

Dataset

Between 1997 and 2000, there were four annual LIDAR data acquisitions over the study area (Table 1). The 1997 data set was acquired on September 21. The second data acquisition mission was flown on September 5, 1998 just a few days after the passage of Hurricane Bonnie (Figure 7a). Bonnie made landfall in the Wilmington (North Carolina) vicinity on August 26, 1998 as a minimal category three storm. During the fall of 1999, the North Carolina coastline was directly affected by two hurricanes, Dennis and Floyd (Figure 7b-c). Hurricane Dennis, resembling a northeaster, stalled just off the Outer Banks and battered the coast for about five days before making landfall near Cape Lookout on September 4, 1999. Floyd made landfall in the Wilmington area as a category two storm on September 16, 1999. The third LIDAR data-gathering mission was flown on September 18, 1999 just following the passage of the two hurricanes. The last LIDAR data was acquired on August 2 and 3 of 2000. No hurricanes directly impacted the North Carolina coast since the 1999 data acquisition.

Table 1. Dates of ATM flight surveys and Hurricane's landfall		
	<i>ATM survey</i>	<i>Hurricanes</i>
<i>Flight #1</i>	9/21/97	--
<i>Flight #2</i>	9/5/98	Bonnie 8/26/98
<i>Flight #3</i>	9/18/99	Dennis 9/4/99 & Floyd 9/16/99
<i>Flight #4</i>	8/2-3/00	--

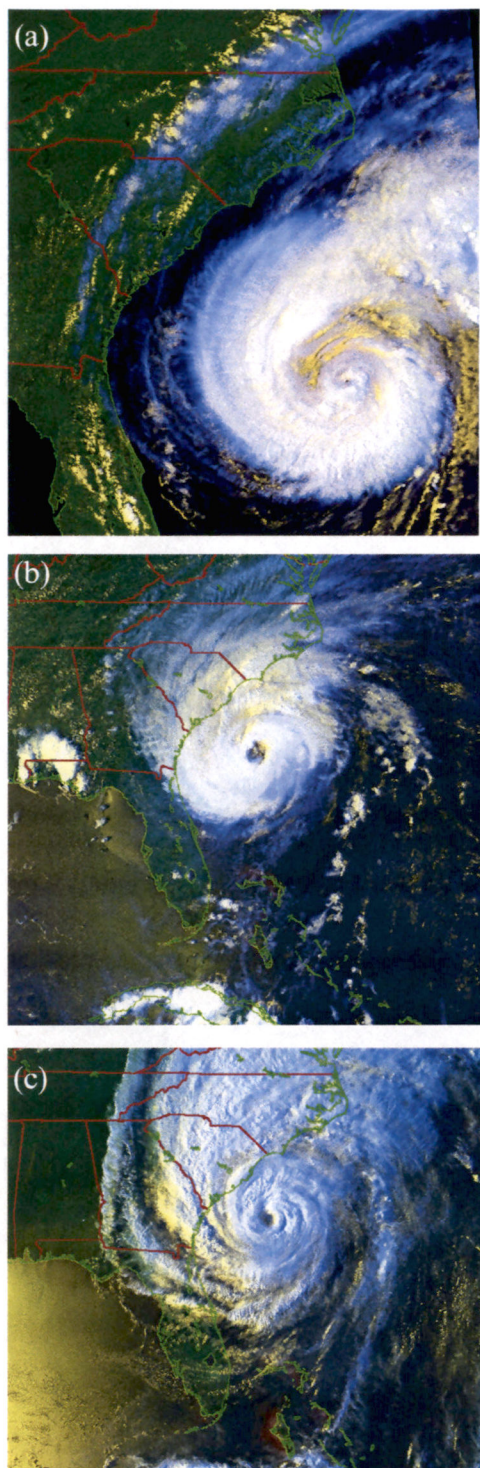


Figure 7. AVHRR imagery of hurricanes that directly affected the study area; (a) Bonnie (b) Dennis and (c) Floyd

Using the collected LIDAR data, DEMs of 1997, 1998, 1999, and 2000 were created for the study area, respectively. The DEMs represent the topography of the study area at the time of data acquisition. Resolution of the DEMs was 1.5 m by 1.5 m, with a vertical resolution of 0.10 m. Also, during the creation of DEMs, if there were multiple vertical (z) values in a cell, all values were averaged to create one z value for that cell (<http://www.csc.noaa.gov/crs/tcm/index.html>), and if there were no data points in a cell, an inverse distance weighting (IDW) method was used to interpolate a z value for that cell from nearby cells that contain z values. Finally, all the DEMs were geo-referenced to the same coordinates using the World Geodetic System (WGS) 84 model as spheroid and North American Vertical Datum (NAVD) 88 as vertical datum. NAVD 88 depicts mean sea level as zero. The projection is Universal Transverse Mercator (UTM).

Data Derivation

To facilitate the analysis of topography and topographic change (erosion, deposition, or no change) areas of interest (AOIs) on each island were created. Each AOI designated a particular segment of coastline and consisted of the primary portion of the dune line and dry beach where the processes of erosion and deposition can be best detected and studied. The AOI also allowed for exclusion of areas of significant vegetation, structures such as houses and piers, variability in shoreline position, and wave activity that may add significant error into the volumetric analysis. Lastly, each AOI covered approximately the same location and portion of coastline for each yearly analysis. The spatial and surface profiles of the DEMs, slope and relief data of the DEMs, panchromatic and video data acquired concurrently with LIDAR acquisition, USGS's

color infrared (CIR) digital orthophoto quarter quads (DOQQs), and ground observations were used to help in the identification and creation of each AOI. In particular, the spatial and surface profiles assisted in comparing the accuracy of the DEMs between each yearly survey. The slope and relief data, panchromatic and video data, CIR DOQQs, and ground observations helped identify areas where the morphology of a barrier island was not well depicted in the DEMs alone. The number of AOI's delineated on each barrier island for each time interval is shown in Table 2.

Table 2. The number of area of interest (AOI) constructed to designate particular portions of islands for analysis, excluding those where no data was acquired.

Islands	1997-1998	1998-1999	1999-2000
Masonboro Island	16	16	16
Wrightsville Beach	10	10	10
Figure Eight Island	12	12	12
Lea and Coke Island*	15	13	13
Topsail Island	46	46	46
<i>Total</i>	<i>99</i>	<i>97</i>	<i>97</i>

*Due to the variation of ground coverage of the LIDAR, DEMs for two AOIs of Lea and Coke Island are not available in 1999 and 2000.

Using DEM data pairs between years 97-98, 98-99, and 99-00, a method was created to analyze, on a cell-by-cell basis volumetric changes due to erosion and deposition within each AOI for the five barrier islands. There were two major steps: 1) differencing the vertical value of year 2 (current) to year 1 (previous), and 2) computing the volume. A positive, negative, or zero volumetric value at a location or cell indicated the amount of deposition, erosion, or no change that occurred within that cell. The

individual cell values were then totaled for each AOI giving total volumes of deposition, erosion, and net-change for each AOI, and each island. Dividing the net change by the area of each AOI normalized the data for each AOI. This normalization of net changes allowed AOIs with different sizes to be compared. Then for each AOI, the spatial patterns of erosion, deposition, and no change were studied between each time interval.

This thesis research examined and compared portions of natural undeveloped barrier islands to sections of developed islands found within the study area. Nordstrom's (1995) and Jackson et al.'s (2000) discussions on how human intervention affects the dynamic responses of barrier islands was used to guide coastline delineations defined for volumetric analysis. Various management practices have been used along barrier islands, including beach nourishment, the use of jetties at inlets, the placement of groins, and efforts to create dune lines. In order to account for these different management practices, the AOIs were classified as developed or undeveloped or whether it has been the recipient of artificial beach fill between data acquisitions (Table 3).

Table 3. The number of AOIs constructed to designate sample groups based on particular management practices, excluding inlets.

Management Practices	1997-1998	1998-1999	1999-2000
Beach nourishment	11	--	7
Dune modification	18	19	36
Developed beach	35	43	18
Undeveloped beach	24	18	26
Jetty	2	2	2
<i>Total</i>	<i>90</i>	<i>82</i>	<i>89</i>

AOIs were classified as developed if commercial establishments, roads or other cultural features were present, and no additional sediment was supplied to either the beach or dune between LIDAR surveys. Zones where there was substantial modification or creation of a dune line were represented as dune modification. AOIs where a large addition of sediment to extend or build up the beach was characterized as beach nourishment. Jetty zones were designated if hard stabilization engineering significantly influences the coastline. An AOI was classified as undeveloped if overwash is evident or if almost no human intervention can be found present along a coastal reach. Also, it is possible that an AOIs category can be changed through time. For example, a developed beach may have undergone a beach nourishment program in the second yearly interval; the AOI was grouped into the beach nourishment category. This is one reason that the number of AOIs in each category varies in each time interval (Table 3). Therefore, the AOIs not only delineated where morphologic change occurred, but also helped identify management practice zones used on barrier islands.

Analysis

Three tests of analysis of variance (ANOVA) were executed to examine if net-volumetric change per unit area of categorically designated AOIs was statistically different from each other. The assessment of the response each particular island exhibits over three consecutive yearly intervals was the first ANOVA test executed. Next, examination for significant differences between all the islands in the study area within the temporal frame of each yearly interval was investigated. Morphologic change that occurred on barrier islands were then inspected based upon how the barrier island was

managed. Inlet zones, AOIs where complete data coverage was not obtained, and AOIs affected by jetties were not included within the ANOVA testing of management practices. These particular AOIs were deleted from the analysis, because the inclusion of these samples would lead to inaccurate results in the statistical computations.

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CHAPTER 4

RESULT AND DISCUSSION

Spatial patterns of erosion, deposition, and net change have been analyzed and illustrated. A presentation of volumetric changes of specific yearly intervals is performed based on the processing of DEMs derived from LIDAR for each island. Volumetric derived change is then normalized and discussed. This chapter then concludes with the implementation of the ANOVA method for comparing and contrasting portions of coastline.

Spatial pattern of morphologic change

The distribution of net volumetric changes for each study period is presented in Figure 10. Between 97-98, erosion predominated along the lower beach face on the majority of the islands, such as Masonboro Island (Figure 9). This erosion may be attributed to the effects of Hurricane Bonnie that made landfall in the Wilmington vicinity on August 28, 1998. Despite the hurricanes, significant gains did occur in locations where beach nourishment was conducted such as near the pier on Wrightsville Beach (Figure 10) and on Masonboro Island where a small portion of the beach was nourished as part of a bypass project associated with Masonboro Inlet. The northern portion of Wrightsville Beach, not included within the nourishment project, however, experienced noticeable loss of sediment along the shoreline. The two nourishment projects and closure of Old Topsail Inlet can be recognized as the three depositional spikes found in Figure 8a, a bar graph of total net change of each AOI. Two predominantly undeveloped islands Lea and Coke and Masonboro had significant

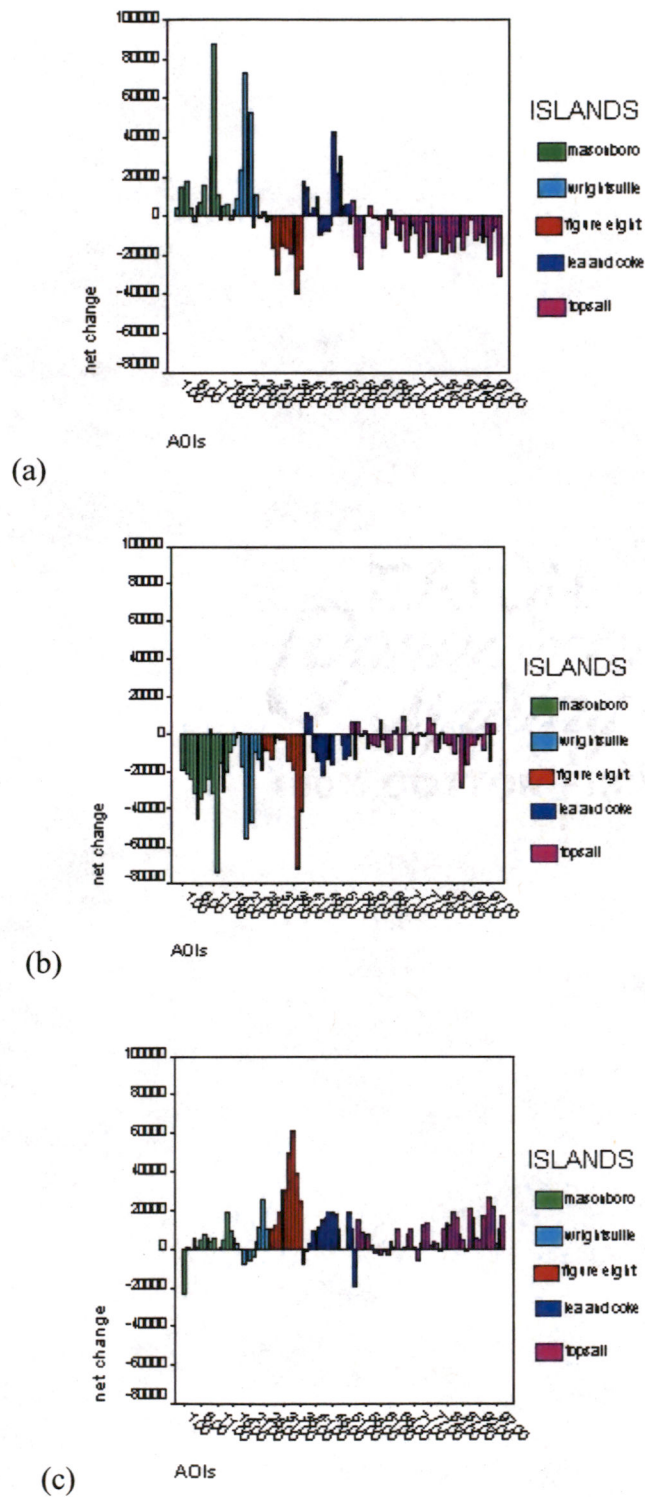


Figure 8. Volumetric net change (m^3) of each AOI at each yearly interval; (a) 1997-1998, (b) 1998-1999, and (c) 1999-2000.

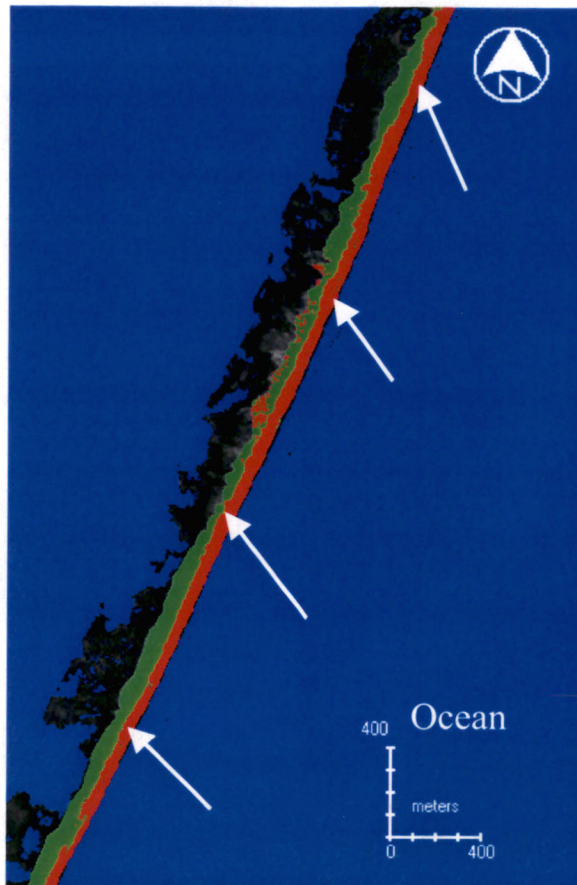
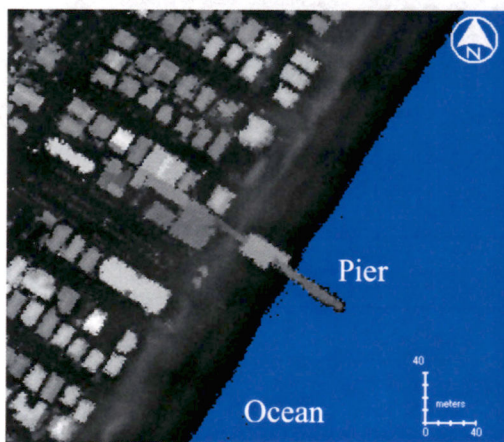
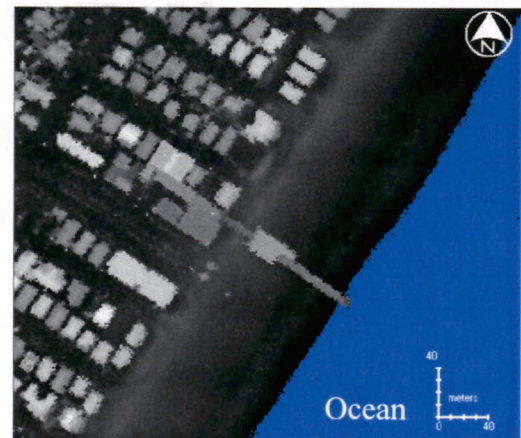


Figure 9. White arrows point to shoreline erosion (red) detected along the lower beach face of Masonboro Island between 1997 and 1998. Deposition (green) can be attributed to overwash fans.



(a) DEM in 1997.



(b) DEM in 1998.

Figure 10. Beach nourishment performed on Wrightsville Beach between 1997 and 1998 extended the beach seaward. Houses and real estate properties behind sand dunes looked roughly like white rectangles oriented by a row and column pattern. Light tones show high elevation, and dark tones low elevation.

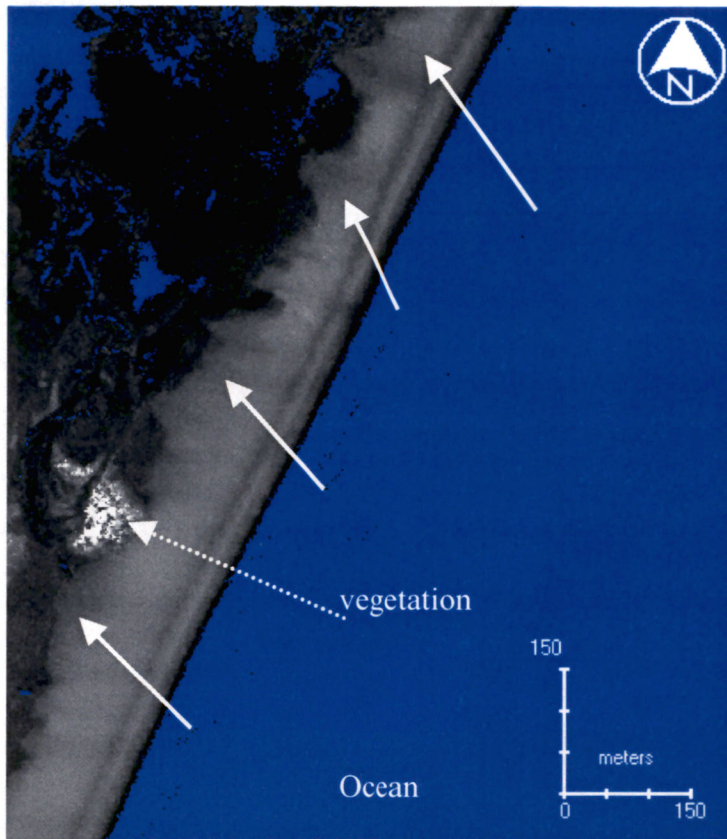
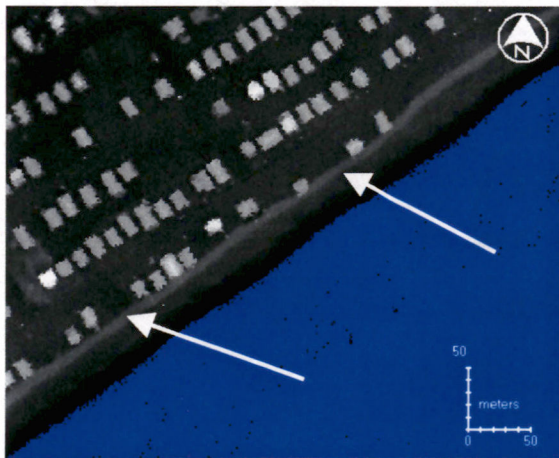


Figure 11. Overwash fans present on Masonboro Island in 1998 DEM are pointed to by white arrows.

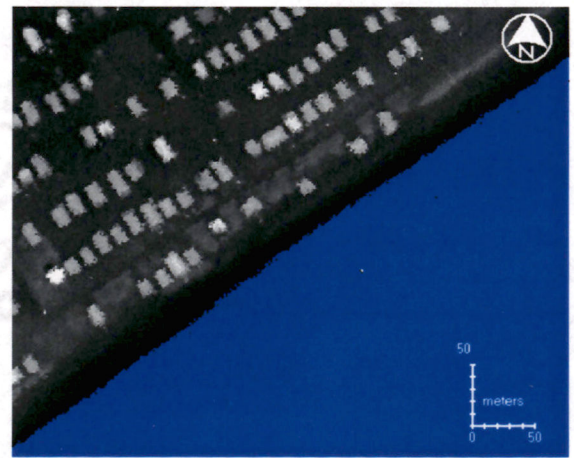
depositional sites in association with overwash fans (Fig. 11) a direct result of allowing the coast to respond in an almost natural manner. The overwash fans are an apparent morphologic feature present along the majority of Lea and Coke and Masonboro. The depositional AOIs (as seen in Table 4) of these two islands can be largely attributed to overwash. Overwash appears to help in sustaining an island's budget of sediment when compared with the erosive environments of developed Figure Eight and Topsail, which did not undergo a beach nourishment project during this time interval. In varying locations along Topsail Island, deposition to the dune line was apparent. Also, in other sites on Topsail, the dune line was destroyed in response from the effects of Bonnie

(Figure 12). On Figure Eight Island, there were more places of erosion than deposition (Table 4).

During 98-99 period, significant erosion along the lower beach face caused mainly by Hurricanes Dennis and Floyd was apparent within the majority of the study area (Figure 13). Substantial erosion also occurred at two locations on Wrightsville Beach. One was located in the center of the island where the largest amount of beach nourishment was performed between 97 and 98, and the other at the northern end of the island near Mason Inlet as seen in Figure 8b. Deposition was again noticed in response from overwash in locations along Masonboro and Lea and Coke Islands (Figure 14). Scattered sites of deposition were present along Figure Eight resulting from the addition of sediment to the dune line (Figure 15). Erosion of the foredune on Topsail Island was noticeable in numerous locations, but the sediment being eroded appeared to be redistributed in depositional sites in the corresponding back beach (Figure 16).



(a) DEM in 1997



(b) DEM in 1998

Figure 12. White arrows point to a dune line that was present in 1997 on Topsail Island, but destroyed due to Hurricane Bonnie in 1998.

Table 4. Number of AOIs Experiencing Erosion or Deposition by Barrier Islands
between Three Time Intervals.

1997- 1998		
Islands	<i>Erosion</i>	<i>Deposition</i>
<i>Masonboro</i>	2	14
<i>Wrightsville</i>	3	7
<i>Figure Eight</i>	11	1
<i>Lea and Coke</i>	5	10
<i>Topsail</i>	41	5
Total	62	37

(a)

1998- 1999		
Islands	<i>Erosion</i>	<i>Deposition</i>
<i>Masonboro</i>	15	1
<i>Wrightsville</i>	9	1
<i>Figure Eight</i>	12	0
<i>Lea and Coke</i>	11	2
<i>Topsail</i>	30	16
Total	77	20

(b)

1999- 2000		
Islands	<i>Erosion</i>	<i>Deposition</i>
<i>Masonboro</i>	3	13
<i>Wrightsville</i>	5	5
<i>Figure Eight</i>	2	10
<i>Lea and Coke</i>	1	12
<i>Topsail</i>	10	36
Total	21	76

(c)

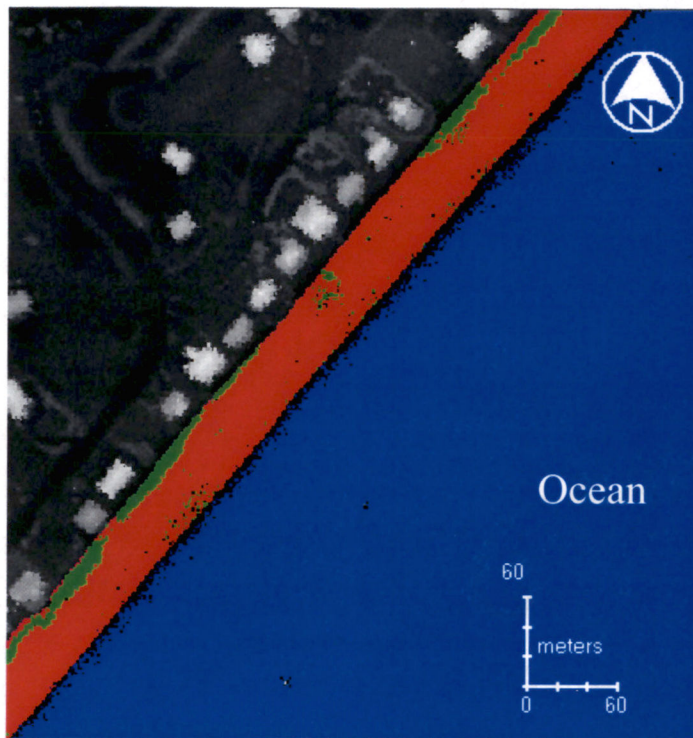


Figure 13. An example of erosion (red) along the lower beach face occurred on Figure Eight Island between 1998 and 1999. Deposition is depicted as green.

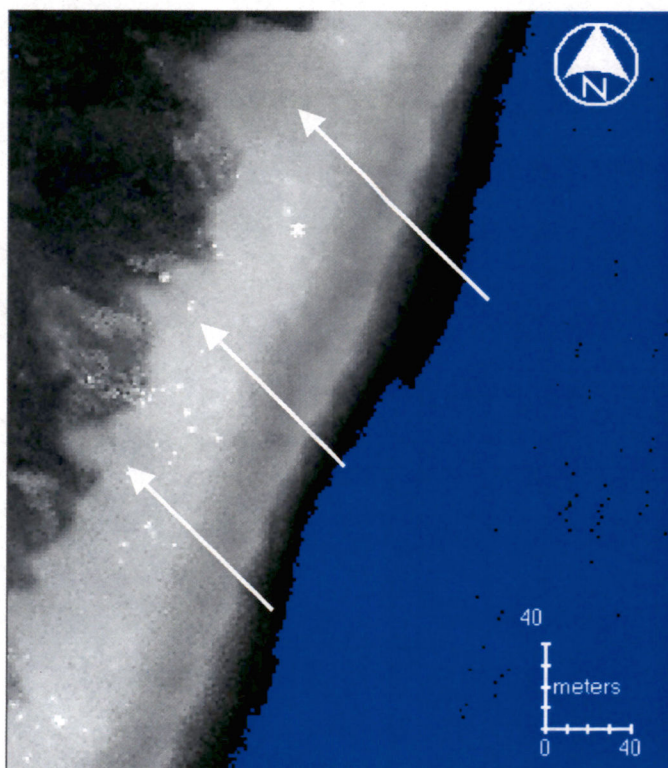


Figure 14. Overwash fans present on Masonboro Island in 1999 DEM are pointed to by white arrows.

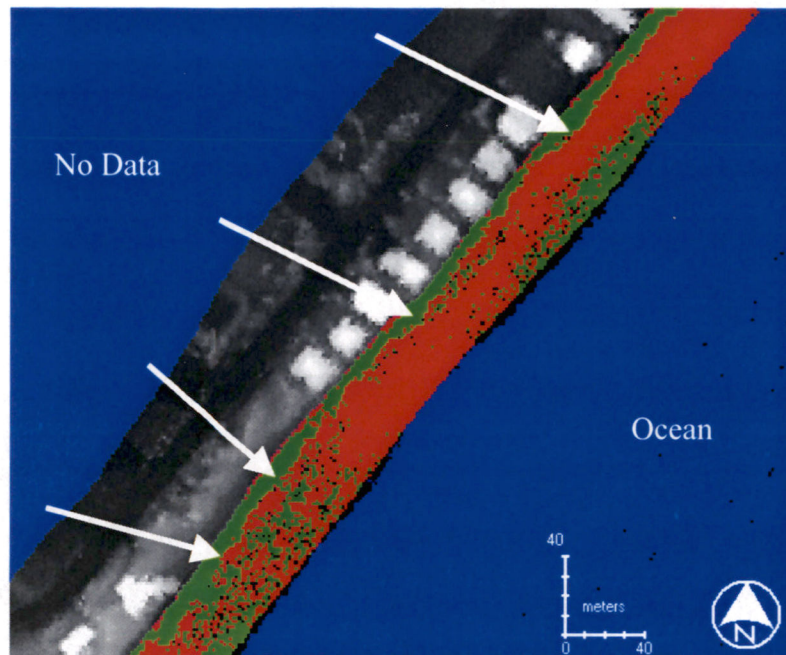


Figure 15. Spatial patterns of erosion (red) and deposition (green) detected between 1998 and 1999 on Figure Eight Island. White arrows show location of dune nourishment.

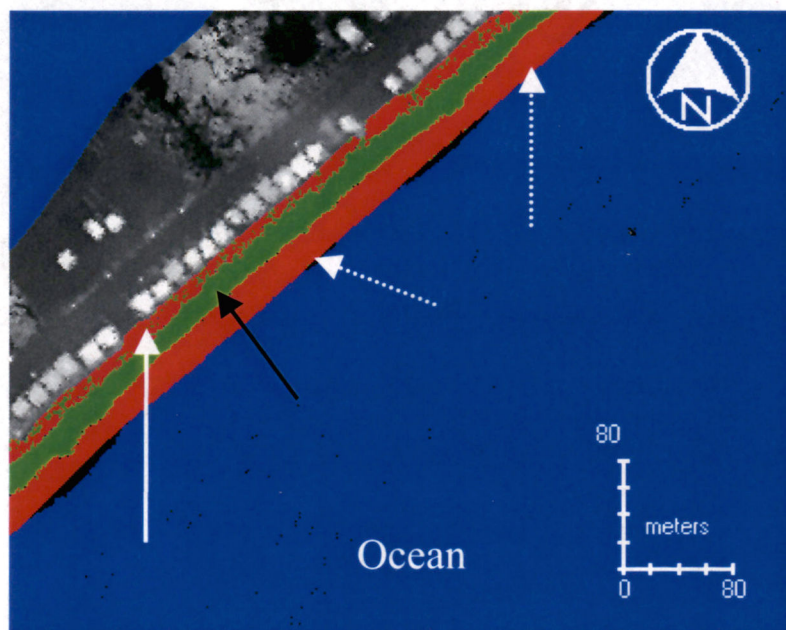


Figure 16. Dotted white arrows point to erosion (red) along the lower beach face of Topsail Island between 1998 and 1999. The solid white arrow shows erosion along the dune line, while the black arrow shows deposition (green) in the back beach.

This may be attributed to the lack of major storms and hurricanes during 99 and 00. Accretion and deposition were found in most AOIs for the period 99-00 (Table 4 and Figure 8c). The shoreline accretion and deposition was an opposite morphologic response than what was noticed at the same spatial locations before; the shoreline was highly erosive in 97-98 and 98-99 periods. On Masonboro and Lea and Coke islands, most of the shoreline accretion and deposition occurred on the foreshore and lower back beach as seen in Figure 17. This was due in part by the lack of overwash occurring in relation to a decrease in storm activity. Masonboro and Lea and Coke Islands, both not nourished, also show higher depositional patterns than non-nourished (during 99 and 00) highly developed Wrightsville Beach (Table 4). Wrightsville Beach demonstrated actually some losses of shoreline along the middle and southern portions of the island, excluding the most southern end where a jetty is located to help trap sediment. Even though the northern portion of the island, in the Shell Island Resort vicinity was very erosive during 97-98 and 98-99, deposition occurred between 99 and 00. Deposition was also recognized on Figure Eight due to the beach nourishment project that was performed along the island's extent (Figure 8c and 18). Topsail Island showed alternating patterns of erosion and deposition along the extent of the island's shoreline (Figure 13c). Depositional sites were also evident in response to dune nourishment practices along Topsail.

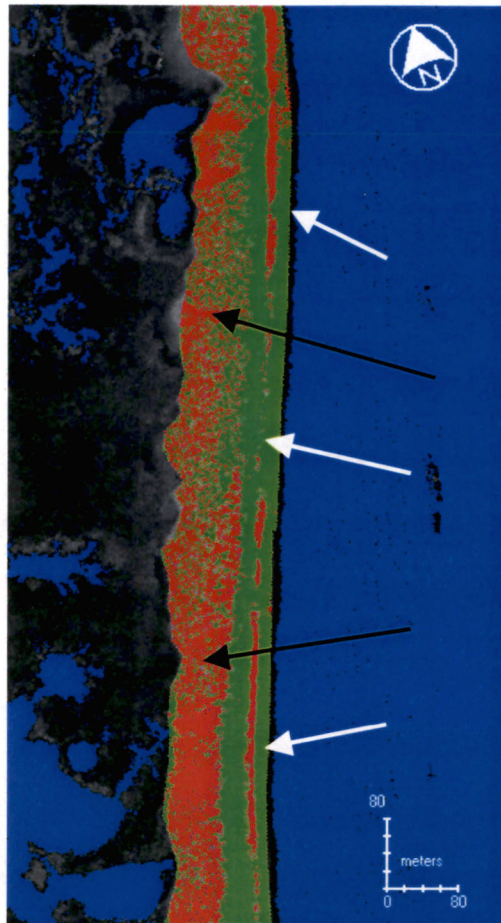


Figure 17. The white arrows show the accretion or deposition (green) along the lower beach face on Masonboro Island during 1999 to 2000. Black arrows demonstrate sediment being eroded (red) from overwash fans formed during the yearly intervals of 97-98 and 98-99.

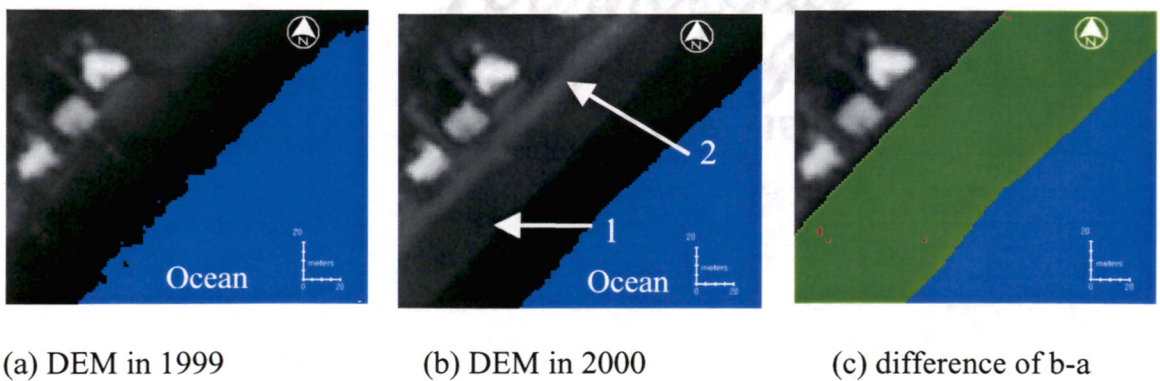
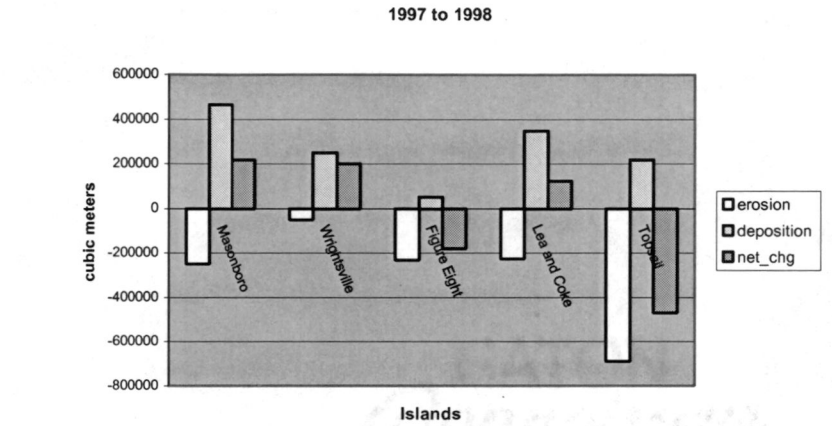


Figure 18. White arrows show the creation of a back beach through beach nourishment (1) and dune nourishment (2) of Figure Eight Island between 1999 and 2000. Image (c) illustrates the spatial extent of deposition (green) and erosion (red).

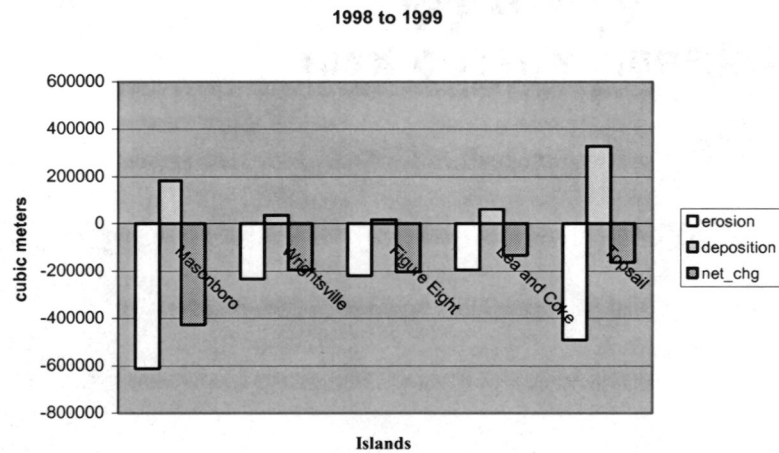
Volumetric changes of barrier islands of years 97-98, 98-99, and 99-00

To quantify the topographic changes on each island, deposition, erosion, and net-change for all the AOIs on the island was analyzed using the DEMs. Figure 19a presents the results in 97 and 98 period. Masonboro Island had the largest amount of deposition ($464,876 \text{ m}^3$) and Figure Eight Island showed the least amount of deposition ($50,409 \text{ m}^3$). Topsail Island had the largest amount of erosion ($-688,144 \text{ m}^3$), whereas Wrightsville Beach showed the least amount of erosion ($-50,515 \text{ m}^3$). Masonboro Island, Wrightsville Beach, and Lea and Coke Island experienced positive net volumetric gains. The over $200,000 \text{ m}^3$ gain on Masonboro Island could be largely attributed to the overwash caused by Hurricane Bonnie, as well as a nourishment project that occurred on a small portion of the beach. Wrightsville Beach's gain, near $200,000 \text{ m}^3$, might largely be attributed to the beach nourishment project performed along the majority of the island's extent (see also Figure 9). Lea and Coke Island's gain was in response to the closure of Old Topsail Inlet and prevalent overwash along the majority of the island. The AOI that encompasses the Old Topsail Inlet closure site demonstrated one of the greatest amounts of deposition ($45,700 \text{ m}^3$) of AOIs between 97-98. Topsail and Figure Eight, both non-nourished developed islands exhibited net volumetric losses.

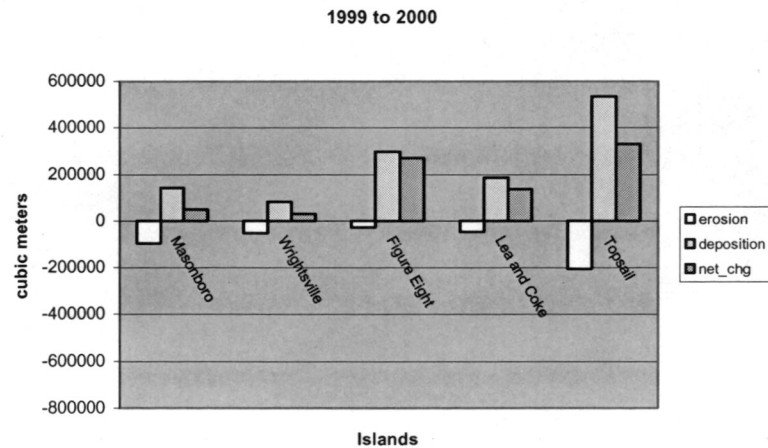
Volumetric changes for the yearly interval of 98-99 showed that all islands experienced more erosion than deposition or net losses (Fig. 19b and Table 4). The losses were most likely attributed to the impacts of Hurricanes Dennis and Floyd in 1999. In particular, Masonboro Island had the largest amount of erosion over $-600,000 \text{ m}^3$ and



(a)



(b)



(c)

Figure 19. Volumetric changes (erosion, deposition, and net change) derived from the DEMs of each yearly interval.

exhibited the greatest net loss, over $-400,000 \text{ m}^3$. Topsail Island demonstrated the highest amount of sand exchange (between deposition and erosion), most likely attributed to the island's extent (35 km long), disposal of sediment in the swash zone, dune modification projects between 98 and 99, and erosion caused by two hurricanes. Both the northerly and southerly ends of Topsail received approximately $45,600 \text{ m}^3$ of beach quality material from inlet dredging, which is disposed in the surf zone on an annual basis. Figure Eight Island underwent dune modification, but showed the lowest overall deposition (Fig. 19b). If the nourishment projects on both Topsail and Figure Eight islands were not performed, results would show these islands as being much more erosive environments. It should be noted that overwash might have possibly occurred in marsh areas along the back portion of Masonboro Island where deposition in vegetated areas cannot be easily identified by the LIDAR data. Also for Lea and Coke Island the LIDAR data might not completely cover all areas of overwash fans. Depositional rates for this particular yearly interval may therefore be somewhat less erosive than what this analysis reported.

Wind data was used to recognize the occurrence of potential coastal storms. This assisted in examining whether or not the volumetric change derived from DEMs derived from LIDAR between 1997 to 1998 and 1998 to 1999 could be largely attributed to hurricanes Bonnie, Dennis, and Floyd or are northeasters and cold fronts the larger contributors. The wind data was collected on an hourly basis from the Wilmington airport. Wind data is processed to see if thresholds of certain defined parameters are met. These parameters include a wind speed of greater than twenty-five knots, a wind direction of between 80 degrees to 210 degrees from north, and duration of at least 8

hours. The wind speed and duration parameters are derived from the deep wave forecasting curve compiled by the US Army, Coastal Engineering Research Center from equations developed by Charles L. Bretschneider (US Army Corps of Engineers 1984). This is all based upon the thought that if these parameters are met over a 40 nautical mile stretch of open ocean, the formation of a 2 meter wave height has the potential of beginning to affect barrier island beach morphology. A number of events and their magnitude based upon the Dolan/Davis Scale of Atlantic Coast Northeaster Storms (Dolan and Davis 1992) was examined and commented on.

During winter 97-98 three northeasters were recognized, two occurrences categorized as being a Class 1 and the other a Class 2 storm. In winter 98-99, four storms were detected; three classified as Class 1 and one at a borderline of Class 2 or 3 northeast storm. Based on Dolan and Davis' (1992) conceptualized intensity scale of Atlantic coast northeast storms, a Class 4 (severe) storm or greater is needed to create severe dune erosion or destruction, overwash, and the occasional inlet formation, as seen evident in our analysis during these two yearly intervals. Therefore, the majority of morphologic change that we detect based on the topographic analysis of LIDAR derived DEMs could be accredited to the hurricanes that impacted our research site in the hurricane seasons of 1998 and 1999.

From 1999 to 2000, the five islands were not affected directly by any significant storm of tropical nature. In response to the spatial location of morphologic change variations, the limitation in data coverage for the previous yearly analyses of Lea and Coke Island was not as great of an issue for 99-00. Volumetric figures for the 99-00

period resulted in more deposition than erosion or net increase to all islands (Fig. 19c and Table 4). The findings appeared to show a rehabilitation stage for the barrier islands following a series of previously stormy periods. Also, the two significant net increases of Topsail ($329,725 \text{ m}^3$) and Figure Eight ($270,519 \text{ m}^3$) should be partially attributed to either beach nourishment or dune modification projects occurring during that period.

Normalized volumetric net changes per unit area

Due to each AOI not covering exactly the same area, using volumetric net-change per area (m^3/m^2) should minimize/eliminate the effect on the analysis due to varying AOI's size and potentially better characterize the changes that occurred in each AOI. Statistical summaries of the volumetric net-change per unit length and unit area (Table 5) were calculated from each AOI of the five islands, at time intervals of 97-98, 98-99, and 99-00. All medians and means were in agreement in sign (positive or negative).

In period 97-98 (Table 5a), Wrightsville Beach had the largest median value ($0.15 \text{ m}^3/\text{m}^2$) and mean value ($0.38 \text{ m}^3/\text{m}^2$) due to a large beach nourishment project performed during 97 and 98. In contrast, Figure Eight Island had the most negative median ($-0.35 \text{ m}^3/\text{m}^2$) and mean ($-0.32 \text{ m}^3/\text{m}^2$) although Topsail Island experienced the greatest absolute loss (e.g., Figure 19a). For each island, its mean was greater than or equal to its median, thus, the distribution of each volumetric net-change per unit area may be slightly positively skewed or symmetric.

During 98-99, all medians and means were negative (Table 5b). Thus, most AOIs on each island were erosive as seen in Table 4b and Figure 20b, a graph illustrating the spatial patterns of volumetric net change per area of AOIs. By mean values, developed

Wrightsville Beach or Figure Eight Island had a greater loss of sand per unit area than undeveloped Masonboro Island or Lea and Coke Island. Topsail Island had the least median, $-0.09 \text{ m}^3/\text{m}^2$, or mean, $-0.08 \text{ m}^3/\text{m}^2$ due largely to dune modification practices performed between 98 and 99. Again based on means and medians, the distributions of volumetric net-change per unit area at Masonboro and Topsail islands may be symmetric, the distribution at Lea and Coke Island slightly positively skewed, and the distributions at Wrightsville Beach and Figure Eight Island slightly negatively skewed.

Between 99 and 00, all medians and means were positive (Table 5c). All islands had a greater number of AOIs representative of a depositional environment, except for Wrightsville Beach where there was a tie (Table 4c). Figure Eight Island showed the highest net gain, measured by a relatively large positive median ($0.44 \text{ m}^3/\text{m}^2$), and mean ($0.45 \text{ m}^3/\text{m}^2$). The gain could be largely attributed to the intense beach nourishment project performed at the island during 99 and 00 (Figure 20c). Topsail's gain, measured by median and mean volumetric net-change per unit area, and might be in part due to significant nourishment and construction of dunes, annual inlet dredge disposal, and accretion patterns during a rehabilitation phase.

Table 5. Statistical summary of net volumetric change per AOI area (m^3/m^2).

97-98	Islands	Median	Mean	Std. Deviation
	<i>Masonboro</i>	0.06	0.12	0.15
	<i>Wrightsville</i>	0.15	0.38	0.50
	<i>Figure Eight</i>	-0.35	-0.31	0.24
	<i>Lea and Coke</i>	0.06	0.08	0.18
	<i>Topsail</i>	-0.28	-0.28	0.23

(a)

98-99	Islands	Median	Mean	Std. Deviation
	<i>Masonboro</i>	-0.26	-0.27	0.14
	<i>Wrightsville</i>	-0.22	-0.37	0.34
	<i>Figure Eight</i>	-0.25	-0.37	0.37
	<i>Lea and Coke</i>	-0.25	-0.19	0.19
	<i>Topsail</i>	-0.09	-0.08	0.21

(b)

99-00	Islands	Median	Mean	Std. Deviation
	<i>Masonboro</i>	0.05	0.03	0.11
	<i>Wrightsville</i>	0.02	0.03	0.18
	<i>Figure Eight</i>	0.44	0.45	0.39
	<i>Lea and Coke</i>	0.22	0.14	0.34
	<i>Topsail</i>	0.16	0.19	0.20

(c)

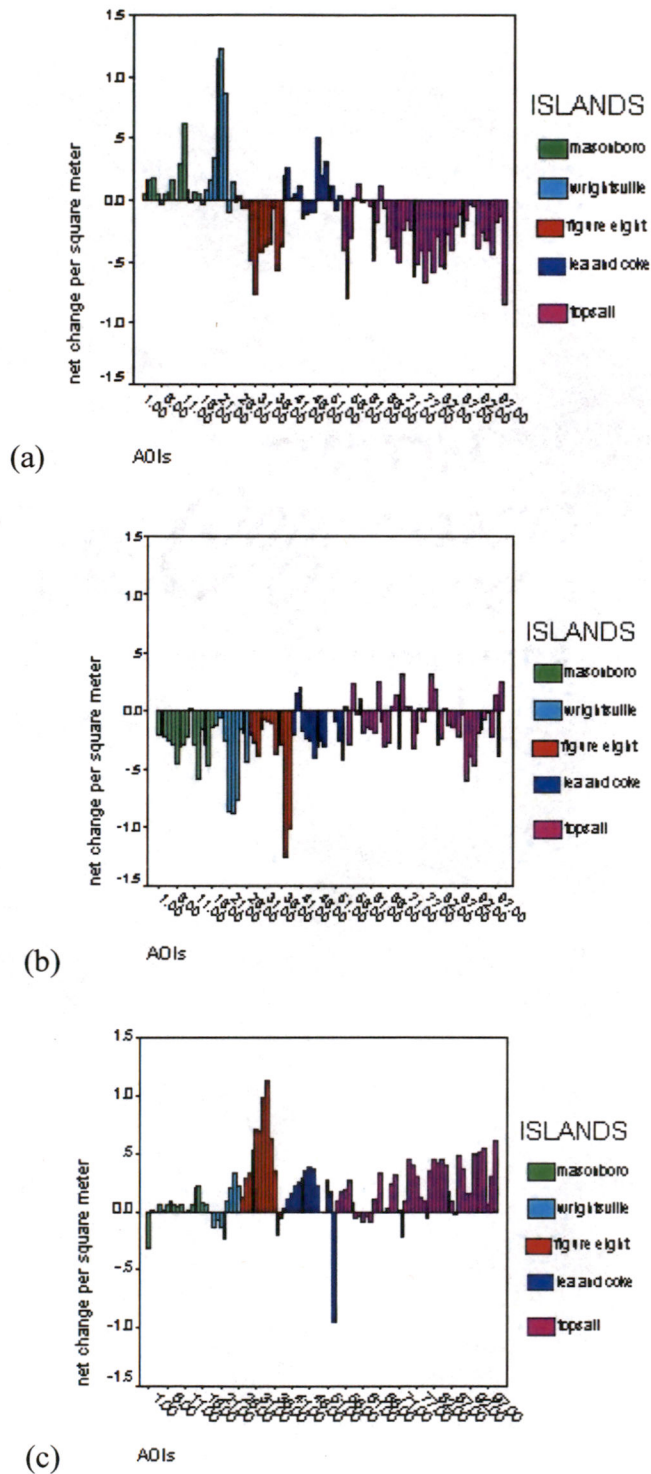


Figure 20. Volumetric net change per unit area (m^3/m^2) of each AOI at each yearly interval; (a) 1997-1998, (b) 1998-1999, and (c) 1999-2000.

It should be noted that the volumetric analysis of the yearly interval 97-98 was also performed by Meredith et al. (1999). They evaluated erosion, deposition, net change, net-change per unit length, and net-change per unit area induced by Hurricane Bonnie along the entire North Carolina coastline. (Bonnie made landfall on August 26, 1998.) For the five islands used in both studies, their results and these are similar in terms of erosion, deposition, net change, and net change patterns. However, the amount of erosion, deposition, net change, and net-change rates from this study are slightly less than those reported by Meredith et al. (1999). These differences could likely be attributed to the higher spatial resolution used in this study and the careful delineation of coastline for analyses. The 1.5 m by 1.5 m spatial resolution used in this study is thought to better depict the morphology of the beach with more detail than that of an approximately 5 m by 5 m resolution adopted by Meredith et al. (1999). The delineation of AOIs along coastline could also affect the results; the delineation determined what AOIs/areas were included in the volumetric analysis. The comparison of Meredith et al. (1999) and the results found in this thesis research yield similar patterns to that of Woolard (1999) which was an increase in the estimated amount of net volumetric change as the LIDAR derived DEM is increased to a coarser spatial resolution. This supports the conclusions of Woolard (1999) that a spatial resolution for DEMs of somewhere between 1 to 2 m is needed when trying to capture coastal topography of beaches and dunes.

ANOVA Analysis

Test on means of each island at three consecutive yearly intervals. The first set of significant tests is to see whether the means of net volumetric change per unit area of AOIs of an island differ or not when 97-98, 98-99, and 99-00 data sets are compared simultaneously. Five ANOVA tests have been conducted; one test for each island. Over the three consecutive yearly intervals, *p*-values of Masonboro, Wrightsville Beach, Figure Eight, Lea and Coke, and Topsail were 0.0%, 0.0%, 0.0%, 3.8%, and 0.0%, respectively. If a 5% significant level is used, means of AOIs of each island statistically differs. It should be noted that all the assumptions of the ANOVA test were met except the equality of variances for Wrightsville Beach. For Wrightsville Beach, a nonparametric Kruskal-Wallis test was conducted, and the result concluded that that means were different. (Kruskal-Wallis nonparametric test does not require an equal variance assumption.)

A *post hoc* contrast test option in the ANOVA can discriminate which means of net-change for yearly intervals are similar or not by providing *p*-values for each comparison (Table 6). Among 15 test cases, if a significant level of 5% is used again, there are 8 cases in which the means are statistically different, and 7 cases in which the means are statistically similar. For the 7 similar mean cases, the following are discussed. The overwash being prevalent during 97-98 and the recovery period of 99-00 may be the main cause that their means were similar at Masonboro Island. The beach nourishment project that took place on Wrightsville Beach between 97-98 might be similar to the recovery period of 99-00; their means were statistically the same. The similarity of means

between 97-98 and 98-99 time intervals at Figure Eight could be explained well by the erosive processes (Table 4), which occurred during those two periods. Also, the extensive beach nourishment project performed during 99-00 on Figure Eight Island (e.g., Figure 18) could contribute to a significantly higher mean volumetric net-change per unit area value ($0.45 \text{ m}^3/\text{m}^2$ in 99-00, see also Table 5). Thus, these means were significantly different. The Lea and Coke Island's means were statistically the same for all three yearly intervals (despite a small *p*-value of 5.1% between means of 98-99 and 99-00 intervals). It should be noted that all *post hoc contrast* assumptions were met for all 15 test cases.

Table 6. *p*-values (%) of ANOVA *post hoc* contrast tests of means between each pairs of time interval on each island.

<i>Yearly Comparisons</i>	<i>Islands</i>				
	<i>Masonboro</i>	<i>Wrightsville Beach</i>	<i>Figure Eight</i>	<i>Lea and Coke</i>	<i>Topsail</i>
97-98 vs. 98-99	0.0	0.0	92.7	7.3	0.0
97-98 vs. 99-00	21.4	11.8	0.0	97.5	0.0
98-99 vs. 99-00	0.0	6.6	0.0	5.1	0.0

Test on means of all five islands together at each yearly interval. Another three significance tests determining whether the mean of net-change per unit area of AOIs of all islands differ or not at each yearly interval were also completed; one test for each yearly interval. *p*-values of less than or equal to 0.1% were found. If a 5% significance level was employed, the five islands' means at each time interval were statically different. Again, all assumptions of ANOVA test were met except for equality of

variances. When the equality of variance assumption was not met, a nonparametric test was then performed, which showed the means are significantly different.

p-values of thirty *post hoc* contrast tests were tabulated in Table 7. During 97-98, means of volumetric net change per unit area of Masonboro Island, Wrightsville, and Lea and Coke Island were statistically similar (see also Table 5 for the means). The overwash processes occurring at undeveloped Masonboro Island and Lea and Coke Island might have a similar effect to that of the beach nourishment program performed at Wrightsville Beach; both accumulation of sand on barrier islands. Means of Figure Eight Island ($-0.31 \text{ m}^3/\text{m}^2$) and Topsail Island ($-0.28 \text{ m}^3/\text{m}^2$) were also statistically similar. Both islands were erosive, in part by not being nourished or permitting overwash to occur.

Table 7. *p*-values (%) of ANOVA *post hoc* contrast tests of means among five islands at each yearly interval

<i>Comparison between islands</i>	<i>Yearly Interval</i>		
	<i>97-98</i>	<i>98-99</i>	<i>99-00</i>
Masonboro vs. Wrightsville	17.9	86.8	1.0
Masonboro vs. Figure Eight	0.1	84.7	0.1
Masonboro vs. Lea and Coke	1.0	98.8	85.9
Masonboro vs. Topsail	0.0	27.5	30.9
Wrightsville vs. Figure Eight	0.0	1.0	0.4
Wrightsville vs. Lea and Coke	20.9	72.3	88.0
Wrightsville vs. Topsail	0.0	3.3	45.4
Figure Eight vs. Lea and Coke	0.2	70.0	4.7
Figure Eight vs. Topsail	99.7	1.7	3.8
Lea and Coke vs. Topsail	0.0	92.0	97.7

The *post hoc* contrast test of 98-99 (Table 7) reveals that mean net-change per unit area of all islands were similar except for pairs Wrightsville Beach and Topsail Island, and Figure Eight Island and Topsail Island. All islands were erosive (Figure 19b and Table 4b). Even though Wrightsville Beach, Figure Eight Island and Topsail Island were developed, the mean at Topsail Island ($-0.08 \text{ m}^3/\text{m}^2$) was much larger than Wrightsville Beach's mean ($-0.37 \text{ m}^3/\text{m}$) or Figure Eight Island's mean ($-0.37 \text{ m}^3/\text{m}$). The smallest mean at Topsail Island could be attributed to dune modification, disposal of dredge material in the swash zone and the response of sediment from foredune erosion being redistributed along the back beach.

During 99-00, all islands' means of volumetric net-change per unit area were statistically similar except for the mean of Figure Eight Island ($0.45 \text{ m}^3/\text{m}^2$). The largest mean at Figure Eight Island (in comparison with the means of other four islands) resulted from the intense beach nourishment project performed between 99 and 00 data acquisitions.

Comparison of coast based upon management practices. It is well known that varying beach management practices can be permitted or allowed to occur along a single island. Thus, it would be interesting to compare and contrast the differing management practices within the study area, and to offer another vantage point into the analysis than just the categorization of islands. Volumetric net change rates are believed to be significantly affected by the differing management practices permitted along a portion of coastline. By regrouping the AOIs based on beach management practices, beach nourishment, dune modification, developed beach, undeveloped beach, and jetty (Table

3), means of AOIs from the five categories were tabulated (Table 8). Again, ANOVA tests were carried out for the means at three time intervals. Since there were only two AOIs in the jetty category (Table 3), this category was excluded from the significant testing.

For the ANOVA test, p -values near zero were obtained during 97-98 and 99-00 periods, but the p -value was 25.2% for 98-99 interval. Thus, if a 5% significant level was used, means of AOIs grouped by four beach management practices were statistically different during 97-98 and 99-00, but similar during 98-99. All the assumptions of the ANOVA test were met except equality of variance for 97-98 and 99-00. When ANOVA's assumption was not met, a nonparametric chi-squared (χ^2) test was performed. Both ANOVA and χ^2 tests concluded the means differ during 97-98 and 99-00, but were the same during 98-99.

Table 8. Mean volumetric net-change per unit area (m^3/m^2) categorized by beach management practice occurring at the AOIs of five islands during each time interval.

Management Practices	97-98	98-99	99-00
Beach nourishment	0.407	--	0.718
Dune modification	-0.343	-0.106	0.250
Undeveloped beach	0.111	-0.237	0.112
Developed beach	-0.295	-0.192	0.012
Jetty*	0.058	-0.305	0.151

* Mean value from the jetty category is provided for a reader's information.

Fifteen *post hoc* contrast tests on means of differing management practices were also finished to further delineate their differences. In 97-98, the mean ($0.407 \text{ m}^3/\text{m}^2$) of AOIs in beach nourishment category was significantly greater than those of AOIs in dune

modification, undeveloped beach, and developed beach categories, respectively (Table 8). *p*-values of the *post hoc* contrast tests between mean in beach nourishment group vs. mean in dune modification, undeveloped beach, or developed beach group were close to zero; they were statistically different. Also, based on zero *p*-values (Table 9), the mean of AOIs in the dune modification category and the mean of AOIs in the undeveloped beach category, and the mean of AOIs in the undeveloped beach group vs. the mean in developed beach group statistically differed. It is interesting to note that the portions of coastline where human intervention is at a minimal, the volumetric net change rates were not as erosive. Because of a large *p*-value (93.4%, Table 9), the mean of AOIs in the developed beach category ($-0.29 \text{ m}^3/\text{m}^2$) and the mean of AOIs in the dune nourishment category ($-0.34 \text{ m}^3/\text{m}^2$) were statistically the same. Even though the addition of sediment to the dune line was apparent, net change rates per unit area for these AOIs characterized as dune modification were negative. This can be attributed to severe erosion along these portions of coastline, which prompted the supplement of sediment to modify or create dunes to help protect structures, such as an individual's house. Without the modification of the dunes lines, these stretches of coastline would have most likely demonstrated even greater net loss rates.

In 98-99 no beach nourishment projects were performed within the study area. The *pos hoc* test on means of AOIs in dune modification, developed beach, and undeveloped beach categories showed that the means in the three types of management practice categories were significantly similar (Table 9). The impact from two hurricanes

on these beaches during this interval may overwrite any significance of different management practices applied to these beaches.

Table 9. *p*-values (%) of the ANOVA *post hoc* test on means of AOIs categorized by four types of beach management practices at each yearly interval.

<i>Management Practice Comparisons</i>	<i>Yearly Intervals</i>		
	<i>97-98</i>	<i>98-99</i>	<i>99-00</i>
Beach nourishment vs. Dune modification	0.0	--	0.0
Beach nourishment vs. Developed beach	0.0	--	0.0
Beach nourishment vs. Undeveloped beach	2.2	--	0.0
Dune modification vs. Developed beach	93.4	50.7	0.0
Dune modification vs. Undeveloped beach	0.0	32.9	4.6
Developed beach vs. Undeveloped beach	0.0	83.0	38.6

During 99-00, the mean ($0.718 \text{ m}^3/\text{m}^2$) of AOIs in the beach nourishment category was much greater than the means of AOIs in the dune modification, developed beach, and undeveloped beach categories, respectively (Table 8); the beach nourishment category's mean was statistically different from the means of the other three categories (Table 9). Beach nourishment is recognized as the only management practice with a mean rate greater than dune nourishment ($0.25 \text{ m}^3/\text{m}^2$). Also, the mean of AOIs in the dune nourishment category was much larger than the mean of AOIs in the developed beach or undeveloped beach categories. The comparisons of means of dune modification vs. developed beach and means of dune modification vs. undeveloped beach showed that they differ (Table 9). In response to the apparent recovery phase, the addition of sediment

to the dune is seen as an influence that contributes to a larger volumetric net change rate response, than areas of coastline not receiving supplemental sediment. Finally, the means of developed beach and undeveloped beach were statistically similar, since the p-value is 38.6% (Table 9). This can be attributed to the lack of overwash occurring during 99-00, and the majority of deposition being located in close proximity to the shoreline.

It is also interesting to compare the response of net volumetric change per unit area of undeveloped beach sites to that of the developed beach management practice delineations over the temporal frame analyzed in this research. The AOI sites at undeveloped beaches experienced net depositional trends during 97-98, followed by a significant loss in 98-99, and a significant gain or recovery in 99-00. In contrast, the AOI sites at developed beaches experienced significant loss in 97-98, and a continued loss during 98-99. Between 99-00, the developed sites appear to show a small and insignificant recovery (much less than that at the undeveloped beaches). These results appear to confirm the thoughts of Dolan (1973) that more natural barrier islands are better suited for extreme events and steady processes when compared to that of a developed barrier island. This thesis research also seems to verify Dolan (1973) that sediment transfer rates are different between these two types of barrier island systems.

Nordstrom (1995) examined the role of human intervention in relation to changes that occur on barrier islands along the New Jersey coast. A number of the human alterations cited by Nordstrom (1995) are found present in this thesis research. The comprehensive nature of volumetric change parameters extracted from processing DEMs derived from LIDAR can begin to shed insight into the dynamic responses found present

on barrier islands in response from human intervention, and with the addition of more consecutive-year DEMs, an accurate understanding of these anthropogenic related changes should be obtained. Lastly, analysis, similar to this thesis, of characterized portions of coastline by the management practices permitted could be added to enhance the classification system developed by Jackson et al. (2000). They used, for example, beach and dune widths, and distance to inlets to present the physical characteristics of barrier islands. LIDAR derived DEMs can not only measure the widths and distance, but provide highly accurate topographic information in a more comprehensive manner for representation of the physical characteristics, as well as intertwining the extracted volumetric parameters to help understand the affects of human intervention.

CHAPTER 5

CONCLUSIONS

This thesis analyzed topography and topographic changes in terms of erosion, deposition, and net-change on five barrier islands of a portion of the North Carolina coastline. In the analysis, four sets of hi-resolution and hi-accuracy DEMs (digital elevation model) created from the LIDAR (light detection and ranging) data acquired in 1997, 1998, 1999, and 2000 were used to represent the topography of each barrier island at the time of data acquisition. Approximately 100 study sites or areas of interest (AOIs) were extracted from the DEMs. Each AOI designated a particular segment of coastline and consisted of the primary portion of the dune line and the dry beach where the processes of erosion and deposition could be best detected and studied. The AOI also allowed for exclusion of areas of significant vegetation, structures such as houses and piers, variability in shoreline position, and wave activity that may add significant error into the volumetric analysis. Lastly, each AOI covered approximately the same location and portion of coastline for each yearly analysis. The AOIs of the DEMs were then paired as 97-98, 98-99, and 99-00, which facilitated the analysis of topographic change between each time interval. Deposition, erosion, and net-change of each AOI at each time interval were calculated on the cell-by-cell basis first, and then summed separately to have the total deposition, erosion, and net-change for the AOI. Knowing the spatial pattern and value of the deposition, erosion, and net-change for all the AOIs, the topographic change of each barrier island has been studied. Since there were hurricanes that made landfall near the study area in 1998, and 1999, their impacts on the islands were also studied by

analyzing the AOIs. Finally, to study the impact of different beach management practices, the AOIs were regrouped into developed, undeveloped, beach nourished and dune nourished categories.

The different stages that barrier islands encounter based on level of storm activity seemed to be apparent in the analysis. The majority of erosion along the lower beach face detected during the 97-98 and 98-99 intervals was attributed to the impacts of hurricanes, which directly affected the study area. From 1999 to 2000, the five islands were not affected directly by any significant storm of tropical nature as in the previous two periods. Due to the lack of major storms and hurricanes, volumetric values for the 99-00 period resulted in more deposition than erosion net increases to all islands. The shoreline accretion and deposition was an opposite morphologic response than what was noticed at the same spatial locations before; the shoreline was highly erosive in 97-98 and 98-99 periods. Volumetric figures for the 99-00 period resulted in more deposition than erosion or net increases to all islands. The results appear to show a rehabilitation stage for the barrier islands following a series of stormy periods previously.

During 97-98, three islands had net-change gain of sand ranging from (121,983 m³ to 217,886 m³), but the other two islands experienced net loss (from -179,159 m³ to -469,792 m³). Between 98-99, all islands had net-loss, -134,554 m³ to -427,248 m³, whereas between 99-00, all islands gained sand, 30,059 m³ to 329,725 m³.

Since the size of each AOI differed, the net-volumetric change of sand between each time period has been normalized by its area (m³/m²). Between 97-98, three islands had positive mean rates ranging from (0.08 m³/m² to 0.12 m³/m²), while the other two

islands experienced mean negative rates (from $-0.28 \text{ m}^3/\text{m}^2$ to $-0.31 \text{ m}^3/\text{m}^2$). During 98-99, all islands exhibited negative mean rates ($0.08 \text{ m}^3/\text{m}^2$ to $0.37 \text{ m}^3/\text{m}^2$) while the islands in 99-00 demonstrated positive mean rates ($0.03 \text{ m}^3/\text{m}^2$ to $0.45 \text{ m}^3/\text{m}^2$).

Three types of ANOVA tests on means of the volumetric net-change per unit area for the AOIs of five islands have been conducted: 1) comparisons of each island itself at three time intervals, 2) comparisons among five islands at the three time periods, and 3) analyses of delineations of study sites based upon beach management practices at the three time intervals. If 5% significant level was used for all three types of comparisons, the following results were obtained. Out of fifteen comparisons between each pairs of time interval on each island, there were seven cases in which the means were statistically similar, whereas eight cases in which the means differed (Table 6). Out of thirty comparisons between islands at each time interval, there were fifteen cases in which the means were similar, and for the other fifteen cases, the means differed (Table 7). Out of fifteen comparisons between AOIs categorized by beach nourishment, dune modification, developed beach, and undeveloped beach at three time periods, in five cases, the means were statistically the same, whereas for the other ten cases, the means were different (Table 9).

The results from the ANOVA helped assist in comparing and contrasting varying temporal frames of islands for further investigation into the spatial variations that might be apparent. The ANOVA method also indicated the usefulness of utilizing AOIs to delineate how segments of coastline were managed. The delineation of beaches into beach nourishment, dune modification, developed beach, and undeveloped beach helped

facilitate more in-depth inquiries into the study and comparison of the complex morphological changes that occur naturally or human-induced on barrier islands.

This analysis of topography and topographic change from 97-98 also demonstrated that the process of overwash has been seen as an important component that is integral in the landward migration of these transgressive barrier islands. At islands or portions of islands where overwash was permitted and using net volumetric change per unit area as a measurement, the areas were not as erosive as the developed beaches that have not undergone extensive nourishment practices.

It is evident that the North Carolina coastline is a very complex and dynamic system that is in desperate need of being better understood. The continual increase in development along the immediate coastal area and the management practices that we allow to occur, will greatly affect the responses and outcome that the coastline will have in the future. DEMs derived from LIDAR sensor provide an extraordinary capability for capturing the coastline's ever-changing morphology in a quick, cost-effective manner. DEMs of hi-resolution and accuracy hold enormous possibilities to enhance the knowledge of the coastal zone. With the integration of data that capture the dynamics of waves, bathymetry, and topography, insight into the processes that shape and mold the forms of the very dynamic coastal zone can be gained. With additional studies and research similar to this in the near future, more intelligent decisions can be made about the effective planning and management of the coastal area.

In summary, here are five significant findings:

- It is feasible to use DEMs derived from LIDAR data to map beach and dune topography with a high accuracy of vertical value (z), and its location (x, y). z could be less than or equal to 10 cm. The location is within 1.5 by 1.5 m.
- It is capable to visualize and monitor spatial patterns of beach and dune changes through time.
- Topographic change caused by erosion and deposition is quantified. The erosion and deposition can be nature-induced (such as wind and wave) and human-induced (such as beach nourishment, dune modification, etc.).
- The DEMs provide needed data and this thesis investigate methods to study spatial variations of different beach/dune management practices.
- The validation of methods by using DEMs derived from LIDAR to provide a better understanding of topographic changes of beaches and dunes has been achieved.

It should be noted that there are possibly numerous paths in which this study can be further advanced in the future. The incorporation of greater detailed oceanographic and atmospheric data coupled with the affects the underlying geologic framework presents, holds the possibility of helping enhance the analysis of morphologic change. For greater comprehension of inlet dynamics, the spatial location and orientation of the main ebb channel and ebb tide delta, coupled with predominant direction of littoral current for each particular yearly interval should be included. It would also be interesting to further delineate portions of coastline into smaller units that represent morphologic

features such as the beach, dune system, overwash fans, and many others. This would help enhance the analysis by allowing for a more in-depth inquiry into sediment fluxes between and among these individual morphological landforms.

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