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# Using LIDAR to Monitor a Beach Nourishment Project at Wrightsville Beach, North Carolina, USA

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**ABSTRACT**

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With beach nourishment widely used today to combat shoreline erosion, it is desirable to monitor the postnourishment shoreline to evaluate the projects' success. Implementing a monitoring program is difficult because of time and personnel requirements. Remotely sensed elevation data, in particular that derived from airborne light-detection and ranging (LIDAR) sensors, could be used because of its extensive coverage. In 1998, a beach-fill project was carried out at Wrightsville Beach, North Carolina, and coincidentally LIDAR data were collected annually in this location from 1997 to 2000. This project uses the LIDAR data to identify beach and dune zones and to compute volumetric changes for each zone. Spatial variations are analyzed by examining shoreline segments, in which beach and dune volumes are determined for the different surveys. Spatial and temporal changes in both the beach and dune zones are monitored following the initial fill project. The passage of hurricanes Bonnie and Floyd in the fall of 1998 and 1999, respectively, provided an opportunity to evaluate how the nourishment project was affected by major storms. About two thirds of the initial fill material was removed from the subaerial part of the beach in the first year, probably mostly as a result of the hurricanes. The highest rates of beach sediment loss occurred in the nourishment zones. There was some recovery in the following years. The dune system also changed, both losing and adding sediment in different time periods. The influence of human manipulation of the dune is evident in the cross-shore profiles and the volumetric data. There is little evidence that the fill material moved alongshore to nourish subaerial areas adjacent to nourished zone. Although the nourished beach undoubtedly provided a buffer against the storm waves, poststorm beach recovery was not evident 2 years after the storms, making the long-term success of this project questionable.

**ADDITIONAL INDEX WORDS:** *Shoreline stabilization, horizontal beach and dune change, volumetric beach and dune change.*

## INTRODUCTION

Beach nourishment is viewed by many as the most acceptable form of shoreline stabilization used in the United States today (MAGOON *et al.,* 2001). Large projects have been implemented at numerous places, such as Miami Beach, Florida; Santa Monica, California; and Atlantic City, New Jersey (HOBBS, 1988; LEONARD *et al.,* 1990; WALKER and BRODEUR, 1993). As sea level rises during the next few decades, producing greater shoreline erosion, demands by coastal residents for action to protect their property will increase, and states will look increasingly to beach nourishment as the method of choice for coastal stabilization (KRIEBEL, 1988).

A major question regarding beach nourishment concerns the success of the project. For many projects, there is no regular protocol for monitoring the changes that occur following sand emplacement (LEONARD *et al.,* 1990; STAUBLE, 1988). Most frequently, transects across the beach are surveyed with varying degrees of regularity to determine changes, but the density of the transects and frequency of surveys vary from project to project (DAVIS *et al.,* 1993). Transects spaced a considerable distance apart and surveyed infrequently give a limited picture of the changes to the beach as a whole, especially in areas adjacent to the nourished area. There are ample reasons for monitoring beach nourishment projects. From a scientific perspective, a useful goal would be to understand the behavior of the beach fill area in response to various coastal processes. From a management perspective, determining the success of beach-nourishment projects would establish justification for future projects.

A sediment budget approach to examining beach behavior is an accepted practice used by various researchers and provides a detailed view of changes in landforms (KOMAR, 1983; SHERMAN and BAUER, 1993). This approach relies on determining the volumes of sediment added or removed from specific parts of the coastal system, such as the beach, dunes, or overwash fans. When the additions and reductions are known, they can be balanced to give a picture of whether the system is gaining or losing volume. Furthermore, when the budgeting involves subunits within a larger system, it is possible to identify where additions and losses are occurring. The application of this approach to monitoring beach nourishment

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projects would provide information about the redistribution of the fill materials from the nourished area to adjacent areas. Such an analysis could be used to evaluate the degree of success of the beach nourishment project.

Despite it's potential benefits, the implementation of a sediment-budget calculation can be problematic when a large area is being analyzed over a long period of time. Volumetric measurements become difficult to obtain because the size of the area to be analyzed can limit data gathering. For example, detailed topographic coverage can be obtained by the same surveying methods used to monitor cross-shore transects, but this is very time consuming and requires significant personnel to complete. Small sections of shoreline have been monitored in this way (ANDREWS *et al.,* 2002), but extending the technique to areas more than 200–300 m in length requires the availability of people and time. As a result, coastal researchers have resorted to using survey transects oriented perpendicular to the shoreline and established at regular sampling intervals to represent shoreline changes. When the surveys are repeated regularly through time, a picture of temporal changes emerges. It is assumed that the transect approach is an accurate spatial representation of the entire shoreline under investigation. There has been some effort made to evaluate this premise statistically (DOLAN *et al.,* 1992; PHILLIPS, 1985). Although using transects seems to be acceptable in the case of a linear and consistent feature such as a beach, when topography becomes more varied, the ability of a single transect to represent a larger area is diminished. These issues suggest that the development of an alternative monitoring technique would be desirable. The use of remotely sensed data is a logical alternative, but there are problems with the different existing sources of data. Satellite imagery, such as Landsat, offers the advantage of frequent passes over the desired location, but the coarse resolution of the available data limits their ability to provide detailed information about coastal features. Aerial photographs have a much better resolution than satellite data because flights can be arranged on any schedule one desires, and the spatial/temporal coverage can be very good. However, air-photo data do not easily provide the desired volumetric data (HAPKE and RICHMOND, 2000).

The recent development of light-detection and ranging (LIDAR) represents a technological breakthrough in topographic monitoring. A number of studies have demonstrated the ability of LIDAR data to accurately represent topography over large sections of coastline (REVELL *et al.,* 2002; SALLENGER *et al.,* 2003; WHITE and WANG, 2003), and sequential LIDAR surveys have shown that shoreline changes can be monitored over time (STOCKDON *et al.,* 2002). Given these attributes, this data collection technology seems well suited for use in monitoring coastal changes, both natural and human produced, over varying spatial and temporal scales. This is particularly true in the case of beach nourishment that is based on the premise that the addition of a considerable volume of sediment to the beach system offsets losses of sediment due to various factors, including sea level rise, a major storm event, or loss of natural sediment supply. Because beach nourishment is a volume-based technique, it is reasonable that a sediment-budget approach should be used to monitor the project's progress.

The purpose of this article is to examine the usefulness of LIDAR data for monitoring beach nourishment projects. Such projects often involve fairly strict specifications regarding such issues as the total volume of sediment to be emplaced, a design beach form involving a minimum backbeach elevation, and accommodation for the construction of a protective dune. In addition, projects often place the sediment in specific locations along the shoreline so that the fill zone will become a feeder beach, a source of sediment for downdrift zones. This article examines these issues, as well as the question of how the fill material changes the coastal landforms through time in response to coastal processes, especially due to large coastal storms that might affect the beach/dune sediment budget. In particular, this article examines the following questions:

1) Can LIDAR data represent changes in both the beach and the dune at a resolution that allows observation of sediment transfers from nourished to adjacent nonnourished areas, thus leading to an improved understanding of the dynamics of the sedimentary system?
2) What is the general subaerial sediment budget for this beach and how does it change over time?
3) How do large coastal storms affect the fill material and to what extent does the system recover following the event?

The study focuses on Wrightsville Beach, North Carolina, where beach nourishment has become a regular occurrence over the last 15 years. In recent times, government agencies have conducted LIDAR surveys along this coastline. The occurrence of a beach-nourishment project during the period in which LIDAR surveys were conducted provided the opportunity to examine beach changes that resulted from the artificial influx of sediment. During the same period, this particular coastline was affected by several hurricanes, and these events provided the opportunity for evaluating the response of the fill to the high-energy conditions associated with the storms.

## STUDY AREA

Wrightsville Beach is located on the southern North Carolina coast (Figures 1A and 1B) 14 km east of Wilmington. The community occupies an 8-km-long barrier island bordered by Mason Inlet to the north and Masonboro Inlet to the south. The barriers along this stretch of coastline migrate in a southerly direction. Figure Eight Island, the barrier to the north, has been migrating southward into Mason inlet at an average rate of 33 m $yr^{-1}$ since 1938 (www.csc.noaa.gov/products/nchaz/htm/lidtopo/htm). The north shore of Wrightsville Beach in Mason Inlet eroded at a rate of 76 m $yr^{-1}$ between 1981 and 1993, increasing to 99 m $yr^{-1}$ between 1993 and 1995. This erosion has threatened the Shell Island Resort, an upscale condominium community whose plight has received considerable attention in the state of North Carolina. The high rate of erosion along this shoreline has resulted in efforts to stabilize the shoreline and the U.S. Army Corps of Engineers has conducted a number of beach-nourishment projects on this barrier island to offset the losses of sediment.

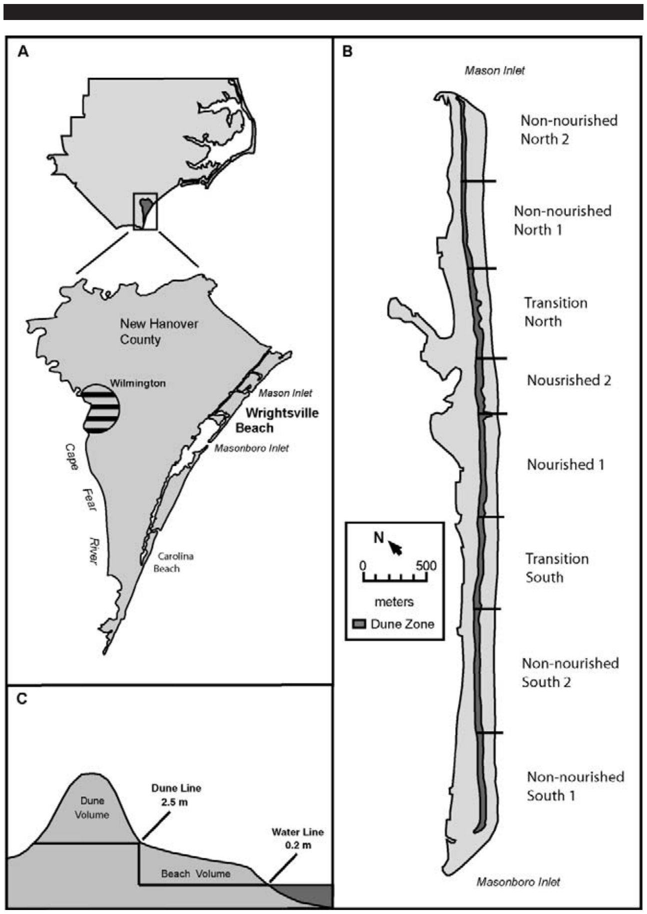


Figure 1. (A) Eastern North Carolina, with New Hanover County, Wilmington, and Wrightsville Beach. (B) Wrightsville Beach beach and dune zones, divided into study segments. (C) Method for delineating beach and dune zones.

The barrier island has been significantly altered by human activities. Development density is very high (on the order of 15 houses/ha), resulting in the truncation of the foredune and filling in of marshes. Protection of property is the crucial management issue. Protection is obtained through regular beach nourishment projects (LEONARD *et al.,* 1990) that involve the placement of sediment on the beach in the middle section of the barrier island. The new sediment is generally tapered on the northern and southern margins of the main nourishment area, so that it gradually merges with the existing beach. A protective dune is maintained along the length of the barrier. The dune is linear, with a consistent elevation, bulldozed into place following nourishment projects, and stabilized with fencing and grass planting. The resulting foredune bears little resemblance to the natural landform.

Since 1996, the stretch of North Carolina shoreline from Cape Fear to Topsail Island has seen the landfall of five hurricanes, including Bonnie (1998), Dennis (1999), and Floyd (1999) (Table 1). The Wrightsville Beach shoreline was severely eroded during these storms, although the amount of erosion did vary in each storm. There was extensive dune damage due to high storm surge that led to dune breaching and overwash in places. Following each storm, there were extensive clean-up activities involving bulldozing of overwash sand back into the dunes to create a protective dike against future storm surge, as well as reworking of beach sand to create a protective beach profile.

Table 1. *Physical characteristics of hurricanes affecting the NC shoreline 1996–99. Source: Archive of Past Hurricane Season (www.nhc.nooa.gov).*

| Hurricane | Category | Date of Landfall | Storm Surge Height (m) | Significant Wave Height (m) | Ave. Wave Period (s) |
|---|---|---|---|---|---|
| Bonnie | 2–3 | 8/27/98 | 1.5–2.5 | 1.5–2.5 | 12–16 |
| Dennis | 1–2 | 8/30–31/99 | 1.5–2.7 | 0.9–1.5 | 12–14 |
| Floyd | 2 | 9/16/99 | 1.5–2.7 | 3 | 14 |

## METHODOLOGY

Airborne LIDAR surveys were conducted along this stretch of shoreline in the fall of 1997, 1998, 1999, and 2000 (ARENS *et al.,* 2002). The 1997 LIDAR survey was conducted on September 21. Hurricane Bonnie, a category 2 storm, made landfall on August 26, 1998, near Carolina Beach, 22 km south of Wrightsville Beach. A LIDAR survey was flown on September 5, 1998. In 1999, hurricane Floyd made landfall just south of Wrightsville Beach on September 16. Two days later, a LIDAR mission was conducted along the North Carolina shoreline. The final LIDAR data set was collected on August 2 and 3, 2000. No hurricane made landfall in North Carolina that year. The LIDAR data were downloaded from the National Oceanic and Atmospheric Agency (NOAA) Coastal Services Center web site and were imported into Global Information System software for cartographic manipulation. The first step in data manipulation involves reducing the number of survey points to a manageable size, which is a function of the desired accuracy and of the ability of the computer system to deal with a large data set. For this study, a 1.5- × 1.5-m grid was used to select points to include in our working data set, as advocated by WOOLARD and COLBY (2002).

The study area was divided into separate beach and dune zones (Figure 1B). The beach zone lies between the water–land contact and the base of the foredune slope. On aerial photographs, the water line is often represented by the high-tide mark, clearly identifiable on the foreshore (DOLAN *et. al,* 1978; STAFFORD and LANGFELDER, 1971), but in the case of LIDAR data, resolving where to draw the boundary necessitates using the digital format of this data source. The seaward and landward boundaries of the beach and dune zones were established using specific elevations (Figure 1C). Following STOCKDON *et al.* (2002), an elevation of 0.2 m was used as an estimation of the water line, and became the seaward boundary of the beach area. The landward boundary of the beach zone occurs at the slope break on the seaward side of the dune. Although this dune slope break varies in location and occurs at different elevations, a constant elevation was selected for this feature and was applied uniformly along the entire barrier island. Twenty sample transects extracted from the LIDAR data revealed that, at Wrightsville Beach, the elevation of the dune slope break occurred between 2.25 and 2.75 m. The landward boundary line of the beach zone was established at 2.5 m. The beach extends across the width of the island to the estuary to the rear, and the dune is an accumulation of sand on top of the beach. The seaward boundary of the dune, therefore, at an elevation of 2.5 m, was also used as the landward boundary of the dune.

In order to obtain data for each zone, a digital elevation model (DEM) of the barrier island was produced for each of the four LIDAR surveys and the boundary contour lines were highlighted on each DEM. Thus, the beach and dune zones change for each survey. The volume of each pixel was obtained by multiplying the area of the pixel (2.25 $m^2$) by the elevation value for the pixel. When there was more than one elevation value in a single pixel, the average of all values for the pixel was used as the pixel elevation. When there were no LIDAR data in a pixel, an elevation value was obtained using data from adjoining pixels in an inverse-distance–weighted interpolation process. The elevations used for beach pixels are the absolute elevation values obtained; in the case of the dune, 2.5 m was subtracted from the absolute elevation to obtain the vertical dimension of the dune. The total volume was derived by summing the volumes for the pixels in each zone.

It is accepted that LIDAR data have some accuracy issues. These pertain to the technology used to obtain the data and to interpreting the surface from which the laser signal is reflected. Technology issues involve the accuracy of the horizontal and vertical data values. Sallenger *et al.* (2003) focus on the vertical component, comparing elevation values obtained from the LIDAR to ones obtained from various ground surveys. Three different types of error are identified. Mean error is the mean difference between the LIDAR data and the ground data. It is attributed to drift in the differential Global Positioning System used to establish the spatial coordinates for the data value. Random error is the variation about the mean difference between the two data sets. The source of this error is not identified, but it appears it might be associated with elevation variations produced as a result of varying surface conditions yielding different laser returns. Sallenger *et al.* (2003) claim that the random errors cancel out for many applications, including volume calculations. The third error is total error, which is the combination of mean and random error, calculated as the root mean square of the differences between the values in the two data sets being compared. In a conservative analysis of elevation data, they propose using the total error value of 15 cm for individual LIDAR data. This error value is used in this study to establish a range of possible variation about the mean volumetric data presented. It is also used in the examination of profile data as a minimum value for assuming that elevation change has occurred between profiles.

Stockdon *et al.* (2002) examined the horizontal error associated with individual LIDAR points, following the same methodology used by Sallenger *et al.* (2003). Their analyses suggest a total error of 2.9 m. However, they cite test studies of data from Assateague Island, Virginia, and from the Outer Banks, North Carolina, that give total-error values of $\pm 1.4$ m and $\pm 1.1$ m, respectively. In this study, this would mean that the beach and dune zones could be wider or narrower by one $1.5 \times 1.5$ m pixel. In the analysis of cross-shore profiles, these results suggest that horizontal changes of less than 2 m can be considered within the range of error.

The nature of the surface is in itself a potential source of error. There is little problem where bare sand surfaces are involved (Meredith *et al.,* 1998; Sallenger *et al.,* 2003), but the presence of dense or tall vegetation cover or of human artifacts may give a false elevation. Given that this project focuses on the beach and an artificially created dune, it is assumed that the return signal accurately represents the surface elevation. While it is true that dune grass was planted on the dune, the density of the vegetation is very low and the height of the plants is small. These conditions should have minimal effect on the accuracy of the LIDAR signal.

The volumes were recalculated using the error estimate of 15 cm advocated by Sallenger *et al.* (2003). This produced a range for the volume value within which one would confidently expect the actual volume to exist. Once the maximum and minimum values were obtained for each of the barrier island zones, the error percentage was determined. The error percentages for the eight zones were then averaged. Overall, the average volumetric error is 11.7% of the total volume for the beach zones and 15.9% of the total volume for dune zones.

The Corps of Engineers assumes that the area nourished will serve as a feeder beach for adjacent shoreline segments. To evaluate the distribution of sediment from the feeder zone, the study area was divided eight zones in the alongshore direction (Figure 1B). These included two zones in the main nourishment area in the middle of the barrier, single transition zones north and south of the nourished area where the fill material was tapered, and two zones in each of the nonnourished areas at the northern and southern extremities of the island. The nonnourished zones at the island extremities do not extend fully into the inlet throats because the LIDAR flight line did not cover the landward half of the barrier island. Thus, full analysis of changes associated with inlet processes is not possible.

In order to conduct a more detailed analysis of alongshore variation, 120 sampling transects were established along the barrier using Imagine software. A north–south baseline was delineated along the entire length of the barrier, and the sampling transects were established perpendicular to the baseline at 60-m intervals. The distances from the baseline to the backdune boundary, the foredune boundary, and the water–land contact were measured with the measurement tool in Imagine. These data show changes in the position of each line through time, as well as fluctuation in the widths of the beach and dune zones.

## RESULTS

### Horizontal Changes

There is positive horizontal change for 1997–98 (Figure 2A) in the area of beach nourishment in the central part of the Island, with areas of lesser beach accretion in the transition zones adjacent to the main nourishment area. At the southern end of the island, there is some accretion along the shoreline immediately adjacent to Masonboro Inlet, but there was

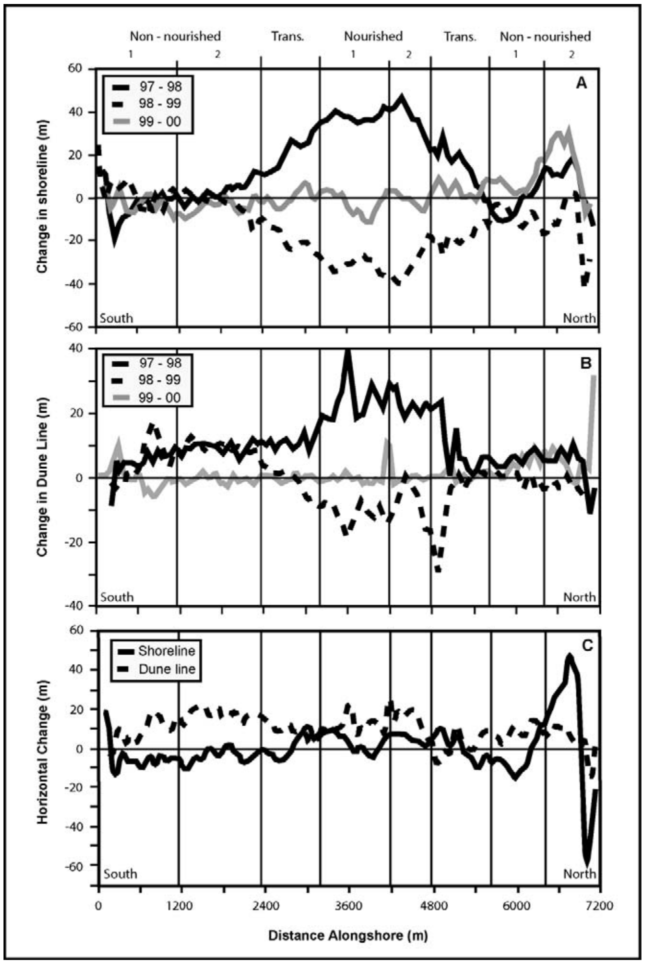


Figure 2. Horizontal changes in the location of the shoreline (A) and the dune line (B) for paired dates; horizontal changes for the shoreline and dune line for the study period 1996–2000 (C).

also as much as 20 m of erosion 200–600 m north of the inlet zone. At the north end of Wrightsville Beach, the erosion that had been occurring along Mason Inlet continued during this period, receding 10–20 m at the seaward end of the inlet. The rest of nonnourished north 2 had accretion of 5–15 m, whereas erosion occurred in much of nonnourished north 1.

In 1998–99, nearly all the fill sediment placed on the beach was removed. The shoreline in the nourishment zones eroded by 20 to 40 m and by as much as 25 m in the transition zones (Figure 2A). In the nonnourished areas at the northern and southern ends, the changes were highly variable, with accretion occurring in much of the southern end, nearing 25 m in the vicinity of Masonboro inlet. The shoreline adjacent to Mason Inlet eroded nearly 50 m although there is a small area of accretion about 400 m from the inlet.

In 1999–2000, the shoreline in the nourished and transition areas showed little change (Figure 2A). In the southern nonnourished zones, most of the shoreline remained stable in this time interval, but there were places where on the order of 10 m of erosion occurred. At the northern end, there was considerable accretion, reaching 35 m at a distance of 400–600 m from the inlet, but erosion continued to occur in the vicinity of the inlet.

Changes in the dune-beach contact paralleled the beach changes in the 1997–98 period (Figure 2B). Accretion of 20–30 m occurred throughout the nourished areas with one particular area showing 40 m of growth. In the southern transition and nonnourished zones, dune advance was on the order of 5–10 m. Data are lacking for the area immediately adjacent to Masonboro Inlet, but just to the north there was an area with 10 m of dune retreat. In the northern transition and nonnourished zones, the accretion was generally 2–5 m, but in the area of Mason Inlet, the dune eroded by as much as 10 m. In general, the pattern of accretion along the dune front visually appears to be more variable than along the shoreline.

In 1998–99, the dune front in the nourished area receded 10–20 m, with one area in the northern transition zone reaching 30 m of retreat (Figure 2B). The dune line was fairly stable from the middle of the northern transition zone to the area nearest Mason Inlet. Erosion also occurred in transition south, nearest nourished 1, but the remainder of the dune in this zone shows no change. The dune line grew seaward by about 10 m through nonnourished south 2, continuing about halfway into nonnourished south 1. Little change or slight erosion occurred in the area nearest Masonboro Inlet.

In 1999–2000, the dune front had little change along much of the length of the island (Figure 2B). The dune front generally advanced by as much as 10 m in the middle of the northern nonnourished area, and major accretion of 30 m adjacent to Mason Inlet. At the southern end of the island, adjacent to Masonboro Inlet, there was some 10 m of dune advance in an area 400 m north of the inlet.

Overall for the 1997–2000 period, the shoreline in the nourishment and transition zones shows accretion, of up to 10 m in places (Figure 2C). There was considerable accretion in nonnourished north 2, reaching as high as 45 m, just 500 m from Mason Inlet. In the area adjacent to Mason Inlet, there was as much as 60 m of erosion. The beach in the southern nonnourished areas eroded by 5–15 m starting about 1500 m north of Masonboro Inlet. Nearer Masonboro Inlet, the beach accreted by as much as 20 m. In this same period, the dune front advanced 10–20 m along most of Wrightsville Beach, except in the areas adjacent to the inlets. In the north, next to Mason Inlet, there was up to 20 m of dune erosion at one location.

## Volumetric Changes

The volumetric data (Table 2) are based on the LIDAR elevation data measured for each survey. Information from previous studies (Sallenger *et al.,* 2003; Stockdon *et al.,* 2002) indicate that these volumes may misrepresent the actual change by 11.7% and 15.8% for the beach and dune zones, respectively.

For the period 1997–98, the beaches in the nourishment and transition zones in the middle of the island gained 78,620 $m^3$ of sediment whereas the dunes in these areas grew by 21,688 $m^3$, for an overall increase of 100,308 $m^3$ (Table 2). In

Table 2. *Volumetric changes (m³) for each area of interest in the beach and dune zones.*

| | 1997–98 | 1998–99 | 1999–2000 | 1997–2000 |
|---|---|---|---|---|
| Beach | | | | |
| Nonnourished north 2 | 4669 | −20,669 | 13,959 | −2041 |
| Nonnourished north 1 | −3660 | −8070 | 13,573 | 1843 |
| Transition north | 9072 | −21,561 | 81,933 | −4296 |
| Nourished 2 | 18,110 | −7845 | −37 | 10,228 |
| Nourished 1 | 35,699 | −16,757 | −8648 | 10,294 |
| Transition south | 15,739 | −9846 | −3978 | 1915 |
| Nonnourished south 2 | 5814 | −682 | −12,512 | −7380 |
| Nonnourished south 1 | −12,311 | −2453 | 372 | −14,393 |
| All zone change | 73,133 | −87,884 | 10,922 | −3830 |
| Change in nourished zone | 78,621 | −56,010 | −4470 | 18,141 |
| Nourished percentage of all zone | 107 | 64 | 41 | 474 |
| Dune | | | | |
| Nonnourished north 2 | 1658 | −4384 | 4451 | 1725 |
| Nonnourished north 1 | 5244 | −7858 | 9360 | 6746 |
| Transition north | 2460 | −2261 | 763 | 962 |
| Nourished 2 | 3471 | −2132 | 396 | 1735 |
| Nourished 1 | 7516 | −7077 | 5557 | 5996 |
| Transition south | 8241 | −3257 | 1573 | 6557 |
| Nonnourished south 2 | 11,110 | −4051 | 2642 | 9701 |
| Nonnourished south 1 | 6446 | −997 | 1428 | 6877 |
| All zone change | 46,237 | −32,019 | 26,169 | 40,299 |
| Change in nourished zone | 21,689 | −14,728 | 8289 | 15,250 |
| Nourished percentage of all zone | 47 | 46 | 32 | 38 |
| Beach and Dune | | | | |
| Total beach and dune change | 119,369 | −119,903 | 37,091 | 36,468 |
| Nourished beach and dune change | 100,309 | −70,738 | 3818 | 33,391 |
| Percentage beach change of total | 61 | 73 | 29 | 10 |
| Percentage beach change of nourished | 78 | 79 | 117 | 54 |
| Percentage nourished of total | 84 | 59 | 10 | 91 |

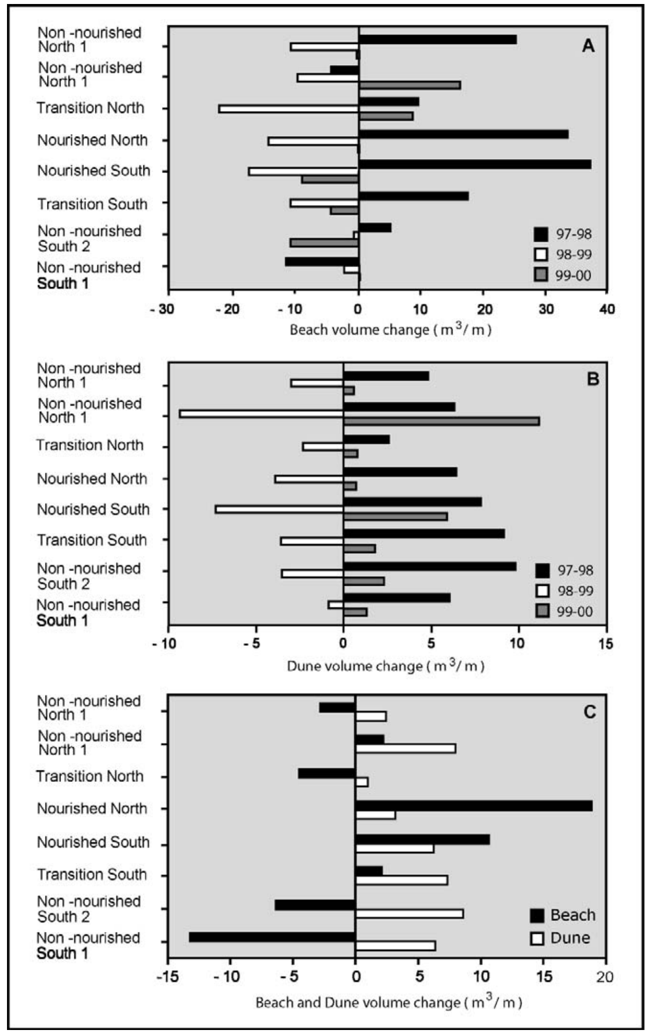


Figure 3. Volumetric change per unit shoreline length by nourishment zone for paired years in the beach (A) and dune zones (B), and for the 1996–2000 period in beach and dune zones (C).

the nonnourished zones, there was slight accretion of about 1000 m³ in the northern beach zones and loss of about 6500 m³ in the southern beach zones. The dune gained 6900 m³ in the north, and about 17,500 m³ in the south. For the entire island, the beach and dune volumes increased by 73,131 m³ and 46,146 m³, respectively, producing a total sediment increase of 119,277 m³. For the entire island, 61% of the gains occurred in the beach volume and 84% of the total change took place in the nourished areas.

When normalized for the length of each zone, the two nourished areas show an increase of 33–37 m³/m in the beach and 6–8 m³/m in the dune in 1997–98 (Figures 3A and 3B). In transition north, the beach volume increased by 10 m³/m and the dune grew by 3 m³/m. In transition south, 18 m³/m of sediment were added to the beach zone and 9 m³/m to the dune. Beach-volume changes varied in the nonnourished zones. The beach in nonnourished south 2 gained 5 m³/m but lost 11 m³/m in nonnourished south 1. In nonnourished north 1, 25 m³/m of sediment were added to the beach, whereas nonnourished north 2 lost 5 m³/m. All nonnourished zones had dune growth ranging from 2 m³/m to 10 m³/m.

All the sediment accumulated in 1997–98 along the Wrightsville Beach shoreline was eroded in 1998–99, as volumetric loss occurred in both the beach and dune in every zone (Table 2). Of the total 1997–98 subaerial beach gain, 120% was lost during the following year. Beach losses in the nourished areas comprised 64% of the total loss, whereas dune loss in nourished areas represented only 46% of the total. Overall, the dunes lost 69% of the volume that was in the system in the previous time period. In the nonnourished zones, the northern zones had the largest losses both in the beach and dune areas. In the beach and dune combined, 119,901 m³ of sediment were lost along the Wrightsville Beach shoreline in 1998–99 (Table 2). This amounts to 624 m³ more sediment than was gained in the previous year. Loss in the nourished zone amounted to 70,736 m³, or 59% of the

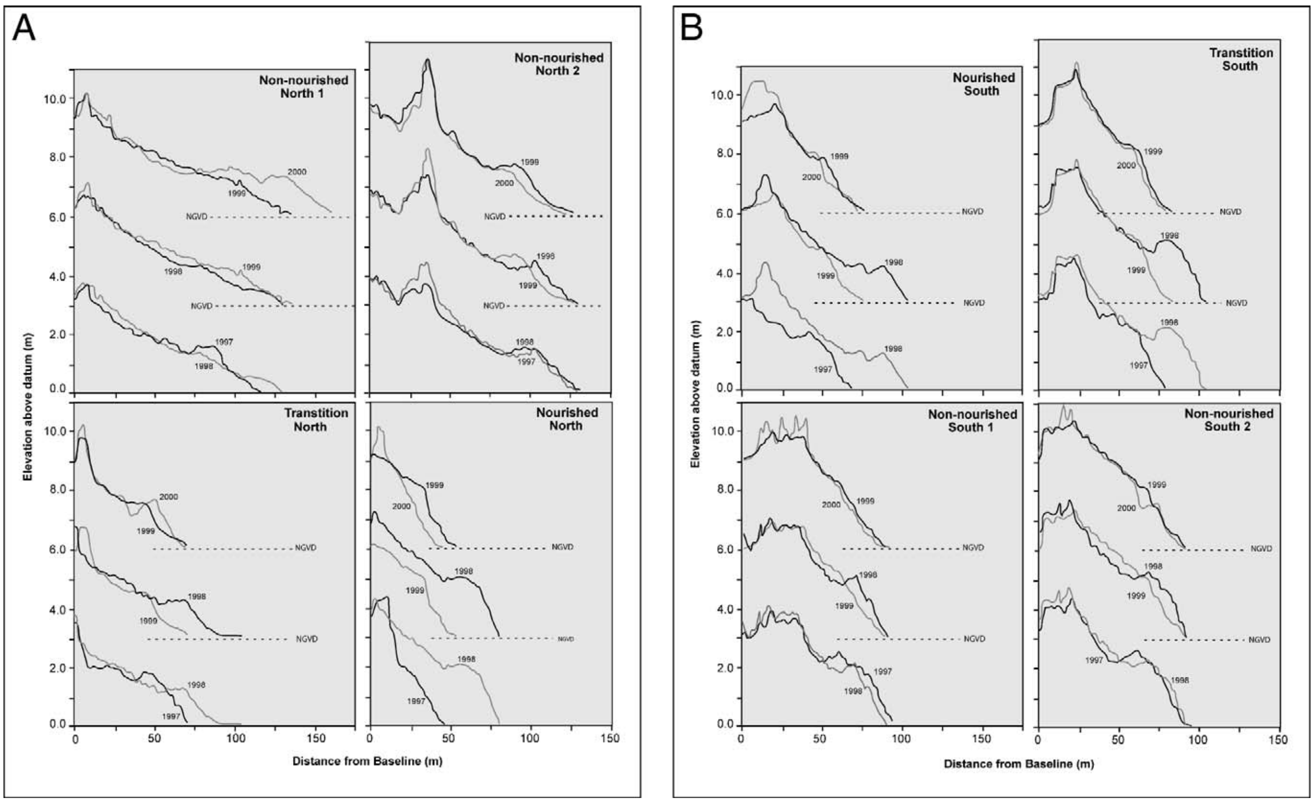


Figure 4. Representative profiles from each nourishment zone on Wrightsville Beach: (A) north zone, (B) south zone.

total loss. The vast majority of volumetric loss occurred in the beaches, with losses amounting to 79% of the total losses in nourished areas and 73% overall.

For 1997–98, the two nourished and the two transition zones had the highest beach losses, amounting to 10–22 $m^3$/m (Figure 3A). The beaches in nonnourished north 1 and 2 lost 10 and 28 $m^3$/m, respectively, whereas nonnourished south 1 and 2 had losses of less than 3 $m^3$/m. The greatest dune losses (7–10 $m^3$/m) occurred in nonnourished north 1 and 2 and in nourished 1 (Figure 3B). The remaining dune zones had less than 4 $m^3$/m of erosion.

In the 1999–2000 period, the northern part of Wrightsville Beach was accretionary while the southern end was erosional (Figures 3A and 3B). Total volumetric change on Wrightsville Beach for 1999–2000 was 37,091 $m^3$. Of this amount, 29% accumulated on the beach and 71% in the dune. Sediment volume changes in the nourished zone represent only 10% of the total island change in this period. The beach volume for the entire island gained 10,922 $m^3$, whereas the entire island's dune system grew by 26,169 $m^3$ (Table 2). Although the nourished beaches continued to lose sediment, the loss in these zones represented only 41% of the total change (Table 2). The largest amount of beach loss was in nourished 1 (9 $m^3$/m), whereas there was no change in nourished 2. The amount of change in the nourished dune zones represented a small proportion of the total loss (32%) for this period. The dunes in nourished 1 gained 6 $m^3$/m; in nourished 2, the increase was under 1 $m^3$/m. The areas to the north of the nourished area had gains in both beach and dune areas. In transition north, the beach grew by 8 $m^3$/m, but the dune gain was less than 1 $m^3$/m. The northern nonnourished zones had large amounts of gain in beach volume (16–19 $m^3$/m), and the dunes in these areas also increased in volume by 6–11 $m^3$/m. Erosion predominated south of the nourished areas during this period. The beach in transition south lost 4 $m^3$/m of sediment, but the dune gained 2 $m^3$/m. The beach in southern nonnourished 2 lost 11 $m^3$/m of sediment, whereas in southern nonnourished 1, there was no change. There was a small increase in dune volume (1–2 $m^3$/m) in both of the southern nonnourished zones.

For the period 1997–2000, the barrier lost 3830 $m^3$ of sediment from the beach but gained 40,299 $m^3$ in the dunes (Table 2). The beach in the nourished zone increased by 18,141 $m^3$ (47% of the total volumetric change), and the dunes added 15,250 $m^3$ of sediment (38% of the total dune gain). The nourished areas in the middle of the barrier added 11–19 $m^3$/m of sediment in the beach and 3–6 $m^3$/m in the dune zone (Figure 3C). Transition north had beach erosion (5 $m^3$/m) and dune accretion (1 $m^3$/m). The beach in nonnourished north 1 gained 2 $m^3$/m but lost 2 $m^3$/m in nonnourished north 2. The dune zones in both these areas grew by 2–8 $m^3$/m. In transition south, the beach had an increase in sediment volume of 2 $m^3$/m, whereas the dune's volume added 7 $m^3$/m. The beaches in

Table 3. *Analysis of variance for horizontal changes between nourishment zones.*

| | Beach | | | Dune | | |
|---|---|---|---|---|---|---|
| | DF | *F*-Value | *p*-Value | DF | *F*-Value | *p*-Value |
| 1997–98 | 110 | 72.33 | $<0.0001$ | 108 | 31.19 | $<0.0001$ |
| 1998–99 | 109 | 46.25 | $<0.0001$ | 107 | 24.83 | $<0.0001$ |
| 1999–2000 | 110 | 16.54 | $<0.0001$ | 107 | 5.22 | $<0.0001$ |
| 1997–2000 | 110 | 3.39 | 0.0026 | 107 | 10.75 | $<0.0001$ |

the southern nonnourished zones were erosional, losing 6–13 $m^3$/m. The dune volume in this area increased by 6–8 $m^3$/m.

### Profile Changes

Representative profiles for each zone (Figure 4), generated from the DEM data, show changes in the morphology of the beach/dune system over the 4-year period of the study. In the nourished zones, sediment accumulation occurred across the entire profile in the 1997–98 period. In the northern nourished zone, the beach was displaced about 40 m horizontally, and its elevation was increased by 2 m at the seaward end of the profile and by 1 m in the middle of the beach. The profile in the southern nourished zone shows less vertical growth (0.5–1 m), and the water–land contact was displaced seaward by about 30 m. The dunes in these nourished zones also were modified. In the northern zone, a distinct dune existed prior to the start of nourishment. By 1998, the lower part of the seaward face of the dune showed about 0.5 m of vertical accretion, presumably as a result of the beach fill. The dune crest at this location was lowered vertically at the seaward side of the dune, but the landward side of the dune showed some accretion. In the southern nourished zone, the dune was quite small before nourishment began. The 1998 profile shows a large dune that had increased in height by as much as 1 m and in width by 40 m.

The 1998 and 1999 profiles in the nourished zones show the effects of hurricane Floyd that made landfall in September 1999 just a few km to the south of Wrightsville Beach. The 1999 LIDAR survey was flown shortly after the storm. The profiles show horizontal beach recession, returning to near their 1997 configuration. They were also lowered vertically nearly to their 1997 elevations. The small dune present on the northern nourished profile in 1998 was totally removed in 1999. In the southern nourished zone, the dune crest was lowered by about 0.5 m.

Beach erosion continued in the nourished zones during 1999–2000. The lower parts of the profiles were landward of their 1998 positions, and some parts on the profiles were landward of their 1997 locations. The dunes, however, increased in size between 1999 and 2000. On the northern profile, a small dune about 0.5 m high and 20 m wide developed. On the southern profile, the dune developed on top of the remnants visible on the 1999 profile, primarily landward of the old dune crest. Vertical growth on this profile amounted to 1.5 m and width increased by 30 m.

Profile changes in the transition zones were more subtle than in the nourished zones. There is evidence of the deposition of fill material on the lower ends of both transition profiles between 1997 and 1998. However, nearly all of this material was removed by 1999, and both profiles returned to their 1997 locations. Beach erosion on the lower part of the northern transition profile continued through 2000, whereas this area remained stable in the southern transition zone. The dunes had only minor changes throughout the entire study period. In the southern transition zone, there was some growth at the lower end of the seaward face of the dune associated with the placement of the fill material, and growth was maintained through 2000. There was no similar growth in the northern transition zone resulting from the fill project, but between 1998 and 1999, a small dune (1.5 m high and 15 m wide) developed.

In the southern nonnourished zones, there were few large-scale changes across the profile. The initial 1997 profiles show a pronounced berm feature at their seaward end. Over time, this berm was gradually removed until a much more linear beach profile developed by 2000. The greatest amount of foreshore erosion occurred in 1998–99, presumably in response to the passage of hurricane Floyd. As the foreshore eroded, there was some small accumulation of sediment on the backshore starting in 1998 and continuing through 2000. The dune crests on both profiles have a number of narrow but high peaks of sediment accumulation. These shapes are suggestive of the emplacement of sand fences that are widely used in developed dune systems and that cause the accumulation of sediment in a narrow band downwind of the fence.

The beach profiles in the northern nonnourished areas show stability in the backshore area, but changes on the foreshore differ along each profile. In the zone closest to the inlet, the beach grew seaward by nearly 50 m between 1997 and 2000. This growth occurred progressively during each of the time intervals despite the 1998 and 1999 hurricanes. About 60% of the overall accretion on the northernmost profile occurred during the 1999–2000 period. In northern nonnourished zone 2, the beach eroded steadily during the study period, but the overall loss was about 15 m. Dune changes also varied in each zone. Near the inlet, the dune was only about 1 m high, but the dune slope break advanced seaward by 15 m during the 1997–2000 period. Farther south from the inlet, the dune grew progressively during the 4-year period both in height (1.5+ m) and width (10+ m). The spikes evident on the dune crests are similar to those evident on the profiles from the southern nonnourished zones.

## DISCUSSION

The LIDAR surveys allow both horizontal and volumetric data to be collected that, in combination, provide a detailed view of the morphologic changes that occurred on these beaches between 1997 and 2000 associated with a beach-nourishment project and with the passage of several hurricanes. Observations that can be made about the nature of these changes are limited because the LIDAR data provide information only about subaerial changes.

Human intervention has governed the general changes that occurred here. The infusion of some 340,000 $m^3$ of sediment on the subaerial portion of the beach/dune profile in the

Table 4. *Paired comparison of beach zones using Fisher's PLSD test.**

| | NN No 1 | TN | N2 | N1 | TS | NN So 2 | NN So 1 |
|---|---|---|---|---|---|---|---|
| 1997–98 | | | | | | | |
| NN No 2 | 0.0121 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | 0.9216 | 0.0001 |
| NN No 1 | | <0.0001 | <0.0001 | <0.0001 | <0.0001 | 0.0281 | 0.0840 |
| TN | | | <0.0001 | <0.0001 | 0.0181 | <0.0001 | <0.0001 |
| N2 | | | | 0.8492 | <0.0001 | <0.0001 | <0.0001 |
| N1 | | | | | <0.0001 | <0.0001 | <0.0001 |
| TS | | | | | | <0.0001 | 0.0256 |
| NN So 2 | | | | | | | 0.0005 |
| 1998–99 | | | | | | | |
| NN No 2 | 0.0983 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | 0.0002 | <0.0001 |
| NN No 1 | | <0.0001 | <0.0001 | <0.0001 | <0.0001 | 0.0188 | <0.0001 |
| TN | | | <0.0001 | <0.0001 | 0.6933 | 0.0001 | 0.0506 |
| N2 | | | | 0.8230 | <0.0001 | <0.0001 | <0.0001 |
| N1 | | | | | <0.0001 | <0.0001 | <0.0001 |
| TS | | | | | | 0.0005 | 0.1113 |
| NN So 2 | | | | | | | 0.0786 |
| 1999–2000 | | | | | | | |
| NN No 2 | 0.1202 | 0.6915 | 0.4432 | 0.9709 | 0.0218 | 0.003 | <0.0001 |
| NN No 1 | | 0.0682 | 0.4596 | 0.2109 | 0.0002 | <0.0001 | <0.0001 |
| TN | | | 0.2737 | 0.7099 | 0.0751 | 0.0021 | <0.0001 |
| N2 | | | | 0.5439 | 0.0035 | <0.0001 | <0.0001 |
| N1 | | | | | 0.0465 | 0.0015 | <0.0001 |
| TS | | | | | | 0.1689 | <0.0001 |
| NN So 2 | | | | | | | 0.0001 |
| 1997–2000 | | | | | | | |
| NN No 2 | 0.9638 | 0.2208 | 0.0800 | 0.0686 | 0.3589 | 0.9995 | 0.0001 |
| NN No 1 | | 0.2262 | 0.0801 | 0.0693 | 0.3702 | 0.9675 | 0.0001 |
| TN | | | 0.6610 | 0.4905 | 0.7706 | 0.2573 | 0.0094 |
| N2 | | | | 0.7491 | 0.4573 | 0.1078 | 0.0212 |
| N1 | | | | | 0.3398 | 0.0875 | 0.0811 |
| TS | | | | | | 0.3961 | 0.0042 |
| NN So 2 | | | | | | | 0.0003 |

* NN No = nonnourished north; NN So = nonnourished south; TN = transition north; TS = transition south; N = nourished.

spring of 1998 represents the greatest change to the system. The volumetric analysis for the 1997–98 period shows a subaerial accretion of only 100,309 m$^3$. Thus, 71% of the fill material is unaccounted for by the volumetric analysis. Part of this loss may be attributed to sediment transfer from the subaerial to the subaqueous part of the beach profile that typically occurs following the placement of fill on a beach (DEAN, 1983; KRAUS and LARSON, 1988). This redistribution was observed following beach-nourishment projects at Wrightsville Beach in 1980–81 (PEARSON and RIGGS, 1981). An important factor governing the loss of sediment was the occurrence of Hurricane Bonnie in late August of 1998. Bonnie was not a particularly strong hurricane (Table 1), but it would have been large enough to move sediment from the beach to the offshore part of the profile, as is typical during storms. Some of the sediment may have been transported alongshore to adjacent segments, as the Corps of Engineers expects to happen with feeder-nourished areas of the shoreline. However, the profile data suggest that there were limited volumetric additions of sediment to the beach either north or south of the transition zones in the period immediately following the nourishment (Figure 2).

Continued loss of fill sediment occurred from 1998 to 2000. Hurricane Floyd made landfall in the middle of September 1999 just south of Wrightsville Beach. The hurricane was only a category 2 storm at landfall (Table 1), but in the 24–48 hours preceding landfall, the winds reached category 4 levels, producing waves that reached 7–9 m at NOAA buoys offshore (www.ndbc.noaa.gov). This event is certainly responsible for the loss of sediment volumes from all beach zones in the 1998–99 period. Beach sediment loss was limited in the 1999–2000 period, when no major tropical storm occurred.

Net subaerial volumetric change for the entire barrier shows a gain of some 37,000 m$^3$ of sediment over the 4-year period (Table 2), which represents about 10% of the amount of fill placed on the beach in early 1998. The majority of the accumulation (90%) occurred within the nourishment zone and in the dune zones. Very little of the nourishment sediment was transferred to subaerial beaches adjacent to the nourishment zones (Figure 3C). Large amounts of sediment loss occurred in the zones within the inlets at the northern and southern ends of the barrier island. It appears that the nourishment project had little net positive effect on the subaerial sediment budget of the Wrightsville Beach barrier island, as the fill sediment was nearly completely removed just 2 years after the project.

The influence of human intervention on this beach is also reflected in the changes that took place in the dunes. The hurricanes produced significant dune erosion along the seaward face of the dune, lowering of the dune crest in some

Table 5. *Paired comparison of dune zones using Fisher's PLSD test.**

| | NN No 1 | TN | N2 | N1 | TS | NN So 2 | NN So 1 |
|---|---|---|---|---|---|---|---|
| 1997–98 | | | | | | | |
| NN No 2 | 0.0135 | 0.0020 | <0.0001 | <0.0001 | 0.0338 | 0.6775 | 0.5474 |
| NN No 1 | | 0.3681 | <0.0001 | <0.0001 | 0.8742 | 0.0567 | 0.0040 |
| TN | | | <0.0001 | <0.0001 | 0.3295 | 0.0106 | 0.0006 |
| N2 | | | | 0.3719 | <0.0001 | <0.0001 | <0.0001 |
| N1 | | | | | <0.0001 | <0.0001 | <0.0001 |
| TS | | | | | | 0.1043 | 0.0111 |
| NN So 2 | | | | | | | 0.3368 |
| 1998–99 | | | | | | | |
| NN No 2 | 0.0225 | 0.0043 | <0.0001 | <0.0001 | <0.0001 | 0.0096 | 0.0003 |
| NN No 1 | | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 |
| TN | | | <0.0001 | 0.0056 | 0.0082 | 0.8285 | 0.3113 |
| N2 | | | | 0.0964 | 0.0246 | <0.0001 | 0.0003 |
| N1 | | | | | 0.7099 | 0.0035 | 0.0840 |
| TS | | | | | | 0.0051 | 0.1344 |
| NN So 2 | | | | | | | 0.2310 |
| 1999–2000 | | | | | | | |
| NN No 2 | 0.7437 | 0.8801 | 0.5703 | 0.6585 | 0.3645 | 0.0002 | 0.0008 |
| NN No 1 | | 0.6362 | 0.3522 | 0.8594 | 0.2062 | <0.0001 | 0.0002 |
| TN | | | 0.6928 | 0.5731 | 0.4638 | 0.0006 | 0.0017 |
| N2 | | | | 0.3463 | 0.7092 | 0.0012 | 0.0035 |
| N1 | | | | | 0.2190 | 0.0002 | 0.0007 |
| TS | | | | | | 0.0056 | 0.0129 |
| NN So 2 | | | | | | | 0.8652 |
| 1997–2000 | | | | | | | |
| NN No 2 | <0.0001 | 0.8948 | 0.0663 | 0.0583 | 0.0029 | 0.8380 | 0.0366 |
| NN No 1 | | 0.0001 | 0.0176 | 0.0865 | <0.0001 | <0.0001 | <0.0001 |
| TN | | | 0.1006 | 0.0836 | 0.0027 | 0.7462 | 0.0316 |
| N2 | | | | 0.7537 | <0.0001 | 0.0524 | 0.0002 |
| N1 | | | | | <0.0001 | 0.0463 | 0.0004 |
| TS | | | | | | 0.0004 | 0.0082 |
| NN So 2 | | | | | | | 0.0689 |

* See footnote for Table 4 for acronym explanations.

instances and completely removing the dune in others (Figure 4). Subsequent to the storms, the dunes grew vertically by as much as a meter within a year. Numerous studies of eolian processes on beaches show that considerable amounts of sediment can be transported landward, but vertical dune growth of a meter or more is very rare in coastal settings (Arens, 1997; Gares, 1990; Sarre, 1989). Furthermore, sediment deposition by wind tends to be distributed rather evenly in a downwind direction rather than concentrated in a single pile in a single place. When deposition occurs in this fashion, it is generally because of the use of sand fences that cause sediment deposition in a single location around the fence and in an amount sufficient enough to cause an obvious narrow sand ridge to form (Gares, 1990; Phillips and Willetts, 1979). The profile data (Figure 4) obtained from the LIDAR surveys suggest that sand fences are widely used along the Wrightsville Beach shoreline. In particular, the spikes on the dune crest in nearly all the profiles are evidence of this activity. When a wider and more substantial dune develops in a 1-year period, as it did between 1999 and 2000 on the profiles for nourished zones 1 and 2 (Figure 4), it suggests that the feature was created with a bulldozer because the wind simply cannot move that much sand and deposit it in a single ridge in a 1-year period. An interview with an official with a Wrightsville Beach Planning Official reveals that the practice of erecting sand fences and bulldozing dunes following storms is standard in this community.

The data generated from the LIDAR surveys allow for a statistical examination of the spatial characteristics of the beach and dune zones along Wrightsville Beach. Analysis of variance (Table 3) shows that the horizontal changes differed significantly between all the barrier island zones for all years analyzed. An analysis of paired zones using Fisher's protected least significant difference test shows that a limited number of pairs are statistically similar at the 0.05 level (Tables 4 and 5). The two nourishment zones have no statistical differences in any of the time periods, as a result of the artificial manipulation of the profile in the fill zones. There is also no statistical difference between beach zones at the northern and southern inlet shorelines (Table 4). The number of similar pairs does increase in number with time passed after the 1998 nourishment project (3 in 1997–98; 6 in 1998–99; 12 in 1999–00; and 22 for 1997–2000). By 2000, only the southern nonnourished zones were different from the other zones, although the changes in the southern transition zone and the adjacent nonnourished zone south 2 were statistically similar. This suggests that, as time passed, the nourishment zones became similar to the other beach zones, a reflection of the increasing importance of natural processes as the control on the beach form.

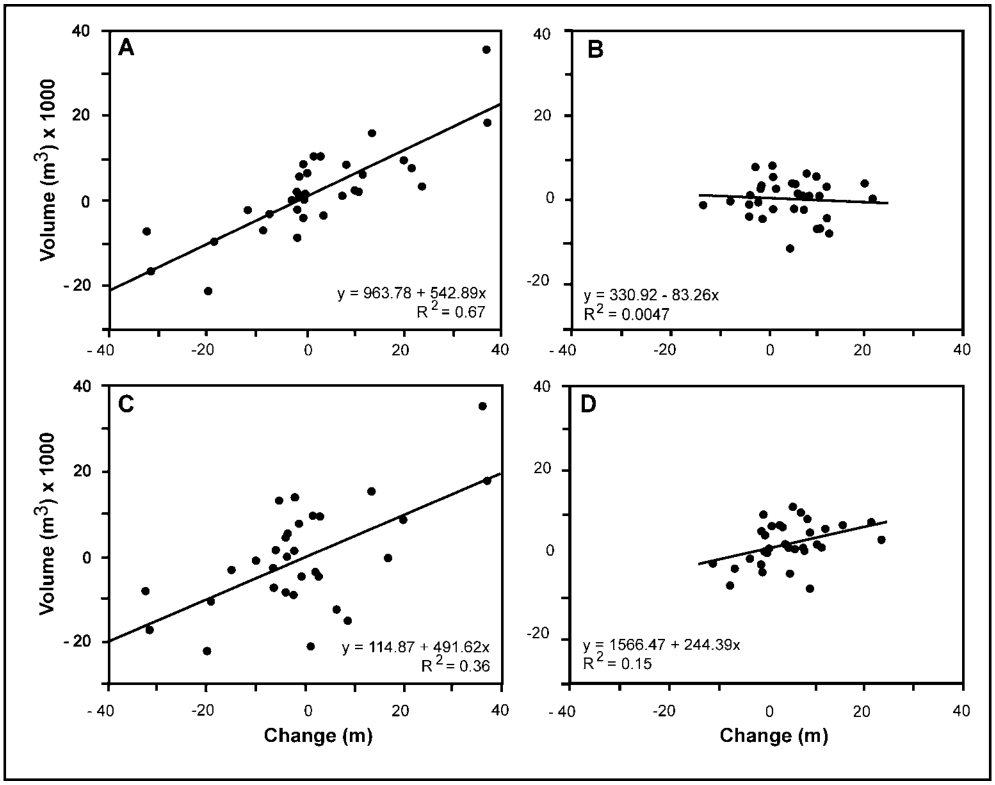


Figure 5. Regression plots of horizontal change and volumetric change for the study period 1996–2000—nourished all sites (A), nonnourished all sites (B), beach all sites (C), and dune all sites (D).

Changes in the barrier zones for the 1997–2000 period were similar in 22 of the 28 pairs. The only beach zone that changed differently than all the rest over this period was the southernmost zone, along Masonboro Inlet. This location showed substantial extension south during the 3-year period that was not recorded by the change data because the LIDAR surveys did not cover this area consistently. Thus, the statistical differences between nonnourished zone south 1 and the others may be an artifact of the data set.

The dune zones show more consistency in their year-to-year changes (Table 5). The number of pairs that show no statistical difference remains about the same during 1997–98 and 1998–99 (9 and 7, respectively). The number of similar pairs in the 1999–2000 period jumps to 16. This coincides with the passage of hurricane Floyd, which resulted in dune erosion in many locations (Figure 4). The traditional management response to dune erosion is to rebuild the dunes as soon as possible following the storm either by bulldozing sand into a dike or by installing sand fences to promote deposition of wind-blown sand. These efforts to create a new dune produce a landform of consistent height and width. This would explain the similarities between zones in the case of dune data.

The two nourished zones are not different statistically in any of the study periods, reflecting the manner in which shoreline manipulation results in a consistent shoreline configuration. The transition zones are more often statistically similar to the nonnourished zones to which they are adjacent than to the nourished zones. This may be because the fill contractor made less of an effort to establish a consistent dune profile outside of the primary nourishment zones.

This analysis of variance illustrates the degree to which human manipulation determines the type of changes that can be expected along a shoreline, as observed by NORDSTROM (1995). It also suggests that changes at the extremities of this shoreline are quite consistent, despite inlet processes that are often seen to create changes that differ from those on the remainder of barrier island shorelines (FITZGERALD *et al.,* 1978; NORDSTROM, 1987).

Shore-perpendicular transects have been widely used to analyze coastal changes (DOLAN *et al.,* 1992), but volumetric analysis may often reveal more about barrier island changes. The availability of both types of data from the LIDAR surveys allows the two types of data to be compared. Regression analysis of horizontal and volumetric changes (Figures 5–7) shows the nature of the relationship under varying circumstances. A high $r^2$ occurs for the nourished conditions (Figure 5A), whereas nonnourished areas show no relationship between the variables (Figure 5B). Beach data are more highly correlated than dune data. When the data are split into nourished and nonnourished beach and dune zones (Figure 6), the analysis reveals that nourished beach data have the highest $r^2$. There is no relationship at all between volumetric change and horizontal change in dune areas in either nourished or

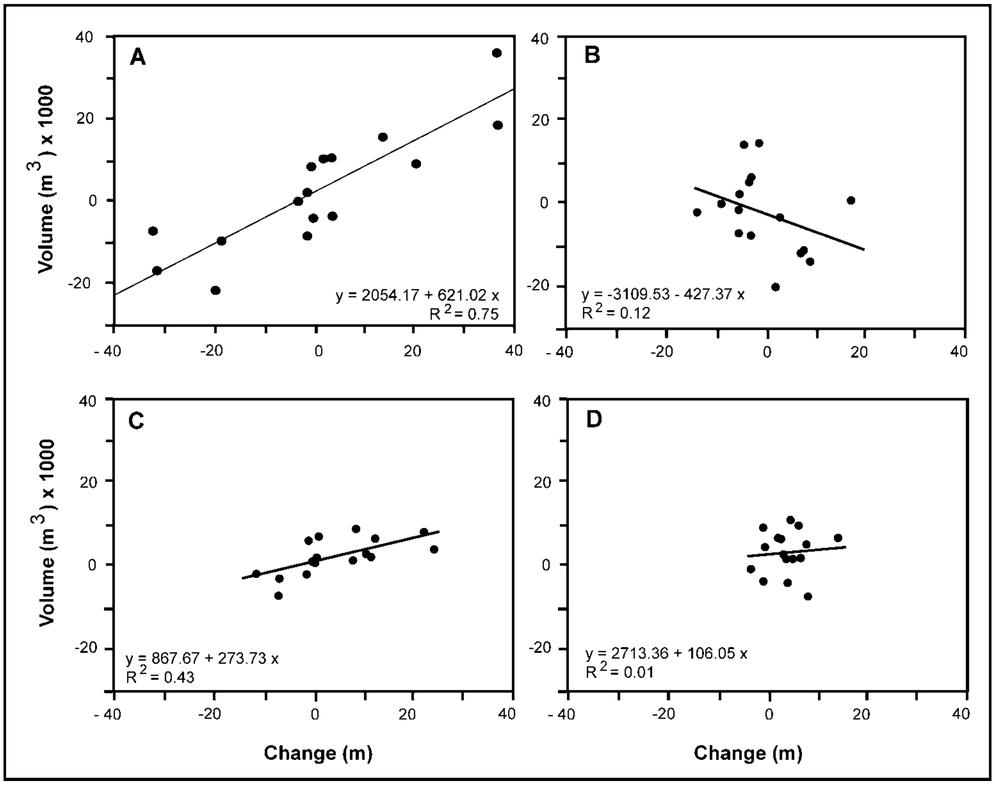


Figure 6. Regression plots of horizontal change and volumetric change for the study period 1996–2000—nourished beach (A), nonnourished beach (B), nourished dune (C), and nonnourished dune (D) zones.

nonnourished zones. Finally, there are large differences in the $r^2$ values when the data are separated by year (Figure 7). The highest $r^2$ occurs for the 1997–98, period when the nourishment project took place. As time passes, the $r^2$ diminishes and the relationship becomes inverse. For the entire 3-year study period, there is no relationship between horizontal changes and volumetric changes. These statistical comparisons suggest that human intervention in the form of the placement of fill on the beaches at Wrightsville Beach is the overriding factor in establishing the topographic form of this barrier island. Under the highly controlled situation that beach nourishment represents, the establishment of a design cross-sectional profile is the factor that controls the volume of sand in the system. However, the relationship deteriorates when different zones and different time intervals are analyzed. In the dune zone, there is a much weaker relationship between volumetric and horizontal change, although the $r^2$ is higher for dune areas in nourished zones than it is for nonnourished zones. The situation in the dune areas would seem to be dictated by the highly variable dune manipulation that takes place along the length of the shoreline. The beach profiles (Figure 4) show that dunes were bulldozed or controlled with sand fences at different places at different times. These variations affect the volume/change relationship. The importance of nourishment to creating a strong volume/change relationship is emphasized by the high $r^2$ for the 1997–98 nourishment period. The lower $r^2$ for subsequent years suggests that, as natural processes rework the nourishment sediment over time, the volume/change relationship becomes altered. The overall impression of this analysis is that horizontal change does not represent volume very well, particularly in dune areas or in more natural situations, as opposed to human-modified situations.

## CONCLUSIONS

The examination of LIDAR data for Wrightsville Beach, North Carolina, shows that this source of information provides considerable digital data for representing coastal topography for use in both horizontal and volumetric analysis of change. It has advantages over almost any other type of data-generating technique. The LIDAR data effectively depict the outcomes of a beach-fill project conducted in 1998. Analysis of the data shows that the emplacement of fill in the central part of the island had significant consequences to the beach/dune systems along the entire barrier. The areas of heavy human intervention produced landforms and changes to those landforms that are consistent throughout the nourishment area, both on the beach and the dune, as a result of profile manipulation during the fill project. In the transition areas adjacent to the primary fill zone, the beach changes showed some consistency with those that occurred in the nourished zones, but the dunes changed differently. Dune changes both in the transition zones and in the nonnourished

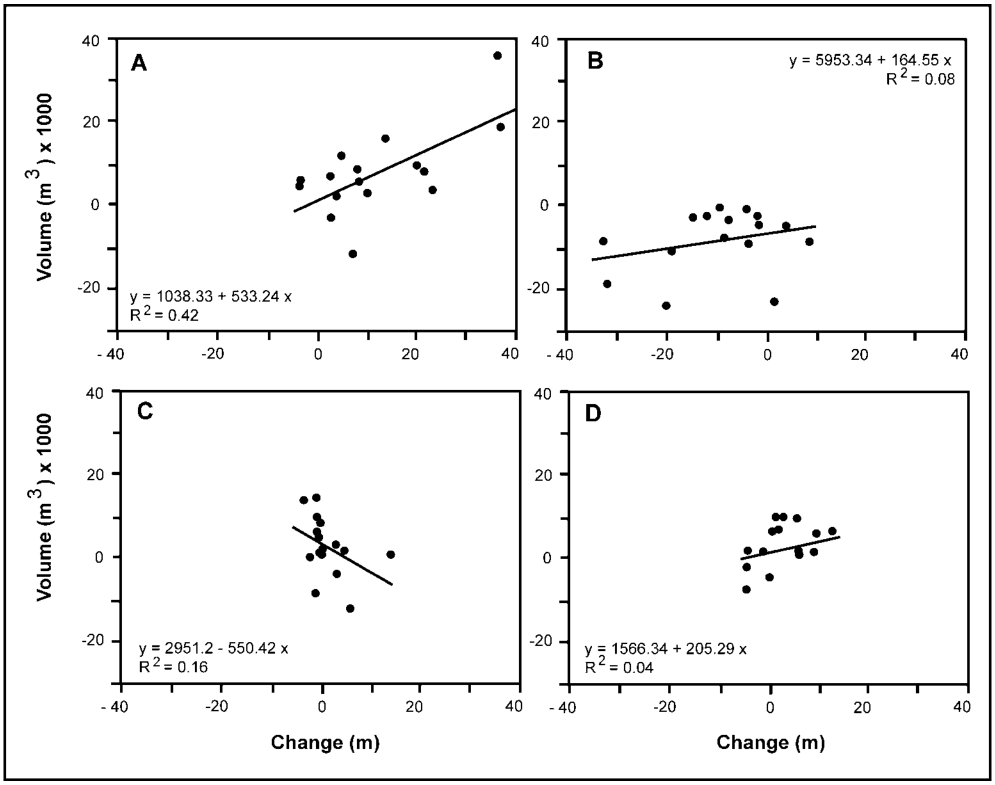


Figure 7. Regression plots of horizontal change and volumetric change for paired years 1997–98 (A), 1998–99 (B), 1999–2000 (C), and for the entire study period 1997–2000 (D).

areas are mainly the result of human efforts to rebuild dunes following storms. Beach changes in the nonnourished zones were more variable but did show similarities both between adjacent zones and comparable zones at the island extremities, which suggest the inlet processes are similar regardless of whether they pertain to the northern or southern end of this barrier. Finally, the LIDAR data allow changes to be evaluated both in terms of horizontal and volumetric changes. The horizontal data provide relevant information about shore-perpendicular movement of the shoreline or the dune line, but give no information about the changes in the topography of the system. LIDAR data allow the researcher to develop across-shore profiles that depict the nature of the changes and illustrate where sediment is accumulating or eroding. The volumetric data that are obtained from the LIDAR surveys give an overall picture of the sediment budget of coastal morphologic units, indicating whether the unit is losing or adding sediment.

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