Shoreline and Beach Volume Change Before and After the 2004 Hurricane Season, Palm Beach County, Florida

By

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ABSTRACT
This paper quantifies the shoreline and volume change utilizing three LIDAR data sets that were collected in Palm Beach County before and after the 2004 hurricane season. The beaches in Palm Beach County were significantly affected by Hurricanes Frances and Jeanne. Shoreline positions were extracted from the LIDAR-derived digital elevation models (DEMs), and the DEMs were differenced to yield volume change. The 52.4-kilometer-long study area lost nearly 5.8 million cubic meters (m^3) of sediment due to the 2004 hurricane season, with major erosion occurring to the berm, sandbar, and the northerly sections of ebb tidal deltas. On average, nearly 10 meters of shore erosion was observed. Correlation between shoreline movement and volume change was quantified. A poor R^2 value of 0.39 was found between shoreline and volume change before the hurricane season in the northern section of Palm Beach County because of beach nourishment and inlet dynamics. However, a relatively high R^2 value of 0.78 in the southern section of Palm Beach County was found due to little disturbance from tidal inlets and coastal engineering projects. The 2004 hurricane season reduced the R^2 values to 0.02 and 0.42 for the north and south sections, respectively.

Additional Keywords: LIDAR, bathymetry, beach profiles, hurricane impacts.

INTRODUCTION
Beaches are an extremely valuable resource for the recreation and tourism business. Most sandy beaches along the U.S. East Coast suffer from chronic and episodic erosion. Quantifying these changes is critical for understanding why they occurred, for designing and evaluating beach nourishment projects, and for beach management. Three-dimensional measurements of subaerial topography and nearshore bathymetry are required for quantifying change because beach morphological change occurs along the entire beach profile. Until the recent advent of airborne light detection and ranging (LIDAR) technology, it has been difficult to obtain measurements of beaches over large areas with sufficient resolution and accuracy to adequately measure three-dimensional volume change.

Traditionally, there were two methods to quantify beach change. One was to compare the beach profile observations along the shore to locate morphological differences and interpolate volume change (Aubrey, 1979; Morton, et al., 1994; Morton, et al., 1995). This method has been employed by Florida Department of Environmental Protection to monitor beach volume change. A series of monuments along the entire sandy coastline of Florida has been installed, and profiles at monuments have been ground surveyed repeatedly for change determination. However, since the monuments are spaced approximately 300 meters apart, interpolation is necessary to estimate the volume change between monuments. Swales (2002), Finkl (2004), and Zhang, et al. (2005) found the sparse sampling intervals may lead to an inaccurate representation of coastal change, and higher resolution data are needed to accurately quantify beach volume change.

Beach change can be determined by analyzing the position of the high water line (Galgano, et al., 1998; Pajak and Leatherman, 2002; Zhang, et al., 2002). Although shoreline position change only represents two-dimensional beach variation, the shoreline data are often used to estimate volume change due to a lack of three-dimensional measurements (Jarrett, 1991; Rosati, 2005). It is assumed that the entire active profile which spans from the berm to the depth of closure moves at the same rate as the rate of shoreline change, while the active profile shape remains unchanged. Detailed information for converting shoreline variations into volume change based on this assumption can be found in Rosati (2005). However, little systematic investigation has been undertaken on the relationship between shoreline position and volume change, and the accuracy of such estimations has suffered due to the lack of high-resolution three-dimensional measurements.

LIDAR mapping allows for rapid and dense three-dimensional measurements of the subaerial beach and nearshore bathymetry. The significant increase in resolution makes it possible for researchers to analyze coastal change with great detail. Several studies have demonstrated the effectiveness of LIDAR data when applied...
to the analysis of coastal morphological change (Shrestha and Carter, 1998; Shrestha, et al., 1999; Brock, et al., 2002; Sal-lenger, et al., 2003). The shoreline position (Stockdon, et al., 2002; Robertson, et al., 2004) and beach volume (Irish and White, 1998; Woolard and Colby, 2002; White and Wang, 2003; Zhang, et al., 2005) can be computed from LIDAR data due to the three-dimensional properties of these remotely sensed measurements. Therefore, LIDAR measurements allow for a direct comparison of two separate methods for measuring coastal change: shoreline position and beach volume.

The direct comparison between shoreline position and volume change methods also allow for quantifying their correlation. It has long been recognized that beach profile will adjust to seasonal wave climates or major storm events (Shepard, 1950; King, 1972; Aubrey, 1979). This adjustment leads to erosion in the upper beach and deposition in lower beach in the form sand bars due to storm events. The profile adjustment will influence the correlation between shoreline and volume change, but previous studies have not quantified the correlation for normal or storm conditions.

Hurricanes Frances and Jeanne affected Palm Beach County’s beaches in 2004. Frances was a Category 2 hurricane that made landfall on Sept. 5, 2004 over the southern end of Hutchinson Island, FL (Beven, 2004). Jeanne made landfall at almost the same position on Sept. 26, 2004 as a Category 3 hurricane (Lawrence and Cobb, 2005). Palm Beach County was approximately 20 kilometers south of the landfall of both hurricanes, and on the left or weak side (Figure 1). However, Palm Beach County beaches still experienced significant erosion from the storms.

This study utilizes two LIDAR data sets collected before and after one collected after the 2004 hurricane season along the Palm Beach County coast. These data consist of both subaerial and bathymetric measurements that provide excellent information for quantifying beach change under normal and storm conditions. The beach extends from the toe of the dune to the depth of closure. The primary objective of this paper is to quantify shoreline and beach volume change for central and southern Palm Beach County before and after the 2004 hurricane season. A second objective is to quantify the correlation between shoreline movement and volume change under normal and storm conditions.

STUDY AREA

Palm Beach County is located in the southeastern section of the Florida peninsula with more than 72 kilometers of sandy beach coastline. This study focuses on the southernmost 52 kilometers of coastline in Palm Beach County and the bathymetry extends approximately 600 meters offshore (Figure 1). The coastline is relatively straight and oriented north-northeast to south-southwest. The study area includes two inlets, and offshore is characterized by one to two sandbars. Beach sediments are bimodal containing shell fragments and quartz grains. The average deep water wave height is 0.98 meters with the predominant wave direction from the northeast (Benedet, et al., 2004).

DATA AND METHODS

LIDAR Data

LIDAR is an active remote sensing technology that determines ground elevations by measuring the travel time of laser pulses transmitted from an aircraft. Over the last decade, several LIDAR systems have been employed to collect data of Florida beaches. This study utilizes LIDAR data collected by two systems: LADS and CHARTS. Laser airborne depth sounding (LADS) was flown in October to November 2002, by the Tenix LADS Corporation, Coastal Planning and Engineering, and Palm Beach County. The LADS system fired a green laser (532 nm) at 900 Hz yielding a point spacing of approximately 4 meters. In June 2004 and November to December 2004, the U.S. Army Corps of Engineers (USACE) deployed the compact hydrographic airborne rapid total survey (CHARTS) system. CHARTS has two lasers: one hydrographic and the other topographic. The hydrographic laser fired at 1 kHz while the topographic laser fired at 10 kHz. This produced point spacing on the ground of approximately 1.5 meters and a bathymetric point spacing of approximately 4 meters.

Vertical offsets between LIDAR data can add a bias to shoreline and volume change calculations. Fortunately, these biases can be estimated by comparing elevations from different LIDAR surveys on unchanged (hard) surfaces such as roads (Zhang, et al., 2005). Four profiles were extracted from concurrent roads distributed throughout the study area. The root mean square (RMS) differences between the three data sets were calculated. Results show that the RMS differences were less than 12 centimeters, suggesting that the three LIDAR data sets match well and there were no large systematic offsets. The LIDAR data were provided as irregularly spaced point measurements including horizontal coordinates and vertical elevations of topography and bathymetry. Further analysis required interpolating these data onto a regularly spaced grid to produce a digital elevation model (DEM). The data were gridded at 2 meters resolution using kriging interpolation and a linear variogram.

Shoreline Change

Since the shoreline is not a topographic feature, its position cannot be directly measured by LIDAR points. Therefore, local tidal datums were used to extract a shoreline contour from the three dimensional LIDAR data. Previous studies indicate that the digitized high water line

Figure 1. Map shows study area with location of transects and hurricane tracks.
The increased profile detail produced from LIDAR data provides a qualitative perspective on the morphodynamic change of the beach.

Volume change was quantified by using an ArcView extension called ALTM, developed by Keqi Zhang of the International Hurricane Research Center (IHRC). The same spine and 524 transects used for shoreline change were applied with the ALTM tool. The transects created 100-meter bins in the alongshore direction where volume change was calculated (Figure 2). This allows the calculation of volume change as a function of distance along the shoreline.

### Summary Statistics for the Entire Study Area

Summary statistics for the entire study area were compiled to reflect shoreline and volume change before and after the 2004 hurricane season (Table 1). Shoreline change before the 2004 hurricane season represents the difference between the shorelines extracted from the November 2002 LADS and June 2004 CHARTS LIDAR data. Shoreline change after the 2004 hurricane season represents the difference between the shorelines extracted from the June 2004 and November 2004 CHARTS LIDAR data. Positive values represent seaward movement of the shoreline, and negative values represent landward movement of the shoreline.

Results show the shoreline on average moved seaward 3.9 meters before and retreated more than 10 meters after the 2004 hurricane season. Conditions before the 2004 hurricane season showed maximum accretion at Transect 119 and maximum erosion at Transect 418. The maximum accretion was due to the 2003 Midtown Palm Beach nourishment project. The maximum

### Table 1. Shoreline and Volume Change Before and After the 2004 Hurricane Season.

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Max</th>
<th>Min</th>
<th>St.D.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoreline Change Before (m)</td>
<td>2.4</td>
<td>23.1</td>
<td>-17.8</td>
<td>10.1</td>
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<tr>
<td>Shoreline Change After (m)</td>
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<td>15.6</td>
<td>-33.0</td>
<td>13.0</td>
</tr>
<tr>
<td>Volume Change Before (m³)</td>
<td>-4235.2</td>
<td>37742.9</td>
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<td>11240.0</td>
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<tr>
<td>Volume Change After (m³)</td>
<td>-10974.8</td>
<td>75851.8</td>
<td>-134218.4</td>
<td>15667.7</td>
</tr>
</tbody>
</table>

### BEACH CHANGE BEFORE AND AFTER 2004 HURRICANE SEASON

Figure 2. Map of volume change for area surrounding Transect 175 due to the 2004 hurricane season.

Figure 3. Plot of shoreline and volume change along entire study area. North to south is from left to right. The interval between two adjacent transects is 100 meter. Data was filtered by a five-point moving average for clarity.
erosion at Transect 418 was due to the LADS data being collected immediately after the 2002 Delray Beach nourishment project, and therefore is showing the retreat following the project. Following the 2004 hurricane season, maximum erosion occurred at Transect 515. This area was nourished as part of the 2004 central Boca Raton nourishment project, and the area was significantly eroded following the 2004 hurricane season. The maximum accretion occurred at Transect 12, which is the northern limit of our study area, and appears to be due to the offshore bar being driven onshore.

Volume change represents the amount of change that occurred between transects and within the user-specified mask as described in the methods. Average volume change for the entire study area was found to be an erosion of -4,235 m³/transect before the 2004 hurricane season and -10,975 m³/transect after (Table 1). Since the study area contained 524 transects, and each transect was 100 meters, the average volume change before the 2004 hurricane season was -2.2 million m³, and -5.8 million m³ after. Increased erosion due to the 2004 hurricane season was expected, and locations of maximum accretion and erosion are caused by site-specific hydrodynamics and beach nourishment projects.

Maximum accretion of 37,743 m³ occurred at the 2003 midtown Palm Beach nourishment site at Transect 119 before the 2004 hurricane season, and following the 2004 hurricane season a maximum accretion of 75,852 m³ occurred at Transect 49 at the Lake Worth Inlet channel due to deposition of sediments in the dredged portion of the channel. For maximum erosion, the loss of -93,085 m³ at Transect 67 before the hurricane season was due to the dredging between Transects 55 and 90 for the 2003 midtown Palm Beach nourishment project. Following the 2004 hurricane season, a maximum erosion of -134,218 m³ was found at Transect 40. This area before the 2004 hurricane season had a large amount of sand just north of Lake Worth Inlet in the form of an ebb tidal delta. The two hurricanes not only moved the delta closer to the inlet, but they significantly decreased the ebb tidal delta size, resulting in the large volume of sediment loss.

A longitudinal north to south profile of shoreline and volume change is shown in Figure 3. The figure shows a qualitative example of shoreline and volume change as a function of along shoreline distance. The shoreline change values were multiplied by 500 to match the signal range of the volume change values. In general, shoreline change values are above zero, and volume change values are below zero before the 2004 hurricane season as summarized in Table 1. Volume and shoreline change following the 2004 hurricane season are below the zero line representing the overall erosion caused by the hurricanes. Extremes in the signals were found at and north of the dredged area for the 2003 nourishment project (Transect 69).

**RELATIONSHIP BETWEEN SHORELINE AND VOLUME CHANGE**

The shoreline and volume change curves were further compared to examine their correlation. Figure 3 shows a good in phase match between two curves before and after the 2004 hurricane season south of Transect 304, and a poor match to the north of Transect 304. The apparent match occurs between South Lake Worth and Boca Raton Inlets. To help understand the relationship between shoreline and volume change, four profiles were extracted from the before and after hurricane LIDAR data (Figure 4). Profiles at Transect 420 in Figure 4 show berm erosion and shoreline retreat after the 2004 hurricane season. The volumes of sediment eroded and accreted between 100-300 meters along the transect are approximately equal and are averaged out. The volume change mainly reflects the change for the upper portion of the profile, which is closely related to variation in shoreline position.

The relatively poor match spans from just north of Lake Worth Inlet to South Lake Worth Inlet. Large volume change differences between Transects 33 through 47 and 300 to 304 are due to Lake Worth Inlet and South Lake Worth Inlet, respectively. Each inlet area experienced erosion and reduction of the northern half of the ebb tidal delta along with deposition immediately south of the inlet following the 2004 hurricane season. In 2003, a nourishment project was completed between Transects 104 and 140. This project was responsible for the berm build-up and volume accretion before the 2004 hurricane season, and berm reduction and large volume erosion found after the 2004 hurricane season (Figure 4, Transect 110). Transect 110 shows a typical beach nourishment profile, where the steep berm and beach face slope was reduced by eroding the berm and depositing that sand just offshore. The reworking of sediments resulted in a large sediment loss between 90 and 350 m along Transect 110 due to the hurricanes.

There were two areas of shoreline accretion between Lake Worth and Boca Raton Inlets following the 2004 hurricane season at Transects 170 through 174 (Figure 2) and Transects 241 through 244. For each area, the position of the offshore bar was completely eroded, with some of the sediments driven to shore and the others moved...
slightly offshore (Figure 4, Transect 171). The sediments being driven onshore and pulled offshore resulted in the shoreline position migrating seaward, but a significant negative volume change (Figure 3). These areas provide an excellent example of how shoreline movement does not coincide with the volume change of the entire profile. However, just south of Transect 171 was Transect 178, where little change occurred between 2002 and spring 2004 (Figure 4). Following the 2004 hurricane season, the offshore bar was completely eroded, leading to a significant volume decrease and shoreline retreat. This demonstrates that the coastal morphological response to storms can be different within a short alongshore distance.

To test the correlation between shoreline migration and volume change for before and after the 2004 hurricane season, a plot of shoreline position against volume change for each transect along the study area was generated (Figures 5 and 6). A few outliers greater than three sigma representing locations at or close to inlets were removed. The data was then split into north and south sections at Transect 305 for correlation analysis due to the distinctive beach change behavior based on previous analysis. The R² value for the south section was 0.78 between 2002 and 2004, and 0.42 following the 2004 hurricane season. The R² value for the north section was 0.38 and 0.02 for before and after hurricane data, respectively. The correlation in the south was significantly better than the north, and the 2004 hurricane season significantly reduced the correlation for both areas.

It is understandable that the correlation between shoreline and volume change was better before the 2004 hurricanes (Figure 5). The shoreline position change only reflects the variation of the upper portion of the beach profile, not volume change for the entire beach profile. The requirement for perfect correlation between shoreline and volume change is that the active beach profile has to remain constant and move at the rate of shoreline migration. This is rarely the case for beach profile because the profile changes constantly as hydrodynamic factors vary. However, during a normal condition, the profile change is small thus a high 0.78 R² value was derived. This demonstrates that it is reasonable to use shoreline change position to estimate the volume change if the shoreline positions are measured during a normal condition. The correlation decreased significantly when a large beach profile adjustment, especially episodically storm-induced, occurs between two observations as pointed out by the previous studies (King 1972). Therefore, it is not appropriate to use the storm shoreline positions to estimate volume change.

The spatial correlation difference between north and south section is mainly due to the inlet activity and beach nourishment projects at the north section. The inlet activity and beach nourishment complicated the beach profile adjustment to changes in hydrodynamic factors. However, locations...
of tidal inlets and beach nourishment do not explain the shoreline migration and volume mismatch between Transects 165 and 208. Reasons for the weak correlation could be due to an active profile beyond the areas captured by the LIDAR data. To fully quantify beach volume change, the offshore profile must cover all significant volume change. Figure 2 shows volume change at the offshore edge of the LIDAR measurements, suggesting that sediments were exchanged between the offshore portion and the area beyond the scope of current LIDAR surveys. The role of this sediment exchange on beach volume change has to be investigated further.

CONCLUSIONS

This study quantified shoreline and volume change before and after the 2004 hurricane season in Palm Beach County, FL. Data used for analysis were three topographic and bathymetric LIDAR surveys flown 22 months before, three months before, and two months after the hurricane season. In general, the study area lost 5.8 million m$^3$ of sediments due to the 2004 hurricane season, with major erosion occurring to the berm, sandbar, and northerly sections of ebb tidal deltas. On average, more than 10 meters of shore retreat was observed.

The difference between shoreline and volume change between two observations is determined by the extent of profile adjustment during the same period. Techniques developed by IHRC researchers allowed for extracting the change data as a function of alongshore shoreline distance for comparison. Alongshore shoreline migration and volume change showed a good correlation with an R$^2$ value of 0.78 south of Transect 305 during normal conditions. North of Transect 305, inlet activity and nourishment projects were responsible for complicated adjustments in the beach profile, which lowered the shoreline and volume change correlation to 0.42 R$^2$. Shoreline and volume change correlation are strong before the 2004 hurricane season and weak after the 2004 hurricane season, indicating that shoreline change is more representative of volume change when data do not include an extreme storm event.

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REFERENCES


