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Authors: Benedet, L., Finkl, C. W., and Hartog, W. M.

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Processes Controlling Development of Erosional Hot Spots on a Beach Nourishment Project

L. Benedet[†‡], C.W. Finkl[†§], and W.M. Hartog[‡]

[†]Coastal Planning and Engineering, Inc.
Boca Raton, FL 33431, U.S.A.
lbenedet@coastalplanning.net

[‡]Delft University of Technology
2600 GA Delft, the Netherlands

[§]Department of Geosciences
Florida Atlantic University
Boca Raton, FL 33431, U.S.A.

ABSTRACT

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Beach erosion, a problem along most sandy shores, can be caused by man-induced interventions to the coast or natural processes. Remediation of beach erosion (*i.e.,* beach restoration) along eroding developed beachfronts is commonly practiced in the United States by periodic beach renourishment with or without coastal structures. Rates of erosion within beach fills generally vary greatly, and areas that erode faster than the nourishment average are commonly termed erosional hot spots (EHSs). Delray Beach, located on the southeast coast of Florida, was renourished for the fourth time on December of 1992 with about 914,000 m^3 of sand dredged from offshore and placed along 2.7 km of beach. About 448,000 m^3 of the fill had eroded away by 2001, about eight and a half years after initial construction. Two beach segments with erosion rates higher than the nourishment average were identified based on analysis of annual beach profile data. About 40% of the eroded volume accrued from one of these beach segments, a 600-m long EHS located on the downdrift end of the nourishment. We evaluated hypotheses to explain EHS development; these included the influence of nearshore features (reefs and borrows) on nearshore wave propagation, variability of grain size alongshore, and changes in shoreline orientation induced by the placement of fill. The nearshore reefs have little to negligible influence on the nearshore waves and are not the cause of the EHSs. Borrow areas significantly influence nearshore waves along the beach. Grain-size differences alongshore were also not the cause of increased erosion of EHS segments since grain sizes are not persistently finer where higher erosion is observed or *vice versa.* Change in shoreline orientation in the south end of the fill (EHS segment) causes an acceleration of the alongshore currents and an increase in sediment transport potential. Shoreline orientation effects appear to play a relatively more significant role in the development of the EHS in the south end of the fill than the other processes evaluated.

ADDITIONAL INDEX WORDS: *Erosional hot spot, beach morphodynamics, beach nourishment, wave transformation, alongshore current, shoreline change, Delray Beach.*

INTRODUCTION

Beach erosion and shoreline recession are major problems along most developed sandy shores. Remediation of beach erosion (*i.e.,* beach restoration) along eroding developed beachfronts is commonly practiced by combinations of periodic renourishments with or without coastal structures to stabilize a beach over the long term. Although beaches can be restored in many ways, beach nourishment is the most commonly practiced method of shore protection in both the United States and Europe (FINKL and WALKER, 2002; HANSON *et al.,* 2002; NRC, 1995).

Properly planned beach restoration requires quantitative assessment of nourishment evolution and an understanding of the main processes that affect fill performance. Additional attention is generally given to erosional hot spots (EHSs) because they erode more quickly than the alongshore average rate of erosion of the placed fill and can negatively affect a beach nourishment project.

Analysis of monitoring data (1992 to 2001) for a renourishment at Delray Beach, southeast coast of Florida (Figure 1), provides a rational basis to explain postplacement fill performance and EHS development. Delray Beach was initially nourished in July 1973 with the placement of 1.25 Mm^3 of sand and has been renourished five times since then (1978, 1984, 1992, 2002, and 2005). The 2005 nourishment was a smaller emergency project designed to mitigate volume losses attributed to two hurricanes that affected the project area. Data from preconstruction and postconstruction and annual monitoring surveys of beach profiles and beach sediments after the 1992 nourishment are analyzed in detail in this manuscript. Beach profiles are used to analyze beach nourishment evolution and volumetric losses and to identify EHSs. Possible mechanisms that cause EHSs are evaluated in terms of wave transformation over bathymetric irregularities, alongshore grain-size distribution, and shoreline orientation.

The main objective of this study is to identify the processes that affect development of EHSs in the nourishment area. Specific objectives include (1) identification and differentiation of EHSs within a beach fill using quantitative parameters; (2) evaluation of the effects of wave transformation over bathymetric irregularities, alongshore grain-size distribution patterns, and shoreline orientation on nourishment erosion; and (3) development of a framework for future, more detailed, numerical modeling studies.

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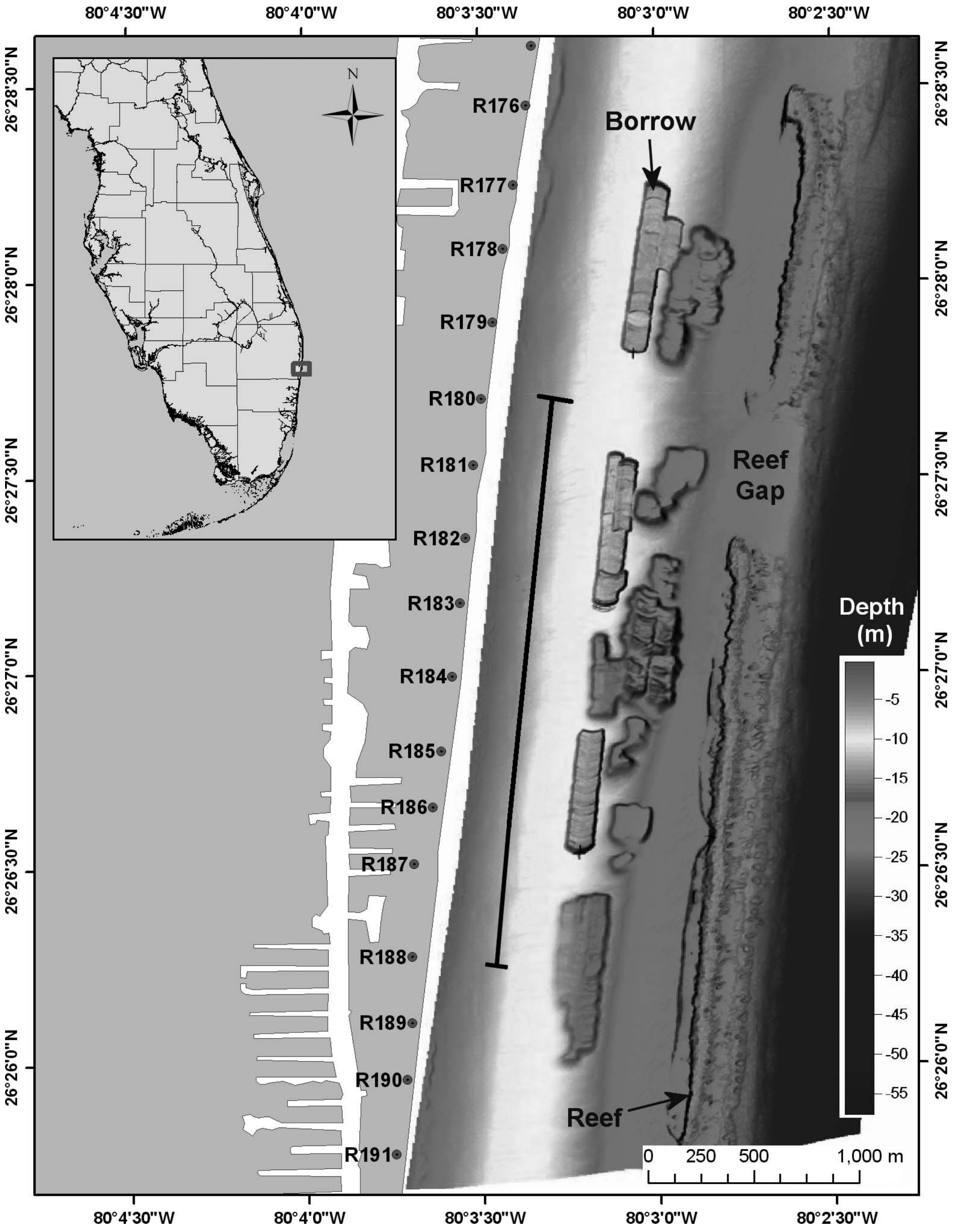

Figure 1. Location diagram showing bathymetry and nourishment boundaries of the study area. Borrow areas and the offshore shore-parallel barrier coral reefs are shown in the three-dimensional bathymetric image. The image was created based on high-resolution laser-airborne bathymetric data. **For color version of this figure, see page 127.**

STUDY AREA LOCATION AND GEOMORPHODYNAMIC FRAMEWORK

Delray Beach is located in the southern part of Palm Beach County about 80 km north of Miami Beach on the Florida southeast coast. Nearby inlets include south Lake Worth Inlet 10 km to the north and Boca Raton inlet 13 km to the south (Figure 1). The locations of beach profile monuments are indicated in Figure 1. The beach profile monuments defined by the Florida Department of Natural Protection are spaced approximately 300 m apart. The study area includes the beach between profile monument R180 to the north and R188 to the south.

Geological Controls on Coastal Geomorphology and Processes

Delray Beach, located in coastal southeast Florida, is situated on the Florida Peninsula, a large carbonate platform containing a thick sedimentary sequence that was constructed generally from the Jurassic to the Miocene (*viz.,* from about 180 to 5 million years ago; DAVIS, 1997). Geological development of the southeast Florida coast was strongly influenced by pre-Holocene topographic highs upon which coastal barriers were built (FINKL, 1993; HOFFMEISTER, 1974), providing a stable base where sediments could accumulate as sea level rose throughout the postglacial period.

When eroded by marine processes, the sandstones and coquina of the Anastasia Formation and coral reefs produce gravel-sized fragments that are commonly washed up on beaches after storms (HINE *et al.,* 1998). These carbonate sediments mix with siliciclastic sediments to form the suite of observed beach sediments.

The present natural shoreline contains 1 to 2 m of beach sand that overlies partly lithified sediments of the Anastasia Formation (FINKL, 1993). Outcrops of the Anastasia Formation occur underwater, where they form nearshore hardgrounds or rock reefs (FINKL, 1994) that serve as benthic habitats. Offshore barrier coral reef systems comprise the northernmost extension of the Florida Reef Tract (LIDZ, ROBBIN, and SHINN 1985) that is best developed along the Florida Keys. In the Delray Beach study area, these barrier reefs typically occur at depths of 18 to 22 m. Additional reef tracts occur farther offshore at greater depths. Sedimentary troughs located between the beach (or nearshore rock reefs) and the offshore coral reefs are infilled with sandy sediments that have been used as borrow materials for Delray Beach nourishments (*e.g.,* FINKL, ANDREWS, and BENEDET 2003). Coarser sediments (carbonate rubble accumulations) are located adjacent to reef gaps (holes, former passes, and inlets in the barrier reef system) and as overwash fans on the leeward sides of the barrier reefs (FINKL, BENEDET, and ANDREWS 2005a).

Wind, Waves, and Tides

The open-ocean, subtropical southeast coast of Florida is affected by northeasters (winter cyclonic northeasterly cold fronts), tropical southeast trade winds, tropical storms, and hurricanes that collectively comprise the wave climate in the study area. Predominant wind direction is from southeast and southwest during northern hemisphere summer months and from the northeast during winter (DAVIS, 1997). These general patterns are occasionally interrupted by extreme meteorological events such as tropical storms and hurricanes. During the last century, southern Florida has been affected by more hurricanes than any other area of comparable size in the United States (DOEHRING, DUEDALL and WILLIAMS, 1994). In 2004, for example, four hurricanes hit Florida, three were major hurricanes, and two affected the study area. Northeasters (winter extratropical storms) are significant weather–wave events that cause a considerable amount of sediment transport. Although wind velocities in northeasters are typically below hurricane force (*i.e.,* less than 120 km/h), they persist for several days (up to a week) generating large swell waves (2–3 m) with relatively long periods (10–12 s). By comparison, hurricanes are more severe in terms of wind speed and storm surge, but the shoreline impacts tend to be confined to coastal segments on the order of 100 km; waves tend to be steep with shorter periods (4–8 s); and hurricane events have relative shorter duration compared to northeasters. Wave conditions associated with northeasters and hurricanes account for most of the sediment removal in the renourished area. Because northeasters occur more frequently than hurricanes and are more persistent, they figure more prominently in the characterization of long-term morphodynamics at Delray Beach.

Calculations of wave statistics were based on the analysis of 20 years of hourly wave records from the U.S. Army Corps of Engineers Coastal and Hydraulics Laboratory wave hindcast for wave information study station A2011 (U.S. ARMY CORPS OF ENGINEERS, 2002), which is located approximately 6 km northeast of Delray Beach at 90 m water depth. The average deepwater wave height is 1 m with a period of 8.0 s and an angle of approach from the east–northeast (64°). Excluding extreme events (hurricanes and tropical storms), higher waves with longer peak periods (*i.e.,* 10 to 12 s) occur from October through March with predominant wave directions from northeast to east–northeast. Between April and September, waves approach mostly from the east and southeast with shorter periods (3–6 s). Tides are semidiurnal, mean water level is at 0.52 m, and average tidal amplitude is about 0.4 m. Episodic fluctuations in water levels occur as a result of storm surges induced by extreme weather events (tropical storms, hurricanes, and to a lesser extent northeasters).

HISTORY OF BEACH NOURISHMENT AT DELRAY BEACH

Since 1973, the study area was renourished five times with a cumulative total of 4.5 Mm^3 of sand (Table 1). Initial nourishment sediment, dredged from an offshore borrow pit (July 1973), comprised 1.25 Mm^3 of sand placed along 4.3 km of beach. The placed fill resulted in beach widths of approximately 80 m above the mean high water line. To restore dune systems and minimize Aeolian transport losses, native dune vegetation was planted in 1974. By 1977, beach profile monitoring (cross-shore surveys) indicated that about 382,000 m^3

Table 1. *Delray Beach nourishment project history.*

Year	Volume (m^3)	Length (m)	Unity Volume (m^3 m^{-1})
1973	1,250,000	4270	293
1978	536,000	2890	185
1984	994,000	4270	233
1992	914,500	2730	334
2002	940,000	3000	313
2005*	350,000	—	—

* Storm emergency restoration, approximate volume.

of sand had eroded from the beach. The first maintenance renourishment project was constructed in 1978 (February through May) when approximately 536,000 m^3 of sand was placed in two beach segments.

The second maintenance renourishment occurred in 1984 (September and October) when approximately 994,000 m^3 was placed over the original 4.3 km of beach. A monitoring report (CPE, 1992) indicated that by October 1992, about 260,000 m^3 of the fill placed in 1984 had eroded from the beach.

In an effort to address this erosion, a third maintenance renourishment occurred in 1992 (November and December) from R180 to about 150 m south of R188 (Figure 2). Approximately 914,000 m^3 of sand was placed along 2.7 km of beach. A fourth maintenance nourishment occurred in 2002 (February and March) from 150 m north of R180 to 150 m south of R188 when approximately 940,000 m^3 of sand was placed along 3 km of beach. A smaller emergency restoration project that used about 350,000 m^3 of sand was also constructed in early 2005 to mitigate sediment losses caused by two hurricanes that affected the project area in September and October of 2004 (Hurricane Frances and Hurricane Jeanne).

Previous Investigations

Studies relevant to the scope of this paper include those by Fernandez (1999), Gravens (1997), Beachler, (1993), and CPE (1994, 1995, 1996, 1998, 1999, and 2001). Salient findings in these studies are described as follows.

Nourishment of Delray Beach affected neighboring beaches as a result of fill spreading effects. Beachler (1993) described that from 1973 (initial nourishment) to 1990 the fill area lost 1.15 Mm^3 of sand when at the same time about 840,000 m^3 of sand was deposited on adjacent beaches 3 km to the north and south of the fill area.

Predictions of a one-line shoreline change model were compared with measured shoreline between 1987 and 1992 by Gravens (1997). The coastal segment between R180 and R181 was defined as an EHS by Gravens (1997). Shoreline change simulations that considered wave transformation over measured nearshore bathymetry (in comparison with an artificially created bathymetry with shore-parallel contours) provided better agreement with measured shoreline changes indicating influence of nearshore bathymetry on shoreline changes. As described by Gravens (1997), the EHS near R181 may be related to a gap in the barrier reef system offshore this location. Theoretically, the gap would cause gradients in nearshore wave height that would induce gradients in alongshore transport that could in turn lead to EHS development.

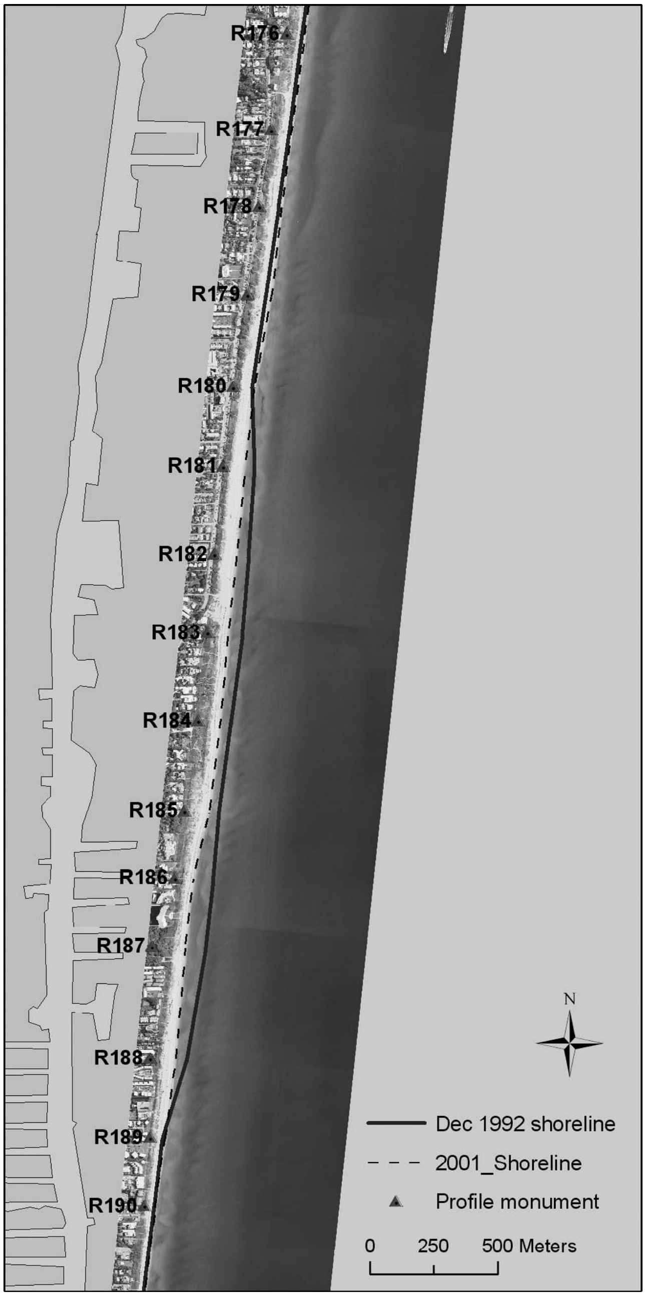

Figure 2. Shoreline positions overlaid on georectified aerial photography obtained in 2001. The 1992 shorelines shown were surveyed immediately after construction of the 1992 nourishment project (December 1992), and June 2001 is the last complete survey of the project area prior to the construction of the fourth consecutive nourishment project in April 2002. **For color version of this figure, see page 128.**

Project performance and development of EHSs from 1975 to 1998 and 1975 to 1990 was evaluated by Fernandez (1999) using shoreline change simulations compared with the measured shoreline change data. Large deviations between the model predictions and the observed shoreline change were interpreted as an indication of an EHS (the model could not simulate an unknown natural process). An updrift location near monument R178 was identified as a cold spot (segment that experiences more accretion than predicted), and an EHS was identified at profile monument R187. Finer sand in the south end of the project was suggested as a potential cause for the EHS at R187.

Numerous monitoring reports (CPE, 1994, 1995, 1996, 1998, 1999, and 2001) indicate greater shoreline recession near R186 and R187. In an effort to emphasize the greater magnitude of erosion in this area, CPE (1995) reported that while the mean shoreline retreat of the fill was about 19 m, the area at R187 receded approximately 56 m since construction. Greater erosion at R187 was qualitatively attributed to the extra amount of fill placed and to end losses. Higher rates of erosion near R181 and R183 are reported in 1995 and 1995 but discontinued in subsequent years (CPE, 1994, 1995, 1996, 1998, 1999, and 2000). Segments 500 m updrift and downdrift of the nourishment area accreted slightly during most of the monitored period.

SHORELINE AND VOLUME CHANGES

Computations of shoreline and volume changes following the 1992 nourishment were based on data from annual beach profile surveys (for monument locations see Figure 2). The shoreline was defined as the 0.52-m contour (National Geodetic Vertical Datum of 1929), which corresponds to the mean water level at Delray Beach. Volume changes were calculated from the monument location (generally on the back of the dune) to the −7.5-m depth contour, which is the offshore limit of most surveys and the estimated closure depth of the study area (CPE, 2001). Shoreline positions in December 1992, after construction survey, and June 2001 were overlaid on top of georectified aerial photography (obtained in March 2001) in a geographic information system framework (Figure 2). This facilitates the visualization and interpretation of shoreline change patterns and their association with beach and dune geomorphology. Because of the clarity of Florida waters, surf zone morphology can be easily mapped and interpreted from aerial photographs (*e.g.,* BENEDET, 2002; FINKL and WARNER, 2005).

Deviations between postconstruction shorelines and the 2001 shoreline (Figure 2) increase on the downdrift segment of the fill (between monuments R186 and R187), indicating more erosion than on other fill segments. Crescentic bars, which are the most persistent type of bar morphology observed at the project area, have horns between bars not attached to the beach near the downdrift end of the fill, whereas on the other areas irregularly spaced crescentic bars with horns attached to the beach occur, suggesting a morphodynamic relationship between erosion rates and surfzone morphology. Shoreline and volume change from the postconstruction survey (December 1992) to the last survey (June 2001) reached −80 m between R186 and R187, about −40 m between R184 and R185, and about −60 m at R183 (Figure 3). The updrift beach segment (R175 to R180) showed an average accretion of 11 m, while the downdrift beach (R189 to R191) accreted about 6 m during the eight and a half years evaluated (Figure 3).

Volume changes to the −7.5-m depth contour (offshore limit of the profile surveys) between 1992 and 2001 show a general trend similar to the shoreline changes (Figure 3). Total volumetric changes were estimated by multiplying the unit volume change by the distance between profile monuments. Between 1992 and 2001, a cumulative volume of about 448,000 m^3 was lost from the fill limits; of this volume, 177,000 m^3 (about 40%) eroded from the beach segment between profile monuments R186 and R187.

Annual Variability of Beach Fill

Annual shoreline and volume change rates vary greatly along the study area. Although updrift and downdrift shorelines were slightly accretional for most of the time period evaluated (1992–2001) (Figures 4 and 5), these segments eroded in 1993–1994 and 1999–2000. The nourishment area eroded for most of the monitored period, but accretion was exceptionally observed between 1995 and 1997, between 1997 and 1998, and between 2000 and 2001. Periods of accretion positively correlated with mild wave conditions (*i.e.,* HARTOG, 2006). Most of the shoreline and volume change occurred during the first 2 years after construction (Figures 4 and 5) and from 1999 to 2000 when three tropical storms affected the study area. Relative high shoreline retreat and volume losses observed during the first 2 years after construction strongly influenced the shape of the shoreline and volume change curves for the entire study period.

Monuments that eroded relatively more than the rest of the fill, shown in Figures 4 and 5, include R183, R186, and R187. The shoreline on R186 and R187 retreated almost every year except for two periods (1993–1994 and 1998–1999) (Figure 4). Greater shoreline retreat also occurred near R183 for most of the time except for 1993–1994, 1998–1999, and 2000–2001 where accretion occurred (Figure 4).

Volume losses of R183, R186, and R187 were also greater than the rest of the project for most years but for two (January 1997 to January 1999) when accretion occurred on these locations. Relatively small volume gains were observed in the updrift and downdrift segments throughout most of the monitoring period simultaneous to erosion of the beach fill, indicating some alongshore spreading of fill sediments. Further analysis of beach profiles shows that accretion of about 200 $m^3\ m^{-1}$ observed at profile R181 between 2000 and 2001 period (see Figure 5) was mostly due to sedimentation in the inner and outer bar systems; thus, although a large volumetric gain occurred, very little shoreline change was observed in this area during the same time period (see Figure 4).

Identification and Parameterization of EHSs

EHSs have been investigated by a number of authors in the past. KRAUS and GALGANO (2001, p. 1), for example, defined an EHS as follows.

> An area that experiences sediment transport potential without having adequate sediment supply erodes more

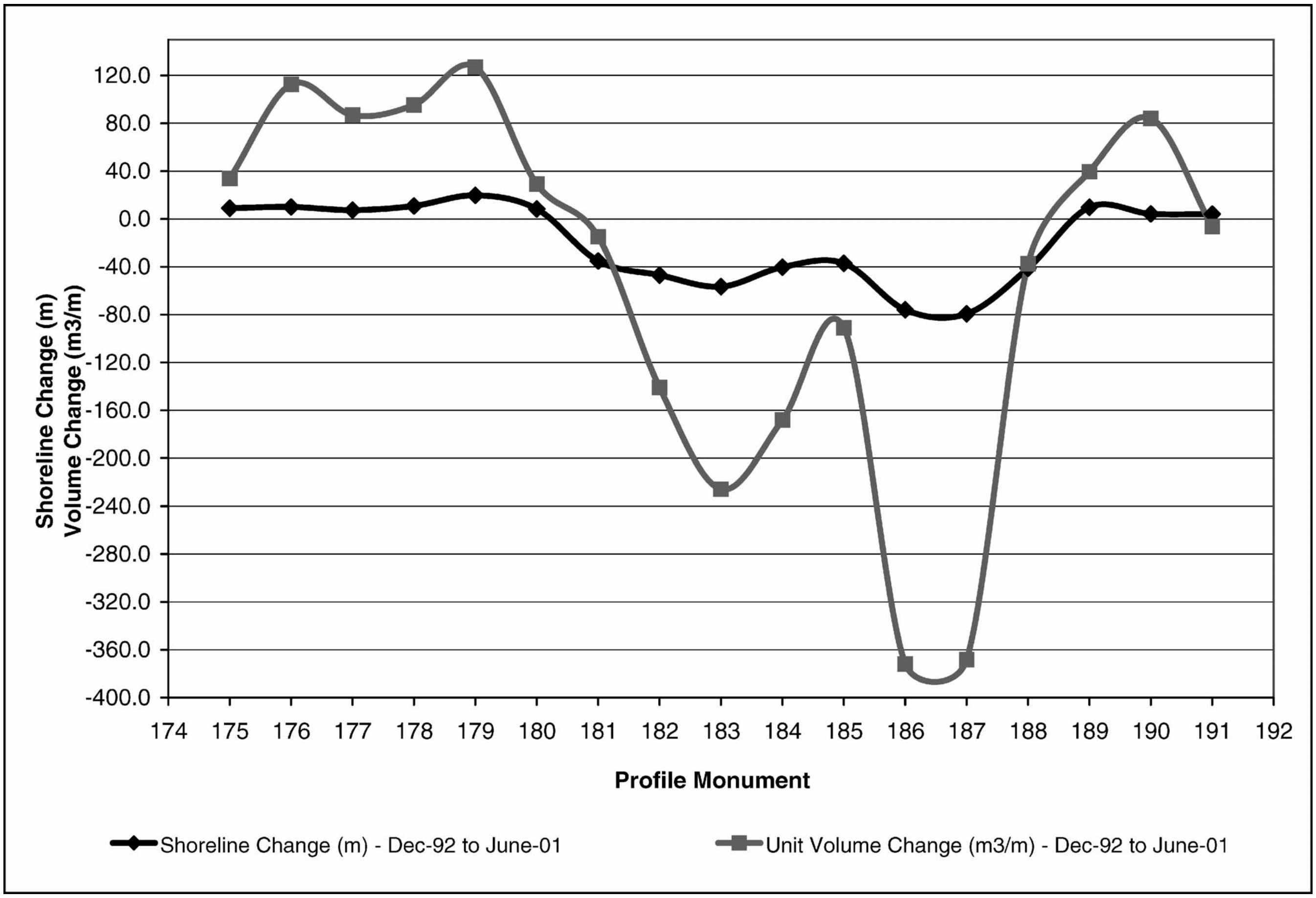

Figure 3. Shoreline changes (m) and volume changes (m^3 m^{-1}) from the postconstruction survey (December 1992) to the last survey of the entire study area (June 2001).

> rapidly than the adjacent beaches or more rapidly than anticipated during design and can be quantified and qualified by several metrics. Examples are loss of beach width, loss of sediment volume and percentage of fill remaining of the amount placed.

The EHS definition adopted in this manuscript was adapted from the one provide by KRAUS and GALGANO (2001), specifically to define EHSs occurring within a nourishment project. An EHS was defined here as follows.

> An erosional hot spot is an area within a beach nourishment project that erodes at least two times more than the nourishment average and can be quantified comparing the volume loss (m^3 m^{-1}) or shoreline retreat (m yr^{-1}) of a specific beach segment with the average volume loss of the entire nourished area.

If the hot spot is quantified based on volume losses (m^3 m^{-1}) over the entire beach profile (from the toe of the dune to the closure depth), it is caused by alongshore processes (cross-shore transport is conserved within the active profile); however, if shoreline change data (m yr^{-1}) are used, the hot spot may be caused by either alongshore processes or cross-shore adjustments (*i.e.,* persistent erosion of subaerial beach and deposition in the surf zone).

Several parameters have been historically used to quantify EHSs, *viz.,* historical shoreline and volume changes (LIOTTA, 1999), percentage of fill remaining in a specific beach segment *vs.* the entire fill area (STAUBLE, 1994), comparison of erosion rates of specified beach segments with background rates or average rate of fill erosion (FINKL and KERWIN, 1997), and comparison of one-line model predictions with shoreline change measurements (FERNANDEZ, 1999; GRAVENS, 1997).

In this paper, EHSs are defined by comparing volume change per unit of beach length, hereafter referred to as "unit volume change" (m^3 m^{-1}), at each monument profile with the average unit volume change of the entire fill. Unit volume loss at each monument profile (m^3 m^{-1}) compared with the average unit volume loss for the entire fill over the entire period monitored is shown in Table 2. Monuments that eroded at least two times (100%) more than the nourishment average were classified as EHSs. Table 2 shows that unit volume loss at monument R183 was about 46% greater than the

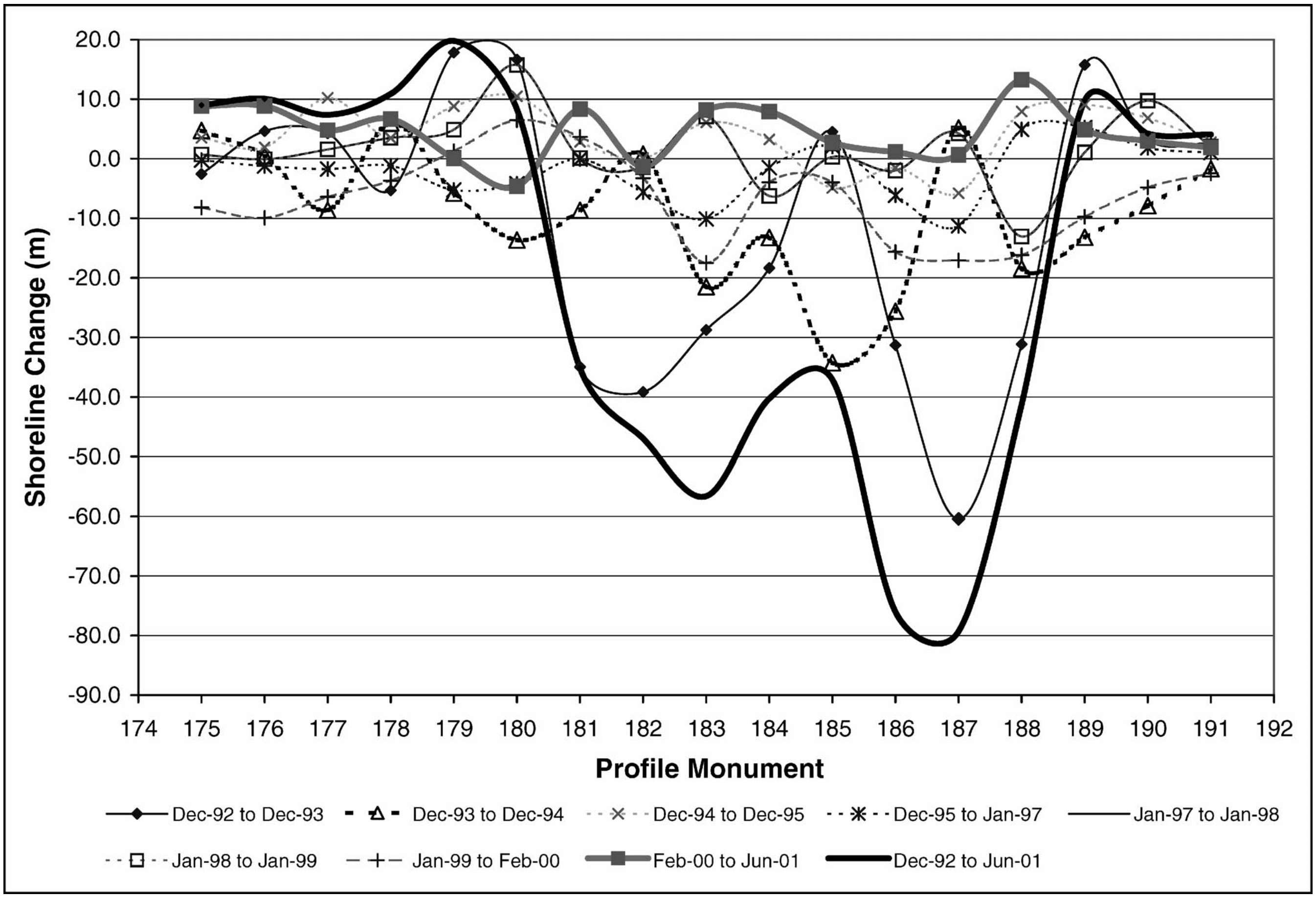

Figure 4. Shoreline changes calculated between annual survey intervals for the Delray Beach project area contrasted with the total changes from December 1992 to January 2001 (thicker black line).

nourishment average and about 9% larger at monument R184. Unit volume losses from monuments R186 and R187 were 141% and 139% greater than the nourishment average during the entire monitoring period (Table 2). Based on Table 2, the area between profiles R186 and R187 is classified as an EHS. Monuments R184 and R183 tend to erode more than the nourishment average but are not classified as an EHS according to the definition of EHSs adopted here.

Some EHSs only develop during adjustment of the artificially placed fill (*i.e.,* initial 2 years after nourishment) as a result of lateral spreading of overfilled areas (erosion of a locally advanced shoreline). On the other hand, EHS areas may persist as a response to recurring physical processes. In order to differentiate persistent EHSs from areas that may have eroded faster than the nourishment average only during the initial adjustment years, volume change rates during the two initial years after construction (where most of the adjustment occurred) were removed from the data set for further analysis.

Volume changes for each monument profile compared with average volume change for the entire nourished area from 1995 (3 y postconstruction) to June 2001 are shown in Table 3. When the two adjustment years are removed from the record, the average fill-volume change decreases from -154 m^3 m^{-1} (Table 2) to -20 m^3 m^{-1} (Table 3). Between December 1995 and June 2001 monument R183 lost about 297% more volume than the average rate of fill erosion, and R184 lost 235%. Monuments R186 and R187, earlier classified as an EHS based on Table 2, lost, respectively, 487% and 224% more volume than the nourishment average (Table 3). According to these results, from 1995 to 2001 there were two areas with higher erosion rates within the fill, one between monuments R183 and R184 and another between R186 and R187. Monument profile R186 was also the only segment where beach width was narrower than the design width at the end of the project lifetime (CPE, 2001), which is also one of the recommended parameters to define hot spots according to the definition of KRAUS and GALGANO (2001). Because the EHS signal was stronger and occurred during and after fill adjustment between profile monuments R186 and R187 (Tables 2 and 3), further analysis of potential mechanisms presented hereafter will focus on this beach segment.

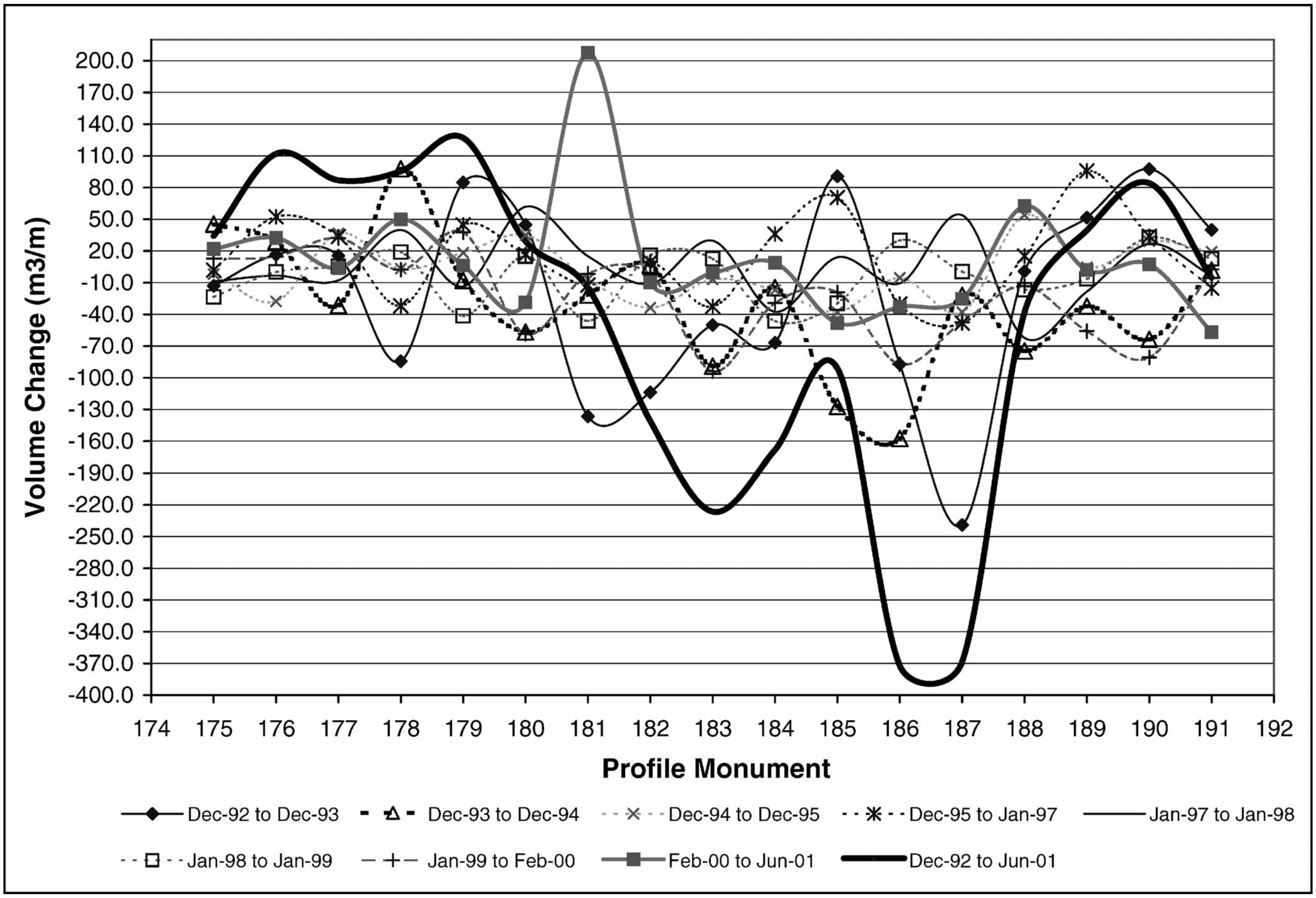

Figure 5. Volume changes per unit length of beach (m^3 m^{-1}) calculated between annual survey intervals for the Delray Beach project area contrasted with the total changes from December 1992 to January 2001 (thicker black line).

Potential Mechanisms for the EHS on the South End of the Fill

Possible causes for localized higher sediment volume losses at R186 and R187 are evaluated in the following sections of this paper using monitoring data and preliminary numerical modeling of waves and currents.

Alongshore Grain-Size Distribution

Alongshore variations of grain size have been suggested as a potential cause for differential rates of fill erosion where finer grained sediments are associated with EHSs and coarser grained sediments are associated with slower erosion rates (FERNANDEZ, 1999).

Table 2. *Volume changes from December 1992 (after construction) to June 2001 for each profile monument compared to the average volume change rate for the entire nourished area. Monuments that eroded at least 100% more than the fill average are marked in bold.*

Beach Profile Monument	Volume Change per Beach Profile Monument (m^3 m^{-1})	Average Volume Change for the Entire Nourished Area (m^3 m^{-1})	Difference between Monument and Nourishment	% Extra Erosion (over background or fill average)
R180	29	−154	184	119
R181	−15	−154	139	90
R182	−141	−154	13	9
T183	−226	−154	−71	−46
R184	−168	−154	−14	−9
R185	−91	−154	63	41
R186	**−372**	**−154**	**−217**	**−141**
T187	**−368**	**−154**	**−214**	**−139**
R188	−38	−154	117	76

Table 3. *Volume changes from December 1995 (3 years after construction) to June 2001 for each profile monument compared to the average volume change rate for the entire nourished area. Monuments that eroded at least 100% more than the fill average are marked in bold.*

Beach Profile Monument	Volume Change per Beach Profile Monument ($m^3\ m^{-1}$)	Average Volume Change for the Entire Nourished Area ($m^3\ m^{-1}$)	Difference between Monument and Nourishment	% Extra Erosion (over background or fill average)
R180	7	−20	27	135
R181	150	−20	170	845
R182	0	−20	20	100
T183	**−80**	**−20**	**−60**	**−297**
R184	**−68**	**−20**	**−47**	**−235**
R185	−15	−20	5	26
R186	**−118**	**−20**	**−98**	**−487**
T187	**−65**	**−20**	**−45**	**−224**
R188	8	−20	28	138

Grain-size information in various years, available from annual monitoring reports (CPE, 1994, 1995, 1996, 1998, 1999, and 2001), was evaluated to investigate alongshore grain-size variations within the nourished area during the studied period. Samples were collected from the toe of the dune to an offshore depth of about −7.5 m at profile monuments R177, R181, R184, and R187. Cross-shore samples were averaged for each monument location to obtain a profile mean or composite grain size. Although variability in grain size in the cross-shore direction occurs, as discussed by Benedet *et al.* (2004), this approach was adopted to perform a comparative analysis of alongshore patterns of distribution in beach grain sizes. A plot of mean grain sizes from 1992 to 2000 (Figure 6) shows that the mean grain size at R184 and R187, which were areas with higher erosion, was similar to grain sizes at other beach locations (R177 and R181) during most of the

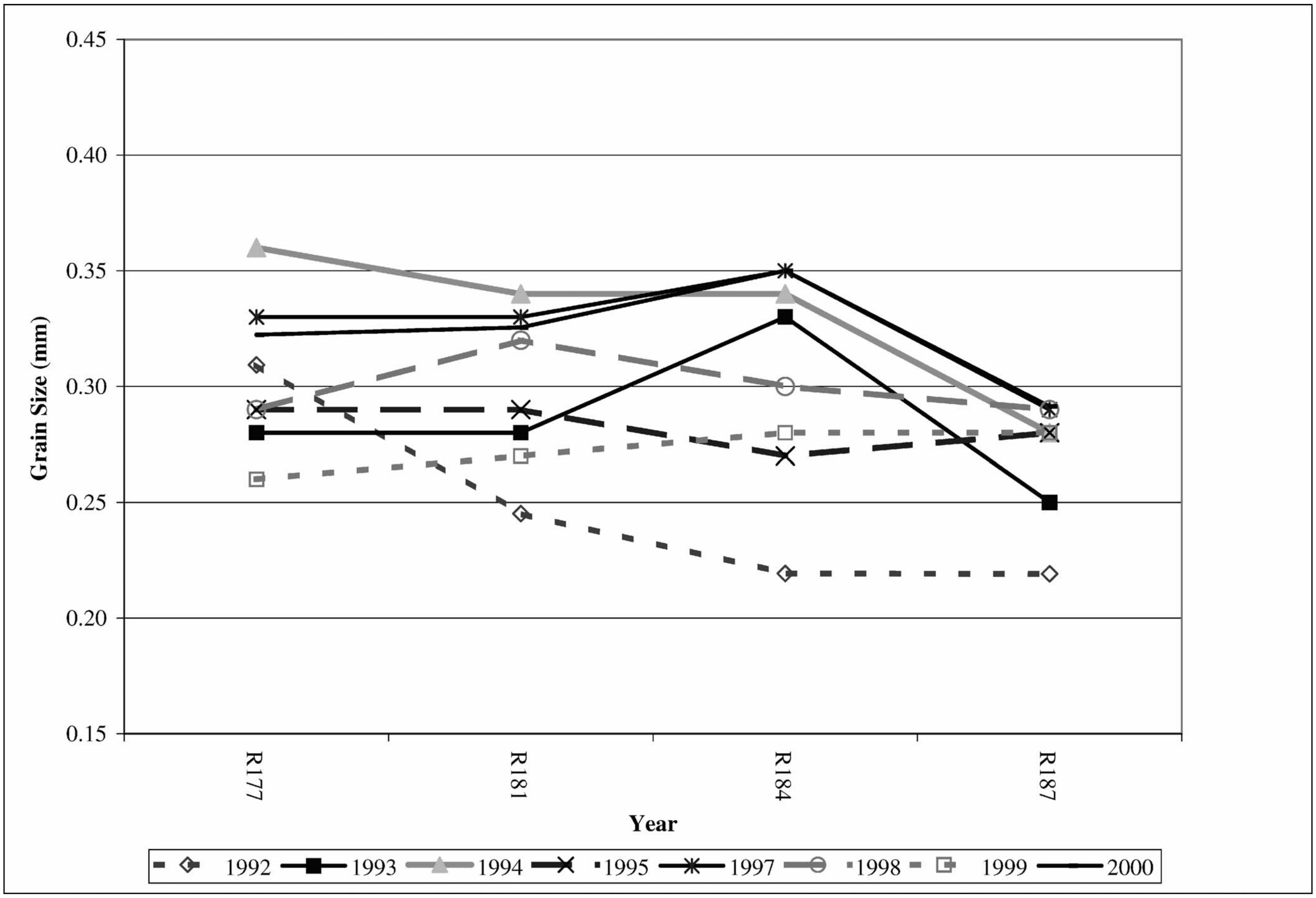

Figure 6. Alongshore distribution of grain size along the project area at selected profile monuments surveyed on an annual basis.

monitored years. Beach sediments at monuments R184 and R187 were finer than beach sediments at monuments located farther to the north (R177, R181) during the first postconstruction survey conducted February 1992 (Figure 6); however, about 10 months later (December 1993), the grain-size difference between R177 and R187 was minimal, 0.28 mm *vs.* 0.25 mm, respectively, and the grain size at R184 is coarser than anywhere else in the beach (0.33 mm), indicating rapid mixing of fill sediments with preexisting sediments. The absence of large alongshore variations in beach grain size that are persistent in time within the beach fill area indicates that grain-size distribution is not a major parameter controlling EHS development, since the higher erosion in the EHS segment occurs throughout the monitoring period.

Effects of Shore-Parallel Reefs and Borrows

Nearshore rock outcrops, coral and rock reefs, gaps between shore-parallel barrier reefs, and sand borrows along the southeast Florida coast may affect nearshore wave heights and influence currents and sediment transport patterns that in turn would affect adjacent beach fills (FINKL, BENEDET, and ANDREWS 2005a; GRAVENS, 1997). An EHS observed near R180 and R181 between January 1997 and October 1992 could be related to a reef gap offshore as suggested by GRAVENS (1997). In a numerical wave modeling exercise, FINKL, BENEDET, and ANDREWS (2005a) reported large alongshore variability of nearshore wave heights along the Delray Beach fill area and attributed this variability to offshore geomorphic features such as reef shape, reef gaps, and presence of borrow pits. The shore-parallel barrier reefs occur in −15 to −20-m water depths, whereas borrow areas are located in shallower waters (−10 to −15 m). The borrow pits were excavated 2 to 15 m below the seabed surface, with older borrows (dredged in 1973 and 1978) being deeper than recent borrows (dredged in 1992 and 2002).

To further evaluate the influence of the seafloor morphology (borrow areas and barrier reefs) on nearshore wave propagation, numerical wave modeling was conducted using a spectral wave model (SWAN) with original bathymetry (surveyed October 2002) and with artificially created bathymetries where the barrier reef gaps and borrows were removed mathematically by linear interpolation. Borrow depressions were leveled with adjacent areas, and reef elevations were removed by interpolating basal elevations of the reef both seaward and landward. Although simulations were conducted for several wave conditions, only results for the most severe and persistent waves (northeast waves) are shown here.

Figure 7 shows SWAN simulations for northeast waves (60° angle of approach) with H_0 of 2 m and T_p of 11.5 seconds with three different bathymetry scenarios. Because these are swell waves, a narrow wave energy distribution of 5° was used. The numerical simulations included wave transformation over bottom irregularities (refraction) and wave energy dissipation due to breaking and bottom friction. Although effects of reflection from borrow side walls may be relevant in specific cases (*i.e.,* in shallower borrows with steeper side walls as per BENDER and DEAN, 2003; MICHALSEN, HALLER, and SUH 2005), they were not included in the calculations shown herein. Diffraction effects, which may also be relevant in reducing alongshore wave height gradients, were not included in these preliminary calculations. A detailed description of the model settings and physical parameters adopted is available in HARTOG (2006).

Up to 1 m alongshore variability in wave height (50% of the input boundary wave condition) is observed in the simulation that used original bathymetry (see left plot on Figure 7). When the offshore shore-parallel barrier coral reefs are removed (artificially created bathymetry) a pattern of alongshore variability in wave heights, similar to the simulation with the original 2002 bathymetry, is observed (see middle plot in Figure 7). When the borrow pits are removed, the alongshore variability in wave heights is smoothed out and the most prominent wave shadow and wave focusing zones disappear (see right plot on Figure 7 compared to middle and left plot).

For quantitative analysis, wave heights along a shore-parallel grid line located about 600 m offshore were evaluated using the results shown in Figure 7. This analysis indicated that the offshore barrier coral reefs slightly reduce nearshore wave heights at wave focusing locations (generally less than 10% of the boundary wave height). Compared to the effects produced by the borrow areas, the effects of the shore-parallel barrier coral reefs are minor along the study area. Although significant, gradients in nearshore wave height may not be directly linked to the development of the hot spot on the south end of the project (between R186 and R187) because the locations of the major wave focusing and wave shadow zones do not coincide with this hot spot location. The other erosional area (R183 to R184), however, occurs in a zone where high variability in alongshore wave height is observed.

Fill Residual Bathymetry and Planform (Shoreline Orientation)

The shoreline orientation and morphology induced by the beach fill may also be partially responsible for EHS development on the downdrift end of the fill. The areas with the highest erosion rates are also the areas that received the larger amount of fill originally (Figure 8) (CPE, 1994, 1996, 1999, 2001), suggesting that postnourishment template distribution affected overall sediment redistribution patterns and fill erosion rates. Figure 8 shows that locations where higher erosion rates were observed (profile monuments R186 and R187) received the significantly higher amounts of fill. During the initial years after construction it is thus expected that erosion of a locally advanced segment of the shoreline (lateral spreading) occurred in this area, causing the higher erosion rates observed. Two years after construction, however, fill distribution is relatively homogeneous, but the two profile monuments in the end of the fill continued to erode at faster rates than the rest of the fill.

The planform of an eroded beach is modified by introduction of sediments into the beach system via beach nourishment. Modification of shoreline orientation on the downdrift end of a nourishment increases wave obliquity that in turn leads to an increase in alongshore current velocity in the transition zone between the nourished and the nonnourished

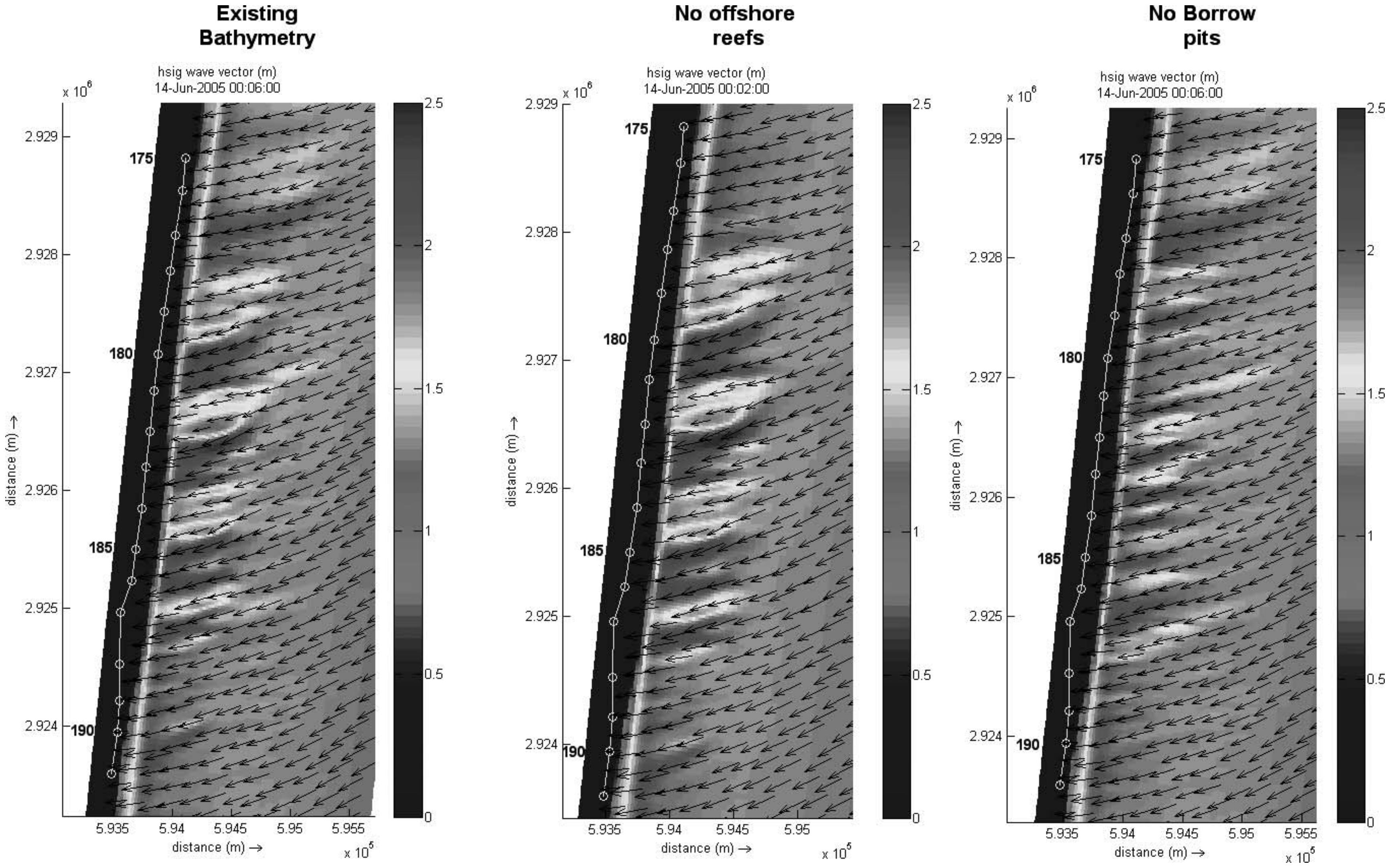

Figure 7. Results from SWAN simulations for northeast waves (60° angle of approach) with H_0 of 2 m and T_p of 11.5 s and 5° wave energy distribution. The left plot was conducted with existing postconstruction bathymetry, the offshore shore-parallel reefs were removed in the middle plot, while the offshore borrows are removed in the right plot. Alongshore patterns in wave height are similar between the left plot (existing condition) and the middle plot (reefs removed). Once the borrow pits are removed (right plot), the alongshore variability in wave heights is smoothed out as the most prominent wave shadow and wave focusing zones disappear. Variations in wave height are, however, relatively small in the hot spot area (R186 and R187). **For color version of this figure, see page 129.**

Figure 8. Volume changes from October 1992 (preconstruction survey) to December 1992 (postconstruction survey) showing distribution of fill sands. The nourishment is delimited between monument profiles R180 to R188; higher volumes were placed in the south end of the fill (profile monuments R186 and R187) to counteract higher erosion rates observed in this area after the previous fills.

downdrift beach. Volume losses at the end of nourishment projects, referred to as end losses, are common along open-coast nourishments (*e.g.,* DEAN, 2002). FERNANDEZ (1999) indicated that the losses on the downdrift end of the Delray nourishment were higher than predictions of beach nourishment diffusion estimates. Waves from the northeast are predominant at Delray Beach (*e.g.,* FINKL, 1994; FERNANDEZ, 1999; BENEDET *et al.,* 2004) and thus responsible for most alongshore sediment transport. The Delray Beach shoreline is generally oriented in a north–south direction (around 6° east of north), but the shoreline near the downdrift end of the nourishment (EHS segment) assumes a northeast–southwest orientation (10° to 15°) (Figures 1 and 2) associated with fill-induced beach planform modification. Because of the orientation of the shoreline at the downdrift end of the fill, wave rays from the northeast are more shore parallel in this zone; thus, alongshore current velocity (and sediment transport) in this region will increase because those are largely dependent on angle between the incident waves and bottom contours (*e.g.,* LONGUET-HIGGINS, 1970).

To evaluate the effect of beach planform configuration (shoreline orientation) on the alongshore current velocities, a simulation with a hydrodynamic model (DELFT 3D) in two-dimension horizontal mode was conducted. The model calculated depth-averaged current velocities along the nourished area during northeastern wave conditions (Figure 9). The hydrodynamic model was forced by the output from a spectral wave model (SWAN). The SWAN simulation was conducted for a northeast wave event with 2-m waves, 11.5 s T_p, and 60° approach with 5° energy width distribution. A harmonic function to represent tides and a representative wind condition were also included. Lateral boundary conditions were set up as water level gradients, as described by ROELVINK and WALSTRA (2004). The flow calculation grid was nested in a coarser wave grid that provided wave boundary conditions for flow computations. The input bathymetry for the refined flow grid was created from a dense airborne laser bathymetry (ALB) data set (*e.g.,* FINKL, 2004). The ALB survey was conducted about 6 months after the completion of the 2002 nourishment, which was dimensionally similar to the 1992 nourishment. Detailed description of model settings and physical parameters adopted are given by HARTOG (2006).

Simulation results show that current velocities at the surf zone are higher near the end of the fill, where they reach about 1.6 m s^{-1} compared to currents generally less than 1

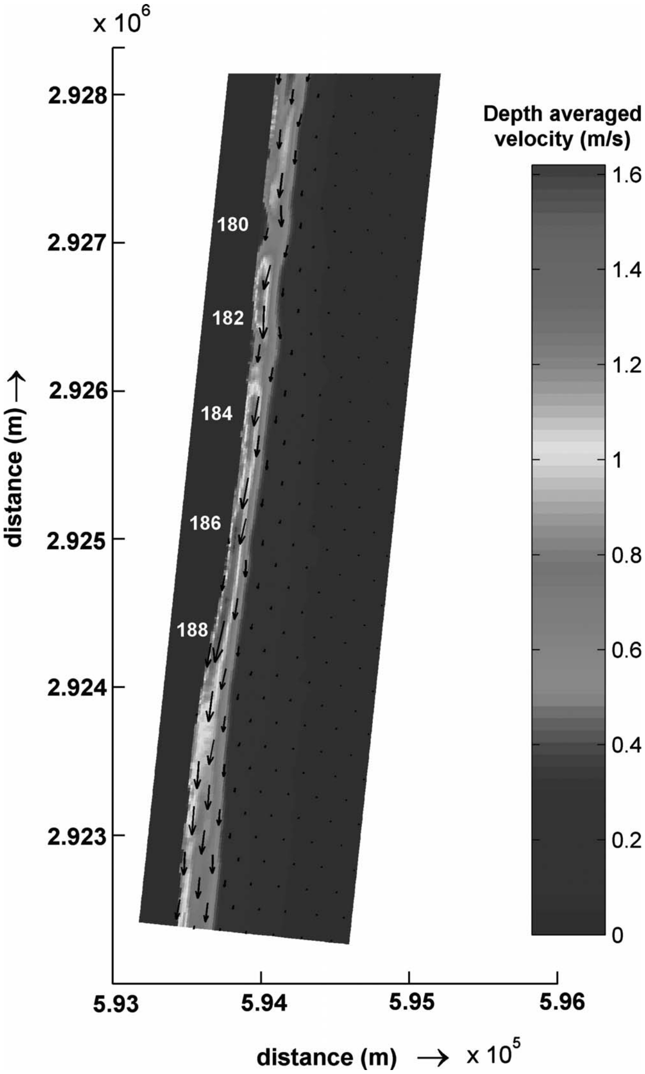

Figure 9. Results from current simulations during a strong northeast wave event (2 m H_s, 11.5 s T_p and 60° approach). The hydrodynamic model was forced by the output from a spectral wave model. Tides and a representative wind condition were also included. The input bathymetric grid was obtained about 67 mo after the 2002 nourishment project (which had similar dimensions to the 1992 nourishment project). Note that current velocities are higher near the end of the fill where they reach about 1.6 m/s when compared to currents of generally less than 1 m/s throughout the rest of the study area. **For color version of this figure, see page 130.**

m s^{-1} throughout the rest of the study area (Figure 9). Smaller areas with stronger current velocities (1.0 to 1.4 m s^{-1}) are observed within the nourished area (near R182 and R184, Figure 9) as a result of combined effects of approaching wave angle and gradients in wave height induced by nearshore features (sand borrows). Alongshore current velocities of similar magnitude (1.5 m s^{-1}) were measured by RENIERS *et al.* (2002) at Duck, North Carolina, during the Delilah experiment, under similar wave conditions, corroborating velocity simulation results reported here. Figure 9 shows that, in addition to nearshore bathymetric features, postconstruction beach orientation and bathymetry influence the hydrodynamics of the nourished area.

Fill Erosion Rates and Identification of EHSs

EHS areas were identified comparing erosion rates of individual beach profile monuments with the average erosion rate of the beach nourishment. The area between monuments R186 and R187 is an erosional hot spot during both time periods evaluated (1992–2001 and 1995–2001; Tables 2 and 3), while R183 and R184 may be classified as an erosional hot spot for the second time period evaluated (1995 to 2001; Table 3). Because the EHS signal was stronger for monuments R186 and R187 (see Tables 2 and 3) further analysis of potential mechanisms focused on this beach segment in this study. A hot spot near R181 as described by GRAVENS (1997) was not observed in the data analyzed here. It is possible that higher erosion near monument R181 observed by GRAVENS (1997) was not observed during the time period evaluated here because of modifications to morphodynamics of this area associated with a new beach configuration created by the 1992 nourishment project, dredging of recent sand borrow areas, or variability in wave activity.

Comparison of volume changes at individual beach segments with the average volume changes of the entire beach fill may be used to define EHSs within a beach nourishment project elsewhere. Special attention must be dedicated, however, to the influence of fill adjustment on hot spot identification; a hot spot may be persistent in time, or may be due to erosion of a locally advanced shoreline during initial fill adjustment years. The statistical meaning of the "fill average volume change" is dependent on the number of sampling stations. The more sampling points (monument locations) available, the more reliability the average measure will have, and the opposite applies.

EHS Mechanisms and Fill Planform Adjustment

Grain sizes at accreting sections of the study area (*i.e.,* R177) are not persistently coarser than the rest of the project, and the grains in the areas with higher erosion *i.e.,* R184 and R187 are not persistently finer than the rest of the project, suggesting that alongshore distribution in sediment grain size is not the main parameter that controls EHS development. Grain sizes in Delray Beach also vary largely in a cross-shore direction (*i.e.,* BENEDET *et al.,* 2004), so small differences in grain size could be due to sample spatial location (*i.e.,* samples just a few meters seaward or landward) or temporal variability of beach grain sizes due to energy regime (*e.g.,* KING, 1959).

Wave model analysis showed that although large variability in nearshore wave heights occurs, the wave focusing and wave shadow zones do not seem to coincide geographically with the EHS in the south end of the project (between R186 and R187). There seems to be, however, a link between fluctuations in alongshore wave height and associated fluctuations in current velocity with higher erosion near monuments R183 and R184.

Because the EHS was identified on the basis of volume changes of the entire active beach profile (from the toe of the dune to the approximate closure depth) and analysis of beach profiles showed that the profiles closed well at the seaward limits of the surveys (no significant volume losses by cross-shore processes beyond the beach profile survey limits), it is assumed that it is caused by alongshore processes.

Alongshore current accelerations are observed on the south end of the project (EHS segment between R186 and R187). Increased current velocities in this area are attributed to fill-induced changes in shoreline orientation and may cause the higher erosion rates observed in this beach segment. Since this effect is a function of fill-induced shoreline orientation it is generally expected to decrease with time as the nourishment planform adjusts to smoother curvature and the project increases in length (eroded sediments from the project area deposit in adjacent shorelines). Although volumetric losses from the EHS area are significantly higher during the first 2 years after construction as a result of alongshore adjustments of a locally advanced shoreline segment, higher than average erosion rates persist in the south end of the fill even after the fill adjustment years (Table 3). As shown in Figure 2, about eight and a half years after project construction, the change in shoreline orientation in the downdrift (south) end of the project persists (from about 6° north–south throughout most of the fill to 10°–15° northeast–southwest in the south end), although translated to the updrift (to the north). Sediments eroded from the project area did not deposit on the subaerial beach immediately downdrift of the nourished area, and, instead of adjusting to a semistraight shoreline, the area with increased orientation in the end of the project migrated north (updrift) while roughly maintaining its angle. Because the EHS in the south end of the fill (between R187 and R186) is located halfway between the area with increased curvature observed after construction (December 1992) and in June 2001, it is reasonable to assume that higher current velocities and an increasing sediment transport predominated in this area during most of the project lifetime, thus leading to persistent higher erosion of this area.

CONCLUSIONS

Alongshore variability on the morphodynamic response of a nourished beach was evaluated here, and hypotheses to explain the development of one EHS in the downdrift end of a beach nourishment project were analyzed. During the Delray Beach nourishment of December 1992 about 914,000 m^3 of sand was placed along 2.7 km of beach. In 2001, eight and a half years after construction, 448,000 m^3 of fill sediments were lost from the nourished area. Since volume changes were calculated to the approximate closure depth of the project area, it can be assumed that volume losses are attributed to fill lateral spreading and gradient in alongshore sediment transport. Most of the volume loss occurred in the first 2 years after the nourishment as the fill adjusted in planform. Large annual variability in rates of erosion was also observed, and during years where wave conditions were mild the project remained stable or showed slight accretion, while in 1999, an extremely active year in terms of waves, high volume losses were observed.

Two zones with higher erosion were identified. Volume losses at one EHS occurring in the south end of the fill were at least 100% more than the average volume loss of the nourished area during and after beach nourishment adjustment. About 40% of the total volume loss accrued from this 600-m long EHS area.

Potential mechanisms to explain the EHS development in the south end of the fill were analyzed. Mechanisms analyzed include the influence of nearshore features (barrier coral reefs, reef gaps, and borrow pits) on nearshore wave propagation, alongshore grain-size distribution patterns, and beach nourishment planform—shoreline orientation.

Gaps in the offshore barrier reef system did not cause the EHS; in fact the effects of the barrier reefs on the nearshore waves are relatively minor. Alongshore variability in wave height and associated wave shadow and focusing zones observed along the northern and central part of the nourishment were due to wave transformation over the dredged borrows. Near the EHS on the south end of the project (between R186 and R187), however, variations in nearshore wave heights were minor.

Grain-size differences alongshore were not the cause of increased erosion of EHS segments, since grain sizes are not persistently finer where higher erosion is observed or *vice versa*. Grain-size distribution trends within the project area vary significantly temporally and spatially, and grain-size differences within the project area can be considered minor.

Alongshore currents are stronger in the downdrift end of the project on the EHS segment where the highest volumetric losses are observed. This localized increase in current velocity is caused by changes in shoreline orientation induced by the beach nourishment and is the probable cause of the additional erosion of this beach segment. The effects of increased current velocities on magnitudes of sediment transport and beach morphology change can be further evaluated and quantified using process-based numerical modeling of currents, sediment transport, and morphology change. Similar phenomena (increased current velocities in the downdrift end of beach fills) may be able to explain higher than expected end losses in other open-coast fills where a strong net alongshore current is observed. Bathymetric modifications such as selective dredging or submerged structures aimed at reducing wave obliquity at the downdrift end may be able to reduce volume losses on this highly erosional area (downdrift end of the fill) and should be further investigated.

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