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Comparison of the Performance of Three Adjacent and Differently Constructed Beach Nourishment Projects on the Gulf Peninsula of Florida

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ABSTRACT

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Detailed beach-profile monitoring was conducted at the three phases of Sand Key beach nourishment on the Gulf Coast of Florida. The nourishment at Indian Rocks Beach, Indian Shores, and Redington Beach was monitored during six years, four years, and eight years respectively after nourishment. Quarterly or more frequent beach and nearshore profile surveys were conducted in order to determine short-term (1 year) and long-term (4 to 8 years) rates of shoreline and beach-nearshore volume changes. The overall performance of the Sand Key beach nourishment is excellent. Redington Beach project has already exceeded the design lifetime of 7 years, and Indian Rocks Beach and Indian Shore projects are likely to exceed the design lifetime. The measured beach-nearshore volume loss is small: 31% at Indian Rocks Beach over six years, 30% at Indian Shores over four years, and only 10% at Redington Beach during eight years.

Performance of beach nourishment is influenced by many factors. Those that are directly related to the three nourishment projects include: (1) relative location in the regional longshore sediment transport regime, (2) magnitude of wave energy, (3) sediment characteristics of the borrow material, (4) local reversal and/or gradient in longshore transport, (5) presence of hard structures, (6) adjacent beach nourishment, (7) variation of shoreline orientation, and (8) sand transfer and beach-fill construction technique. The shoreline and beach-nearshore volume change patterns at the three nourishment projects were different due to the different degrees of influence from the above factors, however, construction style is deemed to be an important contributor. The much less costly dragline and conveyor-belt transfer technique used in the construction of Indian Shores project does not prove to be most cost effective for long-term performance.

ADDITIONAL INDEX WORDS: *Beach nourishment, beach erosion, nearshore sediment transport, shoreline change, beach profile, hurricane impact, Florida Gulf coast.*

INTRODUCTION

Beach nourishment has become a widespread approach to mitigating erosion problems throughout the world. It is the standard practice in Florida where it has been generally quite successful. Virtually all of the nourishment projects along this coast use subtidal borrow areas; generally ebb-tidal deltas at the mouths of inlets, drowned beach/barrier sand bodies, or wave-generated subtidal shoals. In some areas of Florida, appropriate nourishment material is scarce and insufficient for the million-cubic-meter size projects that are common along this coast. As a consequence, it is sometimes necessary for sediment to be transported more than 30 km from the borrow site to the nourishment site resulting in very high coasts per unit volume of borrow material, up to US$15/m^3. Consequently, there are continual efforts being expended toward reducing the cost of nourishing Florida's beaches while still providing a product that will perform well. One of the efforts is to monitor time-series shoreline and sand volume changes to improve the understanding of the relationship among nourishment performance, hydrodynamic conditions, and geological factors.

Sand key is the longest barrier island on the Gulf Coast of the Florida peninsula. Its shoreline orientation changes from northeast to southeast, spanning approximately 60 degrees, along its extent due to the presence of a broad headland at Indian Rocks (Figure 1). The island is extensively and intensively developed, and has experienced serious erosion problems throughout the period of residential and tourism development since at least the 1950s (DAVIS, 1997). Because of this erosion, a comprehensive beach nourishment program was implemented in the late 1980s and continues to the present day.

This paper summarizes the results from detailed monitoring projects, from 1988 to 1996, to assess the performance of the three phases of this large scale nourishment project. A brief summary of the borrow sediment properties and construction techniques are provided. The beach-nourishment performance is discussed mainly in terms of time-series shoreline and volume changes. A comparative evaluation of

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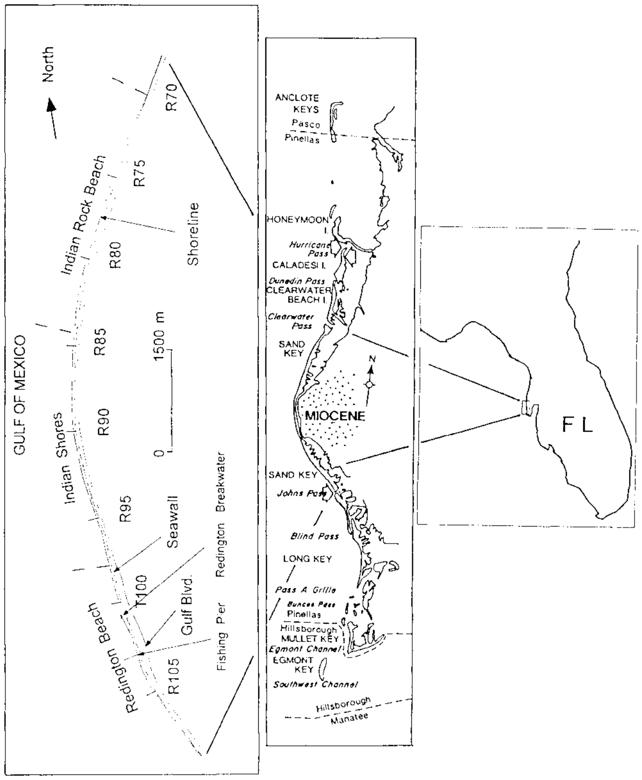

Figure 1. Study area showing the three phases of Sand Key beach nourishment and profile locations.

the three projects constructed differently with different borrow material is discussed.

STUDY AREA AND THE BEACH NOURISHMENT PROJECTS

Coastal Setting

The Sand Key barrier is located in front of a broad bedrock headland composed of the Miocene Tampa Limestone which is exposed along the Intracoastal Waterway in the Indian Rocks area. As a consequence of the geological framework and the associated antecedent topography, Sand Key shows a wide range of shoreline orientations from northeast to southeast (Figure 1). There is also a divergence of the net direction of longshore sediment transport at this headland, which complicates the situation (DAVIS, 1988; 1997). The result is that the southern part of Sand Key experiences a net southerly littoral drift with sediment accumulating at John's Pass on the large and tide-dominated ebb-tidal delta, whereas the northern portion of the barrier has a distinct northerly transport of sediment accumulating in the large fillet at the jetty that stabilizes Clearwater Pass (Figure 1).

This coast overall experiences a generally southerly sediment transport direction with numerous local reversals. The southerly net transport is not large, less than 50,000 cubic meters per year by most accounts (WALTON, 1976). There is, however, considerable sediment movement in both directions throughout the year (DAVIS *et al.,* 1993). This situation is caused by the bimodal wind patterns that typify this area: the prevailing condition is one of southerly wind moving sediment to the north, and the predominant situation is winds from the north associated with the passage of frontal weather systems from October through March (HENRY *et al.,* 1994). Although these northerly winds represent only about 5–10 percent of the time, they are strong in comparison with the low energy conditions that are associated with the prevailing conditions from the south, and they transport sediment at rates that are much higher (WANG, 1995, 1998; WANG *et al.,* 1998).

Mean annual wave height along this coast is about 0.3 m (TANNER, 1960; GIBEAUT, 1991). During passage of frontal systems, waves of 1.0 m are common at the coast. One of the most important aspects of the sediment transport along Sand Key is the angle of incidence of the large waves during the high-energy conditions generated by nearly shore-parallel, northerly winds. The breaker angle during such conditions is typically 15 degree or more, influenced strongly by the shore-parallel winds (WANG, 1995). The result is much higher rates of longshore sediment transport as compared to normal conditions (CERC, 1984).

Another important factor influencing the dynamics of this coast is the slope or gradient of the inner shoreface, *i.e.,* within the storm surf zone. It is steepest at Indian Rocks and Indian Shores, the position of the limestone headland (Figure 1), and becomes more gentle both to the north and to the south. Gradients range from about 1:400 to 1:700 throughout Sand Key. The general configuration of the profile is rather steep to a depth of about 4–5 m and then there is a broad terrace of little depth change and which is influenced by underlying limestone in much of the study area. The average depth of this gentle, broad terrace decreases from Indian Rocks Beach on the north to Redington Beach on the south (WANG and DAVIS, 1998; WANG and DAVIS, 1999). Sediment on this broad terrace is commonly dominated by shell debris and may be absent locally. Bedrock ledges of about 0.5 m of relief are also present at some places, especially in the Redington area.

Nourishment Projects

Sand Key is being nourished in four phases with this paper covering the first three. The general design profile for each of the three phases is similar with a berm elevation of 1.8 m (6.0 ft) and beach width of 31 to 46 m (100 to 150 ft). The constructed gradient of the foreshore is 1:20. Each of the projects has a unique combination of borrow materials and style of construction, which are outlined below.

Redington Beach

The Redington Beach nourishment project, phase I of the four phase program, was constructed from May through July 1988. The project extended from benchmark R99 to R107 in the southern portion of Sand Key (Figure 1). This project was constructed with borrow material that was taken by suction dredge from the ebb-tidal delta at Johns Pass (Figure 1). It was then pumped in a slurry of water and sediment directly from the dredge to the construction site. There the sediment was graded to specifications described above. Approximately 700,000 m^3 of borrow material was placed on the beach at a total cost of 2.9 million U.S. dollars, or \$US4.1/m^3. The low per-unit cost, as compared to the other two projects discussed below is attributed to the proximity of the borrow area, which significantly reduced the cost of transporting the borrow material.

Indian Rocks Beach

The construction of Indian Rocks Beach, phase II of the nourishment program, began in September, 1990 and was completed in December. The project extended from benchmark R72 to R84 (Figure 1). The borrow site was a shallow shoal on the north side of the main shipping channel into Tampa Bay on the huge Egmont ebb-tidal delta. A suction dredge was used and the borrow material was placed in barges and transported 32 km to just offshore the construction site, where the barges were offloaded by pumping the sediment as a slurry onto the beach. Grading to design specifications followed the usual style for this type of construction. The Indian Rocks Beach project extended for 4.2 km and included approximately 1.0 million cubic meters of borrow material at a high cost of 14.5 million U.S. dollars, or \$US14.5/m^3. The very high unit cost, about 3.5 times of that of the Redington Beach nourishment, was directly related to the long transport distance of the borrow material.

Indian Shores

Construction at the Indian Shores project, phase III of the nourishment program, began in January, 1992 and was completed in December. The borrow area for the project was the same as the Indian Rocks Beach project; the Egmont ebb-tidal delta. This project is unique along the Gulf Coast because the removal and delivery systems were quite different than the typical methodology. Borrow material was recovered using a dragline to remove sediment and place it into large barges for transport to just offshore of the construction site. The barges of sediment were anchored in the surf zone adjacent to the project site and sediment was removed with a dragline and placed on a conveyor belt for transfer to the beach. Once on the beach, sediment was graded to the usual specification. The borrow material was at no time pumped in a slurry. The conveyor-belt delivery system resulted in a very loosely-packed sediment as compared to the traditional construction used on the other two phases of Sand Key nourishment.

The Indian Shores project extending from benchmark R85 to R98 was approximately 5.0 km long. It included approximately 900,000 m^3 of borrow material and cost about 10 million U.S. dollars, or \$US11.1/m^3. The cost per cubic meter was 2.7 times higher than that of Redington Beach nourishment due to the transportation cost but 23% less than that of Indian Rocks Beach nourishment which was directly related to the dragline and conveyor belt construction technique which cost nearly 4 million dollars less than that of the conventional techniques (J. Terry, *pers. com.*).

MONITORING SCHEME

Monitoring of the cross-shore profiles and the sediment characteristics has taken place at all three phases of the project before and after the construction. There have been various methodologies and frequencies of data collection at each of the three phases. The overall study represents one of the most comprehensive monitoring programs of any beach nourishment project in the United States, and is the most comprehensive in Florida. Each of the phases of this overall project was monitored in three distinct sub-programs: 1) sediment sampling and analysis, 2) beach and nearshore profile surveys, and 3) offshore profile surveys. The survey benchmarks established by the Florida Department of Environmental Protection were used during the monitoring. Elevation was relative to the National Geodetic Vertical Datum (NGVD). Present mean sea level at the study area is about 15 to 20 cm above NGVD.

Redington Beach

A pre-nourishment and post-nourishment survey was completed at each of 26 benchmarks spaced approximately 150 m (500 ft) apart. The monitoring at Redington Beach included 5 profiles at each end of the project beyond the actual nourishment, plus 16 located within the project. This was conducted to monitor end loss caused by planform adjustment (DEAN and YOO, 1992) of the nourishment.

Each profile location was monitored monthly for the first two years after construction (May 1988–May 1990). During each monthly visit, three sediment samples were collected and the profile was surveyed from the benchmark to a depth of approximately 1.5 m (5 ft) below NGVD. Sediment samples were taken from backbeach, foreshore, and −0.9 m (−3 ft). The offshore profile was surveyed quarterly to a depth of approximately −3.7 m (−12 ft) by boat survey using a precision depth recorder and theodolite location at quarterly intervals by the Coastal and Oceanographic Engineering Department of the University of Florida (DEAN and LIN, 1990). A sediment sample was collected at the −3.7 m (−12 ft) depth during each of these surveys.

After completion of this intensive two-year study, the monitoring program was modified to include only 16 profiles spaced at 300 m (1000 ft) intervals. Surveys of the beach and nearshore were conducted quarterly, and surveys of the offshore profile were conducted annually. Offshore surveys during this time period were conducted using a CERC-type sled and a theodolite operated by the Pinellas County Surveying Department. Sediment sampling was limited to the foreshore and −0.9 m (−3 ft) depths for the quarterly intervals with a −3.7 m (−12 ft) sample taken during annual offshore surveys.

From 1992 through 1996 the monitoring program was further modified. During the first two years of that period, beach and nearshore profiles were measured quarterly and offshore profiles were surveyed semi-annually. The offshore profiles were surveyed annually in addition to the quarterly beach and nearshore surveys during 1995–1996. Sediment sampling was limited to foreshore samples throughout this four-year period.

Indian Rocks Beach

The Indian Rocks Beach monitoring was initiated immediately following the completion of construction in December, 1990. A pre-nourishment survey was conducted in September 1990. For the first two years (1990–1992), profiles were monitored monthly at 34 locations at 150 m (500 ft) spacing; including 28 locations within the nourishment project and three at each end to determine the end losses due to planform adjustment. Similar to the monitoring at Redington Beach, each of the beach profile surveys extended from the benchmark, typically located on the seawall, to a depth of −1.5 m (−5 ft) NGVD. Sediment samples were collected from the backbeach and the foreshore. Offshore profiles were surveyed using an automated theodolite controlled by a computer notebook. These surveys extended to a depth of −4.6 m (−15 ft) NGVD. The offshore surveys were conducted quarterly during the first year and semi-annually during the second year.

There was substantial modification of the monitoring program during the final four years of the study (1992–1996). The number of profile locations was reduced to 17 at 300 m (1000 ft) spacing. The beach and nearshore profiles were surveyed quarterly for the 4-year period. Sediment sampling was limited to the foreshore only. Offshore profiles were surveyed semi-annually during the first two years (1992–1994) and annually during the last two years (1995–1996).

Indian Shores

Monitoring of the third phase of the Sand Key program at Indian Shores was initiated in December, 1992, immediately after completion of the construction. The monitoring was limited to quarterly profile surveys of the beach and nearshore zone to a depth of −1.5 m (−5 ft) NGVD at 300 m (1000 ft) spacing. Offshore surveys to a depth of −4.6 m (−15 ft) NGVD were conducted semi-annually during the first two years (1992–1994) and annually during the last two years (1995–1996). Sediment samples were collected at the foreshore during each survey.

Summary

The overall monitoring scheme at each of the first two phases of the Sand Key nourishment was initially intense and comprehensive with a decrease in frequency and increase of alongshore profile spacing as time passed. This was to provide detailed information on the initial adjustment of the entire profile, with the premise that the rate of beach adjustment decreased with time. The Indian Shores phase was never monitored in as much detail.

For the last four years of the study (1992–1996), a uniform monitoring scheme was employed throughout the three-phase program. Forty profiles (Figure 1) were monitored, extending from north of the actual nourishment (R70) to south of the nourishment (R109), thereby enabling the end losses of the entire system to be monitored. The final program of quarterly beach/nearshore profiles and annual offshore profiles appears to be appropriate for beach fills that were more than two years old, such as the Redington Beach and Indian Rocks Beach. It is not, however, sufficient for quantifying the first year performance. All data indicate that rapid and significant adjustments in the profiles take place during the first 6–12 months during which monitoring intervals should be more closely spaced. Sediment samples from only the foreshore are probably not sufficient to obtain necessary information on the influence and performance of borrow material, due to selective sediment transport and deposition in the swash zone (WANG *et al.*, 1998). Both the foreshore and the −0.9 m (−3 ft) samples should be included, at least during the first two years.

RESULTS AND DISCUSSION

The following discussion is based on regional and annual changes of shoreline and beach volume instead of detailed analysis of individual profile changes. The objective is to provide regional comprehension of mid- to long-term performance of the three nourishment projects. Beach-volume calculations were mainly based on the beach and nearshore profiles in the present study. Characteristics of offshore profiles are discussed in WANG and DAVIS (1998). Time-series shoreline and beach-volume changes after the replenishment are discussed along with characteristics of the sediments and their distribution. A comparative evaluation of the performance of the three projects is provided.

Sediment Characteristics and Distribution

Grain-size characteristics of foreshore sediments change rapidly in response to the wave and tidal conditions at any given time (HANEY, 1993). This is one reason that the use of only foreshore sediments is probably insufficient to characterize the sediments for the entire beach profile, and to determine any long-term changes in their characteristics. Four sediment samples have been collected on backbeach, foreshore, −0.9 m (−3 ft), and −3.7 m (−12 ft) at Indian Rocks beach and Redington beach during the first two years of monitoring. It is beyond the scope of the present paper to discuss the details of sediment grain-size distribution patterns across the profiles. The following discussion focuses on the general characteristics of the borrow material as reflected in the foreshore sediment samples and their changes with time. This issue is directly related to the performance of the beach nourishment in terms of time-series shoreline and volume changes.

The following discussion compares the characteristics of the foreshore sediments immediately after nourishment and that of the foreshore sediments at the end of the monitoring. Such information will give a general indication of the differences in sediments as placed on the beach and also the situation after a significant period of time. It will also show how much change, if any, has taken place in this energetic portion of the coastal zone.

Although sediment statistics obtained from samples collected at monthly intervals from the most dynamic part of the beach/nearshore profile are not very meaningful in representing the entire profile, they should provide information on essential differences, if any, in the grain size of the borrow material. Mean grain size, sorting and skewness were determined based on the statistical procedures described by FOLK

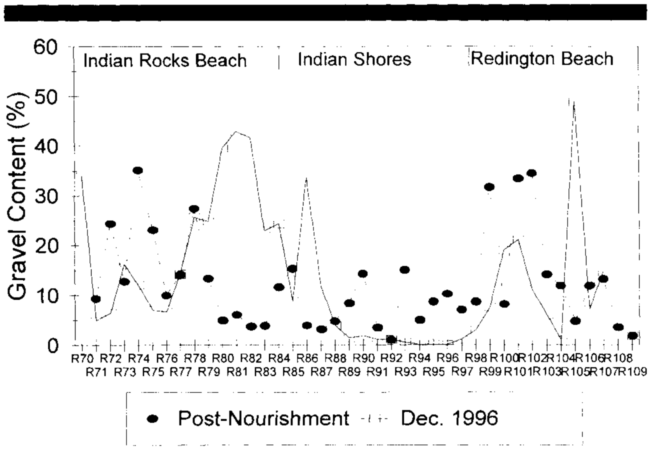

Figure 2. Distribution of gravel content, immediately after the nourishment and at the end of the monitoring (December 1996).

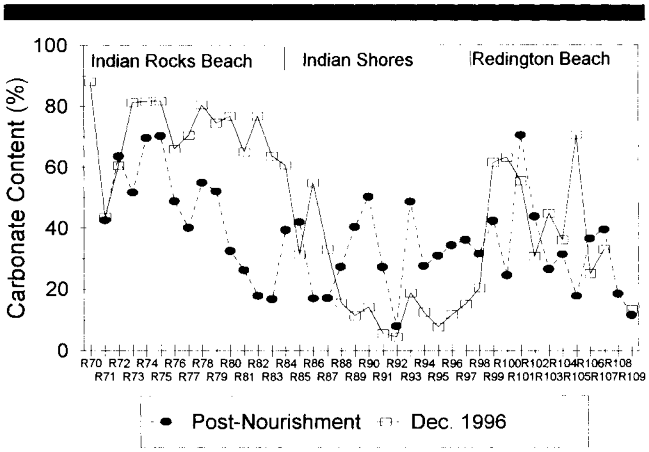

Figure 3. Distribution of carbonate content, immediately after the nourishment and at the end of the monitoring (December 1996).

(1974). The grain-size analyses of most of the sediment samples were conducted using a settling tube (WRIGHT and THORNBERG, 1988). For samples containing a significant amount of shell gravel grains, a combination of sieving and settling was used (BLAND and DAVIS, 1988; DAVIS *et al.*, 1992; DAVIS 1993; WANG *et al.*, 1998).

Sediment grain size in the study area is typically composed of two fractions: biogenic and non-biogenic. The non-biogenic fraction is well-sorted fine quartz sand. The mean grain size is strongly influenced by the biogenic fraction which is almost all shell debris. Generally, high shell content produces coarse mean grain size, typically poorly sorted with negative skewness. The lower the shell content, the finer, better sorted and more normally distributed are the sediments. Virtually all the gravel content is shell debris. The content of calcium carbonate basically reflects the deviation of the sediment grain size from that of fine quartz sand although some is sand sized. The siliciclastic fraction of the sediment is highly mature fine quartz sand with little grain-size variation (SUSSKO and DAVIS, 1992). Therefore, gravel and carbonate content (including that in all size fractions) better reflect the grain-size variation than the mean grain size.

There is a general difference in gravel content among the three phases of nourishment (Figure 2). The post-nourishment gravel content shows great variability from location to location but does show that the central area (Indian Shores) has less than at each end, even though the Indian Rocks project used the same general borrow area as for Indian Shores. The gravel content at the end of the monitoring in 1996 showed a similar trend and the Indian Shores phase is characterized by low gravel content (Figure 2). There is abundant gravel at the northern end of the Indian Shores at the end of the study due to end loss from Indian Rocks Beach as a result of the net southerly littoral drift. This is shown at locations R85 to R87 (Figure 2).

The total content of calcium carbonate indicates the role played by shell in the overall composition of the sediment. All of the gravel fraction is carbonate, and virtually all of that is shell debris. A few limestone clasts were found. The carbonate content shows a pattern that relates to the three nourishment phases. At initiation of the monitoring, there was less distinction among the three phases than at the end (Figure 3). It is still possible to see that values are high for Indian Rocks Beach, low for Indian Shores and quite variable for Redington Beach.

At the end of the monitoring, there was considerable difference in carbonate content among the three nourishment phases. Indian Rocks Beach has values that are near 80% and Indian Shores is only about 10%. Notice also that there is a significant difference between the gravel percentage and the carbonate content (Figures 2 and 3), indicating that much of the carbonate is in the sand sized fraction of the sediment. This suggests that the higher energy conditions that Indian Rocks experiences relative to the other two nourishment phases has resulted in the breaking of the rather fragile bivalve shells until they become sand sized. The Redington Beach phase continues to display variation but is noticeably higher in carbonate content than the Indian Shores phase (Figure 3).

Beach and Nearshore Changes

Data on shoreline and volume change to a depth of −1.5 m (−5 ft) NGVD were analyzed from multiple time frameworks. Included in the order of their discussion are: 1) the last year of the monitoring (1995–1996) during which significant storms occurred; 2) the last four years (1992–1996), the period of which all three phases were monitored uniformly; 3) the first year of monitoring for each phase of nourishment; and 4) the entire monitoring period for each phase representing approximately 6, 4, and 8 years post-nourishment duration from north to south. Each of these time frames is discussed from north to south for convenience.

December, 1995 to December, 1996

Shoreline changes were determined using the NGVD position, which is the mean sea level datum of 1929, as the definition of the shoreline. Conditions during this final year of the monitoring were rather typical of most years with winter frontal passages having a prominent influence on coastal dynamics. One hurricane (Opal) influenced the area in October, 1995 (DAVIS and WANG, 1996) and there was one significant tropical storm (Josephine) in October, 1996. The overall response of all the three phases to the impact of Hurricane Opal was similar (DAVIS and WANG, 1996), displaying a general trend of 1) shoreline erosion ranging from 2 to 10 m; 2) upward and landward migration of the nearshore bar; and 3) backbeach accumulation and increase in the berm height (Figure 4), especially at Indian Shore. Eight months after Opal in June 1996, the shoreline erosion was recovered to a certain extent in all three phases (Figure 4). The backbeach accumulation, however, remained in place because wave action was limited to seaward of the berm crest under non-storm conditions.

The beach response to the impact of Tropical Storm Josephine was quite different from that of the passage of Hurricane Opal (Figure 4). The most apparent change caused by the Tropical Storm Josephine was the erosion of the high berm accumulated during Hurricane Opal. Some of the sediments eroded from the post-Opal berm were deposited in the vicinity of the shoreline, especially at Indian Shores, resulting in a slight shoreline accretion after Tropical Storm Josephine (Figure 4). The substantially different beach responses, especially in the backbeach and the swash zone, to the passages of Opal and Josephine are not clear due to the lack of *in situ* wave and water-level data during the storms.

Indian Rocks Beach showed a small landward retreat of the shoreline during the year from December 1995 to December 1996 (Figure 5A) except at the northern end of the project which receives sand from end loss due to continued planform adjustment, even 6 years after the nourishment. All of Indian Shores experienced shoreline progradation except at R96 (Figure 5A). Shoreline accretion from 1995 to 1996 at Indian Shores seems to be related to the beach-change patterns induced by the impact of the Tropical Storm Josephine (Figure 4), as described above. Redington Beach showed a great variation, including both advance and retreat of the shoreline. Beach behavior at Redington Beach has been significantly influenced by an offshore breakwater, located directly adjacent to T100 where the most shoreline accretion was measured. The greatest retreat was at R101, just downdrift of the offshore breakwater. The shoreline retreat at R101 was more than twice that of the next severe retreat (R96) and shows the magnitude of the influence of this structure on the adjacent shoreline (Figure 5A).

The volume change from December 1995 to December 1996 showed a modest loss throughout the entire Sand Key nourishment project (Figure 5B). Small volume gains were measured just updrift of the offshore breakwater at T100 indicating the trapping of littoral drift by the structure. Small volume gains measured at the north end of the projects (R70–R72) and downdrift of the Indian Rocks Beach (R86) were probably caused by end loss from the Indian Rocks nourishment. The volume gain at profile R105 is not clear. The greatest volume losses occurred just downdrift of the offshore breakwater (R101) and downdrift of the Redington fishing pier (R103) (Figure 5B).

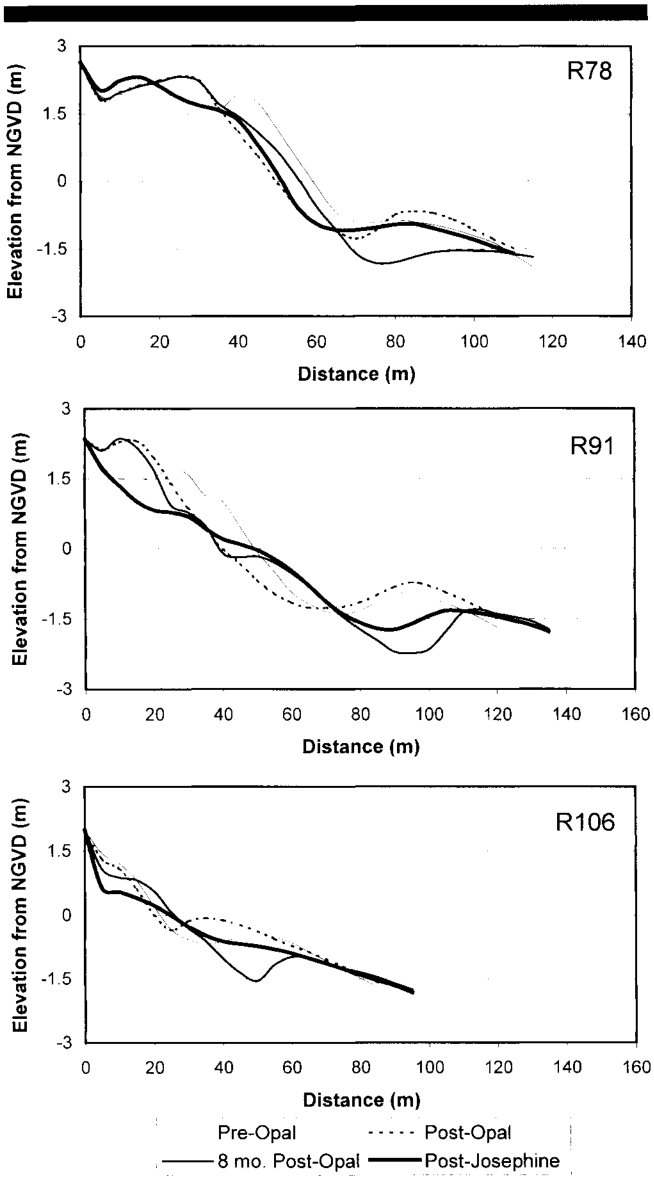

Figure 4. Beach changes induced by the impact of Hurricane Opal and Tropical Storm Josephine; typical examples from Indian Rocks Beach (R78), Indian Shores (R91), and Redington Beach (R106).

Data from each of the 40 profile locations were combined for each of the three nourishment phases in order to determine if there are regional differences among the three nourishment projects (Table 1). The mean shoreline change indicates that Indian Shores experienced a gain of approximately 2 m per profile, and both of the others had losses on the average of 1 to 2 m per profile. All three of the nourishment phases showed a modest volume loss ranging from 10 to 16 m^3/m, with Redington Beach having the highest value (Table 1). Substantial volume losses adjacent to the offshore breakwater (Figure 5B) and the fishing pier apparently contributed to the relatively high average loss at Redington Beach.

The average shoreline gain and volume loss at Indian

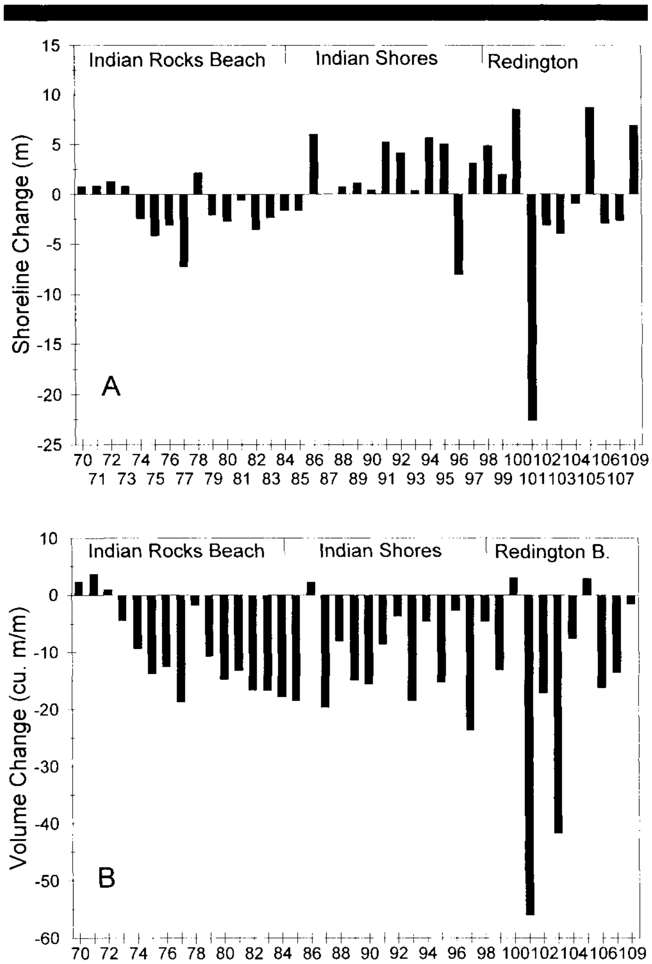

Figure 5. Shoreline (A) and volume changes (B) for the three projects from December, 1995 to December, 1996. The x-axis indicates the monument number.

Shores can be explained by the pattern of profile adjustment in response to the passage of Tropical Storm Josephine in October 1996 (Figure 4). The impact of Josephine was most severe at the protruding Indian Shores area (Figure 1). A large portion of the backbeach accumulation that resulted from Hurricane Opal was redistributed in the nearshore zone (Figure 4). Similar beach responses were measured at Indian Rocks Beach but to a lesser degree due to some of the sheltering of the headland. The gentle offshore slope offered some protection at Redington Beach.

December 1992 to December 1996

The monitoring was conducted using a same scheme at all three nourishment phases from December 1992 to December 1996. All sites were surveyed on the same schedule and all locations were surveyed within a three-day period throughout the four-year monitoring study. The Indian Rocks Beach and Indian Shores phases showed shoreline retreat throughout this period; rather consistently between 10 to 20 m (Figure 6A). The only exception to this pattern in these two phases is at the erosional hot spot R90 where the shoreline retreat was approximately 50 m (Figure 6A). The Redington Beach phase showed a much different performance over this four-year period with both advance and retreat of the shoreline. Locations of advance were north (updrift) of the offshore breakwater (R99 and R100) and south of the fishing pier (R105). It is apparent that these two structures have had an influence on the shoreline over the study period (Figure 6A).

Table 1. *Sum and average of shoreline and volume changes for each project December, 1995–December, 1996. Profiles beyond the nourishment limit but included in the monitoring are included in the averaging and sum.*

	Shoreline Change	Volume Change
Total Sum[1]	−7.10	−459.25
Total Average (m^3/m)	−0.18	−11.78
Indian Rocks (R70–R84) Sum	−24.09	−143.69
Indian Rocks (R70–R84) Average	−1.61	−9.58
Indian Shores (R85–R98) Sum	27.17	−155.94
Indian Shores (R85–R98) Average	1.94	−11.14
Redington (R99–R109) Sum	−10.19	−159.61
Redington (R99–R109) Average	−1.02	−15.96

[1] "Sum": the sum of all the profiles, total change can be roughly estimated by multiplying the distance, 300 m, between adjacent profiles.

The pattern of volume change during the 1992–1996 period mirrors that of the shoreline performance (Figure 6B). There was a little accretion at the northernmost profile (R70) due to continued end loss. An overall greater volume loss was measured at Indian Shores, as compared to those at Indian Rocks Beach and Redington Beach (Figure 6B and Table 2). Similar to the shoreline change pattern, the Redington Beach phase showed both gains and losses in volume over the four-year period. The most pronounced loss was at R101, directly downdrift from the offshore breakwater. The other site of significant loss was at R106, a location that has been a "hot spot" for several years (Figure 6B).

Average values of both shoreline and volume changes show considerable difference among the three nourishment phases (Table 2). Indian Shores experienced the greatest shoreline retreat of 23 m per profile during the 4-year period and Redington Beach was the least, with an average of only 3 m retreat during the 4 years. A similar pattern is shown by the volume change. Indian Shores lost on the average of 66 m^3/m during the 4 years, while the loss at Redington Beach was only 15 m^3/m. This is in light of the fact that the Indian Shores phase was completed 2 years after Indian Rocks and 4 years after Redington, the most stable of the three. Field observations during each beach survey also indicated that wave energy was typically lower along the southern Redington Beach than along the northern Indian Rocks Beach and at the headland.

First Year of Monitoring at Each Nourishment Phase

Considerable shoreline retreat took place throughout the nourished beaches on Sand Key during the first year after the nourishment was completed. The only shoreline accretion that was measured was a small amount at each end of the monitoring area due to end loss associated with planform ad-

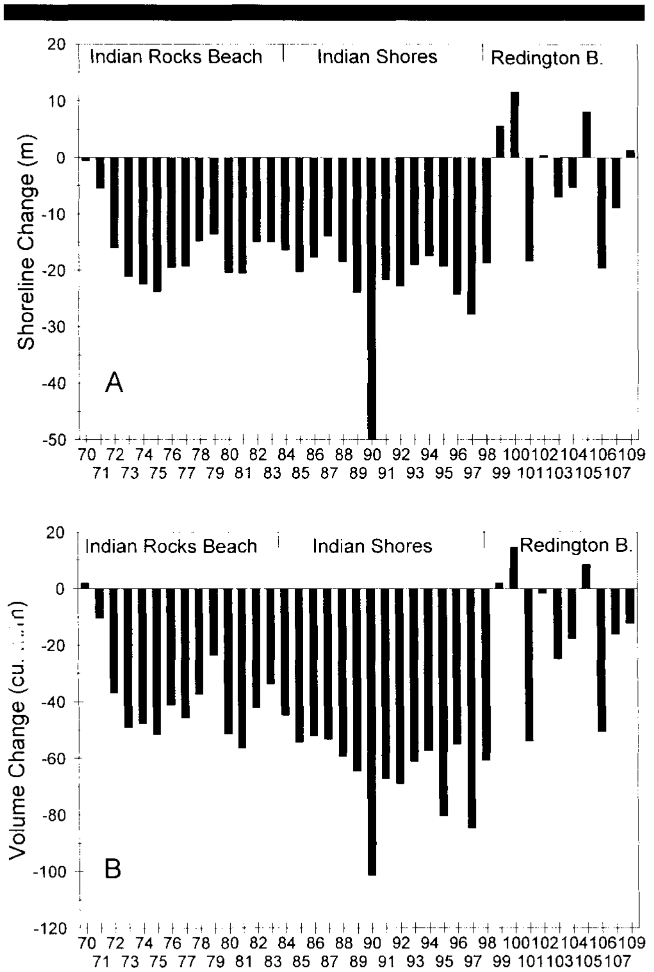

Figure 6. Shoreline (A) and volume changes (B) for the three projects from December, 1992 to December, 1996. The x-axis indicates the monument number.

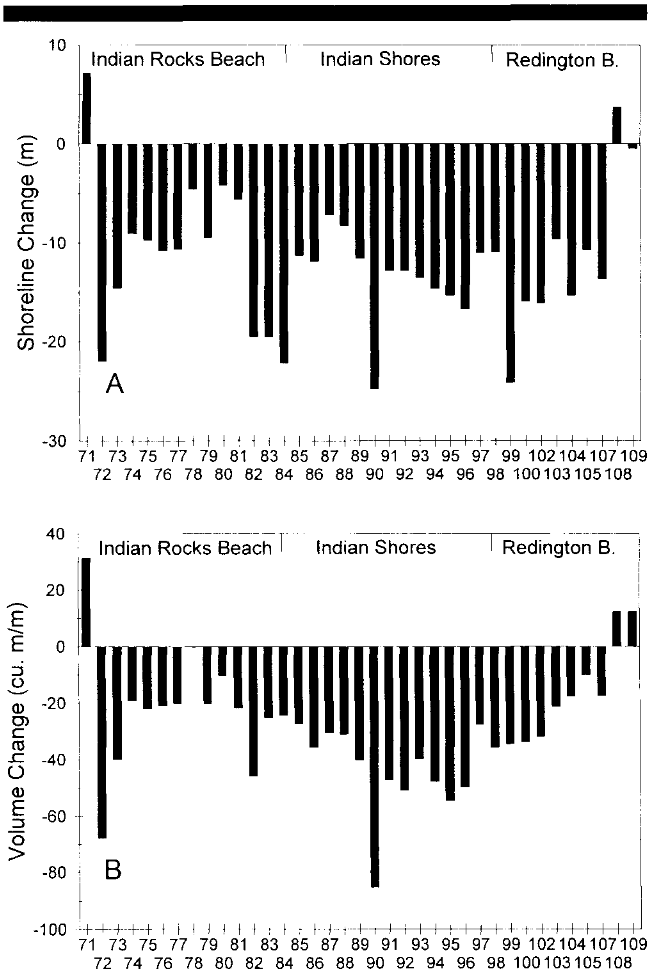

Figure 7. Shoreline (A) and volume changes (B) for the three project during the first year after the beach nourishment. The x-axis indicates the monument number.

justment (Figure 7A). Most locations experienced 6–20 m of shoreline retreat during the first year after the nourishment.

The shoreline change pattern, as well as the volume-change pattern, at the Indian Rocks Beach demonstrated an apparent pattern of initial planform beach-fill adjustment described and modeled by DEAN and YOO (1992) and YOO (1993). Significantly greater shoreline retreat and volume loss were measured toward the two ends of the nourishment project, R72 and R73 at the northern end, and R82, R83, and R84 at the southern end. The planform adjustment is not apparent at Redington Beach where the nourishment perfor-

Table 2. *Sum and average of shoreline and volume changes for each project, December, 1992–December, 1996. Profiles beyond the nourishment limit but included in the monitoring are included in the averaging and sum.*

	Shoreline Change		Volume Change	
	4-Years	Per Year	4-Years	Per Year
Total Sum[1]	−592.17	−148.04	−1642.69	−410.67
Total Average[2] (m^3/m)	−15.18	−3.80	−42.12	−10.53
Indian Rocks (R70–R84) Sum	−244.28	−61.07	−570.61	−142.65
Indian Rocks (R70–R84) Average	−16.29	−4.07	−38.04	−9.51
Indian Shores (R85–R98) Sum	−315.70	−78.93	−920.35	−230.09
Indian Shores (R85–R98) Average	−22.55	−5.64	−65.74	−16.44
Redington (R99–R109) Sum	−32.19	−8.05	−151.73	−37.93
Redington (R99–R109) Average	−3.22	−0.81	−15.17	−3.79

[1] "Sum": the sum of all the profiles, total change can be roughly estimated by multiplying the distance, 300 m, between adjacent profiles.

Table 3. *Sum and average of shoreline and volume changes for each project during the first year of performance. Profiles beyond the nourishment limit but included in the monitoring are included in the averaging and sum.*

	Shoreline Change	Volume Change
Total Sum[1]	−439.30	−1053.32
Total Average (m^3/m)	−11.87	−28.47
Indian Rocks (R70–R84) Sum	−154.61	−306.93
Indian Rocks (R70–R84) Average	−11.04	−21.92
Indian Shores (R85–R98) Sum	−182.54	−603.83
Indian Shores (R85–R98) Average	−13.04	−43.13
Redington (R99–R109) Sum	−102.16	−142.56
Redington (R99–R109) Average	−11.35	−15.84

"Sum": the sum of all the profiles, total change can be roughly estimated by multiplying the distance, 300 m, between adjacent profiles.

mance was complicated by the offshore breakwater and the fishing pier.

Patterns of initial planform adjustment at Indian Shores were quite different from that at Indian Rocks Beach. Maximum shoreline retreat and volume loss were measured near the center of the nourishment project, at the hot spot R90, instead of at the two ends as is generally the case (DEAN and YOO, 1992). This abnormal initial adjustment at Indian Shores was apparently influenced by the two previous neighboring nourishment projects. The headland and the change of shoreline orientation may also have considerable influence. A divergence of longshore sediment transport has been identified in the vicinity of the headland (DAVIS, 1997). It is reasonable to believe that the persistent hot spot at R90 is related to this longshore transport divergence which may also contribute to the abnormal planform adjustment at Indian Shores.

The volume change shows similar patterns as those of shoreline change (Figure 7B). Indian Rocks Beach shows apparent end loss associated with initial planform nourishment adjustment. Indian Shores experienced most volume loss near the middle of the project. The volume change at Redington Beach does not demonstrate any regular pattern, apparently complicated by the offshore breakwater and the fishing pier.

Shoreline retreat during the first year of post-nourishment shows a large range from one location to another (Figure 7A) but the average change for each phase was quite similar. Indian Shores had the greatest retreat of 13 m per profile and Indian Rocks Beach had the least of 11 m (Table 3). Volume change showed much more variation among the three nourishment phases, which probably relates to the construction slope as compared to the natural slope after adjustment. Indian Shores had twice the loss of 43 m^3/m as compared to the other two of 22 and 16 m^3/m, respectively (Table 3).

Post-Nourishment to December, 1996

At the end of the monitoring program, 8 years have elapsed since the completion of the Redington Beach nourishment on the southern end of the overall project, while 6 years at Indian Rocks Beach on the northern end, and 4 years at Indian Shores in the middle. Total shoreline change at each location shows an overall pattern of retreat except at the ends (Figure 8A). There is a noticeably large retreat at Indian Rocks Beach as compared to both the Indian Shores and Redington Beach phases. Also, significantly more shoreline retreat was measured at the two ends of the project than that in the middle, indicating the persistent planform adjustment. Although the Indian Rocks Beach was the middle phase in age, its steep nearshore slope and higher wave energy caused the great shoreline retreat. Being at the updrift end of the regional southward trend of longshore sediment transport may also contribute to the largest shoreline loss at the northern Indian Rocks Beach. A similar but less distinct pattern is shown for volume change (Figure 8B). It is worth mentioning again that changes shown in Figure 8 represent different post-nourishment time intervals for each project: 6 years for Indian Rocks Beach, 4 years for Indian Shores, and 8 years for Redington Beach.

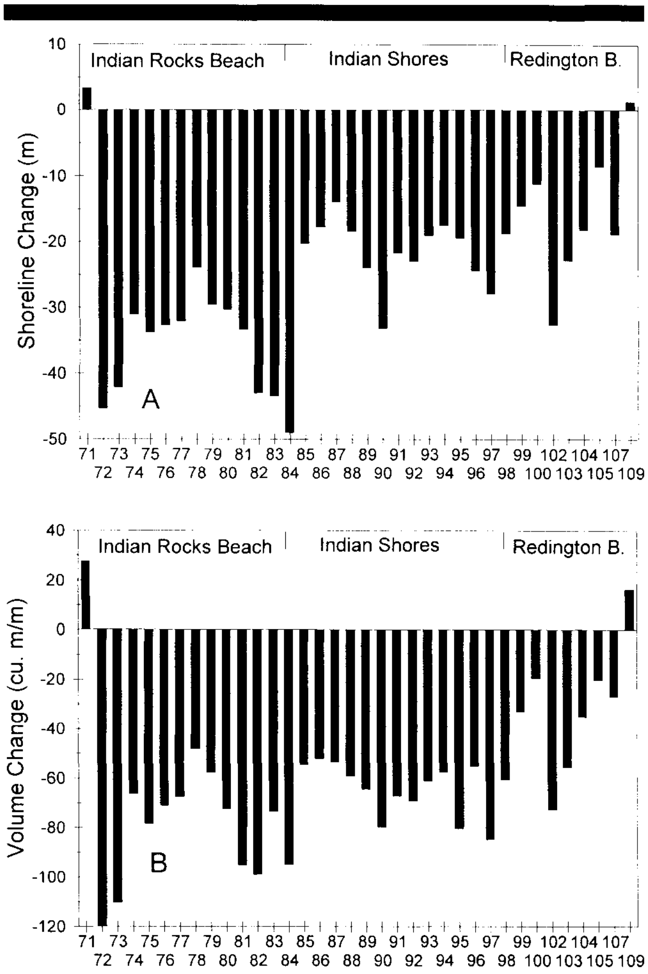

Figure 8. Shoreline (A) and volume changes (B) for the three project during the period of monitoring. The x-axis indicates the monument number.

The average loss per profile throughout the entire monitoring program indicates important differences among the three nourishment projects with the highest values measured in Indian Rocks Beach segment (Table 4). Mean values for each segment show that the Indian Rocks Beach phase had

Table 4. *Sum and average of shoreline and volume changes for each project during the entire period of monitoring. Profiles beyond the nourishment limit but included in the monitoring are included in the averaging and sum.*

	Shoreline Change		Volume Change	
	Entire Period	Per Year	Entire Period	Per Year
Total Sum[1]	−890.71	—	−2172.14	—
Total Average[2] (m^3/m)	−24.74	—	−60.34	—
Indian Rocks (R70–R84) Sum	−466.24	−77.71	−1026.95	−171.16
Indian Rocks (R70–R84) Average	−33.30	−5.55	−73.35	−12.23
Indian Shores (R85–R98) Sum	−299.06	−74.77	−898.71	−224.68
Indian Shores (R85–R98) Average	−21.36	−5.34	−64.19	−16.05
Redington (R99–R109) Sum	−125.41	−15.68	−246.48	−30.81
Redington (R99–R109) Average	−15.68	−1.96	−30.81	−3.85

"Sum": the sum of all the profiles, total change can be roughly estimated by multiplying the distance, 300 m, between adjacent profiles.

the highest per-profile volume loss of 73 m^3/m during the 6 years followed by Indian Shores with 64 m^3/m during the 4 years. Redington Beach experienced the least per-profile shoreline and volume loss, losing only 16 m in shoreline and 31 m^3/m in volume over the eight years after the beach nourishment. Per-profile shoreline loss at Indian Rocks Beach and Indian Shores was 33 m and 21 m, respectively. Taking into consideration the different temporal duration, Indian Shores has the greatest annual rate of per-profile volume loss of 16 m^3/m, as compared to 12 m^3/m at Indian Rocks Beach and 4 m^3/m at Redington Beach. Despite the higher annual rate of per-profile volume loss at Indian Shores, its annual rate of per-profile shoreline retreat was slightly lower than that at Indian Rocks Beach. Both were significantly higher than the 2 m per year per profile at Redington Beach. Beach changes caused by Tropical Storm Josephine, as discussed earlier (Figure 4) contributed to the slightly smaller shoreline retreat rate at Indian Shores, while the updrift location of the Indian Rocks Beach contributed to its greater rate of shoreline retreat.

Discussion

The above results and the present discussion are mainly based on data from beach and nearshore profile surveys (extended to −1.5 m NGVD). The beach and nearshore profile survey had better temporal coverage and was more accurate than the offshore profile survey which extended the profile to −4.6 m (−15 ft) NGVD. The volume changes obtained from the beach and nearshore profiles directly reflect the volume change of the beach fills. Characteristics of offshore profiles are discussed in WANG and DAVIS (1998).

The magnitudes of the total volume loss during the entire period of monitoring, *i.e.,* approximately 6 years post-nourishment for Indian Rocks Beach, 4 years for Indian Shores, and 8 years for Redington Beach, are compared with the volume of the sand fill for each project. Redington Beach performed extremely well, partly due to its downdrift location and the sand trapping at the offshore breakwater. The sediment loss from beach and nearshore zone was only 10% of the total volume of the sand fill (Table 5) for eight years after the nourishment, or only 1.3% per year. The volume loss at the updrift Indian Rocks Beach project constitutes about 31% of the total volume of sand fill during the six years after nourishment, or 5.2% per year. The volume loss at Indian Shores is about 30% of the total volume of the sand fill during the four years after the nourishment, or 7.5% per year. The great annual rate of volume loss at Indian Shores may be attributable to 1) its location at the headland with a divergence in longshore sediment transport, and 2) loose packing of fill sediment resulting from the conveyor-belt sand transfer method of delivery. The loose packing is apparently responsible for the much higher rate of first year volume loss at Indian Shore (Table 3) of 43 m^3/m, nearly twice of the 22 m^3/m at Indian Rocks Beach project and triple that of the 16 m^3/m at Redington Beach project. The high annual rate of volume loss at Indian Shores may also be skewed by its young age as compared to the other two phases of nourishment.

Table 5. *Percentage estimates of the percentage volume loss of the sand fill during the entire period of monitoring.*

	Volume Loss	Sand Fill Volume	Total Loss (% loss/ fill)	Annual Loss (% per year)
	(× 1000 m^3)			
Indian Rocks Beach (~6 years)	308	1000	31%	5.2%
Indian Shores Beach (~4 years)	270	900	30%	7.5%
Redington Beach (~8 years)	74	700	10%	1.3%

It is generally expected that coarse material may result in a relatively slow rate of shoreline retreat and volume loss (e.g., DEAN, 1983, 1991; CERC, 1984; NATIONAL RESEARCH COUNCIL, 1995). The Indian Rocks Beach nourishment used considerably more coarse shell material than at Indian Shores and Redington Beach (Figures 3 and 9). This coarser borrow material did not result in a noticeably slower long-term rate of shoreline retreat or volume loss (Table 4). The high long-term rates of shoreline retreat and volume loss at Indian Rocks Beach (Table 4) are probably controlled by regional factors including 1) the location at the updrift end of the longshore transport system, and 2) exposure to relatively high wave energy from the passage of cold fronts. Despite the above two factors, the coarser material, however, probably contributed to the relatively slow rate of shoreline retreat and volume loss during the first year after beach nourishment (Table 3), especially when compared to those at Indian Shores.

During the first year after the beach nourishment, Indian Shores project experienced an average of 13 m of shoreline

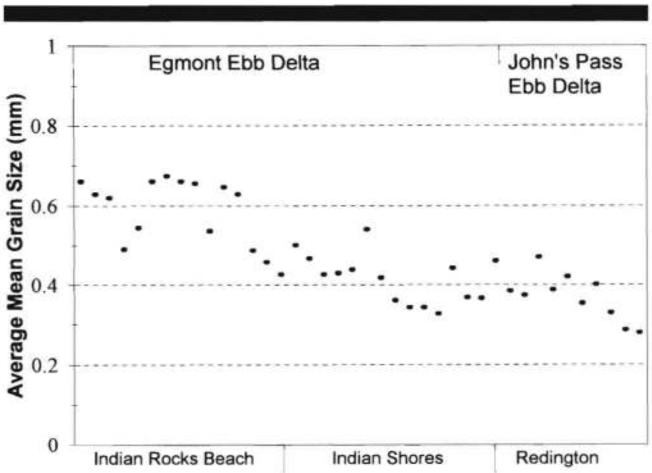

Figure 9. Time-series average mean grain size at each profile from December 1992 to December 1996. Samples were taken from the swash zone.

retreat and 43 m^3/m volume loss (Table 3), significantly greater than the adjacent Indian Rocks Beach and Redington Beach, despite its downdrift location relative to Indian Rocks Beach. The annual rates of shoreline retreat and volume loss are 2.44 and 2.69 times the four-year averages, respectively (Tables 3 and 4). At Indian Rocks Beach, the first-year rates of shoreline retreat and volume loss are 1.99 and 1.79 times the six-year averages, respectively. At Redington Beach, the first-year rates of shoreline retreat and volume loss are 5.79 and 4.11 times the eight-year averages, respectively. The significantly reduced long-term rates of shoreline retreat and volume loss at Redington Beach were apparently influenced by the its downdrift location relative to the other two projects, the impoundment by the offshore breakwater, and its protection from the relative high wave energy during the passage of cold fronts.

As discussed earlier, the Indian Shores project was constructed using a different technique as compared to that used in the nourishment of Indian Rocks Beach and Redington Beach, resulting in a looser packing (DAVIS *et al.*, 1999) at Indian Shores. The substantially rapid rate of initial volume loss (Table 3), as well as the sustained rate of volume loss (Table 4), may be associated with the loose packing resulted from the less costly conveyer belt transfer.

The long-term rate of shoreline retreat at the Indian Shores was influenced by the Tropical Storm Josephine in October, 1996. Although the entire beach and nearshore system experienced a net volume loss, a substantial shoreline accretion was measured throughout Indian Shores due to the fact that the backbeach accumulation that resulted from Hurricane Opal in October, 1995 was transported to the vicinity of the shoreline. This shoreline gain during the period of December, 1995 to December, 1996, significantly influenced the four-year average (Table 4) for the Indian Shores monitoring.

Patterns of shoreline retreat and volume loss at the northern, updrift Indian Rocks Beach, including both initial and long-term change, demonstrate the influence from typical planform adjustment of sand fill, *i.e.,* more shoreline retreat and volume loss at the two ends of the project than those in the middle (Figures 7 and 8), (DEAN, 1983; NATIONAL RESEARCH COUNCIL, 1995). Long-term volume changes also demonstrate the influences of the regional southward longshore sediment transport, with generally more loss at the northern portion of Sand Key than that at the southern portion (Figure 8). The performance at Redington Beach apparently benefited from its downdrift location, as indicated by the dramatic decrease in the long-term rates of shoreline retreat and volume loss when compared with the first-year adjustment.

Some persistent "erosional hot spots" (NATIONAL RESEARCH COUNCIL, 1995) were identified on Indian Shores and Redington Beach. No apparent hot spot was found on Indian Rocks Beach. High rates of shoreline retreat and volume loss were measured at R90 at Indian Shores consistently for several years (Figures 6, 7, and 8). The pattern of volume change (Figure 8) suggests that R90 is located at a divergence of longshore sediment transport. Its location near the apex of the headland seems to support that premise. Detailed wave measurement and modeling are necessary to analysis this important erosional hot spot.

Situations at the Redington Beach were complicated by the existence of two structures, the Redington Breakwater just north of T100 and the Redington Fishing Pier just south of R103. The erosional hot spot at R101, which became extremely severe during the last 4 years of monitoring (Figures 5 and 6), was apparently influenced by the offshore breakwater. The shoreline propagation at T100 during the last 4 years (Figure 6) had significantly influenced the sand supply at R101, resulting in erosion. Another hot spot at Redington Beach during the last 4 years was at R106 (Figure 6). The reason for this hot spot is not clear but the updrift R105 accreted during 1992 to 1996. A local divergence of longshore sediment transport at R106 may be the reason for the hot spot, but further hydrodynamic data are needed to verify this.

CONCLUSIONS

Except at a few erosional hot spots, the three phases of the beach nourishment on Sand Key have performed extremely well. The measured volume loss across the entire project is about 25% of the total volume of sand fill during the period of monitoring. The high volume loss of 31% was measured at the updrift Indian Rocks Beach during a 6-year period of post nourishment, and the least volume loss of only 10% was measured at the Redington Beach during an 8-year period. Indian Shores has the fastest annual rate of volume loss, partly attributable to its less costly conveyor-belt sand transfer method of construction. The performance at Redington Beach has already exceeded the projected 7-year re-nourishment period. Both Indian Rocks Beach and Indian Shores are very likely to exceed the expected 7-year nourishment lifetime.

The performance of beach nourishment is influenced by many factors. Some that are directly related to the present three nourishment projects are: 1) relative location in the regional longshore sediment transport regime, 2) relative wave energy, 3) sediment grain size of the borrow material, 4) local reversal and/or gradient in longshore sediment transport, 5) presence of hard structures, 6) adjacent beach nourishment,

7) variation of the shoreline orientation, and 8) sand transfer and beach-fill construction techniques. Random storm activities also have significantly influenced on beach-nourishment performance.

The updrift Indian Rocks Beach, being devoid of hard structures and significant shoreline orientation change, exhibited classical planform sand-fill adjustment with more shoreline retreat and volume loss at the two ends of the project and less retreat and loss in the middle of the project.

Situations at Indian Shores are complicated by the shoreline-orientation change across the headland. The possible existence of a local longshore sediment transport divergence caused a sustained erosional hot spot in the middle of the project, the location of which coincides with the apex of the headland.

The dry, loosely packed sediment produced by conveyor belt delivery resulted in a 30% saving on initial cost of construction. The very high rates of first-year shoreline retreat and volume loss, as well as the sustained high rate of volume loss during the 4 years of monitoring, indicates that the savings on the initial cost of construction may not be cost-effective over the long term.

The performance of the Redington Beach nourishment benefited considerably from its downdrift location and its relative low wave energy resulting from the protection of the protruding headland against the relatively high waves from the north accompanying cold fronts. Patterns of shoreline and volume changes at Redington Beach were significantly influenced by the offshore breakwater which has trapped substantial amount of sand from the updrift, resulting in a severe erosional hot spot a short distance downdrift of the structure.

Future studies on detailed patterns of wave propagation and longshore sediment transport are critical in relating the morphological changes to the driving hydrodynamic forcing, and in understanding the development of the erosional hot spots.

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