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Immediate profile and planform evolution of a beach nourishment project with hurricane influences

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Abstract

In this study, planform adjustment began during a period of calm weather immediately after nourishment and then the passage of one strong storm caused a substantial portion of the total profile equilibration. Weekly beach profiles, shoreline surveys, and nearshore wave measurements were conducted before, during, and immediately after construction of the 1100-m long Upham Beach nourishment project on the low-energy, west coast of Florida. This project was constructed in three segments: the wide north segment, the central segment, and the narrow south segment. With the exception of the relatively distant passage of Hurricane Charley, calm weather prevailed for 45 days following completion of the south and central segments. Construction of the wide north segment was completed on August 27, 2004. Substantial planform diffusion occurred prior to construction completion via formation of a 300-m long spit extending from the wide north segment. The shoreline orientation was changed abruptly due to this diffusion spit formation, as opposed to the gradual adjustment predicted by most long-term models. Planform adjustment was initiated prior to profile equilibration, and it did not require high-energy conditions. A simple vector sum model for determining the orientation of a potential diffusion spit was developed. This study recommends designing end transitions at the predicted diffusion spit orientation to avoid post-nourishment spit formation during future projects.

Profile equilibration occurred rapidly due to the passage of three hurricanes soon after nourishment was complete. Nine days after completion, Hurricane Frances passed by the project area generating high wave conditions ($H_{sig}=1.7$ m) for this region. The steep post-nourishment beach slope of 0.078 was reduced to 0.036, nearly to the equilibrium slope (0.034), due to this storm. Hurricanes Ivan and Jeanne, which were nearly as energetic, passed by the project area within 1 month after Frances and resulted in much less profile slope change. Examination of the ratio of total volume to plan area remaining in the project area also suggested that a substantial portion of the total profile equilibration occurred as a result of Hurricane Frances. This study indicates that profile equilibration can be an event-driven process, which contradicts the concept of longer-term gradual profile equilibration. Both profile and planform adjustment can occur rapidly given the appropriate site conditions and energy levels.

Keywords: Nearshore sediment transport; Cross-shore; Longshore; Profile equilibration; Shore protection; Design

1. Introduction

In the ongoing effort to confirm beach nourishment as an economically and technically sound shore protection practice, project performance monitoring is vital. Over the last several decades, beach nourishment has proven to be an effective solution to erosion problems in some areas, while elsewhere, the controversy over the technical merits of the practice continues. Sufficient project monitoring is a necessity, particularly in chronically eroding locations that pose a challenge to coastal engineering practitioners. Well-planned performance monitoring allows for verification and future improvement to project design and modeling, as well as justification of project necessity and renourishment intervals (Dean and Campbell, 1999). Unfortunately, monitoring data are often collected without clear site-specific objectives for analysis (Weggel, 1995). Often, data produced from inadequately planned monitoring programs are unable to address the pertinent issues, and crucial performance questions remain unanswered (NRC, 1995).

Generally speaking, a beach nourishment project is a large nearshore perturbation that eventually equilibrates with the

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surrounding system via longshore and cross-shore sediment transport (Dean, 1983). These forcing mechanisms influence the evolution of beach nourishment projects through planform adjustment, i.e. longshore spreading, and cross-shore evolution, i.e. profile equilibration (Fig. 1). Beach nourishment also provides a good opportunity for the study of intensified sediment transport gradients and associated morphological changes.

One-line models that predict the long-term planform evolution of nourishment projects (Dean, 1983, 1996; Hanson and Kraus, 1989) have been developed from the Pelnard-Considére (1956) diffusion equation. In an idealized case of an initially rectangular planform, with project width Y and length l, on an infinitely long shoreline, the solution to the diffusion equation is

$$y(x,t)=\frac{Y}{2}\left\{erf\left[\frac{l}{4\sqrt{Gt}}\left(\frac{2x}{l}+1\right)\right]-erf\left[\frac{l}{4\sqrt{Gt}}\left(\frac{2x}{l}-1\right)\right]\right\} \tag{1}$$

where x and y are the longshore and cross-shore coordinates, respectively, and t is time. The longshore diffusivity, G, is dependent on wave height and sediment characteristics,

$$G=\frac{KH_b^{\frac{5}{2}}\sqrt{\frac{g}{\kappa}}}{8(s-1)(1-p)(h_*+B)} \tag{2}$$

in which K is the sediment transport coefficient, H_b is the breaking wave height, ê is the ratio of H_b to water depth (h), s is the specific gravity of the sediment, p is the in-place sediment porosity, $h*$ is the depth of closure, and B is the berm elevation. During the diffusion process, the post-nourishment shoreline perturbation is smoothed by incoming wave energy that drives longshore transport. The beach fill gradually diffuses from a rectangular planform to a bell-shaped curve that spreads out to a straight shoreline eventually over time (Fig. 1A). Eq. (1) illustrates this diffusion process, which develops smooth end transitions over time (Dean, 1996).

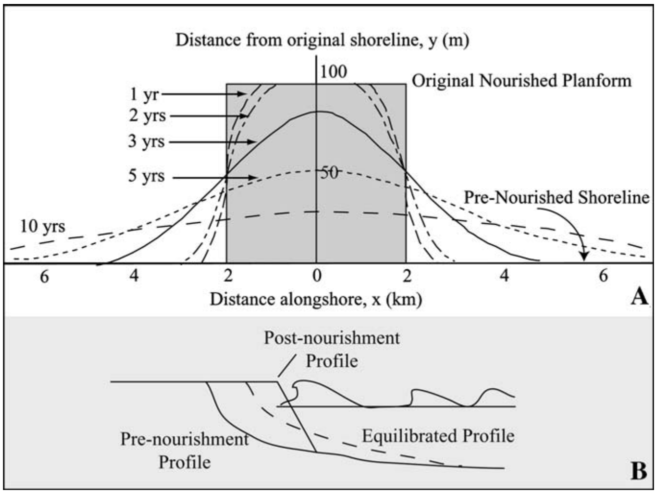

Fig. 1. Schematic sketches of beach nourishment project evolution illustrating A) planform adjustment via longshore transport; B) profile equilibration via cross-shore transport (modified from Dean (2002)).

The proportion of material remaining in the project area over time, $M(t)$, is an important overall parameter characterizing beach nourishment performance. $M(t)$ can be determined by integrating Eq. (1) over the length of a beach project (Dean, 1988). Fig. 2 illustrates that $M(t)$ decays exponentially indicating a rapid material loss immediately after construction. With the introduction of a large perturbation to a dynamic system, a significant initial adjustment should be expected. Initial changes occurring along the steep slope of the exponential decay curve (Fig. 2) should play a crucial role in determining the overall trend of fill evolution. Processes that govern the initial adjustment are therefore critical throughout project evolution. Thus, it is important to understand and quantify the processes that drive the immediate post-nourishment adjustment.

Given the importance of the rapid initial adjustment, it is surprising that immediate high-resolution post-nourishment monitoring is typically not conducted. Although frequent post-nourishment monitoring has been recommended (Davis et al., 2000; Gravens et al., 2003), post-nourishment monitoring surveys are normally conducted one to several months after completion of the project and annually thereafter (Leadon et al., 2004). The temporal resolution of these surveys is often not adequate to quantify immediate post-nourishment adjustment, particularly when high-energy events occur after nourishment.

Eq. (1) assumes small changes in shoreline orientation due to beach nourishment. In fact, Pelnard-Considére (1956) limited the application of Eq. (1) to beaches with incident wave angles of less than 25°. The assumption is reasonable when applied to relatively large spatial scales. However, the substantial nourishment perturbation created along the local shoreline is particularly evident at the project ends where the transitions, which can be designed smoothly or abruptly, merge into the adjacent shoreline. The greatest shoreline orientation change obviously occurs at these end transitions. Here, local wave transformation patterns are altered and the gradients in longshore transport increase. This process often results in high "end losses" (Gravens et al., 2003) that occur immediately following construction. Because Eq. (1) represents long-term and large-scale diffusion, post-nourishment evolution at the end transitions may not be adequately described. Quantifying short-term, local project adjustment, such as transport gradients at end transitions, is essential in improving the present state-of-the-art predictive capabilities.

Profile equilibration refers to the reduction of a steep nourished profile to a gentler characteristic, or equilibrium, profile (Fig. 1B). The equilibrium profile form that is frequently estimated with the simple model of Brunn (1954) and Dean (1977, 1991)

$$h=Ax^{2/3} \tag{3}$$

is dependent on sediment grain size. In Eq. (3), h is the water depth relative to mean sea level, x is the horizontal distance from the shoreline, and A is a scale parameter correlated with

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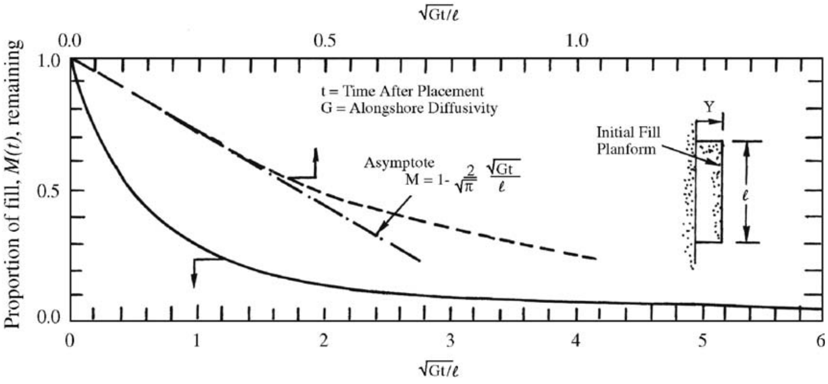

Fig. 2. Proportion of fill remaining, *M*(*t*), along an initially rectangular planform (from NRC, 1995).

grain size (*D*). The *A* value can be determined graphically from Moore (1982), or according to Dean (1987) as

$$A = 0.067w^{0.44} \tag{4}$$

in which *A* is in units of $\mathrm{m}^{1/3}$ and *w* is the settling velocity, in units of cm/s, which can be determined from Hallermeier (1981) as

$$w = 14D^{1.1} \tag{5}$$

Nourished beaches are almost always constructed with sediment that differs from the native grain size of the natural beach. Nourished beaches are also constructed on considerably steeper slopes than natural profiles. During the process of profile equilibration, most of the volume of placed material remains within the project area landward of the closure depth, and is simply redistributed across the profile. The dry beach width is usually reduced during this process (Fig. 1B). Profile equilibration time is considered one of the design issues for which design guidance is limited (Dean and Campbell, 1999). Presently, no cross-shore sediment transport models have been employed to accurately predict time scales of profile equilibration (Dean, 2002).

Understanding the immediate post-nourishment adjustment also has important management implications. Nourishment projects tend to be highly scrutinized by the public during construction and immediately after project completion (i.e. Pilkey and Clayton, 1989). Public education is important to explain the cost–benefit ratios of nourishment to storm protection. In addition, profile and planform adjustment must be explained to avoid misinterpretation of immediate project adjustment as a permanent loss of sand or a misuse of public funds (NRC, 1995; Elko, 2005). Thus, it is important to understand the physical processes and time scales governing adjustment during and immediately following construction when public interest is at its peak.

This study analyzed detailed monitoring data collected before, during, and immediately after a beach nourishment. The objective was to understand the immediate profile and planform response of a beach nourishment project. Specifically, the time scales and energy levels associated with initial project adjustment were examined. To our knowledge, this paper represents the first high-resolution post-nourishment monitoring study that measured profile and planform adjustment on a fine-scale. This study will contribute to the understanding of processes governing profile equilibration and immediate post-nourishment planform adjustment, particularly at end transitions. Results will also contribute to improved profile and planform design considerations for rapidly eroding nourishment projects.

2. Study area

The west coast of Florida is typically a low-energy coastal system with annual average breaking wave heights of 0.3 m (Tanner, 1960) and a mean tidal range of about 0.8 m (NOAA, 2004). The wind and weather conditions along the Gulf Coast of Florida consist of prevailing breezes from the south during the summer and cold fronts that approach from the northwest during the winter. This wind and wave climate results in a regional net littoral drift to the south with several local reversals (Davis, 1994, 1999). Occasionally, tropical storms impact the west coast of Florida; however, 1921 was the last year a hurricane made direct landfall in the study area. During the hurricane season of 2004, four strong hurricanes made landfall in Florida (Fig. 3). All four hurricanes impacted the west-central Florida coast. Due to the proximity of passage, Hurricanes Frances and Jeanne generated wave heights that were up to 6 times greater than the annual average. The swells produced by the more distant Hurricanes Charley and Ivan were 2 and 3 times the annual average, respectively.

Long Key is located in southern Pinellas County along the barrier-inlet chain of the Gulf peninsular coast of Florida (Fig. 3). The northern 700 m of Long Key, called Upham Beach, is a rapidly and chronically eroding beach that has been nourished every 4 to 5 years since 1975. Upham Beach is located immediately downdrift of Blind Pass (Fig. 3). This wave-dominated tidal inlet has been stabilized with bulkhead-type seawalls and a weir jetty, creating the most structured inlet along Florida's west-central coast (Davis and Barnard, 2000). Over the last two centuries, various natural and anthropogenic factors have led to reduction of the tidal prism of the inlet, and the collapse of the ebb tidal shoal. Elko and Davis (in press) describe the morphologic evolution of Long Key and Blind Pass in detail.

When the first condominiums were constructed on Upham Beach in the 1960's, the ebb delta of Blind Pass was collapsing

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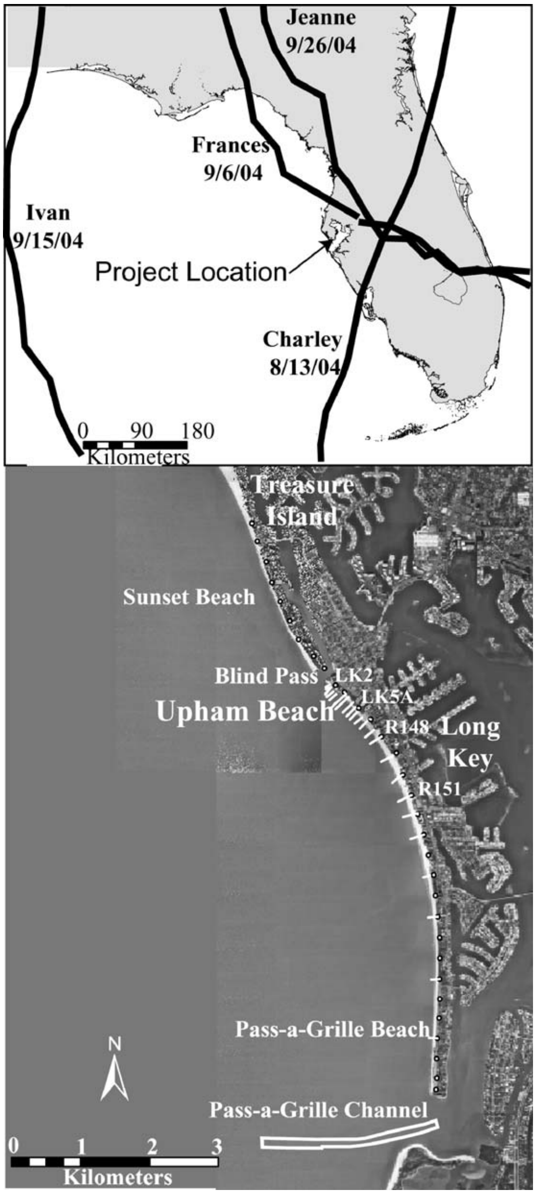

Fig. 3. Study area (lower) and the tracks of the four hurricanes that impacted Florida in 2004 (upper).

and migrating onshore, creating an abnormally wide beach. This seawall and condominium construction anchored Upham Beach in a seaward advanced position, creating a headland at the northern end of Long Key (Fig. 3). Once Upham Beach was no longer protected from wave energy by the diminished ebb delta, erosion began to dominate this region. Presently, the combined effect of long jetties at Blind Pass, a diminished ebb shoal, and periodic dredging of the inlet has largely eliminated natural sand bypassing around Blind Pass. This prevents an adequate sediment supply from reaching Upham Beach.

2.1. Previous Upham Beach nourishment projects

Based on results from the 1996 fill, the half-life for the plan area of the Upham Beach project, the time at which $M(t)=0.5$, is approximately 1 year (Elko et al., 2005). Longshore currents transport the nourished material to the downdrift beaches; thus, Upham Beach has been labeled a “feeder beach” for the rest of Long Key (USACE, 1999). A feeder beach is a nourishment project in which material is introduced at the updrift end of the littoral cell intended to receive fill. Longshore transport distributes the fill to the rest of the project area.

Prior to the 2004 project, Upham Beach had been nourished six times in 1975, 1980, 1986, 1991, 1996, and 2000. Typically up to 200,000 m^3 of material was placed along the northernmost 700 m of Long Key. The fill limit typically extended from Blind Pass to LK5A (Fig. 4). The maximum berm width typically constructed was 115 m. During the 1996 project, half of the planform area eroded within 1 year of placement (Elko et al., 2005). After 4 years, 100% of the nourished material was eroded from the project area.

Blind Pass is the preferred borrow area for Upham Beach nourishment projects, due to its proximity. However, the dredging interval of Blind Pass is about 8 years, whereas the renourishment interval for Upham Beach is 4 years. Every other project requires the use of an alternate borrow area, such as Pass-a-Grille Channel (for 1986 nourishment) (Fig. 3) and Egmont Shoal (for 1996 nourishment), approximately 13 km south of the project area.

Previous studies have concluded that between 64,500 and 86,000 m^3 (up to 40% of the total fill volume) of sediment erodes from Upham Beach during the first year after nourishment (CPE, 1992; Elko, 1999; USACE, 1999, 2001). Positive volume change is routinely measured on the downdrift beach following nourishment, however the sediment budget for material eroding from the project area (Q_{out}) and material accreting downdrift (Q_{in}) has not been balanced, likely due to insufficient monitoring.

2.2. 2004 nourishment project

The 2004 Upham Beach nourishment project extended beyond the typical limit at LK5A for an additional 400 m to R148 (Fig. 3). To accommodate this additional area, the 2004 project was designed with three distinct segments (Fig. 4): 1) the wide north segment, from Blind Pass to LK3A, 2) the central segment, from LK3A to LK5A, a large end transition that typically ties into the natural beach, and 3) the south segment, from LK5A to R148, which was nourished for the first time in 2004. The total project length in 2004 was 1100 m, the total volume was 294,000 m^3, and the design berm elevation (B) was 1.8 m. The north and central segments had a maximum berm width of 140 m, the widest berm width ever constructed on Upham Beach, and an average nourishment volume density of 360 m^3/m. The south segment had an average berm width of 40 m and an average volume density of 95 m^3/m. To accommodate the additional project length, the fill was designed with two transitions: 1) the large transition in the central segment of fill that reduced the berm width from 140 m to 40 m over 260 m, and 2) the slight transition at the south end which tied in with the natural berm width of about 40 m. This design was implemented to provide advance mitigation for the planned T-groin field to be installed following nourishment.

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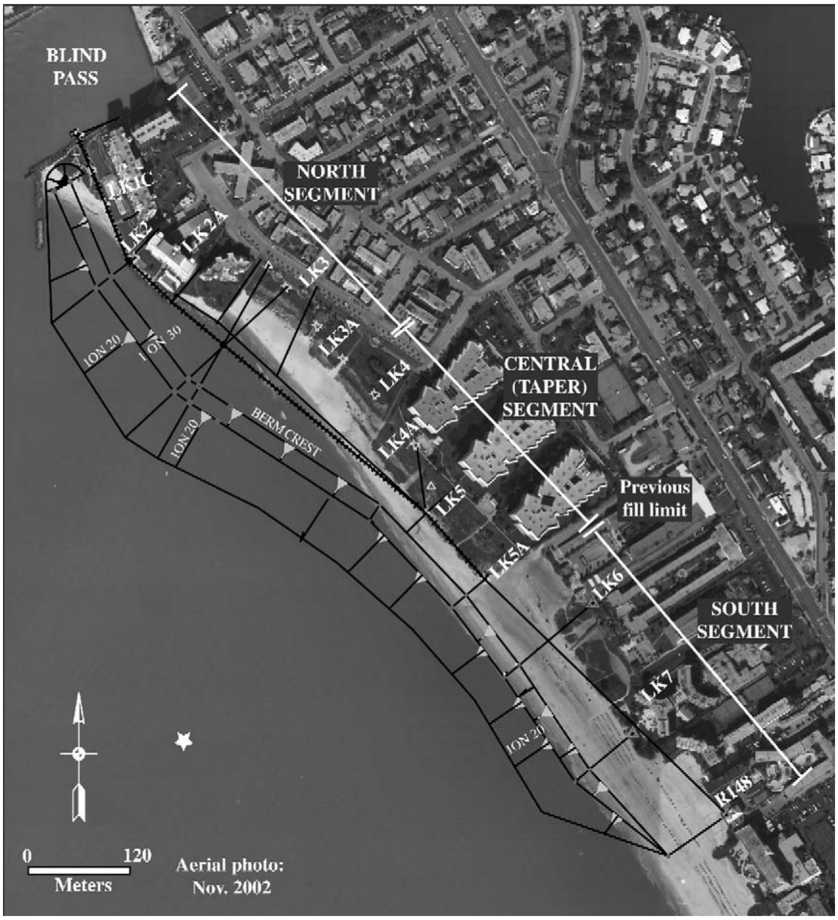

Fig. 4. The planform design template of the 2004 Upham Beach nourishment project. The star at the lower left corner marks the location of the directional wave gauge.

Five geotextile T-groins were planned for Upham Beach after the 2004 nourishment in an effort to improve the longevity of the project. The T-groins would be evenly spaced along the north segment. Based on previous studies, sediment that erodes from Upham Beach supplies the downdrift beach. If the T-groins successfully retain sediment on Upham Beach, a downdrift sediment deficit would be created. Thus, additional fill was placed in the south segment, downdrift of the future T-groin field, to mitigate for potential downdrift impacts. The T-groins had not yet been installed at the time of writing this paper.

The 2004 beach fill was also designed with a multiple slope that has become known as a “turtle friendly” design. A gently sloping berm is designed to minimize scarping and prevent overtopping of the berm, which leads to ponding in the backbeach. The 2004 Upham Beach project was designed with a wide flat berm that sloped at 1:30 (0.03) from 1.5 to 0.75 m NGVD (National Geodetic Vertical Datum 1929, to which all elevations are referenced; 0 m NGVD is roughly 0.15 m below present mean sea level). The design then transitioned to a 1:20 (0.05) slope below 0.75 m (Fig. 4).

2.2.1. Construction

The borrow area for the 2004 project was the Pass-a-Grille Channel and ebb shoal located 5 km south of Upham Beach (Fig. 3). This borrow area provided fill not only for the Upham Beach nourishment project, but also for the concurrent Treasure Island project and the Pass-a-Grille Beach emergency project, which was nourished to repair damage from the 2004 hurricanes. In order to provide a sufficient volume of material, the pre-project channel alignment was straightened, cutting through the ebb shoal along the western portion of the Pass-a-Grille navigational channel. Nearly 600,000 m^3 of sediment was removed from the channel and shoal by a 24-inch (61-cm) cutterhead pipeline dredge, the “Charleston” of Norfolk Dredging Company. The average depth of water before dredging was 2.4 m and the borrow area was excavated to an average depth of 3.4 m. Material was pumped hydraulically to the nourishment area through more than 6500 m of submerged pipeline located approximately 600 m offshore. The pipeline was left in place during dredge demobilizations due to stormy weather. Production rates were approximately 13,000 m^3/day (17,000 yd^3/day). The addition of a booster pump halfway along the pipeline increased production to 15,300 m^3/day (20,000 yd^3/day).

Fill placement began on Upham Beach on July 28, 2004 (Table 1). Fill was placed from south to north (Fig. 5) in the opposite direction of net littoral drift. Placement from north to south was not possible due to environmental permit requirements that restricted the pipeline corridor location. In addition, the contractor was not permitted to generate turbidity above background conditions. To reduce turbidity, shore-parallel or longitudinal sand dikes were constructed to prevent the sand slurry runoff from entering the adjacent waters. The longitudinal

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Table 1
Construction schedule for the three segments of the 2004 Upham Beach project

Segment	Completion date (2004)	Completion to the passage of Hurricane Frances on September 5, 2004 (days)
South	July 22	45
Central	July 28	39
North	August 27	9
Repair	October 28	n/a

dike was maintained at a length of at least 150 m in advance of the filling operation (Fig. 5). Occasionally, it was necessary to construct a shore-perpendicular dike to control sediment runoff. A Y-valve was installed at the end of the shorepipe such that material could either be pumped Gulfward for dike construction or landward for beach construction. This method of construction resulted in little to no turbidity and minimal sand loss.

Due to the passage of four hurricanes during August and September 2004, during and shortly after the completion of the project, a large amount of sediment eroded rapidly from the design template. A repair nourishment, authorized for Upham Beach following the storms (Elko, 2005), was completed on October 28, 2004. This renourishment repaired a section from Blind Pass to LK4 (Fig. 4) to the original design template. Profile equilibration following the repair nourishment was also examined in this paper. However, the introduction of this additional sediment complicated continued analysis of the short-term planform evolution. Planform diffusion of the original fill, which was already underway, was disrupted by the additional sediment. Consequently, the planform evolution of the repair nourishment is not discussed herein.

3. Methodology

An intensive field-monitoring program was initiated prior to construction of the 2004 nourishment project with the goal of understanding the processes governing immediate post-nourishment project adjustment in the longshore and cross-shore directions. Of course, the impact of four hurricanes was not anticipated, but was an interesting addition to the field study.

Beach profiles, offshore bathymetry, planform configuration, and offshore waves were measured from June to October 2004. Along Long Key, 21 profiles were surveyed with the closest spacing of about 100 m within the north and central segments (Fig. 3). Profile spacing increased downdrift of the project where less short-term change was anticipated. Based on experience from previous monitoring efforts, traditional wading depth profiles were extended to approximately −3 m. Wading profiles, which are typically surveyed to approximately −1.5 m, were extended to capture nearshore changes and measure profile equilibration. In general, the beach profile surveys extended offshore nearly to the depth of closure, which is approximately −3 m in southern Pinellas County (Wang and Davis, 1999). These wading beach-profile surveys followed level-and-transit procedures using an electronic total survey station.

Thirteen surveys of the 21 profile lines were conducted during this field effort. Weekly beach profiles were surveyed before, during, and immediately after nourishment until October 1, 2004. As discussed in the following sections, significant beach profile changes were measured even on a weekly basis. The pre-construction beach survey was conducted on June 6, 2004, and the post-construction surveys were conducted at different times along different segments. For profiles at the south end of fill, the post-construction survey was conducted on July 28, 2004, while for profiles on the north end of the fill, the post-construction survey was conducted on August 28, 2004 (Table 1), a month after the south segment was completed. In the meantime, up to three weekly surveys were conducted along the central and south segments during construction of the north section of the project.

Bathymetric surveys extending to a water depth of approximately 5 m and 1500 m offshore were also collected in June, September (before the hurricanes), and October 2004

Fig. 5. Construction of the Upham Beach nourishment project. The aerial photo was taken on July 28, 2004, looking north. Inserts: longitudinal dikes near the outflow to control turbidity.

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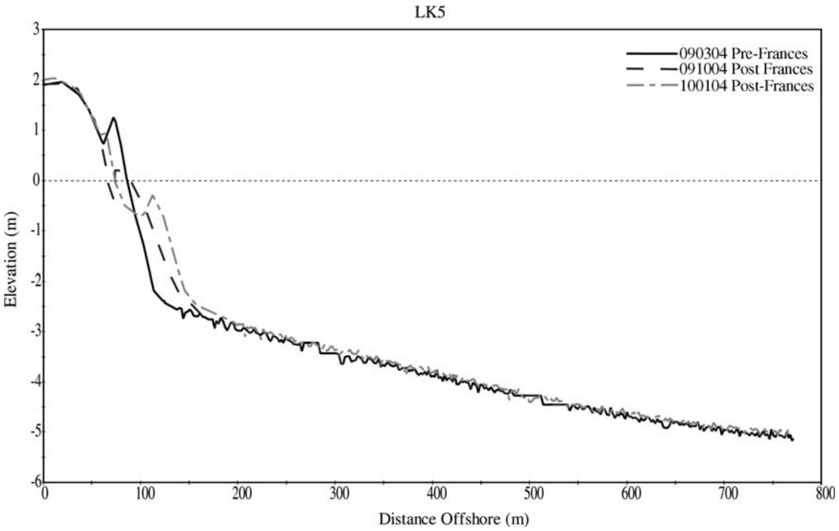

Fig. 6. Combined beach and offshore surveys. The transition from the wading profile to the jagged bathymetric profile is evident.

(after the hurricanes). The offshore survey was conducted using a synchronized precision echo sounder for water depth and RTK-GPS (Real Time Kinematic-Global Positioning System) for horizontal positions. Tidal water level variations were removed based on measurements from the wave gauge (Fig. 4).

Beach and offshore surveys were combined (Fig. 6). The jagged line along the offshore portion of the profile reflects the sampling interval of one point per second (1 Hz). The short, straight, line segments on the profile reflect linear interpolations between data gaps. Minimal change in the offshore portion of the surveys suggests that the beach surveys captured most of the nearshore changes and that little sediment was transported offshore beyond about −3 m. This concurs with the depth of closure determined by Wang and Davis (1999).

The spring-tide high water line, berm crest, dune and vegetation line, and other features (e.g., seawall) were mapped with the RTK-GPS mounted on an ATV (All Terrain Vehicle). The spring high water level can generally be identified in the field from a rack line left from the previous high tide. Elko (2005) describes this morphologic mapping in detail.

A PUV directional wave gauge was deployed about 600 m offshore of the center of the Upham Beach nourishment project in approximately 4 m of water (Fig. 4). Wave conditions were measured every 90 min and sampled at 2 Hz. Tidal water levels were measured every 15 min.

Sediment samples were collected before and during construction. One hundred and eighty seven sediment samples were obtained, representing every 1500 m^3 of fill placed. The sampling locations were evenly distributed across the fill template in a 30-m grid. The mean sediment grain size was determined using standard sieves. To determine the mean grain size for each profile, samples located 30 m to the north and south of the profile line were averaged.

A large amount of detailed field data was collected over 71 days before and during construction and in the initial post-nourishment phase of the project. The data allowed for analysis of the immediate post nourishment response, which is the focus of this paper. The data were also used to analyze the effect of multiple storm impacts on a recently nourished beach, and in emergency management decision making following the hurricanes (Elko, 2005).

4. Results

During the 2004 hurricane season, four hurricanes made landfall in Florida (Fig. 3). On August 13, Hurricane Charley made landfall approximately 110 km south of the project area. Charley generated maximum wave periods (T_p) of about 8.3 s and significant wave heights (H_{sig}) of up to 0.92 m at the project area (Fig. 7). Prior to the passage of Charley, a storm event from August 1 to August 6, generated maximum wave conditions of $H_{sig}=0.78$ m and $T_p=6.1$ s. This storm forced construction to pause for several days. Following the passage of Charley, calm conditions were characterized by an average H_{sig} of 0.13 m and a bimodal wave period (Fig. 7B) that was likely a combination of swells ($T_p=7.5$ s) and locally generated wind waves ($T_p=3.0$ s) that are commonly observed in the Gulf of Mexico. Hurricanes Frances, Ivan, and Jeanne made landfall on September 5, 15, and 26, respectively. Hurricane Frances passed by the project area 9 days after nourishment was complete. Hurricanes Frances and Jeanne passed by the project area within 50 and 80 km, respectively. These storms generated steep storm waves with maximum wave heights of $H_{sig}=1.7$ m (Fig. 7), roughly six times the annual average wave height along this low-energy coast. Waves generated by Hurricane Ivan (max: $H_{sig}=1.0$ m, $T_p=15.9$ s) approached the project area as a well-organized swell. Wave direction data are not included in Fig. 7 due to equipment malfunctions; however, wind direction data are included. The wave direction during the passage of Hurricanes Frances and Jeanne can be estimated from wind direction, as these were wind-generated waves. Waves generated by Hurricane Ivan approached shore normal.

The pressure port on the wave gauge was later clogged due to sediment suspension and subsequently malfunctioned in November and December. However, wave conditions were measured during the previous winter season (2003). Cold fronts

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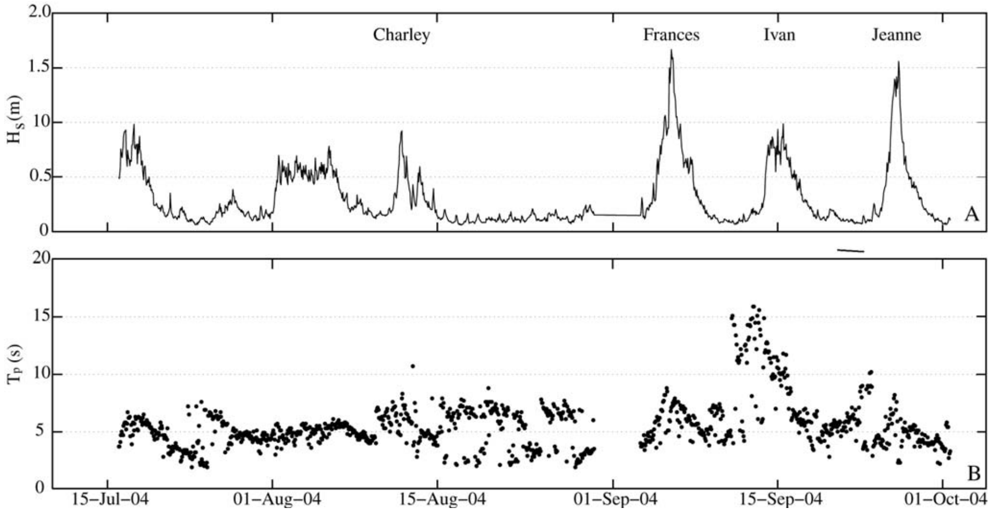

Fig. 7. Wave conditions from July 18 to October 1, 2004 (gauge location shown in Fig. 4) measured in 4 m of water depth.

generated high-energy events with maximum $H_{sig} = 1.3$ m. Several similar cold fronts occurred during the months following the repair nourishment in 2004, but wave data are not available.

The mean sediment grain size of the fill material (D_F) was 0.52 mm (Fig. 8). The fill material was similar but slightly coarser than the native sand ($D_N = 0.45$ mm) with the exception of the section from LK3 to LK5 (Fig. 4). The nourishment sediment grain sizes ranged from 0.3 to 0.9 mm. About 75% of the samples ranged from 0.3 to 0.6 mm. Of the remaining 25% of samples greater than 0.6 mm, 92% were located in the section between LK3 and LK5. The use of relatively coarser sediments between LK3 and LK5 was expected to improve nourishment performance in this rapidly eroding area. The sediment borrow area was Pass-a-Grille Channel and ebb shoal (Fig. 1). It is likely that the relatively coarser sediment was dredged from the channel (lag deposits) and the finer sediment was removed from the ebb shoal.

Due to differences in construction schedules, fill templates, and morphologic responses in the different fill segments, planform and profile adjustment results are presented in the following sections separately for 1) the north segment and 2) the central and south segments of the fill. Although planform and profile adjustment after nourishment are typically analyzed as separate processes, the processes actually occur simultaneously and are related. In this case, relatively small-scale planform evolution began at the end transitions. Calm weather that persisted prior to the passage of Hurricane Frances (Fig. 7) resulted in this rapid planform evolution. During this time, little profile adjustment occurred. The subsequent passage of Hurricane Frances resulted in significant profile change. The time scales and energy levels associated with the processes of planform and profile adjustment are discussed in the following sections.

5. Planform adjustment

Significant morphologic change was measured prior to the passage of Hurricane Frances on September 5, 2004, only 9 days after nourishment was complete. Much of the initial planform adjustment in the central and south segments of the project occurred during construction of the north segment. After construction, morphologic changes were measured up to 900 m downdrift of the nourished planform to R151. The morphologic changes discussed herein were analyzed in the three segments in accordance with the planform design (Fig. 4). The downdrift segment, extending approximately 1000 m south of the fill (south of R148 to R151), was also analyzed. The locations of the beach profiles and the fill segments are illustrated in Figs. 3 and 4, respectively.

5.1. North segment

Little morphological change occurred in the north segment between the completion of nourishment in this segment on August 27, 2004 and the passage of Hurricane Frances (Fig. 9A). Although strict turbidity requirements precluded fine sediment runoff, some fill material was transported to the south, predominantly in the swash zone, during construction. Erosion,

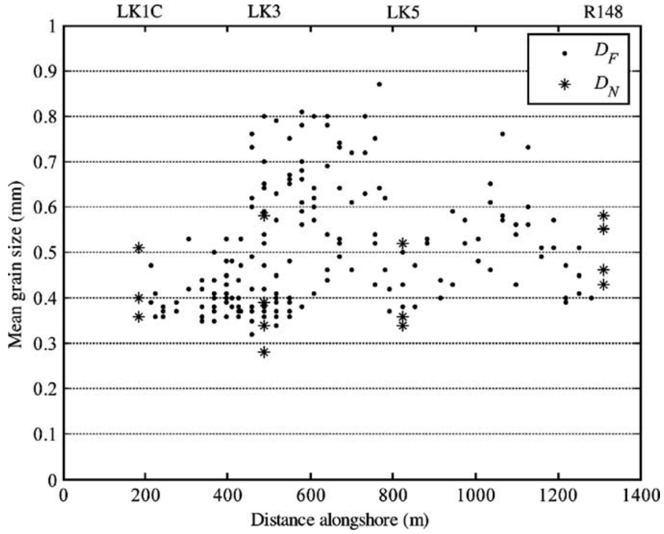

Fig. 8. Mean sediment grain size before (D_N) and after nourishment (D_F). The x-axis refers to distance from Blind Pass at the north end of the fill.

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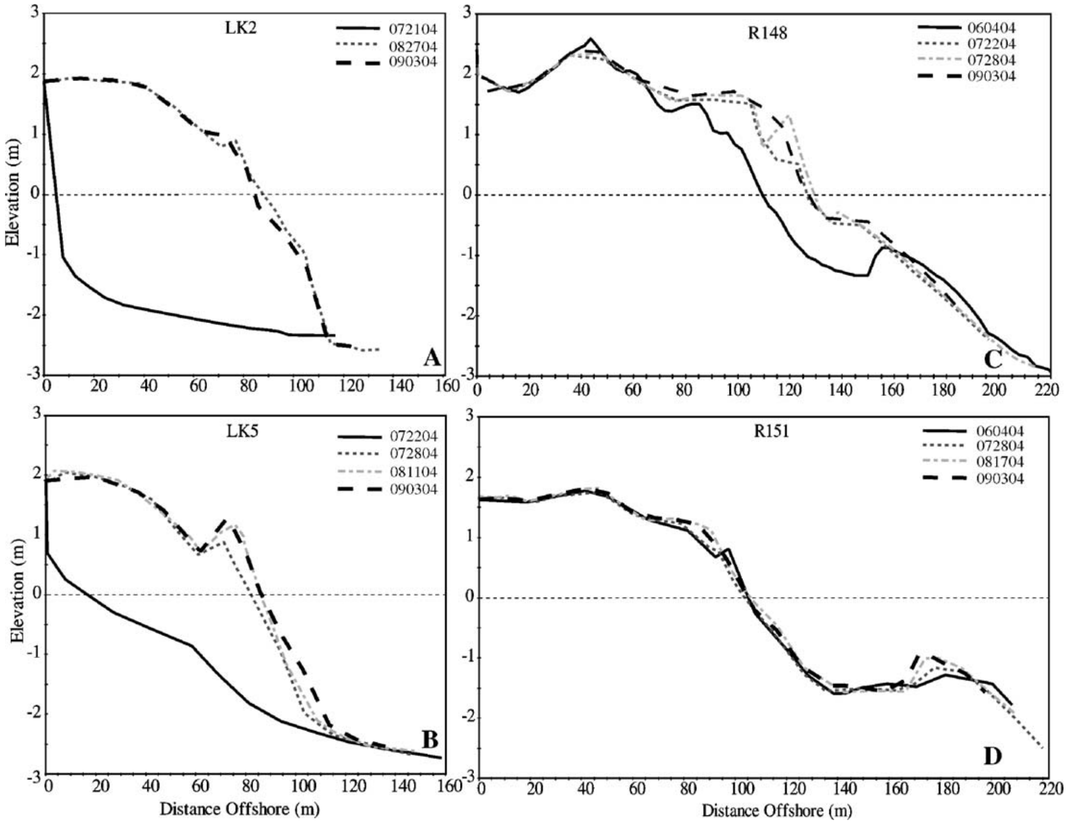

Fig. 9. Profile response after nourishment from: A) the north segment, B) the central segment, C) the south segment, and D) downdrift of the nourished area. See Fig. 1 for profile locations. Note that the post nourishment survey dates are different for A (082704), B (072804), and C (072204).

e.g., in the form of scarping, took place in the loose sediment that was placed in the intertidal zone, for example in the longitudinal dikes (Fig. 5). By the time construction of this segment was complete on August 27, a considerable volume of material had been transported to the south. Obviously, the post-construction survey for the north segment does not illustrate this volume loss because transport occurred during construction and prior to the final grading of the beach. This transport contributed to the development of a spit, as discussed in detail in the following paragraphs.

5.2. Central and south segments

Construction in the central and south segments of fill was completed earlier, on July 28 and 22, respectively (Table 1). Planform adjustment began to occur soon after nourishment of the central and south segments was complete. About 40 days elapsed between completion of nourishment in the central and south segments and the passage of Hurricane Frances. During this time, the beach in the central and south segments prograded, as sediment that eroded from the north segment was deposited in the nearshore and intertidal zones (Fig. 9B and C). In the downdrift region, offshore sand bars accumulated sediment and migrated onshore (Fig. 9D).

Transport to the downdrift beaches during construction was also measured during the January 2000 Upham Beach nourishment, which took 6 months to construct due to oil contamination of the Blind Pass borrow area. By the time post-nourishment monitoring began in July 2000, the downdrift beaches had already accumulated almost 30,000 m^3 of sediment (11% of the total fill) (USACE, 2001).

Deposition in the central segment was first measured on August 11, about 2 weeks after nourishment was complete in this segment. Weekly survey data indicated the formation of a large inter- to supratidal sediment body in the central segment of the project. Contour maps derived from morphologic mapping illustrate the sediment body extending over 300 m from profile LK4A to the south to LK6 (Fig. 10). It resembled a spit spreading from the transition of the wide north segment of the planform (Fig. 11A). A similar sand body was also observed extending from the end transition of the south segment (Fig. 10 insert).

Formation of the 300-m spit suggests that substantial longshore transport of the nourished material, and therefore planform adjustment, occurred before construction of the entire nourishment project was complete (Fig. 10, insert). In other words, the diffusion process began during fill placement. The direction of spit formation reveals that the source of the sediment is from the northern end of the project. The dominance of shell material in the at least subaerial part of the spit (Fig. 11A) indicates that selective transport was important during the initial formation of the diffusion spit.

Quantification of beach profiles surveyed on September 3, 2004 indicated that the diffusion spit was composed of approximately 7000 m^3 of sediment. The spit resulted in shoreline

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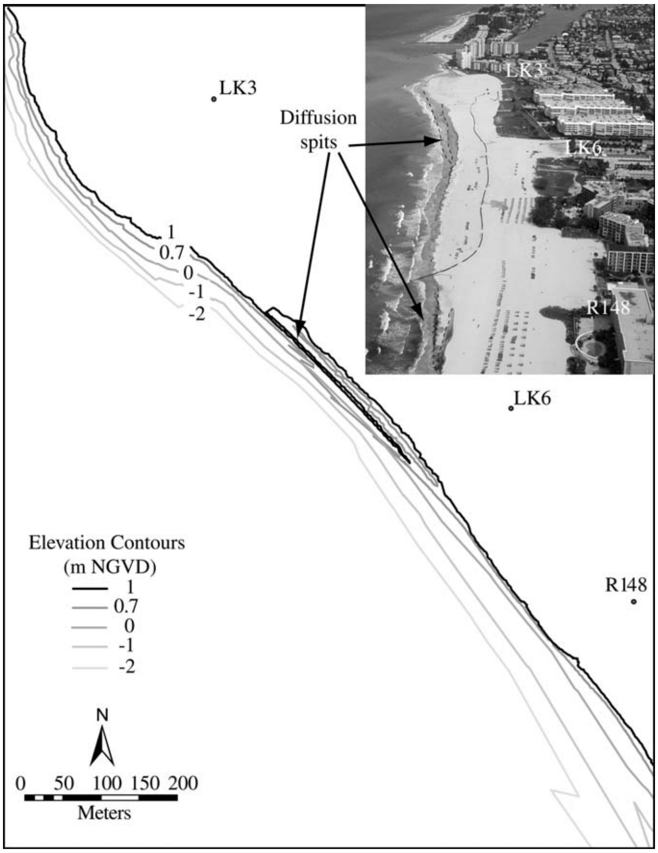

Fig. 10. Contour map of the beach fill based on survey data from September 1, 2004. Insert: aerial photo taken on August 12, showing the well-developed diffusion spit (outlined by dashed line) at the south end of the project and the development of the spit at the transition between the north and central segments.

advancement of 8 m on average as compared to the immediate post-nourishment survey. During this time, the spit accreted to an elevation of over 1.3 m (Fig. 9B). The beach profiles prograded, essentially translating seaward. The post-nourishment profiles steepened slightly due to spit formation (Fig. 9B). As shown in Fig. 10, the shape of the diffusion spit and the associated runnel are depicted well by contours at elevations 1.0 and 0.7 m, respectively. These elevations also correlate with the shape of the spit shown on the beach profiles (Fig. 9B), confirming that the contour map revealed the spit morphology accurately.

The modest storm event from August 1 to August 6 (Fig. 8), with wave heights reaching 0.6 m (or twice the annual average) may have initiated and accelerated diffusion spit formation. The spit persisted through the relatively distant passage of Hurricane Charley. Net onshore transport occurred during this time, as indicated by continued spit accretion (Fig. 9B) and numerous overwash tongues along the landward side of the spit (Fig. 11A). The diffusion spit persisted for about 40 days and was dispersed during the passage of Hurricane Frances in early September. The substantial profile changes caused by the hurricane impacts are discussed in detail in the next section.

Another large diffusion spit extended from the south end of the project at R148 shortly after the completion of the fill in the south segment (Fig. 10, insert). Only one survey line (R148) intersected this southern spit, so the spit volume cannot be accurately calculated. The southern diffusion spit was first documented on July 28, 2004 (Fig. 9C) only 6 days after construction of this section was complete. It had a maximum elevation of 1.3 m.

Similar diffusion spits were observed on the 2004 Treasure Island project, on the 2004 emergency nourishment project at Pass-a-Grille Beach, and on the 1996 Upham Beach project. Diffusion spit formation was observed on the Pinellas County Sand Key nourishment in 1998, a nourishment project about 18 km north of Upham Beach. Development of this diffusion spit abruptly changed the shoreline orientation at the large end transition (Fig. 11B). A similar abrupt end transition constructed on Anna Maria Island in 2002 also resulted in diffusion spit formation (Fig. 11C). The elevation and width of this spit increased for about 1 year until a storm event generated

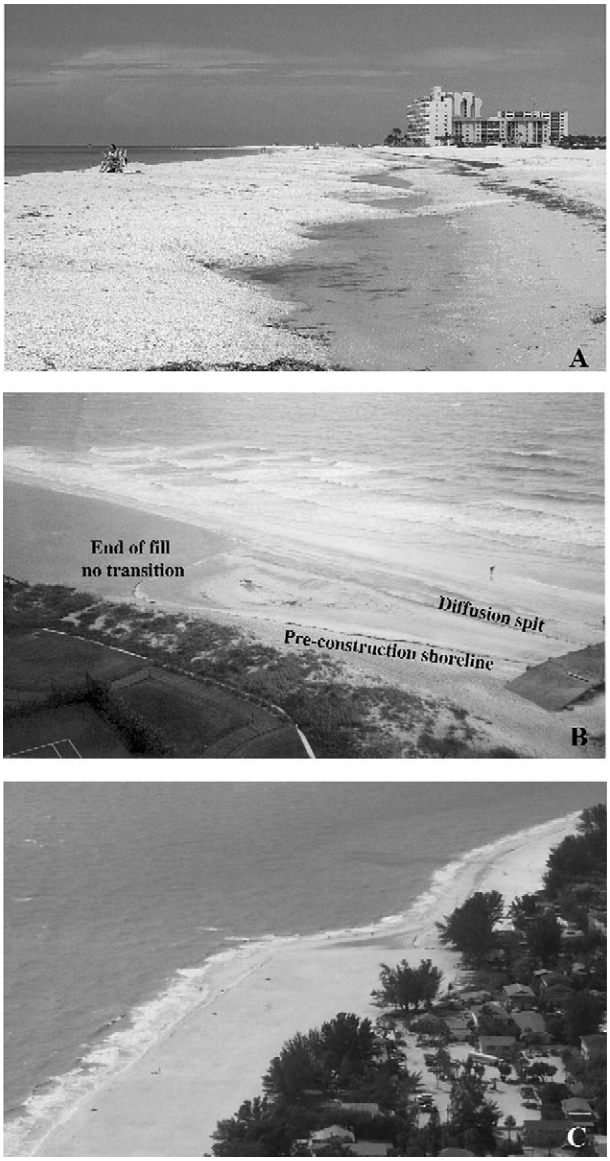

Fig. 11. Photos of diffusion spits on A) Upham Beach on August 27, 2004, note the numerous overwash tongues on the landward side, B) the 1998 Sand Key nourishment, and C) the 2002 Anna Maria Island nourishment (photo courtesy of Rick Spadoni, CPE).

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sufficient wave energy to overwash the feature and fill in the landward runnel/lagoon (Spadoni, pers. comm.). Kraus (1999) reported the formation of similar, but longer-term spit development downdrift of the Corpus Christi Beach nourishment project in 1977. This is a bay shore beach on the western side of Corpus Christi Bay. In the 4 years following nourishment, this diffusion spit extended over 500 m until reaching a causeway that prevented further extension. Note that the diffusion spits cited above formed on relatively low-energy beaches. In addition, Sauvage de Saint-Marc and Vincent (1954) presented physical modeling results indicating that spit formation occurred at incident wave angles of greater than 55°.

In summary, diffusion spit formation seems to be a common feature during the initial planform adjustment at the end of a beach fill. Shoreline orientation may be changed abruptly as the spit extends and attaches to the downdrift shoreline. For the case at Upham Beach, considerable longshore transport of nourished material was initiated during fill placement. Large gradients in longshore transport are not uncommon, particularly at erosional hot spots such as Upham Beach and at end transitions of nourishment projects. Although spit growth was largely driven by sediment supply from longshore sand transport, cross-shore processes served to redistribute sediment both seaward and landward. In this case, the seaward redistribution resulted in sand accumulation in the immediate offshore area (Fig. 9B). The landward redistribution deposited material above mean water level (Fig. 9B and C) and resulted in overwash and landward migration of the spit. The form of the spit was destroyed by the passage of Hurricane Frances.

5.3. Predicting immediate planform adjustment

Various definitions and formation processes for spits exist in the literature. A spit is an elongated depositional feature extending away from an eroding headland in the direction of longshore sediment transport (Dean and Dalrymple, 2002). Spit formation allows the storage of large quantities of sediment released from point sources through an extension of the downdrift segment of the littoral cell (Swift, 1976). Spits extend alongshore in the direction of sediment transport as they simultaneously move onshore (Carter, 1988). Johnson (1919) observed that spit growth is most common on irregular coastlines where spit formation aids in smoothing the initially irregular coast. Findings from the present study support these definitions and suggest that a spit can also develop at the end transition of a beach nourishment project.

The one-line GENESIS (*GENE*ralized model for *SI*mulation *S*horeline change) model (Hanson and Kraus, 1989) was previously applied to simulate the evolution of the Upham Beach nourishment project (USACE, 1999). The model was calibrated to the site-specific conditions with survey data from the 1991 project. The GENESIS modeled shoreline for a five-year simulation represented the measured shoreline well. Both the measured and modeled shorelines over a five-year interval indicated total erosion of the fill. Increasing the width and/or length of the beach fill did not significantly change the longevity of the project in simulated model runs. The model runs indicate a smooth transition from the design planform to an eroded, straight shoreline, similar to the concept presented in Fig. 1A. The model assumptions and the low temporal resolution of model output did not allow for simulation of rapid spit formation.

5.3.1. Shoreline orientation changes

Changes in shoreline orientation, $\Delta\beta$, due to nourishment are generally assumed to be small, in terms of the overall spatial scale (Dean, 2002). The increased beach width, Δy, is typically much less than project length, l. According to Dean (2002), the average change in shoreline alignment due to nourishment is

$$\tan\Delta\beta = \frac{\Delta y}{l/2}. \tag{6}$$

For the idealized nourishment project illustrated in Fig. 1A with $\Delta y = 100$ m and $l = 4000$ m, $\Delta\beta = 2.86°$. The typical small difference between these values suggests that the change in shoreline orientation due to nourishment is generally small. The analytical model of Eq. (1) therefore assumes small changes in shoreline orientation due to beach nourishment. In this model, the linearization of the sediment transport equation is justified because $\sin(2\Delta\beta)$ roughly equals $2\Delta\beta$ for small $\Delta\beta$ (less than 0.02% difference for the above example). However, the design template for many feeder beaches and erosional hotspots, or short nourishment projects, creates a relatively large shoreline perturbation. In the case of Upham Beach, the typically nourished north and central segments had a maximum berm width (Δy) of 140 m and a length (l) of 700 m, which yields a $\Delta\beta = 20.38°$. This large $\Delta\beta$ yields an 8.2% difference between $2\Delta\beta$ and $\sin(2\Delta\beta)$ suggesting that a considerable error may result from the assumption of $\sin(2\Delta\beta) \approx 2\Delta\beta$. Abrupt end transitions that do not taper into the natural beach may have values of $\Delta\beta$ that approach 90°. This extreme shoreline orientation change is obviously significant, and also invalidates the above assumption.

The beach orientation and its change at the transition zone can be measured directly from the GPS shoreline maps. The measured orientations, β of the pre-nourishment shoreline (X) and of the design transition (T) from LK4A to LK5A were 35° and 57°, respectively (Fig. 12). Thus, the measured $\Delta\beta$ was approximately 22°, which is similar to the $\Delta\beta$ calculated from Eq. (6), as expected. This large $\Delta\beta$ was reduced abruptly upon formation of the diffusion spit. The measured β of the diffusion spit was 45°, considerably reducing the orientation difference from 22° to 12°. The orientation of the diffusion spit can be calculated from the orientation of the pre-nourishment shoreline and the design transition (Fig. 12). Assuming the orientations of the pre-nourishment shoreline and the design transition can be represented by two unit vectors, $\overrightarrow{X}$ and $\overrightarrow{T}$, respectively, the sum of the two unit vectors yields the vector of the diffusion spit $\overrightarrow{S}$

$$\vec{X} + \vec{T} = \vec{S} \tag{7}$$

In this case, $\overrightarrow{X} = 35°$ and $\overrightarrow{T} = 57°$, yields $\overrightarrow{S} = 46°$, which closely approximates the measured β of 45°. This simple model for determining the orientation of a potential diffusion spit can be

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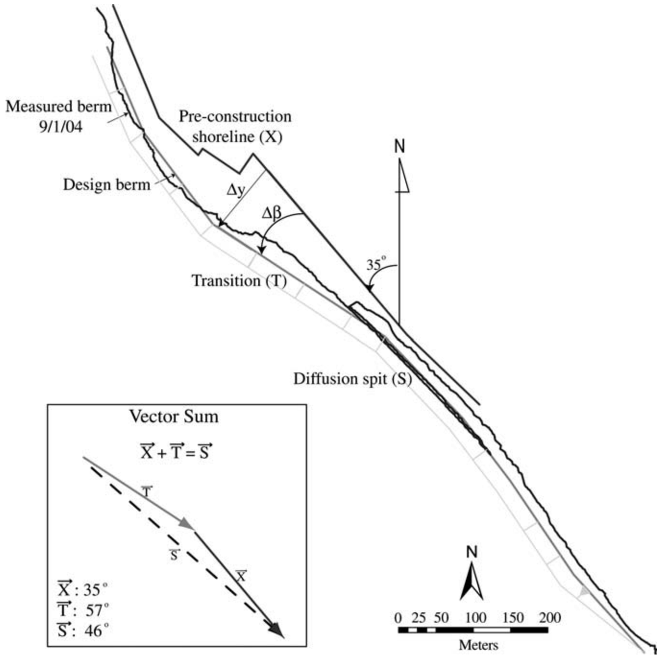

Fig. 12. Vector sum analysis of the diffusion spit formation. The pre-construction shoreline (X) and the designed transition (T) are shown with the 1-m contour (from Fig. 10) that was measured on 9/1/04. The 1-m contour illustrates the diffusion spit (S). Δâ is the change in shoreline orientation from the pre-construction shoreline to the design template. The inset shows a schematic of the diffusion spit orientation as the vector sum of the transition and pre-construction shoreline orientations.

utilized during the design process. In particular, designing end transitions with a shoreline orientation similar to that of the predicted diffusion spit may reduce the likelihood of post-nourishment spit formation. Diffusion spit formation may be undesirable due to the ponding that tends to occur on the landward side of the spit. Detailed modeling incorporating the computation of the gradient in longshore sediment transport is beyond the scope of this paper.

5.3.2. Sediment transport rate

Kraus (1999) developed an analytical model for calculating the longshore sediment transport rate based on spit evolution. The model was based on formation of a diffusion spit that formed downdrift of the Corpus Christi Beach nourishment project. The model assumed that spit growth was induced by gradients in longshore transport. Another assumption was that the spit maintained a constant width, W, and prograded within a fixed vertical elevation, $h*+B$, from the berm (B) to the depth of closure ($h*$). Based on the spit morphology, Kraus (1999) proposed the following equation to predict an annual average longshore transport rate,

$$\bar{Q} = \frac{W(h_* + B)}{t} x_s = \frac{V_s}{t} \tag{8}$$

where t is the time for the spit to elongate a distance of x_s. The volume of the spit, V_s, assumed to be a rectangular prism, is the product of W, $h*+B$, and x_s.

The 16-m wide diffusion spit that formed at Upham Beach extended 275 m in approximately 1 month. Substituting the morphologic parameters into Eq. (8) yields an annual longshore transport rate of about 180,000 m^3, which is considerably higher than the predicted rate for this region. However, because V_s can be calculated directly from beach profiles, the concept presented in Eq. (8) can be applied more accurately with the field data collected in this study. On September 3, 2004 (37 days after nourishment), $V_s = 7{,}000$ m^3, which yields a transport rate of 69,000 m^3/year. This value of Q is in agreement with previous studies, which calculated annual sediment losses from the project during the first year after nourishment between 64,500 and 86,000 m^3 (Elko, 1999; USACE, 1999). This longshore transport rate is also considerably less than the Q determined from Eq. (8).

6. Profile adjustment

Profile shape and slope were relatively constant until the passage of Hurricane Frances on September 5, 2004 resulted in remarkable beach profile changes. The steep post-nourishment profile slopes along the entire project were reduced considerably by this single storm event (Fig. 13). Hurricanes Ivan and Jeanne passed by later in September 2004 and resulted in much less overall profile-shape and slope change, as compared to the changes caused by Frances. The swell waves generated by Hurricane Ivan transported some sediment onshore, and then the storm waves generated by Hurricane Jeanne returned the profiles to a similar configuration as the post-Frances situation in Fig. 13. The nearshore bar was transported slightly further offshore by Hurricane Jeanne.

6.1. Profile-shape adjustment

Beach profile changes resulting from the passage of Hurricane Frances differed in the three nourished segments. The same four profiles from Fig. 9 (except LK5A replaces LK5) are displayed in Fig. 13 to illustrate these changes. Beach profile locations are illustrated in Fig. 4.

6.1.1. North segment

In the north segment, beach profiles maintained a steep post-construction slope for 9 days until the passage of Hurricane Frances on September 5, 2004 (Fig. 9A). The slight changes measured in the surf zone before the storms likely resulted from longshore sediment transport, which is consistent with southward growth of the diffusion spit. The newly constructed, wide, north segment of Upham Beach lost over 25 m shoreline during the week of Frances' passage (Fig. 13A). However, significant profile change due to net cross-shore transport, e.g., offshore transport and formation of sand bars, as is typical during storms, did not occur along this portion of the fill. The profile-shape change was largely caused by net longshore transport, resulting in substantial volume loss (60 m^3/m) over the entire profile. This section typically exhibits a monotonic beach profile, unlike the downdrift sections that contain a nearshore bar. This section is also characterized by large gradients in longshore sediment

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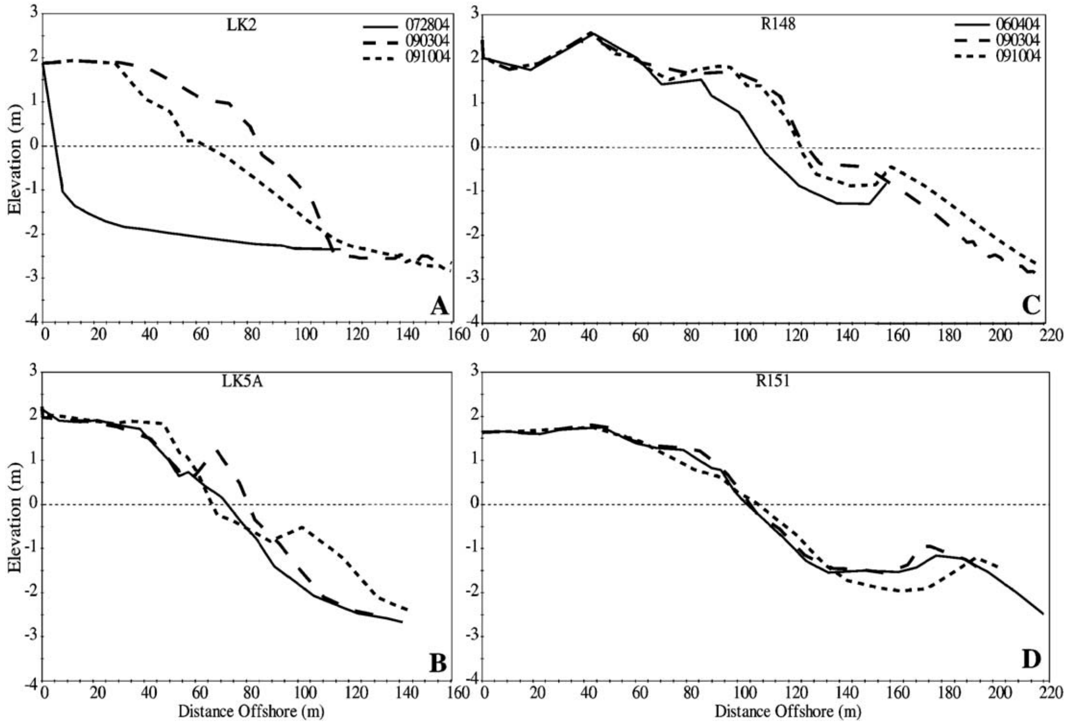

Fig. 13. Beach-profile changes induced by Hurricane Frances: A) the north segment, B) the central segment, C) the south segment, and D) downdrift of the nourishment area. See Fig. 1 for profile locations.

transport; however, the processes that preclude bar formation are unclear.

6.1.2. Central and south segments

Nourishment was completed earlier in the central and south segments. Here, the steep post-construction slope persisted for up to 40 days after nourishment (Fig. 9B and C). During this time, the passage of Hurricane Charley generated up to a 0.9 m swell for a short time (Fig. 8), but did not induce sufficient cross-shore sediment transport to reduce the beach slope. Due to the passage of Frances, erosion within the intertidal zone resulted in deposition on the nearshore sand bars (Fig. 13B and C). Net offshore transport during the passage of the storm is responsible for the profile change. As compared to the north segment, little berm erosion took place in these segments. In fact, along the central segment, up to 8 m of berm progradation was measured (Fig. 13B), apparently benefiting from the erosion of the northern segment and dispersion of the material in the diffusion spit.

Overall, the morphologic changes within the fill area caused by Frances resulted in reduction of the steep post-nourishment slope. Downdrift of the fill, the pre-storm sand bar was moved offshore in response to the passage of Hurricane Frances. Otherwise, the profile shape, which was likely already in an equilibrium form, changed little (Fig. 13D).

6.2. Profile equilibration

The processes and time scales of profile equilibration are important factors in understanding and predicting beach-nourishment evolution. To examine profile slope equilibration and to compare with the equilibrium shape of Eq. (3), the coordinates of the surveyed profiles were shifted, such that a vertical elevation of zero ($z=0$) corresponded to a horizontal distance of zero ($x=0$). This provided a comparison of changes in profile slope and shape, and essentially removed the erosion/accretion signal. The shifted surveyed profiles were compared with the calculated equilibrium profile (Fig. 14). Native (pre-nourishment) grain sizes, $D_N=0.4–0.5$ mm (Fig. 9), were utilized to determine the parameter A in Eqs. (3) through (5). Equilibrium profiles were calculated from $x=0$ to at least $x=100$ m. Then, the shape of the equilibrium profiles was compared to the pre-nourishment profiles, the post-nourishment profiles, and the post-storm (post-Jeanne, October 1, 2004) profiles.

6.2.1. North segment

Equilibrium profiles calculated for the north segment were gentler than the oversteepened pre-nourishment profiles (Fig. 14A). Pre-nourishment profiles were exceptionally steep due to scour in front of the seawall in this location. The calculated equilibrium profile corresponds to the pre-nourishment profile only along the offshore portion, as to be expected in the presence of a seawall. If the seawall did not exist in this region, erosion would continue to a point landward of the horizontal position of the seawall. This has been termed a virtual origin by Dean (1991). When the calculated equilibrium profile was translated landward (Fig. 14A), it approximated the slope of the 2004 pre-nourishment survey for LK2. This suggests that the virtual origin for Upham Beach is located approximately 20 m landward of the existing seawall.

As expected, post-nourishment profiles were steeper than both the pre-nourishment and equilibrium profiles. The beach

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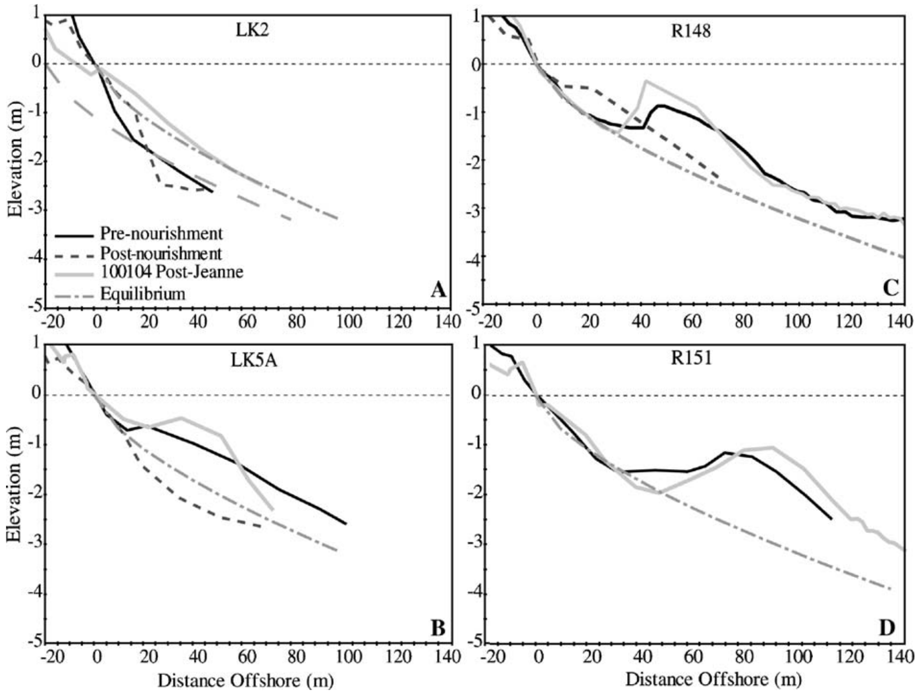

Fig. 14. Translated measured and calculated profiles from: A) north segment, B) central segment, C) south segment, and D) downdrift of the nourished area.

was constructed according to the design template that required a 1:20 (0.05) slope below 0.75 m.

Post-storm profiles in the north segment were similar to the calculated equilibrium profile suggesting that the wave energy generated by the passage of the hurricanes resulted in profile equilibration. Although the equilibrium profile calculated with Eq. (3) represented the post-Jeanne profiles quite well, it did not represent the pre-nourishment profiles along this seawalled segment. This suggests that Eq. (3) is capable of predicting an equilibrium shape for this segment until the beach erodes to the seawall.

6.2.2. Central and south segments

Equilibrium profiles in these segments were similar but slightly steeper than the pre-nourishment profiles. Profiles in the central, south, and downdrift segments contained a substantial nearshore sand bar (Fig. 14B–D). This makes it difficult to compare the measured profile with the monotonic equilibrium profile of Eq. (3). Due to the presence of a sand bar on these profiles, the overall slope of the equilibrium profile was steeper than the pre-nourishment profile, specifically in the offshore segment. The calculated equilibrium profile provided a reasonable fit from the shoreline to the bar trough. On barred profiles, the region of the profile offshore of the bar crest often has a different equilibrium slope than that described in Eq. (3) (Inman et al., 1993; Wang and Davis, 1999).

Post-nourishment profiles in the central segment of fill were substantially steeper than both the pre-nourishment and equilibrium profiles (Fig. 14B). In the south segment of fill, a narrow design berm (Fig. 4) and a nearshore bar resulted in fill placement between the berm and bar. Consequently, the post-nourishment profile "tied in" with the natural profile and was not as steep as along the north and central fill segments.

In the central and south segments, the slope of the post-storm profiles was gentle, resembling the pre-nourishment profile slopes (Fig. 14B and C). This suggests that the profiles returned to a pre-nourishment, or equilibrium, slope as a result of the storms. Thus, the wave energy produced during the month of September appears to have been sufficient to induce cross-shore transport resulting in profile equilibration of the nourished beach.

6.3. Beach slope

To further quantify this apparent rapid profile equilibration, an overall beach slope (γ) was calculated for all 106 measured and equilibrium profiles. This overall slope was determined via linear regression from mean high water (MHW = 0.12 m) to the toe of fill (−2.5 m). It is worth noting that the seaward limit of this calculation extends seaward of the bar. Although this calculation is not capable of representing the details of slope variations along the profile, the linear-regression slope represents the beach slope trend from the shoreline to the toe of fill.

The measured "equilibrium" beach slope was estimated from the slope of the pre-nourishment beach profiles assuming that the beach was in equilibrium before the beach fill. Pre-nourishment profiles are typically used to represent the natural beach slope, unless scour in front of a seawall has occurred (Fig. 14A). The calculated equilibrium beach slope was estimated based on the profiles calculated with Eq. (3).

Slope results are presented as average values for the north, central, and south segments of the fill, as well as the mean slope for the entire project (Table 2). Overall, the mean slope of the calculated equilibrium profiles (γ_{eq}) was 0.034 and the mean slope (γ_m) of the pre-nourishment profiles was 0.025. The slightly gentler measured slope (γ_m) is influenced by the presence of a nearshore sand bar as discussed in the following sections.

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Table 2
Calculated beach slope (γ) during the study period

	Calculated Equilibrium (γ_{eq})	Pre-nourishment (060404)	Post-construction (072204 to 082704)	Post-Frances (091004)	Post-Jeanne (100104)	Repair post-construction (102904)	Winter (121304)
North	0.033	0.026*	0.102	0.046	0.035	0.064	0.034
Central	0.032	0.023	0.075	0.035	0.027	0.055	0.031
South	0.037	0.026	0.041	0.023	0.020		
Mean (γ_m)	0.034	0.025	0.078	0.036	0.028	0.063	0.033

*Pre-nourishment slope of LK2 and LK2A was omitted from this calculation due to scour in front of the seawall.

When construction of the project was complete on August 27, the overall mean slope (γ_m) was 0.078 (Table 2), indicating a steep post-nourishment slope, as expected. Nine days later, due to the passage of Hurricanes Frances, this γ_m was dramatically reduced to 0.036, or less than half of the post-construction slope. The γ_m decreased further due to the passage of Hurricanes Ivan and Jeanne, from 0.036 to 0.028; however, the slope reduction was much less than that induced by Frances. In fact, Hurricane Jeanne generated similar wave conditions to those generated by Frances (Fig. 8). However, the magnitude of beach change caused by these two events was quite different, with much more change induced by Frances.

6.3.1. North segment

As discussed earlier, no dry beach remained in the north segment prior to nourishment (Fig. 9A). The water depth directly in front of the seawall and associated riprap was approximately 0.5 m and increased to about 2 m within a short distance from the wall (<30 m). When fill was placed in this region, a 1:20 (0.05) slope was constructed to about −1 m, within the range of the construction equipment. Below −1 m, the fill settled at a slope of about 1:7 (0.14) resulting in an exceptionally steep post-construction γ_m of 0.102 for the north segment (Table 2). This slope change at around −1 m is evident in the post-nourishment survey (Fig. 9A). Rapid reduction of this steep post-construction slope began during the first week after nourishment (Fig. 15A). The impact of Hurricane Frances resulted in a sharp drop of γ_m, from 0.102 to 0.046. The post-Jeanne slope of 0.035 was similar to the equilibrium slope of 0.033.

After passage of the storms, the beach slope in the north segment did not return to the pre-nourishment slope, rather it returned to the mean calculated equilibrium slope, γ_{eq} (Fig. 15A). As stated above, the pre-nourishment profile was oversteepened due to scour in front of the seawall. Post-storm profiles, which were not yet experiencing the effects of the seawall, returned to the calculated equilibrium slope. Due to the absence of a nearshore bar, the monotonic equilibrium profile (Eq. (3)) represented the post-storm profile shape well. This explains the good fit between the post-storm profile and the calculated equilibrium profile (Fig. 14A), and also the agreement between the mean post-storm and the calculated equilibrium beach slopes (Table 2).

6.3.2. Central and south segments

In the central segment of fill, the γ_m was relatively constant at 0.075 for about 40 days after nourishment was complete on July 28 until the passage of Frances on September 5, 2004 (Fig. 15B). During this time, a diffusion spit formed in this region (see Section 5.2). The formation of the diffusion spit and the resulting berm accretion are responsible for the slight increase of γ_m during this period of relatively calm weather. Similar to the north segment, a sharp decrease of γ_m, from 0.075 to 0.035, was measured following the passage of Hurricane Frances. The post-Jeanne slope of 0.027 was similar to the pre-nourishment slope of 0.023.

As mentioned previously, fill was mainly placed between the berm and bar in the south segment (Fig. 9C). Consequently, the post-nourishment profile was not as steep (Fig. 15C) as in the north and central fill segments. The post-nourishment γ_m was constant at 0.041 for about 45 days, followed by a drop to 0.023 induced by the passage of Hurricane Frances. The slope decrease was not as dramatic as in the other segments due to the gentler post-nourishment γ_m.

After passage of the storms, profile slopes in the central and south segments of fill returned to the pre-nourishment slope (Fig. 15B and C). As opposed to profiles in the north segment, which approximated the mean calculated equilibrium slope, γ_{eq} (Fig. 15A). This difference can be explained by the presence of a nearshore bar in the central and south segments. The monotonic equilibrium profile in the form of Eq. (3) does not represent the barred profile well. Therefore, once the post-nourishment profile equilibrates, it should return to the pre-nourishment shape in these regions.

6.3.3. Rapid equilibration

The slope-change patterns as shown in Figs. 14 and 15 indicate that profile equilibration was controlled by high-energy wave events. The steep nourished profile was flattened by the single event of the passage of Hurricane Frances, reducing the overall beach slope to nearly the pre-nourishment slope. Based on this morphologic response and the calculated beach slopes (Table 2), it is reasonable to conclude that profile equilibration was largely complete by October 1, 2004, 35 days after nourishment was complete.

This rapid equilibration due to high-energy events is also supported by the cross-shore profile adjustment during the winter season following the repair nourishment. When the repair nourishment was complete on October 28, 2004, the measured overall slope γ_m for the renourished profiles increased sharply to 0.064 in the northern segment and 0.055 in the central segment (Table 2, Fig. 15). Within 6 weeks, γ_m decreased to 0.034 in the northern segment and 0.031 in the central segment, once again approaching the equilibrium slope. Several energetic

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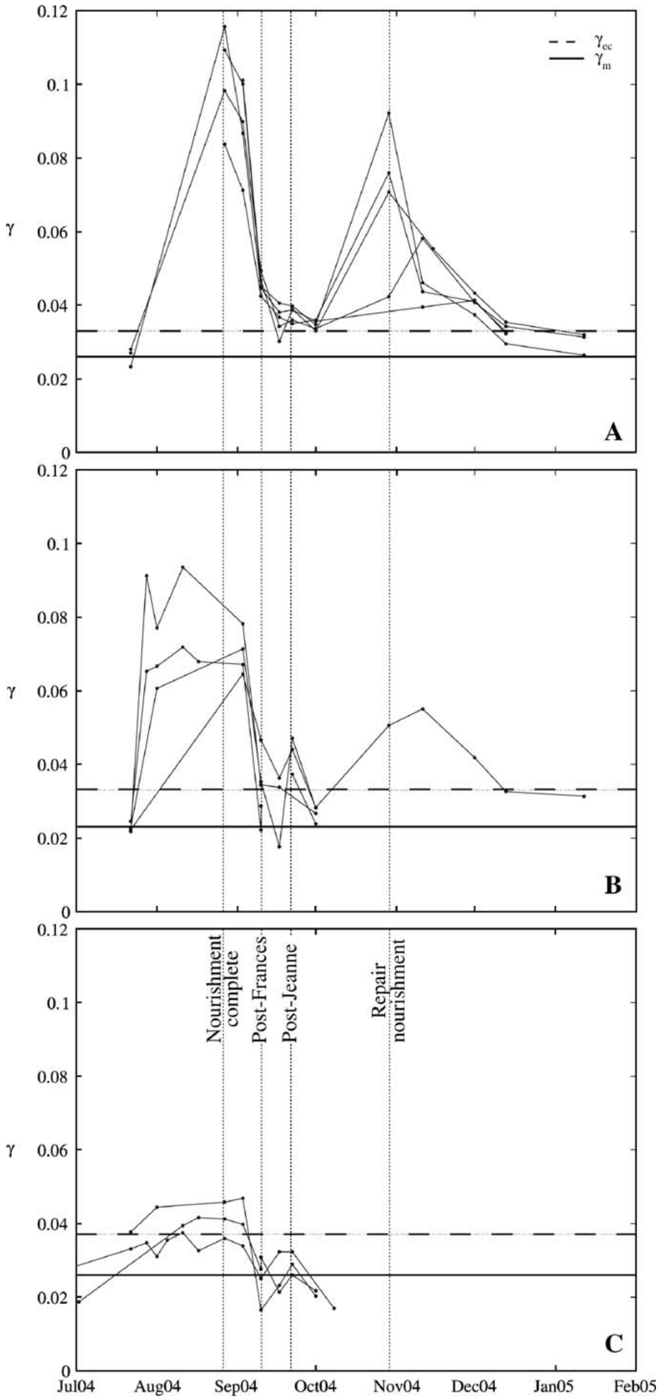

Fig. 15. Time series of measured beach slopes for the 12 surveyed profiles in the (A) north, (B) central, and (C) south segments. The calculated equilibrium and measured pre-nourishment slopes are shown as dashed and solid horizontal lines, respectively.

cold fronts, capable of generating waves exceeding 1.2 m, impacted the study area during this time. This rapid slope reduction following the repair nourishment was apparently a result of the passage of these cold front events. This suggests that the event-driven equilibration that occurred following the initial nourishment was not simply an anomalous result influenced by the passage of three strong hurricanes. Event-driven profile equilibration also occurred during this winter season.

6.4. Predicting immediate profile adjustment

To examine the large-scale equilibration process over an entire nourishment project, Dean (2002) recommended comparing the volume remaining in the project area some time (t) after nourishment (V_t) to the plan area remaining after nourishment (PA_t). When sediment is transported offshore to equilibrate the profile, the plan area decreases while the volume should remain relatively constant. As PA_t diverges from V_t over time, profile equilibration results. This concept, which incorporates the entire project area, reflects the overall equilibration process more comprehensively than analyzing the equilibration time based on individual profiles. From this concept, Dean (2002) proposed a calculation for profile equilibration time that resembles an exponential decay curve; however, it was noted that additional monitoring results are necessary to model this process. Dean (2002) also suggested that the ratio,

$$R(t) = \frac{V_t}{PA_t(h_* + B)} \tag{9}$$

should approach unity as the project evolves.

Fig. 16 illustrates $R(t)$ for Upham Beach following the 2004 nourishment project. The increase in this quantity following the passage of Hurricane Frances indicates that a substantial portion of the total profile equilibration occurred as a result of this storm. Due to the passage of Frances, shoreline recession of up to 30 m reduced PA_t from 86,000 m^2 to 70,000 m^2, whereas V_t reduced from 294,000 m^3 to 279,000 m^3. This loss of nearly 20% of the plan area, and only 5% of the total volume, in 9 days following nourishment suggests that a large portion of the nourished material was redistributed offshore, typical of profile equilibration. The large dry beach loss in such a short period of time is typically perceived as a dramatic loss by the public and should be incorporated into the planning and public education phase of the project (NRC, 1995; Dean, 2002; Elko, 2005).

Following the passage of Hurricane Frances, $R(t)$ continued to increase slightly (Fig. 16). This implies that overall cross-shore equilibration was achieved and that the project was continuously eroding due to longshore transport. This further confirms the finding that profile equilibration was largely complete due to the single event of the passage of Hurricane Frances, 9 days after

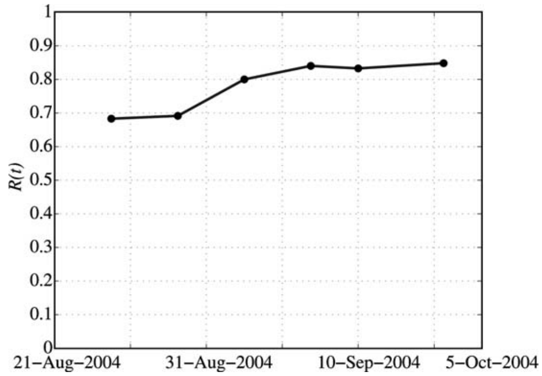

Fig. 16. $R(t)$, from Eq. (9), following the 2004 Upham Beach nourishment.

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nourishment was complete. It is worth noting that the relatively high-energy conditions of $H_s = 1.7$ m along this low-wave energy coast, which resulted in this rapid equilibration, would not be considered particularly energetic in many locations. These waves generated sufficient energy to transport sediment of $D_F = 0.5$ mm offshore and equilibrate the steep post-nourishment profiles.

6.5. Profile adjustment discussion

This study measured rapid beach profile equilibration as a result of high-energy events immediately following nourishment completion. This response is different from the present general understanding, which suggests that profile equilibration continues for several years after nourishment (Dean and Campbell, 1999; Browder and Dean, 2000; Dean, 2002). The present study suggests that profile equilibration, along both a barred and a non-barred beaches, can be an event-driven, dramatic process rather than a process that occurs gradually as the project evolves. The rate of profile equilibration can considered a function of energy rather than time. Results from this study are contrary to the generally accepted notion that profile equilibration is a longer-term gradual process. Rapid initial profile evolution toward dynamic equilibrium was also measured in both medium- to large-scale laboratory experiments (Wang et al., 2003; Wang and Kraus, 2005).

This study suggests that storm conditions may be required for profile equilibration to occur on a nourished beach, particularly in the offshore portion of the profile. By definition, transport to the depth of closure is only initiated during energetic conditions (e.g., Hallermeier, 1981). For sediment redistribution from a steep post-construction slope to a gentler slope that is relatively constant from the shoreline to the depth of closure, high-energy conditions are necessary. In the case of Upham Beach, transport to a depth from 2.5 to 3 m was induced during the passage of Hurricanes Frances and Jeanne during the month following nourishment.

The duration between the completion of nourishment and the first high-energy event to impact the project area is likely an important factor in determining the time scale of profile equilibration. The exponential decay model of Fig. 2 may not apply. If significant profile adjustment does not occur until the passage of the first high-energy event, post-nourishment adjustment may behave as stasis, punctuated by rapid change, as opposed to a smooth decay curve.

Profile equilibration should be considered complete once the slope is reduced to near the equilibrium, or pre-nourishment slope. Post-nourishment profile equilibration should demonstrate a clear trend of profile-shape changes (e.g., decreasing beach slope) and should not be confused with dynamic variations in profile shape without a distinctive trend. Overall, once $R(t)$ stabilizes, profile equilibration should be considered complete. A combined analysis of individual beach profile slope response and a time series analysis of Eq. (9) is a comprehensive method to determine profile equilibration time.

7. Conclusions

A wide nourished planform, large gradients in longshore transport, and the impact of severe storms following nourishment were all complicating factors in analyzing profile and planform adjustment with the data presented in this study. However, it is clear that planform adjustment began immediately after nourishment and that the relatively high-energy wave events following both the initial and repair nourishments resulted in profile equilibration. Both profile and planform adjustment can occur rapidly given the appropriate site conditions and energy levels.

In this study, planform adjustment via diffusion spit formation began immediately after construction of each segment of the nourished beach was completed. Planform adjustment was initiated prior to profile equilibration, and it did not require high-energy conditions. This initial planform evolution did not follow the traditional spreading models, which develop smooth end transitions in the form of, e.g., a bell-shaped curve. Rather, a diffusion spit quickly formed at the end transition of the planform and extended to the downdrift shoreline. The large shoreline orientation change in the design planform was reduced abruptly upon spit formation. Diffusion spit formation seems to be a common feature on low-energy coasts during the initial planform adjustment at the end transitions of a beach fill. The orientation of a potential diffusion spit can be determined from a simple unit–vector sum model developed in this study. To avoid spit formation, end transitions should be designed at the predicted shoreline orientation of the diffusion spit.

Based on individual profile–shape analysis, calculated beach slopes, and Eq. (9), the steep post-nourishment slope equilibrated nearly to the pre-nourishment slope (for a barred beach) or the equilibrium (Eq. (3)) slope (for non-barred beach) within weeks of construction. This equilibration was largely dominated by one high-energy event, Hurricane Frances. Subsequent storms completed the profile equilibration process. This study suggests that profile equilibration can be an event-driven process rather than a process that occurs gradually as the project evolves. The duration between nourishment completion and the passage of the first high-energy event appears to be an important factor controlling the time scale of profile equilibration.

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