Evolution and Equilibration of Artificial Morphologic Perturbations in the Form of Nearshore Berm Nourishments Along the Florida Gulf Coast

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Evolution and Equilibration of Artificial Morphologic Perturbations in the Form of Nearshore Berm Nourishments Along the Florida Gulf Coast

by

Katherine E. Brutsché

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy
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Keywords: nearshore sediment transport, coastal morphodynamics, beach-nearshore nourishment, equilibrium beach profile, nearshore bar

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DEDICATION

To my incredibly supportive family.

In memory of Granddaddy, Dr. Robert L. Brutsché.
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Inlets and channels are dredged often to maintain navigation safety. It is beneficial to reintroduce the dredged material back into the littoral system, in the form of beach or nearshore nourishments. Nourishment in the nearshore is becoming an increasingly utilized method, particularly for dredged material that contains more fine sediment than the native beach. This research examines the morphologic evolution of two different nearshore nourishments.

A nearshore berm was constructed at Fort Myers Beach, Florida using mixed-sized sediment dredged from a nearby channel. The nearshore berm was placed in water depths between 1.2 and 2.4 m with the berm crest just below MLLW in the shape of a bar. The nearshore berm migrated onshore while the system was approaching a dynamic equilibrium. Near the end of the fourth year, the beach profiles had returned to the equilibrium shape characteristic of the study area. Gaps in the berm allowed water circulation and should be considered as a design parameter. The fine sediment fractions in the original placed material was selectively transported and deposited offshore, while the coarser component moved onshore. The dry beach maintained the same sediment properties throughout the study period and was not influenced by the fine sediment in the initial construction of the berm.

Another nearshore nourishment was placed along eastern Perdido Key, Florida in 2011-2012 using maintenance dredged material from nearby Pensacola Pass. Different from the Fort Myers Beach berm, the material was placed within the swash-zone, with a maximum elevation of +0.91 m NAVD88 (or 0.62 m above MHHW). The low constructed berm elevation allowed
natural overwash processes to occur frequently, which resulted in net onshore sediment transport and growth of the active beach berm. Sediment volume gain west of the project area due to longshore spreading of the nourishment occurred mostly in the trough between the shoreline and the bar, rather than on the dry beach. The swash-zone berm evolved back to the natural equilibrium profile shape maintained in the study area within 8 months. The performance of the swash-zone nourishment was compared to two previous beach nourishments at the same location in 1985 and 1989-1991, with higher berm elevations, at +3 m and +1.2 m NAVD88, respectively. The 1.2-km 1985 nourishment performed the poorest with a shoreline retreat rate of 40 m/year. The 7.3-km 1989-1991 nourishment performed the best with a retreat rate of 11 m/year. This suggests that high berm elevations do not necessarily lead to better nourishment performance. Longshore extent of a nourishment may play an essential role.

The distant passage of two tropical storms (Tropical Storm Debby and Hurricane Isaac) generated high waves for the study areas. The two berm nourishments responded differently to the storm. Response was also compared to a beach nourishment in Sand Key. The bar-shaped Fort Myers Beach berm was split into two smaller bars, while a storm berm developed for the swash-zone nourishment at Perdido Key. In both cases, the energetic storm conditions accelerated the evolution of the berm profiles toward equilibrium. As compared to the measured nearshore waves by this study, CMS-Wave accurately propagated the WIS Hindcast waves. SBEACH accurately captured the maximum water elevation, consistent with measured upper limit of morphology change. The model correctly predicted beach and nearshore erosion during the storms. The growth of the storm berm at the Perdido Key swash-zone nourishment was predicted reasonably well by the SBEACH model. However, the magnitudes of the storm-induced erosion and the locations of the offshore bar were not accurately predicted consistently.
CHAPTER 1
INTRODUCTION

Channels are often dredged to maintain navigation safety. Historically, large amounts of sediment dredged from inlet channels were disposed of offshore out of the littoral system. For example, by 1989 approximately 75% of the 28 million m$^3$ of beach quality sand dredged from Pensacola Pass was placed far offshore, outside of the littoral system (Browder and Dean, 2000). This can create a substantial deficit in the nearshore sediment budget, resulting in medium term (decadal scale) beach erosion issues. Given the fact that most of the sediment deposited in the channels ultimately comes from the nearshore zone, as part of modern regional sediment management, it is essential to properly reintroduce this sediment back into the littoral system. To that end, depending on compatibility with native sediment, it is often the goal to place dredged sediment on the beach or in the nearshore.

This research provides a field-oriented study documenting the performance of several different types of beach-nearshore nourishments including a nearshore berm nourishment at Fort Myers Beach, Florida, a swash-zone berm nourishment at Perdido Key Florida, and briefly, a beach nourishment in Sand Key, Florida. A nearshore berm nourishment is the placement of sediment in the nearshore in the form of a mound or a bar. Swash-zone berm nourishments are neither a nearshore berm nourishment nor a typical beach nourishment. In this case, the nourishment sediment is placed in the swash zone for rapid mobilization. The research herein highlights new information on the equilibration of nourishments after construction, and the role
of storms in that process. Few studies exist regarding the evolution of nearshore berms from construction to equilibration, or the placement of a low berm elevation nourishment as the swash-zone berm nourishment.

The morphodynamic and sedimentologic evolution of nearshore berm and swash-zone berm nourishments is discussed at length, as well as a discussion on the storm impacts to these types of nourishments in addition to a typical beach nourishment. Chapter 1 is a brief introduction to the dissertation. Chapter 2 provides general background information regarding topics that are discussed throughout the dissertation. Chapter 3 discusses the morphologic and sedimentologic evolution of a nearshore berm located in Fort Myers Beach, Florida, as well as its equilibrium with the natural system. In Chapter 4, the morphodynamics of a swash-zone berm nourishment located in Perdido Key is discussed including its equilibration and the impact constructed berm elevation has on nourishment performance. Chapter 5 discusses the impacts of two tropical cyclone impacts (Tropical Storm Debby and Hurricane Isaac) on three different nourishments: the previously mentioned nourishments in Fort Myers Beach and Perdido Key, as well as a nourishment on Sand Key. Modeling of the storms using the Coastal Modeling System Wave model (CMS-Wave) and the Storm Induced Beach Change model (SBEACH) is described. Finally, Chapter 6 summarizes overall conclusions reached as a result of this research.

The objectives of this dissertation are to describe and quantify the morphologic and sedimentologic evolution of beach-nearshore nourishments, including the impacts of storms and their role in the equilibration of the nourishment, as well as provide evaluations of nourishment performance and future considerations for nourishment design.
Approximately two-thirds of the world’s population lives near a coastline (Komar, 1998), making the understanding of beaches and coastal processes extremely important to protect lives and infrastructure. Often, anthropogenic structures such as beach and nearshore nourishments, jetties and groins, and seawalls are constructed to protect upland infrastructure, as well as maintain a beach for recreational purposes. The following section provides a general overview of coastal geomorphology and processes, in addition to discussing engineering methods to protect our coastlines.

2.1 Beaches: Sedimentologic and Morphologic Characteristics

Generally, a beach marks the location of the interaction between land and sea. Komar (1998) defines a beach as an accumulation of unconsolidated sediment (sand, gravel, cobbles, and boulders) extending from the mean low-tide line to some physiographic change such as a sea cliff or dune field or to the point where permanent vegetation is established. However, also important to the morphology and formation of the beach is the portion that is permanently underwater (i.e. the nearshore). The nearshore environment begins where the beach ends, and extends offshore until sediment is less actively transported by wave forcing (Davis and Fitzgerald, 2004; Komar, 1998). The beach and nearshore are also commonly referred to as the littoral zone (Komar, 1998). Beaches can be classified as mainland beaches, strand plain
beaches, or barrier island beaches based on their overall morphologic setting. Regardless of the broad classification, general characteristics of beaches remain similar.

Beaches consist of unconsolidated sediments of varying sizes and composition, ranging from fine quartz sand to large rock cobble. Sediment grain size and composition are largely controlled by the sediment source, wave energy level and the general offshore slope upon which the beach is constructed (Komar, 1998). In order to calculate grain size, sieve analysis is usually conducted, and statistics such as mean, median, and standard deviation of the sediment distribution are calculated (Folk and Ward, 1957). Generally, mean grain size is used to in the classification based on the Wentworth Scale (Wentworth, 1922) (i.e., gravel, sand, silt, and clay), and the standard deviation describes the extent to which the sediment is sorted (i.e. well sorted, moderately sorted, poorly sorted, etc.). A well-sorted sediment sample contains sediment of generally the same size, whereas a poorly sorted sample contains sediment of varying sizes. Most of the beaches along the US Gulf of Mexico and Atlantic coast are composed of well sorted sand.

Composition of the sediment that a beach consists of is based on the composition of the source materials that created the sediment (Davis and Fitzgerald, 2004). There are two general types of sediment based on composition: siliciclastic and carbonate. Siliciclastic (or terrigenous) sediments are the result of weathered rock and subsequent transport to the coastline through rivers (Dean and Dalrymple, 2002). Many siliciclastic beach sediments consist of quartz, as this mineral is highly resistant to erosion, and creates the common white sandy beaches along the Florida Gulf coast. However, because the composition of the beach sediment depends on the source rock, therefore, source rocks that do not consist largely of quartz and feldspar may result in a different beach composition. For example, in Hawaii, black sand beaches can occur due to
the weathering and erosion of basalt (Dean and Dalrymple, 2002). Carbonate sands are created from chemical and biological processes in situ. Authigenic sands are created chemically through precipitation of calcium carbonate (Boggs, 2006). Biogenic sands are the result of biological processes such as secretions of calcium carbonate from seagrasses and algae and fragments of shells and reefs (Boggs, 2006). Beaches can contain both siliclastic and carbonate sediments as well. For example, central Florida beaches contain largely quartz sands with some carbonate shell fragments. While beaches along Florida Keys are composed of 100% carbonate grains.

Beaches can be described as reflective, intermediate, and dissipative based on their morphodynamics (Wright and Short, 1984). Reflective beaches have a steep gradient, and a significant amount of wave energy is reflected back (Davis and Fitzgerald, 2004). For a reflective beach, incident waves break close to shore with little prior loss of energy and many do not have bars (Komar, 1998). Dissipative beaches are those that have a gentle gradient. Often they contain multiple gentle bars offshore, and a wide surf zone that allows waves to lose energy before they travel to the shoreline (Davis and Fitzgerald, 2004; Komar, 1998). Intermediate beaches are those that are between dissipative and reflective.

The beach and nearshore environment can be zoned both morphologically and hydrodynamically. Morphologically speaking, from landward to seaward, a beach profile generally contains a back-beach (or backshore), berm crest, foreshore, trough, and longshore bar (if present) (Figure 2.1). The backshore extends from the berm crest landward to the vegetation or change in physiography and contains one or more berms (Komar 1998). Generally, this portion of the beach is subaerial, except in the case of storms, and contains fine relatively well sorted sediment. The berm crest is the point where the beach breaks from the mild back-beach slope to the steeper foreshore slope. This area is highly active, and consists of coarser, relatively
poorly sorted sediment. The foreshore extends seaward into the trough, which leads to a longshore bar, if present. Hydrodynamically, the littoral zone begins at the shoreline, and contains the swash zone, surf zone, and breaker zone (Figure 2.1). The swash zone is the portion where the beach face is alternately covered with water from wave runup and exposed by backwash (Komar, 1998). The surf zone is where bore-like waves occur after breaking in the breaker zone (Komar, 1998).

Figure 2.1. The morphologic and hydrodynamic zones of the beach and nearshore (modified from Komar, 1998).

2.2 Barrier Islands

Many beaches along US Gulf of Mexico and Atlantic coasts are a part of a barrier island system. Barrier islands are elongate strips of sand that are generally parallel to the mainland coast. They are separated from the coast by estuaries, and usually form in chains that are segmented by tidal inlets (Davis and Fitzgerald, 2004; Davis, 1994). They are generally low profile, extending only several meters above sea level (Davis and Fitzgerald, 2004). There are
three main theories for barrier island development: offshore bar theory, spit accretion theory, and submergence theory. The offshore bar theory states that waves moving into shallow water churn up the sand, and subsequently create a bar. The bar then accretes vertically, until the barrier is formed (de Beaumont, 1845; Johnson, 1919). The spit accretion theory states that the sediment that forms the barrier came from an alongshore source, and created a spit. The spit may then be breached during a storm event, thus creating an island (Gilbert, 1885; Fisher, 1968). Finally, the third theory is that as sea level rises low-lying coastal environments get submerged, and the barrier islands are then exposed coastal ridges (McGee, 1890; Hoyt, 1967).

Barrier islands can be categorized based on relative dominance of wave or tide forcing, often controlled by the wave height and tidal range (Davis and Fitzgerald, 2004). The Hayes model (Hayes et al., 1974; Davis and Hayes, 1984) is often used to describe the morphology of barriers based on these two factors as either wave-dominated or mixed energy. Wave-dominated barrier islands exist along coasts where waves dominate and tidal forcing takes a secondary role (Davis and Fitzgerald, 2004). Barrier islands in this type of environment are long and linear. They are generally narrower and have low relief. Mixed energy barriers experience more tidal influence than the wave-dominated barriers and thus have a different morphology. These barriers are often called “drumstick” barriers due to the fact that one end of the barrier is usually more bulbous than the other and its subsequent shape resembling a chicken leg. They are generally shorter and wider than wave-dominated barriers.

Barriers may be progradational (regressive), retrogradational (transgressive), or aggradational. The evolution and migration of barrier islands have been described in many studies and summarized in several reviews (e.g. Otvos, 1970; Schwartz, 1973; Leatherman, 1979; Leatherman, 1985; Oertel 1985; Rosati and Stone, 2009). Schwartz (1971) stated that
barrier formation and subsequent evolution is dependent on sediment supply, coastal and geologic setting, and trends in relative sea level change. Progradational barriers form when sediment supply is large as compared to relative sea level rise. Retrograding barriers are those whose sediment supply is small as compared to relative sea level rise. These types of barriers move landward. For these types of barriers, effects of inlets, aeolian transport, and overwash are important in transgression of the island (Moslow and Heron, 1979; Armon, 1979). Through a thorough review of papers regarding barrier migration, Leatherman (1975) documented two primary theories of landward barrier island migration which are continuous migration and in place drowning. Continuous migration involves the landward movement of a barrier through “rolling over” itself (Leatherman, 1975; Rosati and Stone, 2009). Significant processes allowing the shoreface retreat include inlets, overwash, and aeolian processes (Leatherman, 1979; Rosati and Stone, 2009). In place drowning occurs if the sea level rise rate is faster than the mechanisms that cause roll overs. Aggradation barriers are relatively rare and occur when the sediment supply is equal to the sea level rise rate, causing the island to build upward (Davis and Fitzgerald, 2004). Three different barrier islands along the Florida Gulf Coast are investigated in this dissertation.

2.3 Coastal Processes

The main processes that control the morphodynamics along beaches include tides, wind, and waves. All three of these processes also create currents and contribute to both cross-shore and longshore sediment transport. Storms exhibit extremes in each of these processes and will be discussed throughout this section as they tend to create large changes in beach morphology. All of these processes will be discussed throughout the different chapters in this dissertation.
Tides are an important process in the nearshore. Generally, tides are caused by the gravitational pull between the sun, moon, and earth, however there are over 400 constituents that impact tides. Spring tides occur when the sun, moon, and earth are all aligned (i.e. full moon or new moon), and generally create higher high tides and lower low tides. Neap tides occur when the earth and moon are at 90 degrees to each other (i.e. 1st and 3rd quarter moons), and generally experience higher low tides, and lower high tides. Regions experiencing semidiurnal tides have two high tides and two low tides (usually a high high tide, a low low tide, a low high tide, and a high low tide) in one day, and diurnal tides occur in regions that experience one high and one low tide in one day. Tidal range (elevation difference between high and low tides) is also dependent on continent locations and basin shapes (Dean and Fitzgerald, 2004). During storms, extreme water levels are observed and are called storm tides. The storm surge is the total water elevation (storm tide) observed minus the astronomical tidal elevation (Luther et al., 2007), and can create a significant amount of destruction in the coastal zone. Tides are also important for sediment transport at or near an inlet. Ebbing tides (low tides) transfer water from estuaries into the ocean through tidal inlets. Flooding tides (high tides) transfer water from the ocean into estuaries. Both flooding and ebbing tides can create nearshore currents that are important to sediment transport. Additionally, tidal mixing, along with fresh water inflow and winds, is a primary forcing function for residual circulation in an estuary (Pritchard, 1955; Pritchard, 1967). There have been many studies conducted on estuary circulation. (e.g. Hess, 1976; Allen et al., 1980; Officer and Kester, 1991; Meyers et al., 2007).

Wind is also an important process as it induces aeolian sediment transport on the dry beach. Aeolian transport is responsible for the build-up and subsequent movement of dunes. It is an important process in the recovery of dunes following storm-induced dune erosion by
moving sediment from the dry beach to the back beach. Average winds on most beaches are landward due to seabreeze caused by the differential heating of the land during the day and associated expansion over the land (Dean and Dalrymple, 2002). Storms, which often have strong winds, also transport sediment to the dunes, which gets trapped in the vegetation (if present). Aeolian transport selectively moves finer fractions of sediment, which can leave a lag layer of coarser sediment along the berm (Dean and Dalrymple, 2002).

Wind is also important in the generation of waves. Often waves are generated by local winds, and their characteristics depend on the speed, duration and fetch (distance over which the wind blows) of the wind as well as water depth. As wind blows over the ocean, water particles are moved from their initial position, and then returned to their position by gravity (the restoring force). This creates the orbital motion of the water particles. Energy is transferred in the propagation of waves, but the water particles themselves move very little.

More specifically, there are two processes of energy transfer from wind to wave, which together is called the Miles-Phillips mechanism. The Phillips (1957) mechanism describes the initial growth of the wave. It is a linear increase in wave energy, where turbulent eddies within the wind associated with air pressure fluctuations, interacts with the water to produce small waves. Miles (1957) analyzed a logarithmic velocity profile of small sinusoidal waves that had already been generated. He quantified the sheltering effects created by the small waves and assumed by Jeffreys (1925). Specifically, Miles (1957) examined the pressure variations on the water surface that resulted from the perturbation of the airflow on the water surface. This pressure distribution causes flow on the lee side of the crest to turn back, and leads to a flow separation. The result is the wind pressing more strongly on the windward slope of the wave, causing the water surface to move downward (enhancing the natural downward movement due to
gravity), transmitting an extra force that causes the wave to grow. The weakened air pressure in the lee of the crest enhances the upward motion of the water surface, resulting once again in a transfer of wind energy to wave energy.

Once the waves have been generated, waves travel across the sea. Important basic characteristics of waves include the wave length, period, and height, as well as the water depth over which they are propagating (Dean and Dalrymple, 1991). The wave length is defined as the distance between two crests or two troughs, while the period is the time it takes for two crests or two troughs to cross through a certain point. The wave height is the vertical distance between the trough and the crest. Other wave parameters including celerity, and velocity and acceleration of water particles can be quantified using these wave characteristics.

Often, wave propagation is quantified using the linear wave theory, also called the Airy wave theory. This theory assumes that the waves are small amplitude (i.e. the amplitude is much less than the wave length or water depth), the water is non-viscous and irrotational, the water depth is constant, water is incompressible, the bottom is smooth and impermeable, Coriolis forcing and surface tension are negligible, atmospheric pressure is uniform, and the assumption that there is homogeneity in the y-direction (Dean and Dalrymple, 1991). Many wave characteristics are based on calculations derived from the linear wave theory, including the dispersion equation, which relates the wave period and length to the water depth (Dean and Dalrymple, 2002). As waves propagate over deep waters, orbital motions of the water particles are largely circular. As the waves move into the nearshore, waves begin to feel bottom and shoal due to friction. The wave “feels bottom” when wavelength is more than half of the water depth, and causes the orbital velocities of the water particles to become more elliptical. As the waves shoal, the celerity (wave speed) lowers because the wavelength is shortening due to increase in
friction as the waves feel bottom in shallower water, while the wave period remains the same. Wave height increases and becomes more peaked until it eventually breaks in the surf zone. Waves generally break when the wave height is approximately 80% of the water depth (McCowen, 1894). However, this number, called the breaker index, is not always this simplistic, and the type of breaking wave that occurs depends significantly on this number. Many studies have been done to quantify the breaker index and the type of waves it will produce (e.g. Horikawa and Kuo, 1966; Weggel, 1972; Battjes, 1974; Dally et. al, 1985).

Generally, waves are not generated perpendicular to the shoreline. Usually, waves propagate at some angle to the shoreline (i.e. the wave direction). The wave direction is defined as the direction the wave crests are coming from. However, as the waves propagate into the nearshore and feel bottom, they tend to refract based on the bathymetry. Oblique incident waves generate longshore currents in the nearshore, and ultimately longshore sediment transport (LST). The longshore current is generated by the longshore component of the radiation stress of incoming waves, which exerts a thrust on the water within the nearshore (Longuet-Higgins, 1970; Komar, 1998). Most of the longshore sediment transport occurs in the surf zone. The velocity of the longshore currents can vary depending on location across the surf zone. The velocity of the longshore currents can vary depending on location across the surf zone (Longuet-Higgins, 1970). According to the *Shore Protection Manual* (US Army Corps of Engineers, 1984), the longshore current velocity, $v_l$, can be calculated as

$$v_l = 41.4S \sqrt{gH_{bs}} \sin \alpha_b \cos \alpha_b \cos \alpha_b$$

(2.1)

where $H_{bs}$ is the significant wave-breaker height, $\alpha_b$ is the wave breaker angle, and $S$ is the beach slope. The velocity of longshore currents can vary depending upon location across the surf zone. In general, the amount of sediment moved alongshore is related to the amount of energy available in the waves arriving at the shoreline. The most commonly used equation to calculate
longshore sediment transport (LST) rate is the CERC formula (US Army Corps of Engineers, 1984). The creation of the CERC formula was based on the Munch-Peterson formula (Svendson, 1938), which is based on an empirical correlation between the transport rate and the longshore energy flux factor, $P_{ls}$, as (Fredsoe and Deigaard, 1992)

$$
P_{ls} = E_{fb} \cos \alpha_b \sin \alpha_b
$$

(2.2)

where $E_{fb}$ is the wave energy flux at the point of wave-breaking and $\alpha_b$ is the angle between the waves and the coast at the point of breaking (Fredsoe and Deigaard, 1992). Using tracer experiments (Ingle, 1966; Komar and Inman, 1970) established the relationship

$$
Q = CP_{ls}^n
$$

(2.3)

Where $Q$ is the longshore sediment transport, $C$ is a dimensional constant of proportionality, and $n$ has been found to have a value close to unity. Inman and Bagnold (1963) critiqued equation 2.3 as it is not dimensionally correct and introduced the formula

$$
Q = \frac{K \rho_l}{(\rho_s - \rho)g(1-p)}
$$

(2.4)

where $\rho_s$ is the density of the sediment, $\rho$ is the density of water, $p$ is the porosity of the sediment (typically 0.3-0.4), $K$ is a dimensionless parameter that has been found to be 0.77. Combining equations 2.2 and 2.4, the CERC formula becomes

$$
Q = \frac{K}{16\sqrt{\gamma}} \rho g^{3/2} H_{sb}^{5/2} \sin 2\alpha_b
$$

(2.5)

where $\gamma$ is the breaker index, $\rho$ is the density of water $g$ is the acceleration due to gravity, $H_{sb}$ is the significant breaking wave height, $\alpha_b$ is the incident breaker wave angle.

Because the direction and magnitude of longshore current, and thus LST is dependent on wave breaker height and angle, transport rates can vary from day to day or seasonally, depending on overall wave climate, seasonal wind directions, or forcing due to an incoming storm. Net LST is the sum of the positive and negative components, and the gross drift is the sum of the
drift magnitudes. Updrift refers to the direction from which the sediment is coming, and downdrift refers to the direction to which the sediment is going. Sediment is transported in several modes including bedload transport, suspended load transport, and swash load transport. Local reversals of LST can occur due to refraction of waves around structures, headlands, or ebb tidal deltas. Amount of LST is made apparent through impoundment of sediment on structures, shoaling of inlets and channels, and experimentally by sediment traps and tracer studies.

Whereas longshore sediment transport is caused by longshore currents induced by breaking waves, cross shore sediment transport is created by the interaction between incoming waves and undertow (Dean and Dalrymple, 2002). Undertow is the return flow of water, beneath the action of the incoming waves. It is caused by wave-set up from waves breaking near the shoreline producing a seaward pressure gradient, which is generated by onshore directed mass transport by the surfing wave (also often described as surface roller (Svendsen, 1983). Although there is no consensus as to how offshore bars form, it is believed that undertow associated with breaking waves is responsible (Dean and Dalrymple, 2002).

Original thought on cross shore sediment transport was that it was closely linked to the offshore wave steepness, however, it was realized that the height of the waves and grain size were also important (Kraus et al., 1991). Dean (1973) created a heuristic model for sediment transport in the surf zone based on the suspension of sediment due to wave breaking, and the amount of time it takes the sediment to settle, which is related to its fall velocity. The so called Dean Number can be represented by the following equation

\[ \frac{H_b}{\omega T} = D < \frac{1}{2\beta} \]  \hspace{1cm} (2.6)

Where \( H_b \) is the wave breaking height, \( \omega \) is the sediment fall velocity, \( T \) is the wave period, and \( \beta \) is a constant related to the wave breaking height and the distance the sediment lifts from the
bed. Many studies have been conducted to empirically relate some form of the Dean Number to erosion or accretion on beaches (e.g. Kriebel et al., 1986; Kraus and Larson, 1988; Kraus et al., 1991).

Another simple cross-shore transport model was first proposed by Moore (1982) and modified by Kriebel (1982) and Kriebel and Dean (1985) and is based on the Dean (1977) equilibrium beach theory, which will be discussed in more detail in the following section. Simply put, in this model, the amount of sediment moved in the cross shore direction is dependent on the difference between the actual energy dissipation rate and that for an equilibrium profile $D^*$ (Dean and Dalrymple, 2002)

$$q_s = K(D - D_*)$$

where $q_s$ is the volumetric cross-shore transport rate per unit width in the offshore direction and $K$ is a dimensional constant.

Generally speaking, cross shore sediment transport occurs from the extent of wave run up to the depth of closure. The depth of closure is the water depth, where further offshore, net sediment transport is minimal, if present at all. Hallermeier (1981) defines the depth of closure to be

$$h_c = 2.28H_e - 68.5\left(\frac{H_e^2}{gT_e^2}\right)$$

where the effective wave height $H_e$ is

$$H_e = H + 5.6\sigma_H$$

and is only exceeded 12 hours out of the year, $T_e$ is the associated wave period, and $\sigma_H$ is the standard deviation of in annual wave heights. Through beach profiles taken at the Field Research Facility in Duck, North Carolina, Birkemeier (1985) empirically simplified this formula to be

$$h_c = 1.75H_e$$

with an average error of 0.5 m (Dean and Dalrymple, 2002).
Cross shore sediment transport, like longshore sediment transport, can vary hourly, daily, seasonally, etc. For example, during an energetic storm near the coast, usually mostly offshore directed cross shore sediment transport will be seen. As a storm subsides however, onshore cross shore sediment transport will be seen as the beach begins to recover, and return to its equilibrium shape. In terms of seasons, due to more energetic conditions during winter months, usually there is a deflated beach with one or more large offshore bars. During summer months, there is usually a large beach with a small bar or in some cases no bar.

Like longshore sediment transport, there is no specific gage or instrument that can directly measure cross shore sediment transport. Usually, wave and current measurements are taken, and sediment transport is calculated based on these measurements. There are many types of current, wave, and water level measurement tools used in academia, resource management, and industrial applications (Alliance for Coastal Technologies, 2005). There are advantages and disadvantages to each type of tool related to costs, application restrictions, biofouling and interference by marine life, mooring and deployment requirements, maintenance and calibration issues, and data interpretation (Luther et al., 2008). Some examples of current measuring tools include vertical or horizontal Acoustic Doppler Current Profilers (ADCP), Acoustic point Doppler Velocimeters (ADV) and surface current mapping with high frequency (HF) radar (Luther et al., 2008). Wave measurements can be made using in situ sensors or remote sensing methods (Luther et al., 2008). In situ methods include buoys, pressure sensors (also called PUV sensors that measure pressure and the u and v velocity components), acoustic sensors (with or without pressure) for measuring wave orbital, non-acoustic sensors for measuring wave orbital velocities, wave staffs, and subsurface arrays of pressure sensors (Luther et al., 2008). Water level measurements can be taken by tide staffs and pressure gages. Accurate water level
measurements are important in the prediction tides as well as modeling the impacts of storm surge (Luther et al., 2007). Chapters 3-5 of this dissertation employ the use of many of these types of sensors including a PUV sensor and several National Oceanic and Atmospheric Administration (NOAA) wave buoys and tide gages.

2.4 Equilibrium Beach Profiles

Generally speaking, the equilibrium beach profile theory refers to the concept that beaches have a certain equilibrium shape that is dependent on hydrodynamic conditions as well as sediment grain size. Without the effects of waves, a beach profile would be linear, with an angle equal to the angle of repose of the sediment (usually approximately 30 degrees). Due to the constructive and destructive forcing of waves and tides, real beach profiles often have a concave up shape (Dean and Dalrymple, 2002). There are several known empirical relationships between grain size, wave height, wave period, and water level. An increase in grain size creates a steeper beach, while an increase in wave height creates a flatter beach (Beach Erosion Board, 1933; Bascom, 1951). An increase in wave period (i.e. swell type waves) transports sediment shoreward, and an increase in water level causes sediment to be transported seaward (Dean and Dalrymple, 2002).

There have been many studies to quantify the shape of the equilibrium beach profile. Bruun (1954) first introduced the equation

\[ h = Ax^m \]  

(2.11)

where \( h \) is water depth, \( x \) is the horizontal distance, \( A \) is a parameter related to grain size, and \( m \) is equal to 2/3. Bruun (1954) studied beach profiles in Monterey, California to come to the 2/3 value for \( m \). Using the data from Hayden et al. (1975), Dean (1977) analyzed 504 profiles in the
U.S. east coast and Gulf of Mexico to verify at the 2/3 value for \( m \). Bodge (1992) created an exponential expression of an equilibrium beach profile based on the data from Dean (1977) and Hayden (1975):

\[
h = B(1 - e^{-kx})
\]

(2.12)

where \( B \) and \( k \) are empirical coefficients. However, both of these simple equations do not take into consideration a sand bar, which is common in many beach profiles. Wang and Davis (1998) created an equilibrium profile with a bar by segmenting the profile into three sections: inner surf zone, landward side of the bar, and the nearshore. For each section, a separate equation was used to describe the profile:

\[
h(x) = A_1 x^{m_1}
\]

for \( 0 < x \leq x_{tr} \)

(2.13)

\[
h(x) = h_{tr} + \frac{h_{bt} - h_{tr}}{x_{bt} - x_{tr}} (x - x_{tr})
\]

for \( x_{tr} < x < x_{bt} \)

(2.14)

\[
h(x) = A_2 (x - x_2)^{m_2}
\]

for \( x_{bt} \leq x < x_{cd} \)

(2.15)

where \( A_1 \) and \( A_2 \) are dimensional scale parameters for the inner surf and nearshore zones, \( m_1 \) and \( m_2 \) are empirical shape parameters controlling the beach slopes, \( h_{tr} \) and \( x_{tr} \) are the water depth at trough bottom and its distance to the shoreline, \( x_2 \) is the intercept of the nearshore portion with 0 water level, \( h_{bt} \) and \( x_{bt} \) are water depth at bar top and its distance to the shoreline, \( x_{cd} \) is the distance from the shoreline to the seaward limit of the profile (Wang and Davis, 1998). Inman et al. (1993) also developed a segmented equilibrium profile implying the different sections of the beach may experience different processes.

The concept of equilibrium beach profiles allows us to predict the response of a profile based on its shape as compared to the equilibrium profile. Some common applications are the prediction of the profile response to sea level rise and storm impacts. The Bruun Rule, which was named by Schwartz (1967), but is based on Bruun (1962), uses the concepts of equilibrium
beach profiles as related to sea level rise. The model states that the material eroded from a shoreline will be deposited within the nearshore. The volume of the deposited sediment will be equal to the sediment eroded from the beach, and the thickness of the layer will be equal to the amount of sea level rise. Mathematically the Bruun Rule is

$$R = \frac{L^*}{B + h^*} = \frac{1}{\tan \theta} S$$  \hspace{1cm} (2.16)

Where $R$ is shoreline retreat, $L^*$ is the distance from the original shoreline to the closure depth $h^*$, the berm height is $B$, $\theta$ is the beach slope, and $S$ is the amount of sea level rise. The assumptions of the model are that the profile is two dimensional and normal to the shoreline so that all net sediment transfers are onshore-offshore and no consideration is given to alongshore transport; the profile is assumed to be an equilibrium profile entirely developed in sand, with the mean profile form reflecting the wave climate and the size of the sediment; and the material landward of the shoreline consists of easily erodible sand with characteristics similar to those in the nearshore (Bruun, 1962; Schwartz, 1967; Davidson-Arnott, 2005). Although extremely useful, the Bruun Rule is rather simple, and has led to some re-evaluations of the model. For example, Dean and Maume (1983) extended the concept of the Bruun Rule equilibrium beach profiles to the entire barrier island. Davidson-Arnott (2005) used the same assumptions as the Bruun Rule, but included beach and dune interaction as well as landward sediment transfers by aeolian processes. Komar et. al (1991) improved the prediction of shoreline retreat rate using sediment budgets. And finally, Rosati et al. (2013) modify the use of the Bruun Rule to include landward transport of sediment through overwash and/or aeolian processes. Another application is to employ the concept of equilibrium beach profile to the beach response to artificial perturbations such as beach-nearshore nourishments. The concept of equilibrium beach profile
and profile response due to out of equilibrium perturbation will be discussed throughout the chapters in this dissertation.

2.5 Shore Protection

Due to the fact that there is an abundant population of people living on or near a beach, shore protection is an important practice to shield against wave action and ultimately beach erosion. There are two ways to protect a beach: building hard engineering structures or building soft engineering structures. Hard structures are intended to be permanent structures that slow erosion, or impede longshore sediment transport to protect and stabilize the coast (Dean and Dalrymple, 2002). Soft engineering structures are the addition of sediment to the beach and/or nearshore to control erosion (Dean and Dalrymple, 2002). Both types of engineering require an understanding of the wave climate and longshore sediment transport of the area before beginning construction.

2.5.1 Hard Engineering Structures

Hard engineering structures are a common practice to stabilize and protect the coast. Often they are constructed from materials such as concrete, rock, sheet piling, wood, or anything else that will help to stabilize the beach (Davis and Fitzgerald, 2004). In general, there are two types of hard engineering structures: shore perpendicular structures and shore parallel structures. Common types of these structures include jetties and groins, seawalls and revetments, and breakwaters.
2.5.1.1 Jetties and Groins

Jetties and groins are a common way to armor a coast. They are permanent structures usually built perpendicular to the coastline and extend across the beach seaward into the surf zone. Often these structures are built using large boulders, however, concrete and geotextile tubing may also be used.

Jetties are structures built along one or both sides of the channel of a tidal inlet (Figure 2.2). They keep the inlet stable by not allowing it to migrate alongshore. Jetties also impede longshore sediment transport to keep sediment from depositing and eventually shoaling the channel, which is important for safe navigation through inlets. Subsequently, the sediment that is moving alongshore impounds along the updrift side of the jetty. The impounded sediment extends the beach seaward, and as a consequence, the downdrift beach tends to erode because of the interruption in sediment supply across the inlet. Intentional sediment bypassing by mechanical means is becoming increasingly utilized along jettied inlets (Davis and Fitzgerald, 2004). Jetties should be built long enough that they do not allow sediment transport around the ends and into the navigation channel, and should be oriented so that the channel is aligned with the approach direction of the more severe waves (US Army Corps of Engineers, 2008). The spacing between two jetties should consider the tidal processes, wave protection requirements, river flood discharge requirements, and safe navigation requirements of the area (US Army Corps of Engineers, 2008).

Groins are generally shore-perpendicular structures also designed to impound sediment as it is transported alongshore. They are designed to maintain minimum dry beach width for storm damage reduction or to control the amount of sand moving alongshore (US Army Corps of
Similar to jetties, this may result in downdrift beach erosion because of the interruption of sediment supply.

Figure 2.2. Example of groins and jetties. Note that in this case, the groins are in a “T” shape, and made of geotextile tubing. Photo courtesy: Andy Squires, Pinellas County.

Often multiple groins are constructed into a so called “groin fields” (Figure 2.2). Kraus, Hanson, and Blomgren (1994) describe circumstances when a groin field is an appropriate engineering technique: at divergent, nodal points of littoral drift; in the diffraction, shadow zone of a harbor, breakwater or jetty; on the downdrift side of a harbor, breakwater, or jetty; at the updrift side of an inlet entrance where intruding sand is to be managed; to reduce the loss of beach fill, but provide material to downdrift beaches in a controlled manner; along banks at inlets, where tidal currents alongshore are strong; and along an entire littoral cell (spit, barrier island, submarine canyon) where sand is lost without return within an engineering time frame. Often, groins are constructed in conjunction with a beach nourishment (to be discussed in the following sections) to retain the fill sediment and increase the longevity of the nourishment (US
Army Corps of Engineers, 2008). Although sediment is impounded by these structures, some sediment may bypass groins by moving around the tip, overtopping them (over-passing), moving through permeable groins (through-passing), or behind the end of the structure (shore-passing) (US Army Corps of Engineers, 2008). Important design factors to consider when constructing a groin include its length, elevation, porosity, configuration, orientation to the shoreline, spacing between groins and tapering (US Army Corps of Engineers, 2008). Also important to consider is the longshore transport of the project site.

2.5.1.2 Seawalls and Revetments

Seawalls are hard structures that protect the upland from wave attack (Dean and Dalrymple, 2002). They are generally vertical or sloped structures built parallel to the shoreline, and are usually made of concrete. Seawalls often stop landward retreat of the shoreline, and are usually placed in front of structures that are deemed to require protection from this movement (Davis and Fitzgerald, 2004). The key functional element in design is the crest elevation to minimize the overtopping from storm surge and wave runup (US Army Corps of Engineers, 2008). However, there are several problems that can occur due to their impermeability. Scour from waves can cause the seawall to collapse. Waves are also reflected off of the structure and may cause issues elsewhere (Kraus, 1988). One of the most famous seawalls is located in Galveston, Texas, and was built in 1902 following the impact of a major hurricane in 1900 (US Army Corps of Engineers, 2008), and has since saved many lives and millions of dollars in cost of rebuilding after storms (Davis, 1961).

Revetments are similar to seawalls in that their position parallel to the shoreline. However, revetments are not solid concrete feature; rather they are often built completely of
24

riprap. This creates several advantages over seawalls: they dissipate more of the wave energy, they allow less overtopping by run-up because of their roughness, they may settle more under wave attack because of their flexibility, and they are easily maintained by the placement of more rock (Komar, 1998). Generally, revetments consist of an outer layer armor rock backed by smaller rocks (Komar, 1998).

2.5.1.3 Breakwaters

Breakwaters are similar to seawalls and revetments in that they are shore-parallel structures, however, this hard engineering method is placed seaward of the shoreline in the nearshore zone. The purpose of these structures is to “break” the wave energy nearshore to prevent it from reaching the shoreline and eroding the beach (Davis and Fitzgerald, 2004). They can also increase the longevity of a beach nourishment, provide a wide beach for recreation, and stabilize wetland areas (US Army Corps of Engineers, 2008). Generally, they are made from boulders, and can either be completely submerged or exposed. Different than jetties and groins, breakwaters do not interrupt sediment transport alongshore. However, because of the structures shadow effect and reduction of wave energy, the rate at which sediment moves alongshore slows. This results in sediment depositing on the beach leeward of the structure, and creates tombolos and salients. Tombolos occur when the beach extends and attaches to the structure, while a salient is a cusp in the beach that does not attach to the breakwater. It is preferable for salients to form as they allow sediment to continue to transport alongshore (Chasten et al., 1993). While the tombolos and salients extend the beach locally, they result in the erosion of downdrift beaches due to the reduction in sediment supply. Variables to consider for salient and tombolo formation include the distance of the breakwater from the nourished shoreline, the length of the
breakwater structure, the gap distance between adjacent breakwater segments, and the depth of the breakwater structure below mean sea level (US Army Corps of Engineers, 2008). Many studies have been done to describe the formation of salients and tombolos (e.g. Suh and Dalrymple, 1987; Hsu and Silvester, 1990; Black and Andrews, 2001) Also, wave refraction around the ends of the breakwaters may cause erosion on the beach.

There are several types of breakwaters including detached breakwaters, headland breakwaters, reef breakwaters, and low-crested breakwaters (Pope, 1989; Dally and Pope, 1986). Detached breakwaters are constructed offshore and are not connected to the shoreline, whereas headland breakwaters are placed close to the shoreline and are designed to promote beach growth out to the structure (Chasten et al, 1993). Often, many shore parallel segments of detached breakwaters are constructed at one location to slow erosion. The gaps allow water circulation between the structure and the beach. Reef and low-crested breakwaters are designed with a lower crest elevation, and in the case of reef breakwaters have a homogenous stone size (Chasten et al, 1993).

Techniques for designing detached breakwater systems can be classified into three categories: models, empirical methods, and prototype assessment (Rosati, 1990). Dally and Pope (1986) suggest a three step process in the design of breakwaters: begin with using empirical relationships to identify design alternatives, then create physical or numerical models to simulate and revise alternatives, and if time and funding allow, create a prototype to test and verify the design.
2.5.2 Soft Engineering Structures

Soft engineering structures are the main focus of the research throughout this dissertation. They can be a preferred method of shore protection over hard engineering structures under many circumstances due to the fact that they add sediment to the littoral system, and reduce negative impacts to surrounding beaches compared to hard engineering structures. The following sections describe two types of soft engineering structures that are discussed in this dissertation: beach nourishments and nearshore berm nourishments.

2.5.2.1 Beach Nourishments

Beach nourishment is the addition of sediment to the nearshore and subaerial beach to advance the shoreline seaward. The goals of beach nourishment are to build additional recreational area, offer storm protection, and to provide an environmental habitat (Dean, 2002; Stauble and Kraus, 1993; Dean and Dalrymple, 2002; Finkl and Walker, 2005). Dean (2002) states that “an ideal candidate for nourishment is a beach with a substantial upland economic base with a small to moderate erosional trend such that with modest amounts of nourishment, the system can be restored to balance.”

Sediment used in beach nourishment is dredged either from offshore, or from nearby channels for beneficial use as part of regional sediment management. Usually sediment is dredged and pumped onto the beach where earth moving vehicles move the sediment into the desired location (Figure 2.3). Once the sediment is placed, waves begin to restore a natural equilibrium state both in cross-shore profile and longshore planform (Dean and Dalrymple, 2002). The subsequent shoreline change can be summarized in three stages: 1) the profile equilibrates, which generally results in the cross-shore movement of sand from the upper to
lower part of the profile, resulting in sand transfer rather than loss; 2) transfer of sand along the beach as the nourishment begins to spread out; and 3) background erosion due to ongoing processes that existed before the nourishment was placed (Dean, 2002). Design of the nourishment must consider all of these factors, in addition to the impacts of storms and wave climate to address variables such as quality, quantity, and placement shape of beach fill along the shore (Finkl and Walker, 2005). Standard practice in the United States is to create a construction profile that is designed to nourish the beach from the toe of the dune to the depth of closure, which is defined as the depth at which seaward there is no significant net sediment transport (Finkl and Walker, 2005; Kraus et al., 1998).

Figure 2.3. Example of a beach-nearshore nourishment being placed at Perdido Key, Florida. (Photo courtesy of the U.S. Army Corps of Engineers Mobile District).
There are many design parameters for beach nourishment, but the most important considerations include equilibrium beach profile shape, sediment grain size, berm height, alongshore extent of fill, and fill volume density. Grain size determines the equilibrium beach profile shape and ultimately the behavior of the beach under waves and currents, and therefore it is important for nourishment sediment to be compatible with the native sediment to ensure that the additional beach will behave in the same way. Current practice is to employ considerations of equilibrium beach profiles (EBP), rather than direct granulometric comparisons (i.e. mean grain size and sorting) as a measure of suitability of a sand source, where the EBP method provides the basis for determining main variables in the design, specifically the equilibrium dry beach width (Dean, 2002; Dean and Dalrymple, 2002). In addition to grain size compatibility, the berm height is another important factor. A constructed berm higher than its natural elevation may be beneficial as it can potentially more effectively protect the upland vegetation and infrastructure from wave action. However, an artificially elevated beach berm may be undesirable for recreational and environmental reasons due to potential scarping, which can be dangerous for beach-goers as well as deter sea turtles from nesting (Dean, 2002). A lower constructed berm elevation allows for relatively easy overtopping or overwash by high waves, which may reduce the beach’s function to protect the natural environment (e.g., wetland and dune) and infrastructure landward. Therefore, often nourishments are built to the natural berm elevation, or approximately 0.5 m below the natural berm to allow for natural processes to form an equilibrium berm (Dean, 2002). The nourishment volume density refers to the volume of sediment placed per unit length of beach alongshore. In the United States, a nominal volume density of 250 m³/m is considered reasonable, however a “healthy” nourishment density depends on wave climate, background erosion rates, among many other factors (Dean, 2002). Numerous
studies have been performed to document the equilibration and controlling factors of beach nourishments (i.e. Dean, 2002; Benedet et al., 2007; Elko and Wang, 2007; Roberts and Wang, 2012). Many of these studies found that storms have a large influence on the equilibration of a nourishment, as did the interruption of longshore sediment transport by structures.

2.5.2.2 Nearshore Berm Nourishments

Nearshore berm nourishments are different than beach nourishments in that the fill is largely submerged, often in the shape of a mound (circular or oval) or a bar (elate). They are usually constructed using maintenance dredged material from nearby inlets. Nearshore berm nourishments can be the preferred method of placement over beach nourishment due to the potential lower cost of construction, and fewer environmental concerns such as sea turtle and shorebird nesting. They can also have more lenient restrictions on grain size compatibility than beach fill. For example, presently in the state of Florida, nearshore berm nourishments composed of up to 20% fine sediment (defined as sediment grain sizes less than 0.063 mm) are allowed, whereas beach nourishments may only have up to 10% fines (Florida Department of State, 2001).

The concept of a nearshore berm was first realized in the mid-1930s when dredged material was placed offshore of Santa Barbara, California in hopes that the sediment would nourish the downdrift beaches (Otay, 1994). However, this berm was considered to be unsuccessful due to the fact that location and volume were unchanged for several years following placement (Hall and Herron, 1950). After two more placements in Atlantic City and Long Beach, New Jersey in 1942 and 1948, respectively (Hall and Herron, 1950), were also considered
unsuccessful, nearshore berms were no longer considered a favorable option for the use of
dredged material for several decades (Otay, 1994).

A series of studies on nearshore berm design and placement were conducted in the 1980s
and 1990s as reviewed by Brutsché (2011). Beck et al. (2012), and Wang et al. (2013). Many
were conducted as part of the U.S. Army Corps of Engineers’ Dredging Research Program (e.g.
Hands and Bradley, 1990; Hands and Deloach, 1984; Hands and Allison, 1991; Scheffner, 1991;
Allison and Pollock, 1993; McLellan and Kraus, 1991; McClellan, 1990). As a result, several
predictive models of berm mobility were developed to provide qualitative planning level
guidance (e.g. Hands and Allison, 1991; Larson and Kraus, 1992; Douglass, 1995; Hwung et. al,
2010). A general conclusion was reached that detailed field studies are important in
understanding the dynamics of cross-shore and alongshore berm migration and the associated
temporal and spatial scales for berm profile evolution.

Nearshore berms can be built to be active (or feeder) or stable. Active or feeder berms
move within the first few weeks or months of placement and are intended to provide sediment to
the beach under accretionary wave conditions. Stable berms retain the same volume in the same
location for years and are intended to attenuate high wave energy and slow erosion, similar to a
submerged breakwater, and may also serve as a fish habitat (Hands and Allison, 1991; McLellan
define at what depth a berm should be placed to be active or stable based on empirical
observations of 11 nearshore berms. It was concluded that a berm placed at least 50% shallower
than the outer depth of closure should be active. Anything placed deeper than that should be
stable (Figure 2.4).
Various studies on nearshore berms have been conducted worldwide (Otay, 1994). Two berms were placed and studied in the Netherlands: the Egmond aan Zee berm (van Duin, et al., 2004) and the Terschelling berm (Kroon et. al, 1994). Both study areas’ nearshore profile exhibited a characteristic two-bar morphology. At Terschelling, the berm was placed in the trough between the two bars, while at Egmond aan Zee, the berm was placed seaward of the outer bar. Regardless of placement location, in both cases the profile eventually returned to its natural two-bar morphology after several years. It was also noted that during high wave energy events, the berms behaved similarly to submerged breakwaters by dissipating wave energy at the shoreline and were correlated to shoreline accretion on the leeward side of the berm. Andrassy (1991) and Juhnke et al. (1990) studied a nearshore berm placed at Silver Strand State Park in San Diego, California. This berm was placed shallower than the depth of closure, and was active, as expected. The berm moved onshore, and in addition to providing protection to the shoreline, an accumulation of sediment occurred within and above the intertidal zone. Based on a review of 27 artificial berms by Wang et al. (2013) and Brutsché (2011), the Silver Strand berm was the only case with significant subaerial beach accumulation. Browder and Dean (2000) studied a large nearshore placement in Perdido Key, Florida. Although the Hands and Allison (1991) model would predict this berm to be active, in contrast to the previously mentioned berms, the Perdido Key berm remained stable for the 8 years of the study period.

The following chapters of this dissertation will discuss a nearshore berm nourishment in Fort Myers Beach and a low profile beach nourishment (or “swash-zone berm nourishment”) in Perdido Key, as well as the impacts of tropical storms on these types of soft engineering structures. Many of the topics addressed in this chapter will be discussed in the following sections, with emphasis on the morphologic, sedimentologic, and hydrodynamic evolution and
impacts of the presence of the nourishments, as well as their equilibration with the natural system.

Figure 2.4. Placement depths for active or stable berms. From Beck et al. (2012) modified from Hands and Allison (1991).
3.1 Introduction

Maintenance dredging of navigation channels along the coast is often conducted to sustain safe navigable depths. In an attempt to retain beach quality sediment, or near beach quality sediment within the littoral system, the clean dredged material is often reintroduced into the system as part of regional sediment management practice either in the form of subaerial beach nourishment or submerged berm placement within the nearshore (Dean and Dalrymple, 2002). However, key factors involved in berm evolution are not well understood including forcing processes, temporal and spatial scales of cross-shore and alongshore movement and how sediment within the berm will redistribute based on grain size.

As discussed in the previous chapter, nearshore berm nourishments can be the preferred method of nourishment over beach nourishment. Benefits of a nearshore berm can include wave dissipation for erosion mitigation, nourishment of the beach through onshore migration, potential fish habitat, and additional retention of sediment to the littoral system (McLellan and Kraus, 1991). Another practical benefit is eased restrictions on grain size compatibility. For example, the State of Florida allows <20% fine sediment for nearshore berm placement rather than <10%

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1 Portions of this chapter have been previously published in *Coastal Engineering*, 2014, 91: 29-44, and have been reproduced with permission from Elsevier Publishing. The co-authors on the article include Dr. Ping Wang, Ms. Tanya M. Beck, Dr. Julie D. Rosati, and Dr. Kelly R. Legault who all provided editorial comments and thoughtful discussion to improve the article.
for beach placement. Fine sediment is defined as less than 0.063 mm or as mud according to the Wentworth Scale (Wentworth, 1922) for grain size classification. Fewer environmental concerns such as interference with turtle and shorebird nesting are also practical benefits of nearshore berm placements. In order for the future construction of nearshore berms to effectively realize these potential benefits, it is necessary to better understand the dynamics of the berm after placement and the controlling factors that contribute to its evolution and integration into the beach profile. Presently several predictive models of berm mobility exist to provide qualitative planning level guidance (e.g. Hands and Allison, 1991; Larson and Kraus, 1992; Douglass, 1995; Hwung et. al, 2010); however, information is limited concerning the dynamics of cross-shore and alongshore berm migration and the associated temporal and spatial scales for berm profile evolution.

A nearshore berm was constructed at Fort Myers Beach, located in west-central Florida, in October 2009 as part of maintenance dredging of the navigation channel at Matanzas Pass and the north tip of Estero Island. The Fort Myers Beach nearshore berm was placed closer to the shoreline and in shallower water than the nearshore placements discussed previously. Due to its placement location, it was expected that a portion of the berm would move onshore and nourish the beach. After construction, the nearshore berm largely resembled a natural nearshore bar both in cross-section and planview, with unintentionally constructed gaps in portions of the bar. This situation provided a unique opportunity to study coastal morphodynamics, as the constructed berm represented an “out of equilibrium” morphological feature similar to a nearshore bar. This study is based on 57 beach profile transects established by the University of South Florida Coastal Research Lab (USF-CRL), and 32 beach profile transects established by the U.S. Army Corps of Engineers (USACE) within the study area. The profiles were surveyed 10 times
approximately semi-annually within the four year study period. Contour lines including approximate mean higher high water line (estimated based on wrack line), the approximate mean lower low water line (estimated based on water line at spring low tide), and dune line were also surveyed using a vehicle-mounted GPS to document shoreline/dune-line configuration and associated changes throughout the study period. Sediment samples were collected twice during the study period for a total of over 200 surface samples to document change in sediment characteristics at the study area. Both data sets provide insight on beach profile equilibration and associated trends in sediment transport at known temporal and spatial scales. This study aimed to address the following questions:

1. Will the berm reach an equilibrium that is maintained by the natural processes of the regional study area? Or will the perturbation establish a new equilibrium state in the study area?

2. What is the dominant driving mechanism toward a dynamic equilibrium for a low energy coast? Do infrequent high energy events or frequent low energy events dominate berm behavior?

3. What are the temporal and spatial scales of berm evolution?

4. How does an artificial berm nourish the beach? Is it through attachment of the discrete berm feature to the shoreface, or does the nearshore berm behave as a source that continually and gradually supplies sediment to the beach?

5. What are the effects of the nearshore berm on the wave and current fields in the study area?

6. How did gaps in the placement affect evolution of the berm? Are these a valuable design feature that should be considered in the future?
7. Can mixed-sized sediments be placed in the nearshore, and finer sediments be winnowed from the placement, while coarser, beach quality sediments move onshore to nourish the beach? Will there be differences in alongshore and cross shore transport of sands versus fines?

3.2 Study Area

Fort Myers Beach is located on Estero Island, a low lying extensively developed barrier island, in southwest Florida, USA. Estero Island is bordered by San Carlos Bay to the north, and Big Carlos Bay to the south. Matanzas Pass, a Federally maintained channel located at the north end of the island, is often used for recreation and fishing, and provides passage to the United States Coast Guard station (Figure 3.1). The channel was initially constructed in 1961, and has been dredged in 1986, 1998, and 2001 to maintain a navigable channel. The material dredged in 2001 was used for beach nourishment, however, sediment dredged from the pass is no longer permitted to be placed on the subaerial beach due to the State of Florida’s restrictions on the percent of fine sediment in borrow material.

The morphology of west-central Florida barrier islands is influenced by the passages of cold fronts approximately every 10 to 14 days between October and April (Wang et. al, 2011). Northerly winds associated with the cold fronts produce relatively large northerly approaching waves, which contribute to the net southward longshore sediment transport along the west-central Florida coast (Beck and Wang, 2009; Wang and Beck, 2012). The protrusion of Sanibel Island to the north of Estero Island has a sheltering effect on Fort Myers Beach (Figure 3.1) from wave energy arriving from the north (Balsillie and Clark, 1992). During the summer months, wave conditions are mostly calm, with the exception of the passage of tropical systems, although
the study area rarely experiences direct impacts from tropical storms and hurricanes. The last significant hurricanes to impact the area were Hurricane Charley in 2004 and Hurricane Wilma in 2005. Hurricane Charley made landfall approximately 32 km north of the study area and caused extensive erosion on the beaches and shoaling in the channel (Florida Department of Environmental Protection, 2004). Hurricane Wilma made landfall approximately 70 km south of the study area and caused minor damage due to the largely offshore directed wind forcing (Florida Department of Environmental Protection, 2006).

Figure 3.1. Study area map of Estero Island including Fort Myers Beach and Matanzas Pass. Lower map illustrates the dredging stage locations and corresponding placement area. Note: Stage One involved mobilization of equipment, and is not pictured in this figure (Modified from Wang et al., 2013).
When not affected by cold front or tropical system passages, nearshore waves in the study area are typically low (0.1 to 0.3 m), and generated by local winds. Table 3.1 summarizes onshore wind conditions during the study period from May 2009 until May 2013. Onshore directed wind (from 130 to 310 degrees) occurred approximately 36% of the time with an average speed of 4 m/s. On average, the strongest and most frequent onshore winds originated from the south-southwest and west. The weakest winds came from the northwest and southeast, with averages of 6.9 m/s and 6.4 m/s, respectively. The weak winds from the northwest are likely due to the sheltering effect of nearby Sanibel Island. The study area is influenced by a mixed tide regime. Spring tides tend to be diurnal with a range of approximately 1.2 m, while neap tides are semi-diurnal with a tidal range of approximately 0.75 m.

Table 3.1. Wind conditions during the study period from NOAA buoy BGCF1 (location shown in Figure 3.1)

<table>
<thead>
<tr>
<th>Wind Speed</th>
<th>Southeast 130-175 deg.</th>
<th>South-Southwest 176-220 deg.</th>
<th>West 221-265 deg.</th>
<th>Northwest 266-310 deg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 4.0 m/s</td>
<td>59.3</td>
<td>37.6</td>
<td>50.6</td>
<td>60.5</td>
</tr>
<tr>
<td>4.1-7.0 m/s</td>
<td>31.2</td>
<td>48.3</td>
<td>45.4</td>
<td>34.8</td>
</tr>
<tr>
<td>7.1-10.0 m/s</td>
<td>8.3</td>
<td>11.8</td>
<td>3.6</td>
<td>4.7</td>
</tr>
<tr>
<td>&gt; 10.1 m/s</td>
<td>1.2</td>
<td>2.3</td>
<td>0.4</td>
<td>0.0</td>
</tr>
<tr>
<td>Avg. Speed (m/s)</td>
<td>3.9</td>
<td>4.9</td>
<td>4.1</td>
<td>3.7</td>
</tr>
<tr>
<td>% of Total Wind</td>
<td>6.4</td>
<td>8.7</td>
<td>13.5</td>
<td>6.9</td>
</tr>
</tbody>
</table>

There are no existing wave measurement buoys near the study area. Wave data during the study period was obtained using NOAA’s WAVEWATCH III (WWIII) hindcast, at a location
approximately 7 km offshore (Figure 3.2). The average hindcast significant onshore wave height, $H_s$, during the study period was 0.16 m, and average peak was wave period, $T_p$, was 4.4 s. Waves tend to be higher during the winter season (Figure 3.2A) than during the summer season (Figure 3.2B). Distant passages of two tropical systems affected the study area within a 2-month time during the third year post berm construction: Tropical Storm Debby (June 2012) and Hurricane Isaac (August 2012). Although only categorized as a tropical storm, Tropical Storm Debby moved very slowly, affecting the study area for approximately four days, while Hurricane Isaac affected the study area for just two days. Tropical Storm Debby had a peak significant wave height of 1.75 m (or 10 times the average) and peak period of 8 s (Figure 3.2C), while Hurricane Isaac produced waves with a peak height and period of 1.3 m and 8.2 s (Figure 3.2D), respectively.

Direction of net longshore sediment transport varies along the study area. The morphological trend of growth at the northern end of the island suggests a local northward longshore transport. A USACE (1969) report determined that the north end of the Estero Island, which is defined as 2 miles south of Matanzas Pass (or approximately the middle of the nearshore berm placement area; Figure 3.1), experiences longshore sediment transport to the north at a rate estimated to be 17,000 m$^3$/year. The south end of the island exhibits southward longshore sediment transport, consistent with the west-central Florida regional trend (Beck and Wang, 2009; Wang and Beck, 2012), at a rate of approximately 50,000 m$^3$/year (USACE, 1969). Another USACE (2001) report states that the longshore transport rate varies along Estero Island from 0 to 53,000 m$^3$/year, citing Walton (1973) as evidence for the maximum value. Poff and Stephen (1998) estimated that the maximum longshore transport rate for the island is 22,000 m$^3$/year. Both of the USACE (1969, 2001) reports cite the protrusion of Sanibel Island blocking
waves from the north and northwest as the explanation for the longshore sediment transport reversal along the northern portion of the island.

The following provides a brief summary of the construction of the nearshore berm at Fort Myers Beach. More detailed information on the artificial berm construction is described in Wang et al. (2013), Brutsché (2011), and summarized in Brutsché and Wang (2012). The project consisted of maintenance navigation channel dredging of Matanzas Pass and the northern tip of Estero Island (including part of the subaerial beach) and placement of the material offshore of Fort Myers Beach, approximately 2.4 km southeast of the dredging site. Construction of the berm was broken into four stages. Placement of the material began in the northwest portion of the project and moved to the southeast (Figure 3.1). Mobilization of equipment took place during Stage One, and no dredging and placement occurred. The area dredged during Stage Two (northern subaerial tip of the island) contained slightly coarser sediment than Stages Three and Four, which involved dredging in the channel and outside the channel, respectively. The average mean grain size of the area dredged during Stage Two was 2.44 phi (0.18 mm). The dredge cut and overdepth cut in the channel (Stages Three and Four) contained sediment sizes of approximately 2.65 phi (0.16 mm) and 2.66 phi (0.16 mm), respectively. Placement of material began at the northwest portion of the designed disposal area, and progressed to the southeast, resulting in coarser sediment in the northwest, and finer sediment in the southeast. As compared to Stages Three and Four, Stage Two progressed more quickly, which resulted in a narrower berm along the northwest portion, with some shore perpendicular gaps of less than 15 m wide, and varying berm heights (Wang et. al, 2013). The berm, completed in late July 2009, was placed roughly 200 m from the shoreline (defined here as the location of the mean higher high
water (MHHW) contour) and was constructed to be approximately 1.6 km long, 120 m wide, and 1 m high, for a total volume of nearly 175,000 m³.

Figure 3.2. WAVEWATCHIII Hindcast wave conditions approximately 7 km offshore of the study area during A) a typical winter, B) a typical summer, C) distant passage of Tropical Storm Debby, and D) distant passage of Hurricane Isaac.
3.3 Methodology

The morphological evolution of the nearshore berm was characterized based on time series beach profile and shoreline surveys during the first four years post construction. The study area was divided into three sections: the control area northwest of the berm, the berm project area, and the control area southeast of the berm. Hereafter the term ‘study area’ will be used to describe all three sections, and the term ‘project area’ will be used to describe the berm project area specifically. Morphological evolution was also characterized by comparing the control areas to the project area.

Construction of the nearshore berm was completed in July 2009. Pre- and post-construction surveys were conducted by USACE Jacksonville District in May and October 2009, respectively. Although the post-construction survey was conducted 3 months after construction ended, no high wave energy events occurred during that time (average significant wave height was only 0.07 m, and average wave period was 3.9 s), therefore, we have assumed that the October 2009 survey accurately illustrated the initial constructed berm morphology. To complete the pre- and post-construction surveys, 32 beach profile transects were established. A Real Time Kinematic Global Positioning System (RTK GPS) was used to survey the beach and nearshore (to roughly 1 m water depth) portions of the profile. The offshore portion of the profile extending to approximately 1 km from the shoreline was surveyed using a synchronized precision echo sounder and RTK GPS system. The two portions of the profile were purposefully overlapped and compared to ensure data quality.

Beginning in April 2010, surveys were conducted by USF-CRL in the project area as well as control areas. Fifty-seven beach profiles were established and surveyed approximately semiannually (survey dates: April 2010, October 2010, June 2011, September 2011, March 2012,
July 2012, September 2012, May 2013). Survey lines in the control areas were established approximately 100-200 m apart, while survey lines within the project area were set approximately 50 m apart to capture longshore variations. Figure 3.3 illustrates the locations of both USACE and USF-CRL beach profile transects. The USF-CRL beach profile transects were surveyed following standard level-and-transit procedures using an electronic total survey station and a 2.5 m survey rod. Surveys were georeferenced to State Plane Florida West (0902) for the horizontal coordinate system (NAD83), and NAVD88 for the vertical datum. Zero (0.0 m) NAVD88 is 0.696 m above mean lower low water (MLLW) in this area. Shoreline surveys were conducted using a RTK GPS mounted on a rigid cart towed behind an ATV (All-Terrain Vehicle). The rigid cart was used to eliminate vertical errors associated with the ATV suspension system. Several shore parallel lines were visually identified and surveyed including the dune vegetation line, the MHHW line, and the MLLW line.

![Figure 3.3. Locations of USF-CRL and USACE survey lines, in which FMB indicates Fort Myers Beach. The red box indicates the designed placement area.](image)

Beach profiles were analyzed to identify location and elevation of berm crest, berm height, rate and direction of berm migration, and volume changes. Berm crest is defined as the
highest survey point on the nearshore berm portion of the survey (Figure 3.4). Berm height is the difference between the berm crest elevation and the landward trough elevation. Berm width is defined as the cross shore width of the base of the berm above the existing profile. Distance to berm crest is the distance of the crest of the berm from the MHHW (+0.178 m NAVD88, according to NOAA gage 8725110) line. Volume change between surveys was also calculated. Average, spatially uniform profiles were created by adjusting the origin of survey lines to MHHW to create a uniform reference contour, and then interpolating the elevation across each profile at 3-m intervals.

Surface sediment samples were collected and analyzed in April 2010 and June 2011 to determine the sedimentological evolution of the nearshore berm. For each sampling period, approximately 9 sediment samples were taken across 6 transects within the control areas, and 11 samples were taken across 5 transects in the project area. In the control area, samples were taken at the toe of the dune (if present), backbeach, high tide line, mean sea level, low tide line, 0.6 m water depth, 1.2 m water depth, 1.8 m water depth, and 2.4 m water depth (depths are approximate). In the berm project area samples were taken at the toe of the dune (if present), backbeach, high tide line, mean sea level, low tide line, roughly in the middle between the berm and the shoreline, landward toe of the berm, midway up the landward slope of the berm, top of the berm, and seaward approximately every 30 m until about 2.4 m water depth, and at 2.4 m water depth. Wet sieving was performed to separate the fine fraction from the coarse fraction of the sample. Standard sieve analysis was conducted on the sand fraction of the sample, and the Moment Method (Folk and Ward, 1957) was used to calculate mean grain size and standard deviation.
Figure 3.4. Definition sketch of a typical nearshore berm design
The Coastal Modeling System (CMS), including both CMS-Wave and CMS-Flow (Lin et. al, 2011; Reed et. al, 2011; Wu et. al, 2011; Sanchez et al., 2011; Wang et. al, 2011), was applied over a local domain to examine and illustrate the wave behavior and hydrodynamics in the vicinity of the nearshore berm. The local domain model grids for CMS-Flow and CMS-Wave were constructed using mostly measured bathymetry by the study. The offshore portion of the bathymetric coverage was obtained from a digital elevation model, specifically the Coastal Relief Model (from NOAA’s National Geophysical Data Center). CMS-Wave was forced with TMA-generated spectra from parameters extracted from the hindcast NOAA WWIII model data. Tidal constituents obtained from the nearby tide gage (National Data Buoy Center buoy BGCF1) were used. A spatially constant Manning's n frictional factor of 0.025 was applied for the entire grid. CMS-Wave was coupled with CMS-Flow to model wave-current interaction in the nearshore to illustrate the complex hydrodynamics that drive the morphodynamics of the artificial nearshore berm. Since no nearshore hydrodynamic data were collected to calibrate and verify the model, the results here are meant to be semi-quantitative with the main goal of illustrating wave pattern and flow field.

3.4 Results

3.4.1 Pre- and Post- Construction Morphology

The pre-construction morphology of Fort Myers Beach included a small bar approximately 0.3 m high, 30-60 m offshore of the MHHW line (located at 0.178 m NAVD88). The dry beach was approximately 30-60 m wide with a mild slope (Figure 3.5).

The morphology of the artificial berm was highly variable alongshore. In Figure 3.5A, the profile at USACE 16 shows a berm approximately 1 m high, with crest elevation of
approximately -0.6 m NAVD88. In this location, the berm was constructed as a smooth symmetrical shape approximately 100 m wide measuring up to 2 m in berm height. Conversely, along line USACE 19 (Figure 3.5B), the berm was only 0.75 m high, with berm crest elevation of approximately -1.0 m NAVD88, and an asymmetrical shape with two peaks.

![Graph A](image)

Figure 3.5. Two example profiles showing pre- and post-construction survey; A) Profile USACE 16 B) Profile USACE 19.

To further illustrate the longshore variability in berm morphology, Figure 3.6 shows all of the beach profiles within the berm project area referred horizontally to the MHHW line.
Substantial longshore variations occur in every aspect of the profile including foreshore slope, location and depth of the trough; location, height, and width of the berm; and the depth and slope of the seaward flank of the berm. Distance of the berm crest from the MHHW line varied from 68 m to 147 m. Berm height ranged from 0.2 m to 0.9 m, with berm crest elevation ranging from -0.5 m to -1.2 m NAVD88. The width of the berm ranged from 84 m to 133 m.

![Graph](image)

Figure 3.6. Profiles within the berm project area referred to mean higher high water (MHHW). Survey taken October 2009 by USACE.

### 3.4.2 Morphological Evolution in Cross Shore

Three areas were defined to examine the morphologic evolution of the nearshore berm in comparison with natural changes without the artificial perturbation: the control area southeast of the berm, the control area northwest of the berm, and the berm project area. The following sections summarize morphologic change of control and project areas based on ten semi-annual surveys performed by USF-CRL and USACE. During the first two years post placement (2010 and 2011), wave conditions were typical for the region, with no tropical systems affecting the
area. During the third year (2012) two tropical systems affected the study area: Tropical Storm Debby and Hurricane Isaac.

3.4.2.1 Control Area Southeast of the Berm

The southeast control area extended approximately 1.5 miles southeast of the berm project area. A total of 16 profiles were established and surveyed in this area. Profile lines furthest from the berm were spaced 200 m apart, while the profiles directly adjacent to the berm project area were spaced 50-100 m apart. Figure 3.7 shows an example profile located in the distant portion of the southeast control area (FMB 3). In general, the beach in the southeast control area remained stable for the first two years. A small ephemeral bar existed approximately 25-60 m offshore in these profiles. When present, the bar was less than 0.5 m high, and became relatively well-defined after the passage of small storms (e.g. 0911 in Figure 3.7A). The two tropical storms had a significant effect on the control area southeast of the berm. After the passage of Tropical Storm Debby, substantial dry beach and foreshore erosion occurred, and a large bar formed approximately 60 m offshore (Figure 3.7B). The bar created by Tropical Storm Debby was approximately 100 m wide and approximately 1 m high. The distant passage of Hurricane Isaac resulted in dry beach accretion to levels measured at the initial profile in April 2010; however, the offshore bar remained largely stable. The survey from May 2013 (0513) is typical of post storm recovery of natural profiles. The large bar formed by Tropical Storm Debby, and present through Hurricane Isaac, moved onshore resulting in a large gain of sand in the nearshore (defined here as the portion of the profile landward of the bar) and small bar remained that resembled the bar that had existed during the first two years of the monitoring. The dry beach remained largely stable after recovery from Tropical Storm Debby.
Figure 3.7. Example profile (FMB 3) from the control area southeast of the berm. The first two years of morphological evolution are shown in A) and the second two years are shown in B) with the April 2010 survey as reference for total change.

The profiles in the southeast control area that are closer to the berm project behaved somewhat differently than the previously described example. FMB 15, representing the nearest portion of the southeast control area (Figure 3.8), illustrated a similar pattern to FMB 3 during the first two years, with a small dynamic ephemeral bar approximately 50-75 m offshore. Unlike FMB 3, Tropical Storm Debby and Hurricane Isaac induced little change on the dry beach at FMB 15, and yet a large bar also formed approximately 100 m offshore. In May 2013, the large
bar formed by Tropical Storm Debby and stable through Hurricane Isaac had migrated onshore, and attached to the shoreface, which resulted in considerable sand gain on the dry beach.

Figure 3.8. Example profile (FMB 15) from the control area southeast of the berm, but within 100 m of the berm project. The first two years of morphological evolution are shown in A) and the second two years are shown in B) with the April 2010 survey as reference for total change.

To summarize, profile change in the southeast control area was characterized by a relatively low relief dynamic bar during periods of low energy. During storms, a larger bar formed offshore, which eventually migrated onshore. Profiles further from the nearshore berm
experienced erosion on the dry beach during the storms, while profiles closest to the nearshore berm exhibited a relatively stable dry beach during that time.

3.4.2.2 Berm Project Area

Considerable longshore morphologic variability existed along the nearshore berm, owing to the construction of the berm itself (Figure 3.6). FMB 18 (Figure 3.9) is a representative profile located near the southeast end of the berm project area. In this region, the berm was constructed with relatively low relief and a small depression in the center of the crest. Initially, the nearshore berm morphology resembled two small bars through the April 2010 survey. By October 2010, the inner portion of the berm appeared to have migrated onshore, as the outer berm also migrated onshore slightly. In June 2011, the morphology was no longer a two-bar shape. At this time, the inner portion of the berm migrated onshore and added sediment to the nearshore, while the outer portion of the berm migrated offshore slightly. It is of note that although the berm provided sediment to the foreshore, the dry beach remained largely stable through the first two years. Following the passage of Tropical Storm Debby, the berm split into two bar-like features. Hereafter, the two bar-like features formed after Tropical Storm Debby will be referred to as the inner and outer bar. Although considerable changes occurred in the offshore region of the profile, there was little change on the beach after Tropical Storm Debby, similar to FMB15. The passage of Hurricane Isaac moved the bars formed by Tropical Storm Debby onshore, causing the nearshore to gain sand, while a small offshore bar remained in the same position. By May 2013, a gain of sand on the dry beach occurred, resulting in an overall gain of approximately 20 m of beach width.
Figure 3.9. Example profile (FMB 18) from the southeastern edge of the berm project area. The first two years of morphological evolution are shown in A) and the second two years are shown in B) with the post-construction survey as reference for total change.

FMB 30 and 32 (Figures 3.10 and 3.11, respectively) are typical profiles located in the middle of the berm project area, and showed a different trend than those previously discussed near the southeast edge. In both cases the berm migrated onshore approximately 50 m during the first year (April 2010 survey). During the summer season following the April 2010 survey, onshore migration continued, but to a lesser extent than the previous period of migration (approximately 10 m) due to the relatively low-wave energy. In the case of FMB 32 (Figure
the berm migrated onshore an additional 50 m by June 2011, and an additional 10 m by September 2011, for a total onshore migration of approximately 100 m. At FMB 30, the crest moved onshore only slightly during the second year post placement (approximately 10 m), however, the berm gained some volume of sand on the leeward side. The berm in both cases changed from a symmetrical bell shape to an asymmetric shape with a steep landward slope, morphology that is characteristic of net onshore movement (Larson and Kraus, 1994; Roberts and Wang, 2012). Although substantial change occurred in the berm portion of the profile, the dry beach in the berm project area remained stable through the first two years. Before Tropical Storm Debby, the berm moved onshore approximately 25 m at FMB 30, and remained stable at FMB 32. After the passage of Tropical Storm Debby, both profiles showed a two-bar morphology, which is also evident in all the berm area profiles. Unlike the control profile lines, there was no substantial change to the dry beach along the berm area following Tropical Storm Debby. The two offshore bars became less well-defined after Hurricane Isaac. By May 2013 both profiles illustrated a small, low-relief bar that resembled the natural bar seen in the pre-construction profiles and in the control area (Figure 3.5). Overall, the dry beach gained approximately 15 m of width since construction.

FMB 43 (Figure 3.12) is a representative profile of the northwest edge of the berm project area. Initially the berm was placed approximately 150 m from the shoreline, just below MLLW. During the first year post construction, the berm behaved similarly to FMB 30 and 32, migrating rapidly onshore (approximately 50 m by April 2010). During the summer months until October 2010, the berm continued to migrate onshore, however at a much slower rate (10 m). Between October 2010 and June 2011, the more energetic winter season, 25 m of onshore migration occurred. Minimal onshore migration occurred between June and September 2011.
By March 2012, the berm migrated onshore another 10 m. The passage of Tropical Storm Debby turned the single berm profile into a two-bar profile, similar to other berm profiles. Post Hurricane Isaac, the outer bar moved offshore while the inner bar migrated onshore. By May 2013, the profile had returned to a shape that resembles the pre-construction profile and those in the control area. During the entire study period, the dry beach remained stable.

Figure 3.10. Example profile (FMB 30) from the berm project area. The first two years of morphological evolution, including the post-construction survey, are shown in A) and the second two years are shown in B) with the post-construction survey as reference for total change.
Figure 3.11. Example profile (FMB 32) from the berm project area. The first two years of morphological evolution, including the post-construction survey, are shown in A) and the second two years are shown in B) with the post-construction survey as reference for total change.

To summarize, morphology within the project area was somewhat variable alongshore. Evolution was similar in that the berm moved onshore during the first three years, however to varying extents. Following the passage of Tropical Storm Debby, a two-bar morphology was observed, which was maintained after the passage of Hurricane Isaac. By May 2013, following a full winter season, the profiles in the berm project area returned to a shape similar to that of the pre-construction profiles, and, in many cases, with a wider beach (Figure 3.13).
Figure 3.12. Example profile (FMB 43) from the northwestern edge of the berm project area. For clarity, the first two years of morphological evolution are shown in A) and the second two years are shown in B) with the post-construction survey as reference for total change.

3.4.2.3 Control Area Northwest of the Berm

The northwest control area extends approximately 1.6 km from the berm. During the study, a beach nourishment project was constructed that extended from the northern tip of Estero Island south to approximately survey line FMB 51 (Figure 3.3). The beach nourishment began in the summer of 2011, and was completed by December 2011. Figure 3.14 shows a profile just outside of the nearshore berm project area (FMB 47). Similar to the control area to the
southeast, during the first two years, a small bar was present. Following the passage of Tropical Storm Debby, a relatively large bar formed approximately 100 m offshore. The dry beach remained relatively stable, similar to the profiles in the southeast portion of the berm project area. The passage of Hurricane Isaac did not cause significant profile change at this location. Similar to the rest of the profiles, by May 2013, this profile also returned to the original pre-project profile with a small ephemeral bar.

Figure 3.13. Time-series onshore migration of the nearshore berm. A) Initial berm morphology immediately post-construction; B) Nearshore berm morphology following the Tropical Storm Debby impact; C) Morphology four years post-construction.
Figure 3.14. Example profile (FMB 47) from the control area to the northwest of the berm. The first two years of morphological evolution are shown in A) and the second two years are shown in B) with the April 2010 survey as reference for total change.

3.4.3 Alongshore Morphological Variations

Generally, the nearshore berm as a whole did not migrate or spread alongshore. The longshore variability in morphology inherent from the construction remained throughout the entire study period. Figure 3.15 once again shows the profiles within the berm project area referred to MHHW. After 4 years, including the passage of Tropical Storm Debby, longshore variations remained in every aspect of the profiles. Although the berm as a discrete feature did
not move alongshore during the study period, apparent alongshore migration of smaller features within the berm occurred.

Figure 3.15. Profiles within the berm project area referred to mean higher high water (MHHW) illustrating persistent longshore variability in A) July 2012, after Tropical Storm Debby and B) May 2013.

The small gaps created during the nearshore berm construction were dynamic and moved alongshore as indicated by beach profile changes and planform contour variations. Two types of gaps were observed: oblique gaps and shore-perpendicular gaps. Oblique gaps extended across
the artificial berm at a large angle, and appeared on shore-perpendicular profiles as a two-bar morphology. An example of an oblique gap is shown in a photograph taken in 2010 (Figure 3.16C) and in the contour map (Figure 3.16D). The gap is indicated by the arrow in Figure 3.16C. Shore-perpendicular gaps appeared on profiles as a very low-profile berm, or no berm at all. An example of a shore perpendicular gap is shown in the photograph in Figure 3.17C, which was taken in 2011.

FMB 22 (Figure 3.16) illustrates an oblique gap. In the April 2010 survey (Figure 3.16A), the profile showed a two-bar morphology, which was produced by an oblique gap through the berm. By June 2011 (Figure 3.16A), the gap had filled in. The inner bar migrated onshore and attached to the shoreface. The outer bar also migrated onshore. By May 2013 (Figure 3.16B), the outer bar continued to migrate onshore and also attached to the shoreface. Although this particular example does not show alongshore migration of a gap, it emphasizes that the gaps in the berm are dynamic.

Profiles FMB 34, 35 and 36 illustrate the dynamics of a shore perpendicular gap. In April 2010, FMB 34 (Figure 3.17A), which was located at the southeastern flank of the gap, showed a low-profile berm which is interpreted as a shore-perpendicular gap. During the subsequent surveys, the gap filled in with sediment in the form of a small bar, which gained approximately 0.3 m in height and moved onshore approximately 100 m, similar to the typical berm profiles as discussed earlier.
Figure 3.16. Example of a migrating oblique gap (FMB 22). The first two years of morphological evolution are shown in A) and the second two years are shown in B) with the April 2010 survey as reference for total change. Photographic illustration of the oblique gap is shown in C), and D) illustrates the appearance of the gap in a contour map.

FMB 35 (Figure 3.18) illustrates the northwest migration of the gap. At this location, a typical berm profile was measured in the April 2010 survey (Figure 3.18A). By the October 2010 survey, the berm became largely absent, which was due to the migration of the gap. Although the net loss of sediment across this profile is interpreted as being caused by alongshore transport, the sediment loss could not be accounted for by the adjacent profiles. Based on field observations, the gap migrated less than 50 m. Therefore, the sand volume cannot be balanced by profiles spaced at 50 m. In the subsequent surveys at this location, a small bar formed and migrated onshore similar to typical profiles within the berm project area. The continued migration of the berm to the northwest is shown at FMB 36 (Figure 3.19). Prior to the March 2012 survey, FMB 36 behaved similarly to a typical berm profile. By March 2012 the gap that had previously been located at FMB 34, and then at FMB 35, had migrated to FMB 36.
Subsequent surveys showed morphology evolution similar to FMB34 and FMB35, with a small bar that formed offshore and moved onshore.

![Graphs and images showing shoreline surveys and beach profiles.](image)

Figure 3.17. Example of a migrating shore perpendicular gap (FMB 34). The first two years of morphological evolution are shown in A) and the second two years are shown in B) with the post-construction survey as reference for total change. Photograph illustrating the shore perpendicular berm is shown in C) as well as the corresponding contour map in D).

Over the 4-year study period, several small salients developed landward of the portions of the berm segmented by gaps. Initially, the salients that were observed during the shoreline survey in April 2010 were not evident in the beach profiles. In the subsequent surveys, the salients became more apparent in the profiles, and were marked by a relatively large increase in dry beach width of approximately 10-30 m (Figures 3.17, 3.18, and 3.19). FMB 32 (Figure 3.11) gained approximately 13 m of dry beach after April 2010, and FMB 35 (Figure 3.18) gained approximately 12 m. FMB 38 and FMB 40 (Figure 3.20) near the northwestern end of the berm,
illustrated a large salient formation, and had the greatest dry beach gain of 20 and 27 m, respectively. This accumulation was related to both onshore berm migration, as well as effects of the berm on the waves and currents in the study area.

Figure 3.18. Example of a migrating shore perpendicular gap (FMB 35). The first two years of morphological evolution are shown in A) and the second two years are shown in B) with the April 2010 survey as reference for total change. Note that in October 2010, the berm was no longer present due to the formation of the gap. In subsequent surveys, a small bar formed and migrated onshore, similar to the other berm profiles.
Figure 3.19. Example of a migrating shore perpendicular gap (FMB 36). The first two years of morphological evolution are shown in A) and the second two years are shown in B) with the April 2010 survey as reference for total change. Unlike FMB 35, the gap is not seen in this profile in October 2010. However, by March 2012, the gap is present, indicating that the gap once seen at FMB 35 had migrated to the northwest. Similar to FMB 35, subsequent surveys show a small bar forming offshore and moving onshore, similar to the other berm project area profiles.
3.4.4 Sedimentological Evolution

Sediment sampling was conducted in April 2010 and June 2011 to identify potential trends of selective sediment transport and deposition over the first two years. In total, over 200 surface sediment samples were collected and analyzed for grain size, percentages of fines (smaller than 0.063 mm), and percentages of carbonates.

Sediment grain sizes were temporally averaged to illustrate spatial trends (Figure 3.21). The finest material was located offshore of the southeast control area. Offshore sediment illustrates a coarsening trend from southeast to northwest. As expected, the coarsest, least well-
sorted material was found in the swash zone in all three areas. The dry beach sediments were largely the same throughout the entire study area.

![Figure 3.21. Temporally averaged grain sizes illustrating spatial variation in grain size characteristics.](image)

During April 2010 sampling, the finest sediment in the berm project area was located in the trough landward of the berm (Figure 3.22). Patches of muddy sediment were observed during the sampling. Along one of the sample lines, sediment in the trough had nearly 42% fine material (Figure 3.23). By 2011, the percentages of fines decreased in the trough samples from up to 42% to down to 1%. The surface sediment in the offshore area had an increase in fine material percentage from 2% to 4% in 2010 to nearly 11% in 2011. Generally, all areas within
The berm project area contained slightly finer surface sediment in 2011 than in 2010, with the exception of the trough landward of the berm. The sediments on the dry beach were largely similar. Sediment in the intertidal zone varied considerably, as indicated by the large standard deviation, due to the rather irregular occurrence of shell hash in the swash zone. By 2011, the berm crest and the dry beach exhibited similar grain size.

Figure 3.22. Spatially averaged grain sizes to illustrate temporal changes in grain size characteristics in the berm project area.
Figure 3.23. Example profile in the berm project area showing locations of sediment samples and percentages of fines in the samples in A) 2010 and B) 2011.

3.5 Discussion

3.5.1 Cross Shore Profile Equilibration and Morphological Evolution of the Nearshore Berm

The placement of sediment as a nearshore berm produces a perturbation within a dynamic environment. It is valuable to examine the evolution of the artificial feature toward a dynamic equilibrium and the associated temporal scales.

The average profile is often assumed to represent an equilibrium state. Profile-averaging has been used by various studies to obtain equilibrium beach profiles (e.g., Bruun, 1953; Dean,
Eight profiles adjacent to the berm project area in the southeast control area, FMB 9 through FMB 16 (Figure 3.3), were averaged over eight survey periods between 2010 and 2013 (Figure 3.24). Because of the proximity of these profiles to the artificial berm and the similarity in sediment grain size, it is reasonable to assume that the average profile obtained from these eight profiles also represents an equilibrium profile for the berm project area. Because the portion of the profile between mean sea level (MSL) and MHHW (+0.37 m above MSL) was active, MHHW was used here as the origin of the equilibrium profile.

![Figure 3.24](image)

**Figure 3.24.** Comparison of Dean (1977) and Bodge (1992) equilibrium profiles to the calculated average profile in the study area.

The natural profiles in the study area do not have a substantial and persistent bar; therefore, the monotonic equilibrium profile models developed by Bruun (1954) and Dean (1977) should be applicable (Figure 3.24):

\[
h = Ax^m \tag{3.1}
\]
where $h$ is water depth, $x$ is the horizontal distance, $A$ is a parameter related to grain size, and $m$ is equal to $2/3$. Using the data from Hayden et al. (1975), Dean (1977) analyzed 504 profiles in the U.S. east coast and Gulf of Mexico to arrive at the $2/3$ value for $m$. A representative grain size of 0.140 mm was used to calculate the $A$ parameter for Fort Myers Beach based on Moore (1982) and Dean (1987). The average profile was also compared to Bodge’s (1992) exponential expression of an equilibrium beach profile:

$$h = B(1 - e^{-kx}) \quad (3.2)$$

where $B$ and $k$ are empirical coefficients. A least-square fit of the Bodge (1992) profile yielded a value of 2.3 m for $B$ and 0.015 m$^{-1}$ for $k$.

The largest discrepancy between the average profile and the predicted equilibrium profiles occurred in the nearshore zone (Figure 3.24). The measured profile had a considerably steeper nearshore slope and a gentler offshore profile, as compared to the Dean (1977) and Bodge (1992) equilibrium profiles. The steeper than equilibrium nearshore may suggest a deficit of sediment there. Therefore, it is reasonable to assume that to compensate for this deficit, onshore sediment transport would be expected. This may explain the onshore migration of the nearshore berm to provide sediment to the depleted nearshore zone. Using the Bodge (1992) method for quality of fit, values of 0.92 and 0.83 were calculated for the Dean (1977) and Bodge (1992) profiles, respectively. The above values are comparable to the values obtained by Bodge (1992) for the U.S. East Coast and the Gulf of Mexico. Therefore, the average profile represents an equilibrium state, and will be referred to as the equilibrium profile in the following discussion.

It is assumed here that variation from the equilibrium profile can be used to evaluate the degree to which a set of profiles at a fixed time depart from equilibrium. The variance was
calculated for each profile and averaged spatially along the berm project area and control area. The greater the average variance, the further the profiles at a particular time deviated from the assumed equilibrium state (Figure 3.25). Larger standard deviations about the average variance indicate greater longshore variability.

In the southeast control area, variance from the equilibrium profile was small, and remained relatively constant over the four-year study period. The passage of Tropical Storm Debby and Hurricane Isaac (1105 and 1167 days after construction, respectively) caused a relatively large deviation from the equilibrium state due to the formation of the large bar. The standard deviation associated with the average variance also increased for the two post-storm surveys (Figure 3.25). However, the variance returned to the typical variance prior to the passage of the two tropical systems by May 2013, or nine months after the storms (1402 days after construction). The small average variances from the equilibrium profile and their associated standard deviations at the southeast control site indicate that the system is in a dynamic equilibrium. When the system was forced out of equilibrium by the distant passages of the two storms, it returned to its equilibrium state rapidly (less than 300 days). The behavior of the control profiles confirms the assumption that beach profiles have tendency to return to equilibrium after a disturbance is reasonable.

In the berm project area, the average variance of the October 2009 survey (the post-construction survey conducted 100 days after placement of the berm) of the berm was 0.318 m², with a standard deviation of approximately 0.084 m². Overall, a decreasing trend of average variance from the equilibrium profile was apparent during the 4-year study period (Figure 3.25). Between October 2009 and April 2010 (270 days after construction), the nearshore berm profile experienced the largest decrease in average variance to 0.237 m², due to the initial rapid
adjustment of the berm after placement. The average variance of the berm profiles from equilibrium continued to decrease with time, with just a small increase from 0.129 m$^2$ to 0.131 m$^2$ after the passage of Tropical Storm Debby (1105 days after construction). The decreasing trend resumed after the passage of Hurricane Isaac (1167 days post construction). By May 2013, the average variance of the berm profiles decreased to 0.052 m$^2$, which is a decrease of 84% from the maximum and is similar to the pre-construction value (0.049 m$^2$). This indicates that the berm profiles were close to the dynamic equilibrium state of the natural beach by May 2013. The standard deviation about the average variance also decreased over time, consistent with the interpretation that the system was approaching its natural equilibrium state.

A logarithmic curve was fit to the average variance of the berm profiles to quantify the trend toward equilibrium. The log curve is shown in Figure 3.25, and can be expressed as

$$y = -0.085 \ln(t) + 0.7116$$ (3.3)

where $y$ is the average variance from the equilibrium state and $t$ is time in days. The logarithmic curve fit the measured trend well, with a correlation coefficient $R^2 = 0.94$. The logarithmic trend suggests that the system approached equilibrium rapidly immediately after the introduction of the artificial perturbation, when the profiles departed from equilibrium to the greatest extent. The trend toward equilibration slowed as the system became closer to its equilibrium state. The energetic storms reversed the progress toward equilibrium slightly, but did not change the overall trend. In fact, the rate toward equilibrium increased after the storms.
Figure 3.25. Average variance from the equilibrium profile and associated standard deviations in the berm project area and adjacent control area.

The graph depicts the variance from the average profile over days post construction. The data points for the berm line variance are shown with blue markers, and the control line variance is indicated with green markers. The log fit line is represented by a red dashed line. The equation for the log fit is given as $y = -0.085\ln(t)+0.7116$ with $R^2 = 0.94$. The graph includes labels for “TS Debby” and “H Isaac” on the data points.
Both of the storms had significant effects on the study area; however the impacts of each storm to the control area and the berm project area were different. Tropical Storm Debby was the first long-lasting energetic event impacting the study area over the past 8 years. In the control areas, the dry beach eroded and a large bar formed approximately 100 m offshore. In contrast, for most profiles in the berm project area the dry beach remained largely stable, and the nearshore berm was “split” into two bars. The differing morphologic responses of the berm project area and control areas may be a result of the berm substantially widening the surf zone, especially under high energy conditions, leading to gentler dissipation of wave energy and lower energy at the shoreline.

The impacts of the distant passage of Hurricane Isaac occurred over the post Tropical Storm Debby morphology (Figures 3.7-3.14 and 3.16-3.17). In the southeast control area, the large bar that was formed by Tropical Storm Debby remained mostly at the same location, and retained a similar shape. Within the berm project area, most of the profiles changed from the two-bar morphology back to a single bar morphology due to the inner bar moving onshore and attaching to the shoreface.

Nine months after the passages of the two storms, profiles in both the control area and the berm project area returned largely to the equilibrium shape. This suggests that the energetic conditions generated by the two storms are within the bound of dynamic equilibrium for the study area, and did not push the system to a new equilibrium state. The natural beach in the control area returned to the equilibrium state after considerable deviation, i.e., offshore sand transport and formation of a storm bar, induced by the storm. For the beach in the berm project area, the two storms actually accelerated the progress toward equilibrium. Based on the logarithmic model (Eq. 3.3 and Figure 3.25), the profiles in the berm area would reach
equilibrium approximately 2400 days (approximately 6 years and 7 months) after the placement. The rate of profile equilibration accelerated considerably after the storms, and the profiles reached equilibrium in approximately 1400 days (approximately 3 years and 10 months), or 1000 days (approximately 2 years and 9 months) earlier than the logarithmic model prediction.

3.5.2 Nourishment of Dry Beach by the Nearshore Berm

Often, one of the goals of nearshore berm placements is for beach quality sand to migrate onshore and nourish the dry beach. Figure 3.26 shows the dry beach width and profile-volume change during the 4-year study period from April 2010 to May 2013. In the southeast control area, most of the profiles that were close to the nearshore berm gained sand volume and width on the dry beach. The magnitudes of volume and shoreline gain decreased away from the nearshore berm. On average, profiles in the distant southeast control (i.e. FMB 1-8) area gained a total of 0.14 m$^3$/m of sediment volume, and 1.3 m of dry beach width, while profiles adjacent to the berm (i.e. FMB 9-16) gained a total of 1.3 m$^3$/m of sediment and 9 m of dry beach width.

Of the 28 profiles within the berm project area, only one did not gain dry beach volume and width. The largest gains occurred in the middle of the project area, while the smallest gains were located in the northwest portion. On average, the berm project area profiles gained 10 m$^3$/m of volume, and 13 m of beach width, for a total dry beach volume gain of 17,800 m$^3$, or approximately 10% of the original berm placement. The profiles in the control area to the northwest were not included in the comparison because they were nourished during the study period. However, the two profiles immediately adjacent to the berm showed very little change during the study period, suggesting that the beach nourishment in the northwest control area did not have significant influence to the berm area.
3.5.3 Influence of the Nearshore Berm on Waves and Currents

Similar to nearshore bars and engineered submerged structures, the expenditure of wave energy over the berm reduces breaking wave height, which in turn reduces the longshore current at the shoreline. The presence of gaps in this project may have allowed wave setup landward of the berm to return and flow through the gaps, in addition to allowing tide driven flows through the gaps. Impoundment of longshore moving sand may lead to the formation of salients and tombolos. In the following, the results of numerical modeling of the study area using CMS-Wave and CMS-Flow are discussed. The modeling effort here provides a semi-quantitative illustration of the nearshore berm’s effects on the wave and current fields in the study area.
Figure 3.27 is an example of relatively energetic conditions (see Figure 3.2 for typical wave conditions) during the first survey period.

Numerical modeling of the nearshore berm indicated wave breaking over the berm crest, especially during relatively high waves. As this was much farther offshore than areas without the berm, the berm area had a much wider surf zone resulting in greater dissipation of wave energy. Figure 3.27A illustrates wave heights in the surf zone for the project site and control sites. The waves were approaching from the southwest (incident angle 238 degrees from north), with a wave height of 0.74 m and period of 4.68 s. The tide in this example was approximately -0.01 m NAVD88, and falling. In the berm project area, wave breaking occurred at the seaward slope of the berm and wave energy dissipated over a wide surf zone. In the control areas, the waves broke much closer to the shoreline, resulting in a narrow surf zone and a shorter distance over which wave energy could be dissipated. As expected, and observed in the field, wave heights landward of the berm were smaller than those in the control area.

Longshore currents are generated by oblique waves breaking at the shoreline (Longuet-Higgins, 1970). The longshore current magnitude calculated by CMS-Flow was smaller landward of the nearshore berm than at the control sites (Figure 3.27B). Wave refraction over the wide berm toward the shore-normal direction, in addition to wave dissipation, resulted in lower longshore current velocities calculated near the shoreline, as compared to the control site (Figure 3.27B). In the berm project area, the greatest calculated longshore current magnitude was located directly seaward of the berm crest.
Figure 3.27. CMS modeling results illustrating: A) wave energy dissipation B) reduction of longshore currents and C) flow through the gaps associated with the nearshore berm.
Due to alongshore gradients in breaking wave height and current magnitude, impoundment of sediments being transported in the alongshore resulted in the development of salients at the two ends of the berm project. Salients were also developed landward of the portion of the berm segmented by gaps, similar to salients formed landward of a segmented breakwater (Dean and Dalrymple, 2002). Unlike potential issues with hard structures, the development of the salients was modest and no erosion was measured along the adjacent beaches. In fact, the beach at the south end of the berm project area experienced volume gain in the dry beach (Figure 3.26). This may be attributed to the sand supply from the nearshore berm to the beach. In other words, the structure itself also provides sand to the system.

As discussed previously, due to construction techniques, several gaps were created in the berm. The gaps were dynamic, with modest alongshore migration measured during the study period. This may be attributed to the flow through the gaps, as observed in the field and modeled by CMS-Flow. A circulation pattern of offshore directed currents circulating back onto the berm platform, somewhat similar to rip cells, was modeled (Figure 3.27C). For this particular example, the exit flow through the gaps was oblique to the shoreline and the overall orientation of the berm. The orientation and magnitude of the flow through the gaps may be the forcing mechanism for alongshore migration of the gaps. It is worth noting that the above modeled results are not verified with field measurements. However, qualitatively, the modeled flow patterns seem to be reasonable and provide a mechanism for longshore migration of the gap.

3.5.4 Selective Sediment Transport

Due to the more lenient restrictions on grain size for nearshore berm nourishment as compared to beach nourishment, nearshore berms may contain a higher percentage of finer
sediment (often cohesive mud). One practical concern is whether the finer (muddy) components would negatively affect the quality of the beach sand, and in turn would have negative impacts to environmental factors. As described earlier, a trend of offshore transport and deposition of the finer fraction, and an onshore transport and deposition of coarser fraction, were measured during the time series sediment sampling. In addition, the dry beach sediment properties remained largely stable over the four year study period.

The energetic conditions in the surf zone likely prevented the deposition and preservation of the finer fraction of sediment. Shortly after the construction of the artificial berm, some patches of fine (muddy) sediment were found in the relatively low-energy trough area landward of the berm. Finer sediment (e.g. the thin layer of fine sediment in the trough) was mobilized relatively easily under energetic conditions and could not be preserved for an extended period in the surf zone. Therefore, over time, the fine portions of the sediment were selectively transported, deposited, and preserved in the lower energy offshore area, while energetic conditions associated with wave shoaling and breaking likely prevented the fine portion from being preserved in the nearshore zone for an extended period of time. This explains the seaward fining trend of sediment grain size observed at the study area. The extensive sediment sampling did not reveal any fine sediment on the beach due to wave runup or overwash, both inherently energetic processes.

3.6 Conclusions

An artificial nearshore berm was constructed approximately 200 m offshore of Fort Myers Beach, Florida using maintenance dredged material from Matanzas Pass at the north end of Estero Island. The berm project area and adjacent control areas were monitored with semi-
annual beach surveys beginning May 2009 through May 2013. Numerical modeling was conducted to determine the nearshore berm’s influence on the wave and current fields. This nearshore berm project was unique in that it was placed in a low-energy wave environment, and shallower than previous projects. Additionally, small gaps were created in the berm during the construction. The following are conclusions reached through the course of the four year study period:

- The shape of the artificial berm evolved rapidly from a roughly symmetrical bell-shaped bar to a highly asymmetrical shape with a steep landward slope, typical of a landward migrating nearshore bar. The Fort Myers Beach nearshore berm migrated onshore as a discrete morphologic form of a nearshore bar, although with considerable alongshore variations that were maintained throughout the entire study period. The rate of onshore bar migration was much greater during the first year post construction. Furthermore, the rate of migration was greater during the energetic winter than the calmer summer.

- The relatively large artificial berm did not create a new equilibrium state for this low-energy environment, rather it evolved back to the natural equilibrium profile shape maintained in the greater study area. The rare high wave-energy conditions associated with the distant passages of Tropical Storm Debby and Hurricane Isaac in 2012 accelerated the equilibrium process, instead of deterring and slowing the processing. The logarithmic model developed by this study predicted that the berm would reach equilibrium in nearly 7 years post construction. The 2012 storms accelerated the equilibrium processes to just less than 4 years.

- The nearshore berm led to considerable sand gains on the dry beach in the berm project area and the control area immediately adjacent to the southeast end of the berm. This is
likely due to the berm’s function as a nearshore sediment source, as well as its modification of the wave and current fields. Approximately 10% of the 175,000 m$^3$ of sediment placed in the nearshore berm was accounted for by the dry beach gain.

- As compared to the control area, the nearshore berm created a wider surf zone, allowing for increased wave dissipation, and subsequently lower wave energy near the shoreline. Longshore currents near the shoreline were also reduced. In the berm project area, the strongest longshore currents were modeled just seaward of the berm crest, while in the control areas, the strongest currents were much closer to the shoreline.

- Although the gaps in the nearshore berm at Fort Myers Beach were unintended in the design, they were integral to the hydrodynamics as they allowed circulation of water landward of the berm, as well as access to the beach for recreational boaters. Gaps should be considered in the design of nearshore berms, particularly in shallow placement locations.

- Fine sediment initially located in the trough landward of the berm was transported and deposited offshore. The dry beach maintained the same sediment grain size as compared to the pre-project condition, indicating that the fine sediment in the initial construction of the berm did not impact the beach.

- The nearshore berm protected the landward beach from energetic events associated with the passages of Tropical Storm and Hurricane Isaac. A portion of the nearshore berm migrated onshore and nourished the dry beach landward. No erosion associated with the nearshore berm nourishment was measured along the adjacent beaches.
CHAPTER 4
INFLUENCE OF BERM ELEVATION ON THE PERFORMANCE OF BEACH-NEARSHORE NOURISHMENT ALONG PERDIDO KEY, FLORIDA, USA

4.1 Introduction

As discussed in the previous chapters, in the coastal zone, often it is preferred to utilize maintenance dredged material beneficially as a part of regional sediment management by placing the sediment directly on the beach (beach nourishment) or as a nearshore berm (nearshore berm nourishment) to keep sediment within the littoral system. Although the placement methodology is different in terms of construction and location, both nourishment types have the same ultimate goal, to protect coastlines and add sediment directly or indirectly to eroding beaches.

Beach nourishments are typically designed to advance the shoreline seaward to protect the coast from inundation caused by storm and wave action as well as for recreational purposes (Finkl and Walker, 2005). As discussed in Chapter 2, key design parameters for beach nourishment include equilibrium beach profile shape, sediment grain size, berm height, alongshore extent of fill, and fill volume of density. Once the sediment is placed, waves begin to restore a natural equilibrium state both in cross-shore profile and longshore planform (Dean and Dalrymple, 2002); and, therefore, it is important to consider both cross-shore and longshore design aspects when planning a nourishment. In addition, the design must consider rates of long-term erosion as well as impacts of storms and wave climate to address variables such as quality, quantity, and placement shape of beach fill along the shore (Finkl and Walker, 2005).
Nearshore berm nourishments are different than beach nourishments in that the fill is largely submerged, as discussed in detail in Chapters 2 and 3. Under certain circumstances nearshore berm nourishments can be the preferred method of dredge material placement due to the potential lower cost of construction, and fewer environmental concerns such as sea turtle and shorebird nesting. They can also have more lenient restrictions on grain size compatibility than beach fill. For example, presently in the state of Florida, nearshore berm nourishments composed of up to 20% fine sediment (defined as sediment grain sizes less than 0.063 mm) are allowed, whereas beach nourishments may only have up to 10% fines (Florida Department of State, 2001).

Pensacola Pass, located at the eastern end of Perdido Key in the Panhandle of Florida, is periodically dredged to maintain safe, navigable channel depths. In the past, the dredged sediment was placed offshore and out of the littoral system (Browder and Dean, 2000). More recently, the dredging of Pensacola Pass has resulted in sediment being placed as both beach and nearshore berm nourishments to beneficially use the sediment and keep the material in the littoral system as a part of regional sediment management of the inlet and adjacent beaches. The inlet and ebb-tidal delta were most recently dredged in December 2011 until January 2012. Sediment dredged from the pass was compatible with the native beach sediment and was placed in a somewhat unique form in that it is neither a typical beach nourishment, nor a typical nearshore berm nourishment. The placement was limited to be in the extent of the swash zone, with maximum fill elevation of +0.91 m NAVD88, or 0.63 m above the mean higher high water level (NAVD88 is approximately 0.09 m below Mean Sea Level in this area), which is substantially lower than the natural berm elevation of approximately +2.0 m NAVD88 (Dean, 1988). Based on current regulations in Florida, the lower berm elevation reduced the cost of environmental
monitoring. In the following discussion, we refer to the Perdido Key nourishment as a swash-zone berm nourishment to distinguish it from typical beach and nearshore berm nourishment. Compared to two previous nourishments in 1985 and 1989 with much higher berm elevations of +3.0 m and +1.2 m NAVD88, respectively, the Perdido Key swash-zone berm nourishment provides an opportunity to study the influence of berm elevation on nourishment performance.

In order to understand this unique swash-zone berm nourishment practice, 44 beach profile transects, spaced approximately 150 m apart, were established and surveyed bi-monthly to semi-annually by the U.S. Army Corps of Engineers (USACE) and the University of South Florida Coastal Research Lab (USF CRL). A total of 7 survey periods occurred during the 1.5-year study period. Sediment samples were collected pre- and post-placement to analyze impacts of the nourishment sediment on the native sediment. This study aims to quantify the morphologic evolution of the swash-zone berm constructed at Perdido Key and compare with the two previous beach nourishments that were constructed at higher berm elevations. Influences of constructed berm elevation on nourishment performance are discussed.

4.2 Study Area

East-west trending, low-lying sandy barrier islands are characteristic of the northwest “panhandle” portion of Florida. The beaches consist of largely quartz sand, and where buildings and infrastructure are absent, natural dunes of up to 10 m tall are present (Claudino-Sales, Wang, and Horwitz, 2010). Generally, sediment transport is to the west, except for local reversals caused by wave refraction over ebb deltas (Browder and Dean, 2000). The region experiences moderate wave energy, and is often impacted by tropical storms and hurricanes, therefore, overwash deposits are often observed in the panhandle (Wang and Horwitz, 2007; Stone et al.,

Perdido Key is a 24-km long sandy barrier island bounded by Pensacola Pass to the east and Perdido Pass to the west (Figure 4.1). The study area is located along the eastern end of the island, directly adjacent to Pensacola Pass. It is within the Gulf Islands National Seashore, and is largely undeveloped with the exception of a road and several park structures (i.e. picnic areas and parking lots).

Figure 4.1. Location of study area, Perdido Key Florida, USA, the project area outlined in red, survey transects (e.g. R46), and the wave gage deployed by USF CRL.
The study area experiences a diurnal tide regime, with a spring tidal range of up to 0.60 m and a neap tidal range of 0.18 m. The average significant wave height during the study period, measured by this study at roughly 700 m offshore of the center of the swash-zone berm project area (Figure 4.1), was approximately 0.55 m, with an associated average peak period of 5.5 s.

Two distant tropical systems affected Perdido Key during the study period: Tropical Storm Debby (June 2012) and Hurricane Isaac (August 2012). Wave heights up to 2.1 m and periods of up to 10.4 s occurred during Tropical Storm Debby. Hurricane Isaac was a more energetic storm, creating nearshore waves up to 2.7 m, and periods up to 12 s. More detailed information on wave conditions during the study period will be discussed in the following sections.

Browder and Dean (1999) estimated that the net longshore sediment transport is between approximately 30,000 and 55,000 m³/year to the west. Caucus Shoal, the large ebb tidal delta of Pensacola Pass, extends from the western portion of the pass, and likely contributes to the erosion on the eastern end of the island due to wave refraction around the shoal and subsequent divergence of longshore sediment transport (Browder and Dean, 2000). Additionally, tidal inlet processes such as strong current along the beach associated with flooding tides may contribute to the erosion of the beach immediately adjacent to the inlet. Generally, the beach in the study area contains an extensive dune field, with a fairly flat back beach, and a relatively steep foreshore.

Pensacola Pass is a Federally maintained channel with depths up to 13.4 m below mean lower low water (MLLW) to allow for safe navigation of large ships (Browder and Dean, 2000). Between 1883 and 1989, the channel had been dredged approximately bi-annually (Browder and Dean, 2000). No dredging took place after 1989 until the most recent event in 2011-2012. As of 1989, approximately 75% of the 28 million m³ of the dredged material was placed offshore outside of the littoral zone, with only approximately 1.9 million m³ placed on the beach.
Browder and Dean (1999) found that the dredging of Pensacola Pass has led to erosion of the eastern portion of Perdido Key, due to the channel acting as a sediment sink and trapping sediment from gross longshore sediment transport. The erosion rate of eastern Perdido Key between 1974 and 1984 was documented to be approximately 1.5 m/yr (Dean, 1988).

In addition to the swash-zone berm nourishment completed in 2012, two other beach nourishments were constructed at this site in 1985 and 1989-1991. Although each of these nourishments was placed in the same general area, their designs were quite different. Specifically, the constructed berm elevation differed for each one, as well as the length of the project. Generally, the natural beach has a +2.0 m NAVD88 berm elevation, which is also the elevation of most of the overwash terraces (Browder and Dean, 2000; Claudino-Sales, Wang, and Horwitz, 2010). The 1985 nourishment was constructed with a much higher berm elevation of +3.0 m NAVD88, while the 1989-1991 nourishment was built to +1.2 m NAVD88 and included a large nearshore berm nourishment that was placed in 5-6.5 m water depth approximately 800 m offshore. The 2012 swash-zone berm nourishment was constructed with a maximum elevation of +0.91 m NAVD88. The effects of the differing berm elevations will be discussed in more detail in the following sections.

The Perdido Key swash-zone berm nourishment was constructed between late 2011 and early 2012, in conjunction with the dredging of Pensacola Pass to approximately -13 m NAVD88. Sediment dredged from the pass was placed along the eastern portion of the island between Florida Department of Environmental Protection range monuments (FDEP R-monuments) 53.5 and 64, or approximately 3 km (Figure 4.1). The placement of the sediment was not to exceed elevation of +0.91 m NAVD88, or about 0.63 m above the mean higher high
water (MHHW) contour. The fill material was graded in a similar manner as that of a beach
nourishment. A total of approximately 400,000 m$^3$ of sediment was placed to extend the beach
roughly 60 m seaward. Native sediment grain size in the study area is homogenous and
approximately 0.40 mm. The 2011-2012 nourishment used similar sized sediment as compared
to the 1985 and 1989-1991 nourishments, which were approximately 0.40 mm and 0.32 mm,
respectively.

4.3 Methodology

To quantify morphologic changes of the swash zone berm at Perdido Key, beach profile
transects were set over 300 m spaced R-monuments, established by the FDEP, as well as 150 m
spaced mid-points (e.g. R55, R55.5, R56, etc.) A Real Time Kinematic Global Positioning
System (RTK GPS) was used to establish benchmark and equipment locations. Transects were
established approximately every 150 m (Figure 4.1). In total, 44 transects were surveyed bi-
monthly to semi-annually for the first year and a half after placement. The study area was
divided into three sections: the adjacent area west of the swash zone berm, the swash zone berm
project area, and the adjacent area to the east of the swash zone berm. Hereafter, the term ‘study
area’ will refer to the entire study area, and the term ‘project area’ will refer to the swash-zone
berm nourishment project area.

Pre- and post-nourishment surveys were completed by the U.S. Army Corps of Engineers
(USACE) Mobile District in November 2011 and January 2012, respectively. Surveys were
completed using RTK GPS from the benchmark to approximately -1.0 m NAVD88. The pre-
nourishment survey also included a hydrographic survey, completed using RTK GPS coupled
with a precision echo sounder. Hydrographic surveys extended approximately 1 km from the
shoreline to water depths of approximately 6 m. Another hydrographic survey was conducted at the end of the study period (July 2013).

Five surveys in addition to the pre- and post-nourishment surveys were completed by the USF CRL in March 2012 (2 months post-nourishment), May 2012 (4 months post-nourishment), July 2012 (6 months post-nourishment), September 2012 (8 months post-nourishment), and July 2013 (18 months post-nourishment). The USF CRL surveys were conducted using standard level-and-transit procedures with an electronic total station and 4 m survey rod, extending to roughly 3.5 m water depth. All surveys were conducted in the regional State Plane Florida North (NAD83) horizontal datum and the North American Vertical Datum 1988 (NAVD88), all in metric units.

Wave and water-level data were acquired using a PUV gage deployed approximately 700 m offshore of the middle of the study area, in approximately 5 m water depth (Figure 4.1). Average water-levels over a 2-minute interval were measured every 30 minutes. Directional wave measurements were conducted every 1.5 hours at a rate of 2 Hz over a sampling period of 8.5 minutes.

Sediment properties and spatial and temporal variations were characterized by surface sediment samples from the project area and adjacent areas pre-nourishment, in November 2011, and post-nourishment, in March 2012. During the pre-nourishment sampling, 7 samples were taken across 14 beach profile transects, 6 of which were located in the project area. The post-nourishment sampling across the same 14 beach profile transects consisted of 7 samples per transect in the adjacent areas, and 9 samples per transect in the project area. A total of 198 sediment samples were collected and analyzed. Standard sieve analysis was performed, and the
Moment Method (Folk and Ward, 1957) was used to calculate mean grain size and standard deviation (sorting).

4.4 Results

The entire study area was divided into three portions to describe morphologic evolution of the swash-zone berm nourishment in comparison with the adjacent areas to the west and east of the nourishment. The following sections summarize the wave conditions in the study area, morphologic change of the adjacent and project areas based on the 7 surveys taken by USACE and USF CRL, and the sediment characteristics pre- and post-nourishment.

4.4.1 Wave Conditions in the Study Area

For this study, directional wave data was collected in the region using a PUV sensor, from November 2011 until September 2012, with some gaps due to loss of battery power. No measured wave data was available for the 1985 and 1989-1991 nourishments, which are compared with the 2011-2012 nourishment in the follow sections. Therefore, USACE Wave Information Study (WIS) hindcast model data were used as a basis to compare wave conditions during each of the nourishment periods. Only onshore directed waves were used, as they are the ones relevant to beach processes. The measured data were also compared to WIS model data to validate the hindcast results. The WIS numerical buoy used for comparison was 73164, located at 20 m water depth and 10 km seaward of the wave gage deployed for this study.

The WIS hindcast captures the variations of Hmo reasonably well, however, some divergence in the larger magnitude values of Hmo are notable owing to energy loss due to friction and likely wave breaking as the waves propagate into the shallower measurement
location (approximately 5 m water depth) near the project site (Figure 4.2). Since the greatest amount of beach change is caused by energetic waves (related to the square of the wave height), the top 50% of all of the wave heights were used here to examine a percent difference between the two data sets. On average, the WIS waves were approximately 14% higher than the measured data. Given that the overall trends are similar (Figure 4.2), the WIS data should provide reliable representation of the wave conditions. In the following sections, WIS data will be used to compare the wave conditions during the three nourishments. In addition, WIS data are used to fill in gaps in time where the sensor did not measure data due to loss of power.

For the 2011-2012 nourishment, during the winter season, cold fronts occurred approximately every 10 to 14 days, which is typical for the Florida Gulf Coast (Wang et al., 2011; Beck and Wang, 2009; Wang and Beck, 2012). Significant wave heights of up to 2 m were measured during these storm events, with wave periods up to 8 s (Figure 4.2) and wave directions generally from the south to south-southeast (United States Army Corps of Engineers, Wave Information Study). Typically, the project area experienced smaller waves during the summer season, on the order of 0.5 m, with the exception of the passages of tropical storms (Figure 4.2). Both Tropical Storm Debby and Hurricane Isaac generated waves greater than 2 m high measured at the nearshore gage. Farther offshore at 20 m water depth, WIS calculated 5 m wave heights during Hurricane Isaac. The relatively small summer swells typically have periods of up to 10s, with peak periods of just over 10 s and 12 s during Tropical Storm Debby and Hurricane Isaac, respectively.
Figure 4.2. Comparison of hindcast WIS data to measured wave data during the study period, which experienced two tropical storms, Debby and Isaac. Top: Significant wave height. Bottom: Peak wave period.
For the 2011-2012 nourishment, during the winter season, cold fronts occurred approximately every 10 to 14 days, which is typical for the Florida Gulf Coast (Wang et al., 2011; Beck and Wang, 2009; Wang and Beck, 2012). Significant wave heights of up to 2 m were measured during these storm events, with wave periods up to 8 s (Figure 4.2) and wave directions generally from the south to south-southeast (United States Army Corps of Engineers, Wave Information Study). Typically, the project area experienced smaller waves during the summer season, on the order of 0.5 m, with the exception of the passages of tropical storms (Figure 4.2). Both Tropical Storm Debby and Hurricane Isaac generated waves greater than 2 m high measured at the nearshore gage. Farther offshore at 20 m water depth, WIS calculated 5 m wave heights during Hurricane Isaac. The relatively small summer swells typically have periods of up to 10 s, with peak periods of just over 10 s and 12 s during Tropical Storm Debby and Hurricane Isaac, respectively.

4.4.2 Pre- and Post-nourishment Morphology

The pre-nourishment beach in the study area included a back beach of various widths, with an elevation of +2.0 m NAVD88 or above. A steep foreshore extended from nearly +2.0 m to -1.0 m NAVD88 over a short distance of roughly 20 m, or a slope of 1:7. A relatively large bar (close to 10 m wide and 1 m in relief) existed approximately 50 m offshore with a broad and relatively shallow trough (Figure 4.3). A relatively steep profile extended seaward of the bar until roughly 6 m water depth, where the profile flattened.

The nourishment was placed between R53.5 and R64. The post-nourishment morphology closely resembles a nourished beach with a wide and flat constructed back beach. Different from a typical nourished beach, the designed berm elevation was much lower at
approximately the +0.91 m NAVD88 contour. The steep slope of the pre-nourishment foreshore was still apparent in the post-nourishment morphology despite the extension of the swash zone berm. The nourishment extended the shoreline approximately 60 m from the pre-nourishment profile in this example (Figure 4.3).

![Perdido Key: R54](image)

Figure 4.3. Example of pre- and post-construction profiles.

4.4.3 Beach Morphodynamics in the Adjacent Area West of the Swash-zone Berm

Owing to the net westward longshore transport, sand volume gain was expected in the west adjacent area due to longshore spreading. Figure 4.4 shows an example of a profile in the western area immediately adjacent to the berm. In general, profiles in this area experienced little change on the dry beach throughout the entire study period. The natural back beach at approximately +2.0 m NAVD88 and steep foreshore were maintained throughout the entire study period. A dynamic bar existed offshore at the beginning of the study, separated by a broad and
shallow trough. After the swash-zone berm nourishment, large and persistent sediment volume gains were measured in the nearshore, with the largest gain being after the distant passage of Tropical Storm Debby. A small volume of sediment was lost following the passage of Hurricane Isaac.

Figure 4.4. Example time-series profile in the western area, immediately adjacent to the berm (R52).

Further west from the berm (Figure 4.5), the beach was approximately 50 m wide at the beginning of this study, with the characteristic steep foreshore slope. The dry beach remained rather stable until the passage of Hurricane Isaac, when the beach lost about 10 m in width. Some of the eroded sediment was deposited on the dry beach above the +2.0 m NAVD88 contour in the form of overwash, as can be seen by the large gain of sediment volume on the backbeach. It is noted here that the extent of the overwash is unknown due to the location of the
benchmark, and the fact that some sediment was overwashed past the landward limit of measurements for this profile. Similar to the profiles immediately adjacent to the berm, the more distant profiles also experienced sediment gain in the trough before the passage of Hurricane Isaac, during which the entire profile was shifted landward. Substantial sediment volume gain occurred during the year after Hurricane Isaac.

Figure 4.5. Example time-series profile in the western area, further west of the berm (R48).

In summary, the adjacent area to the west of the berm experienced sediment gain, likely driven by the combination of longshore spreading of the nourishment and the net westward longshore transport. However, most of the sediment gain occurred between the shoreline and the bar, with little to no net gain on the subaerial beach. Profiles immediately adjacent to the berm experienced little change on the dry beach during the entire study period, while profiles further
west of the berm experienced substantial erosion during the passage of the energetic Hurricane Isaac.

4.4.4 Evolution of the Swash-zone Berm Nourishment

Profiles located at the western end and in the middle of the berm project area behaved quite similarly and will be discussed using the example profile shown in Figure 4.6. Pre-nourishment beach morphology was consistent within the entire study area as discussed earlier, which showed a relatively flat back beach at approximately the +2.0 m NAVD88 contour, and a steep foreshore. The post-nourishment morphology showed a wide flat beach at approximately the +1.0 m NAVD88 contour. The constructed berm at this location was approximately 70 m wide (the average width of the nourishment was 60 m). Throughout the study period, the berm eroded and the shoreline receded landward. During the first four months (until May 2012), the berm eroded approximately 20 m, while the active berm crest increased in height by approximately 0.5 m. Following the distant passage of Tropical Storm Debby, approximately 10 m width of the swash-zone berm nourishment was lost while the characteristic steep foreshore was maintained. The impact of Tropical Storm Debby led to the development of a large storm berm between the +1.0 m and +2.0 m NAVD88 contours. The passage of Hurricane Isaac resulted in erosion of the dry beach and in the nearshore zone, and formed a more distinct bar offshore. Some of the sediment eroded from the beach and nearshore likely contributed to the landward deposition, or overwash, above the +2.0 m NAVD88 contour. The profile remained quite stable between September 2012 (post Hurricane Isaac) and July 2013. During the entire study period, the profile maintained the characteristic steep foreshore.
Near the east end of the project area, profiles behaved differently than those to the west. Figure 4.7 illustrates an example from the eastern end of the swash-zone berm project area. During the first four months, the swash-zone berm eroded with some deposition on the subaerial portion of the backbeach, similar to the findings along the rest of the berm area. However, this profile was in the vicinity of Pensacola Pass, and, therefore, is greatly influenced by tidal inlet processes. When compared to the middle and western portion of the project area, the measured changes on the dry beach following the passage of Tropical Storm Debby were generally much smaller than those caused by Hurricane Isaac. Hurricane Isaac eroded the dry beach landward beyond the pre-nourishment position. In the subsequent survey 10 months later, the beach regained some sediment in the subaerial berm and shoreface, and the recovered beach was slightly wider (approximately 10 m) than the pre-nourishment beach.
In summary, the profiles within the project area lost most of the volume of the swash-zone berm nourishment sediment during the 1.5-year study period, with the foreshore location retreated to near the pre-nourishment location. Some of the eroded sediment was deposited on the beach in the form of an active berm, a storm berm, or an overwash terrace. Tropical Storm Debby had a greater impact on the profiles to the west, resulting in the formation of a large storm berm of up to 1 m high and 30 m wide. The berm formed by Tropical Storm Debby was smaller in the eastern portion of the swash-zone berm project area than the western potion. Hurricane Isaac had a greater impact on the profiles in the eastern portion of the project closer to Pensacola Pass.
4.4.5 Beach Morphodynamics East of the Swash-zone Berm Project Area, near Pensacola Pass

The profiles in the eastern area, directly adjacent to Pensacola Pass, have a different orientation than all of the previously discussed profiles (Figure 4.1). The profile immediately adjacent to the berm project area and Pensacola Pass (Figure 4.8) lost a substantial amount of sand between the pre- and post-nourishment surveys. This is likely due to a cold front that passed through the study area during construction (Figure 4.2) and the dynamic nature of beaches in the immediate vicinity of tidal inlets. Subsequent surveys showed that the beach gained back the sediment lost during the construction period, eventually leading to a return to the pre-nourishment survey shape. The accretionary trend continued through the distant passage of Tropical Storm Debby. The passage of Hurricane Isaac reversed the 6-month accretionary trend and eroded the beach to its post-nourishment, deflated morphology. It is worth noting that the at times when the profile experienced deposition, it maintained the shape of a flat back beach and a steep foreshore, similar to the profiles away from the inlet.

Profiles along the side of the inlet channel exhibit a steep slope that leads into the channel (Figure 4.9). This example profile remained relatively stable throughout the entire study period, with some slight beach changes due to the fact that it is directly along the inlet channel. There is not a significant sediment gain or loss at this profile even after the distant passage of Tropical Storm Debby. The shoreline propagated inlet-ward after the passage of Hurricane Isaac, but retreated landward after.
Figure 4.8. Example time-series profile east of the swash zone berm project area, immediately adjacent to Pensacola Pass (R65).

Figure 4.9. Example time-series profile along the channel of Pensacola Pass (R66.5).
4.4.6 Sediment Characteristics

The northwest Florida barrier islands are characterized by well sorted mature quartz sand (Stone et al. 2004; Wang and Horwitz, 2007). The mean grain size of the dry beach (pre-nourishment) and berm (post-nourishment) sediment samples were calculated and averaged for each line (Figure 4.10). The average pre-nourishment dry beach sediment grain size was 0.40 mm, and post-nourishment berm sediment was 0.34 mm or about 15% finer. The average mean grain size on the pre-nourishment beach decreased from west to east from approximately 0.5 mm to 0.3 mm. Although the pre-nourishment sediment was fairly uniform alongshore (with a standard deviation (σ) of ± 0.07 mm), post-nourishment the sediment grain size became more uniform along the entire berm project area (σ = ± 0.02 mm), and was generally finer than the pre-nourishment sediment. Cross-shore variation of sediment mean grain size was found to be negligible. Overall, the sediment in the study area is well-sorted, medium-sized quartz sand with little variability in space and time.

Figure 4.10. Alongshore distribution of dry beach sediment grain size pre- and post-nourishment of the swash-zone berm nourishment.
4.5 Discussion

4.5.1 Profile Equilibration

The placement of a large amount of sediment in the swash zone artificially created an out-of-equilibrium perturbation within a dynamically equilibrated beach environment. It is important to understand the major processes of profile equilibration and their associated time scales. To determine whether the nourishment profiles had reached equilibrium during the study period, it is necessary to first establish an average or equilibrium profile that is representative of the study area. In order to create an average profile, adjacent profiles to the west were averaged both temporally and spatially for all survey periods. Additionally, pre-nourishment profiles within the swash-zone berm project area were also used in the averaging. In total, 43 profiles were averaged and used here to represent an equilibrium profile, similar to approaches used by Bruun (1954), Dean (1977, 1991), Bodge (1992), and Wang and Davis (1998, 1999). It is reasonable to assume the average profile represents an equilibrium profile for the study area. The +0.6 m NAVD88 contour was used as the origin of the average (equilibrium) profile because it coincides with the upper foreshore and does not fluctuate on the timescale of tidal cycles, which may influence the field survey operation.

The equilibrium profile obtained from the averaging of the measured profiles was compared to the Bruun (1954) and Dean (1977) equilibrium profile (Figure 4.11) represented by the equation:

\[ h = Ax^m \]  

(1)

where \( h \) is water depth, \( A \) is a parameter related to grain size, \( x \) is cross-shore distance, and \( m \) is 2/3 based on Dean (1977). A representative grain size of 0.40 mm was used to calculate the \( A \)
parameter for Perdido Key based on Moore (1982) and Dean (1987). The average profile was also compared to Bodge’s (1992) exponential expression of an equilibrium beach profile:

\[ h = B(1 - e^{-kx}) \]

where \( h \) is water depth and \( B \) and \( k \) are empirical coefficients. A least-square fit of the Bodge (1992) profile to the average profile yielded a value of 5.94 m for \( B \) and 0.0082 m\(^{-1}\) for \( k \) (Figure 4.11).

![Figure 4.11. Average profile of the study area compared to Dean (1977) and Bodge (1992) empirically derived equilibrium beach profiles for the region.](image)

Both the Dean (1977) and Bodge (1992) equilibrium profiles significantly underpredicted the steep measured foreshore slope, while over-predicting the slope of the broad and gentle trough. The slope of the offshore portion of the profile is considerably under-predicted. Both the Dean (1977) and Bodge (1992) models yielded a similar profile shape.
In order to determine whether the swash-zone berm had reached equilibrium at a certain time, the deviation of the spatially averaged profiles from the equilibrium profile obtained above was examined. It is assumed here that the smaller the variance, the closer the spatially averaged profile at a certain time is to an equilibrium state. A similar approach was used in Brutsché et al. (2014) to examine the equilibration process of a submerged bar-shaped nearshore berm in Fort Myers Beach, Florida. Figure 4.12 shows the average variance from the equilibrium profile for each survey period for the berm profile lines and the control area lines to the west.

In the adjacent area to the west, the variance remained similar to the pre-nourishment variance, throughout the entire study period, as expected. The passage of Hurricane Isaac caused a slight increase in variance of the adjacent area lines from the equilibrium profile (0.41 m2; 247 days post construction). The variance remained approximately the same a year after the passage of Hurricane Isaac (Figure 4.12).

Figure 4.12. Average variance of the profiles from the equilibrium profile for each survey period.
In the swash-zone berm project area, the immediate post-nourishment variance in March 2012 was much larger than the adjacent profiles and the pre-nourishment. A modest increase in variance was obtained for the May 2012 (124 days post construction) profiles. The succeeding surveys showed a rapid decrease in variance, particularly through the passages of both Tropical Storm Debby and Hurricane Isaac. Unlike the adjacent area, the swash-zone berm project area profiles continued its decrease in variance following the passage of Tropical Storm Debby, suggesting that high energy events played a significant role in the equilibration of nourished profiles. Following the passage of Hurricane Isaac, the average variance in the swash-zone berm project area had become similar as the adjacent area, indicating that the nourishment has reached a dynamic equilibrium similar to that of the natural beach. A year later, the average variance remained the same. The acceleration to equilibrium by storms was also documented by Brutsché et al. (2014) at the Fort Myers Beach submerged nearshore berm. Due to the overall lower wave energy conditions and different location and shape of the berm at Fort Myers Beach, the equilibrium process took longer (approximately 4 years as compared to 1.5 years).

4.5.2 Longshore Spreading

One of the goals of this unique swash-zone berm nourishment was to place the sediment in a location where it could rapidly mobilize and move alongshore and cross-shore (preferably onshore). In order to examine active beach width spatially, a common reference location from which the beach width is measured is defined here as +1.5 m NAVD88, or, the top of the pre-nourishment foreshore. Beach width is then defined as the distance of a particular contour to the reference point. Figure 4.13 illustrates the distance from the landward reference to selected active beach elevation contours for each of the profiles in the western adjacent area and the
swash-zone berm project area for March of 2012 (Figure 4.13A) and July of 2013 (Figure 4.13B). The eastern adjacent area was omitted due to its proximity to the inlet and subsequently very different morphodynamic processes. In March 2012 (Figure 4.13A), two months after the completion of the berm nourishment, the project area is easily distinguished by a wider beach measured from several contour levels extending much further offshore than the adjacent area contours. Small rhythmic features are observed along several contours in the entire study area. The swash-zone berm, marked by the +0.91 m contour, extended approximately 50 m seaward of the +1.5 m NAVD88 contour. In the adjacent area, the contours ranging from -0.3 m to +0.91 m NAVD88 follow the same alongshore pattern controlled by the planar foreshore slope (Figure 4.13). In the swash zone berm project area, the contours in the intertidal zone do not follow the same alongshore pattern as the dry beach contours, likely influenced by the equilibration of the beach profile.

By July 2013, or 1.5 years after the nourishment (Figure 4.13B), the protruding swash-zone berm had dispersed. Furthermore, the contour lines in the adjacent area did not extend further seaward during the 1.5-year period. This suggests that the beach above MLLW in the adjacent area did not gain significant amount of sediment from the nourishment. Figure 4.14 shows the total volume change (from the monument to the depth of closure) along the profiles from March 2012 to July 2012. The September 2012 and July 2013 surveys were not used for this illustration because it is believed that Hurricane Isaac’s influence on the study area was much greater than the perturbation of the nourishment, and the study area had largely equilibrated by that point. Overall, the berm project area lost sand volume, while several of the lines in the adjacent area to the west gained some amount of sand. However, the total amount of loss in the berm project area is greater than the small amount of gain in the rest of the project.
area. This imbalance could be due to sediment being transported out of the measured project area, either moving east into the large ebb-tidal delta or adjacent channel, west beyond the extent of the study area, or landward beyond the measured landward extent of the profiles. The two offshore bathymetric surveys performed in November 2011 and July 2013, extending approximately 1 km offshore, suggest that the net sediment volume loss is not attributable to offshore transport beyond the short-term closure depth due to the fact that the surveys are nearly identical.

Several studies have documented large rhythmic features along the Perdido Key beach (Browder and Reilly, 2008; Arifin and Kennedy, 2011; Dean, 1999), as also observed in this study (Figure 4.13). Aerial photos of the study area often illustrate beach cusps and crescentic bars. Although the mechanism for formation of these persistent features is often debated, recent studies have suggested that small existing variations in offshore bathymetry cause corresponding variations in waves and currents, which cause changes in sediment transport rates and bathymetry in a feedback loop (Arifin and Kennedy, 2011). Browder and Reilly (2008) suggested that both nourishments and storm impacts tend to reset the morphology to a more longshore uniform state. However, the rhythmic features tend to return rather rapidly during normal conditions. This may explain why the cusps and crescent bars in March 2012 (just after the nourishment) are not as distinctive as those in July 2013, approximately 18 months post nourishment.
Figure 4.13. Contour positions of different active beach elevations with respect to the +1.5 m NAVD88 contour in A) March 2012 and B) July 2013.
4.5.3 Influence of Constructed Berm Elevation on Nourishment Performance

Two previous beach nourishments in the study area were constructed in 1985 and 1989-1991, respectively with different constructed berm elevations. In the following, the two previous nourishments are compared to the 2011-2012 swash-zone berm nourishment to examine the influence of constructed berm elevation on the nourishment performance. The 1985 nourishment was monitored for 2 years and described by Dean (1988). The 1989-1991 nourishment was monitored for 9 years (Browder and Dean, 2000). The 2011-2012 nourishment was monitored for 1.5 years by this study.

In order to compare the performance of three nourishments, it is important to examine wave conditions during each period to distinguish whether differences in nourishment performance, if any, were caused by the different constructed berm elevation or different wave conditions (Figure 4.15). For consistency, WIS data were used in obtaining wave statistics. For each nourishment period, the highest 1%, 5%, 10%, 20%, 30%, 40%, and 50% significant wave
heights were averaged for each study period: 2 years for the 1985 nourishment; 9 years for the 1989-1991 nourishment; and 1 year for the 2011-2012 nourishment. Overall, the statistical properties of wave conditions are similar during the three study periods, with the 2011-2012 period averaging slightly higher than the other two periods, likely due to the passages of Tropical Storm Debby and Hurricane Isaac that year. The largest discrepancy in average wave heights for each study period was the highest 1%, with 2011-2012 having the highest values. It is worth noting that the WIS dataset terminated at the end of 2012 and therefore does not cover the entire period for this study. The influence of this is not expected to be significant. It is acknowledged here that the above statistical comparison does not distinguish the timing of a particular storm. In other words, a storm impact immediately following construction may have a larger effect on the nourishment than a later storm passage.

Figure 4.15. Comparison of wave characteristics during each study period using WIS data.
The 1985 nourishment consisted of 1.9 million m$^3$ of sand placed between FDEP R-monuments R60 and R64, a total of 1.2 km, (or less than half of the longshore extent of 2011-2012 nourishment) at a very high nourishment density of 1550 m$^3$/m (Dean, Otay and Work, 1995). Two months after the beach fill, Hurricane Elena impacted the study area, and the first post-nourishment survey was conducted following the storm. According to the survey, the nourishment extended the beach 120 m (Dean, 1988; Dean, Otay, and Work, 1995). The very high nourishment density was caused by the high elevation of the constructed subaerial berm at approximately +3.0 m NAVD88. Because the constructed berm was approximately 1 m higher than the natural berm, natural overwash processes were less likely to occur (Dean, Otay, and Work, 1995). Wind forcing winnowed out the fine sand, leaving an unnatural shelly lag deposit on the surface of the beach (Dean, Otay, and Work, 1995). Dean (1988) recommended that future nourishments should not exceed +2.0 m. Despite the higher berm, by October 1987 (27 months after placement), the shoreline had retreated landward approximately 90 m, or 75% of the original placement width (Dean, Otay, and Work, 1995). The very short project length may have had significant influence of that beach nourishment’s performance.

The 1989-1991 nourishment consisted of a beach nourishment and a submerged nearshore berm nourishment. On the beach (constructed 1989-1990), 4.1 million m$^3$ of sand was placed from R40 to R64, which is approximately 7.3 km (or about 2.3 times the length of the 2011-2012 nourishment) at a nourishment density of 560 m$^3$/m (Dean, Otay, and Work, 1995). The wide nourished beach extended approximately 140 m seaward, with a constructed berm elevation of +1.2 m, or nearly 2 m below the 1985 nourishment, and 0.3 m above the 2011-2012 nourishment. Over the first year, the project lost approximately 10% of its volume, and then tapered to approximately 3% of loss of volume per year over the next two years (Browder and
Because of the very large amount of sand placed, the 10% volume loss equals 400,000 m$^3$, which is equal to the entire volume placed in 2011-2012. Two hurricanes affected the area during the study period: Hurricanes Erin and Opal, both in 1995. Hurricane Opal had a much larger effect on the area, causing erosion of approximately 16% of the total placed volume, or 656,000 m$^3$ (Browder and Dean, 2000). As of August 1998, or 9 years after the nourishment, the project retained approximately 56% of the originally placed volume with a beach width 53 m wider than the pre-nourishment beach (Browder and Dean, 2000), which accounts for 38% of the post-nourishment shoreline width (in other words, the nourishment had retreated 62%). The erosion rate during the study period was approximately 7.6 times the historical erosion rate of 1.5 m/year (Browder and Dean, 2000; Dean, 1988). It is worth noting that the performance of the 1989-1991 nourishment may be considerably influenced by its long 7.3 km extent.

The nearshore berm associated with the 1989-1991 project was constructed in 1990-1991. The berm consisted of approximately 3 million m$^3$ of sand placed at the -6 m contour. By 1998, the berm had experienced little movement. It appeared that the landward edge of the berm had moved onshore approximately 50 m (Browder and Dean, 2000), which is minimal for its scale, but overall the berm mostly just smoothed and retained the same volume and location (Work and Otay, 1996; Otay 1995). The berm did however provide some shelter to the beach nourishment (Work and Otay, 1996; Otay 1995).

The most recent swash-zone berm nourishment was constructed at a much lower berm height than either of the previous nourishments (+0.91 m NAVD88). Sediment was placed between R53.5 and R64 (3.2 km). The nourishment was on average approximately 60 m wide, for a total of approximately 400,000 m$^3$ of sediment placed at a much smaller nourishment
density of 125 m$^3$/m, or less than 8% of the 1985 nourishment density and 22% of the 1989-1990 nourishment density.

The lower berm height constructed in the 2011-2012 Perdido Key swash-zone berm nourishment allowed the run up and overtopping of waves to move and deposit sediment onto the back beach, similar to the 1989-1991 nourishment (Dean, 1988; Dean, Otay, and Work, 1995). In fact, as the profiles approached equilibrium, sediment was moved onshore and above the +0.91 m NAVD88 contour, resulting in the growth of an active beach berm with a resultant natural berm height of approximately +2.0 m NAVD88. To illustrate the growth of the active beach berm, Figure 4.16 shows an example profile with all of the surveys shifted to the shoreline (defined here as +0.6 m NAVD88, or approximately 0.3 m above MHHW) position. Following completion of fill construction in January 2012, subsequent surveys showed sand accumulation above the +0.91 m NAVD88 contour, at nearly the pre-nourishment (November 2011) berm elevation contour at +2.0 m NAVD88 by September 2012, and remained until July 2013. Tropical Storm Debby, a modest storm, resulted in substantial growth of a storm berm. The more energetic Hurricane Isaac resulted in the erosion of the subaerial berm formed by Tropical Storm Debby and overwash into the dune field.

The growth of the active and storm berms following the completion of the swash-zone berm construction resulted in sediment volume gain above +0.91 m NAVD88, i.e. the volume of sediment moving onshore and building the beach naturally up to +2.0 m NAVD88 (Figure 4.17). Volume gains above the +0.91 m NAVD88 contour increased through the first three surveys, and peaked following the passage of Tropical Storm Debby, with a total sand volume gain of nearly 35,000 m$^3$, or 8.8% of the total placed volume (Figure 4.17). However, the more energetic
Hurricane Isaac had a much greater impact on the study area, causing a significant amount of erosion and overwash beyond the landward extent of our surveys.

Figure 4.16. Example profile adjusted horizontally to the +0.6 m NAVD88 contour to illustrate the accretionary building of the berm back to the natural elevation of +2 m NAVD88.

Figure 4.17. Total volume change above and contour width of the +0.91 m NAVD88 contour along the swash-zone berm project area.
Overall, the 2011-2012 swash-zone berm nourishment evolved much more rapidly than the previous nourishments. Figure 4.17 shows the changes in width of the +0.91 NAVD88 contour (referenced to the +1.5 m NAVD88 contour line). Following the nourishment, the width reduced from approximately 60 m to 46 m by March 2012 (6 m/month). In May 2012, the project area grew wider by approximately 4 m (to 50 m). The passage of Tropical Storm Debby (July 2012) caused erosion, resulting in an average width of 36 m. Hurricane Isaac (September 2012) had a much greater impact, causing the average width of the remaining nourishment to be only 15 m. By July 2013 (just 18 months post-construction), the remaining width of this nourishment was an average of approximately 7 m. The nourished contour width had retreated 88% of its post-nourishment width. On average, the beach eroded 34 m/year, which is 23 times the historical average before any of the nourishments.

Table 4.1 compares the performance of the three nourishments with different constructed berm elevations and alongshore extent. In terms of rates of landward retreat, the shortest nourishment, in 1985, had the greatest rate of retreat at 40 m/year despite having a much higher berm height and nourishment density. The longest nourishment from 1989-1991 had the smallest rate of 11 m/year. The lowest berm elevation nourishment from 2011-2012 had a retreat rate of 34 m/year despite the overall slightly higher waves and the distant passages of two tropical storms. This suggests that the alongshore extent of nourishment may play a crucial role in the performance, as found by previous studies (Browder and Dean, 2000; Elko and Wang, 2007; Roberts and Wang, 2012; Dean, 2002; Work and Dean, 1995; Finkl and Walker, 2005). Although the 1985 has the highest rate of retreat, the 2011-2012 nourishment has a higher percentage of placement width loss (57%) per year due to its much smaller placement width, and
fill volume. Overall, the 2011-2012 nourishment had the highest percentage of total placement width eroded (88%) in the shortest amount of time (1.5 years post-nourishment).


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<thead>
<tr>
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<tbody>
<tr>
<td>Project Volume</td>
<td>1.9 million m³ (beach)</td>
<td>4.1 million m³ (beach)</td>
<td>400,000 m³ (berm)</td>
</tr>
<tr>
<td></td>
<td>3 million m³ (berm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Project Length</td>
<td>1.2 km</td>
<td>7.3 km</td>
<td>3.2 km</td>
</tr>
<tr>
<td>Volume Density</td>
<td>1550 m³/m</td>
<td>560 m³/m</td>
<td>125 m³/m</td>
</tr>
<tr>
<td>Additional Beach Width</td>
<td>120 m</td>
<td>140 m</td>
<td>60 m</td>
</tr>
<tr>
<td>Nourishment Erosion Rate (pre-nourishment rate estimated to be 1.5 m/yr)</td>
<td>~40 m/yr (i.e. 33% of the placement width per year)</td>
<td>~11 m/yr (i.e. 8% of the placement width per year)</td>
<td>~34 m/yr (i.e. 57% of the placement width per year)</td>
</tr>
<tr>
<td>Berm Elevation</td>
<td>3 m</td>
<td>1.2 m</td>
<td>0.91 m</td>
</tr>
<tr>
<td>Impact of Berm Elevation</td>
<td>No overwash could occur</td>
<td>Natural run-up occurred to build berm back to natural +2 m</td>
<td>Natural run-up occurred to build berm back to natural +2 m</td>
</tr>
<tr>
<td>Overall Project Performance</td>
<td>75% of original placement width eroded 2.25 years post nourishment</td>
<td>62% of original placement width eroded 9 years post nourishment</td>
<td>88% of original placement width eroded 1.5 years post nourishment</td>
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4.6 Conclusions

A nourishment was placed within the swash-zone along eastern Perdido Key, Florida using maintenance dredged material from nearby Pensacola Pass, referred to here as a “swash-zone berm nourishment.” The swash-zone berm project and adjacent areas were monitored with beach surveys beginning November 2011 through July 2013. The 2011-2012 nourishment was compared to two previous nourishments in 1985 and 1989-1991. The following are conclusions reached:
• The studied beach is characterized by a steep foreshore that is maintained throughout the entire study period including following the construction of the project, and the passages of two tropical storms. Prior to the tropical storms, the low constructed berm elevation allowed overwash processes to occur frequently, which resulted in a net onshore sediment transport and growth of the active berm up to +2.0 m NAVD88, the elevation of the natural berm crest.

• The swash-zone berm did not create a new equilibrium state; rather it evolved back to the natural equilibrium profile shape maintained in the study area within 8 months. High wave-energy conditions, in this case caused by the passages of Tropical Storm Debby and Hurricane Isaac, accelerate the equilibrium process.

• The sediment volume gain west of the project area occurred mostly in the trough between the shoreline and the bar. Little to no shoreline accretion associated with the swash-zone berm nourishment was measured in the western adjacent area during the study period.

• In terms of rate of shoreline retreat, the short 1.2-km 1985 nourishment performed the poorest with a rate of loss of 40 m/year, despite the very high constructed berm of +3 m NAVD88. The long 7.3 km 1989-1991 nourishment performed the best with a retreat rate of 11 m/year. This suggests that high berm elevation does not lead to better nourishment performance. Instead, alongshore extent of a nourishment project may dominate project performance.
CHAPTER 5

IMPACTS OF TROPICAL STORM DEBBY AND HURRICANE ISAAC ON DIFFERENT TYPES OF BEACH-NEARSHORE NOURISHMENTS ALONG THE FLORIDA GULF COAST, USA

5.1 Introduction

One of the many objectives of beach and nearshore nourishments is to protect the landward infrastructure from storm impacts. In addition, storms may cause erosion of the beach, as well as flooding due to storm surge, which can impact environmental habitats. Important storm characteristics that determine severity of impact include alongshore variability of the storm processes, geographic location relative to the storm center, prior storm history, duration of beach inundation by waves, high wind speeds, flow regime of washover currents, morphology and elevation of the ground surface, grain sizes of transported material, density of vegetative cover, and human modifications (Morton, 2002). Other important factors include location relative to the storm path, timing of the storm events, duration of backbeach flooding, wind stress, flow confinement antecedent topography and framework geology (Morton, 2002). Beach profile response can vary based on these conditions. Often, storms cause erosion on the dry beach, and the formation of a bar offshore (Bascom, 1953). In other cases, eroded sediment deposits in the nearshore, however not in the form of a bar, rather in a plateau (e.g. Roberts et al., 2013). Many barrier islands experience overwash due to the low-lying nature of the island (e.g. Morton and Sallenger, 2003; Wang and Horwitz, 2007; Claudino-Sales et al., 2010).
The addition of sediment to the beach and nearshore can make a wider beach, which is important for tourism and recreation. There are many ways to accomplish this, including beach nourishment, nearshore berm nourishments, and swash-zone berm nourishments, as discussed in detail in the previous chapters. Beach nourishments are typically designed to advance the shoreline seaward to protect the coast from inundation caused by storm and wave action as well as for recreational purposes (Finkl and Walker, 2005). During storm events, the additional sediment increases the width of beach available to protect the upland vegetation and infrastructure from flooding and potential collapse due to erosion. Nearshore berm nourishments are another type of beach-nearshore nourishment, however in this case the nourishment is submerged in the nearshore in a mound or bar. During storms, nearshore berm nourishments can protect the shoreline through dissipation of wave energy as the waves break over the berm. A third, less common, type of beach-nearshore nourishment is a low-elevation or “swash-zone” berm nourishment (Wang et al., 2013; Brutschê et al, 2014). This is similar to a typical beach nourishment, however, in this case, the constructed berm elevation is built much lower than the natural berm elevation with the expectation that the nourishment will mobilize quickly. Similar to a beach nourishment, swash-zone berm nourishments add sediment to the beach and nearshore that should help to protect the upland vegetation and infrastructure.

It is important to understand the impacts of storms to beach and nearshore nourishments to better design them for future needs. Data-intensive monitoring programs are important in this regard, and can provide verification and future improvement to project design and modeling (Elko and Wang, 2007; Dean and Campbell, 1999). Many models exist to calculate hydrodynamic conditions as well as beach morphology change (e.g. Hanson and Kraus, 1989; Warren and Bach, 1992; Elias et al., 2001; Sanchez et al., 2011; Connell and Permenter, 2013).
Two such models are U.S. Army Corps of Engineers Coastal Modeling System Wave model (CMS-Wave) and Storm-Induced Beach Change (SBEACH). CMS-Wave is a two-dimensional spectral wave model formulated from a parabolic approximation equation with energy dissipation and diffraction terms (Lin et al., 2008). It simulates a steady-state spectral transformation of directional random waves co-existing with ambient currents in the coastal zone (Lin et al., 2008). SBEACH is a numerical simulation model for predicting beach, berm, and dune erosion due to storms (U.S. Army Corps of Engineers, 1994; Larson and Kraus, 1989; Larson et al., 1990; Rosati et al., 1993). The model assumes that the profile change caused by the storm is dominated by cross-shore processes. It was developed and tested based on laboratory experiments conducted with prototype-scale wave heights and periods, together with physical considerations of profile evolution and coastal processes (U.S. Army Corps of Engineers, 1994).

A nearshore berm nourishment, swash-zone berm nourishment, and beach nourishment were placed in Fort Myers Beach, Perdido Key, and Sand Key, respectively. The Fort Myers Beach nearshore berm was constructed in 2009 and is discussed in detail in Chapter 3. The Perdido Key berm was constructed in 2012 and is discussed in Chapter 4. The Sand Key beach nourishment was completed in 2012. All three nourishments were at least partially placed before the passages of two storms in 2012: Tropical Storm Debby and Hurricane Isaac. The purpose of this chapter is to apply the CMS-Wave and SBEACH to model the hydrodynamic conditions and morphology changes due to the storm impacts to each type of nourishment.
5.2 Study Area

The three study areas have different types of beach and nearshore nourishments (Figure 5.1). Fort Myers Beach is located on Estero Island, a low lying extensively developed barrier island, in west-central Florida, USA. Estero Island is bordered by San Carlos Bay to the north, and Big Carlos Bay to the south. In 2009, Matanzas Pass, the Federally maintained channel located at the north end of the island, was dredged. Material dredged from the pass was placed in the nearshore in the form of an artificial nearshore berm (Brutsché et al, 2014; Wang et al, 2013; Brutsché and Wang, 2012; Brutsché, 2011). The nearshore berm was not uniform alongshore, and was constructed to be much larger than the small natural bar that exists in the area. Generally, the nearshore berm was approximately 1.6 km long, 120 m wide, and 1 m high, with a total volume of 175,000 m³. Waves in this area are generally small, except for during high wave energy events such as winter cold fronts (occurring approximately every 10 to 14 days, October through April) or tropical systems. No wave buoys exist near Fort Myers Beach, therefore U.S. Army Corps of Engineers Wave Information Study (WIS) data were used for wave characteristics. Average offshore wave height in the study area according to WIS buoy 73296 (40 km offshore in 15 m water depth) is approximately 0.46 m, with average peak wave period of 4.4 s. However, due to the sheltering effects of nearby Sanibel Island (Balsillie and Clark, 1992), the wave heights closer to the study area are much lower. This is reflected in WIS buoy 73295, only 5 km offshore in 5 m of water. The average wave height from the nearshore buoy is 0.22 m with average wave period of 3.7 s. The study area is influenced by a mixed tide regime, with spring tides being diurnal and neap tides being semi-diurnal. Tidal ranges are 1.2 m and 0.75 m for spring and neap tides, respectively.
Perdido Key is a barrier island in the northwest Florida. The study area is located on the eastern portion of the island, entirely within Gulf Islands National Seashore. Similar to Estero Island, it is also a low lying barrier island; however, the study area in this case is virtually undeveloped, with the exception of several park structures (i.e. benches and parking lots) and a road. The island is bounded by Pensacola Pass to the east and Perdido Pass to the west. Beginning in late 2011, Pensacola Pass was dredged, and material was placed immediately adjacent to the pass in the form of a swash-zone nearshore berm (Wang et al., 2013; Brutsché et al., 2014). The berm was placed so that the constructed berm crest was no higher than +0.91 m NAVD88, or approximately 1 m below the natural berm elevation. The nourishment was about 1.2 km long and extended the beach 60 m, for a total of approximately 400,000 m³ of sand. The
study area experiences low to moderate wave energy, except during winter cold fronts and tropical storms. According to WIS buoy 73161 (19 km offshore in 23 m water depth), average wave height for the study area is 0.64 m, with an associated average peak period of 5 s. Closer to the shoreline (700 m offshore in 5 m water depth), using data measured by this study from a PUV gage, average significant wave height was 0.58 m with associated average peak period of 5.5 s. The study area experiences a diurnal tide regime, with a spring tidal range of up to 0.6 m and a neap tidal range of 0.18 m.

Sand Key is a heavily developed barrier island located in west-central Florida, 185 km north of Estero Island. The island is bound by Clearwater Pass to the north and Johns Pass to the south. Most of the island is considered critically eroded (Florida Department of Environmental Protection, 2011), and is regularly nourished (Roberts and Wang, 2012). The most recent nourishment occurred in 2012 using sediment dredged from a borrow area offshore. The nourishment was a typical beach-nearshore nourishment, that extended the beach varying amounts alongshore depending on the erosion rates of the particular location. At the specific location of this study, the beach was highly erosive and was therefore extended approximately 60 m, while maintaining the natural berm elevation of approximately +2.0 m NAVD88. Sand Key is generally a low-wave energy environment except when affected by winter cold fronts or tropical storms. Average wave heights are less than 0.30 m based on a PUV sensor placed approximately 400 m offshore of the study area (Roberts and Wang, 2012). Offshore wave conditions exhibit an average wave height of 0.52 m, with associated average peak period of 4.3 s (WIS buoy 73264; 20 km offshore, 15 m water depth). Spring tides at this location are diurnal with ranges of up to 1 m. Neap tides are semi-diurnal with a range of approximately 0.18 m (Roberts and Wang, 2012).
5.3 General Storm Characteristics

Two tropical systems affected all three study areas in 2012: Tropical Storm Debby (June 2012) and Hurricane Isaac (August 2012). Tropical Storm Debby formed in the southeast Gulf of Mexico on June 23, 2012, approximately 560 km offshore of Fort Myers Beach (Figure 5.2). The storm moved to the northeast, and by June 24th and 25th was impacting much of the Florida Peninsula and Panhandle. On June 26th, the storm tracked due east, and began to move over the Florida Peninsula towards the east coast. The track over land caused the storm to downgrade to a tropical depression, until it moved further offshore of the east coast of Florida on June 27th. According to the best ship track used by NOAA, pressure associated with the storm ranged from 990 mb to 1002 mb, with the lowest pressure being on June 25th (Kimberlain, 2013). Wind speed of the storm ranged from 15 m/s (55 km/hr) to 28 m/s (102 km/hr) (Kimberlain, 2013). Storm surges from 0.6 m to 1.4 m were reported from southwestern Florida to the Florida Panhandle (Kimberlain, 2013).

Hurricane Isaac formed in the Atlantic Ocean on August 20th, and moved into the Gulf of Mexico as a tropical storm on August 26th (Figure 5.2). It then followed a northwest track towards the Panhandle of Florida, within 280 km and 420 km of Fort Myers Beach and Sand Key, respectively. Just before making landfall in Louisiana (approximately 280 km west of Perdido Key), Hurricane Isaac became a category 1 hurricane. The remnants of Hurricane Isaac then moved through the Midwest portion of the United States, until its subsequent dissipation on September 1st. According to NOAA ship track data, the lowest pressure of the storm was 965 mb, ranging up to 1010 mb (Berg, 2013). Wind speed ranged from 13 m/s (46 km/hr) to 36 m/s (130 km/hr) (Berg, 2013). Along the Panhandle of Florida, storm surge associated with
Hurricane Isaac was up to 1.1 m, and along the southwestern portion, surge was approximately 0.3 m to 0.9 m (Berg, 2013).

Figure 5.2. Storm tracks from Tropical Storm Debby and Hurricane Isaac. Modified from NOAA National Hurricane Center (http://csc.noaa.gov/hurricanes/).

It is worth noting that both storms were rather large. Although the centers of the storms were fairly far from the study areas, they generated strong winds and high waves. Due to the distant nature of the storms, the waves in the study area were mostly swell type with quite long wave period. A more detailed discussion of wave conditions at each study site is included in the following sections.

5.4 Methodology

5.4.1 Field Methodology

The impacts of Tropical Storm Debby and Hurricane Isaac were quantified using time series beach-profile surveys. The transects were surveyed following standard level-and-transit procedures using an electronic total survey station and survey rod. Surveys were georeferenced to State Plane Florida West for the horizontal coordinate system for Fort Myers Beach and Sand
Key, State Place Florida North for the horizontal coordinate system for Perdido Key, and North American Vertical Datum of 1988 (NAVD88) for the vertical datum. Profiles in Sand Key were surveyed every 300 m, and in Perdido Key they were surveyed every 150 m, using Florida Department of Environmental Protection Range monuments. In Fort Myers Beach, transects were established 50-200 m apart, with the closer transects in the berm project area for better survey density. For Sand Key and Perdido Key, offshore surveys were completed using a precision echo sounder coupled with a Real Time Kinematic Global Positioning System (RTK GPS). Surveys were completed at each site pre-storm and post-storm for both Tropical Storm Debby and Hurricane Isaac.

At Perdido Key (for both Tropical Storm Debby and Hurricane Isaac) and Sand Key (only Hurricane Isaac), a PUV sensor was deployed to measure waves and water level. Average water-levels over a 2-minute interval were measured every 30 minutes. Directional wave measurements were conducted every 1.5 hours at a rate of 2 Hz over a sampling period of 8.5 minutes. WIS data were also used to illustrate wave and water level conditions for each study site during both storms. For consistency, WIS hindcast buoys were chosen approximately 15 km offshore of each study site. For Fort Myers Beach, WIS buoy 73295 was used (5 m water depth), WIS buoy 73266 (13 m water depth), and WIS buoy 73165 (20 m water depth) were used for Fort Myers Beach, Sand Key, and Perdido Key, respectively. It is worth noting that the offshore WIS wave data represent wave conditions at different water depth. Water level data were taken from NOAA NDBC tide gauges: 8725110 (Fort Myers Beach), 8726724 (Sand Key), and 8729840 (Perdido Key).

Representative grain sizes were obtained based on sediment samples from each site. At all three study sites, cross shore sediment samples were taken along beach profile transects.
Sediment sampling at Ft. Myers Beach and Perdido Key have been discussed in Chapters 3 and 4. Sediment sampling at Sand Key followed similar procedures. Standard sieve analysis was conducted on the samples, and grain size was calculated using the Moment Method (Folk and Ward, 1957). Representative $D_{50}$ and $D_{90}$ grain sizes were calculated for use in the modeling efforts.

5.4.2 Model Methodology

The Coastal Modeling System (CMS) Wave model was applied to calculate wave spectra across a local domain for each study site (Lin et. al, 2011; Reed et. al, 2011; Wu et. al, 2011; Sanchez et al., 2011; Wang et. al, 2011). The purpose of this modeling effort was to propagate the WIS data onshore to validate both the WIS and CMS-wave models by comparing the modeled data to the measured wave data. The local domain model grids were constructed using NOAA’s Coastal Relief Model. The model was forced with TMA-generated spectra from the wave parameters obtained from each of the offshore WIS hindcast buoys. For Perdido Key, a spatially constant Darcy-Weisbach friction coefficient of 0.08 was applied to the entire grid. Through calibration of the model, it was also found that a Darcy-Weisbach coefficient of 0.08 best fit the measured data at Sand Key. Because there are no measured data for Fort Myers Beach and because of the shallow inner continental shelf, it is assumed here that the friction coefficient of 0.08 is appropriate for this location as well, since the offshore region here is similar to that of Sand Key. The above friction coefficients were determined based on a series of calibration model runs, discussed in the following sections. The selected friction coefficients yielded the closest fit with the measured wave conditions.
For each study site, data were exported from the offshore most point of several example profile transects. Following the CMS-Wave model runs, SBEACH was used to model morphology change. The output wave data from the CMS-Wave model was used in the SBEACH modeling of each profile transect. For SBEACH, a constant grid of 5 m was used for each transect. Propagated wave data in hourly increments were interpolated to 10 min increments for SBEACH modeling, based on typical cell and time step sizes given by Rosati et al. (1993). More details regarding the calibration and validation of the models will be discussed in the following sections.

5.5 Results and Discussion

The following discussion consists of the results from the modeling and field efforts associated with this study. Calibration and validation of the CMS-Wave and WIS models are addressed, as well as measured morphologic changes using time series beach profile surveys. Finally, the SBEACH model is applied and discussed.

5.5.1 Calibration and Validation of the CMS-Wave Model and WIS Hindcast

Transect-specific wave conditions for each of the storms at each study area were calculated using WIS Hindcast data propagated into the nearshore by CMS-Wave. In order to determine whether the WIS data were valid to use, and that CMS-Wave accurately calculated waves in the nearshore, the two models were calibrated and validated using measured data at Perdido Key during Tropical Storm Debby and Hurricane Isaac, and at Sand Key during Hurricane Isaac.
The measured and modeled results for Tropical Storm Debby and Hurricane Isaac at Perdido Key are shown in Figures 5.3 and 5.4, respectively. During Tropical Storm Debby, the offshore WIS hindcast data illustrated a longer storm duration than that measured in the nearshore. This is likely due to the variation of wind direction. As shown in Table 5.1, the strongest winds during Tropical Storm Debby came from the northeast, i.e. offshore directed, which likely suppressed the waves measured in the nearshore as compared to the hindcast offshore waves. Various friction coefficients were used as a calibration parameter (Figures 5.3 and 5.4). A value of 0.08 yielded predicted wave heights to have a root mean square error deviation (RMSD) of just 0.20 m. The same calibration run was performed for the Hurricane Isaac modeled data. In this case, the WIS hindcast predicted storm duration reasonably, likely due to the rather constant onshore directed wind. A friction factor coefficient of 0.08 also exhibited the best fit with an RMSD value of 0.19 m. At Perdido Key, offshore waves during Hurricane Isaac were much higher than during Tropical Storm Debby. Substantial dissipation occurred as the long waves propagate into shallower water, especially during Hurricane Isaac. Peak wave height in the nearshore was found to be approximately 2.5 m as compared to approximately 2 m during Hurricane Isaac and Tropical Storm Debby, respectively.

A sensitivity analysis using different friction coefficients was performed for Sand Key (Figure 5.5) as well. It was found that the friction coefficient value of 0.08 most closely reproduced the modeled data, with an RMSD value of 0.13 m. Due to the reasonable model results, the same friction coefficient was applied to the CMS-Wave model for Tropical Storm Debby at Sand Key. Because the offshore bathymetry of Fort Myers Beach is similar, but slightly gentler, as compared to that of Sand Key, and no wave data were measured for that study
area, it was assumed that the same friction coefficient would be reasonable to apply, and was used for both of the CMS-Wave models for Tropical Storm Debby and Hurricane Isaac.

![Figure 5.3. Measured and modeled wave height data from Perdido Key during Tropical Storm Debby. This also illustrates a comparison of the modeled wave height using different friction coefficients.](image)

Overall, the WIS hindcast data and the propagation by CMS-Wave yielded reasonably accurate nearshore wave conditions as compared to the measured data. This suggests that WIS hindcast data propagated using CMS-Wave can provide an accurate representation of nearshore wave conditions for north, west-central, and south-central Florida coast. Since the measured nearshore wave data have considerable gaps, the propagated WIS wave data were used in the following beach-profile modeling efforts.
Figure 5.4. Measured and modeled wave height data from Perdido Key during Hurricane Isaac. This also illustrates a comparison of the different tested friction coefficients.

Table 5.1. Wind forcing during Tropical Storm Debby at Perdido Key. Directions were divided based on the strike of the island (75-255 degrees).

<table>
<thead>
<tr>
<th>Direction (degrees from North)</th>
<th>Percentage of Occurrence</th>
<th>Average Wind Speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>76-120</td>
<td>27.0</td>
<td>7.2</td>
</tr>
<tr>
<td>121-165</td>
<td>3.2</td>
<td>4.2</td>
</tr>
<tr>
<td>166-210</td>
<td>9.3</td>
<td>3.3</td>
</tr>
<tr>
<td>211-255</td>
<td>22.2</td>
<td>4.9</td>
</tr>
<tr>
<td>256-300*</td>
<td>2.3</td>
<td>3.3</td>
</tr>
<tr>
<td>301-345*</td>
<td>0.5</td>
<td>2.4</td>
</tr>
<tr>
<td>346-30*</td>
<td>15.7</td>
<td>6.9</td>
</tr>
<tr>
<td>31-75*</td>
<td>19.4</td>
<td>10.8</td>
</tr>
</tbody>
</table>

*Offshore directed wind.
Figure 5.5. Measured and modeled wave height data from Sand Key during Hurricane Isaac. This also illustrates a comparison of the different tested friction coefficients.

5.5.2 Measured Morphologic Changes

Each study site was divided into nourishment or project area and control areas. Time-series beach profile surveys were taken at each of the three study sites in the project and control areas pre-construction, post-construction, and before and after both Tropical Storm Debby and Hurricane Isaac. It is important to note that the surveys were taken days to weeks before or after the construction and storms. The following section describes morphologic changes at each study site.

5.5.2.1 Nearshore Berm Nourishment- Fort Myers Beach

At Fort Myers Beach, the nearshore berm nourishment had moved onshore approximately 80 m before Tropical Storm Debby (Figure 5.6). Following the passage of Tropical Storm Debby, the berm largely stayed in the same place, however it split into two smaller bars, each approximately 0.5 m high. The passage of Hurricane Isaac, maintained the two smaller berms, in
roughly the same place. The smaller, inshore bar largely resembles the small natural bar seen in the pre-construction profile. At this particular profile (Figure 5.6, FMB 32, the middle of the project area), there was no erosion after Tropical Storm Debby and some erosion after Hurricane Isaac (approximately 15 m). At FMB 43 (Figure 5.7), near the northwest end of the project area, the berm also split into two smaller berms following the passage of Tropical Storm Debby. However, in this profile, the two berms became much more distinct after Hurricane Isaac, and the inner bar moved onshore as the outer bar moved offshore. At this location there was no beach erosion, in fact, the beach gained approximately 12 m of dry beach width since construction of the berm. In all of these examples, the berm itself lost minimal volume.

Figure 5.6. Measured morphology change at FMB 32.
Figure 5.7. Measured morphology change at FMB 43.

In the non-nourished sections of the beach, the profile behaved quite differently. As would be expected, the storms created a large bar offshore (Figure 5.8 and 5.9). Large bars are common in beach profiles following high-energy wave events (Komar, 1998; Roberts and Wang, 2012; Elko and Wang, 2007). In the case of FMB 5 (Figure 5.8, approximately 1 km southeast from the project area), there was substantial erosion from the beach and nearshore, and the large bar (approximately 1 m high) formed approximately 100 m offshore. The bar remained largely in the same place following the passage of Hurricane Isaac. FMB 9 (Figure 5.9, approximately 350 m southeast of the project area) also exhibits a large bar following the passage of Tropical Storm Debby and Hurricane Isaac. After Tropical Storm Debby, the bar is 100 m offshore, and approximately 1 m high. Hurricane Isaac caused the bar to be lower in relief, however it remained largely in the same place. At this profile, not much beach erosion occurred, however there was substantial erosion in the nearshore.
Immediately northwest of the berm (Figure 5.10, FMB 48), the profile behaved much like the profiles southeast of the berm, with some beach erosion, and the formation of a relatively large bar offshore after Tropical Storm Debby. Further northwest (Figure 5.11, FMB 54), a beach nourishment was constructed during the study period. Tropical Storm Debby caused substantial erosion on the dry beach, and a smaller bar formed offshore. The profile remained largely stable following the passage of Hurricane Isaac. The bar at FMB54 that formed offshore following the storms resembles the small natural bar that existed before the nearshore berm nourishment.

![FMB-5](image)

Figure 5.8. Measured morphology change at FMB 5.

In summary, in the nearshore berm project area, the artificial berm split into two following the passage of Tropical Storm Debby. Following Hurricane Isaac, the two smaller berms remained largely in the same place. Some beach erosion was seen at a few profiles,
however, overall the beach remained largely stable through both storms. In the areas southeast and northwest of the berm, a large bar formed offshore, and some beach erosion occurred.

Figure 5.9. Measured morphology change at FMB 9.

Figure 5.10. Measured morphology change at FMB 48.
5.5.2.2 Swash-zone Berm Nourishment- Perdido Key

Within the swash-zone berm nourishment, response to the storms varied alongshore. In the eastern portion (Figure 5.12 and 5.13, PK-R55.5 and PK-R58.5), the initial width of the nourishment was approximately 70 m. Initial adjustment four months after construction of the nourishment led to the loss of approximately 30 m. A small active berm developed as the nourishment equilibrated. Following the passage of Tropical Storm Debby, more of the nourishment was eroded (approximately 10 m landward retreat of shoreline), and a large storm berm was built, approximately 1 m higher than the nourishment elevation. Following Hurricane Isaac, another 20 m and 25 m landward shoreline retreat occurred at PK-R55.5 and PK-R58.5, respectively, with a small amount of overwash on the dry beach. At these two locations, the beach was still wider than the pre-construction beach. Further east, the profiles behaved quite differently (Figure 5.14, PK-R62.5). In these profiles, Tropical Storm Debby had a much smaller impact (a loss of only 7 m of the nourishment), and no large storm berm was formed.
Hurricane Isaac had a much larger impact, eroding the beach landward of the pre-construction profile (approximately 40 m landward shoreline retreat from the post-Debby profile, which is 7 m landward of the pre-construction profile).

Figure 5.12. Measured morphology change at PK-R55.5.

Figure 5.13. Measured morphology change at PK-R58.5.
Figure 5.14. Measured morphology change at PK-R62.5.

The area to the west of the berm had two distinct patterns of erosion following the passages of the two storms (Figures 5.15 and 5.16). Closest to the swash-zone berm (Figure 5.15, PK-R52.5), the beach did not experience erosion during either of the storms. The small erosion occurred on the berm crest occurred before the passage of the two storms. However, some accretion was measured in the nearshore following initial adjustment of the swash-zone berm nourishment, which remained through Tropical Storm Debby. Hurricane Isaac eroded the sand in the nearshore, and deposited it in the offshore in the form of a bar. In contrast, further away from the nourishment (Figure 5.16, PK-R50), the beach experienced no erosion during Tropical Storm Debby, however some modest erosion occurred during Hurricane Isaac (approximately 8 m). Some sand was also overwashed during Hurricane Isaac, which is evident by the volume gain in the back beach. In the nearshore, sand was eroded during Tropical Storm Debby, and then during Hurricane Isaac, and in both cases, deposited offshore in the form of a bar.
In summary, profiles in the eastern portion of the swash-zone berm experienced a relatively small amount of erosion during Tropical Storm Debby as compared to the large...
amount of erosion seen during Hurricane Isaac. The substantial erosion during Hurricane Isaac caused the profile to shift landward of the pre-construction profile. In the western portion, there was more erosion during Tropical Storm Debby and less erosion during Hurricane Isaac than the eastern portion. Areas far west from the nourishment experienced more erosion than the closer profiles.

5.5.2.3 Beach Nourishment- Sand Key

The nourishment along northern Sand Key began in early June of 2012, just before the passage of Tropical Storm Debby. Figure 5.17 is an example profile (SK-R60) that was nourished just before the passage of Tropical Storm Debby. The nourishment extended the beach approximately 60 m. Following the passage of Tropical Storm Debby, the shoreline retreated landward for approximately 7 m, and a bar roughly 0.5 m high formed 110 m offshore. Minor loss of the nourishment sand occurred after Hurricane Isaac (approximately 5 m shoreline retreat).

SK-R62 (Figure 5.18) is south of SK-R60, and was nourished after the passage of Tropical Storm Debby, but before the passage of Hurricane Isaac. After Tropical Storm Debby, the back beach retreated 10 m, however, some sand was gained just above the MHHW line. Erosion was measured in the nearshore, and the offshore bar gained some sand. Following Hurricane Isaac, the nourishment lost approximately 12 m of beach, and a small but wide bar formed offshore.
SK-R67 (Figure 5.19) was not nourished. At this location, there was a gain of sand on the dry beach, and some erosion in the nearshore following the passage of Tropical Storm Debby. The bar moves onshore following the passages of both storms, 11 m and 12 m for
Tropical Storm Debby and Hurricane Isaac, respectively. Similarly, at SK-R71 (Figure 5.20), which just north of a nourishment profile, the beach actually gained a small amount of sand regardless of the two storms. The offshore bar became much larger than the pre-storm bar following the passage of Tropical Storm Debby. In this particular profile, there was a substantial gain of sand in the nearshore following the passage of Hurricane Isaac.

In summary, nourished profiles lost some sand after both the passage of Tropical Storm Debby and Hurricane Isaac. Following both storms, a relatively large bar formed offshore. The dry beach on non-nourished profiles remained largely stable through Tropical Storm Debby and Hurricane Isaac, while the nearshore of the profile immediately adjacent to the berm gained a substantial amount of sand.

Figure 5.19. Measured morphology change at SK-R67.
5.5.3 Modeling Morphologic Changes and Nearshore Hydrodynamics Using SBEACH

SBEACH was used to propagate the nearshore waves obtained from the CMS-Wave model toward the shoreline, and model morphology change and nearshore hydrodynamics at each study site. Initially, default values were used for various sediment transport parameters in the model (i.e. the transport rate coefficient, overwash transport parameter, and coefficient for slope-dependent term) based on Larson et al. (1990), Rosati et al. (1993), Wise et al., (1996), Larson and Kraus (1998), and Larson et al. (2004). Adjustments were made to the default parameters based on initial model results and recommendations of Rosati et al. (1993) to calibrate the model to each specific transect. It is worth noting that pre-storm surveys were taken weeks to months before the storm passages, and post-storm surveys were taken days to weeks following their passages. Therefore the measured beach-profile changes may not be entirely related to the storms. It is possible that some profile changes occurred during the normal
weather conditions. SBEACH model focuses on storm-induced beach changes. Little to no profile changes are predicted under calm weather conditions (Larson et al., 1990).

5.5.3.1 Nearshore Berm Nourishment- Fort Myers Beach

Figure 5.21 illustrates results from the SBEACH model run for a profile in the berm project area of Fort Myers Beach. Generally, the model over-predicted the amount of erosion on the beach and accretion in the nearshore. The model did re-produce some net offshore sediment transport and the nearshore bar was represented to a certain degree. However, the SBEACH model was unable to accurately predict the “splitting” of the berm into two bars. The modeled maximum water elevation agreed with the highest elevation where morphology changes were measured. Agreement between maximum water level and elevation of beach changes was also measured in large scale laboratory experiments (Roberts et al., 2010). The model predicted maximum water elevations approximately 0.6 m above MHHW water during Tropical Storm Debby, which agrees with field observations. Initial wave breaking over the offshore bar and secondary breaking nearshore the shoreline were represented reasonably by the SBEACH model.

During Hurricane Isaac, beach erosion was well predicted by the model while sediment gain in the trough was over-predicted. The behavior of the two nearshore bars was not accurately predicted (Figure 5.22). Modeled maximum water elevation agrees with the maximum extent of measured morphology change, indicating that SBEACH is capable of capturing the maximum elevation of morphology change. Wave dissipation in the wide surf zone also seems to be represented well. The waves break approximately 200 m offshore, just seaward of the berm crest. Waves re-formed over the trough landward of the berm, and broke once more just
seaward of the foreshore (Figure 5.22). Maximum water elevations during Hurricane Isaac were similar to Tropical Storm Debby at approximately 0.6 m above MHHW.

![Graph showing elevation relative to NAVD88 against distance from monument](image)

Figure 5.21. Modeled morphology change, maximum water elevation with setup, and peak wave height in the berm project area of Fort Myers Beach during Tropical Storm Debby. Arrows indicate locations of breaking waves.

In the control area, the large bar that formed offshore during Tropical Storm Debby was not predicted by the model (Figure 5.23). Beach and nearshore erosion, and deposition in the trough of post-storm profile, was over-predicted. Maximum water elevations were accurately predicted as was wave height decay, based upon the maximum extent of morphology change on the dry beach. The incident waves only broke once before reaching the shoreline, and much closer to the shoreline than in the berm project area. The model predicted waves breaking at the location where the measured offshore bar formed, which may indicate that the wave break point helped create the bar, as many studies on bar formation have shown (Evans, 1940; Keulegan, 1948; King and Williams, 1949; Shepard, 1950). During Hurricane Isaac (Figure 5.24), the model over predicted erosion on the beach and deposition in the trough (post-storm profile), and
smoothed out the bar. Two wave breaking points are modeled during this storm, likely owing to the large bar that remained after Tropical Storm Debby.

Figure 5.22. Modeled morphology change, maximum water elevation with setup, and peak wave height in the berm project area of Fort Myers Beach during Hurricane Isaac. Arrows indicate locations of breaking waves.

Figure 5.23. Modeled morphology change, maximum water elevation with setup, and peak wave height in the control area of Fort Myers Beach during Tropical Storm Debby. Arrow indicates location of breaking waves.
Figure 5.24. Modeled morphology change, maximum water elevation with setup, and peak wave height in the control area of Fort Myers Beach during Hurricane Isaac. Arrows indicate locations of breaking waves.

5.5.3.2 Swash-zone Berm Nourishment- Perdido Key

Figures 5.25 and 5.26 illustrate the modeled changes in the swash-zone berm project area following the passages of Tropical Storm Debby and Hurricane Isaac, respectively. In the case of Tropical Storm Debby, the model rather accurately predicted the large storm berm formed after the storm, as well as the erosion of the dry beach and foreshore. The maximum elevation of morphology change is well captured. However, the model formed a bar offshore which did not occur in the actual measured profile. Hydrodynamic data appear to be accurate in terms of the location of the breaker zone, and maximum extent of the water elevation. During Hurricane Isaac, the model once again fairly accurately predicted erosion of the beach and foreshore. In this case, a bar was measured offshore and was also predicted by the model, however, the model predicted the bar to be much further offshore than it actually was. Wave heights were almost a meter higher during Hurricane Isaac than Tropical Storm Debby, and the water elevation was approximately 0.3 m higher. The model over-predicted the peak elevation of the storm berm.
Figure 5.25. Modeled morphology change, maximum water elevation with setup, and peak wave height in the swash-zone berm nourishment area of Perdido Key during Tropical Storm Debby. Arrow indicates location of breaking waves.

In the control area, the model predicted erosion of the beach reasonably well, however, it under predicted erosion in the trough landward of the bar during Tropical Storm Debby (Figure 5.27). It did create a bar offshore, however it was seaward of the measured bar and a smaller relief. Waves at this location broke approximately 160 m offshore, which was similar to the project area during Tropical Storm Debby. During Hurricane Isaac, the model over predicted erosion on the beach and under predicted erosion in the nearshore (Figure 5.28). While the measured bar did move offshore, the model over predicted the distance the bar moved offshore. Waves during Hurricane Isaac at this location were just over 3 m high, breaking approximately 200 m offshore which is reasonable based on the morphology. Water elevation increased approximately 1 m above MHHW during Hurricane Isaac, while during Tropical Storm Debby it was approximately 0.5 m higher than MHHW.
Figure 5.26. Modeled morphology change, maximum water elevation with setup, and peak wave height in the swash-zone berm nourishment area of Perdido Key during Hurricane Isaac. Arrow indicates location of breaking waves.

Figure 5.27. Modeled morphology change, maximum water elevation with setup, and peak wave height in the control area of Perdido Key during Tropical Storm Debby. Arrow indicates location of breaking waves.
5.5.3.3 Beach Nourishment- Sand Key

For the case of a typical beach nourishment, the model significantly over predicted erosion on the dry beach (Figure 5.29) during Tropical Storm Debby. It created a storm bar, albeit further offshore than the measured bar. It also accurately predicted that there would be some amount of overwash. Similar to previous results, the nearshore hydrodynamics in terms of maximum water elevation and wave-height dissipation seem to be reasonably predicted. Bar formation occurred close to wave breaking location (approximately 150 m offshore). Surge in this case was approximately 1 m above MHHW. During Hurricane Isaac (Figure 5.30), the model predicted dry beach erosion very well, however, it calculated a bar further offshore than the relatively smaller natural bar was created. Again, hydrodynamic data appear to be predicted reasonably, with a slightly smaller surge than Tropical Storm Debby. Wave heights were also much smaller than that during Tropical Storm Debby. This is likely due to the track of the storm making Tropical Storm Debby a stronger storm in Sand Key than Hurricane Isaac was.
In the control area of the project, the model over predicted beach erosion caused by Tropical Storm Debby. It did form a small bar, however, further offshore than the bar that was maintained through the passage of Tropical Storm Debby (Figure 5.31). At this location, there are two breaking points for waves: one just seaward of the bar crest, and one just seaward of the foreshore. Surge is virtually identical to that of the nourished profile. During Hurricane Isaac, beach erosion was over predicted by the model (Figure 5.32). However, bar formation was further offshore than the natural bar. In both the cases of Tropical Storm Debby and Hurricane Isaac, the relatively offshore bar location could be due to the timing of the survey, meaning that there may have been some recovery and onshore movement of the bar before the survey was completed. One breaker zone was located just seaward of the bar at this location during Hurricane Isaac.

![Graph](image-url)

Figure 5.29. Modeled morphology change, maximum water elevation with setup, and peak wave height in the nourishment area of Sand Key during Tropical Storm Debby. Arrow indicates location of breaking waves.
Figure 5.30. Modeled morphology change, maximum water elevation with setup, and peak wave height in the nourishment area of Sand Key during Hurricane Isaac. Arrow indicates location of breaking waves.

Figure 5.31. Modeled morphology change, maximum water elevation with setup, and peak wave height in the control area of Sand Key during Tropical Storm Debby. Arrows indicate locations of breaking waves.
Overall, CMS-Wave accurately propagated the WIS hindcast waves into the nearshore region, as compared to the measured nearshore waves during the storms. The SBEACH model accurately captured the maximum water elevation, consistent with measured upper limit of morphology change. The model correctly predicted trends of beach and nearshore erosion during the storms. However, the magnitudes of the storm-induced erosion were not accurately predicted consistently. The model was not able to predict the “split” of the artificial berm at Fort Myers Beach. Offshore migration or formation of an offshore bar was correctly predicted by the SBEACH model, although the magnitude of the bar and the distance offshore were not correctly predicted consistently. The growth of storm berm, particularly over the low-elevation beach (nourished in this case), was predicted reasonably well by the SBEACH model. Overall, SBEACH model demonstrated a solid ability to predict profile change, in this case nourished profile changes, induced by storms.
5.6 Conclusions

Two nearshore nourishments at Fort Myers Beach and Perdido Key were placed 2009 and 2012. A beach nourishment at Sand Key was placed in 2012. During the summer of 2012, two tropical cyclones impacted the three study areas: Tropical Storm Debby and Hurricane Isaac. A comparison between each type of nourishment response to the storms was illustrated based on time series beach profile surveys. CMS-Wave and SBEACH models were used to simulate nourishment response to the storms. The following conclusions were reached.

- At Fort Myers Beach, Tropical Storm Debby split the berm into two smaller bars, while at Perdido Key a large storm berm of up to 1 m high and 30 m wide was formed. This is different from the morphological response of a typical beach nourishment along the Gulf of Mexico coast, which consisted of erosion of the nourished beach berm and foreshore, and formation of a bar offshore.

- Following calibration of the model using a sensitivity analysis of friction coefficients, CMS-Wave accurately propagated the WIS hindcast waves into the nearshore region, as compared to the measured nearshore waves during the storms. RMSD error on the comparison data was 0.2 m or less.

- SBEACH model accurately captured the maximum water elevation, consistent with measured upper limit of morphology change. The growth of storm berm, particularly over the low-elevation beach (nourished in this case), was predicted reasonably well by the SBEACH model. However, the magnitudes of the storm-induced erosion were not accurately predicted consistently. Offshore migration or formation of an offshore bar was correctly predicted by the SBEACH model, although the magnitude of the bar and the distance offshore were not correctly predicted consistently.
CHAPTER 6
CONCLUSIONS

As part of regional sediment management, it is beneficial to reintroduce the dredged material back into the littoral system, in the form of beach or nearshore nourishments. Nourishment in the nearshore is becoming an increasingly utilized method, particularly for dredged material that contains more fine sediment than the native beach. This research examines the morphologic evolution of two different nearshore nourishments. The first artificial nearshore berm was constructed approximately 200 m offshore of Fort Myers Beach, Florida using maintenance dredged material from Matanzas Pass at the north end of Estero Island. The second nearshore nourishment was placed within the swash-zone along eastern Perdido Key, Florida using maintenance dredged material from nearby Pensacola Pass. The conclusions regarding the morphodynamics of these two nearshore nourishments are reached:

- The bar-shaped nearshore berm at Fort Myers Beach evolved rapidly from a roughly symmetrical bell-shaped bar to a highly asymmetrical shape with a steep landward slope, typical of a landward migrating nearshore bar. The nearshore berm migrated onshore as a discrete morphologic form of a nearshore bar, although with considerable alongshore variations that were maintained throughout the entire study period. The rate of onshore bar migration was much greater during the first year post construction. Furthermore, the rate of migration was greater during the energetic winter than the calmer summer.
• The low elevation of the swash-zone nourishment at Perdido Key allowed overwash processes to occur frequently, which resulted in a net onshore sediment transport and the growth of a natural beach berm up to +2.0 m NAVD88, the elevation of the natural berm crest. Both the nourished and natural beaches are characterized by a steep foreshore that is maintained throughout the entire study period including following the construction of the project, and the passages of two tropical storms.

• Both the Fort Myers Beach nearshore bar-shaped berm and the Perdido Key swash-zone berm did not create a new equilibrium state, rather they evolved back to the natural equilibrium profile shape maintained in the greater study areas. The rare high wave-energy conditions associated with the distant passages of Tropical Storm Debby and Hurricane Isaac in 2012 accelerated the equilibrium process at both locations, instead of deterring and slowing the process. For the lower energy environment at Fort Myers Beach equilibration processes took 4 years, while at the higher energy Perdido Key, the equilibration was reached in 8 months.

• The nearshore berm at Fort Myers Beach led to considerable sand gains on the dry beach in the berm project area and the control area immediately adjacent to the southeast end of the berm. This is likely due to the berm’s function as a nearshore sediment source, as well as its modification of the wave and current fields. Approximately 10% of the 175,000 m$^3$ of sediment placed in the nearshore berm was accounted for by the dry beach gain.

• The sediment volume gain west of the project area at Perdido Key occurred mostly in the trough between the shoreline and the bar. Little to no shoreline accretion associated with
the swash-zone berm nourishment was measured in the western adjacent area during the study period.

- Although the gaps in the nearshore berm at Fort Myers Beach were unintended in the design, they were integral to the hydrodynamics as they allowed circulation of water landward of the berm, as well as access to the beach for recreational boaters. Gaps should be considered in the design of nearshore berms, particularly in shallow placement locations.

- In terms of rate of shoreline retreat at Perdido Key, the short 1.2-km 1985 nourishment performed the poorest with a rate of loss of 40 m/year, despite the very high constructed berm of +3 m NAVD88. The long 7.3 km 1989-1991 nourishment performed the best with a retreat rate of 11 m/year. This suggests that high berm elevation does not lead to better nourishment performance. Instead, alongshore extent of a nourishment project may dominate project performance.

- Fine, mud-sized sediment in the Fort Myers Beach nearshore berm nourishment was transported and deposited offshore. The dry beach maintained the same sediment grain size as compared to the pre-project condition, indicating that the fine sediment in the initial construction of the berm did not impact the beach. No mud-sized sediment was contained in the Perdido Key nourishment.

- At Fort Myers Beach, Tropical Storm Debby split the berm into two smaller bars, while at Perdido Key a large storm berm of up to 1 m high and 30 m wide was formed. This is different from the morphological response of a typical beach nourishment along the Gulf of Mexico coast, which consists of erosion of the nourished beach berm and foreshore, while forming a bar offshore.
CMS-Wave accurately propagated the WIS hindcast waves into the nearshore region, as compared to the measured nearshore waves during the storms. SBEACH model accurately captured the maximum water elevation, consistent with measured upper limit of morphology change. The model correctly predicted trends of beach and nearshore erosion during the storms. The growth of storm berm, particularly over the low-elevation beach (nourished in this case), was predicted reasonably well by the SBEACH model. However, the magnitudes of the storm-induced erosion were not accurately predicted consistently. Offshore migration or formation of an offshore bar was correctly predicted by the SBEACH model, although the magnitude of the bar and the distance offshore were not correctly predicted constantly.
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APPENDIX A

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Katherine E. Brutsché graduated from Virginia Polytechnic Institute and State University in 2007 with a Bachelor of Science degree in Geosciences, dual emphasis in Geology and Earth Science Education. She continued her education at the University of South Florida in Tampa, Florida beginning in 2009. There she received a Master of Science degree in Coastal Geology under the advisement of Dr. Ping Wang in 2011. Her thesis was titled *First Year Sedimentological Characteristics and Morphological Evolution of an Artificial Berm at Fort Myers Beach, Florida.* She has written and co-written several technical notes and technical reports for the U.S. Army Corps of Engineers, and has presented her research at several different national conferences. In addition to her own research, Katherine has been involved in many research projects within the Coastal Research Lab at the University of South Florida including physical monitoring of Pinellas County Beaches, the Deepwater Horizon Oil Spill, and studies regarding sand bar formation and morphodynamics before, during, and after a storm. She is actively involved with the American Shore and Beach Preservation Association (ASBPA), having served both on the Science and Technology Committee as well as the Student Involvement Committee. At Virginia Polytechnic Institute and State University, Katherine was the recipient of the 2007 Outstanding Service Recognition Award. In 2010, she received the ASBPA Student Educational Award. The following year, she received the ASBPA Nicholas Kraus Coastal Scholar Award. She was also the recipient of the 2014 University of South Florida School of Geosciences Richard A. Davis, Jr. Endowed Fellowship in Geology.