SAND BAR BEHAVIOR: OBSERVATIONS AND MODELING

By

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A DISSERTATION PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

UNIVERSITY OF FLORIDA

2012

To my mom, dad, grandmother and sister

ACKNOWLEDGMENTS

I would like to thank Capes and Fulbright for providing the scholarship that allowed me to come to UF to pursue my PhD. Also the committee members that are taking their time to read, criticize and give suggestions to improve the quality of this dissertation.

All the friends (Andy, Berkay, Chloe, Cihan, Leslie, Miao, Shih-Feng,Tianyi, Uriah and other coastal fellows) that shared their culture, experience and knowledge and made these four years in Gainesville more interesting. To Amy, for her help, incentive and good friendship during this difficult journey pursuing the PhD.

Special acknowledgement to my adviser, Dr. Robert Dean, who was always available to help me with all my questions regarding the dissertation (and there were many) and valuable suggestions and guidance. He has also been a great inspiration as a person, for his great character and passion for coastal engineering. I hope that I was able to assimilate at least 1 % of his qualities during this period that I was his student.

Um outro agradecimento especial para minha família (Mãe, Pai, Vó e Lela) que sempre me apoia em todos os momentos (a maior parte de alegria) e incentiva nesta minha vida de estudante profissional. Sem vocês, com certeza, isto não seria possível.

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FDEP	Florida Department of Environmental Protection
LIDAR	Light Detection and Ranging
MHW	Mean High Water
NDBC	National Data Buoy Center
NOAA	National Oceanic and Atmospheric Administration

Abstract of Dissertation Presented to the Graduate School
of the University of Florida in Partial Fulfillment of the
Requirements for the Degree of Doctor of Philosophy

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August 2012

Chair: Robert G. Dean
Major: Coastal and Oceanographic Engineering

The relation between the number of sand bars in the nearshore zone and the forcing wave conditions was evaluated using observations and numerical modeling at Walton and Volusia Counties, in the State of Florida. The decadal behavior of the number of bars was well represented using a simple quantitative model that correlates the wave forcing and number of bars. The Dean and Profile non-dimensional parameters, used to determine the number of bars in equilibrium with the wave forcing, presented the best correlation between model and observations, indicating that wave and sediment characteristics are important to predict the number of bars in the nearshore zone. The model succeeded in representing the rapid increase in the number of bars during major storms or hurricanes and the slower decrease in number of bars during calm periods.

The breakpoint theory used in the short term model captured the relationship between the inner and outer bars, where the outer bar tends to be more linear, since only high waves are able to effectively transport sediments into greater depths. The inner bar morphology is more three dimensional where alongshore differences are more evident. The offshore migration or increase in the outer bar depth was observed to be

the trigger for the inner bar formation. The short term model represented the number of sand bars when the surveys were conducted close to periods of high energy when the sand bars were formed or migrated to the position and depth according to the wave forcing that generated the system with multiple bars. It was also observed that the inner and outer bars are interconnected systems with multiple bars and the study of this system has to be conducted including all bars at the same time.

CHAPTER 1
INTRODUCTION

Sediment transport inside the nearshore zone is highly dynamic where morphological features and hydrodynamics are intimately associated. Prominent morphological features encountered on sandy beaches are the shoreline, berm and bars. The shoreline is usually the main feature in which coastal managers, stakeholders and the general public are interested. The principal reason for this special interest is that several states and countries have a significant part of their economy directly or indirectly related to the use of this area and shoreline changes, especially associated with beach erosion, can cause significant financial losses.

Travel and tourism in the United States is the single national largest industry, employer and foreign-revenue earner and U.S. beaches are the leading tourist destination (Houston, 1996). Gable (1997) argued that tourism is the most important source of external revenue in the Caribbean and that all tourism developments were located in the coastal zone. This is not just observed in the USA and Caribbean Islands, but it is a worldwide phenomenon and several other examples for different countries could be shown here.

Miami Beach, in the State of Florida, is a good example where as a result of severe beach erosion and virtually no beach by the mid 1970's, the waves were breaking on coastal structures. Consequently, visitor numbers declined and the facilities had deteriorated. Following beach nourishment and infrastructure improvements in the late 1970's Miami Beach was rejuvenated to such an extent that current annual revenue from foreign tourists alone is $2.4 billion, about 50 times the $52 million cost of the 20 year project. Miami Beach has more than twice (21 million) the combined number of

tourist visits to Yellowstone (2.6 million), the Grand Canyon (4 million) and Yosemite (3.3 million) National Parks combined (Houston, 2002). Clearly beaches are vital to tourism-based economies and careful attention has to be directed to these areas to reduce or avoid problems associated with beach erosion.

Nearshore zones are also important for marine and coastal organisms, e.g. turtles have their nests at beaches and migratory birds use these areas to rest and to obtain their food. The preservation of this habitat is fundamental for the sustainability of the entire ecosystem.

Comprehension of beach dynamics requires monitoring of its natural morphological changes through time, according to different forcing time scales. Certain knowledge of the natural behavior of every beach type can be obtained by means of a field monitoring program long enough for the beach to attain different energetic states and in which their efficiency in protection can be comprehended (Benavente et al., 2002). Understanding the processes governing this system is fundamental to maintaining it attractive to visitors, to diminish the costs associated with coastal management programs and construction of structures or beach nourishment projects to protect landward sites and restore recreational areas.

Shoreline and sand bar behaviors are interconnected responding to the changes in waves, tides and currents. Sand bars strongly influence the cross-shore hydrodynamics and consequently the sediment transport in the nearshore zone. The sand bar behavior inside the nearshore zone, their characteristics, the interaction between inner and outer bars and their response to wave conditions in different time scales are the main focus of this dissertation.

CHAPTER 2
LITERATURE REVIEW

It is well known that sediments are transported offshore during conditions of high energy, through wave driven circulation and this sediment migrates onshore during periods of mild energy, forming the winter/storm and summer/normal profiles.

Torrey Pines Beach, California, is one of several examples of this behavior. The beach undergoes typical seasonal changes in configuration owing to changes in wave climate. During summer wave conditions the beach has a 30 to 60 m wide backshore, a relatively steep foreshore and a pronounced berm. Winter storm waves overtop the summer berm and erode the backshore, thus reducing the exposed beach width. The winter beach is typified by a gently sloping beach face that in places extend shoreward to the toe of the sea cliff (Winant et al., 1975). Another example is Duck, North Carolina, one of the most studied beaches in the world, where this cycle was observed to repeat through many years. Longshore uniform sand bars approximately parallel to the shoreline with little bathymetric changes were observed at Duck after an energetic period between August 25th and October 12th, 1994 (Gallagher et al., 1998).

Dynamically equilibrated coasts with a balance between onshore and offshore sediment migration and predominately cross-shore transport have minimal sediment lost and this cycle can repeat over long periods of time. Problems arise when the sediment transport is not balanced usually with gradients of alongshore or offshore sediment transport and resulting in beach erosion.

2.1 Beach Erosion

The main agents responsible for sediment imbalance are commonly considered as natural or anthropogenic causes. Natural causes are frequently associated with sea

level rise, influencing worldwide beaches on a global scale and on the local scale the natural migration of inlets can cause erosion on adjacent beaches. Anthropogenic causes include the construction of structures perpendicular to the coast (e.g. groins and jetties), parallel to the coast (e.g. seawalls), on top of the dune systems or during periods where the shoreline was advanced. Dam construction reduces the amount of sediment available from rivers to the coast. The High Aswan Dam, built in 1964 in Egypt, diminished the Nile River sediment discharge to near zero and initiated severe beach erosion near the Damietta and Rosetta outlets (Frihy and Dewidar, 2003). Meckel (1975) reported that dams at the Colorado River trapped most of the sediments that otherwise would have been available for delta construction and sediment transport at the coast. Anthropogenic influences usually reduce the amount of sediment available to the coastline and diminish the natural seasonal cycle, creating areas with scarce amounts of sediment and consequently erosion.

Natural causes related to inlet natural migration are of reduced importance presently, since many inlets are fixed for navigational purposes. An example is observed in the State of Florida, where many inlets are fixed for navigation. However, this action results in erosion downdrift and deposition updrift of the inlets, since part of the longshore sediment transport is blocked by the jetties. Davis and Barnard (2003) demonstrated that proximity to inlets can affect shoreline trend rates for several kilometers downdrift of inlets.

2.2 Equilibrium Beach Profile

One of the first attempts to understand the cross-shore behavior of coastal zones was to predict the general beach cross-shore configuration, since a wide range of

morphologic features were observed during beach surveys, and it appears that different agents are acting on the beach to create them.

Bruun (1954) defined an equilibrium beach profile as the statistical average profile which maintains its form apart from smaller fluctuations including seasonal fluctuations. The theory used to develop this concept is based on constructive and destructive forces that can balance on beaches exposed to same, or more realistically, similar hydrodynamic conditions for long periods. After the balance, different sediment sizes are moved to different portions of the beach, where they are in equilibrium according to the balance between constructive and destructive forces. The application can be extended when analyzing long term trends of sea level. Future scenarios with different sea levels can be predicted using this method, since it is based on the average equilibrium forces at the beach and these forces can be estimated by numerical models. Coarser sediments are generally found in shallower areas, since they are exposed to higher energy and there is a decrease in sediment size in deeper zones, where the wave energy is reduced (Charles et al., 1994; Wang et al., 1998).

Different sediment sizes and wave conditions were evaluated to determine their importance in shaping the sea bed. The equilibrium beach profile was created combining these conditions and developing a general equation to represent the cross-shore beach profile. The equilibrium beach profile that relates sediment size with distance from the shore using the 2/3 power, was verified with good agreement in beach profiles at Denmark and USA (Bruun, 1954 and Dean, 1977).

Application of the equilibrium beach profile to ten beaches in New Zealand with arbitrary cross-shore sediment size suggests that the theory is effective to some degree

in reflecting profile characteristics due to sediment size variations (Dean et al., 1993). This function predicts the general beach profile shape, required as a requisite using the statistical definition, however the main restriction of its application, when compared to field data, is that it is not capable of predicting sand bars or troughs (Dean and Dalrymple, 2002).

To include the presence of sand bars in the equilibrium beach profile, Inman et al. (1993) divided the beach profile in two segments using the breakpoint to distinguish the onshore and offshore areas. For each segment they proposed a similar function described above and the best fit was found using a 0.4 power, instead of 2/3. However this method can predict only profiles with one bar and a total of seven parameters is necessary to describe the profile. Profiles with more than one bar still couldn't be predicted using this approach and applicability for engineering or scientific purposes is limited due to the large amount of parameters.

2.3 Differences Between Winter and Summer Profiles

Winter and summer profiles present remarkable differences in their configuration, morphology and time response to wave forcing.

The time scales for the creation of winter and summer profiles are considerably different. In the first case, offshore sediment transport and sand bar creation occurs in a time scale of hours. During hurricanes, or events with large wave heights, beach erosion, offshore sand migration and sand bar formation occurs in few hours.

During extreme events, say a 100 or 500 years storm, the sediments can migrate offshore to locations deeper than the depth of closure, to regions where the net cross-shore sediment transport is weak, and these sediments may not return to the more active beach. Kennedy et al. (2010) verified infilling of seventeen borrow pits in the east

and west coast of Florida, during the 2004-2005 hurricane season, only one of which was considered to be landward of the depth of closure. Borrow pit depths are greater than adjacent areas and the forces acting to remove sediments from them are very weak, creating permanent sediment deposits if the sand enters the borrow pits, and consequently sediment deficit at the beach. Therefore, most of the sediment infilling was the result of sediment transport from outside the depth of closure. Careful analysis is important when selecting borrow area locations for beach nourishment, otherwise beach nourishment longevity can be shorter than predicted since part of the placed material can return to the borrow area during high energy events through cross-shore sediment transport.

Onshore sediment transport occurs over a considerably longer time scale than offshore transport and long periods without significant increases in wave height are required for sediments to migrate shoreward. Sunamura and Takeda (1984) presented one of the first attempts to quantify onshore migration of sand bars using two dimensionless quantities based on the offshore wave height, wave period and sediment size. Sand bars onshore migration rate of 3.5 m/day were observed in Tairua Beach, New Zealand, during four days of observations. The rate was slightly higher since it occurred mainly during periods with low tide, when the water level above the bar were smaller than 0.25 m. Most of the material transported was by bedload transport, since the waves were low and the sediment median diameter is 0.6 mm (van Maanen et al., 2008).

Other than the differences in response time between winter and summer profiles, there is a remarkable difference in the nearshore morphology. In winter profiles,

sediments migrate to a specific depth in the beach profile, associated with the breakpoint and create linear sand bars, with approximately two dimensional morphologies.

In the summer profile, offshore bar characteristics are more variable and alongshore differences become more evident, where bars and beaches show more three dimensional features. Longshore discontinuities of two to three km lengths in bar position exist in the Dutch North Sea Coast, which are caused by the crescentic bar morphology (Stive et al., 1996). Bar splitting, which involves a longshore bar developing a forked or bifurcated appearance, was observed at Wanganui, New Zealand. After bifurcating, the seaward segment that is considered the main bar segment migrates farther offshore while the inner segment moves into the landward trough and completely detaches from the original bar (Shand, 2007). Other three dimensional morphologies are transverse bars, formed when horn areas associated with rhythmic morphology weld onto the beach with a capability to transfer sediments onshore when they detach from the inner bar and realign in the longshore current direction (Konichi and Holman, 2000). These features have an extensive variety of length scales, in the west coast of Florida (Franklin County) with average breaker height of 6 cm, their spacing may vary between 64 to 218 m and cross-shore lengths between 107 and 640 m (Niedoroda and Tanner, 1970).

A geomorphologic review of intertidal and subtidal bars distinguishing seven nearshore types, providing horizontal and vertical scales is presented by Wijnberg and Kroon (2002). These different signatures are associated with differences in wave energy, nearshore slope and tidal range.

Cross-shore migration rates can vary in the longshore direction with waves focusing or diverging, creating complex morphologies and erosional hot spots can be generated at the shoreline (Ribas et al., 2003). Rip currents and beach cusps are morphodynamic beach characteristics often associated with mild wave conditions. Rip currents are narrow seaward-directed jets oriented approximately shore-normal, that originate in the surf zone and broaden outside the breaking region, forming the rip head. A review of rip currents is presented by MacMahan et al. (2006), where theories of formation, comparisons between model and observed values, scaling and flow structures are described. Two features that are interesting to emphasize is that the spacing between rip currents is the order of 100 m and they can achieve velocities greater than 2 m/s, being a constant hazard at the beach. In the State of Florida more people fall victim to rip currents than hurricanes and tornadoes (Lascody, 1998). Beach cusps are crescentic morphological features with regular longshore shapes characterized by seaward protruding features (horns) and gently sloped landward embayments located between two horns. In Melbourne Beach, Florida east coast, the cusps wavelengths varied between 25 m and 45 m (van Gaalen et al., 2011).

The cycle of rapid offshore bar migration and slow onshore movement are observed in places continuously monitored over periods usually greater than one year. If the system is dynamically stable, without cross-shore or longshore sediment transport losses, the sand bars migrate inside the nearshore zone and no shoreline erosion is evident over long periods of time.

2.4 Conceptual Models

Morphodynamic studies of the nearshore zone started with conceptual models classifying different beaches or the same beaches during different periods of the year.

Their main aim is to group beaches with similar morphological features (based on the nearshore plan view) and hydrodynamic forcing to facilitate understanding of nearshore morphodynamics. These classifications are useful for coastal planners, engineers and scientists to quickly identify systems under investigations and initial plans can be developed based on them. However, coastal zones are highly dynamic and it is important to emphasize that these classifications are generalizations and site specific modifications are expected for different coasts. Conceptual models mostly used in the literature to classify beaches are described below.

Wright and Short (1984) developed a model based on observations at 26 beaches in Australia that evolved forming similar features. Their model used the non-dimensional parameter developed by Dean (1973) where the breaking wave height (H_b), wave period (T) and sediment fall velocity (ω_s) were correlated according to Equation 2-1.

$$D = \frac{H_b}{\omega_s T} \qquad (2-1)$$

The model presents six stages changing from the most reflective stage ($D < 1$) through 4 intermediate stages ($1 < D < 6$) to the most dissipative stage ($D > 6$). A general decrease in the mean sediment diameter and beach slope occurs going from reflective to dissipative stages. The relation between an increase in sediment size and an increase in beach face slope was previously observed by Wiegel (1950) and Bascom (1951) with data from different beaches in USA. Other than the grain size, the degree of beach exposure to incident waves affect the beach slope, in which less exposed beaches have steeper slope for a given median grain size, since more onshore sediment transport occurs in this condition.

Nearshore zones with more three dimensional shapes are expected during intermediate stages. These features occur when alongshore differences, rhythmic or irregular become more evident. Rip currents are often observed during intermediate stages cutting the sand bars and increasing alongshore heterogeneities.

Two dimensional features are evident in more dissipative stages that are characterized by bars which are linear, continuous and relatively parallel to the coast. In the reflective stage, nearshore zones without sand bars are expected, where a common morphologic feature is the presence of beach cups.

This conceptual model was developed using traditional beach survey methods and visual observations. The traditional survey methods consist of the use of level and rod and later substituted by global positioning systems (GPS) surveys. Both allow nearly instantaneous beach characterization, usually not during highly energetic conditions, since large wave heights may not allow beach surveys to be conducted. The use of video cameras to monitor nearshore zones introduced a continuous remote tool to monitor the nearshore zone.

Lippmann and Holman (1990) analyzed data derived from video cameras installed at Duck and observed similar behavior as Wright and Short. They developed another conceptual model with eight stages based on the earlier model proposed by Wright and Short (1984) and subdivided two intermediate stages, creating one classification more appropriate to Duck.

Both morphodynamic models described above were developed on microtidal beaches, where waves were the main hydrodynamic forcing, however tide effects are evident in a large portion of coastlines in all latitudes and continents. Davies (1964)

proposed a classification according to the tide amplitude, where tidal ranges smaller than 2 m are considered microtides, between 2 and 4 m are mesotides and greater than 4 m are macrotides.

Short (1991), reviewed the literature on these environments and pointed out the differences between microtidal and meso-macrotidal regions. Masselink and Short (1993) proposed another conceptual model including the tide hydrodynamic effects, using the Dean number and the relative tidal range (that consists of the tidal range divided by H_b). This model is not discussed in detail since the areas studied in this dissertation are on the Florida coastline and influenced by microtides, however it is important to keep in mind that the major influence of the tide is to change the breakpoint position and intensity throughout a cycle, extending breaking processes effects to wider areas inside the nearshore zone.

These conceptual models were based only on beaches with one offshore bar in the nearshore zones and multiple sand bars were not considered in the models. Other conceptual models including the presence of multiple bars are discussed in the next section.

2.4.1 Conceptual Model for Systems with Multiple Sand Bars

Nearshore zones with more than one sand bar are common in many places in the world, however few studies are dedicated to these zones, and understanding their behavior is essential for coastal management and application of correct solutions to mitigate coastal problems. A conceptual study at the long barrier island of Terschelling in the Netherlands observed nearshore bar behavior over a time scale of years and concluded that typically a bar goes through three different stages during its life cycle (Ruessink and Terwindt, 2000). Generation in the inner nearshore zone in shallow

waters, offshore migration through the surf zone to intermediate depths and finishing the cycle decaying in the outer nearshore zone. The offshore bar migration allows higher waves to reach the inner bar, since the same wave heights can break farther inshore. During this process a new bar is created near the shore with relatively fast offshore migration rate, separating from the shoreline, indicating that the trigger of a new cycle is the outer bar offshore migration and decay.

The outer bar may act as an energy filter to the inner nearshore zone, determining the local wave conditions at the shoreward located bar. Waves with large heights dissipate part of their energy by breaking on the outer sand bars and smaller waves break after passing the bar. The sheltering process shows that the morphodynamic behavior inside the nearshore zone in systems with multiple bars is interconnected. Segregating the studies focusing only on one bar and not on the entire system can result in inappropriate interpretations.

2.4.2 Field Observations of the Conceptual Model with Multiple Bars

Some locations where the cycle of sand bar formation, offshore migration and decay was observed using frequent and consecutive surveys are described in the following paragraphs.

Pape et al. (2010) observed this cycle at the Gold Coast (Australia) and Egmond (Netherlands) with periods of 5 and 15 years, respectively. Similarly, at Wanganui (New Zealand) a system with usually two subtidal bars experienced net offshore migration with the mean life-cycle of approximately three years (Shand et al., 1999). Kuriyama (2002) described the same cycle at Horns (Japan), however the cycle is even faster at this location, being completed in only one year.

Nearshore slope differences is one explanation to changes in the bar cycle period. Longer cycles are expected on mildly sloping beaches, since the bar travels greater distances in the nearshore zone until the breaking waves stop influencing their mobility. Other than the trajectory length, Shand et al. (1999) suggested that mildly sloping beaches tend to be more exposed to high waves, which would generate higher bars, with large volumes, that require long time for seaward migration.

The comparison between Hasaki (nearshore slope of 0.008) and results from the Netherlands (nearshore slope between 0.004 and 0.008) confirm the mild slope hypothesis, since the cycle in Hasaki is shorter than in the Netherlands. However, according to the nearshore slope, the duration time at Hasaki should be longer than those at Duck (0.0097) and Wanganui (0.0088) and the opposite is happening. This result indicates that although the nearshore slope influences the duration time, it is not enough to fully explain these differences. Longshore currents were suggested as another agent contributing to changes in the duration time (Kuriyama, 2002), however uncertainties still remain about all agents influencing the cycle duration.

Inner and outer bars can present different behaviors in time and space in systems with multiple bars. Ruessink and Terwindt (2000) proposed that the inner bar is more stable than the outer bar, since the most energetic waves are breaking and dissipating their energy on the outer bar, and only part of the energy is reaching the inner bars. However the opposite behavior was observed at Gold Coast, where the inner bar is more dynamic than the outer bar. It was also observed that the cycle duration can change in the same location. At Duck, it was observed that one bar stayed in the outer

bar phase for seven years and the other bars spent only two years in the same outer bar phase (Plant et al., 1999).

Those conclusions illustrate the complexity of nearshore zones, especially when composed of multiple bars. Conclusive answers for the explanation of the cycle duration and inner and outer bar behavior are still under investigation, but it is clear that several variables are acting on the system and that these variables often have their effects superimposed and/or interconnected, creating a challenge to full comprehension of this zone. Small changes in morphology can quickly grow when currents, waves and sediment strongly interact, like in the nearshore zone of sandy beaches.

2.4.3 Conceptual Models Application for Coastal Management

Morphodynamic conceptual models provide a description of the qualitative beach morphology and hydrodynamic forcing associated with generating different plan forms. However their main focus is not in quantifying the processes associated with the bars formation or shoreline changes, being restricted to qualitative analysis or their combination with quantitative methodologies.

Benedet et al. (2004) applied the Wright and Short (1984) model to the east coast of Florida and classified it in terms of four susceptibility ratings (extreme, high, moderate and low). However some modifications were necessary to account for the perched nature of Floridian morphotypes on reefs, the impacts of morphodynamic feedbacks from sediment starvation, hardground exposure and bimodal nature of beach sediment grain-size distribution. Benavente et al. (2002) used average seasonal values of the Dean Number, Surf Similarity and Surf Scaling Parameters (the last two are described later on (section 2.5.1) to construct a susceptibility matrix for the SW coast of Spain and indicated that it is a useful initial tool in coastal hazard studies related to storms. They

also concluded that seasonal beaches, characterized by an alternation between two or more stages through the year are more resistant to storms than uniform unchanging beaches, where beach seasonality appears to be a key variable in the severity of coastal damage by storms.

Physical processes acting inside the nearshore zone must be qualitatively and quantitatively evaluated to fulfill the limitations described by the conceptual models and achieve better results in the prediction of nearshore processes.

2.5 Breaking Characteristics

The most important processes modulating beach bathymetry is the sediment transport caused by the breaking waves. Morphologic features with different spatial scales can be formed during this process.

The wave height inside the nearshore zone, maximum wave height and position where the waves start to break are often important parameters to be determined for coastal and shore protection structures or coastal management plans for specific locations. These values are not only related to the wave characteristics (wave height and period) but also to the profile bathymetry. Therefore, changes in beach slope, sediment size, morphologic features and sand bars presence (including quantity in the cross-shore profile) or absence alter the breaking point location and the wave height decay inside the nearshore zone.

In some situations the waves might not break and reflect offshore, due to a combination of different factors. The main reason is when seawalls are constructed and the beach is eroded to them, so the waves approaching the shore reach the seawalls directly and are mostly reflected offshore. Additional scour during storms decreasing the sediment amount is observed in front of seawalls (Dean, 1986). On beaches without

structures, more wave reflection occurs on reflective beaches, where the beach slope is steep due to the coarse sediments.

Sediment concentrations and sediment availability to be transported by suspended or bedload inside the nearshore zone are directly influenced by breaking processes. Understanding this process is fundamental to predicting the locations where sediments tend to accumulate/spread inside the nearshore zone and associated position where sand bars/troughs are expected to be formed. Breaking characteristics also affect the shoreline position, since both are directly related to the cross-shore sediment transport and differences in breaking characteristics cause onshore or offshore transport building or eroding the beach.

2.5.1 Wave Breaking Types

Distinct wave breaking types are observed in different beaches or in the same beach but during different periods in the year. It is noticed that some places have waves breaking in wide zones and at other beaches the waves break in a narrow zone with their impact being restricted to a specific location. It is also evident that these waves change their sinusoidal shape approaching the breakpoint and differences in shape and amount of turbulence produced is variable during breaking and broken waves.

In order to differentiate these breaking processes and classify the waves according to their main characteristics, breakers have been organized as spilling, plunging and surging breakers. A brief description of these types provided by Wiegel (1964) is presented below:

Spilling breakers are characterized by the appearance of “white water” at the crest and a gradual break across the nearshore zone. Plunging breakers curl over the top of

the crest and this mass of water plunges down when the crest front becomes steep and then concave. Surging breakers peak up as if to break in the manner of plunging breaker, but then the wave base surges up the beach face with the resultant disappearance of the collapsing wave crest (Wiegel, 1964). Collapsing breakers are sometimes distinguished as a fourth group and their characteristics are between plunging and surging.

Important criteria to differentiate breaker groups are beach slope and wave steepness. Iversen (1952) analyzing waves with different offshore steepness concluded that at large values of deep water wave steepness, the breakers on all beach slopes were spilling. At smaller values of deep water steepness the waves tend to plunge with greater tendencies on beaches with steeper slopes. At the extreme lower values, the breakers tended to surge.

Battjes (1974) combined the beach slope and offshore wave steepness effects to create the Surf Similarity Parameter. This parameter quantitatively distinguishes the four breaker types qualitatively described previously. The Surf Scaling Parameter (Guza and Inman, 1975) is related to the Surf Similarity Parameter, where the same variables were used when it was developed.

2.5.2 Beach Slope and Breaking Point

Offshore waves propagating towards the shore start to shoal in the nearshore zone due to the bathymetry, increasing their height until the point that they become unstable. At this point there is a transition from irrotational to rotational motion and the waves break.

Beach profile relevance to the breaking process was first observed by McCowan (1891), using solitary wave theory, who found that waves would break when the ratio

between wave height and water depth (H/h) exceeds the critical value of 0.78. This value was observed later to vary according to the beach slope. Iversen (1952) used a wave channel changing the beach slope from 1:10 to 1:50 and a rigid bottom and observed that steep beach profiles have larger critical values than mild profiles. Weggel (1972) analyzing data from wave tanks with regular, monochromatic and progressive waves also observed that this ratio is greater on steep beaches and the breaking characteristics changes to more plunging breakers. It is expected, by this observation, waves breaking closer to the shoreline in reflective beaches, while waves with similar characteristics break farther offshore in more dissipative stages, only considering plane beaches. A schematic representation of the breaking point position in relation to changes in the beach slope is presented on Figure 2-1.

Other than the location where waves start to break, the beach slope influences the ratio between offshore wave height and the wave height at the breaking point. Iversen (1952) using a laboratory wave channel with different plane sloping bottoms observed that breakers on the 1:10 slope are approximately 40 % higher than those in the 1:50 slope. He reported that these relatively steep slopes may have produced excessive reflection, particularly for longer waves and consequently measured erroneous wave heights.

Wave steepness also changes the breakpoint position, where an increase in wave steepness increases the critical value (0.78) and waves break more onshore. Stive (1984) conducted an experiment with two different wave steepnesses in a wave flume using periodic waves with minimum second harmonic on a plane concrete slope of 1:40 and observed that increasing the offshore wave steepness (from 0.01 to 0.032) the

breakpoint moved approximately three meters onshore (wave flume total length is 55 m). Komar and Gaughan (1972) used laboratory and field data to develop a relationship between wave steepness and the ratio between the breaking wave height and offshore wave height based on Airy wave theory.

An effort to categorize beach profiles between winter and summer, according to the wave steepness using laboratory measurements has indicated that the wave steepness transition between summer and winter profiles is approximately 0.025, whereas smaller value results from large scale tests. For sustained wave steepness conditions greater than this value, a storm beach profile occurs and for sustained wave steepnesses below this value, a normal profile occurs (Dean, 1973). The relationships developed between waves and beach slope contributed to distinguish beach profiles using only offshore wave conditions.

2.5.3 Cross-Shore Transport Associated with Different Break Types

Dyhr-Nielsen and Sorensen (1970) described qualitatively the breakpoint bar model as a combination of undertow, due to radiation stress arguments, transporting mobilized sand offshore within the surf zone and converging with sand transported onshore due to the skewness of nonlinear waves just outside the surf zone to form a bar near the wave breaking point. The shape stabilizes when the slope gets so steep that the bottom current cannot transport the sand up over it, or when there is equilibrium between the amount of sand carried up by the bottom current and the sand returned in suspension at higher levels.

Large changes in concentration occur over times shorter than a wave period and at spatial scales shorter than a wavelength (Gallagher et al., 1998), and different types of breaking waves have the capacity to suspend variable amounts of sediments.

Therefore, sediment suspension observed in the surf zone is spatially and temporally intermittent and breaking characteristics are important for further sediment transport processes.

The heuristic model developed by Dean (1973) assumes that breaking waves suspend the sediments in the water column. If the time required for the sediments to settle to the bottom is greater than half of the wave period, the sediments are deposited offshore since the average water velocity is directed offshore. If it is smaller than half of the wave period the net transport is onshore since the particles are predominantly influenced by onshore velocities.

The breaking waves associated with those profiles govern the sediment transport inside the surf zone. Spilling waves, usually associated with mild beach slopes and wide surf zones, start to dissipate their energy farther offshore than the plunging breakers. The turbulence generated by these different breaking processes causes differences in the suspended sediment concentration, since it is proportional to the turbulence intensity in the surf zone. Ting and Kirby (1994) observed that during spilling waves the sediments suspended by the breaking waves have large turbulence decay time and only a small portion of the energy is dissipated over one wave period. When the next wave approaches the same position, the sediments are still suspended and have an offshore orbital velocity component, moving offshore and creating erosional profiles with one or more sand bars. Plunging waves, on the other hand, are associated with steep beach profiles and the waves do not dissipate their energy throughout the surf zone. They approach the shore and break in a specific location and create highly turbulent zones, however, turbulence decay occurs over a relatively short time. The sediments

stay in suspension for a short period and when the following wave approaches the same location the sediments are already deposited onshore. In summary, plunging waves are breaking processes that contribute to build back the profiles during periods with mild energy and spilling breakers act to transport sediment offshore.

Differences in the wave shape influence the current characteristics inside the nearshore zone. The waves approaching the shore change from sinusoidal to more peaked with shallow trough shapes, becoming more asymmetric inside the nearshore zone. The effects of varying wave asymmetries is that for small wave asymmetries, the longshore current profile is displaced substantially landward from the current generated without rollers and the longshore current on the bar trough increases (Lippmann et al., 1995). However the effects of longshore currents are not the main focus of the current research.

2.6 Influence of Beach Profile on Wave Setup

Cross-shore bathymetric effects on wave setup are a focus of investigation since it is desired to predict the water level, mainly during highly energetic events, to determine areas that might be affected during floods and quantify the risks during these events. Low areas, e.g. Florida, are especially concerned about changes in the water level, since small variations can inundate extensive areas and cause severe financial damages. Different slopes and presence of absence of bars cause changes in the wave setup at the coast. Stephens et al. (2011) observed through numerical simulations of artificial barred beaches with different shapes that when the bar is deep, substantial wave energy can propagate inshore and dissipate on the beachface, and vice versa when the bar is shallow. Furthermore, a mean water level generated over barred profiles with steep slope offshore of the bar is greater than over that with gentle slope in

the same zone because the wave energy is dissipated more rapidly, producing a faster rate of change in radiation stress. A comparison between the offshore bar slope and the beach face slope is also relevant. Beachface slope becomes more influential at places where the offshore bar slope has lower gradients than beachface slope. It occurs because the water level relatively increases as the bar deepens. Raubenheimer et al. (2001) obtained similar conclusions using numerical modeling and observations at Duck, suggesting that setup near the shoreline depends on the entire surf zone bathymetry and increases with decreasing surf zone beach slope. The sand bar depth can influence the wave setup, where shallow bar crests favor higher setups since there is a decrease in the radiation stress and the setup gradient increases.

2.7 Sand Bar Formation Theories

Two major theories of bar formation are often discussed in the literature. The first theory associates bar formation with infragravity waves and the second assumes wave breaking as the responsible mechanism for bar formation. The common point between these two theories is that incident waves alter the flow field and consequently the bed morphology. However, there are several differences between those theories and it was observed that infragravity waves play a secondary role in the formation of sand bars.

In the infragravity wave theory, it is suggested that the sediments migrate from the nodes towards the anti-nodes, since the orbital velocity below the nodes scour the sediments and they deposit below anti-nodes (Short, 1975; Holman and Bowen, 1984). Secondary importance of infragravity waves to cross-shore sediment transport were noted by Aagaard et al. (2002) where they excluded their influence assuming only the effects of incident waves and mean currents to the sediment fluxes.

The second theory is that bar formation is a result of sediment convergence at the wave breakpoint. Seaward of the breakpoint, sediment moves onshore due to orbital asymmetries induced by the incident waves; shoreward of the breakpoint, sediment is transported offshore due to offshore-directed mean currents (undertow) generated by breaking.

Undertow velocities depend upon local cross-shore radiation stress gradients and scale inversely with local water depth (Svendsen, 1984). Undertow velocities are expected to be larger over steep beaches than on gently sloping beaches (Longuet–Higgins, 1983). The wave breaking intensification on bars during storms causes a maximum in the undertow just shoreward of the bar crest (Gallagher et al., 1998). Similarly, Thornton et al. (1996) analyzing data at Duck during the DELILAH experiment in 1990, observed that the undertow is a maximum over the bar crest and a minimum in the trough.

Aagaard et al. (2002) proposed a model that predicts onshore-directed sediment transport for large bed shear stresses in relatively deep water occurring on gently sloping beaches. With increased breaking intensity in shallow water and for relatively steep nearshore slopes, undertows increase and the sediment transport becomes offshore-directed.

The lower waves during summer do not break over the bar and the accumulating effect under the bars is replaced by an onshore bottom current that erodes the bar configuration and changes the winter profile to summer profile.

Hanes and Huntley (1986) observed that in oscillatory flows, the flow field acceleration may play an important role in suspending sediments where boundary layer

separation is likely to occur during the flow decelerating phase. In this situation, suspension appears to be stronger during the onshore directed phase of the wave motion than during the offshore motion and may be determined by fluid acceleration more than velocity. Field observations and numerical model results conducted by Elgar et al. (2001) suggested that the onshore sediment transport and sand bar migration are related to cross-shore gradients in skewed fluid accelerations associated with pitched forward non-linear waves. Additionally, the region of strongly skewed accelerations moves shoreward with the bar, suggesting that feedback between waves and evolving morphology can result in continuing onshore bar migration when mean flows are weak. Hoefel and Elgar (2003) using a numerical model including gradients in acceleration skewness were able to predict the offshore and onshore sediment migration over a 45 day period at Duck.

2.8 Wave Height Decay inside the Surf Zone

The waves approaching the shore shoal until they start to break in shallow waters according to the parameters described in the previous section. After the breaking point the waves transfer their energy generating turbulence into heat and the wave height decreases in the nearshore zone. Numerical models were developed to describe the wave height decay in plane sloping and barred beaches and their results compared with laboratory and field data.

Thornton and Guza (1983) developed a model similar in concept to Battjes and Janssen (1978), where the wave decay is calculated using the change in energy flux. The energy dissipation is considered primarily due to the conversion of organized potential and turbulent kinetic energy to turbulent kinetic energy, using the bore dissipation function. This model calculates the wave height decay in monotonically

depth decreasing beaches, however the stabilization and following shoaling process are not described using this model. Dally, Dean and Dalrymple (1985) developed a similar wave height decay model, however a stability criterion was used to allow the wave breaking stabilization and the initiation of a second shoaling process in the inner surf zone. The inclusion of this term is especially important on barred and dissipative beaches where multiple breakpoints are commonly observed (more details about this model are presented on section 7.1).

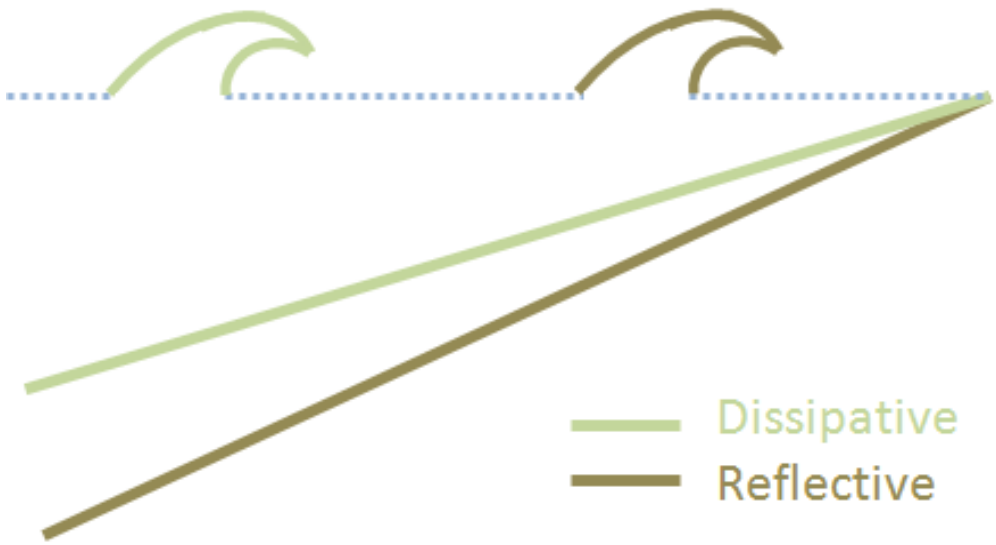

Figure 2-1. Schematic representation of wave breakpoint in dissipative and Reflective Beaches.

CHAPTER 3
MOTIVATION

Morphodynamics in the nearshore are extremely complex, sometimes the outer and inner bars present distinct behaviors, making the predictability of these systems extremely difficult. Understanding the relationship between the wave energy and number of sand bars inside the nearshore zone at different time scales is important to better characterize this environment.

It is expected that if the same wave energy acts on a beach for a long period of time, the beach achieves an equilibrium profile and the number of bars stays constant. The present research uses this assumption to develop a qualitative and a quantitative model to predict the average number of sand bars in a large scale (decadal) in the nearshore zone based on incident wave energy and beach characteristics.

As reflected by the literature review, most of the researches are concerned with the nearshore morphologic response to individual storms or short periods of bar recovery, or in microscale solutions, therefore the development of mesoscale models, require knowledge of more generic properties, where specific conditions are simplified.

Current mesoscale models mostly focus on shoreline changes and neglect subaqueous changes in the beach morphology. The beach morphology, mainly in multiple bar systems, is a result of the beach long-term response to the forces acting on it. Therefore the integrated effects of several storm-recovery cycles have to be understood and long term series of forcing conditions have to be analyzed to explain the variability of the number of bars in the nearshore zone. Such knowledge is probably best obtained from the analysis of long time series of the relationship between

morphology and forcing conditions, where new insights of the sand bar behavior and quantitative estimates for coastal changes can be obtained.

On the other hand, some of the short scale influences of systems with multiple bars are essential. The knowledge of the interaction between inner and outer bars in systems with multiple bars is still poorly understood and better insights between their relations should be addressed to better understand this complex system. Using the assumption that sand bars can focus waves with different heights to break in a narrow zone, the short scale relation between bars and breakpoints can be used to predict the number of bars and their interaction inside the nearshore zone.

CHAPTER 4
FIELD STUDIES

4.1 Beach Profile Data

Beach profiles in Walton and Volusia Counties, on the east and west coasts of Florida respectively, (Figure 4-1), documented by the Florida Department of Environmental Protection (FDEP) were used in the present research. Profiles are usually surveyed every 300 m in the alongshore direction based on physical monuments placed landward of anticipated beach fluctuations. The cross-shore distance is variable, however ideally the surveys extend to the depth of closure. Some of these monuments have been eroded or damaged through time, since most of them were placed approximately 40 years ago, and virtual monuments that are based only on the coordinate position have replaced them.

Some of the Light detection and ranging (Lidar) data available on the http://www.csc.noaa.gov/digitalcoast/data/coastallidar website were used mainly to observe alongshore differences in Walton and Volusia Counties, since this technique provides high density data, with good precision (horizontal and vertical error in the order of decimetres) and reduction in survey time when compared with traditional methods. Few surveys using Lidar were conducted for this area and when Lidar data is available the FDEP extracts the profiles at the monuments from this source.

4.2 Definition of Sand Bars

Criteria to define sand bars were established for the profile analysis, thus allowing a large number of profiles to be evaluated and quantitative comparisons to be made during the analysis. The measured cross-shore profile lengths are variable, as mentioned previously, therefore only profiles deeper than six m were evaluated to

extract the sand bars and all the profiles that didn't extend to the six m depth were excluded. With this threshold depth it is expected that the sand bars in the profiles are correctly measured, even in profiles with more than one bar, and potential errors associated with surveys that didn't extend long enough to capture the presence of offshore bars were minimized. This limit is greater than the depth of closure calculated as 5 and 5.5 m by Dean (2002), for Walton and Volusia Counties, respectively. A total of 1,105 and 540 profiles deeper than six m were analyzed in Walton and Volusia Counties, respectively. More information and concerns associated with the depth of closure were presented by Nicholls et al. (1996).

Beach profile zonation was considered the best approach for the sand bar height definition and three different zones were established according to their depths. Bar height was considered assuming the vertical distance from the bar crest to the landward bar trough. For depths smaller than 4.5 m the morphological features with heights greater than 0.15 m were considered as sand bars. Features with heights greater than 0.9 m were considered as bars in depths between 4.5 and 7.5 m. For depths greater than 7.5 m, only heights greater than 1.5 m were considered. In these three zones the bar width had to be greater than 25 m. This division was based on the theory that bar formation occurs under breaking waves and features not capable of altering the hydrodynamic forces were not considered. A theoretical profile showing the division used for defining sand bars characteristics is presented on Figure 4-2. These limits are somewhat subjective and other depth limits could be proposed, which as more appropriate for other applications or locations. Kuriyama (2002) considered morphological features greater than 0.5 m, from bar crest to landward trough, for the

entire profile, however no explanation for this threshold value was given. Usually researches on sand bar characteristics do not specify these criteria, with sand bars defined visually. Even if uncertain, the limits used here were consistent and were held constant during the analysis, allowing a quantitative way to extract the profile morphology.

Another method to define sand bars is to calculate the equilibrium beach profile and extract bar properties with respect to the equilibrium beach profile. This method was discarded since the area evaluated in both Counties is large and the surveys were not conducted always on the same monuments, which would require applying equilibrium beach profiles that were not always obtained at the same location.

Profiles surveyed at different monuments, but on the same day, were averaged in order to demonstrate general behavior for an area instead of just one representative profile. The issue with averaging beach profiles from different locations is where they should be tied together, since they don't have the same starting position. When this procedure was necessary, the mean high water (MHW) level was used to combine and average the profiles from different monuments, shifting the profiles in the cross-shore direction and making the MHW position coincide on all them.

One problem associated with this approach is that sometimes different features in a profile, for example bar and trough, from different profiles coincide in the same location and the averaging damps the results masking these features. The average of 13 profiles from Walton County illustrates dampening effects when bars and troughs are located in the same cross-shore position (Figure 4-3). Even if this situation was

observed in the data, the average profiles were judged representative of the general trends occurring in the group and the main morphological features preserved.

4.3 Wave Data

Offshore wave heights were obtained from NOAA/NDBC website http://www.ndbc.noaa.gov using buoys 42039 and 41009, for Walton and Volusia Counties, respectively. Buoy 42039 located southeast of Pensacola in 307 m water depth has data available from December 1995 to April 2012. During this period a small quantity of data were missing (3.4%). The buoy used for Volusia County is 41009, located east of Cape Canaveral in 44 m water depth and data from this station is available from August 1988 to April 2012 (Figure 4-4). Waves with periods greater than 7.5 s can start to be influenced by the bottom in the buoy 41009 (considering the deep water limit as half of the wave length). The first beach survey at Volusia County where wave data was available was in May 2001, and only data starting in 2001 were included in the analysis. During this period 0.6 % of the data are missing due wave gauge inoperability.

Significant wave heights from these two buoys were converted to wave energy using Equations 4-1 and 4-2. Where ρ is the water density, g is the gravitational acceleration and H_{rms} and H_s are the rout mean square and significant wave height, respectively.

$$E = \frac{1}{8}\rho g H_{rms}^2 \tag{4-1}$$

$$H_s = 1.416\ H_{rms} \tag{4-2}$$

4.4 Description of Walton and Volusia Counties

An overview of all the available surveys in Walton and Volusia with emphasis on the number of sand bars in a profile, bar crest depth, crest position in relation to the shore and the interaction between inner and outer bars is provided to characterize the nearshore zone in these two Counties. These parameters partially describe sand bar responses to different wave energy conditions and assist by introducing the areas that are analyzed in the following chapters.

Table 4-1. Number of profiles with zero, one, two and three bars and the average number of bars in Walton and Volusia Counties in all surveys from 1972 to 2007.

Walton County						Volusia County					
Year	0 bar	1 bar	2 bars	3 bars	Ave rage	Year	0 bar	1 bar	2 bars	3 bars	Ave rage
1973	0	40	3	0	1.1	1972	3	25	33	4	1.6
1975	15	23	2	0	0.7	1988	30	130	63	8	1.2
1981	1	69	15	0	1.2	2001	0	10	17	9	2
1995	0	114	12	0	1.1	2002	0	41	4	0	1.1
1996	5	78	42	1	1.3	02/2006	0	4	35	2	1.9
1997	5	110	12	0	1.1	09/2006	1	9	31	0	1.7
1998	0	32	19	3	1.5	2007	0	1	72	8	2.1
04/2004	4	112	7	0	1						
11/2004	10	72	45	0	1.3						
2005	4	44	75	4	1.6						
2007	10	81	35	1	1.2						
Total(%)	4.9	70.1	24.2	0.8		Total(%)	6.3	40.7	47.3	5.7	

The bar crest position and depth were obtained for all profiles with sand bars and the number of bars varied from profiles with no bar to three bars. The first surveys in both Counties were conducted in the 1970's, however the surveys were sparse in first 20 years, increasing their frequency after 1995. The majority of the profiles at Walton County presented only one bar (70.1 %) and profiles with three bars were observed on a few occasions. In Volusia County, profiles with two bars (47.3 %) were more frequent

followed by profiles with one bar (40.7 %) and more profiles with three bars were observed when compared with Walton County. Table 4-1 shows the distribution of profiles from zero to three bars throughout the years.

In order to investigate the sand bar linearity or if they have two or three dimensional characteristics, a linearity index (LI) was defined and applied (Equation 4-3). Values approaching unity indicate linear or tendency to two dimensional morphologies and the decrease in this value is associated with an increase in the bar three dimensionality, where alongshore differences in the morphology are more evident.

$$LI_{inner} = 1 - \frac{\sum(b_{n\ inner} - \overline{b_{\ inner}})^2}{\sum b_{\ n\ inner}{}^2 + \sum b_{n\ outer}{}^2} \tag{4-3}$$

$$LI_{outer} = 1 - \frac{\sum(b_{\ n\ outer} - \overline{b_{outer}})^2}{\sum b_{n\ inner}{}^2 + \sum b_{n\ outer}{}^2} \tag{4-4}$$

In Equation 4-3 and 4-4, b is the bar crest depth; the same equation was used replacing b with the distance from the bar crest to the shore, also referred to as bar position.

Sand bars in profiles with two bars were divided according to their position and depth to define differences in the inner and outer bars stabilities, since different wave conditions are affecting the inner and outer bars and their response to the same offshore wave conditions can vary. The third bar (the offshore bar) in profiles with three bars was removed from the analysis since their occurrence was less frequent and creating one division with only these bars wouldn't represent their linearity.

4.4.1 Walton County

The LI for the inner and outer bar didn't show a clear distinction of which bar was more uniform and two dimensional. The LI results presented a large variability, however

after major storms, the outer bar at Walton County was more linear than the inner bar, since the LI were larger after these events. This was observed in the 1998 and November 2004 surveys, after hurricanes Georges and Ivan, respectively.

One example where the outer bar became more linear after an event with high wave heights (Hurricane Ivan) is presented on Figures 4-5 and 4-6. Before the Hurricane only seven of the 127 profiles had two sand bars (diamonds on Figure 4-5) and the inner bar, when observed, was located in very shallow waters (blue diamonds on Figure 4-5) . After Hurricane Ivan, most of the profiles presented two sand bars (diamonds on Figure 4-6), being the majority of profiles in this survey. It is evident that the inner bar, only observed in few profiles before Ivan, was created during this event. The outer bar changed to deeper water as a response to the high waves, however the position stayed almost constant with slightly bar offshore migration. The LI of the outer bar depth increased after Hurricane Ivan (from 0.981 to 0.996) and it was another indication that sand bar formation and their depths are directly related to the wave energy acting prior to the survey. The LI for the outer bar position also increased after Ivan (from 0.968 to 0.977). However the inner bar became more three dimensional after Ivan (with a decrease in the LI) indicating that the beach morphology can still present three dimensional features even after Hurricanes or major storms. Similarly, Gallagher et al. (1998) observed significant bathymetric inhomogeneities developed during a storm at Duck. This fact was associated with the presence of megaripples with wave lengths of few meters that are present during both high and low wave energy periods. The results of Equation 4-3 and 4-4 applied to all surveys in Walton County are presented on Table 4-2.

Table 4-2. Results of the LI applied to all surveys in Walton County, evaluating the inner and outer bars linearity.

Walton County				
Survey Year	Inner Depth	Outer Depth	Inner Distance	Outer Distance
1973	0.988	0.955	0.990	0.975
1975	0.962	0.963	0.961	0.992
1981	0.985	0.989	0.971	0.977
1995	0.964	0.961	0.994	0.976
1996	0.972	0.998	0.973	0.990
1997	0.935	0.947	0.994	0.943
1998	0.997	0.990	0.984	0.977
04/2004	0.999	0.981	0.999	0.968
11/2004	0.994	0.996	0.977	0.977
2005	0.956	0.988	0.977	0.989
2007	0.997	0.984	0.991	0.979

4.4.2 Volusia County

The inner and outer bar depths presented opposite behaviors, an increase in two dimensional morphologies in the outer bar occurred at the same time that an increase in three dimensional morphologies in the inner bar, observing two consecutive surveys. Also, a decrease in the inner bar LI (more three dimensional) was observed when the outer bar became more two dimensional (higher LI). The LI for the bar distance presented a similar behavior, the exceptions occurred in the last two surveys that the LI increase for the inner and outer bars at the same time.

Shand et al. (1999) found that sand bars are higher on more exposed beaches with mild beach slopes. However this was not observed when comparing the profiles with the milder slope in Volusia and steeper slopes in Walton County. The average bar height was greater in Walton County (1.01 m) than in Volusia County (0.71 m). All the

bar heights and widths in both Counties are presented on Figure 4-7, where it is clear that the sand bars are smaller and narrower in Volusia.

Table 4-3. Results of the LI applied to all surveys in Volusia County, evaluating the inner and outer bars linearity.

Volusia County				
Survey Year	Inner Depth	Outer Depth	Inner Distance	Outer Distance
1972	0.991	0.963	0.986	0.978
1988	0.983	0.976	0.993	0.947
2001	0.906	0.998	0.990	0.995
2002	0.999	0.978	0.989	0.968
02/2006	0.969	0.995	0.981	0.989
09/2006	0.990	0.992	0.986	0.991
2007	0.996	0.997	0.978	0.982

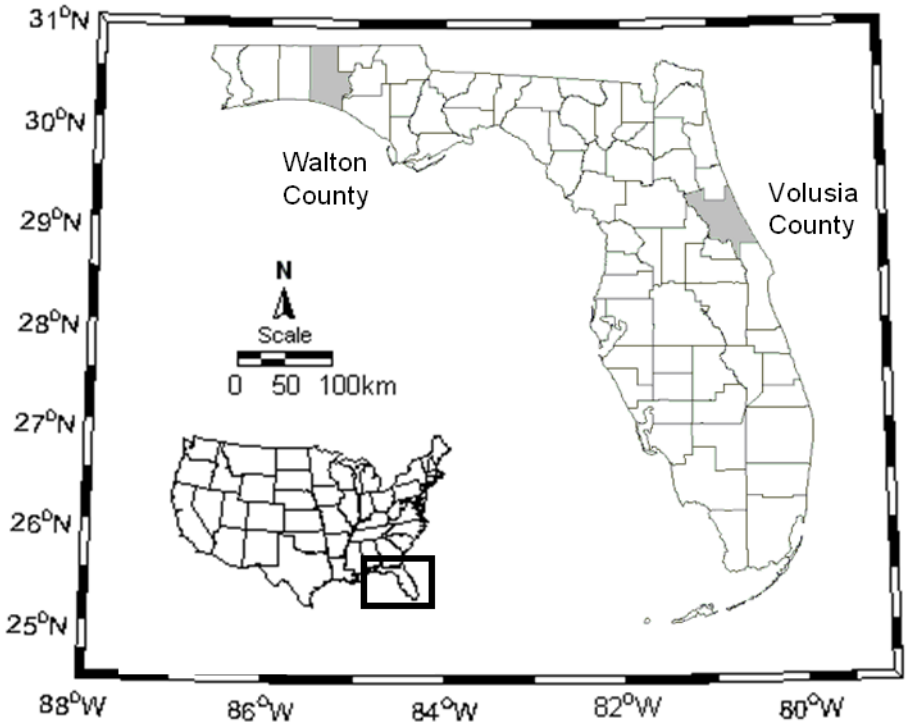

Figure 4-1. Location of the two study areas in the State of Florida. Walton County in the west coast and Volusia County in the east coast.

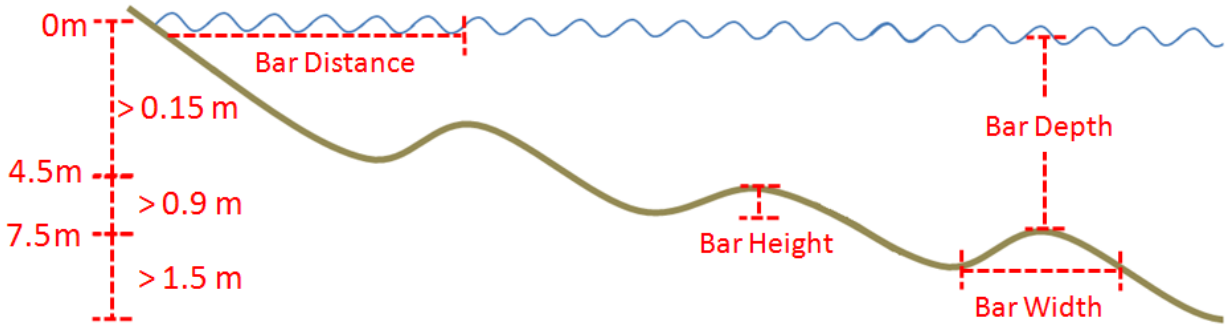

Figure 4-2. Criteria utilized to define the sand bars inside the three zones in the beach profile. Only bars with heights greater than 0.15 m were considered from 0 to 4.5 m; heights greater than 0.9 m from 4.5 to 7.5 m and heights greater than 1.5 m on depths greater than 7.5 m.

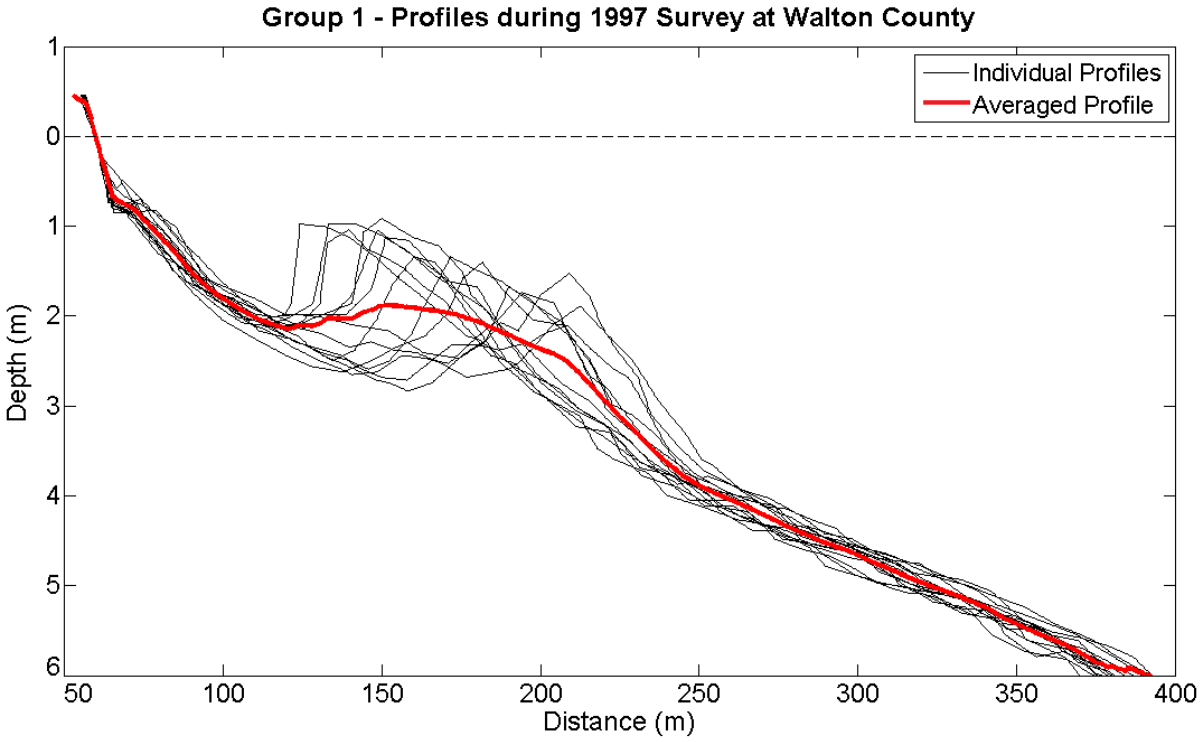

Figure 4-3. The 13 profiles of Group 1 at Walton County during the 1997 survey (black) and the average profile (red).

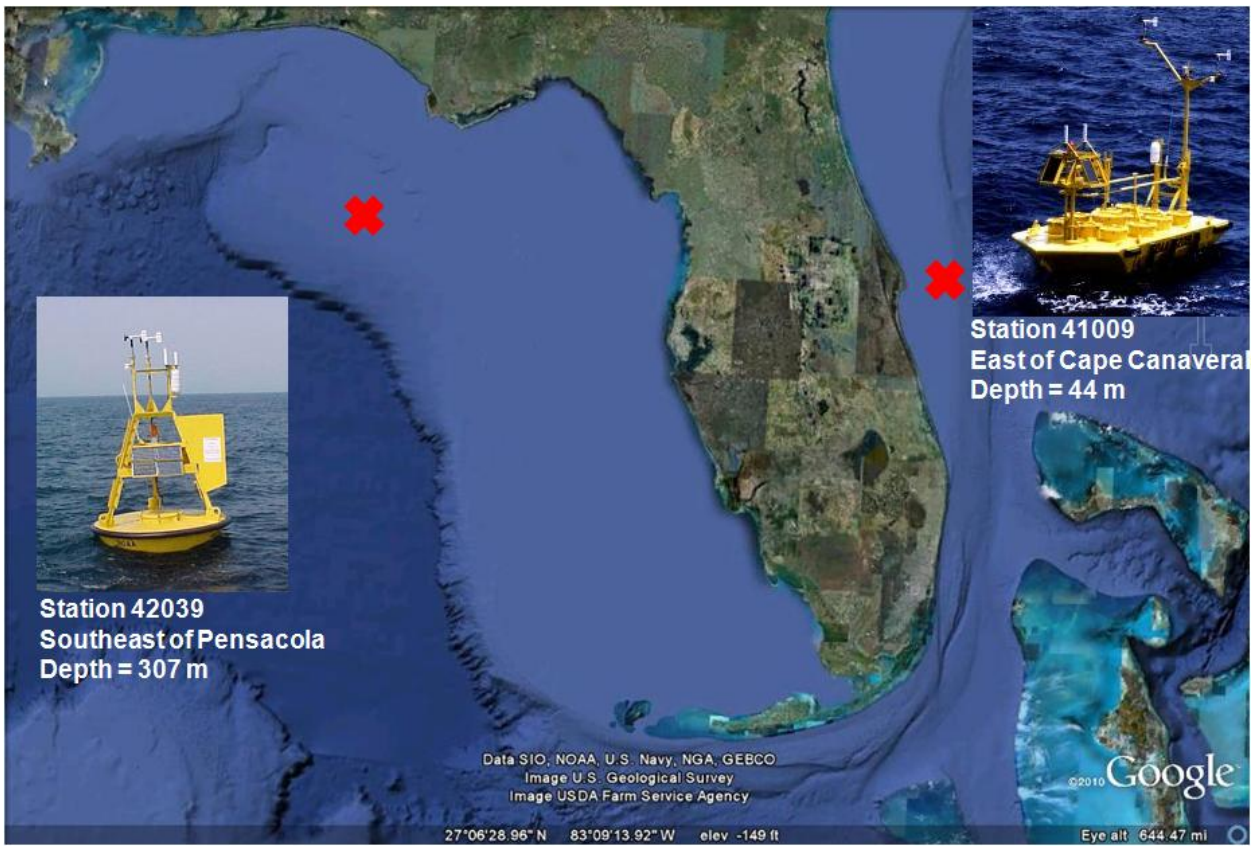

Figure 4-4. Location of the buoys 42039 and 41009 used to extract the wave data for Walton and Volusia Counties, respectively.

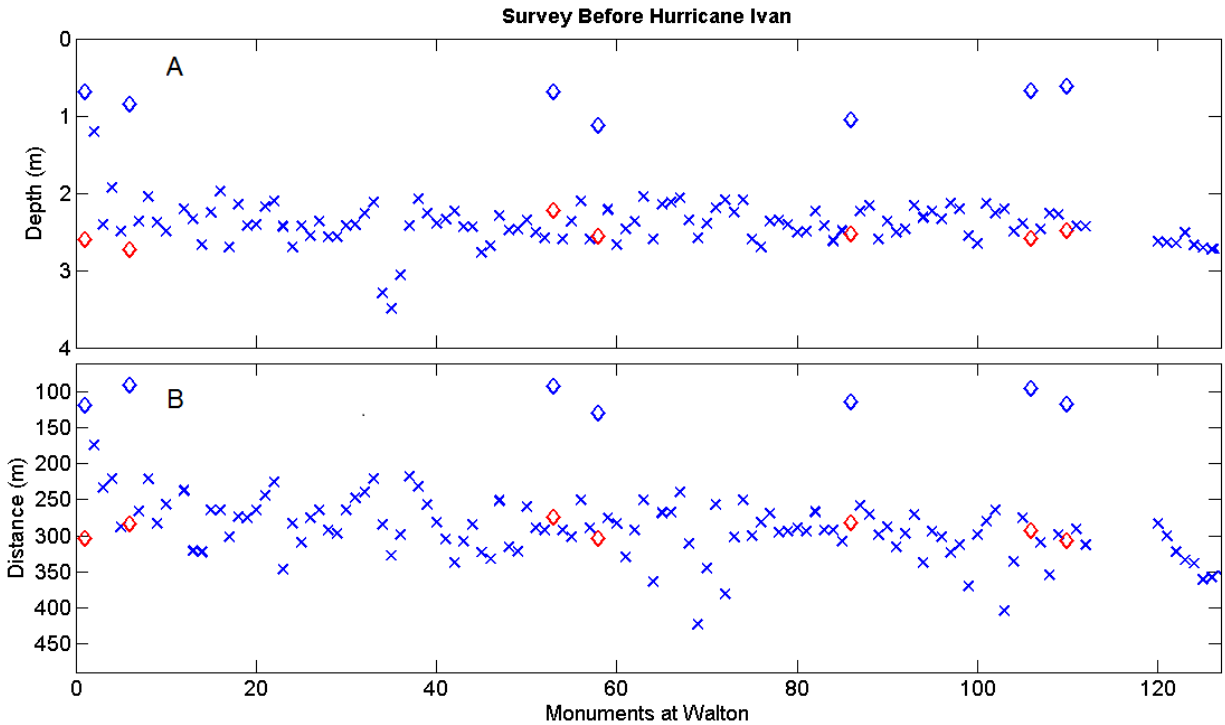

Figure 4-5. Beach survey before Hurricane Ivan. Profiles with one sand bar (blue crosses) and profiles with two sand bars (diamonds). The profiles with two bars have the inner bars represented with blue diamond and the outer bar with red diamond. A) Bar crest depth. B) Bar crest distance to the shore.

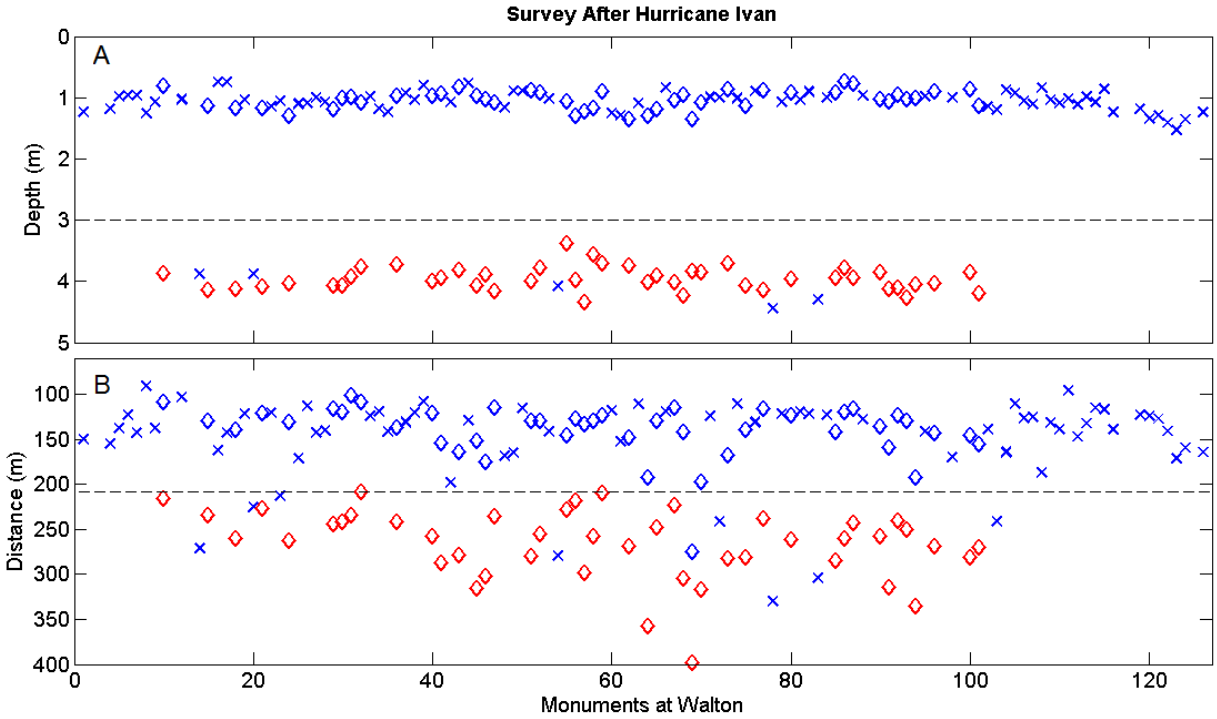

Figure 4-6. Beach survey after Hurricane Ivan. Profiles with one sand bar (blue crosses) and profiles with two sand bars (diamonds). The profiles with two bars have the inner bars represented with blue diamond and the outer bar with red diamond. A) Bar crest depth. B) Bar crest distance to the shore. Depth and distance limits distinguishing the inner and outer bars to calculate the Linearity Index (dashed horizontal line).

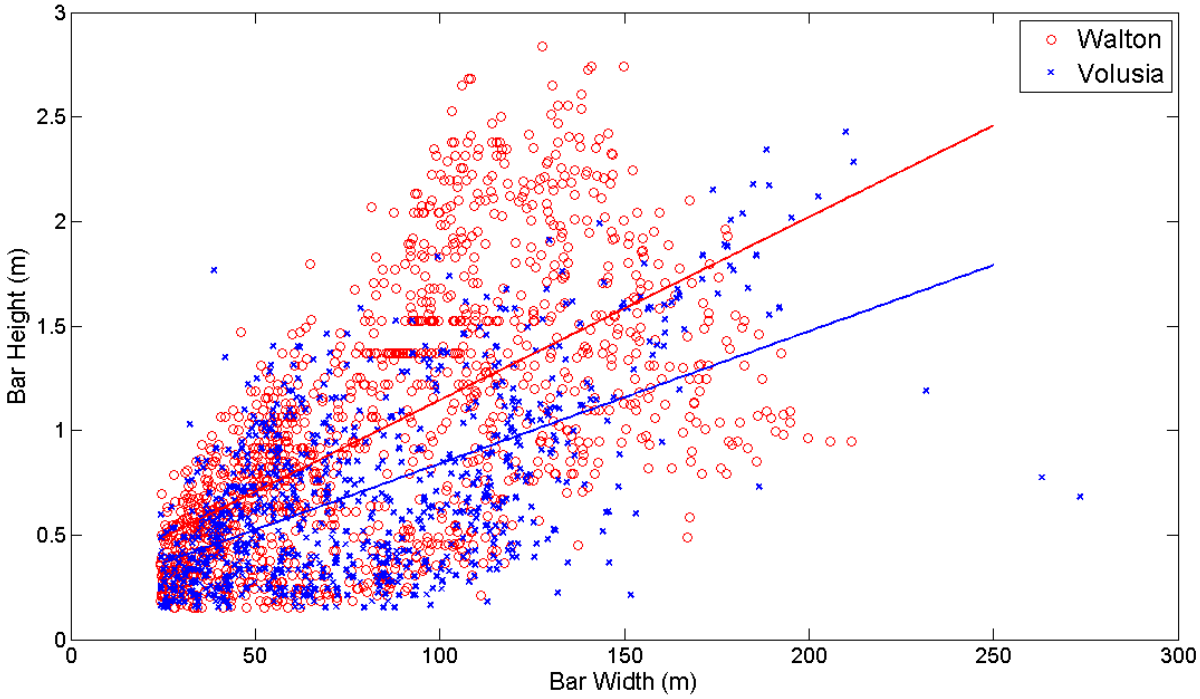

Figure 4-7. Sand bar depths and widths from all profiles in Walton (red circle) and Volusia (blue cross) Counties. Calculated linear trend for both Counties (straight lines).

CHAPTER 5
QUALITATIVE MODEL: WAVE HEIGHT AND NUMBER OF SAND BARS RELATIONSHIP

A qualitative approach was used to determine the correlation between the average number and behavior of sand bars influenced by different wave conditions. This approach is based on the theory of winter and summer conditions developed by Bagnold (1947), on which breaking waves are the main force for bar formation and the sediments move offshore during energetic conditions and migrate onshore during longer periods with mild energy. Bar formation and consequently an increase in the average number of bars is expected with the increase in wave energy. The opposite behavior occurs during calm periods, when the energy decreases and the average number of bars decreases. The effects of different hurricanes that impacted Florida and increased the wave energy in Walton and Volusia Counties were qualitatively observed in this approach.

5.1 Wave Analysis

The average wave energy between two consecutive surveys was used as the characteristic wave energy during that period for the qualitative model, showing the wave energy influencing the beach during those periods. These intervals are not constant and their durations changed according to when beach surveys were obtained in each county. The comparison between the wave energy in consecutive periods indicates if an increase or decrease in the average number of bars would be expected.

Wave energy periods for Walton and Volusia Counties are differentiated with W and V followed by numbers according to the beach survey. The wave energies for the first and last time spans were calculated, however it is not possible to interpret them since no beach profiles were conducted before and after them and the sand bar

morphodynamic responses to the wave conditions are unknown. Also the first period in Walton County, prior to W1, has less than three months of data, and its interpretation as a period with high average wave energy can be biased by the lack of additional data.

5.2 Average Number of Bars and Average Profile

The number of sand bars extracted from the profiles was averaged resulting in one number of bars for each survey (Table 4-1). The average was chosen to minimize potential errors associated with beach three dimensional morphologies, since the profiles are obtained along a single cross-shore line based on the monuments at the beach and not always the same monuments were surveyed for all years. This potential source of error is discussed later.

All the profiles from Walton (1,105) and Volusia (540) Counties were averaged to determine the general nearshore characteristics in both counties, especially emphasizing the beach slope (Figure 5-1). The average beach profile at Walton is steeper (1/65) than at Volusia (1/90) County. The beach slope differences are consistent with the coarser mean sediment size of 0.3 mm in Walton County compared to 0.18 mm in Volusia (Charles et al., 1994). It is also consistent with the greater average wave energy at Volusia, which tends to flatten the beach profile, transport sediments offshore and create sand bars. This large number of profiles includes surveys not used in the model since they were conducted prior to availability of wave data, therefore comparisons between hydrodynamics and morphologies were not possible.

The greater number of bars in the Volusia profiles, observed in the data was expected, as the beach slope is milder in comparison with Walton. The waves are expected to break farther offshore and as the distance to the shore is still large they can

stabilize, shoal inside the nearshore zone and break for a second time, as proposed by Dolan and Dean (1985) for systems with multiple bars. This process can repeat several times and profiles with more than one bar are the consequence of multiple breakpoints. Beach profiles with one, two and three sand bars characterizing the situation described above are presented on Figure 5-2, all from Volusia County.

5.3 Bar Response to Average Wave Energy

5.3.1 Walton County

The average number or bars in Walton County correlated with the wave forcing (R^2 = 0.41). Periods with low (W1, W3 and W6) and high wave energy (W4 and W5) were found, allowing a qualitative evaluation between wave forcing and sand bar response. When the average wave energy decreased between two consecutive periods, the average number of bars also decreased. On the other hand, the periods with an increase in the wave energy were associated with an increase in the average number of bars.

Wave energy increase was mainly associated with the passage of six Hurricanes (Earl, Georges, Ivan, Dennis, Katrina and Ike) in Walton County (Figure 5-3). The effects of the first two Hurricanes (Earl – September 3rd and Georges September 29th 1998) observed during this period were captured by the beach survey in November 1998. The sand bars responded to the increase in the wave energy from 1,723 to 2,335 J/m^2 with an increase in the average number of bars from 1.1 to 1.5. Hurricanes Ivan, Dennis and Katrina happened over a short period of time between September 2004 and August 2005 (time span W4 and W5) and wave energies greater than $1.3*10^5$ J/m^2 were observed during the first two hurricanes and resulted in significant beach profile changes. This large increase in average wave energy, from 1,909 to 2,313 J/m^2 and

later to 2,811 J/m^2 (45 % more than during calm periods) increased the average number of bars from 1.0 (W3) to 1.3 (W4), remaining high (1.6) in the W5 period. The Hurricane Ike effect couldn't be determined, since no survey was conducted subsequently, however another increase in the average number of bars would be expected after this hurricane. A reduction in the average number of sand bars occurred after calm periods W1, W3 and W6. This decrease is associated with onshore sediment transport, where the bars migrate back to the beach. The most significant was during W3, when the average number of bars decreased from 1.5 to 1.0 as a result of more than five years without significant increases in wave energy.

5.3.2 Volusia County

Only five surveys were conducted in Volusia County, resulting in a smaller quantity of data to be compared with the model (Figure 5-4). However the same methodology that was applied for Walton was used for Volusia County. Hurricanes Frances, Jeanne and Wilma occurred in time span V2, however a small decrease in the average wave energy occurred from V1 (2,630 J/m^2) to V2 (2,470 J/m^2). The small wave energy decrease, even with three hurricanes, can be explained by the long period, almost four years, where the data were averaged, decreasing the wave energy peak effects during the hurricanes. The qualitative approach didn't present a good correlation during this time span, where a decrease in the average number of bars was expected in the 2006 survey, rather a significant increase from 1.1 to 1.9. The coefficient of determination (R^2) between the average wave energy and average number of bars was extremely low (0.001) at Volusia. This situation highlighted the necessity of frequent beach surveys in order to apply the qualitative approach with better accuracy. Where beach surveys are not available more frequently, data can be averaged over long periods where wave

conditions can change considerably and the averages become non-representative of the entire situation. Also as the hurricanes, especially hurricane Wilma, occurred close in time to the survey, the beach response still had a morphological “memory” related to the wave forcing that happened during the closest period. The morphological “memory” indicates that the beach morphology is not simply a result of the hydrodynamic conditions acting in the present moment but also during past events. Kriebel and Dean (1993) applied a convolution method for time-dependent beach cross-shore response to calculate the morphological “memory” after short and long storms, obtaining reasonable comparison between predicted and measured time scale for beach response.

This also indicates the importance of when beach surveys are conducted, since it is expected that the beach morphology represents the conditions occurring during periods closer to the survey, with this period being associated with the energy at the beach. If energetic conditions happen, this period is shorter, otherwise it is longer.

The response of the average number of sand bars during the next two consecutive time spans V3 and V4 occurred as expected, decreasing from 1.9 to 1.7 at the calm time span V3 and increasing from 1.7 to 2.1 during the more energetic time span V4.

5.4 Summary of Findings from the Qualitative Examination

The qualitative approach, based on a simple methodology, showed reasonably good results when comparing the average wave energy and the average number of sand bars. It also supported a long term correlation between the wave energy and the number of bars observed on sandy beach profiles with different grain sizes and exposed to different wave energy conditions. Hurricane influences were well represented at Walton; however, the same results were not achieved at Volusia County. The time when the surveys were conducted and the period between two consecutive surveys were

found to be key to the achievement of good results with this methodology. The positive feedback between waves and sand bars obtained using the qualitative approach motivated the development of a simple numerical model to quantitatively predict the number of bars in the nearshore zone. Similar numerical models have not been presented before in scientific reports, and details about the model are described in chapter six.

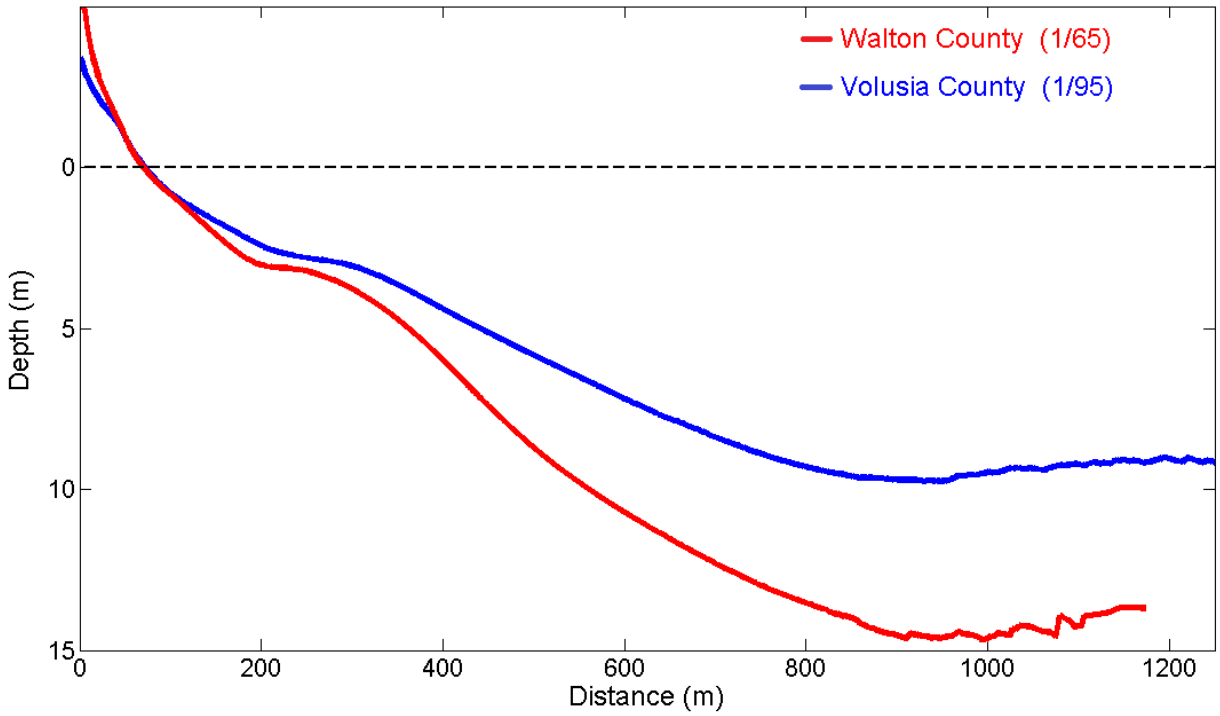

Figure 5-1. Average beach profiles at Walton and Volusia Counties representing the differences in beach profile slope.

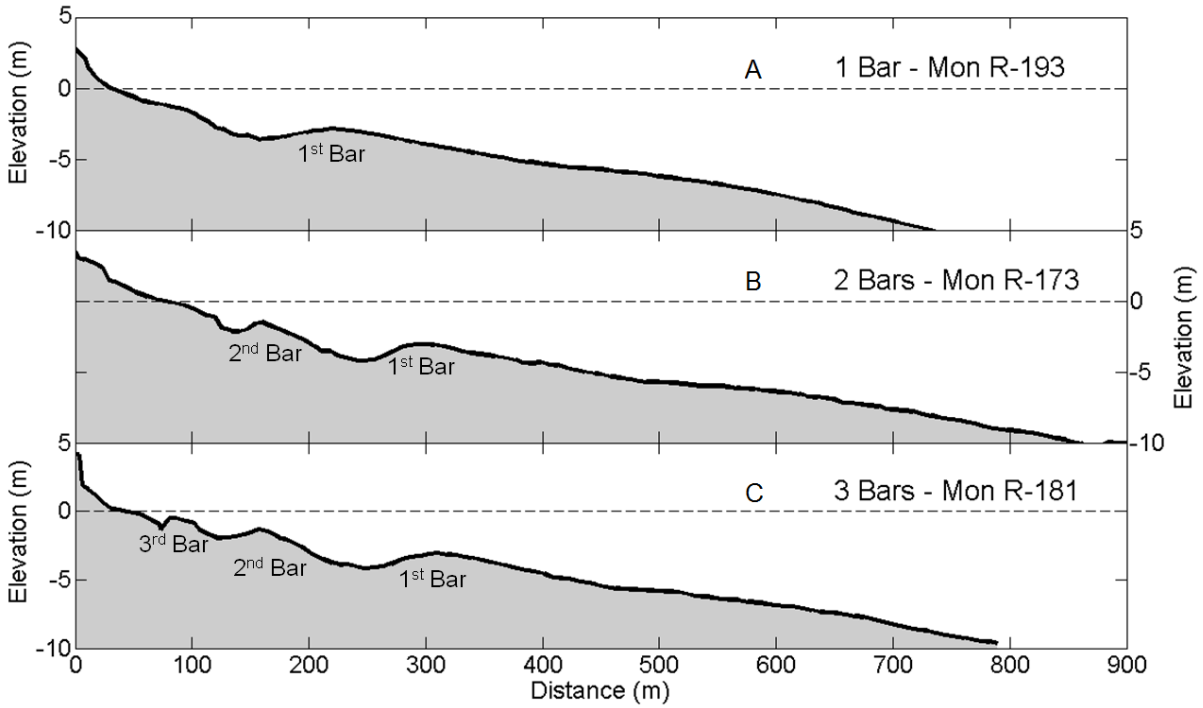

Figure 5-2. Measured profile examples in Volusia County. A) Profile with one bar. B) Profile with two bars. C) Profile with three bars.

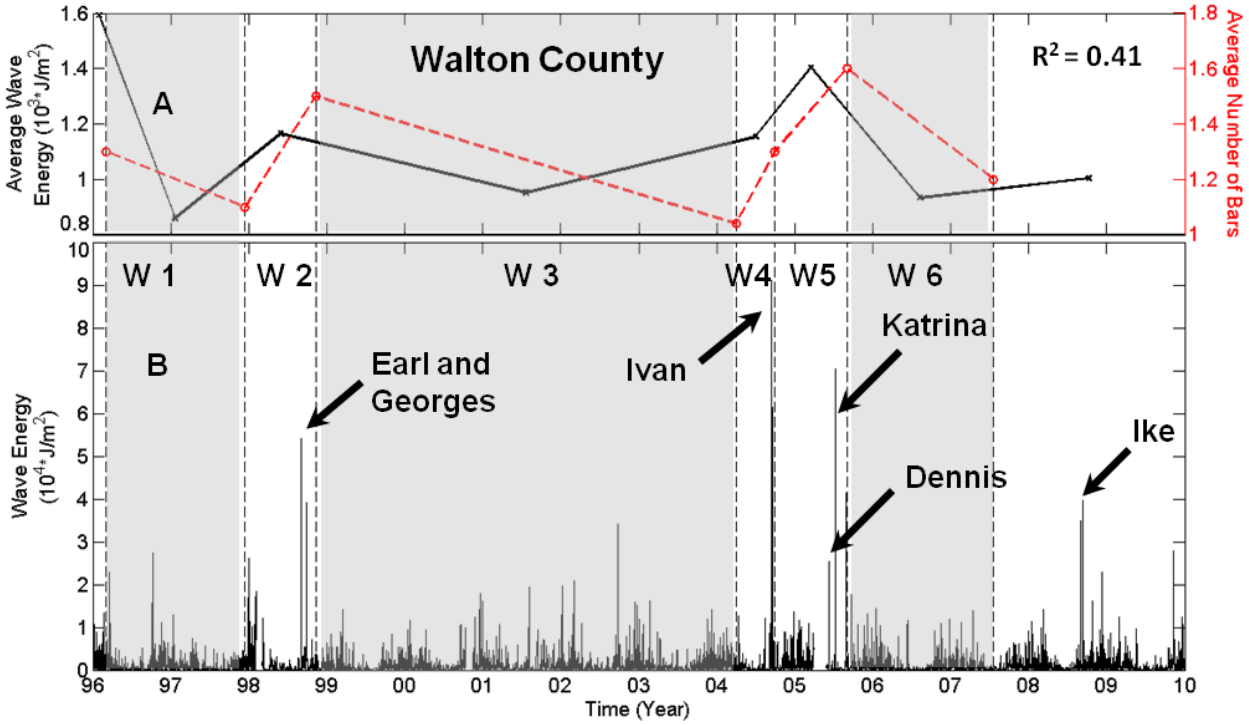

Figure 5-3. Results from the qualitative model for Walton County. A) Comparison between average wave energy and average number of bars. B) Wave energy and indication of Hurricanes. The vertical dashed lines shows when beach surveys were conducted and the highlighted periods indicate when the wave energy decreased between consecutive periods.

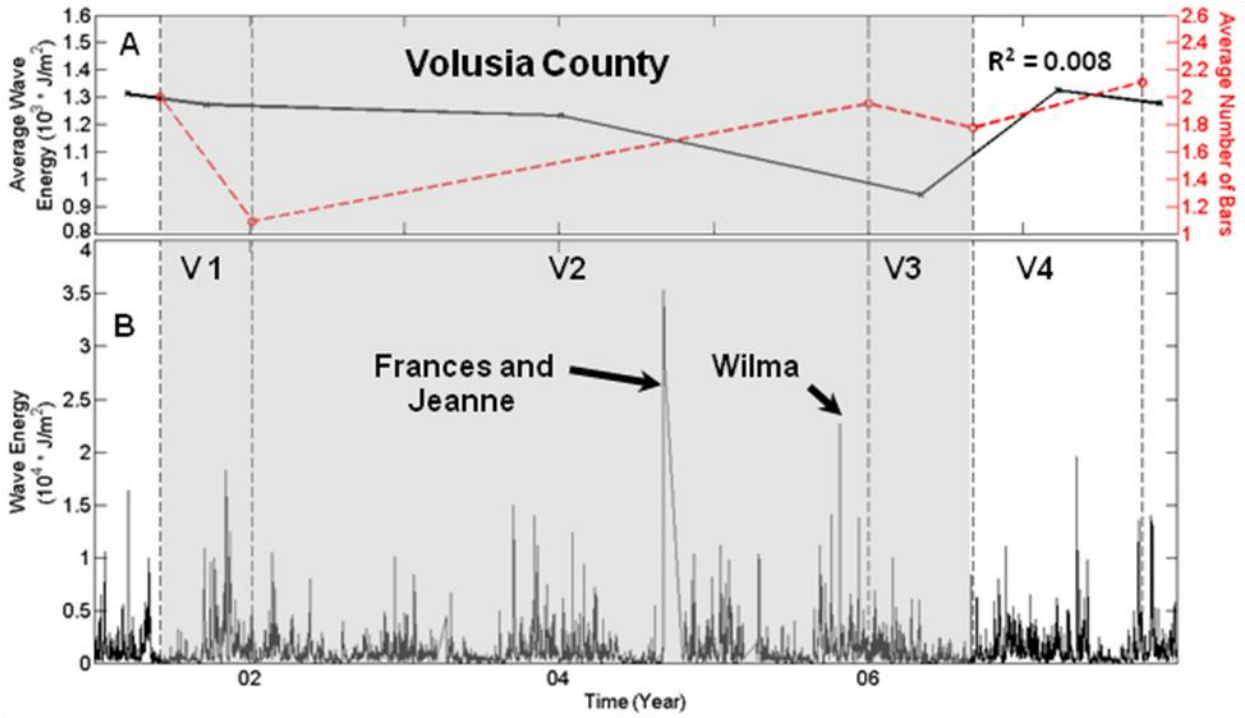

Figure 5-4. Results from the qualitative model for Volusia County. A) Comparison between average wave energy and average number of bars. B) Wave energy and indication of Hurricanes. The vertical dashed lines shows when beach surveys were conducted and the highlighted periods indicate when the wave energy decreased between consecutive periods.

CHAPTER 6
NUMERICAL MODEL TO PREDICT THE EVOLUTION OF SAND BARS IN THE NEARSHORE ZONE

Most of the available qualitative and quantitative models describing the nearshore characteristics are developed for beaches with only one sand bar. The increase in the number of sand bars, resulting in nearshore zones with two or multiple sand bars, increases the complexity in this zone, since morphodynamic interactions occur inside the nearshore zone. The basis forming the model developed here, simplifies these interactions, establishing a relation between the wave forcing and the quantity of sand bars in the nearshore zone, where this relation is dependent on beach and wave characteristics.

6.1 Model Description

The model to predict sand bar evolution was evaluated using the same profile database from the FDEP described previously, in Walton and Volusia Counties. The model considers that the number of bars in equilibrium, N_{eq}, (i.e., the number of bars expected in the nearshore zone) is a function of offshore wave and beach characteristics. To decide which variables are important, two criteria suggested by Wijnberg (2002), were used. Firstly, the location of change in the variable value should match the location of change in the behavior and, secondly, the change in variable value should be equally abrupt as the change in the behavior. This implies that it is implicitly assumed that a gradual change in the extrinsic conditions results in a gradual change in morphologic behavior. Consequently, although the relation between input conditions and morphologic response is probably non-linear, it is assumed that the non-linearity does not cause abrupt changes in the morphologic response.

The model assumes alongshore uniformity, although it is known that this is not representative during calm conditions, it is a reasonable approximation when the model objective is the prediction of the number of sand bars over a large temporal scale of decades, where influences from smaller perturbations can be omitted. The physical variables in this situation are a function of the cross-shore distance and time. Calculation for long time periods encompasses greater variations in the forcing, as observed in Figures 5-3 and 5-4, and is impractical for predictions using transport models based on local quantities. In contrast, transport models for macro-scale require formulations based only on simple descriptors of the forcing, but must include information on the principles underlying key features of the larger scale morphology (Larson and Kraus, 1992). In their paper the authors propose the use of quasi-equilibrium models that describe the transformation between different beach states representing key morphologic features where the rate of change is determined by simple or bulk parameters that characterize the forcing in moving between states.

The parameters frequently identified during the literature review that control the sand bar behavior inside the nearshore zone are the waves and the morphologic characteristics. Some parameters including one or more agents influencing the sand bars were applied in the data analysis. These characteristics are: the offshore wave height (H_0), wave period (T) and sediment size, which is represented in terms of settling velocity and beach slope. N_{eq} was tested using four different functions, which are parameters frequently used in nearshore process studies. First, the function was based only on the offshore wave height. Wave steepness (H_0/L_0) was also tested to include the wave period influence, where L_0 is the offshore wave length.

Two non-dimensional parameters were tested. The first being the Dean number (D), based on the settling time of suspended sediments by breaking waves proposed by Dean (1973). Assuming that for short settling times the sediment is influenced by onshore orbital velocities and deposited onshore and the sediment is influenced by offshore velocities and deposited offshore during long settling times. These two processes create the normal and storm profiles, respectively. N_{eq} as a function of the Profile (P) number (gH_0^2/ω^3T) proposed by Dalrymple (1992) was the last function tested. This is also a non-dimensional number and it was developed based on results reported by Larson and Kraus (1992) obtained in a large wave tank, resulting in a threshold value (~10,400) able to distinguish normal and storm profiles. In contrast with the Dean number which was based on small scale laboratory data, the Profile number was obtained using large wave tank data. In summary, N_{eq} was tested as a function of H_0, H_0/L_0, D and P, using Equation 6-1

$$N_{eq} = k_1 F^{0.5} \tag{6-1}$$

where $F = \{H_0, H_0/L_0, D \text{ or } P\}$

The coefficient k_1 is included to represent site specific characteristics. It is dependent on the beach characteristics, as surf zone width, sediment size and beach slope, where those three parameters are known to be interrelated. The rate of change of the number of bars is based on the difference between the predicted and equilibrium number of bars as follows (Equation 6-2)

$$\frac{dN_b}{dt} = -k_{2,3}(N_b - N_{eq}) \tag{6-2}$$

The model includes that bar formation occurs more rapidly than the decay. The coefficient (k_2) during periods of bar decay ($N_b > N_{eq}$) is smaller than the coefficient (k_3)

during periods of bar formation ($N_b < N_{eq}$). As discussed previously, this accounts for observations that during energetic waves, bars form faster and during calm periods the bars migrate slowly onshore and the number of bars decreases. Calibration methods were applied to determine the minimum error for the three coefficients used in the model (k_1, k_2 and k_3). The same values of k_2 and k_3 were used in Walton and Volusia Counties, only K_1 was changed, since the latter defines the expected number of bars which depends on morphological characteristics and the first two are related to sediment transport time responses.

Figure 6-1 shows a conceptual example to demonstrate the model functionality. It is idealized showing an increase in the wave height (from one to two meters) that remains constant and after a period the wave height decreases back to the original value (Figure 6-1A). A profile without sand bars is used as an initial condition. During the first stage (P1), the number of bars is not in equilibrium with the incident wave conditions and the number of bars increases until it stays in equilibrium with the expected number of bars associated with the current forcing (Figure 6-1B). When the wave height increases, there is a second period that the model is not in equilibrium (P2). A new equilibrium is achieved with a second increase in the number of bars. The wave height decreases and the model achieves the third equilibrium with a decrease in the number of bars (P3). The rate of increase and decrease in the number of bars is not the same. Faster rates are observed during periods of bar formation and slower rates during the periods of bar decay (P1 and P2 < P3), similarly to the natural behavior of sand bars.

6.2 Comparison with Florida Data

The numerical model results were compared with data obtained from Walton and Volusia Counties. These two Counties were selected because they are influenced by different wave conditions and also distinct morphologic features, with coarser sediments at Walton. The average beach profile at Walton is steeper than at Volusia County (Figure 5-1) indicating that forcing and morphology in a mesoscale observation are distinct.

To quantitatively represent those differences in the numerical model, an empirical correlation, based on the dataset described on Section 4.1, between the expected number of bars and wave energy was used (Figures 6-2A and 6-2B). These relations were obtained using different values of k_1 for Walton and Volusia and using N_{eq} as a function of Dean and Profile numbers. The number of bars in equilibrium is larger in Volusia County, due to the wider surf zone, finer sediment and higher waves. The correlations using the other two functions, H_0 and H_0/L_0, are not shown because the correlation with the model results was lower, which are described later (sections 6.4 and 6.5).

The division between a profile with more or less than one bar using the Profile parameter was $P = 3.09*10^5$ and $P = 1.89*10^5$ for Walton and Volusia Counties, respectively. These values are considerably higher than the threshold value of 10,400 for the division between summer and winter profiles proposed by Dalrymple (1992), however that value was obtained using large wave tank data versus the values obtained here based on field data at Florida. The division between storm and summer profiles using D are between four and five, and D = 6.4 and 3.8, for Walton and Volusia Counties were obtained using the empirical relationship.

6.3 Walton and Volusia County Groups

Beach surveys were not conducted on the same day in the entire County because the shoreline in these two Counties, especially Volusia, is extensive and sometimes the surveys were stopped due to high wave conditions. For these reasons, beach segments were surveyed in different days and waves with considerable different heights occurred during one survey period. To avoid data bias due to different wave forcing during the same survey, five areas where separated and analyzed individually in Walton County (Figure 6-3). The five areas had all their profiles surveyed on the same day. Another concern was avoiding alongshore differences in the profiles, mainly during calm periods when beach features become more three dimensional and alongshore differences in the sand bar morphology are likely to occur. Only shoreline lengths greater than three km were used as groups and it is believed that the average number of bars over the three km shoreline minimizes the problems associated with alongshore variations in the profile within a group, making the averages representative of the group for the time scale used in the model.

One continuous beach segment, between R-165 and R-195, with approximately nine km was surveyed four times at Volusia, instead of five surveys in the qualitative approach. This segment wasn't surveyed in 2001, precluding it use during the analysis. This segment is located 4.8 km south of Ponce de Leon Inlet, where the shoreline change fluctuations decrease to the ambient County fluctuations (Absalonsen and Dean, 2011), diminishing the inlet influence.

6.4 Walton County

6.4.1 Comparison between the Groups

The five groups in Walton County showed a similar behavior of the measured average number of bars (Figure 6-4). Group 1, during the 2005 survey, was the only group surveyed before Hurricane Katrina and the only one with a decrease in the average number of bars between the second survey in 2004 and the 2005 survey, since Group 1 survey didn't capture the increase in the number of bars associated with Hurricane Katrina. All the other groups were surveyed after Hurricane Katrina and presented an increase in the average number of sand bars during that survey. The average number of bars varied considerably between the groups in the 1996 survey, used as an initial condition. This difference was the result of an increase in wave height (to 2.5 m) that occurred between February 23rd and March 4th. The dates when the surveys were conducted are presented on Table 6-1.

Table 6-1. Dates that surveys were conducted at Walton County

Survey Dates on Different Groups - Walton County							
	S1	S2	S3	S4	S5	S6	S7
Group 1	3/5/96	11/19/97	11/18/98	4/15/04	8/15/04	8/24/05	7/21/07
Group 2	3/4/96	11/21/97	11/18/98	4/15/04	8/16/04	9/12/05	7/21/07
Group 3	2/23/96	12/7/97	11/17/98	4/15/04	8/17/04	9/17/05	7/21/07
Group 4	2/22/96	12/11/97	11/17/98	4/15/04	8/18/04	9/19/05	7/21/07
Group 5	2/22/96	1/24/98	11/17/98	4/15/04	8/19/04	9/20/05	7/21/07

Changes in decadal coastal behavior on the Dutch Coast showed that large man-made structures appear to have effects that far exceed the spatial extent of known local effects of these hard structures (Wijnberg, 2002). However this is not the reason of the changes between groups in Walton County, where no large hard structures are present along the coastline.

6.4.2 Sand Bars versus Wave Height

The results for group three using different functions for N_{eq} are presented in Figure 6-5. The entire results from the model are not shown in Figure 6-5, but only the comparison between model results for the same time that beach surveys were conducted.

Comparing the results using the four different functions, the best results were obtained using N_{eq} as a function of the Profile number (R^2 = 0.75 and Var = 0.039). The first survey available was not used to calculate R^2 and variance, since it was the initial condition and therefore the model values were set equal to measured values. R^2 and variance results using different functions are summarized in Table 6-2. The shape of all curves, using N_{eq} as a function of the four different variables is similar, increasing and decreasing at the same moment when two consecutive survey dates are compared. The only exception is the 2005 survey, where N_{eq} as a function of P decreased while the model results using the other functions predicted an increase. Even in this case, the prediction was the closest to the measured value.

The results in Figure 6-6 compare the time evolution of the number of bars predicted by the model versus the average number of bars observed in Walton County. Measured offshore wave heights are also included (Figure 6-6A). Only the model results using N_{eq} as a function of the Profile number are showed, since this parameter presented the best agreement with the observations.

Model results are not sensitive to the initial conditions applied. The results for the five groups differ only during the first seven months, after which high waves occur and the model results are the same, demonstrating the insensitivity to initial conditions of the number of bars and greater dependence on wave characteristics. The model

evolution during the first seven months is expanded in Figure 6-7, where it becomes clearer that the model results are more dependent on wave conditions and that high waves tend to cause the model results to converge to the same value. Plant et al. (2004) observed in their hindcast prediction of the beach profile evolution at Duck, that the large number of bathymetric calibration data and the relatively small number of free model parameters led to efficient optimization, which did not depend strongly on the initial parameter values used, albeit their model was used in a different time scale, maximum of 17 days of profile evolution hindcast.

Wijnberg and Kroon (2002) reported that the relaxation time of the nearshore system is small compared to the forcing event duration. In this case, each forcing sequence is uniquely related to a particular morphologic response sequence; i.e. independent of the initial morphological condition, a given forcing sequence produces one and the same morphological sequence. In reality, the duration of events is often not long enough to let the bar system reach an equilibrium with the conditions (e. g., Bauer and Greenwood, 1990; Holman and Sallenger, 1993). When the relaxation time is large compared to the duration of the event, the chronology in the forcing events becomes important for understanding the evolution of the bar system.

Table 6-2. Statistics and coefficient values for Walton County.

Walton County - Group 3				
	H_0	H_0/L_0	Dean	Profile
Variance	0.092	0.094	0.062	0.039
R^2	0.581	0.656	0.548	0.747
k_1	0.680	0.597	0.395	0.002
k_2	0.004	0.003	0.008	0.002
k_3	0.320	1.880	2.400	1.900

The simple macroscale model represented the rapid increase in the expected number of bars after events with high energy. During the three energetic events associated with hurricanes Earl and Georges (1999), Ivan (2004) and Dennis and Katrina (2005) the model predicted a maximum average of 2.1 bars after hurricanes Dennis and Katrina. It also shows the slow decrease in the average number of bars after periods with high energy. This process is evident comparing the mild curve slope during periods with smaller energy and the abrupt increase during periods with high energy. The morphological “memory” associated with previous conditions, not represented in the qualitative approach was preserved in the results using the numerical model.

6.5 Volusia County

The four functions for N_{eq} were compared using the data at Volusia. Larger coefficients of determination were found using all functions (Table 6-3). The small quantity of beach surveys is one factor contributing to these larger values. N_{eq} as a function of Dean Number showed the best correlation and smallest variance. Figure 6-8 presents the comparison between survey data and the four different functions. N_{eq} as a function of the wave steepness was the only situation with a different behavior from the others, decreasing the predicted number of bars from the September 2006 to the 2007 survey.

The previous problem in the qualitative approach, with the misinterpretation of the long period when Hurricanes Frances and Jeanne (2004) and later on Wilma (2005) altered the wave conditions, was represented well using the numerical model with the large number of bar variations during this period. The modelled value increased, with a peak of 2.4 during Frances and Jeanne. The changes in the beach morphology, moving

the sediment offshore and increasing the number of bars were predicted by the model and confirmed in the next survey (Figure 6-9).

Table 6-3. Statistics and coefficient values for Volusia County.

	Volusia County			
	H_0	H_0/L_0	Dean	Profile
Variance	0.021	0.056	0.010	0.013
R^2	0.860	0.840	0.990	0.620
k_1	1.210	9.410	0.510	0.002
k_2	0.004	0.003	0.008	0.002
k_3	0.320	1.880	2.400	1.900

The values of k_2 and k_3 were fixed for both Counties, however they changed according to the function used (Tables 6-2 and 6-3). At Volusia, the coefficients were 0.008 day^{-1} and 2.4 day^{-1}, respectively, using N_{eq} as a function of D. If the difference between the N_b and N_{eq} is one, a period of bar decay, it takes 125 days to the bar decay; on the other hand if this difference is -1, a period of bar formation, it takes less than half a day (0.41 days) to create one bar.

Allowing the use of variable coefficients (k_2 and k_3) for each County increased the correlation between modelled and measured data (these results are not presented). However, it is judged that these coefficients are related to the bar mobility and keeping the same value for both counties is more representative of conditions happening in nature.

6.6 Hurricane Season Effects

Seasonal effects can be determined by the model representing the changes associated with different wave heights during the year. An increase in the predicted

number of bars during the hurricane season and a decrease during the following months resulted in the well know storm and normal profiles.

The results from the model appear to have a seasonal signal (Figures 7-5 and 7-8). To investigate this effect in more detail the model results were divided in one year periods and those periods were superimposed. A total of 13 periods were created in Walton and seven periods in Volusia County (Figure 6-10).

The hurricane season in the Atlantic Coast extends officially from June 1st to November 30th, however 96 % of the major hurricane days occurs from August to October (Landsea, 1993). The hurricane influences are evident evaluating these results, where a major increase in the number of bars modelled occurs during this period. In Walton County, the peak number of bars predicted is 2.1 which occurred after hurricane Ike in 2004. After September there is a tendency of a slow decrease in the average number of bars. The seasonal average characteristics for the 13 periods is also plotted on Figure 6-10 and even with dampened values, expected when averages are applied, the same behavior is observed with an increase from 0.9 to 1.2 bars during the hurricane season.

At Volusia, the small values in May 2002, distinct for the rest of the data, are related to the initial condition applied by the model, using the average number of bars in the first survey. The average number of bars in this survey was considerably lower in comparison with other surveys in the same region in the County.

Seasonal effects were even clearer in Volusia County. A minimum average value of 1.55 bars was calculated in the beginning of August with an increase to 1.95 bars one month later, with a maximum average number of bars predicted occurring in the

beginning of November (1.98). The value stays high until February, then starts to decay during a long period of six months, until the beginning of the hurricane season. Two peaks in the model results occurred close to each other, associated with Hurricane Frances (2.36) and Hurricane Jeanne (2.4).

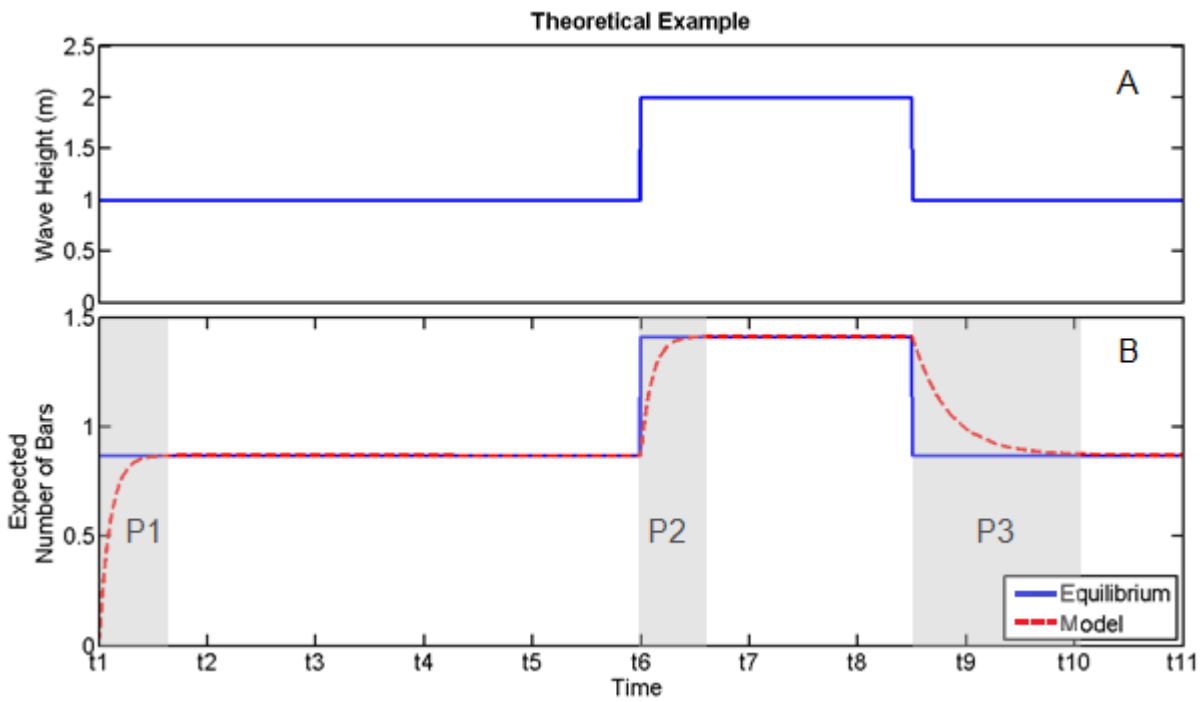

Figure 6-1. Theoretical example demonstrating the model assumptions. A) Wave height. B) The model results (red dashed line) and N_{eq} (solid blue line). The periods where the model is adjusting with the N_{eq} are highlighted in gray. P1 and P2 are periods of bar formation and P3 a period of bar decay.

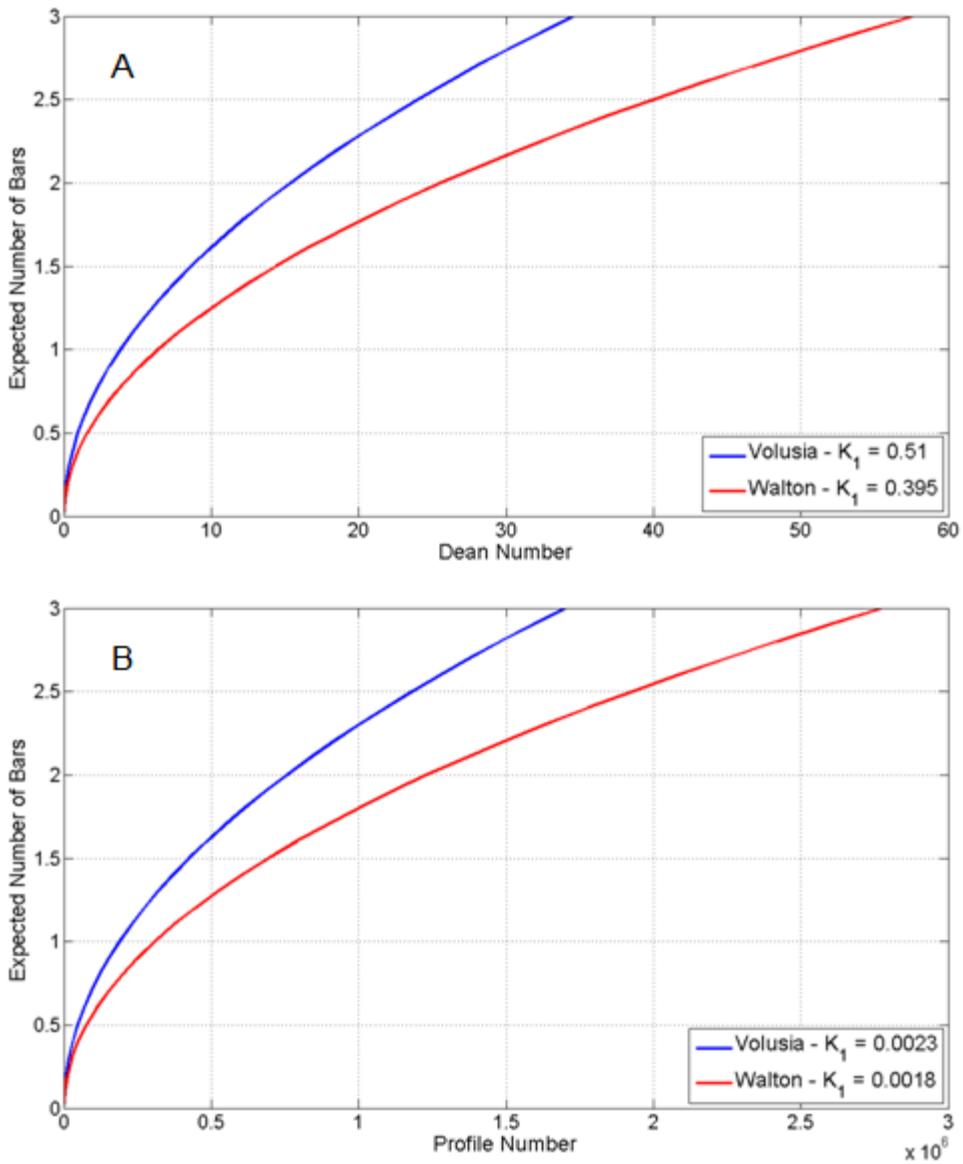

Figure 6-2. Expected number of sand bars. A) Using N_{eq} as a function of Dean Number. B) Using N_{eq} as a function of Profile Parameter, for Volusia (blue) and Walton (Red) Counties. The coefficients used in the equations are also presented.

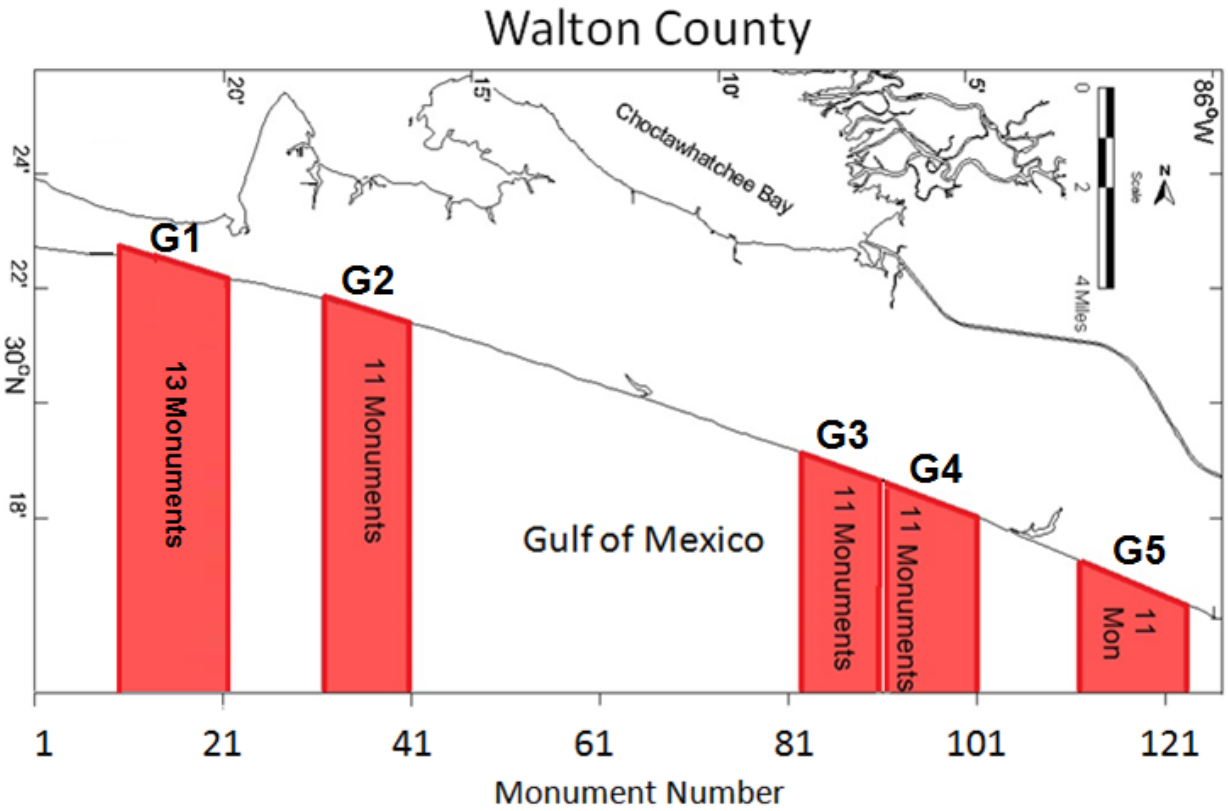

Figure 6-3. Division of the groups with same dates in the seven surveys conducted in Walton County.

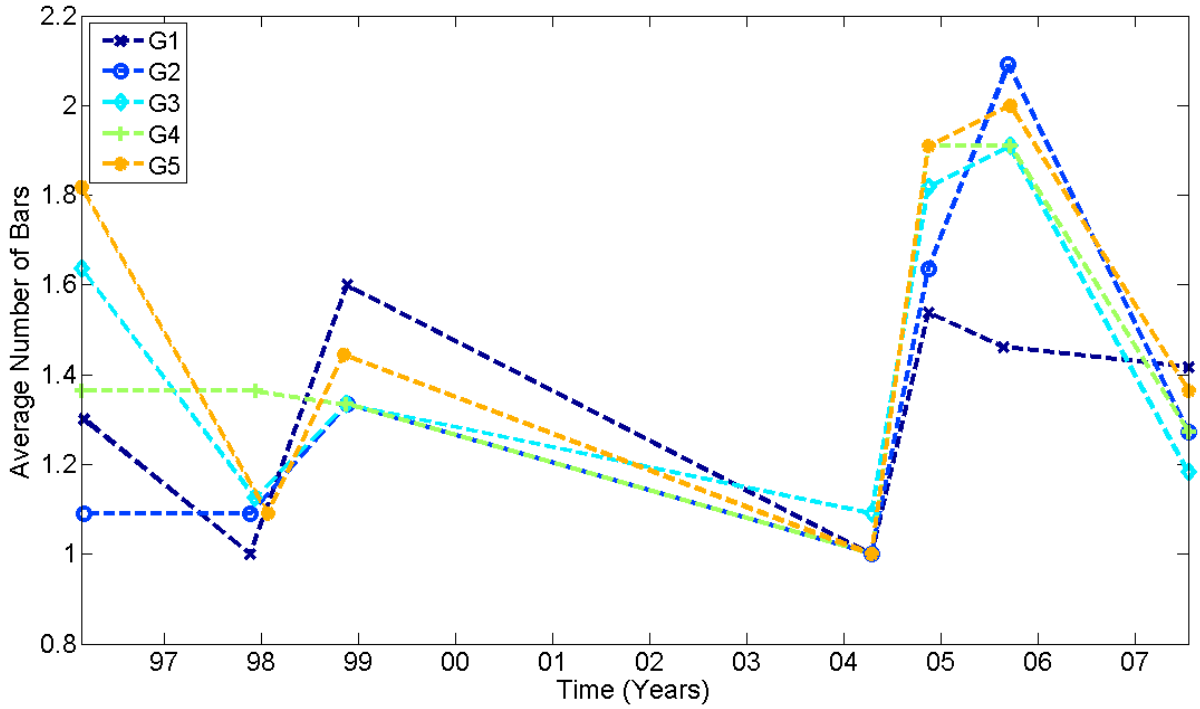

Figure 6-4. Comparison between average number of bars from measured data in the five groups at Walton County.

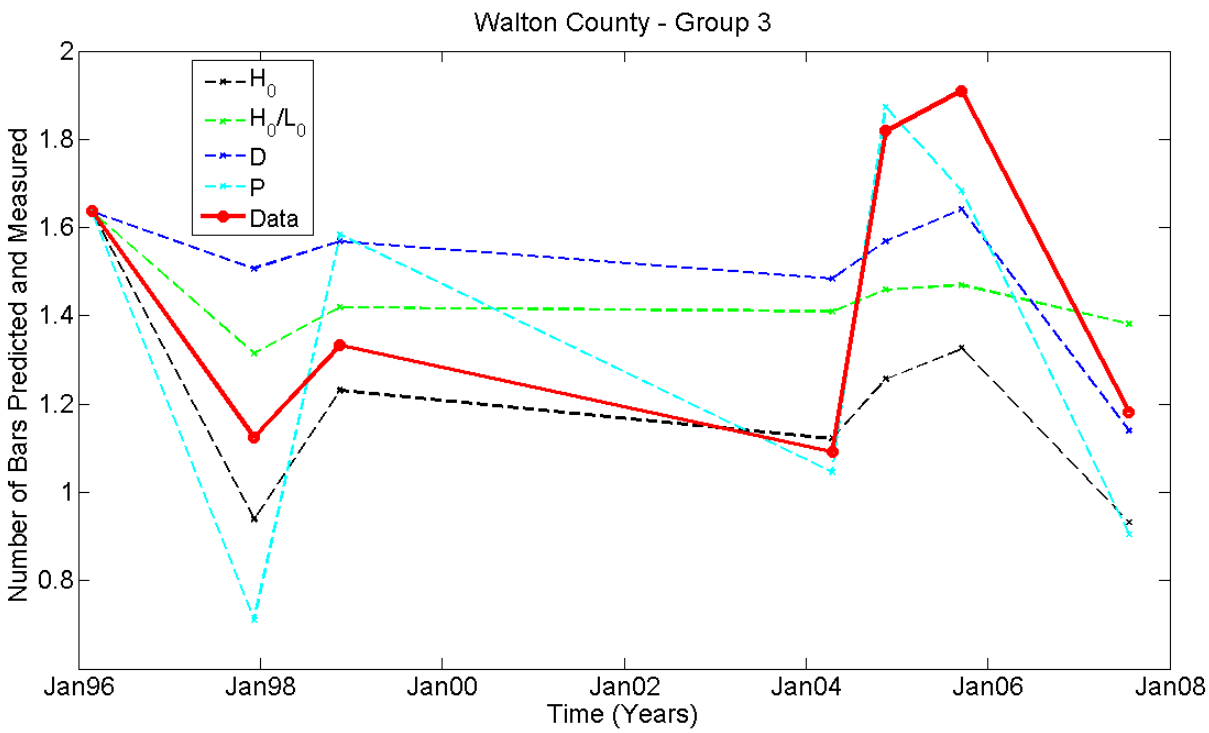

Figure 6-5. Comparison between different N_{eq} functions (dashed lines) used to calculate the number of bars in the nearshore zone for Walton County and measured data (red solid line). The first value is the same for all functions, since it was used as an initial condition.

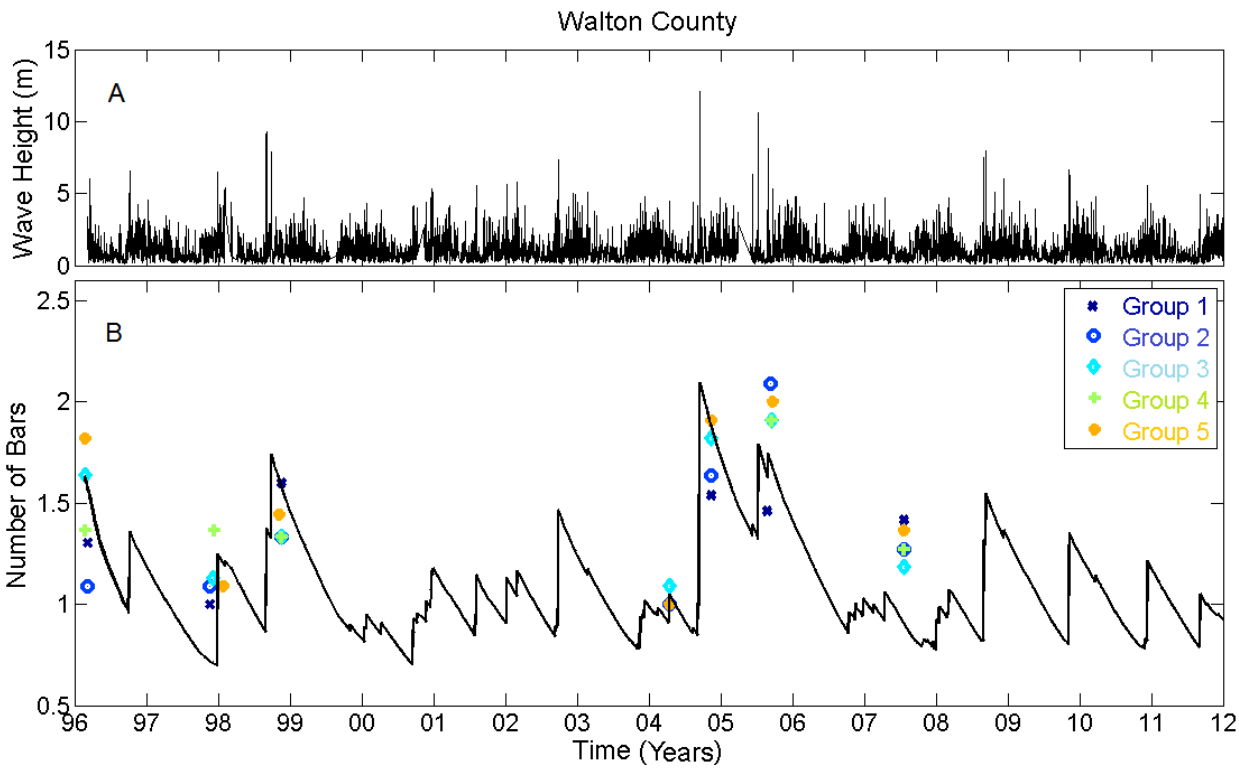

Figure 6-6. Quantitative model results for Walton County. A) Wave height measurements from buoy 42039. B) Predicted number of bars using N_{eq} as function of Profile Number and the average number of bars measured in the five groups at Walton County.

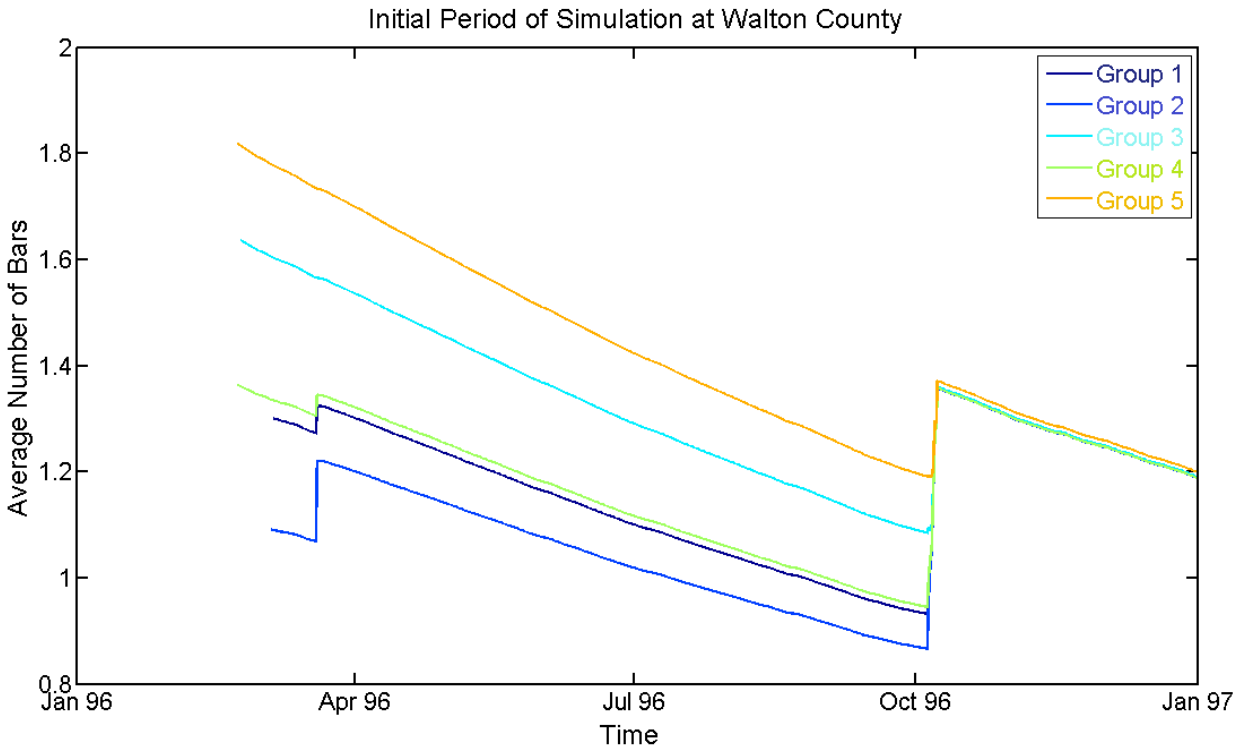

Figure 6-7. Comparison between the number of bars during the initial nine months of simulation for the five groups in Walton County.

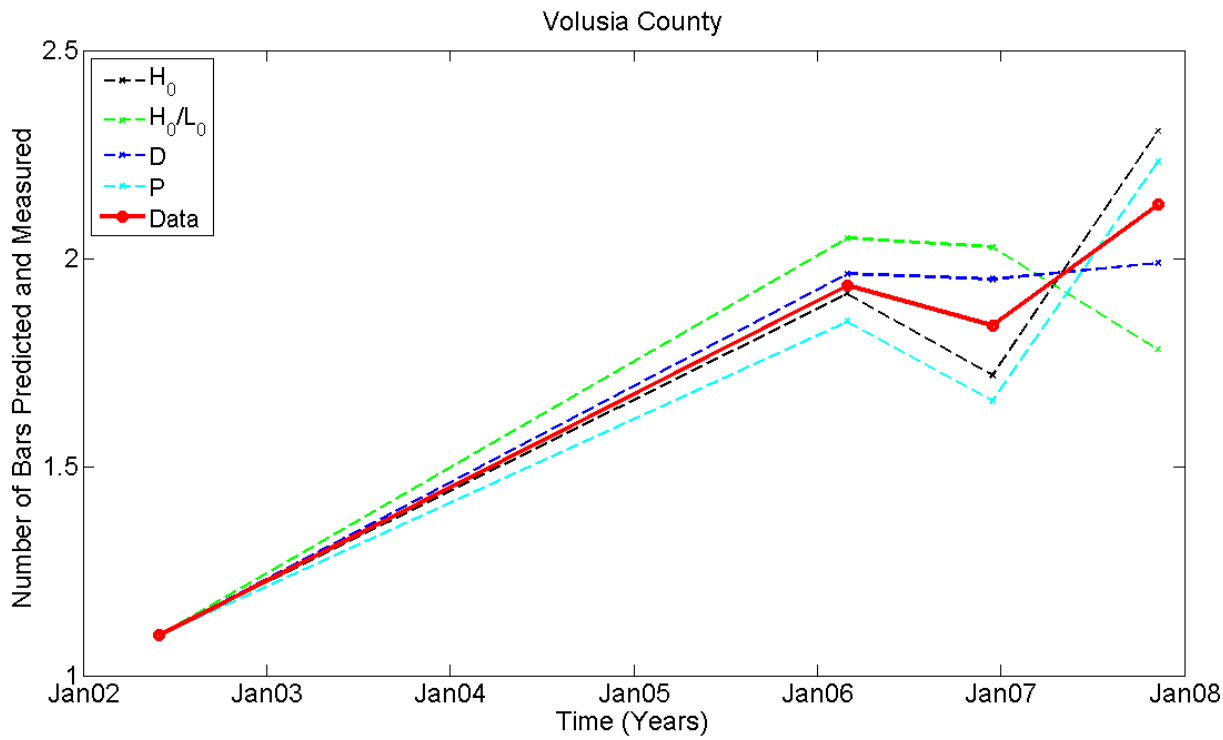

Figure 6-8. Comparison between different N_{eq} functions (dashed lines) used to calculate the number of bars in the nearshore zone for Volusia County and measured data (red solid line). The first value is the same for all functions, since it was used as an initial condition.

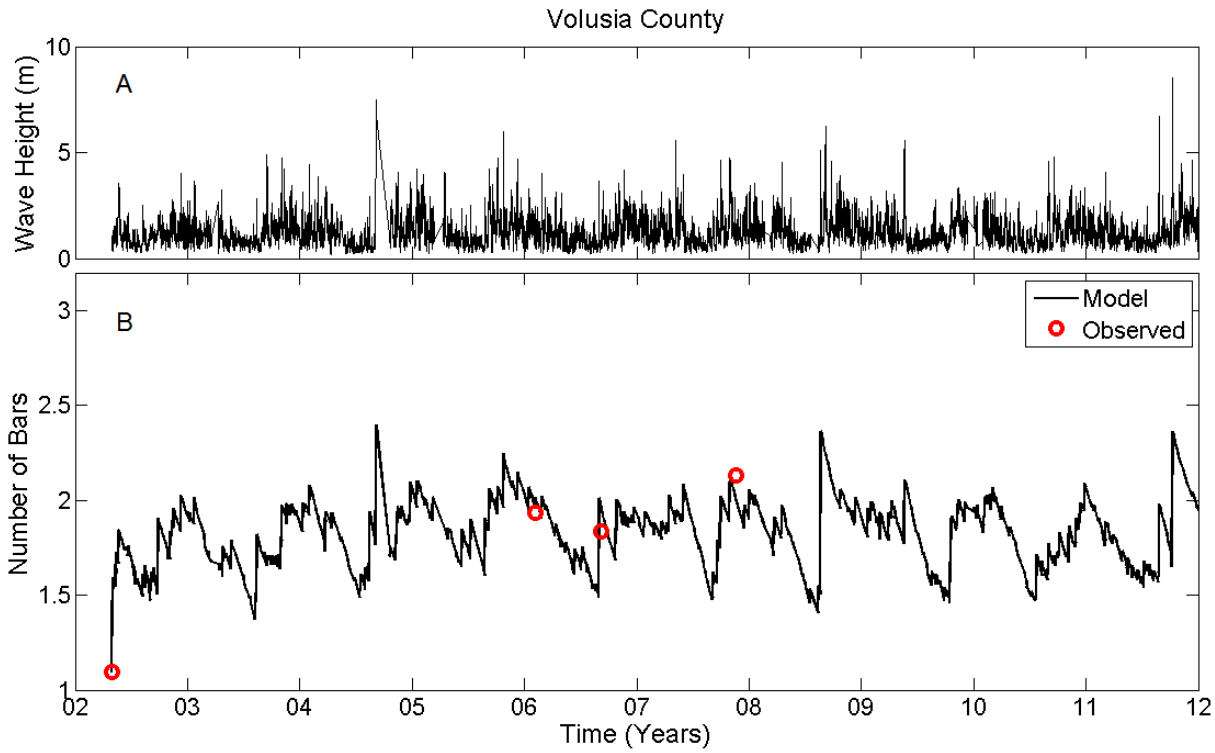

Figure 6-9. Quantitative model results for Volusia County. A) Wave height measurements from buoy 41009. B) Predicted number of bars using N_{eq} as function of Dean Number and the average number of bars measured in Volusia County.

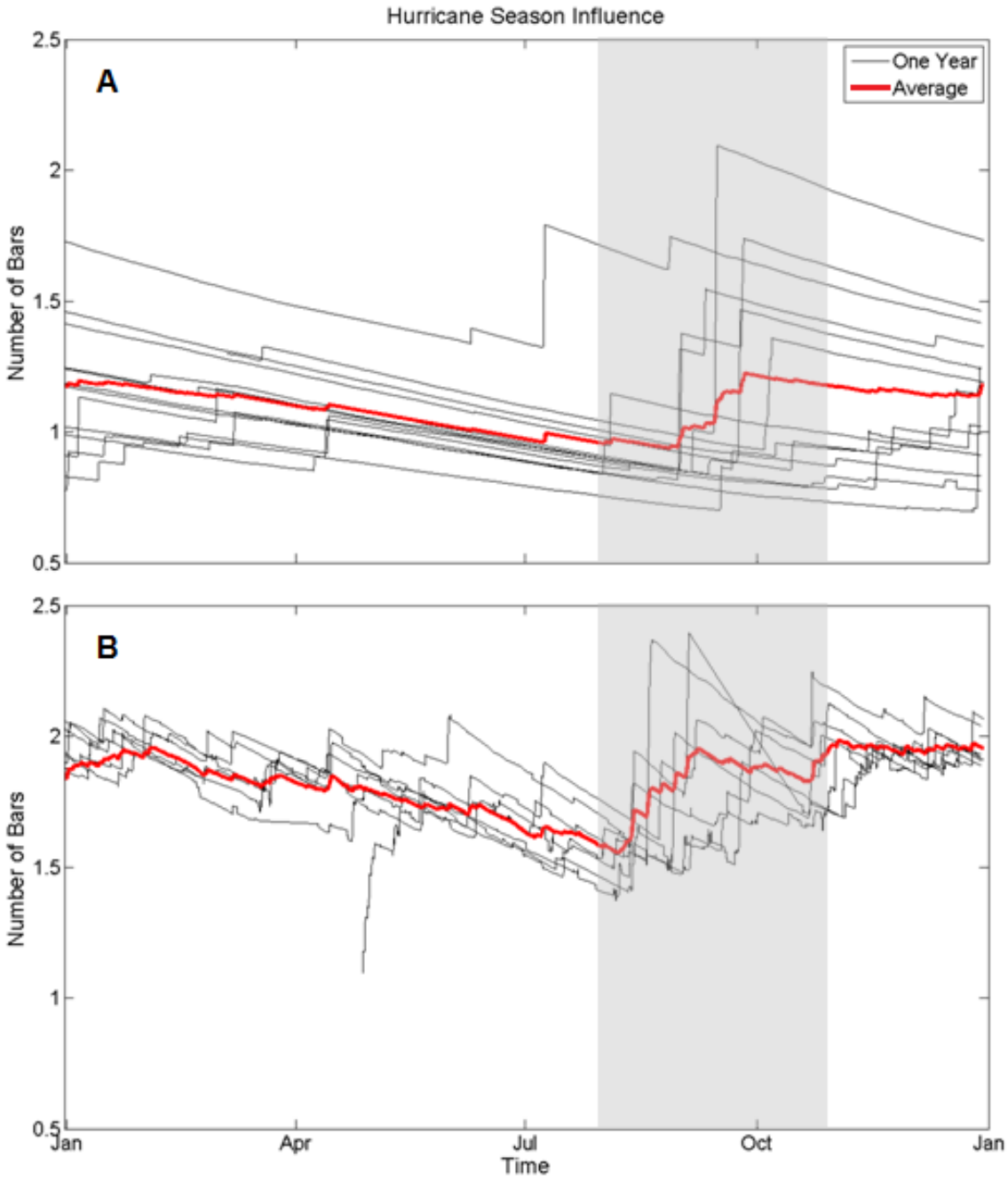

Figure 6-10. Seasonal results obtained from the quantitative model. A) Walton County. B) Volusia County. One year periods (black line) and average season behavior (red line). The period when 96 % of the major hurricanes occur in Florida (gray highlight).

CHAPTER 7
SHORT TERM PREDICTION OF THE NUMBER OF SAND BARS

It was observed that the sand bars at Walton and Volusia Counties are relatively linear and their depths are located in a relatively narrow area of the nearshore zone, especially after major storms. Therefore another method that correlates the number of sand bars with the number and location of the breaking points in the nearshore zone was applied for the same data set described in the previous chapter. This method is focused on the short time scale, or on the sand bar response to wave energy conditions that created the bars. A different focus from the method applied in the previous chapter that described the evolution of the number of bars over a longer time scale (years or decade) is examined here. The Dally, Dean and Dalrymple (1985) wave breaking model was used to calculate the wave height decay in the nearshore zone. This model was applied since it was used in previous research (Dally, 1992; Rakha and Kamphuis, 1995) with good agreement with large wave tank and field data. The model also requires few input conditions, which are the offshore wave conditions and the beach morphology. An advantage of this model when compared with other models that calculate the wave decay in the nearshore zone is that it is able to predict multiple breakpoints and these breakpoints can be associated with sand bar positions. Battjes and Janssen (1978) proposed another method to calculate the wave height decay in the nearshore zone, however that method is not able to predict wave reformation and multiple breakpoints, and it is not possible to correlate the number of breakpoints with the number of sand bars in systems with multiple bars.

7.1 Dally, Dean and Dalrymple Model and Modifications

The Dally, Dean and Dalrymple (1985) model is a two-dimensional model that calculates changes in wave height in the nearshore zone due to wave shoaling and breaking, induced wave setup and bottom stress. The model considers that waves propagating from sloping to horizontal bottom will not instantaneously stop breaking just because the bottom become horizontal (as dictated by the 0.78 criterion), but breaking continues until a stable wave height is attained. The energy dissipation rate per unit plan area is assumed to be proportional to the difference between the local energy flux and the stable energy flux, according to Equation 7-1. Analytical solutions can be obtained using this method for planar and regular sloping beaches and a numerical solution of Equation 7-1 can be used for more complex profiles.

$$\frac{\partial ECg}{\partial x} = \begin{cases} 0 & , EC_g < E_s C_{gs} \\ -\frac{K}{h}\left(EC_g - E_s C_{gs}\right) & , EC_g > E_s C_{gs} \end{cases} \tag{7-1}$$

Where EC_g and E_sC_{gs} are the local and stable energy fluxes, K is a dimensionless decay coefficient and h is the water depth. The two conditions on Equation 7-1 apply after the first break and before the first break Equation 7-1 is always zero.

The model utilizes two threshold values to predict the initial breaking position and the position where the waves stabilize and start to shoal again (stability criterion). Both criteria depend on the water depth. In contrast with the original model, these two threshold values were not constant in the applications herein. The breaking criterion, the threshold value that determines where the waves start to break, is associated with the beach slope, therefore a larger breaking criterion was used in the simulation at Walton, since the profiles at Walton are steeper than at Volusia.

The stability criterion varied also according to the beach slope. The stability criterion for profiles with steep slopes are smaller, since the waves suddenly break in an narrow zone with plunging breaker characteristics and dissipate larger amounts of energy in a specific zone (Ting and Kirby, 1994). Wave stabilization and a second shoaling and breaking process happens less frequently in beaches with steep slope. Figure 7-1 shows the relation of the beach profile with the breaking and stability criteria, where the importance of the bar troughs in stabilizing and commencing the second shoaling process is shown.

7.2 Role of Sand Bars in the Breaking Process

Simulations were conducted to investigate the role of the sand bar as a trigger to the breaking waves and to evaluate focusing effects caused by the bar crests on the breaking waves, where waves with different heights break in a relatively narrow zone on the bar crest. This phenomenon was observed by studies using video cameras to monitor the beach (Lippmann and Holman, 1990). An example of this simulation is showed in Figure 7-2 for a profile with three bars (this was the maximum number of bars observed in a single profile in the database).

This simulation consisted of three separate steps where the sand bars, from the outer to the inner bar, were subsequently included in the simulations after each step and the breakpoint position compared with the bar crest position. Actual beach profiles with three bars from Volusia County were used in these simulations. To initiate the first step, the offshore wave height was determined to shoal in the nearshore zone and to break over the offshore bar crest. An offshore wave height of 1.5 m was used in this simulation and the wave shoaled until the offshore bar crest (835 m from the MHW), where it achieved the breaking criterion with a wave height of 2.1 m and commenced

breaking. This wave dissipates its energy until the stability criterion was reached in the bar trough (at 863 m). After this point the wave re-shoaled and broke again with 1.5 m height at 986 m and the stability criterion wasn't attained and the wave did not shoal a third time. However, the location of the second break in the model is 35 m onshore of the second bar crest (Figure 7-2A).

The second step was initiated including the second and third bars (the first or inner bar was not present in this simulation) and it is shown in Figure 7-2B. The wave height follows the same distribution until the first breaking point, however after that, the second bar changes the beach profile and forces the wave to break offshore (934 m) when compared with the first step (986 m), reinforcing the concentration of breaking waves on the top of sand bars. The bathymetric change, including the second bar, triggered the third breaking processes that occurred at the original third bar location (1,024 m). The third breaking is only possible because the beach slope is gentle (1:48) and there is enough distance for the wave to shoal, if this profile was steeper, the wave would reach the shoreline before shoaling to a breaking height.

The last simulation, the third step, used the original profile, with three bars, and the results were very similar to the simulation without the first bar. The only difference is that the third break was 10 m farther offshore than with the second step. The fourth break wasn't observed, which was a positive result, as this beach profile has only three bars (Figure 7-2C).

The same procedure, a simulation with three steps, was applied on other profiles with three bars at Volusia and similar results were obtained, demonstrating the sand

bars potential to focus the wave energy during the simulations and the good correlation between the number of breaking points and number of sand bars.

7.3 Prediction of the Number of Sand Bars

The simulation presented in section 7.2 confirmed that the sand bars are able to focus the waves breaking on their crest and predict correctly the number of breaking points on the profile can be used as an indication of the number of bars in the nearshore zone. This is the assumption used by the video camera systems, like Argus and CamEra (developed in USA and New Zealand, respectively), to monitor the nearshore zone and sand bar behavior (Lippmann and Holman, 1990; Aarninkhof et al., 2003).

The second application of the Dally model was to predict the number of sand bars in the cross-shore profile. In this application only the surveys conducted on the same day (described in section 6.3) were used for the analysis. The simulations were conducted similarly as described in the previous section, forcing the waves to break at the offshore bar, however the bars were not removed and the original profile (with one, two or three bars) were used. Breakpoints in depths shallower than 0.6 m were not considered in the analysis, since these shallow breakpoints are not directly associated with sand bar formation and they are more correlated with swash processes. Figure 7-3 shows one example where the model was applied in a profile with two sand bars in Walton County and the model predicted two breaking points. It is important to reinforce that the third breakpoint, at 0.2 m water depth in this case, was removed from the calculation and not correlated with a sand bar location.

The same process was repeated using profiles obtained during four surveys at Walton County to evaluate the model capability to predict the number of bars in conditions with high and low waves. The model predicted well the number of sand bars

that occurred in the surveys conducted after Hurricanes Ivan and Katrina, with 71.9% and 70.7% of agreement between the number of bars and the number of breakpoints considering all five groups. Table 7-1 summarizes the results obtained for each of the five groups and also for all the groups together. These values are considered favorable since there are differences in the morphology between the profiles. An over prediction of the number of breakpoints, instead of under prediction, was observed in the majority of the situations where the number of breakpoints and the average number of bars were different. This can be explained because the beach profiles used here are a snapshot representing the energy balance between constructive and destructive forces acting at the beach in the moment prior to the survey and morphologic features that are evolving to became a bar or that are decaying after being a bar are not considered, using just the profile snapshot. This difference is also associated with the abrupt limits used to define sand bars in this dissertation, since no visual interpretations or adjustments were applied to compensate transitory stages in the data.

Table 7-1. Results obtained with the model simulations for four surveys in Walton County. The results are divided according to the beach profiles that were surveyed in the same date. The values indicate the simulations that correctly predicted, over predicted and under predicted the number of bars.

Surveys	1-Apr					Nov-04					Aug-05					Jul-07				
Groups	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Correct	7	6	9	8	5	7	9	9	8	8	5	10	8	10	8	5	5	2	3	4
Over	0	2	0	1	3	0	0	0	1	0	0	0	1	0	1	5	1	0	0	0
Under	6	3	2	2	2	6	2	2	2	3	9	1	2	1	2	3	5	9	8	7
Total (%)																				
Correct	62.5					71.9					70.7					33.3				
Over	10.7					1.8					3.4					10.5				
Under	26.8					26.3					25.9					56.1				

The model is sensitive to changes in the beach slope and the over prediction of sand bars was usually associated with locations with abrupt changes in the beach

profile slope where sand bars were not present. One profile was predicted to have two bars by the model (two breakpoints), but is actually a profile with only one bar (Figure 7-4 exemplifies this situation). The wave shoaled until the offshore bar at 353 m and started to break, the wave shoaled for a second time after reaching the stability criterion and broke the second time at 549 m, in a location without a sand bar but with an abrupt change in the beach slope.

Table 7-2. Results obtained with the model simulations for four surveys in Volusia County. The values indicate the simulations that correctly predicted, over predicted and under predicted the number of bars.

Survey	Jan-02	Feb-06	Sep-06	Oct-07
Correct	6	20	26	18
Over Predict	1	1	0	4
Under Predict	24	10	5	9
Total (%)				
Correct	19.4	64.5	83.9	58.1
Over Predict	3.2	3.2	0.0	12.9
Under Predict	77.4	32.3	16.1	29.0

The other two surveys to which the model was applied occurred after calm periods and the sand bar depth and position were not necessarily associated with the offshore wave conditions (as in the two surveys described previously), but they were influenced by different wave conditions. Smaller wave heights pass directly without breaking on the outer bar causing minimum effects on them. However these waves influence the behavior of the inner bar, changing their depths and positions. The model results for pre-Ivan still presented a good correlation between the number of bars and the number of breakpoints, where 62.5 % of the situations were correctly predicted. However the results in the August 2007 survey were only correct to 33.3 % of the profiles, indicating a methodology limitation for conditions associated with bar formation or migration to deeper areas. When there are large periods between the bar formation and the

application of the model (when surveys are available), the conditions that occurred between them act to modify the profile to the new forces.

At Volusia County the surveys were conducted for long periods after major energetic events. The results for all surveys at Volusia County are presented in Table 7-2. The 2002 survey has most of the profiles with only one bar and the model correctly predicted only 19.4 % of the profiles in this situation. Most of the model results, again, over predicted the number of breakpoints during this survey. The presence of a well developed bar trough and steep slope right after the trough in most of these profiles created the conditions to the waves stabilize at the trough and break for the second time in the steep slope onshore of the trough (Figure 7-5).

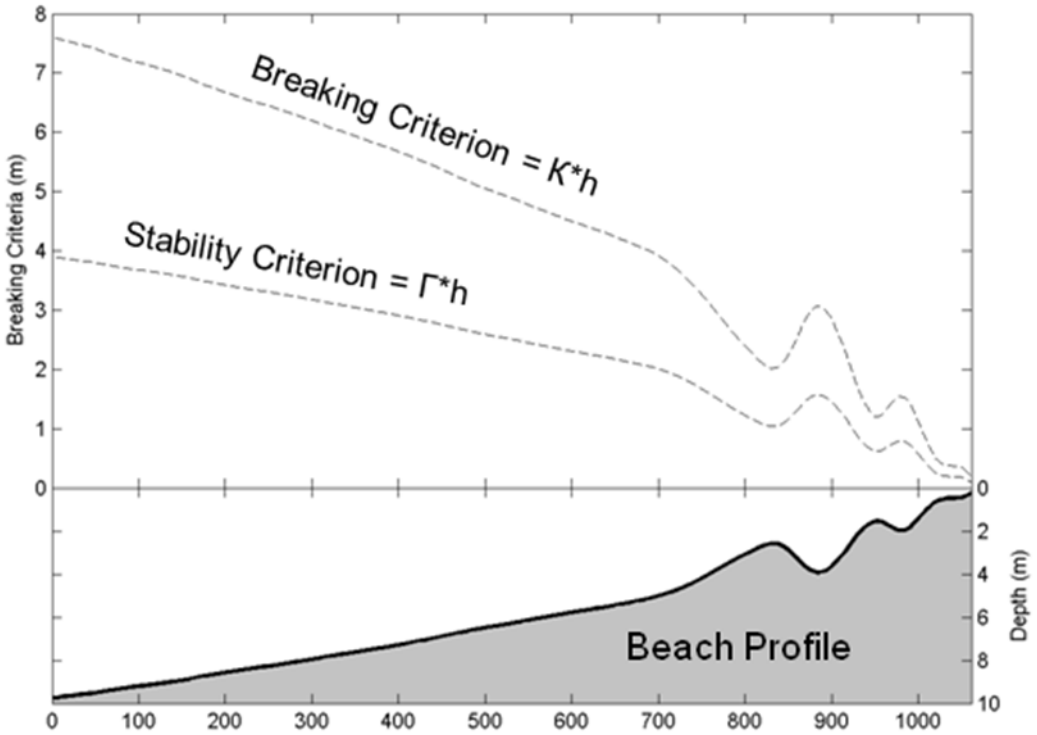

Figure 7-1. Representation of the breaking and stability criteria (dashed lines) used in the Dally, Dean and Dalrymple model. The offshore waves start to break after attaining the breaking criterion and stop breaking and start to shoal after attaining the stability criterion. Both criteria are linearly dependent on depth.

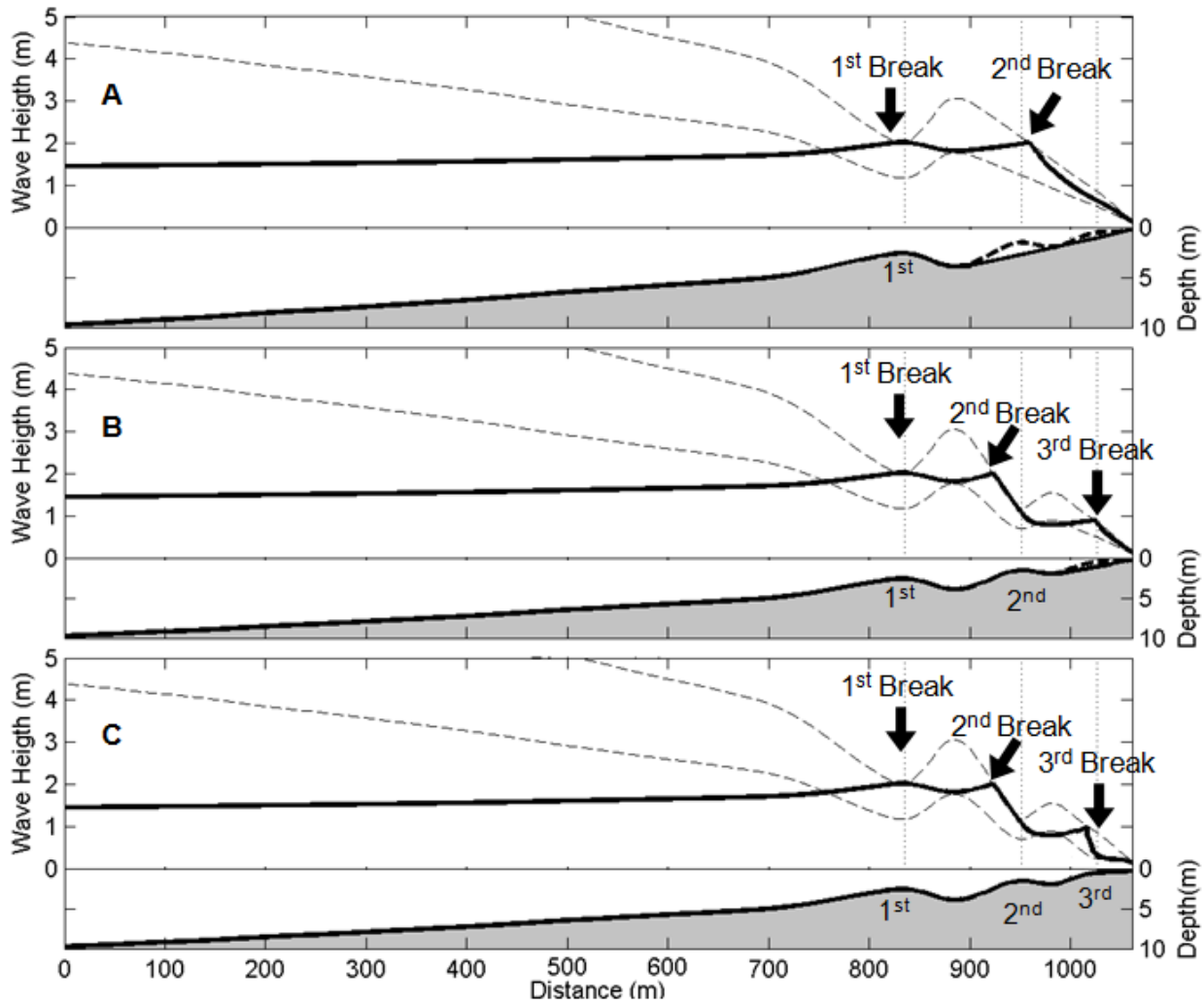

Figure 7-2. Three steps of the simulation showing the sand bar importance on the breaking processes and wave height decay inside the nearshore zone. A) The first step only with the offshore bar. B) The second step including the second bar. C) The third step including the inner bar and applying the simulation in the profile with all bars.

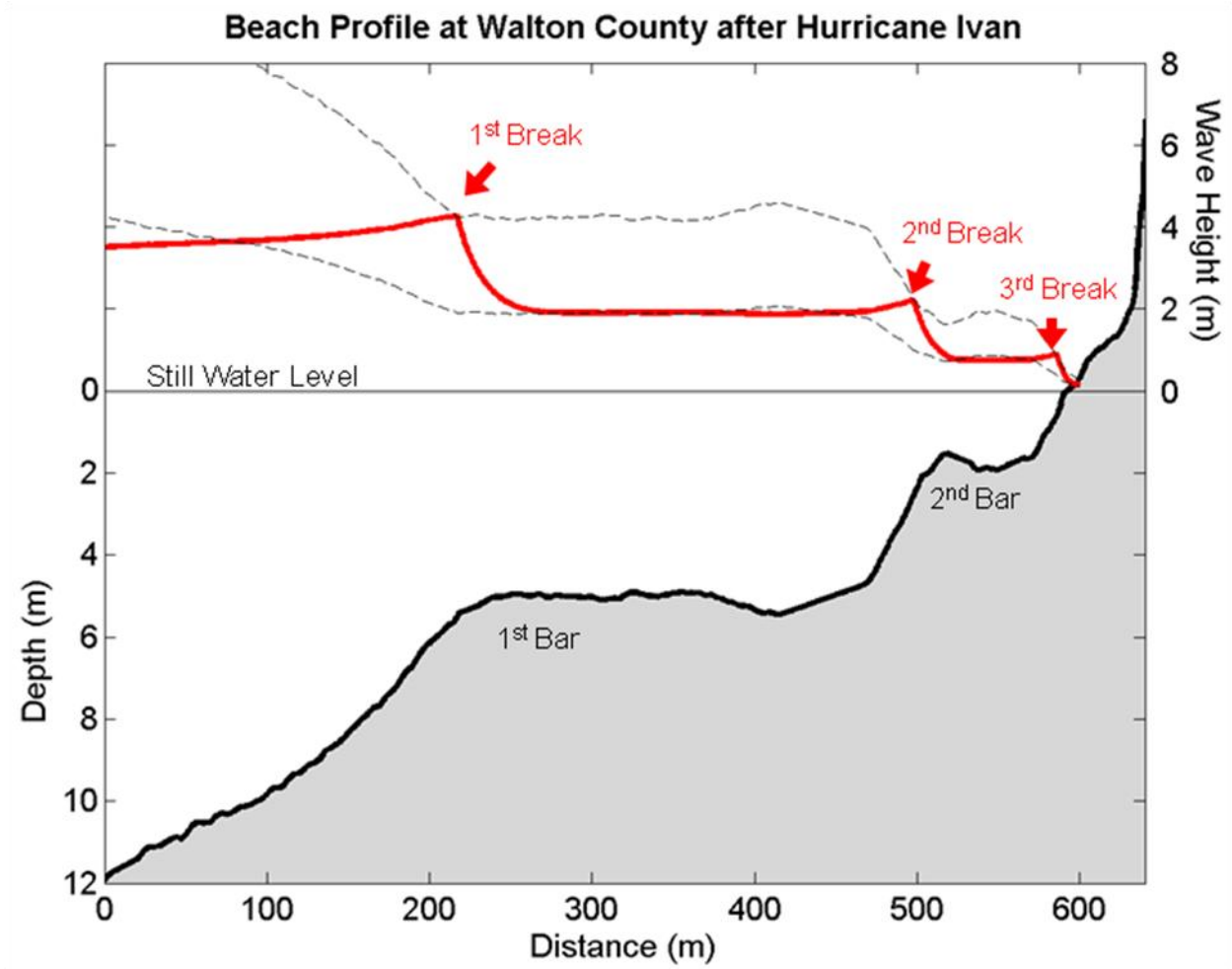

Figure 7-3. Model application to predict the number of sand bars in the nearshore zone. The wave height (red line), breaking criterion (upper black dashed line), stability criterion (lower black dashed line) and beach profile (black solid line). The third break (close to the shore) is in shallow waters (smaller than 0.6 m) and was not considered.

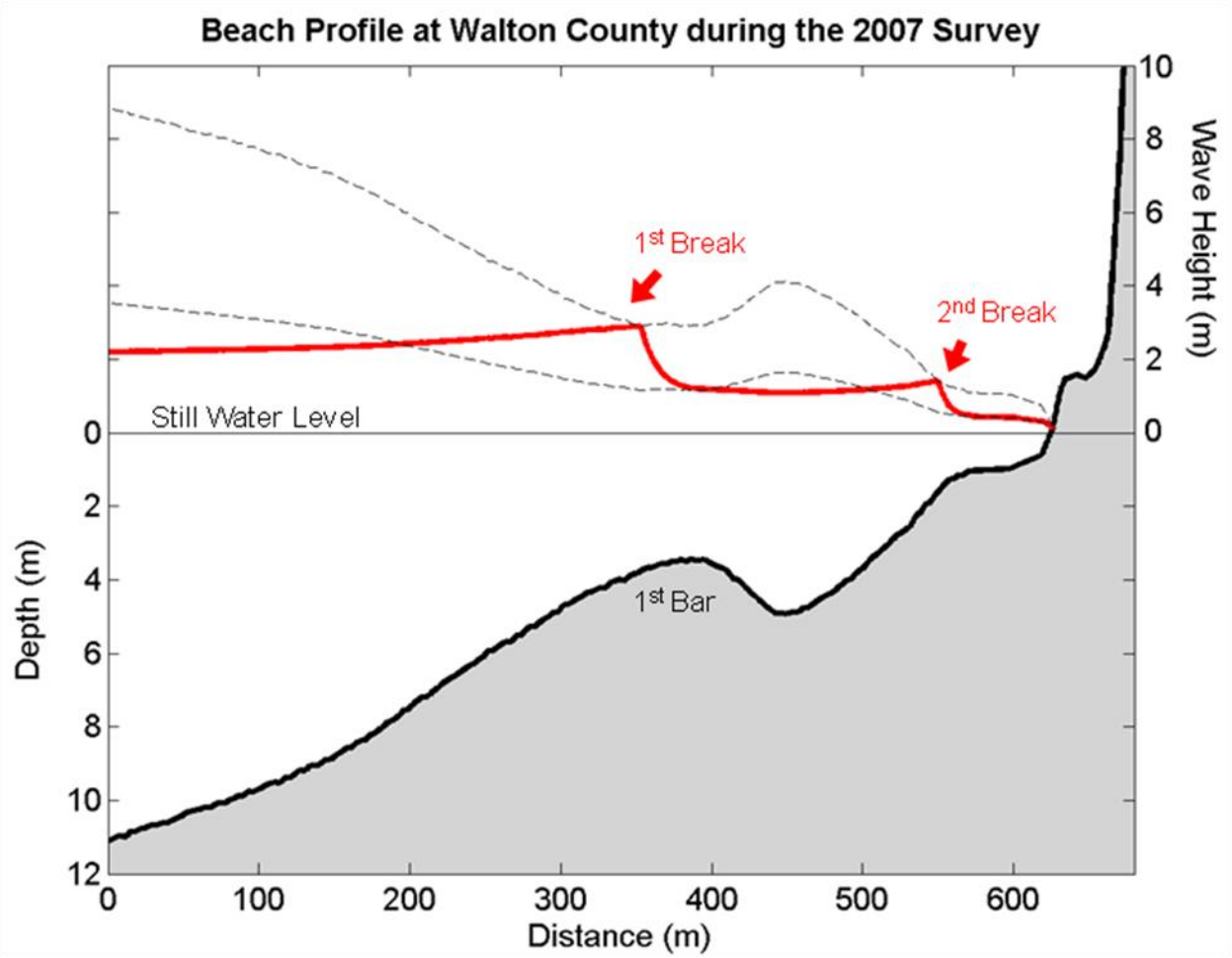

Figure 7-4. Simulation where the second breakpoint is associated with an area with abrupt change in the profile slope and not to a sand bar. The wave height (red line), breaking criterion (upper black dashed line), stability criterion (lower black dashed line) and beach profile (black solid line).

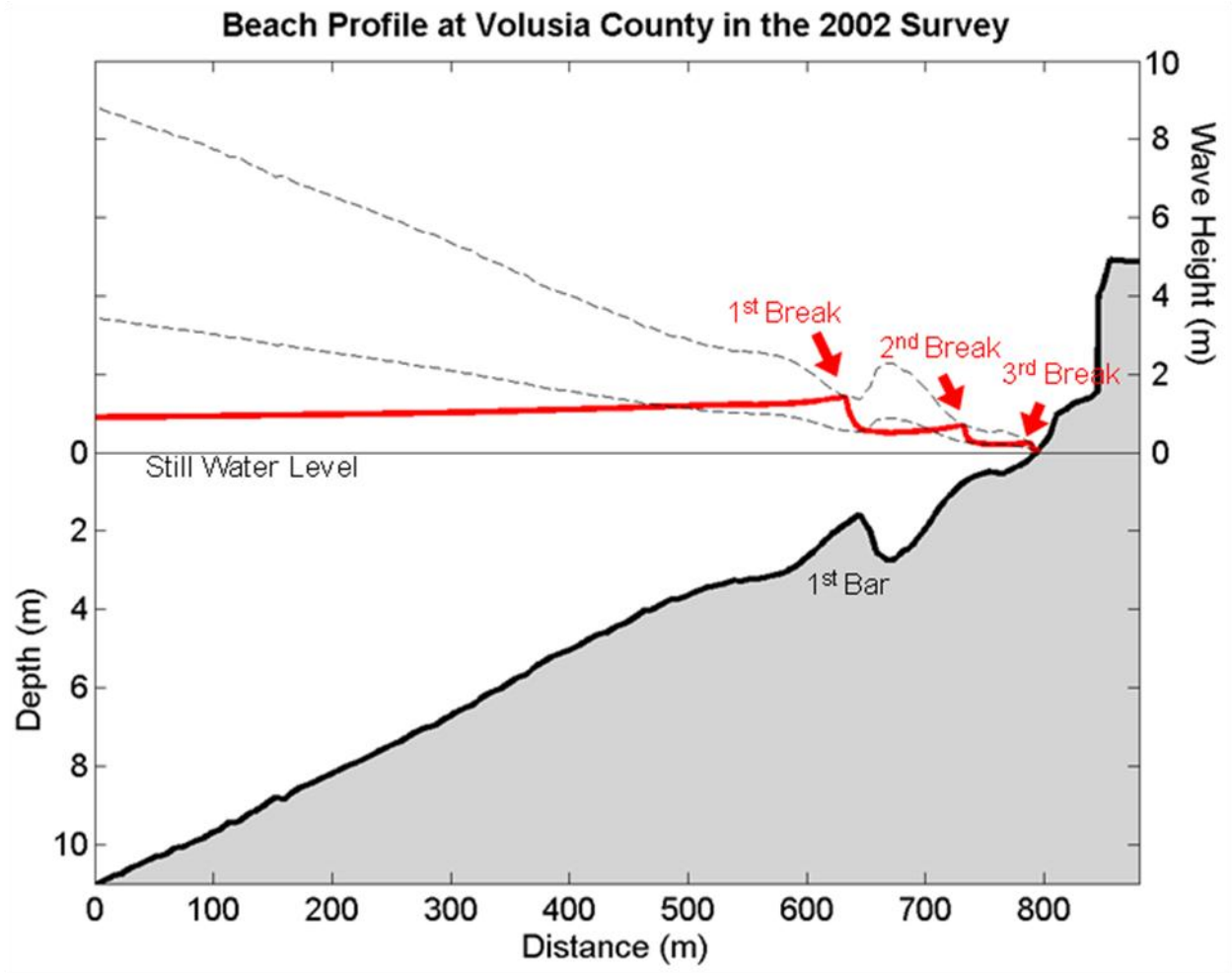

Figure 7-5. Example of the breakpoint associated with a developed bar/trough system in Volusia County. The wave height (red line), breaking criterion (black dashed line), stability criterion (lower black dashed line) and beach profile (black solid line). The third break (close to the shore) at 0.15 m water depth was not considered, since it is shallower than the 0.6 m limit.

CHAPTER 8
CONCLUSIONS

Sand bar dynamics were discussed in terms of long and short time scales, using observation and modeling, to describe their response to different wave conditions and the interaction between bars in systems with multiple bars.

In the long term scale, the simple quantitative macroscale model addressed previous limitations and showed a considerable improvement compared with the qualitative approach. The period between surveys is irrelevant using the quantitative method, since the model is based on wave and beach characteristics and accounts for the “memory” effects of the profiles.

Neq, the number of bars in equilibrium for the current conditions, as a function of the Profile Parameter and Dean Number presented the best results for Walton and Volusia Counties, respectively. These parameters emphasize that the sediment size plays an important role in determining the average number of bars, since the other two parameters that don’t include sediment size presented weaker agreement.

The hurricane season influences are evident for the bar formation and to the increase in linear morphologies. In both counties an increase in the average number of bars occurred mainly during a short period of three months. During the reminder of the year, a decrease in the number of bars was observed, associated with onshore movement of the sand bars when the wave energy is mild.

The comparison between the quantitative model at Volusia and Walton Counties showed maximum and mean number of bars greater at Volusia, which was expected and previously observed in the measured data, since Volusia County has a smaller sediment size, milder beach slope and is exposed to higher wave energy.

The short term model (Dally, Dean and Dalrymple, 1985) based on the assumption that bars are formed under the breakpoints predicted the number of bars in the nearshore zone when the beach profiles were conducted close to the wave forcing that generated and influenced the sediment transport. The predictability decreased when surveys were conducted long periods after major storms and different wave conditions influenced the profiles.

The inner and outer bars behaviors are closely associated in nearshore zones with multiple sand bars. It was observed that the outer bar acts as a filter to the high waves and it is mainly influenced by major storms. The inner bar is influenced by a different set of smaller wave heights, since it is protected by the outer bar. The study of the nearshore zone with multiple sand bars should be conducted including all the bars, otherwise misinterpretation can cause erroneous solutions for coastal problems or coastal management plans.

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BIOGRAPHICAL SKETCH

Luciano Absalonsen received his B.Sc. in oceanography at FURG, Brazil, where he discovered oceanography and his especial interest in coastal processes arouse. He finished his master's in marine geology (UFRGS, Brazil), working with his adviser, Dr. Elírio Toldo Jr., focusing his research on the study of shoreline evolution and understanding processes responsible for beach erosion or advancement. He met his Ph.D. adviser, Dr. Robert G. Dean, during a beach nourishment course offered in Brazil and came to the University of Florida, as a Fulbright scholar in August 2008, developing his research on the behavior of sand bars. Luciano is honored to receive his Ph.D. in coastal engineering and hopes to be working in this fascinating world for the rest of his career.