

Abstract

FREQUENCY/MAGNITUDE ANALYSIS OF WAVE EVENTS AT DUCK, NORTH
CAROLINA

by

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There is a great need for predicting shoreline and beach change due to storms. Firstly, shoreline erosion rates along the East Coast are as high as 70%. And more importantly, people live along the coast. Between 1980-2003 33 million people moved to the coast. Previous research includes looking at successive before and after storm profiles and the application of the partial duration approach for classifying storms events. Storm scales and indicators are widely created but most are qualitative in nature, therefore making them not useful for predicting future events.

Frequency/magnitude in geomorphology quantifies events and puts them into context with regards to integrated landscape change. Past research has concluded that events of moderate frequency/magnitude transport the most sediment along a beach profile. Wave data from the USACE Field Research Facility (FRF) at Duck, North Carolina are used to perform a partial duration series analysis for determining wave events. The standard energy equation along with a duration component is used to quantify event magnitude and the total event energy is standardized into a storm index, based 0-10. Profile data was acquired to determine the beach change associated with these wave events.

It was found that events of low magnitude produced the most change on the beach. There was a great amount of volumetric variability between the profiles suggesting the need to incorporate wave angle to account for alongshore transport of sediment. There is also a need to extend profiles past the 8m depth to fully account for total volumetric change.

FREQUENCY/MAGNITUDE ANALYSIS OF WAVE EVENTS AT DUCK, NORTH
CAROLINA

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By

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CHAPTER 1: INTRODUCTION

Overview

There is great importance in studying land-sea interactions. A key reason for studying land-sea interactions is the fact that the coastal population is rapidly increasing. The population continues to grow in already densely populated coastal areas, increasing by 33 million people between 1980 and 2003 (NOAA, 2005). Another reason for studying these land-sea interactions is the fact that estimates of the proportion of coasts that are currently eroding are as high as 70% (Davis & Fitzgerald, 2004). According to the North Carolina Division of Coastal Management erosion rates are as great as 30 ft/yr along some portions of the North Carolina coast (1998). The combination of eroding shorelines, and the increasing population, makes shoreline/beach erosion a serious problem (Davis & Fitzgerald, 2004).

Numerous studies have examined the phenomenon of land-sea interactions. An early study by Bascom (1959) investigated the relationships between sand size, beachface slope, and wave energy and found that beach-face slope is principally controlled by the size of the sand and the intensity of wave action. Nordstrom (1980) explored the cyclic and seasonal responses of the beach by comparing oceanside and bayside beaches. Nordstrom concluded that cyclic development (change between the storm and non-storm beaches) may be causally related to the difference between the energy levels during storm and non-storm wave regimes. In a study of beach changes on the Outer Banks of North Carolina, Dolan (1966) found that large waves with high water levels cause rapid reductions in beach thickness (volume/depth), width, and slope while small waves with low water levels were associated with thicker, wider, and steeper beaches.

As a result of studies such as these, an accepted model of beach response was developed that involves the transfer of sediment from the beach to the offshore during storms and the return of the sediment back onto the beachface during quiescent periods, causing the beach to accrete. Beach erosion is the result of increased wave heights generated during the storm; the most obvious destructive force is that of gravity coupled with the destabilizing effects of turbulence induced by wave-breaking (Dean, 1991). Wright and Short (1984) showed that wind and wave energy are extremely important in effecting the dynamics of beach morphology (1984). Because wave energy induces the most work on the beach, especially during storm events, it is valuable to focus on waves as the dominant agent of change in beach systems.

There have been an ample number of studies examining the successive before and after response of a profile to a storm event (Bascom, 1959; Komar, 1976; Larson & Kraus, 1994; Zhang et al., 2000, 2002; Birkemeier et al., 1999). These studies have investigated how the shoreline migrates according to storm magnitude by focusing on the migration of offshore bars and assessing volumetric change. Studies by Savage & Birkemeier (1987), Lee et al. (1995; 1998) and Birkemeier et al. (1999) have analyzed storm wave characteristics and the probability of occurrence of storm events. There have also been numerous storm scales and indicators devised (Dolan & Davis, 1992; Sallenger, 2000; Judge et al., 2003). The problem with these classifications schemes is the fact that they are mostly qualitative in nature which does not allow for predicting future events and associated storm damage.

A common analytical approach in geomorphology focuses on the frequency/magnitude of events. Frequency/magnitude was first introduced by Wolman & Miller (1960), who asked an extremely fundamental question regarding the greater importance of small or large events in changing the landscape. They discovered that events of moderate magnitude produce the most

change to the landscape. Frequency/magnitude analysis is quite common in hydrology to determine the probability of occurrence or return interval of floods. The concept of frequency/magnitude attempts to bridge the gap between short and longer term landform changes by placing individual events into a longer-term context.

The goal of this research is to understand the process-response relationship between changes in wave energy and the associated response of the beach. The study focuses on storm events much like hydrologic studies focus on flood events. Coastal storms consist of inputs of energy over a period of time. There is a total amount of energy associated with each event that is a function of the wave size (energy) and of the event's duration. In turn, the wave energy and duration produces a response in the landscape-beach/dune change. The objective is to equate event magnitude to the landscape response.

Research Questions & Objectives

Given that the general model of beach response to storms suggests volumetric loss of sediment on the upper subaerial part of the profile, it is logical to hypothesize that the beach response should increase directly with increased storm energy (Bascom, 1959; Dolan, 1965; Komar, 1976). In this study, frequency/magnitude analysis is explored as a way of quantitatively classifying storms. Storms are considered a cohesive unit of energy to be expended upon the beach. This thesis examines two specific research questions:

1. Can a storm event be defined according to a designated threshold through a frequency/magnitude analysis and classified according to energy?
2. Is there a measurable relationship between overall beach change and energy of storms?

There has been limited use of a frequency/magnitude approach in the analysis of storm/beach interaction. There is great importance for applying frequency/magnitude in geomorphic studies involving coastal storms as coastal storms imply energy. By considering event energy, the probabilities of an event impacting the beach will be facilitated.

When considering the second research question general beach profile theory points out that after the passing of storm, in general, sediment is moved from the upper portion of the profile and deposited along the lower portion of the profile. If an event can be determined from the record then volumetric change can be assessed for that event by viewing the profile for both before and after the event. Theoretically, if events can be extracted from the long term record and volumetric change can be assessed from a corresponding event, then a relationship between event magnitude and geomorphic change associated with that event should be capable.

Study Area

The United States Army Corps of Engineers (USACE) Field Research Facility (FRF) is located along an approximately 1-km long stretch of Atlantic Ocean barrier island beach in Duck, North Carolina (Figure 1). The site was chosen for this facility because it was distant from coastal structures, affected by the high frequency of storms and hurricanes, with limited affect of inlet processes in addition to the fact that the land was already owned and used by the military (<http://www.frf.usace.army.mil/>). The primary mission of the FRF is to collect measurements of the waves, currents, winds, and sediment transport, and to understand the relations between these elements. The data collected at the FRF is incomparable to any other location with regards to the temporal resolution and frequency of data collection. Most of the data collected at the FRF can be obtained for 1981-present. Figure 1 also shows all the buoys

used at the FRF to collect wave data (7 buoys). A station set-up by NOAA is located at the end of the research pier to collect both wind and tide data. The profile data at Duck is conducted on a monthly and bi-weekly basis. The frequent passing of storms and available wave, tide, and profile data make the FRF at Duck, NC the ideal study site for understanding how storms of different frequencies and magnitudes impact the beach.

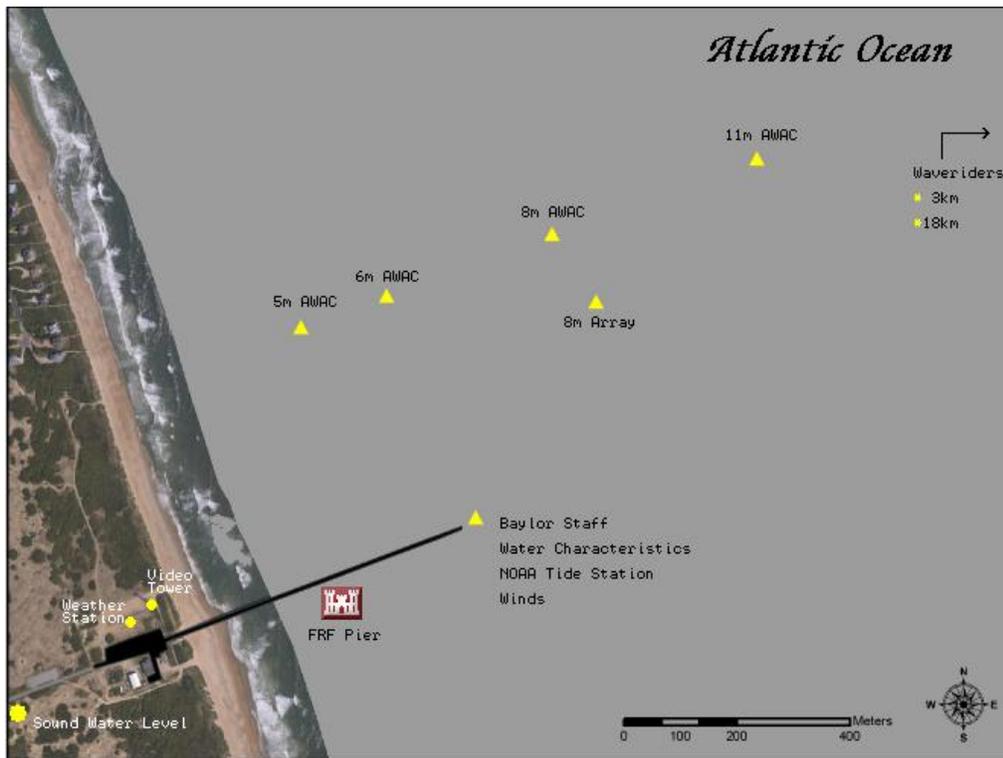


Figure 1- The FRF at Duck, NC; map courtesy of the FRF.

The subaerial beach and shallow nearshore (up to 2m depth in the water) is composed of a bimodal mixture of medium quartz sand and granules and small pebbles, about 1mm in diameter (Lee et al, 1998, Figure 2). The sediment size decreases offshore, becoming unimodal. The average foreshore slope averages 0.108 degrees (Birkemeier et al., 1985). Tides at the FRF are semi-diurnal with a mean range of 1m, with a spring tide range of about 1.2m.



Figure 2- Sample of sediment on the beachface at Duck.

The wave energy on this coastline varies with season and is higher during the fall, winter, and early spring months due to frequent extratropical storms and lower during the late spring and summer (Lee et al., 1998). The wave climate is among the most energetic on the U.S. East Coast, with wave heights averaging near 1.0m height. Approximately 20 storms occur each year during which the waves at 8m depth exceed 2.0m (Leffler et al., 1998).

Research Organization

This research can be viewed as consisting of two separate issues, each with its own data set and methods of analysis. The thesis is, therefore, organized accordingly. Chapter 2 presents the theoretical background and foundational studies in order to properly set the context for this thesis. The literature review contains basic principles of waves and tides, focuses on storm/beach interaction, storm scales and indicators, extreme-event response and multiple-event response and introduces the frequency/magnitude principle in geomorphology, touching upon studies that have used this principle to analyze wave events.

Chapter 3 focuses on the frequency/magnitude analysis of the storm data obtained from the FRF. This section includes:

- 1) A synopsis on the instruments used to collect the wave data.
- 2) The rationale for defining a storm event and the quantification of event magnitude.
- 3) The standardization of total event energy into a storm index.
- 4) A frequency/magnitude analysis of the storm events.
- 5) Discussion of results.

In chapter 4, beach volumetric change is presented as corresponding to the storm events.

This chapter will include:

- 1) An overview of the equipment used at the FRF to conduct the profile surveys.
- 2) An explanation of the volumetric change calculations.
- 3) Results of the volumetric change.
- 4) A discussion of the findings.

Chapter 5 relates the volumetric change to the events in order to understand if the index has any predictive power over the volumetric change along the profiles. This chapter also discusses the relationship between the profiles and explanations for the improvement of the index and volumetric change assessment. Chapter 6 provides the conclusions of the research and suggestions for future research.

CHAPTER TWO: LITERATURE REVIEW

Beach Systems

Beach systems are dynamic, changing environments, constantly exposed to energy sources in the form of waves and wind. Beach erosion is induced by many factors: waves, wind, currents, sea-level rise, human modifications, and even bioerosion (Davis & Fitzgerald, 2004). These factors have been the focus of numerous studies going back as far as the early 20th century. Bascom in 1964 provided the first popular account of waves and beaches (Short, 1999) with research escalating after. The purpose of this chapter is to review the state of knowledge about wave processes and the resulting beach response.

Waves

Waves, the primary force responsible for re-shaping the coast, provide the energy necessary to cause beach form changes. “The motion of the wave itself constitutes a transfer of energy over the sea surface; it is especially in this regard that waves are important to beaches” (Komar, 1976: 45). Komar explains, “the displacement of the wave surface away from the flat, still-water condition gives the wave form a potential energy and the orbital motion of the water under the waves constitutes a kinetic energy for the wave” (1976: 45) (Equations 1 & 2). The total energy of a single wave is expressed as:

$$E = E_p + E_k \quad (1)$$

$$= 1/16\rho g H^2 + 1/16\rho g H^2 \quad (2)$$

$$= 1/8\rho g H^2 \quad (3)$$

where ρ is the water density, g is acceleration due to gravity, and H is the wave height; energy (E) is expressed in joules. This equation shows that wave energy is essentially proportional to the square of the wave height because the remaining parameters, g and ρ , are basically constant. So,

small increases in wave height produce large increases in wave energy. This relationship becomes particularly important during storm events when wave heights are super elevated, increasing the amount of energy released on the beachface. Waves that are under direct influence of the wind are termed sea waves (Davis & Fitzgerald, 2004). Wave height is dictated by wind speed and the duration of that wind speed. The size of the wave is also directly dependent upon the area from which waves are generated by wind that has been blowing from one direction, or the fetch.

As it approaches the shore, entering into shallow water, a wave slows down in response to frictional contact with the bottom. Once it contact with the sea bottom the wave begins to bend and this bending is called wave refraction. If the nearshore topography is irregular the wave refraction will reflect this. Wave energy is then concentrated on the headlands of the beach. This refraction during storm events can cause major erosion along the shoreline because the wave energy, greater during storm events, will be directed to the headlands greatly eroding sediment.

Before the wave comes in contact with the nearshore topography or shoreline it possesses radiative or potential energy which causes the wave to propagate landward. Radiation stress is defined as, “the excess flow of momentum due to the presence of the waves” (Longuet-Higgins & Stewart, 1964). This radiative stress propagates normal to the shoreline and contains an onshore flux of energy plus the energy of the wave and is expressed as:

$$S_{xx} = 1.5E \quad (4)$$

Where S_{xx} is the principle component of the onshore flux and E is the wave energy (Sherman, 1988). Once it comes in contact with the nearshore topography and the wave breaks, the energy is transformed from radiative to kinetic energy, creating a current. The amount of energy in the

wave determines how much energy is transferred to the current. As waves approach the shoreline and go through the breaking process, both shore perpendicular and shore parallel currents develop. The proportion of current transformed in the alongshore direction depends on the angle of wave approach. Waves that approach normal to the shoreline develop primarily an onshore current, but as the angle of approach becomes increasingly oblique to the shoreline the proportion of current diverted parallel to the shoreline increases. Because waves can approach the shore from different direction angles, the alongshore current can move in either direction along the shore. This back and forth direction of the current can cause vast amounts of sediment to be transported back and forth. In practice, not all of the wave energy is retained in the wave system; some is transferred to the current, causing wave height to decrease (Open University, 1989).

Because of high wind speeds and long fetches, hurricanes or northeasters often produce extreme wave conditions that in just a few hours release enormous amounts of energy onto the beach creating drastic changes in morphology. Dolan & Davis (1991) explain that the high waves of strong nor'easters can cause damage comparable to, or even exceeding that of a hurricane, because they can affect stretches of the East Coast over 1,500 kilometers long while hurricanes usually only affect 100-150 kilometers of coastline. Factors, such as type of storm, storm path, speed and magnitude, and the configuration of the coast, determine the extent and type of damage resulting from the associated storm (Dolan & Davis, 1991).

Because these storms, especially hurricanes, can occur out in the middle of the ocean, swell waves become important. The atmospheric conditions at a particular beach can be completely calm but still experience "waves" with very large wavelength. This is known as a swell, or waves that have been generated elsewhere and traveled far from their place of origin

(Open University, 1989). There is a relationship between the storm distance and the swell size because as the distance from the storm center increases the wavelength increases but the overall energy of the wave decreases. Waves with the longest periods travel the fastest. Therefore, if a Nor'easter were pass relatively close to the coast one would assume fast short period waves to expend their energy onto the beach.

Tide and Storm Surge

Tides can modify the destructive power of waves, resulting sometimes in dramatic effects on shoreline processes and coastal landforms. Tides can be either astronomical or storm driven. Astronomical tides occur because of gravitational interactions between the earth and its sun and moon. This interaction is modified by centrifugal forces associated with the Earth's rotation. The combinations of these forces produce tides that vary both in time and place. The orbital patterns of the moon and earth produce both daily, monthly, and annual cycles of high and low water levels across the earth's surface.

Storm surge is the super-elevation of the water surface produced by a storm's strong onshore winds and low atmospheric pressure. Storm surge can be caused solely by the wind that pushes water up against the shoreline, increasing the still water height along the beach. Storm surge can also be caused due to differences in atmospheric pressure between the storm center and surrounding areas. Because a storm has low pressure at its center the water level under the storm can bulge upward compared to surrounding areas where higher pressure pushes the water surface downward. The bulge under the storm center is at a maximum on the northeast side of the storm in the Northern Hemisphere due to the effect of Coriolis. When water levels are higher either due to astronomical high tide or storm surge, the higher water level that has been pushed up against the shore allows waves to reach higher up on the beach resulting in more extensive beach

response. When these conditions are associated with higher astronomical tides, such as spring tides, unprecedented damage to the beachface may occur.

Beach/Storm Interaction

Although the beach profile is a dynamic landform that interacts with the ever changing wave regime, it exhibits characteristic forms during non-storm and storm periods. The beach profile is an important factor in wave dynamics because it causes waves to break and dissipate their energy (Komar, 1976; Wright & Short, 1984). In general, during the summer season, the beachface consists of a wide flat berm with a steeper foreshore at the seaward end sloping down to the water (Figure 3). The winter beachface is much narrower with a flatter and consistent slope extending down into the water. The winter profile also often has one or more subaqueous bars in the nearshore zone. The winter profile is shaped by high energy and frequent storms that occur. The higher storm waves reach further up the beach due to higher water levels and they erode sediment from the beach and transport it offshore to the bars. In summer, longer period swell waves generated by distant, rather than local, storms break on the bars. The turbulence created during the breaking process puts sediment into motion and the current carries the sand to the beach. This process produces the characteristic wide, flat berm typical of the summer profile. Subtle changes may occur on the beach during the summer when small storms occur but, because of the wide berm, changes are confined to the seaward end of the beach.

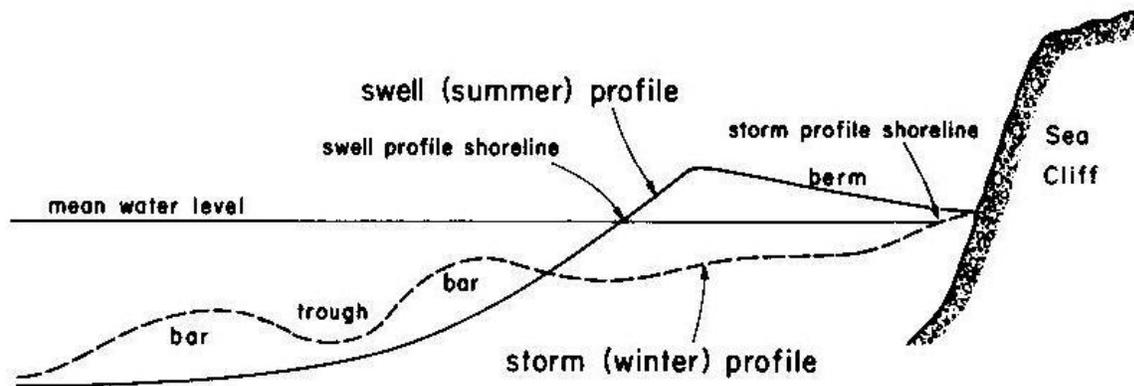


Figure 3- Summer vs winter profile (Komar, 1976).

Bascom (1959) discusses the concept of a beach system consisting of interaction between wave energy, beach slope, and sediment size and investigates this concept by examining a series of profiles along the West Coast of the U.S. According to Bascom (1959:874), “the slope of the beachface is related to the median diameter of the sand and the amount of wave energy reaching that point. The amount of energy is a function of the refraction conditions; consequently, beaches that are protected are steeper for any given sand size than exposed beaches”. There is a relationship between sediment diameter and slope, with finer grain sizes producing flatter beach profiles associated with less energetic beaches. Beaches with coarser sediments tend to be steeper and exist in higher wave energy environments.

The morphology of a beach is dictated by its sediment characteristics, wave climate, tide and wind conditions, and previous beach state (Wright & Short, 1984). After a long period of time a beach will reflect a modal state or the most frequent state of the beach given a specific environment. Wright & Short explain that, “the beach in response to the wave climate consists of a model beach determined by the modal wave conditions, and a range of beach morphologies dependent on the range of wave conditions” (1984: 106). They concluded that the greatest degree of profile mobility is associated with intermediate, breaker heights of 1-2.5m, but highly

changeable wave conditions. Therefore, incorporating these important variables into this thesis should allow for accurate predictions of beach change.

Extreme Event Response

A common trend in studying beach-storm interaction is to thoroughly examine the response of the beach to one extreme storm. Nelson (1991) examined the impact of Hugo on Myrtle Beach, SC, beaches on September 21 and 22, 1989. The purpose of the study was to determine the elevation and distance from bench marks along the beach to points of surface slope change. Twelve profiles were surveyed the day preceding the hurricane and 94 beach surveys were surveyed at 70 locations along Myrtle Beach coast 48 hours after the storm. 30 hours before Hugo, winds reached the shore. Nelson reports that the mean high tide line moved landward an average of 10.4m. In addition, survey data showed that an offshore bar developed at most of the survey locations. Nelson concludes from the profiles that preceded the hurricane that the northern portion of Myrtle Beach accreted due to large amplitude long period waves and high spring tides. There were also differences in erosion amounts in the post-storm profiles, between the northern and southern portions of Myrtle Beach, because of strong littoral transport energy.

Tedesco et al. (1995) studied the impacts of Hurricane Andrew on South Florida's eastern and western coastlines. Pre-storm and post-storm beaches at Cape Florida (southern portion of Key Biscayne) and Highland beach, on the west coast of Florida were examined. The pre and post storm profile data were collected by Florida's Department of Environmental Protection; the post storm profile data were collected for 10 months following the hurricane. The eye of Hurricane Andrew made landfall on August 24, 1992 crossing Elliott Key and Biscayne Bay; Cape Florida and Highland are located within the extent of eyewall. The post-storm beach profiles along the east coast revealed the development of a gently sloping storm ramp during the

storm and a lack of overall shoreline change. Tedesco et al. concluded that wave attack caused a reshaping of the storm ramp, resulting in aggradation on the backshore and berm and a landward migration of the beach face. By June of 1993, the east coast shoreline had returned to its pre-storm shape. The west coast beaches also had gently sloping storm ramps. The profiles regained their pre-storm shape by March 1993, although the shoreline had shifted landward 5-15 meters of its pre-storm position.

These studies go into great detail about profile response to these extreme storms. The availability of pre and post storm profile data make for excellent evaluations of the various storm characteristics on the beach profile. However, the consequence of only examining one extreme event on profile response is that extreme events are usually rare, when previous small magnitude events may have had an influence on the profile and its associated response. Also examining one extreme event does not allow for the understanding of the effects of small successive events on the beach profile which happen on a more frequent basis.

Multiple Event-Induced Response

There have been many studies that examine storm-induced beach erosion and associated response of the beach-nearshore profiles with regards to both large and small magnitude events (Larson & Kraus 1994, Lee et al. 1995, Lee et al. 1998, Birkemeier et al. 1999). Larson & Kraus (1994) used data from the Field Research Facility (FRF) located at Duck, NC to understand the temporal change of beach profiles and to relate the observed changes to the wave data also available at the pier. Larson and Kraus (1994) focus on an extreme storm events during an eleven year period- storms are defined as those periods when significant wave heights exceeded 4m. Beach profiles collected before and after the storms were examined to determine the effects of the storms on profile response. Beach change is quantified by using the average absolute

volume change across the profile. This involves integrating the absolute volume change between two consecutive surveys across shore and dividing by the length of the profile over which the change occurred. They concluded that major storms at Duck can move sand onto the profile from the seaward side from at least the 8-m depth (in the water), thereby increasing sand volume on the total profile from the dune to the 8-m depth. The 8m depth marks the “depth of closure” in which all volumetric change occurs above this depth. This conclusion adds to the understanding of sediment transport during storm conditions, however, Larson & Kraus only included 18 storms in the analysis; more storms need to be included to further understand not only the large storms but also the smaller ones because intermittent small storms may be responsible for major profile change.

Lee et al. (1995) investigated the relationship between fair-weather steepened foreshore profiles followed by storm disturbance also using 10.5 years of storm and wave data along with the available profiles at Duck, NC. The change in the profiles is examined by dividing the profiles into sections: outer bar, inner bar, upper shoreface, and dune, which stretch seaward to landward, respectively. The shoreline was found to retreat during the winter and advance seaward in the summer. The profile data revealed that the intensity and timing of storm events have important effects on the beach-nearshore profiles. The inner bar was found to be highly mobile under all wave conditions and moved offshore and sometimes became the outer bar (if no outerbar was present). The outer bar tended to migrate onshore, decrease in amplitude, and then disappeared after periods of low energy. Lee et al.’s results prove to be important for understanding the processes associated with storm-induced beach erosion but the study only reports on changes for a single profile although they claim the other profiles act in a similar

manner. This study only takes into consideration the largest events in the 10.5 year period and should be updated to include the most recent profiles associated with recent storms.

List and Farris (1999) examined variations of beach response to both fair weather and storm conditions, as well as to single Nor'easter storms using the short-term change in shoreline position. They used an all-terrain vehicle with a mounted GPS to monitor shoreline change before and after storms over a 35 day period at Duck, NC. By using wave heights averaged over approximately two high tides previous to shoreline surveys, 88% of the shoreline variation was explained by varying wave heights. They also conclude that the large variations in the shoreline positions, migrating landward or seaward, can be attributed to the response to small storms. Although, List & Farris (1999) only use a time frame of 35 days, their results emphasize the importance of focusing on small events and beach change. Beach profiles, rather than simply shoreline variations, should be examined to determine the importance of small storms in producing change. A longer time period needs to be assessed to investigate if profiles exhibit the same behaviors over time.

Understanding how the beach recovers after storms of different magnitudes is an important aspect of storm and beach interaction. Morton et al. (1994) examined long-term beach recovery processes following a category 3 hurricane and described the four stages of post-storm recovery based on observations from undeveloped beaches, Galveston Island and Follets Island, in Texas: berm reconstruction and forebeach accretion; backbeach aggradation; dune formation; and dune expansion and vegetation recolonization. After examining profiles for ten years after Hurricane Alicia, it was revealed that beach profiles, only a few kilometers apart can experience completely different storm responses; the responses seen were continuous erosion, partial volumetric recovery, complete volumetric recovery, and excess morphological and volumetric

recovery. The majority of the beach profiles experienced partial volumetric recovery in that 40% of the sediment was recovered to the profile. Four to five years of storm recovery was necessary for some of the profiles while others continually eroded. Because there was variability between the profiles in that some continued to erode and some gained more sediment than was present before the hurricane. Morton et al. (1994) suggest that the storage and release of sand from the shoreface is responsible for variability. But Morton et al. (1994) consider only beach recovery for extreme events. Neglecting the small events that occur between large events does not allow one to adequately predict beach change and recovery.

Zhang et al. (2002) used the Morton et al. (1994) conclusions about beach recovery to examine long-term beach erosion along the U.S. East Coast and investigated whether these beaches recovered to their long-term positions after experiencing erosion from large storms. The long-term trend line was estimated by examining the shoreline position unaffected by major storms. Shoreline retreat and recovery due to storms was estimated by the deviation from the long-term trend line. Historical shoreline data were derived from digital shoreline maps and are 100-150 years in temporal extent and cover almost the entire East Coast of the US. Historical storm surge data were also used to define storms with about a dozen sites along the East Coast providing a 100 year record. Events for the study were then defined as storms if the surge was two standard deviations above the mean. Thus, the data set only includes the largest and most damaging storms. Zhang et al. (2002) conclude that it takes East Coast beaches several years to several decades to recover to their pre-storm positions and imply that long-term trends and storm-induced processes can be treated separately because barrier beaches along the East Coast recover to their long-term trend positions after storms regardless of storm severity. Zhang et al.

(2002) pointed out that the next step is examining off-shore storms that bring in large amounts of sediment to understand if these off-shore storms have a significant impact on the beaches.

Scales & Indicators

Many studies investigate the impacts of storms on the beach and landforms and have devised scales and indicators that help future researchers predict the associated beach erosion with particular storms of certain strengths and magnitudes. Storms such as Nor'easters or hurricanes generate storm surges that can indirectly contribute to changing the beach face. The erosive power of the storm surge depends upon the magnitude and duration of the storm, for a storm can raise the water levels for multiple days and elevate wave heights. Nor'easters are more frequent than hurricanes and can last several days producing wave heights comparable to those generated by hurricanes. Based on wave hindcasts for Cape Hatteras, North Carolina, Dolan and Davis (1992) used 1,347 storms over a 42 year period, each of these storms having a significant deep water wave height of at least 1.5m. This threshold was used because field evidence suggested that a 1.5m deep water waves result in measurable beach face erosion. They then combined significant wave height and duration, to develop "relative wave power" to understand the power of the storm. Then cluster analysis was used to develop storms classes based upon relative wave power (significant wave height x duration) with the classes ranging from class 1 (weak) to class 5(extreme). Although the classification scale was quantitatively derived, each class is merely qualitative in describing the associated work done to the beach. Alternating the classification scale so that one could estimate the associated volumetric change with storm class would be more practical. It would also be useful to add other important wave characteristics such as wave period to better estimate the magnitude of each storm.

While studies such as Dolan and Davis (1992) accommodate both wave heights and storm surge, efforts have been made to determine if one factor or the other is more important in explaining beach change. Zhang et al. (2001) argue that waves are a major agent of erosion but that storm tide, the sum of the astronomical tide and the storm surge, dictates the position and elevation where the storm waves attack the beach making it more important than waves in contributing to beach erosion. In order to conduct their analysis they expand upon the Dolan-Davis power index. They created the Storm Erosion Potential Index (SEPI). The SEPI is the sum of the product of hourly values of storm surge height two standard deviations above the annual surge level and water level greater than the mean high high water (MHHW). Zhang et al. (2001) then used three large storms, the 1962 Ash Wednesday storm, the 1991 Halloween storm, and a 1992 nor'easter, and their associated beach changes to validate the SEPI index. This SEPI tool only takes into consideration the large storms or, events that are two standard deviations above the annual surge level. Northeasters can stay offshore for days at a time, so it is important to include the smaller events as well because a smaller event with a greater duration may cause just as much work to the beach as a larger storm with a smaller duration. It also only takes into consideration storm tide, which Zhang et al consider to be most important in producing beach erosion. Storm tides, astronomical tide and storm surge, are only elevated water levels and without including the associated wave height, a full understanding of the work done to the beach cannot be assessed.

Sallenger (2000) devised a storm impact scale for barrier islands that assessed storm damage in terms of the regimes within the beach system. The impact scale is based on the elevation of storm wave runup relative to the elevation of critical geomorphic features on a barrier island. Wave runup considers local beach slope, deep water significant wave height and

deep wave length. The scales devised by Dolan & Davis (1992) and Zhang et al. (2001) simply incorporate storm magnitude, as defined by wave parameters and storm tide and do not consider the topography of the beach. Sallenger's scale is broken up into four levels according to the part of the beach that has been inundated: the swash, collision, overwash, and complete inundation regimes. In general terms, the swash regime is the condition during the storm where the swash is confined to the foreshore of the beach; the collision regime is the condition where the foredune at the landward end of the beach undergoes net erosion; the overwash regime is the condition where the runup overtops the foredune; and the inundation regime is the condition where the beach is almost or completely inundated (See Appendix B). Sallenger (2000) suggests using this scale for forecasting potential impacts on the beach.

Judge et al. (2003) assessed existing vulnerability indicators for coastal dunes including storm characteristics and dune erosion vulnerability indicators. Storm parameters that were used as indicators were wave height and period, storm tide elevation, and storm duration. Dune erosion vulnerability indicators that were used were median erosion, an intensity index as proposed by Kriebel (1991), crest height, the Storm Impact Scale proposed by Sallenger (2000), and the cross-section centroid. Judge et al. (2003) used these parameters to develop a new indicator of dune vulnerability, the erosion resistance. This new parameter of erosion resistance based on the mass moment of inertia which is defined as the square of the dune's centroid from the cross-sectional area of the dune. This erosion resistance indicator predicted 81% of the failed dunes and 91% of the survived dunes successfully because both dune size and position were taken into account. These previously derived parameters and newly formed parameter of erosion resistance proved successful for predicting the survival and failure during Hurricane Fran but this is simply one storm and has not been tested for other storms.

All of these scales and indices include some form of wave height and duration, but all fail to include other important characteristics such wave period and number of waves to hit the beach throughout the duration of the storm. More importantly, these scales and indicators, although quantitatively devised, are mostly qualitative in assessment damage to the beach. These studies also do not include any form of energy or power behind the storm, in a traditional sense. Dolan & Davis (1992) used relative wave power but only considered wave height x duration. By using the energy or power of the storm one can further understand the magnitude of that storm and use that magnitude to assess the associated beach change.

Frequency/Magnitude

Frequency/magnitude is an analytical approach that has been widely used in geomorphology, especially in fluvial geomorphology, to assess the likelihood of occurrence of an event of a certain severity (Dunne & Leopold, 1978). In a general sense the high magnitude event will happen less frequently. Frequency/magnitude analysis is important for assessing events in the record as frequency/magnitude quantifies events. Most previous studies have not examined the frequency/magnitude distribution of energy forcing events with regard to storm/beach interaction.

Wolman and Miller (1960) published an important article discussing the magnitude and frequency of forces in geomorphic processes. In this paper, they emphasized the relative importance of extreme events and ordinary events and how these events changed the landscape (1960). The principle of frequency and magnitude in geomorphology states that the amount of work done on the landscape is the result of the work done by an event of a given magnitude. Event frequency has an inverse relationship with its magnitude such that extreme events are very infrequent occurrences. Wolman and Miller (1960) stressed the importance of looking at not

only the large events but also at smaller events because one large event may not inflict as much change on the landscape as multiple smaller events. Looking at river flooding, Wolman & Miller (1960:57) say, “although the extremely large floods carry greater quantities of sediment, they occur so rarely that from the standpoint of transport their over-all effectiveness is less than that of the smaller and more frequent floods”. In regard to beach profiles, Wolman and Miller (1960) hypothesize that sediment is mostly transported by events of moderate magnitude and frequency, but note a lack of examples demonstrating the effectiveness of moderate events of frequent occurrence in molding erosional landforms. This same concept can and should be used in terms of waves and their impact on the beachface to understand how events of a certain magnitude occurring at a given frequency affect the beachface and sediment transport.

Schumm (1970:487) defined a geomorphic threshold as “one that is inherent in the manner of landform change; it is a threshold that is developed within the geomorphic system by changes in the morphology of the landform itself through time.” Schumm (1970) also points out that geomorphic thresholds are important for geomorphologists because they make one aware that erosional and depositional changes can be inherent in the normal development of a landscape. Thresholds set the limit for which geomorphic change can or cannot occur. Thresholds for frequency/magnitude studies can be set either using the annual duration series, choosing the largest event within a given time frame, or by the partial-duration series, where every event that exceeded a given threshold would be analyzed.

These two different approaches have been implemented in traditional flood frequency analysis. The annual maximum series considers only the largest events in a time period. The annual maximum series usually requires at least 100 years worth of data in order to produce recurrence intervals. The other is the partial-duration series, also known as the peak-over-

threshold approach. Whereas the annual maximum series looks only at the highest annual events during a period of years, the partial duration series considers all events that exceed a certain threshold. The partial-duration series curve predicts the probability of an event occurring regardless of its place in hierarchy (Dunne and Leopold, 1978). According to Waylen (1985) the advantages of the partial duration series approach are: 1) the probability distributions employed are theoretically based; 2) the event variables other than magnitude are included in the analysis; and 3) the distribution of annual events may be derived from the partial series theoretically.

A majority of the work completed using the partial-duration series analysis has been used in river flooding. Waylen (1985) used a partial-duration series analysis to better understand the transition from winter rain generated floods on the West Coast of British Columbia to the spring snowmelt generated floods. He demonstrates that the method is sufficiently flexible that it may be used in a variety of physical environments to provide a satisfactory statistical fit and yet remain physically interpretable. The use of the partial duration series in this study will allow for the inclusion of both large and small wave events which will help determine their roles in geomorphic change.

Of the little work that has been done using frequency/magnitude of wave events (Dolan & Davis, 1992; Zhang et al., 2001), the majority has been conducted at Duck, NC because of the ample amounts of profile and wave data. Although they did not complete their study at Duck, Savage & Birkemeier (1987) used storm data from 1962-1978 and compared five different sites between New York and New Jersey. The peak hindcast wave height and storm wave duration were used. Storm wave duration was defined as the period in hours that the wave height exceeded a height equal to the twenty year average height plus one standard deviation. Savage & Birkemeier (1987) discovered there was a relatively weak inverse relationship ($R^2 = -.36$)

between waves, water level, and volume change. Savage & Birkemeier (1987) concluded that the lack of trend between volumetric change & waves and volumetric change & peak water level was due to the fact that storm erosion is also dependent upon storm duration, water levels at the site, sediment size, the presence or absence of offshore bars, and prior storm activity. They also conclude that because there is usually variation between profile lines, the median change is a better indicator of overall change than the average value.

A partial-duration series approach for studying storm/beach interaction was introduced by Lee et al. (1995; 1998) then expanded upon by Birkemeier et al. (1999). Lee et al. (1995) wanted to validate their fair-weather storm model based upon a scale of storm intensity. In order to assess the impacts of storms on the beach profile at Duck, NC, Lee et al. (1995) used a partial-duration series approach, using wave heights greater than 2.7m, to determine that 56 storms occurred within the time frame of the study, 1981-1991. The intensity of each storm was based on a wave power function:

$$P = 1/16 \rho g H^2 T/L \quad (5)$$

where ρ is seawater density, g is gravity, H is wave height, L is wave length, and T is peak spectral wave period. Lee et al. (1995) examine the temporal distribution of storms and conclude that there are periods of high energy from the grouping of events. They identify four significant groups of high storm activity within the study period each interrupted by fair-weather. The groups of storms are defined by the occurrence of storm events with more than one event exceeding a 4m wave height. They also determined that the nearshore slope appears to respond to the groups of storms that drive medium term profile change (a year to a decade) which is consistent with the fair-weather/storm model. The intensity and timing of major storm events have important effects on the beach-nearshore profile over a decade.

Lee et al. (1998) also examined whether their previously noted decadal profile response was a result of seasonal-scale processes or long-term processes. The same methodology for categorizing the storms was used. It was concluded that groups of storms could act as large individual events and that the impact of these events on morphologic changes is much larger than that of an individual event. The first storm in a group can destabilize the profile and transport sediment across the profile allowing for the following storms in the group to easily erode even more sediment. The fair-weather that follows the group will compact the sediment with low wave energy conditions making sediment more difficult to erode. While these results are fruitful for future studies, Lee et al. (1995, 1998) focus mainly on low recurrence high magnitude events and associated beach changes and consider group energy as opposed to the energy of a single event.

Birkemeier et al. (1999) expanded upon the work of Lee (1998) to include Duck data from 1981-1998 and examined the importance of storm sequences in terms of duration, intensity, intervening time interval, and profile response. Birkemeier defined a storm as beginning when wave height reached and exceeded 2.35m. Duration was the time from storm initiation until wave height fell back below 2.35m. The 2.35m threshold is the mean height over the time period of the study plus two standard deviations. The analysis included 103 storms and it was stated that storms that occur “back-to-back”, or before the profile has had time to recover, are likely to be additive and produce a profile typical of a less frequent, longer duration and/or more intense storm.

All of these studies use a partial-duration approach to determine a threshold in order to define an ‘event’ but they do not actually implement the probability analysis. Rosbjerg and Knudsen (1984) use the POT method to derive significant wave heights but do not apply these

wave heights to any sort of change on the beach. None of the previously mentioned studies actually use the partial-series duration analysis in order to develop a frequency/magnitude plot in order to determine the probability of occurrence of an event of a certain magnitude.

Summary

An ample amount of research has been conducted on the impacts that storms have on the beach. Numerous impact scales have been devised (Dolan and Davis, 1992, Judge et al., 2003) to be able to predict the amount of damage done to the beach and which areas along the East Coast are more vulnerable to storm impacts, respectively. Many studies have also examined the response of the beach to these storms (Morton & Sallenger 2003 and Zhang et al. 2002), but most have examined the impact of the storms over the course of a given time frame and have not examined the impact of individual storm events. Studies at Duck, NC have used partial-duration series approach with regard to wave data to determine a threshold for defining storm events but none have explored developing a plot to predict the probability of occurrence of a certain event. If this plot is created then it can be understood how the frequency and magnitude of storms can alter the beachface. These studies have not included the most recent profile data that has been collected at Duck, NC by the USACE. Further refinement of storm/beach response studies will ultimately assist planners and emergency managers predict and accurately assess beach damage and further economic impacts that these storms can cause.

CHAPTER THREE: FREQUENCY/MAGNITUDE CLASSIFICATION

Overview

Geomorphic work done to a landscape is a function of the magnitude of a storm and how often a storm of that magnitude occurs. The use of a frequency/magnitude analysis in this thesis allows for viewing storms as individual events. Because the profile data represent an overall change over a relatively long period of time, using an event based approach allows for direct comparison between the processes and landform response. This section takes the first step in defining wave events as storms and understanding the temporal distribution of these events. Individual characteristics of the events will be examined. Methodology will be described in defining these events along with rationale for creating an index based upon individual event energy.

Methods

The analysis involves the use of wave data collected over as long a period of time as possible and that such data are available from the FRF (<http://www.frf.usace.army.mil/>), which was downloaded from their website directly. The wave data used in this thesis is collected using a Datawell Directional Waverider that is located 3 km offshore at a depth of 17.4m (Figure 4). The Datawell Directional Waverider was used by Lee et al. (1995, 1998) and Birkemeier et al. (1999). The Waverider not only collects the wave height, period, and direction, but collect winds and water temperature as well. Because of the versatility of the Waverider, all wave and weather data can be obtained at once. Wave data is available from 1985-present but for the purpose of this project, 1985-2007 wave data will be used as the profile data is only available through 2007. The wave height data from the Datawell Directional Waverider are recorded for 34 minute

periods and are represented as significant wave heights for those 34 minutes. In the initial post-processing steps, significant wave heights are extracted from the record and averaged. This available data represent an averaged significant wave height for each 34 minute period. Figure 5 shows an example of a monthly plot of significant wave heights. This plot is for the month of January 1985 and gives the significant wave heights for the entire month.



Figure 4- Data Directional Waverider at Duck, NC; photo courtesy of FRF.

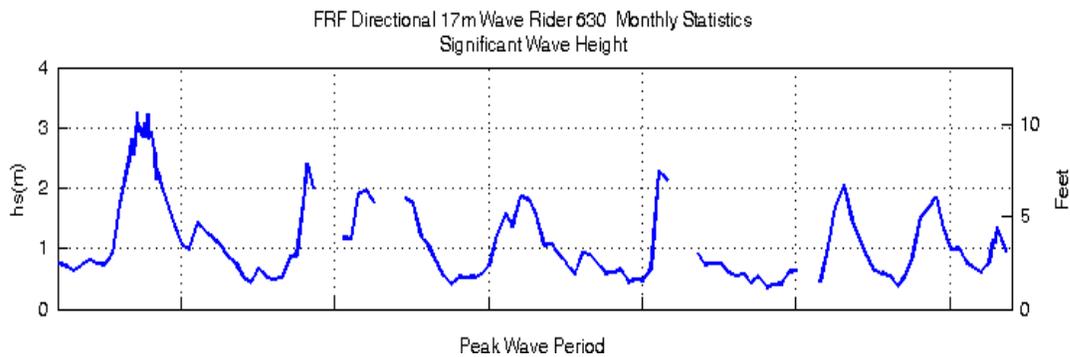


Figure 5- Significant wave heights for the month of January, 1985.

In order to implement the peak-over-threshold method, a threshold for defining a wave event must first be applied. Rosbjerg and Knudsen (1984) stated that “if an appropriate threshold is introduced and the recorded wave heights below this level are deleted, the remaining data

constitute a partial-duration series.” Using this approach, individual wave events can be focused on to assess the associated beach change.

There are a number of ways for determining a threshold of wave height that determines a storm event. Lee et al. (1998) used a threshold of 2.7m, as it was the smallest maximum significant wave height in their dataset. After the analysis of the data, Lee et al. found that wave heights of 4m or greater were producing the changes on the upper shoreface. Birkemeier et al. (1999) defined an event when the wave height exceeded 3.0m. For this project it was decided to use a lower threshold because of the desire to emphasize the importance of looking at both large and small events. The threshold as proposed by Dolan and Davis (1992) of 1.5m, more conservative, was used initially as they confirmed that using a 1.5m deep water wave as a threshold would in fact result in beach face erosion. This relatively low threshold also facilitates the analysis of the relative amount of geomorphic work that is done by events of varying energies.

For frequency/magnitude analysis of Duck wave data, the first step was to extract all average significant wave heights greater than 1.5m. In the resulting dataset, storm events were identified when the period of consecutive wave heights 1.5m or higher lasted at least 3 hours. Average wave conditions (height and period) were then calculated for each event, and the event duration was determined from the time record included in the dataset.

Previous studies have used different metrics to quantify storm magnitude. Dolan & Davis (1992) used “relative wave power” to represent storm magnitude, as expressed by significant deep water wave height x duration, but they completely neglect wave period. They also do not use wave power as defined by the wave power equation, they simply consider wave

height and duration. Lee et al. (1995) used the standard wave power equation which, although it calculates storm magnitude, it only takes into consideration either potential or kinetic energy. For this analysis, it was decided to use the wave energy equation for single wave energy ($E=1/8\rho gH_s^2$), because it accounts for both kinetic and potential energy of the wave. However, the energy function is applicable only to a single wave, so in order to determine event energy it should be integrated across the duration of the event. Previous storm scales (Sallenger, 2000; Zhang et al., 2001, Judge et al., 2003) have used wave height and duration to calculate either wave energy or power but all neglect to integrate the total energy for the duration of the event. Energy integration is done by determining the number of waves in the event. This is obtained by dividing the event duration in seconds by the wave period in seconds. The single wave energy is then multiplied by the number of waves. The overall storm energy equation is:

$$E_e=1/8\rho gH_s^2 * \text{Duration}/T \quad (6)$$

where E_e is the total event energy, ρ is the water density, g is gravity, H_s is the significant wave height and T is the significant wave period of the event (H_s , ρ , and T are all measured at the field site). Variations in water density, although small, were accommodated using density data measured at the field site.

The resulting event energy values are very large numbers because the time component of the equation is represented in seconds. In order to render more usable and to make the approach more universally applicable a storm index (SI) with a scale of 0-10 was developed. To develop the index, the events were first ranked in descending order according to total event energy from greatest energy to least energy. The index was then derived from the following:

$$SI = E_n/E_1*10 \quad (7)$$

where E_1 is the largest event. The smallest energy was divided by the greatest energy then multiplied by 10 as the index ranges from 0-10.

The described data extraction procedure resulted in the identification of a total of 880 events for the 1985-2007 period. A frequency analysis of the energy distribution by index values reveals that 97% of the events have indices below 1 (figure 6). The concentration of events at the lower end of the scale had the potential to severely skew the probability of occurrence of events. This large percentage of events under an index of 1 suggests that the 1.5m threshold was entirely too conservative. Wave height thresholds as proposed by Lee et al. (1995,1998) and Birkemeier et al. (1999) are reasonably better thresholds. Also, events with durations of only three hours are probably too short to produce significant beach response. Therefore, because these events were merely noise within the dataset events had to further have significant wave heights of 2m or greater or a duration of at least 12 hours. A 2m significant deep water wave height was chosen to significantly reduce the large cluster of events under the original threshold of 1.5m, as Birkemeier (1985) stated that wave heights at Duck during storm events are usually around 2m. Twelve hours was chosen as it represents a full tidal cycle from high to low. The index was then recalculated to reflect these events that sufficed these new conditions. Of those 880 events, 530 of them met further requirements of having either a wave height of greater than 2m or duration of 42000 seconds (about 12 hours).

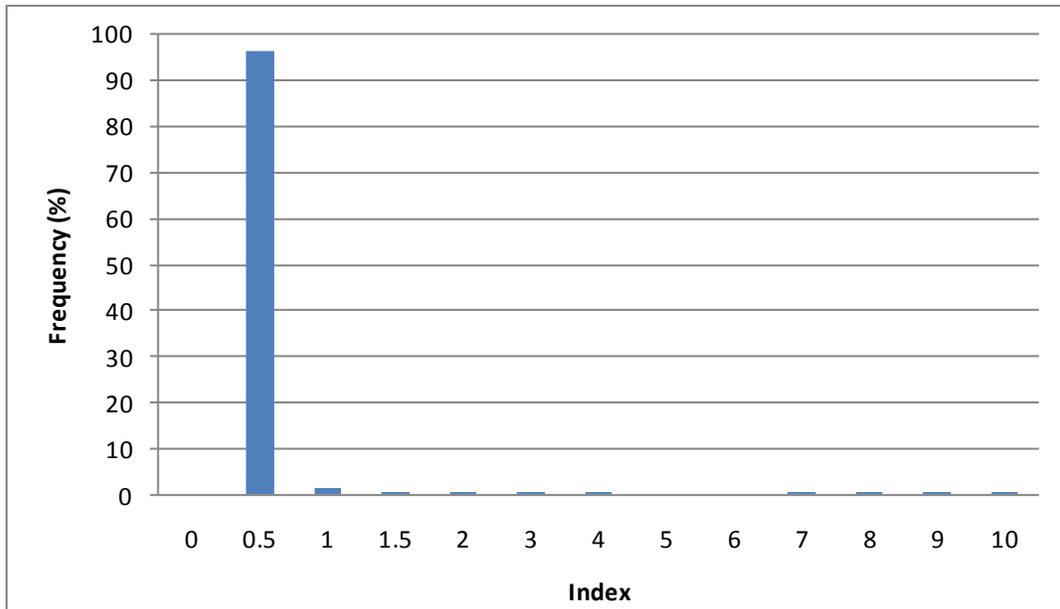


Figure 6- Distribution of 880 events from 1985-2007.

A traditional approach to frequency/magnitude analysis involves computing a Weibull probability distribution for the data, as has been done for assessing wind energy (Ulgen and Hepbasli, 2002). Ulgen and Hepbasli (2002) used the Weibull parameters for wind speed data analysis in Izmir Turkey and found that the Weibull distribution does indeed provide an excellent fit for predicting of future wind speeds in Turkey. This approach facilitates the application of storm wave damage probability to future situations. A two-parameter Weibull distribution is used here:

$$F(v) = (k/v)(v/c)^{k-1} \exp\{-(v/c)^k\} \quad (8)$$

where $f(v)$ is the probability of observing wave height v , k the dimensionless shape factor, and c reference value in the units of wave height. This equation plots out as a probability curve that is described by the shape factor and the reference value which in effect determines where on the y-

axis the curve is located. Ulgen & Hepbasli (2002) used the root mean square error to determine if a Weibull probabilities best represented wind data in Turkey.

Finally, a recurrence interval plot was generated to further explore the temporal distribution of the actual data. The recurrence interval is based on the probability that a given event will be equaled or exceeded in any given year. In order to generate this interval the events were first ranked according to event magnitude. The standard equation for determining a recurrence interval (T) is:

$$T = (n+1)/m \quad (9)$$

where n is the number of events in the record and m is the magnitude ranking. The recurrence interval is then used to create the probability of occurrence plot for understanding the likelihood of an event of a give magnitude. The standard equation for determining the probability of an event is:

$$P = 1/T \quad (10)$$

The plot was generated for the 23 years in the record using only the events with an index of 1 or greater.

Results

Despite modifying the wave height and event duration thresholds used in the data extraction process, an extremely large proportion of the events (87%) have average significant wave heights less than 2.5m (figure 7). The highest average significant wave height was 3.59m and this occurred during Hurricane Dennis in the fall of 1999. The majority of events (89%) had average

significant wave periods below 11 seconds (Figure 8). The greatest average significant wave period was almost 22 seconds. The highest event duration was about 8.5 days but 51% of the events had durations of 24 hours or less (Figure 9). 60% of events had energies below 7×10^7 J. It is noteworthy that 16% fall in the 2×10^8 J range. 43% of the wave events had an index of 0.5 or less (Figure 10).

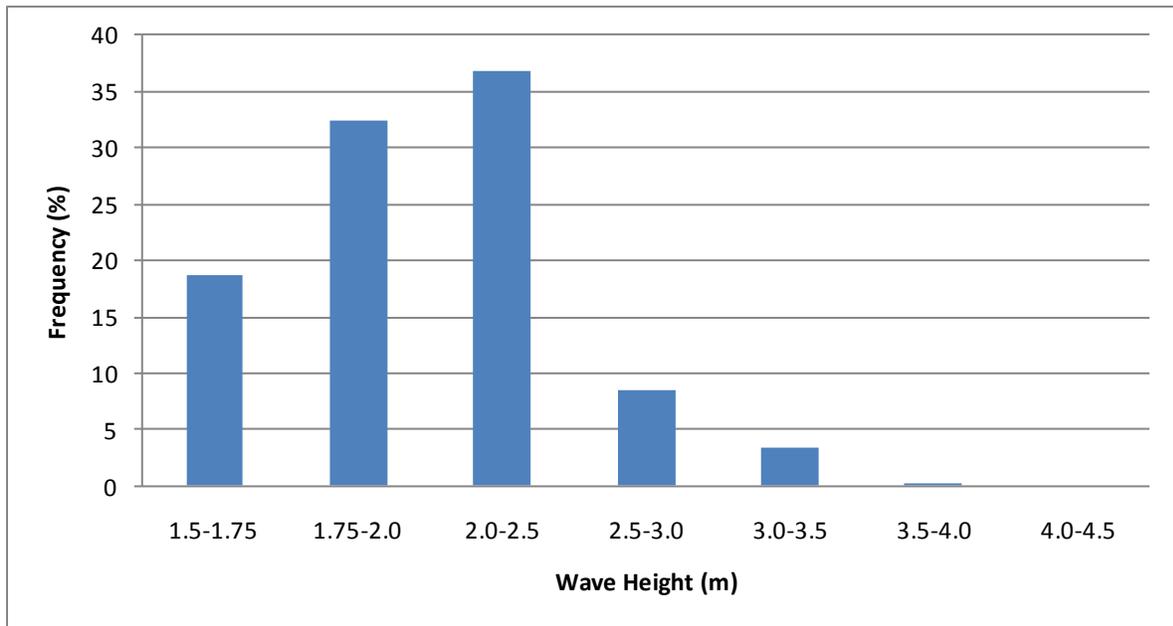


Figure 7- Distribution of wave heights for the 530 events between 1985-2007.

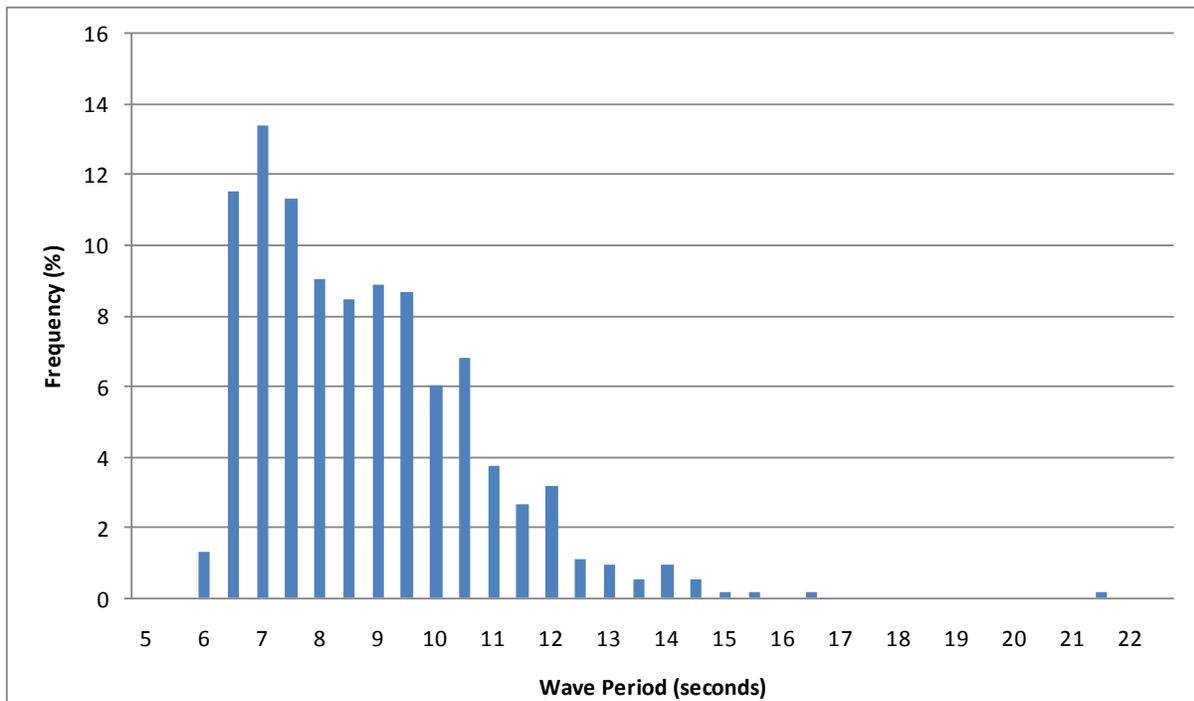


Figure 8- Distribution of wave periods for the 530 events.

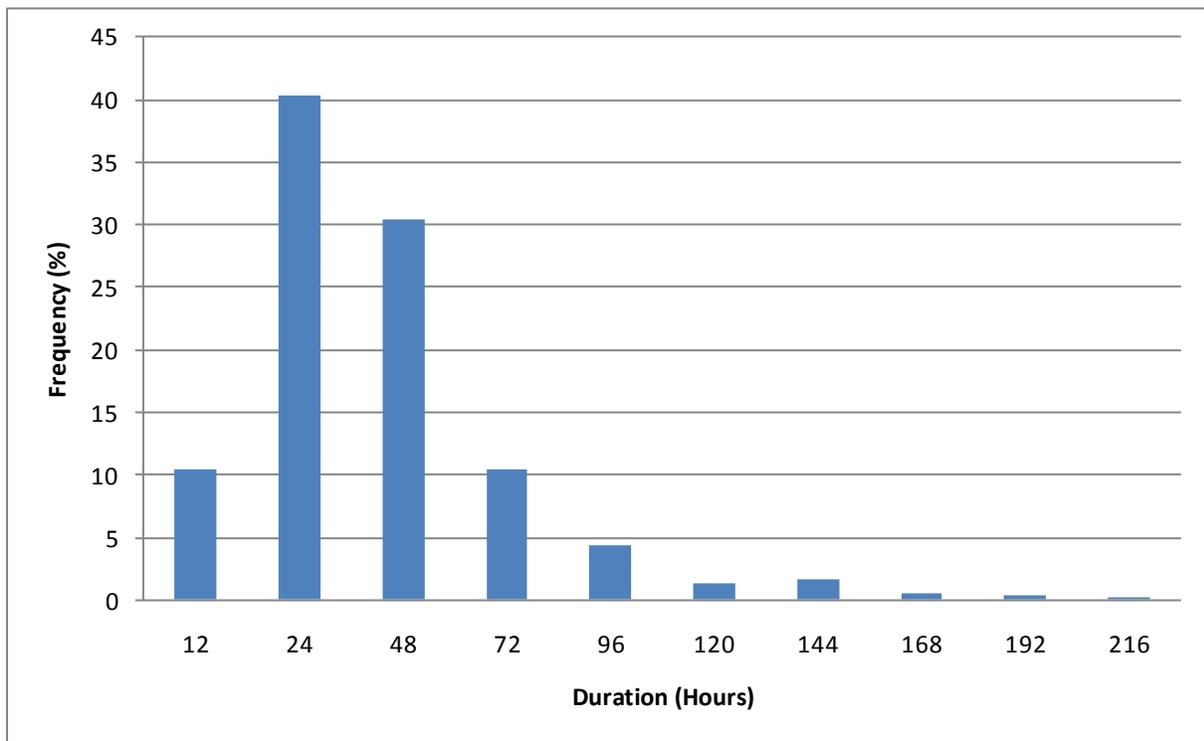


Figure 9- Distribution of wave event duration.

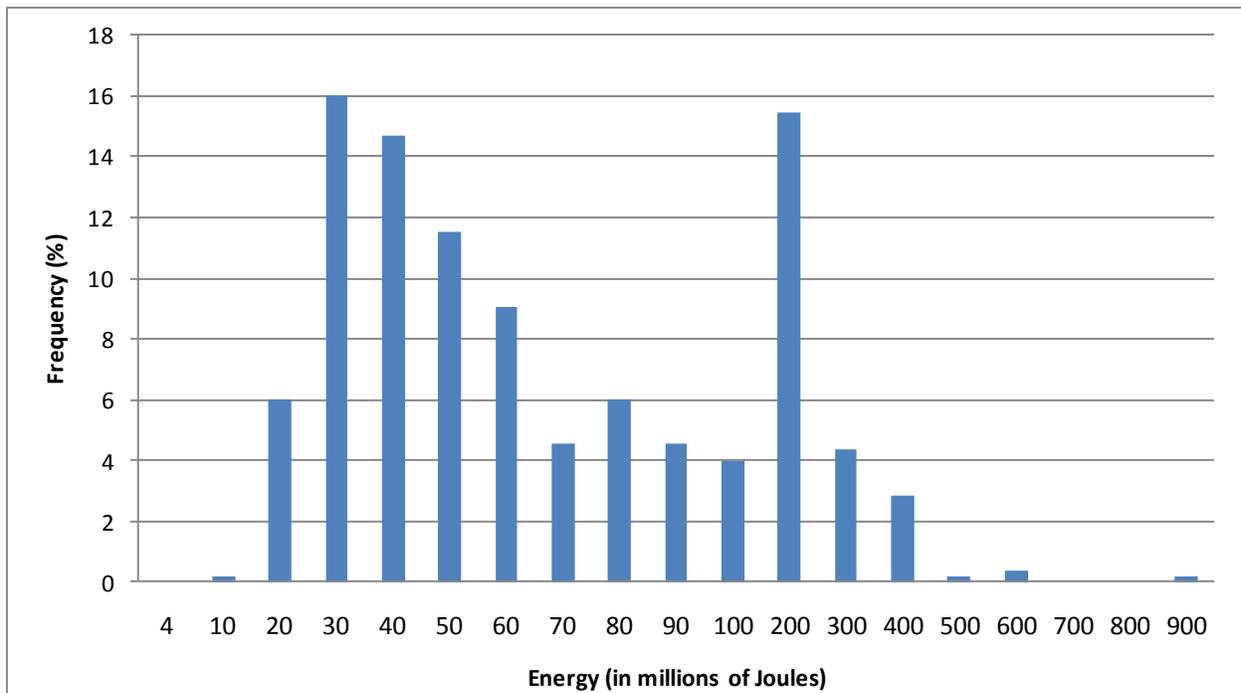


Figure 10- Event energy distribution.

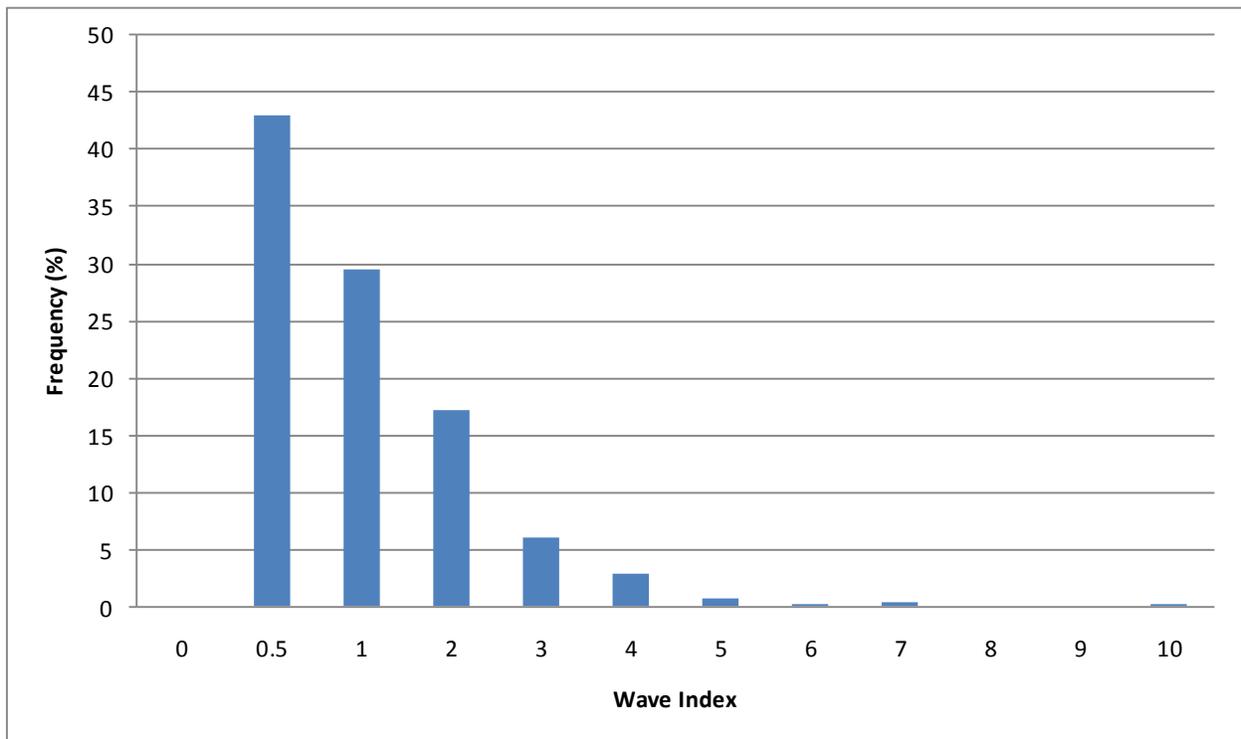


Figure 11- Percentage of wave events per each index magnitude.

The wave period distribution (Figure 8) shows that almost 14% of the events had significant wave periods of around 7 secs. The wide range of event average significant wave periods (15s) suggests that both locally generated (storm) wave events and remotely generated (swell) wave events are induced in the dataset. In order to consider the effects of these wave types, the events were divided into two groups: those with wave periods below 11 secs and those with periods above 11 secs. Relationships between wave period and wave height, duration, and wave energy (without time function) showed almost no relationship with longer wave periods! The average significant average wave height associated with longer wave periods was 2.63m with a standard deviation of 0.36m (Table 1). The average duration for longer wave period events was about 85 hours with a standard deviation of 43 hours and the average energy in J/m^2 was 8.81×10^3 with a standard deviation of 2.444×10^3 .

	Short Period Waves			Long Period Waves	
	Avg.	Std. Dev.		Avg.	Std. Dev.
Wave Height (m)	2.34	0.39		2.63	0.36
Wave Period (s)	8.99	1.14		12.19	0.94
Duration (h)	63.08	29.01		85.43	43.27
Energy (J)	7047.16	2456.27		8813.81	2442.12
Index	1.97	1.18		2.43	1.32

Table 1- Comparison of event characteristics between short and long period waves.

Shorter period waves seemed to have a more important role in the event characteristics. All had positive relationships in that as wave period increased to 10secs, duration (Figure 12A), wave height (12B), and wave energy (12C) would increase. The strongest relationship was between wave period and event duration (Figure 12A), as wave period explained 20% of the variation in event duration. The average duration was about 63 hours with a standard deviation of 29 hours. In general, events with shorter wave periods had relatively shorter durations. With

shorter wave periods one would expect more waves to hit the beach for the duration of the event creating higher energies. However, the average energy was 7.05×10^3 with a standard deviation of 2.46×10^3 J/m². The average significant deep water wave height associated with shorter period events was 2.34m with a standard deviation of 0.39m.

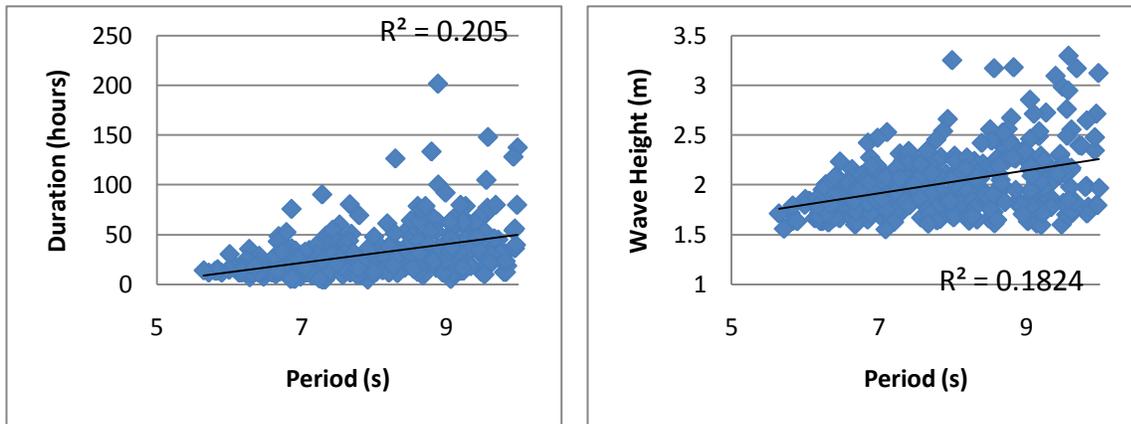
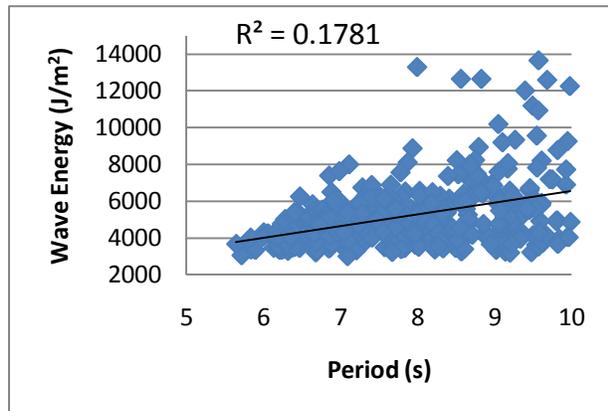


Figure 12A- Wave period vs duration.

12B- Wave period vs. wave height.



12C- Wave period vs. wave energy.

Likewise, event durations were also divided to further determine if longer events exhibited specific wave characteristics. Durations under 48 hours (Figure 9) were considered short and durations above 48 hours were considered long. It is interesting that duration, long or short, had practically no relationship with wave height, wave period, and wave energy. Table 2

shows that the average significant wave height for long duration events was only 2.39m with a standard deviation of 0.4m while the average significant wave height for short duration events was 2.4m with a standard deviation of 0.4m. Significant wave heights are generally higher for the shorter duration events but not by a large amount. Wave energy is also higher for short duration events, which is slightly surprising, with an average event energy of $7.39 \times 10^3 \text{ J/m}^2$.

	Duration Less than 48 Hrs.			Duration Greater than 48 hrs.	
	Avg.	Std. Dev.		Avg.	Std. Dev.
H	2.40	0.40		2.39	0.40
T	9.06	1.75		9.86	1.56
D	39.54	5.50		81.62	32.33
E	7389.26	2604.59		7365.86	2519.90
Index	1.27	0.32		2.46	1.31

Table 2- Comparison of event characteristics between durations of shorter or greater than 48 hrs.

Frequency/Magnitude Analysis

Because 43% of the events were under an index of 0.5 and 72% of all events were under an index of 1 (Figure 13) all wave events under an index of 1 were further extracted from the dataset with 146 events remaining (Figure 14). The largest magnitude event, 10, was Hurricane Dennis which ended on September 5, 1999. This event had an average significant deep water wave height of 3.59m, and duration of about 157 hours (almost 7 days). Hurricane Dennis was a category 2 hurricane but never actually made landfall as a hurricane. On August 30 Dennis brought tropical storm winds to the North Carolina coast and made landfall as a tropical storm on September 4 at Cape Lookout National Seashore (National Hurricane Center, www.nhc.noaa.gov). Figure 14 shows the distribution of events that are 1 or greater. This distribution represents a recalculation of the frequency of events based on the reduced data set.

95% have an index 5 or below and 41% of events have an index of 1.0-1.5. It is also interesting to point out that 50% of the events have an index between 2 and 4.

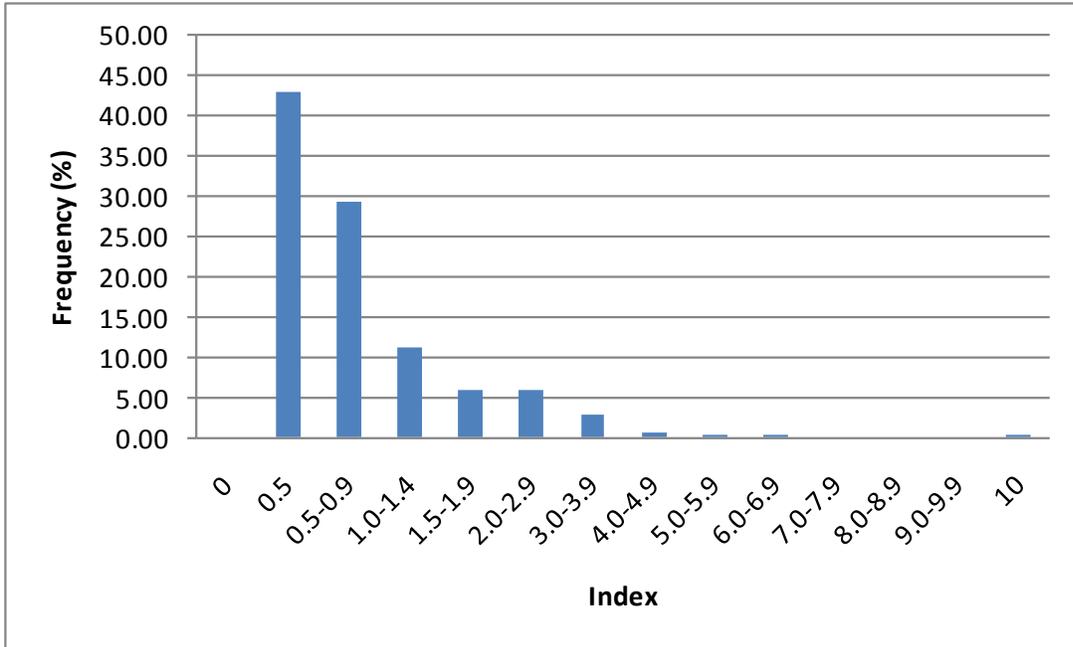


Figure 13- Rationale for eliminating events under the index of 1.

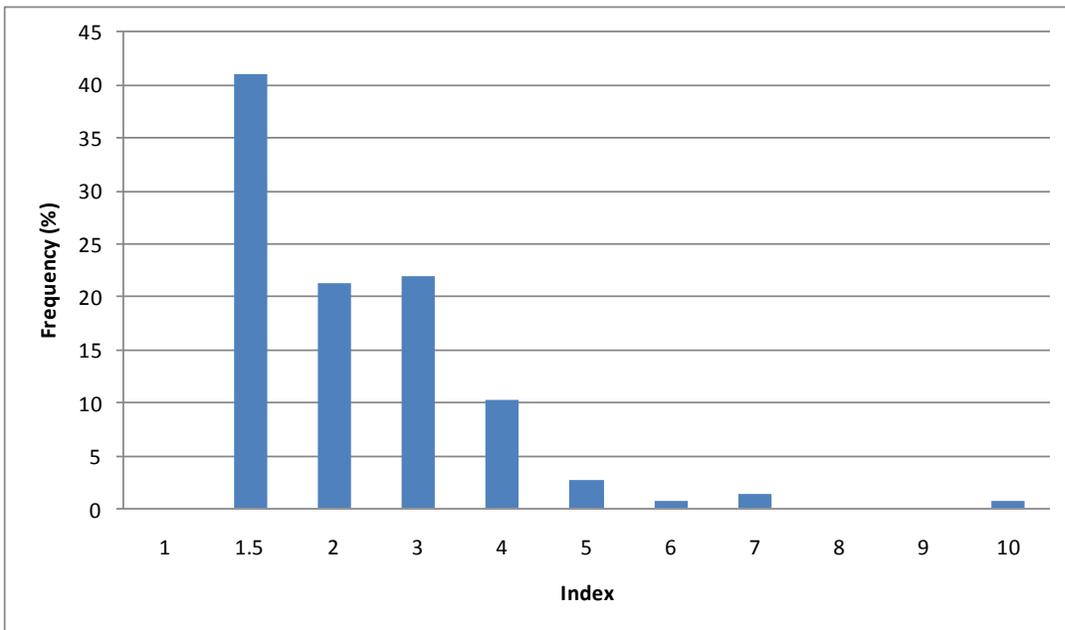


Figure 14- Distribution of events after all events under an index of 1 were filtered out.

The event index represents a combination of three independent variables: wave height, wave period, and event duration. Multiple regression analysis of these variables with the event index as the dependent variable reveals that duration accounts for 92% of the variation in the index (Table 3) with duration and wave height contributing the most to the model, respectively. The event index then can be viewed as the product of the duration and wave height combined, but the same index value can result from infinite combinations of duration and wave height. These combinations can be determined for each index value which represents a total event energy value. To determine these combinations, it is a simple matter to use the event energy value divided by a range of duration values to determine the event wave heights necessary to produce that energy value. This procedure can be repeated for representative index values between 1 and 10. Plotting out the wave height/duration combinations provides an estimate of the requirements for storms of different magnitudes (Figure 15).

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.961 ^a	.923	.922	.3405437

a. Predictors: (Constant), Duration, WH, Period

Coefficients^a

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-2.343	.196		-11.960	.000
	WH	1.950	.083	.636	23.587	.000
	Period	-.253	.021	-.347	-12.107	.000
	Duration	8.904E-6	.000	.872	34.994	.000

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-2.343	.196		-11.960	.000
	WH	1.950	.083	.636	23.587	.000
	Period	-.253	.021	-.347	-12.107	.000
	Duration	8.904E-6	.000	.872	34.994	.000

Table 3- Relationship between the index and wave height, period, and duration.

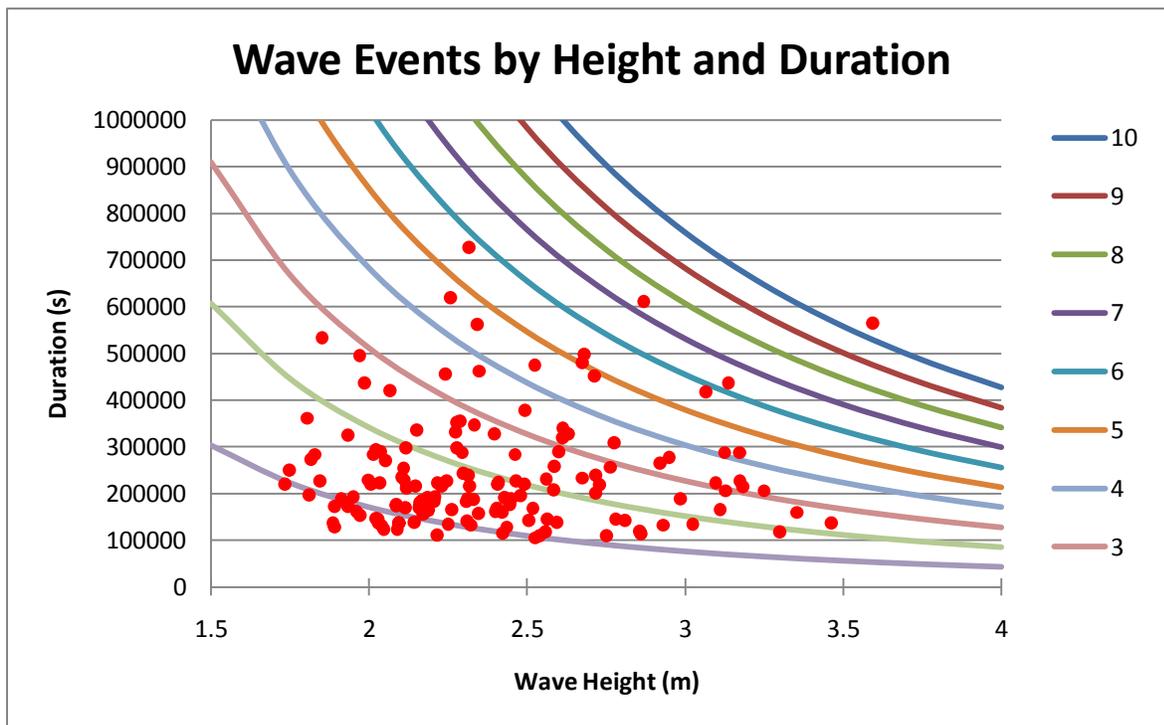


Figure 15- Events plotted according to index devised from durations and wave heights.

Plotting the wave height/duration combinations for the 146 actual events examined confirms the idea that different combinations produce events of similar magnitude. Some events lie outside of the index range due to averages (ρ and wave period) used to devise the index

lines. The graph further shows the majority of events that are below an index of 5 but the graph allows for rough estimates of future events of given durations and wave heights. For instance, if an event has a significant wave height of 3m and a duration of 500,000 seconds then the event would have an index of 6.2. It is also interesting to point out that an event with a wave height of about 3.3m and a duration of 110000 seconds and an event with a wave height of about 2.2m with a duration of 300000 seconds will both produce an index 2 event.

A Weibull analysis was performed on the data set that includes the 146 events above an index of 1. The event energy and index were used as inputs and the index was ranked to perform the analysis. The two-parameter assessment was used, the shape parameter (k) was 1.87 and the scale parameter (c) was 1.491. Figure 16 shows the Weibull distribution and the actual distribution of the data. The Weibull cumulative distribution function overpredicts the low index events. Weibull predicts that 80% of the events will have an index of 1 when in actuality 62% of the events have an index of 1. This could be because of the high abundance of these low index events. The cumulative Weibull almost perfectly predicts events of 5 or above. While the Weibull general probability function underestimates actual events, it almost perfectly predicts events with an index of 5 or greater. Ulgen & Hepbasli (2002) calculated a RMSE of 0.02 for the Weibull distribution for wind energy. A RMSE of 0.033 was determined for the wave events meaning Weibull predicts within a 3.3% probability of the actual probability of an event of a given index. Although a RMSE of 0 is ideal Weibull still reasonably predicts events of varying indexes, particularly those events with an index of 5 or greater.

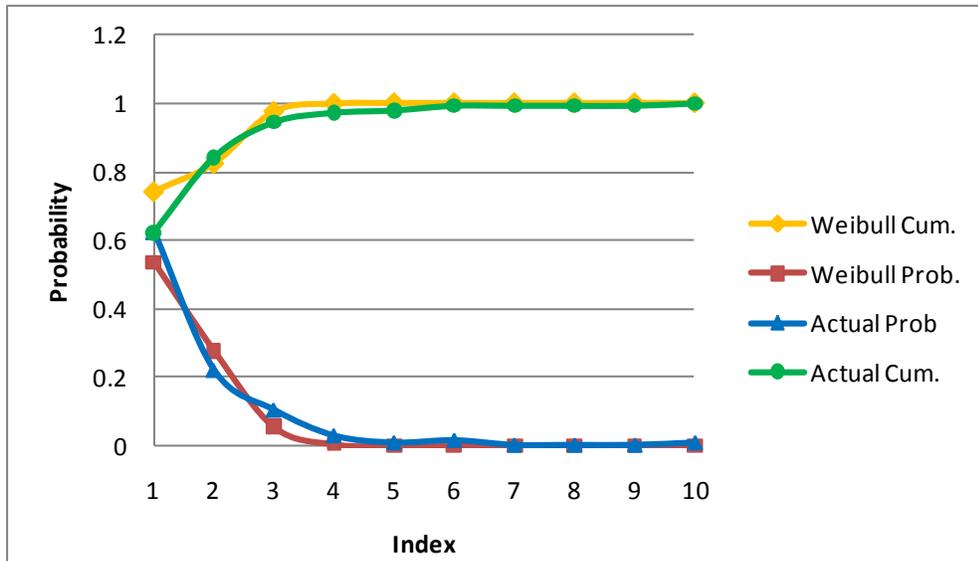


Figure 16- Weibull vs actual distribution for events.

As a final approach to understanding the frequency and magnitude of events at Duck, a probability of occurrence plot was generated based on the index in order to assess event frequency according to magnitude. Generally, probability of occurrence plots are calculated for annual maximum series analysis, and this requires as long a record as possible, preferably 100 years. It was performed here using the partial duration series for exploratory purposes. A probability of an event of a certain index is generated by:

$$P = m/n + 1 \tag{11}$$

where T = the recurrence interval which is based on the ranking of the events according to index. The magnitude ranking was based on the total event energy, with ranking 1 being the largest event. Figure 17 shows the probability of occurrence. The largest event, which ended on September 5, 1999 has a probability of occurrence of about 1% and a recurrence interval of 24 years. The smallest events are likely to occur quite often. The recurrence interval was calculated for any events and the smallest event should only return every 58 days (16% of one year). Most

of the small events in the record have returned at least once a month with as much as a year in between, therefore making 58 days an adequate estimator for low magnitude events. But of course, seasonality needs to be considered.

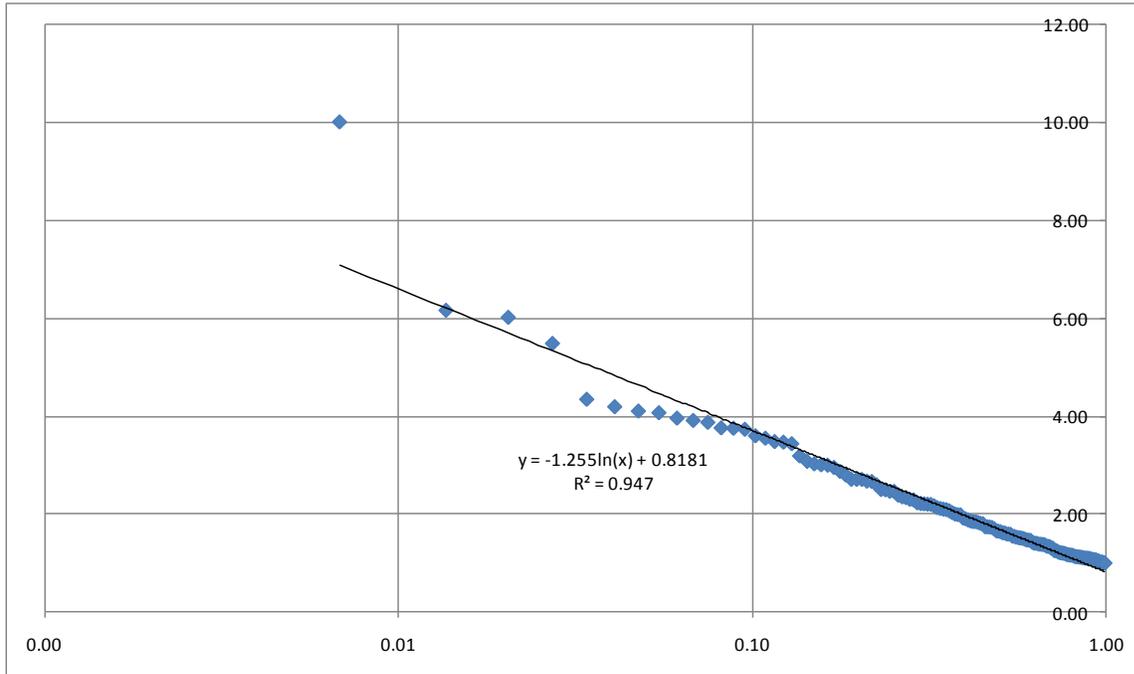


Figure 17- Probability of occurrence for events index 1 and above.

Birkemeier et al. (1999) calculated a recurrence interval based on storm group energy and claimed that an ‘event’ with an energy of 7.5×10^{10} J would return every 20 years. What is interesting to point out is that the largest event in the dataset had a probability of occurrence of 1% and a recurrence interval of 24 years. This contradicts Birkeremier et al.’s findings because one single event in the dataset would not return as often as a rather large storm group producing 75 billion joules of energy! Also, Birkemeier et al. (1999) did not include Hurricane Dennis in their dataset which was the largest defined event in this dataset.

It also important to refer back to Birkemeier et al. (1999) with regards to event seasonality. Table 4 shows the seasonality of the events above an index of 1 in the 23 year period. When examining the seasonality of these events, the greatest number of events occurred during the fall, a total of 54. Of the 103 storms in Birkemeier et al. dataset 13.6 % of the events were also in October, about 14 events. A high number of events also occur during the spring months, 47 total. The seasonal distribution of events coincides with Bascom (1959) and Nordstorm's (1980) conclusions that summer months are generally termed quiet or low energy months allowing for the berm to lengthen and the slope extending into the water to build while fall and winter months provide high amounts of energy, narrowing the berm.

Month	# of Storms	Month	# of Storms
March	16	June	2
April	16	July	0
May	15	August	5
Total	47	Total	7
Month	# of Storms	Month	# of Storms
Sept.	18	Dec.	13
Oct.	21	Jan.	11
Nov.	15	Feb.	14
Total	54	Total	38

Table 4- Seasonality of events, total number to occur each season for 1985-2007.

However, when examining the annual distributions of events the events did not clearly show trends for storm clusters as did Lee et al. (1995, 1998) and Birkemeier et al. (1999). The average number of events per year was 6 events with a standard deviation of 3 events (Table 5). While most events are occurring during fall and winter months there still is no discernable grouping of events unless one only considers the seasonality of events. The most events, 15 total,

occurred in 1993 but because the average number of storms for 1993 is only 6 events no clear clusters could be derived. 1992-1994 are years of more storminess than others.

Year	# of Storms	Year	# of Storms
1985	2	1997	6
1986	4	1998	7
1987	4	1999	9
1988	1	2000	9
1989	8	2001	6
1990	6	2002	2
1991	9	2003	7
1992	10	2004	6
1993	15	2005	7
1994	11	2006	1
1995	7	2007	2
1996	7	Total	146

Table 5- Annual distribution of events, 1985-2007.

Summary

In general, the events at Duck, North Carolina are low in magnitude and frequent, at least one a month. 530 events between 1985-2007 at a significant wave height of 2m or a duration of at least 42000 seconds (about 12 hours). The largest magnitude event, September 5, 1999, occurred during Hurricane Dennis producing a significant wave height of 3.59m and generating an event energy of 8.92×10^8 J. After generating the index and filtering out those below an index of 1, 41% still were between 1.0-1.5 and 95% of the events were an index of 5 or below. The Weibull distribution was a relatively good fit of the actual data, predicting that 80% of the events would be an index of 1. Weibull almost perfectly predicted index 5 and above events. It was determined that the largest event should only return every 24 years, with a probability of

occurrence of 1% and the low magnitude events should return about every 58 days, with the probability of occurrence ranging from 70-100%.

CHAPTER FOUR: VOLUMETRIC CHANGE

Overview

This chapter presents the methodology for computing out the volumetric change corresponding to each event over an index of 1. In order to determine the volumetric change associated with each event above an index of 1, profile data for both before and after each event was obtained. Volumetric change was computed for each of the four profile lines, surveyed bi-weekly in order to determine the total average change per event. Volumes were computed to the 1m depth to determine subaerial change and change was also computed to the 5m depth to determine the subaqueous change.

Methods

Since 1981, the FRF has been collecting detailed surveys of the nearshore bathymetry with great accuracy, ranging from 2-5cm (Birkemeier, 1985). The surveys were conducted with the Coastal Research Amphibious Buggy (CRAB), a 10.7m tall amphibious tripod, and a Trimble 4000SE GPS survey system. Starting in September of 1999 profiles were also conducted using the Lighter Amphibious Resupply Cargo (LARC-5) that uses a GPS unit, a fathometer, and software to provide bottom elevations. The surveys have been conducted over a series of 26 shore perpendicular profile lines spaced at 90m intervals along the shore. The transects extend from the dune to approximately 950m offshore (Figure 18). Four of the 26 lines are surveyed biweekly but all other lines are surveyed monthly. The lines in red represent the four profiles surveyed bi-weekly, 58, 62, 188, and 190. This profile data was downloaded directly from the FRF website.

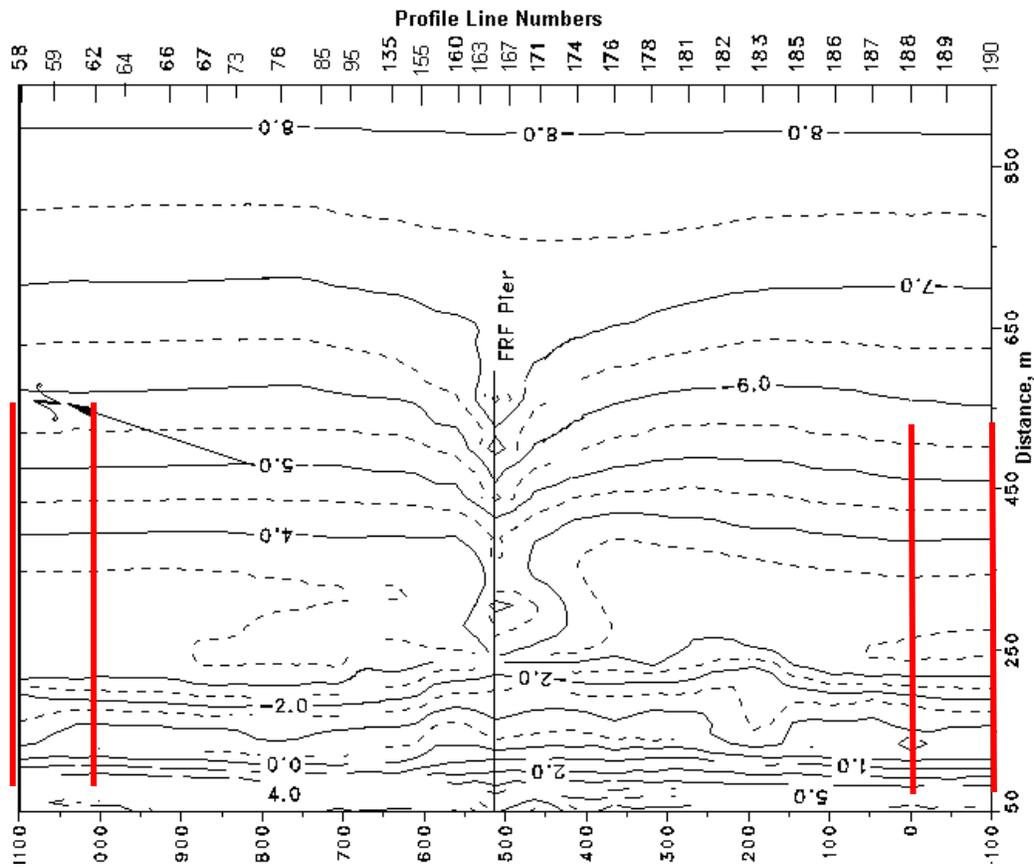


Figure 18- Profile lines conducted one a month or bi-weekly at the FRF in Duck.

Whereas the frequency/magnitude analysis of wave data covered the period 1985-2007, the analysis of beach response focuses on the most recent data from 1997-2007. It was decided to use this more limited data set because these years had not yet been considered for analysis and the accuracy of the profiles was 2cm. In addition, rather than examine all 26 profile lines, the analysis examines the four transects surveyed more frequently (at least bi-weekly) in order to better isolate beach response to storms. FRF profiles collected before and after each wave event are used to calculate the associated volumetric change. X, Y, and Z values are extracted from profile lines that are surveyed bi-weekly (58, 62, 188, 190) and profile plots are created.

Because they vary in their length from one profile to the next, the profiles are truncated to establish consistency. The dune crest is used as the starting point. Visual examination of the profiles over the 10 years study period indicates that the dune crest remained fixed. At the seaward end, the profiles were truncated at the 5m depth. This was chosen because this location is always seaward of the outer subaqueous bar. Because previous research suggests that sediment is regularly exchanged between the subaerial beach and the subaqueous bars, volumetric change was determined for these two zones as well as for the entire profile. The subaerial profile zone covers the area from the dune crest to the 1m depth. This depth was chosen because this location seemed to be the inflection point for an inner bar to develop. Therefore, the subaqueous volume is computed from the 1m to the 5m depth and the subaerial volume from the dune crest to the 1m depth (Figure 19). Average change was used as opposed to median change, as proposed by Savage & Birkemeier (1987), because median change in this instance would not produce good results as only four profiles are being examined. The volumetric change associated with each event will allow for relating these changes to event magnitude (chapter five).

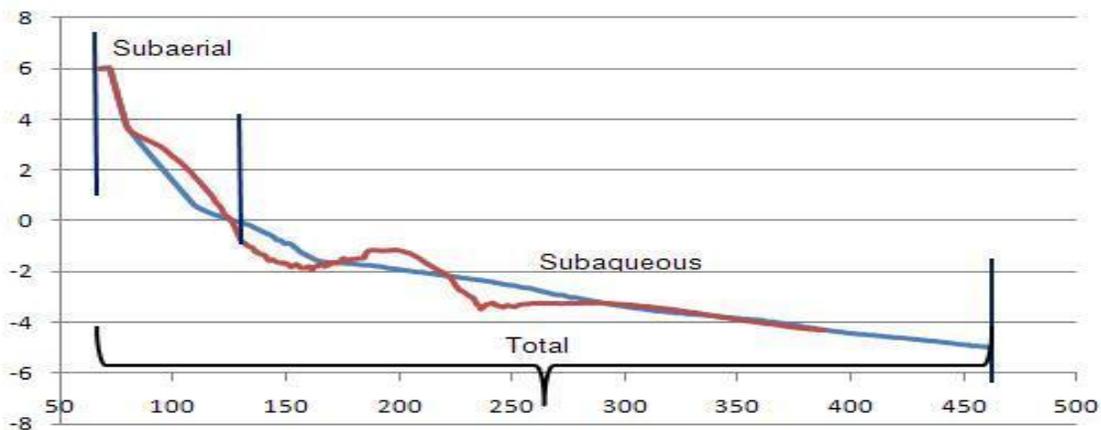


Figure 19- Profile zones for volumetric change assessment: subaerial (dune to 1m), subaqueous (1m-5m), and total (dune to 5m).

Results

Of the 146 events with a storm index (SI) of 1 or greater, 61 occurred between 1997-2007, and volumetric change was calculated from the profiles before and after the event. An inspection of the volumetric change data revealed four outliers were atypical of average erosion/deposition on the beach at Duck. These four events were removed from the dataset, leaving 57 events for the volumetric change analysis. Figure 20 shows the change to the 5m depth per event for each of the profiles: 58, 62, 188, and 190. It is apparent from Figure 18 that there are dramatic differences in volume change between some of these profiles, with the greatest differences in 1999 and 2003. Figure 19 shows the distribution of average volumetric change per event out to the 5m depth and there is no clear trend of average deposition and erosion for these eleven years. When looking at figure 19 it is interesting to point out that there seems to be an equal number of erosional and depositional events which contradicts what one might expect. It would be expected that almost all of these events should produce some sort of erosion.

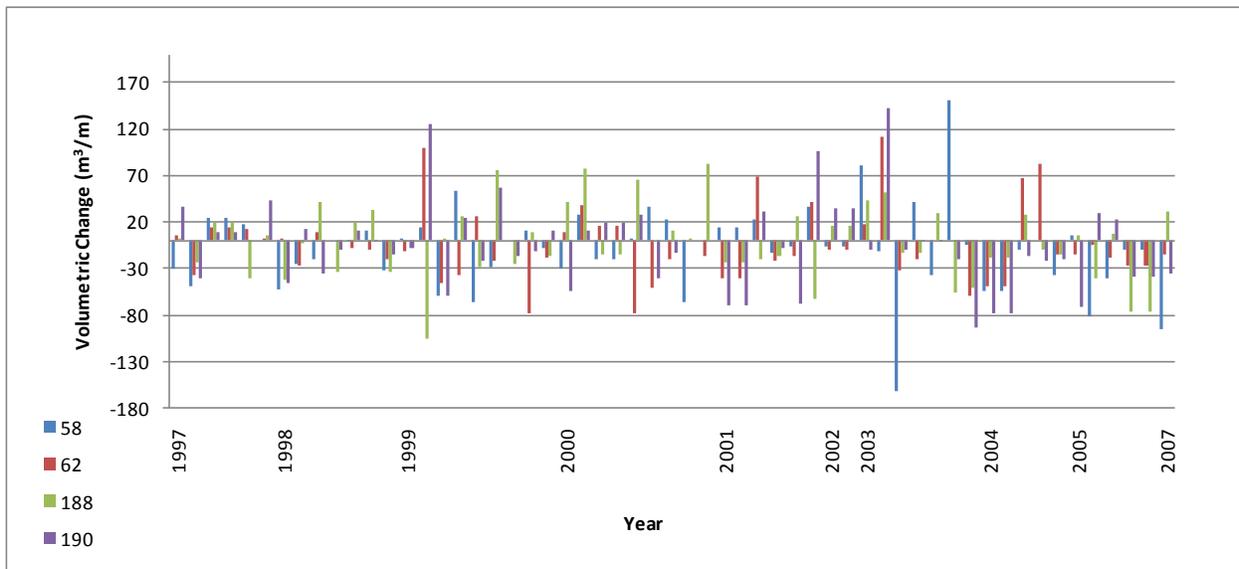


Figure 20: Volumetric change for all 4 profiles (58, 62, 188, 190) to the 5m depth, 1997-2007.

resulted in the deposition of sediment in the trough. This deposition was far exceeded by the overall erosion which amounted to $162 \text{ m}^3/\text{m}$.

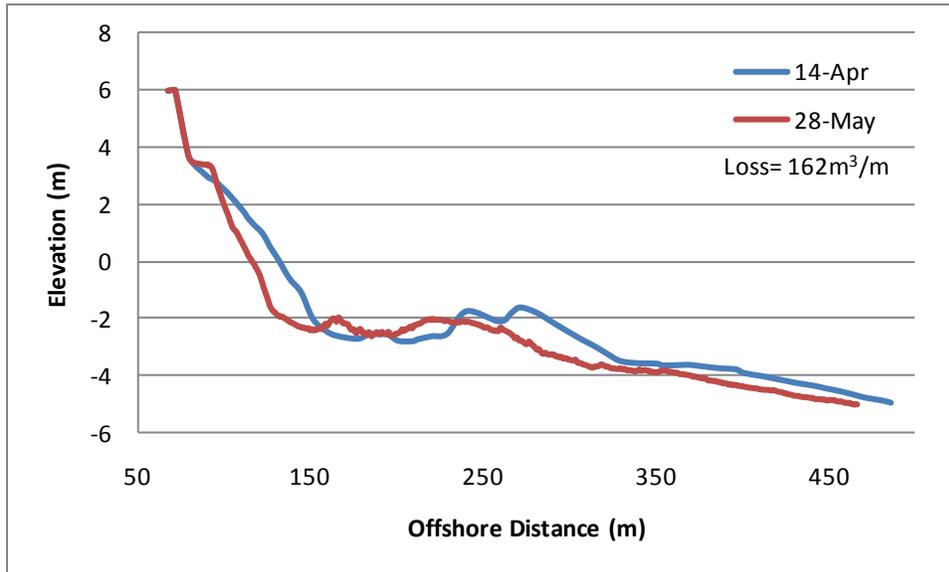


Figure 22- Volumetric change for the April 21, 2003 event along profile 58.

The greatest average volumetric gain occurred with the event that ended on April 12, 2003 with a gain of $73.43 \text{ m}^3/\text{m}$ (Figure 19). The largest volumetric differences were found in line 62 with a change of $111 \text{ m}^3/\text{m}$ and line 190 with a change of almost $142 \text{ m}^3/\text{m}$ (Figure 20). This volumetric gain is not surprising as the index for this event 1.47, significant average wave height was 2.12m with a significant wave period of 9.1 secs; generally periods between events allow for beach recovery. There was deposition on the berm (figure 23 top) on the order of +3m extending to the 2m depth as well as along profile 190 (figure 23 bottom) but a greater amount of sediment was deposited along this length of profile. An offshore bar migrated seaward and a new bar was created at 5m depth (figure 23 top). However, after the event the bar present around

250m offshore was flattened with that sediment being deposited along a gentle slope extending out to the 5m depth (figure 23 bottom).

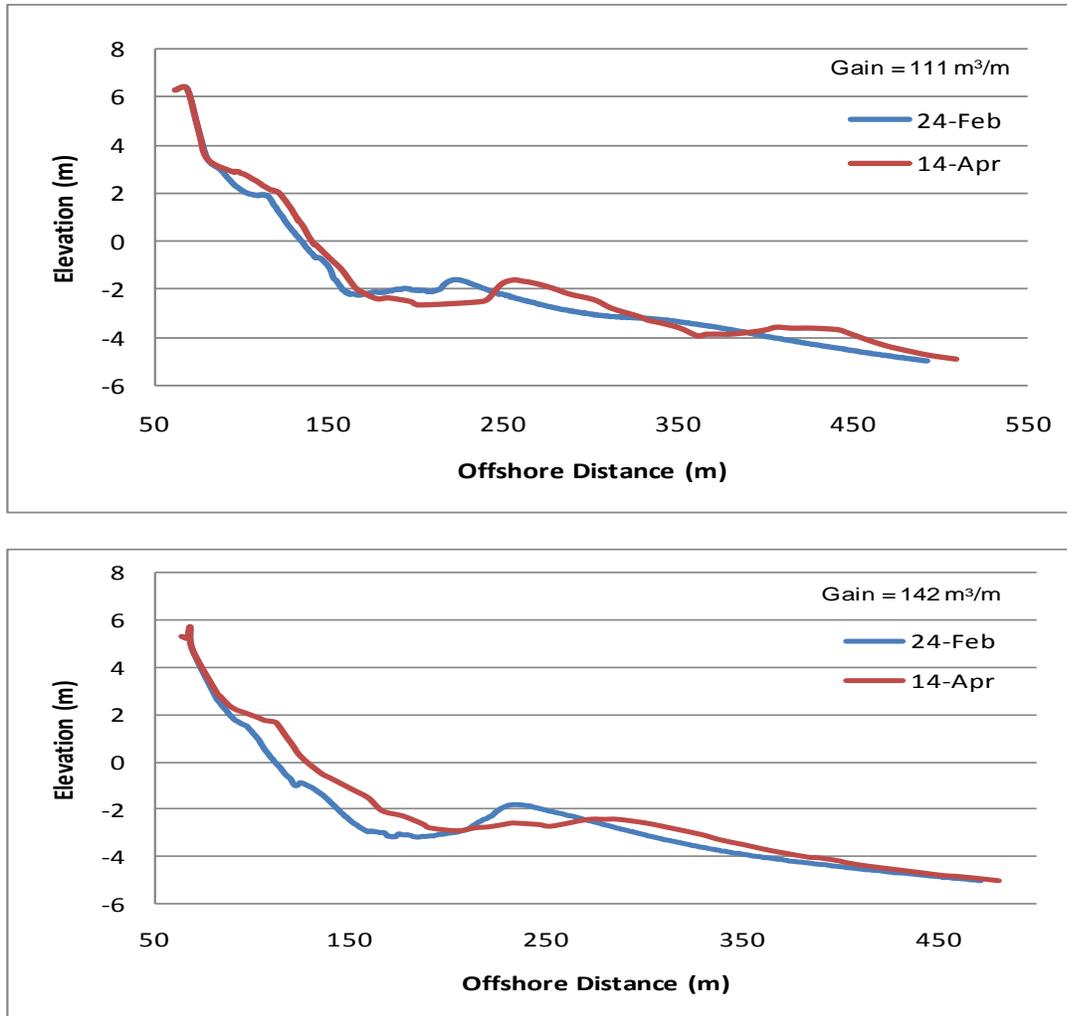


Figure 23- Volumetric change for lines 62 (top) and 190 (bottom) for the April 12, 2003 event.

The largest event the highest SI, which occurred on September 5, 1999, had a total average loss of only $-20.9\text{m}^3/\text{m}$ (Figure 21). However, the average change is based only on data from profiles 188 and 190 because profile data for profiles 58 and 62 were not available. Although Hurricane Dennis made landfall as a tropical storm on September 4th at Cape Lookout

National Seashore (about 188km to the south) its track (Figure 24) shows that beaches along the coast of North Carolina would be affected.

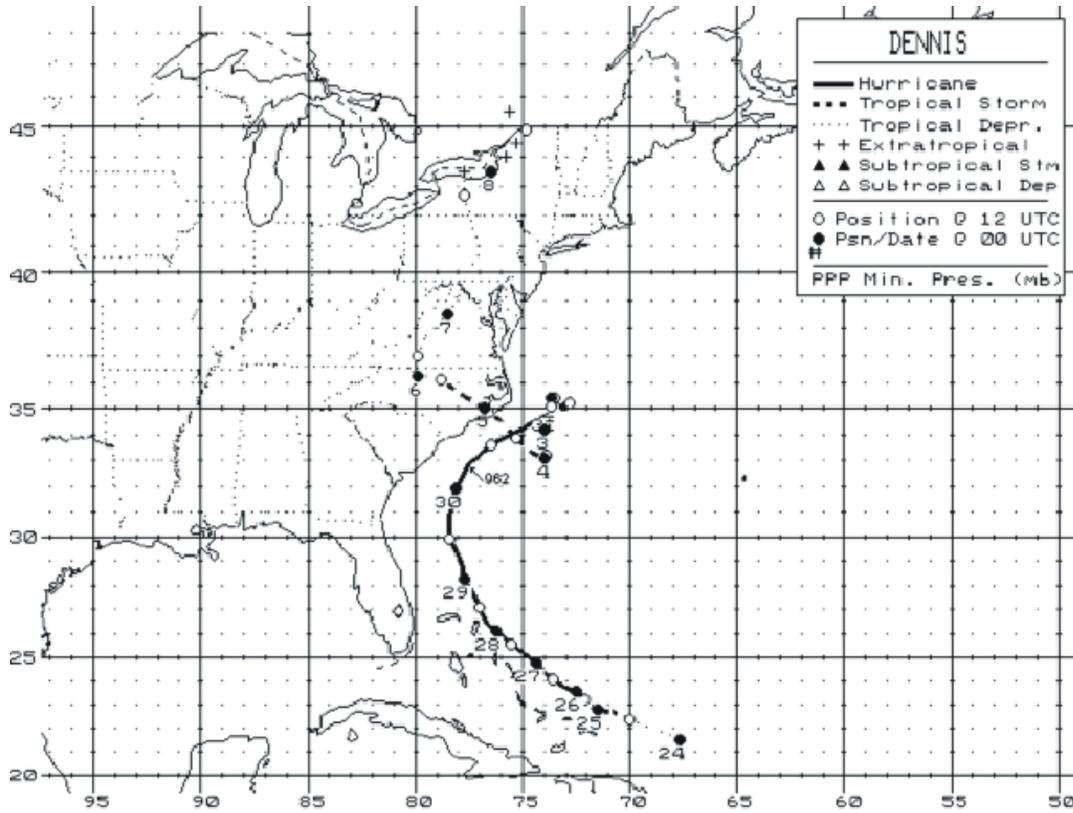


Figure 24- Hurricane Dennis track September, 1999.

It would be expected that because the average significant wave height of the event was 3.59m, wave period was 10.22 seconds, and duration was almost a week, that the volumetric change would be extreme. The largest significant wave height recorded during the duration of the event was 7.12m, which would suggest that significant energy was associated with these waves, creating extensive beach erosion. This of course was not the case. The pre-storm profiles at the southern end of the FRF are very similar, with a gentle slope all the way from the beachface to the 5m depth (Figure 25 top and bottom). There is evidence of a small bar about 300m offshore in a water depth of about 3m. There is also evidence of a bar, perhaps a swash

bar at the base of the foreshore in water depth of about 1m. Following the storm a trough develops where the swash bar had been and a bar developed at a depth of -1m to 2m with the crest approximately 175m offshore. A second bar is present at the seaward end of the profiles at a depth of -4m. This bar is only about 1m high.

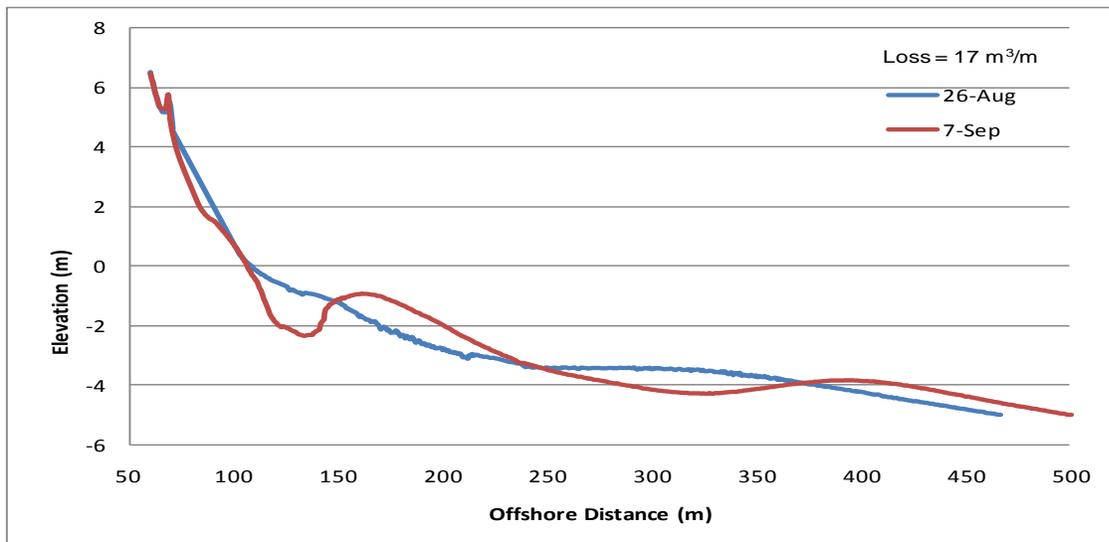
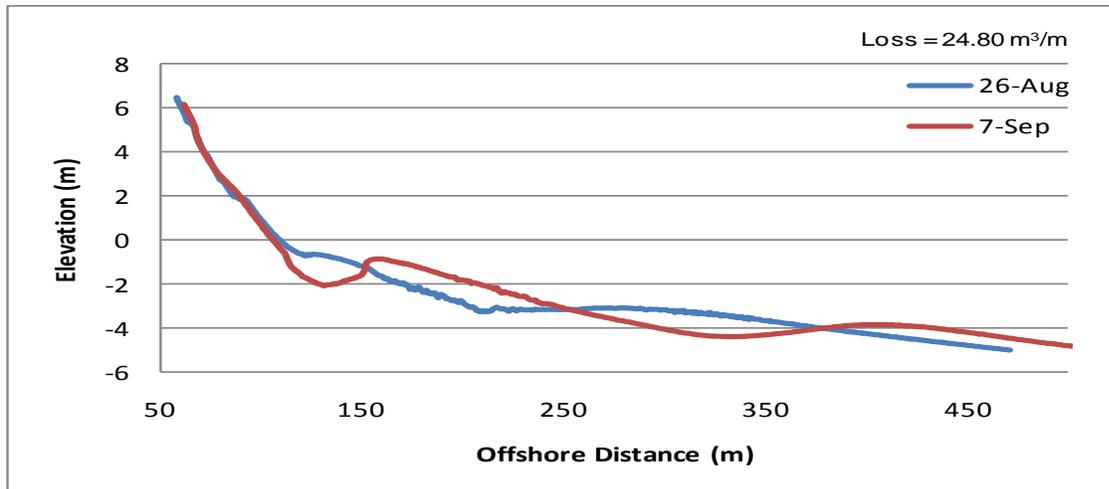


Figure 25- Largest event, index 10, and associated change along profiles 188 (top) and 190 (bottom), September 5, 1999.

Volumetric changes to the 1m depth were also examined, as well as the change between the 1m and the 5m depth. Figure 25 shows the volumetric change per profile to the 1m depth.

The largest volumetric change of any line occurred with the September 23, 1999 event with a gain of 86.9 m³/m along profile 188. Figure 26 shows the total average volumetric change for each event to the 1m depth. The greatest volumetric change was associated with the October 8, 2005 event was a loss of 41 m³/m.

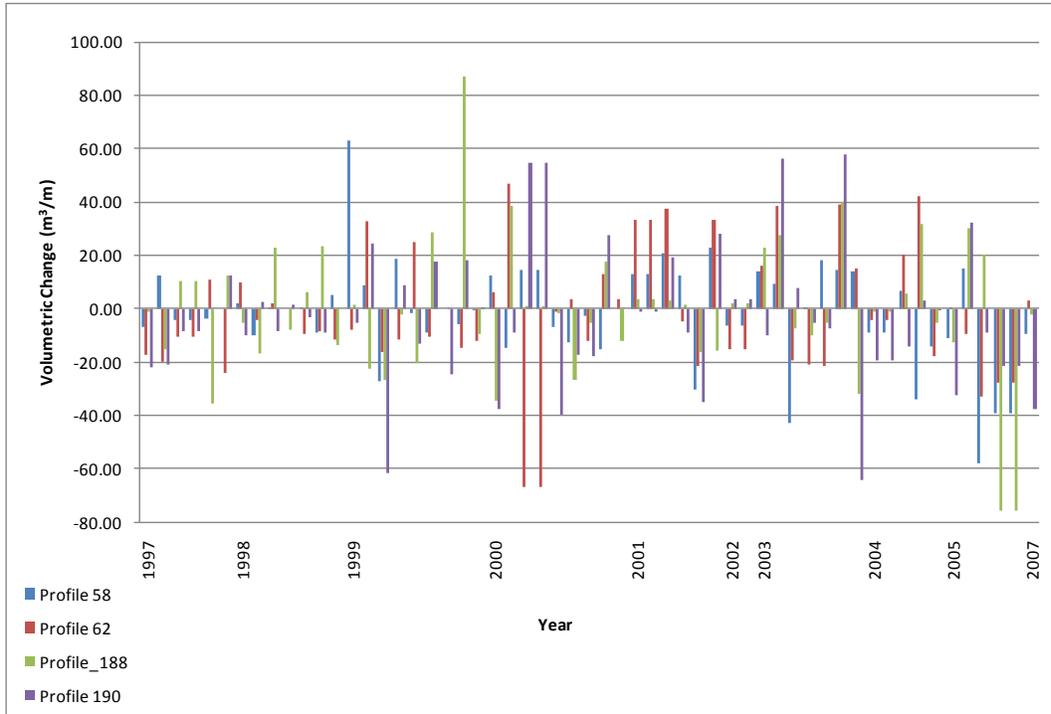


Figure 25- Volumetric change per profile to the 1m depth.

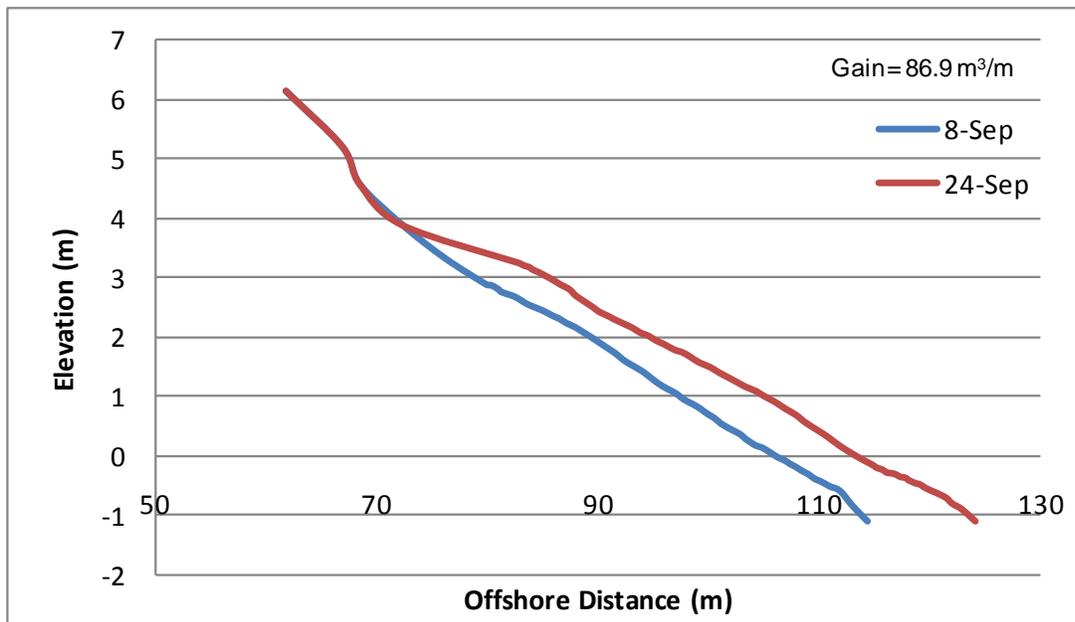


Figure 27- Volumetric change occurring along profile 188 to the 1m depth for Sept. 23, 1999 event.

The largest total average volumetric loss occurred during the October 8, 2005 event with the greatest volumetric change also occurring along profile 188 (Figure 28). The loss along profile 188 was $75.42 \text{ m}^3/\text{m}$. What is interesting is that there was a rather large amount of sediment deposited on the beachface with little actually being eroded from the profile considering the significant wave height was 1.83m, significant wave period was 8.71 secs, with an index of 1.3. A small amount of sediment was eroded in the swash zone, eliminating a very small bar that was present before the event. The event did however, have a duration of just over two days.

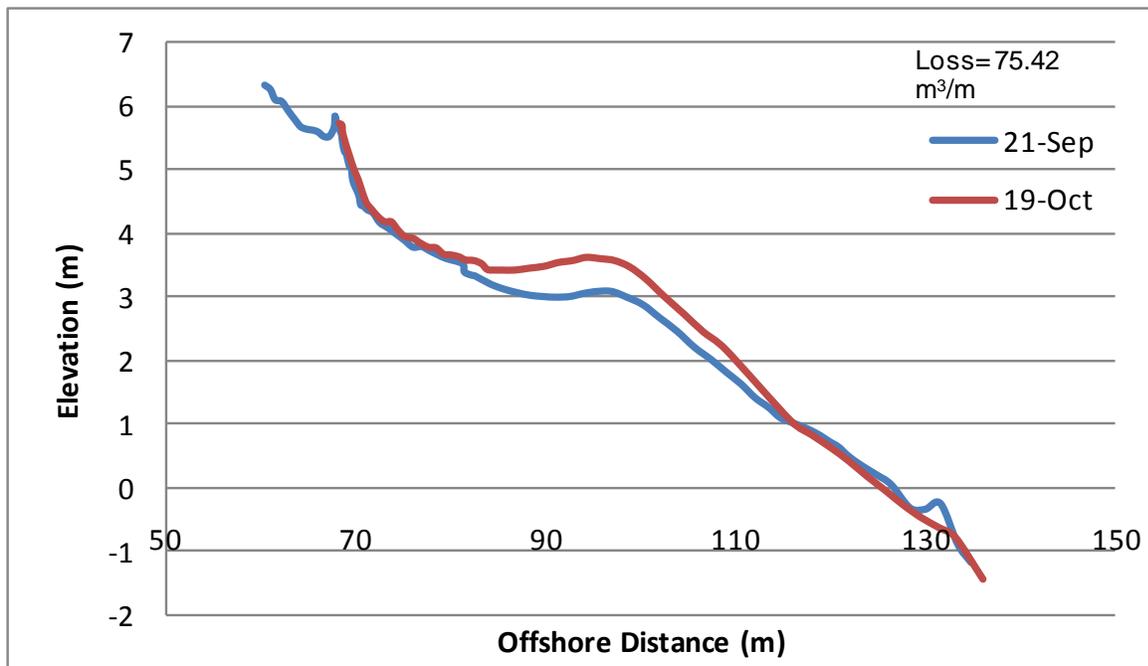


Figure 28- The largest change to the 1m depth along profile 188.

Volumetric change along the subaqueous portions of the profiles were also examined. The greatest volumetric loss along the subaqueous portion of the profile coincided with the October 3, 2000 event, with a total average loss of 43.24 m³/m. The greatest loss along an individual profile occurred along profile 58, with a loss of 51.06 m³/m (Figure 29). The foreshore bar that was represent before the event was completely eroded and deposited in the form of another bar 200m offshore. The bar located around the 425m offshore mark migrated landward with its landward slope steepening. The event had an index of 2.12, a significant wave height of 2.15m and a significant wave period of 10.28 secs.

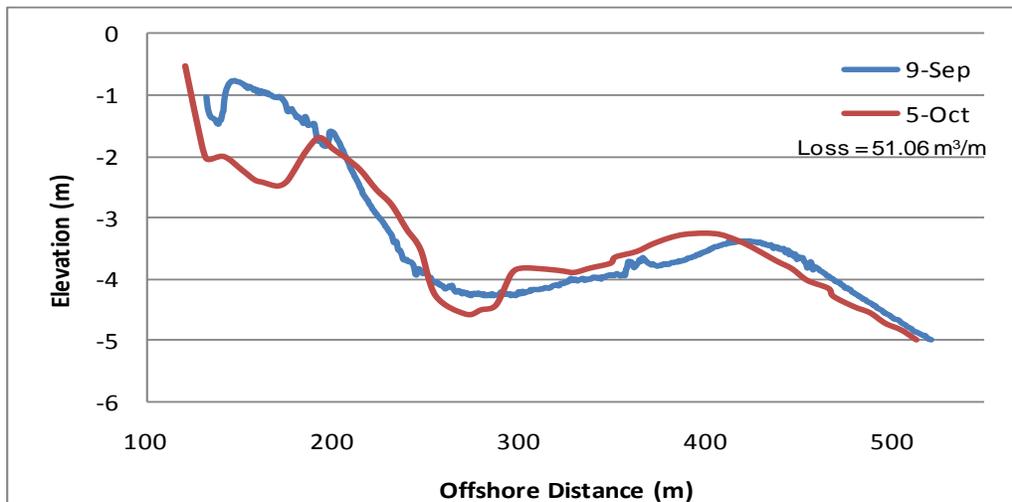


Figure 29- Greatest volumetric loss in the subaqueous portion of profile 58.

The greatest gain the subaqueous portion of the profile was associated with the April 12, 2003 event. The total average gain was $40.49 \text{ m}^3/\text{m}$ with the greatest individual gain along profile 190, gaining $85.47 \text{ m}^3/\text{m}$ (Figure 30). The entire profile migrated seaward, pushing the bar seaward to the 250m offshore mark, creating a trough in the middle of the bar. The slope extending to the 5m depth hardly changes past the 400m offshore mark. The index for this event was 1.47, significant wave height of 2.11m and a significant wave period of 9.09 secs.

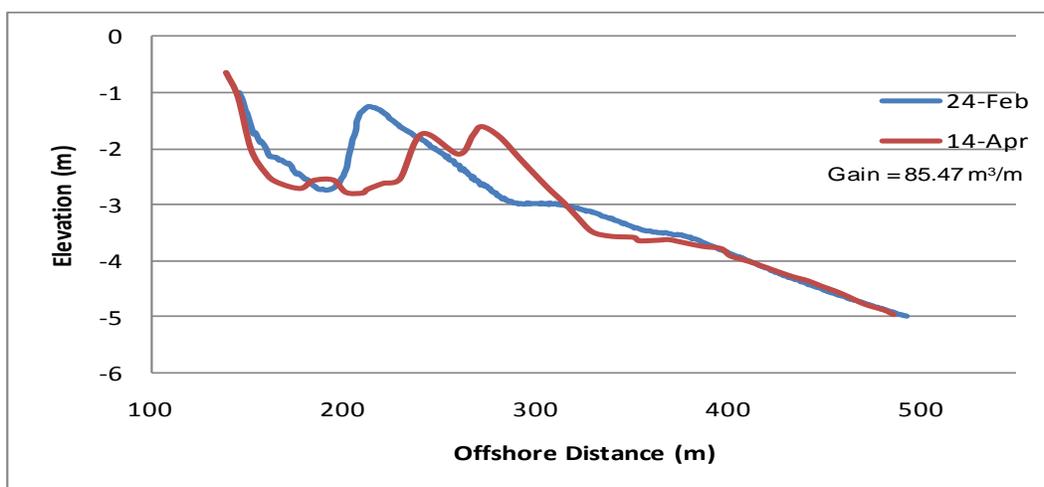


Figure 30- Greatest gain in subaqueous portion of the profile (190).

Volumetric changes to the 1m plus the volume in between the 1m and 5m depths were plotted (figure 31). What is interesting to point out is the fact that in a few cases there is deposition occurring to the 1m depth and then erosion occurring from the 1m to the 5m depth and vice versa. Further investigation will be done in the next chapter to understand the differences in the volumetric change between these events.

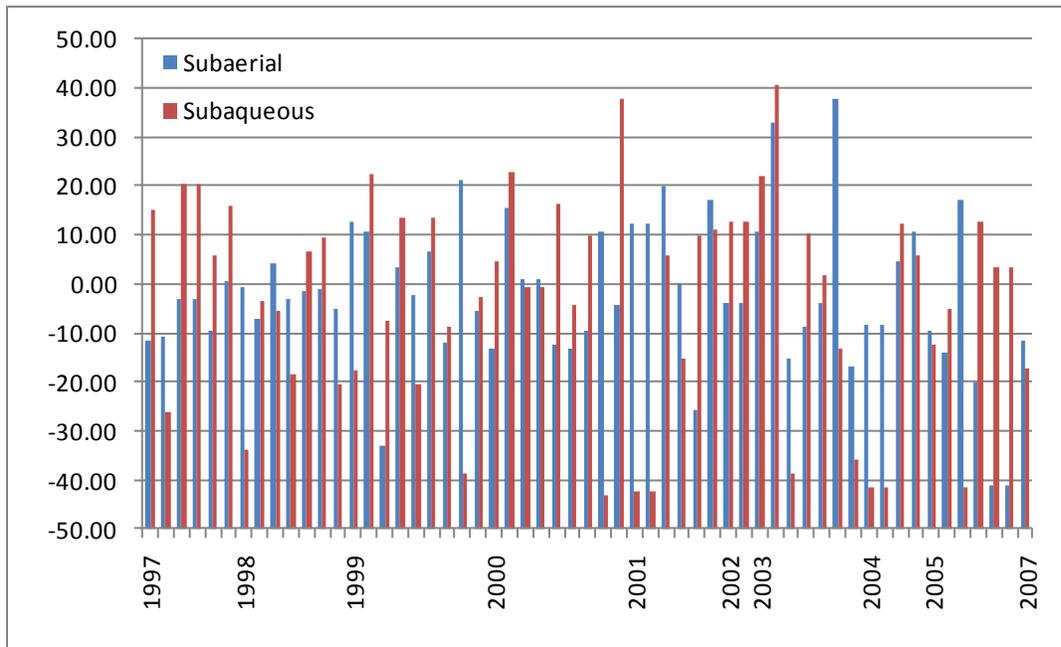


Figure 31- Total volume, divided into volume to the 1m depth, then between the 1m depth and the 5m depth.

The next section attempts to relate the events with these volumetric changes to establish any relationships between magnitude and associated beach change. It will also be examined if the profiles themselves exert any relationships between their associated volumetric changes.

CHAPTER FIVE: ANALYSIS & DISCUSSION

Relating Events to Volumetric Change

Because previous literature has stated that wave height, duration, some form of storm surge/tide, and an energy/power function are the most important variables in producing change on the profile (Zhang et al., 2000; Lee et al., 1995, 1998; Birkemeier et al., 1999), these characteristics were used to derive the index for assessing beach change. When considering the events that were above an index of 1 a series of graphs were made to visualize the index and associated volumetric change. Figure 32 A, B, & C show index 1.0-1.9, 2.0-2.9, and 3 and above, respectively and the volumetric change that occurred because of those events.

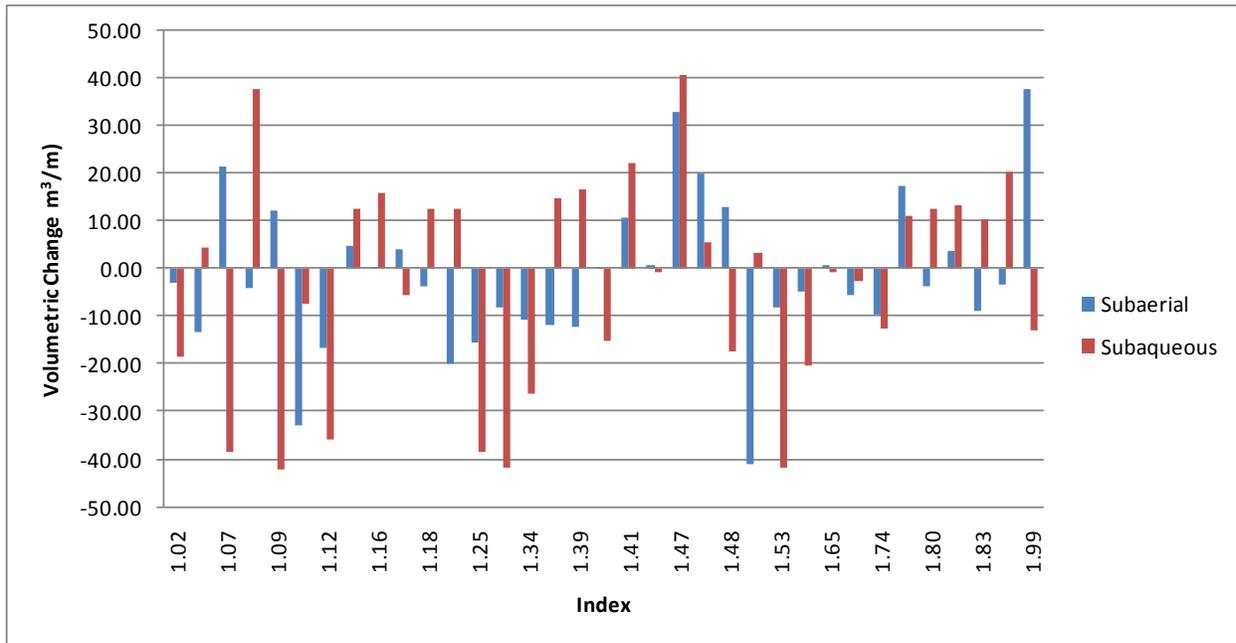


Figure 32A- Volumetric change for all events between an index of 1.0-1.9.

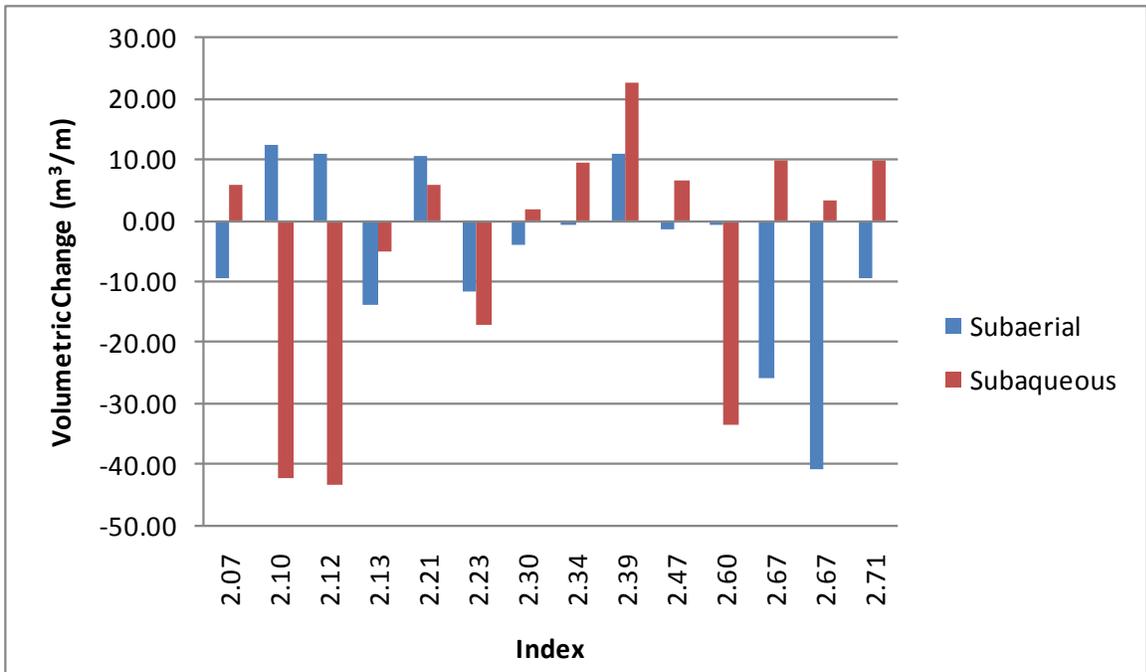


Figure 32B- Volumetric change for all events of an index between 2.0-2.9.



Figure 32C- Volumetric change for all events above an index of 3.

The hypothesized relationship between event magnitude and beach change is that as total event energy increases the total average volumetric change will also increase in beach loss, providing a direct relationship. However, when examining at figure 32A, B, and C there is a lot of variation of volumetric change, especially when looking at the low magnitude events. The largest volumetric change for all indexes above 1 was a gain of about $73 \text{ m}^3/\text{m}$, corresponding to event index of 1.46, which is typical of general storm beach interaction knowledge. Due to the fact that the storm tide, astronomical tide + storm surge, was 1.5m and the duration was two and a half days these conditions allowed for the significant deposition of sediment along the beach. The largest change for indexes 2.0-2.9 was a loss of $38 \text{ m}^3/\text{m}$. There was a total average loss of $41 \text{ m}^3/\text{m}$ to the 1m depth with deposition between the 1m and 5m depth, totaling the loss of $38 \text{ m}^3/\text{m}$. The event energy was $2.39 \times 10^8 \text{ J}$ and the event lasted just over six days, so even though the event was not very large, in comparison to index 10, it exerted this energy over the course of six days producing this loss of sediment. And finally 32C shows indexes 3 and above with the largest volumetric change of surprisingly a gain, to both the subaerial and subaqueous portions of the beach, of $38 \text{ m}^3/\text{m}$. The index for this event was 3.73 and it lasted for seven days! One would expect this event to produce a loss of sediment on the beach. Because there is such a variation in volumetric change with regard to the event index further analysis was performed to try to understand these discrepancies.

A regression analysis relating storm index to volumetric changes reveals that there is no discernable relationship; between the storm magnitude and volumetric change (Figure 33). It only slightly appears that as the index increases the beach volume would decrease resulting in erosion, which is what one would expect.

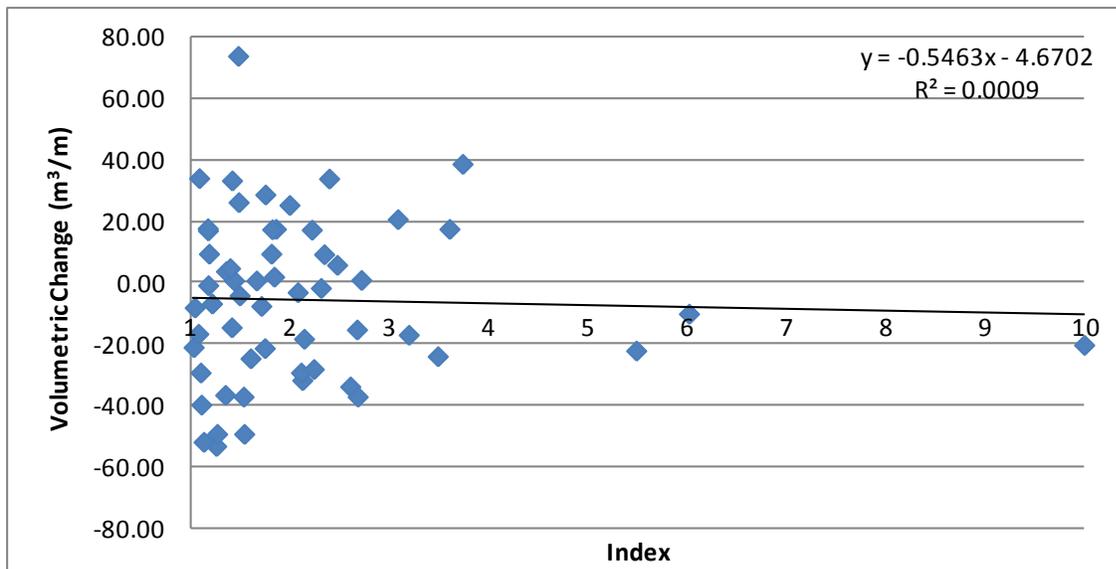


Figure 33- Relationships between event index and total average volumetric change.

The analysis of volumetric change in Chapter 4 suggests that there are significant differences in the nature of change on the individual profiles. Therefore, relationship between the index and volumetric change for each individual profile was examined. The best relationship between the storm index and the individual profile change was for profile 62 (Figure 34) but R^2 shows that only 1% of the variation in volumetric change is explained by the index. A general trend apparent exists within the data; as the index increases there is more volumetric gain rather than displacement. It is expected that the beach would lose sediment as the magnitude of events increases, but this relationship is not quite clear when viewing the data.

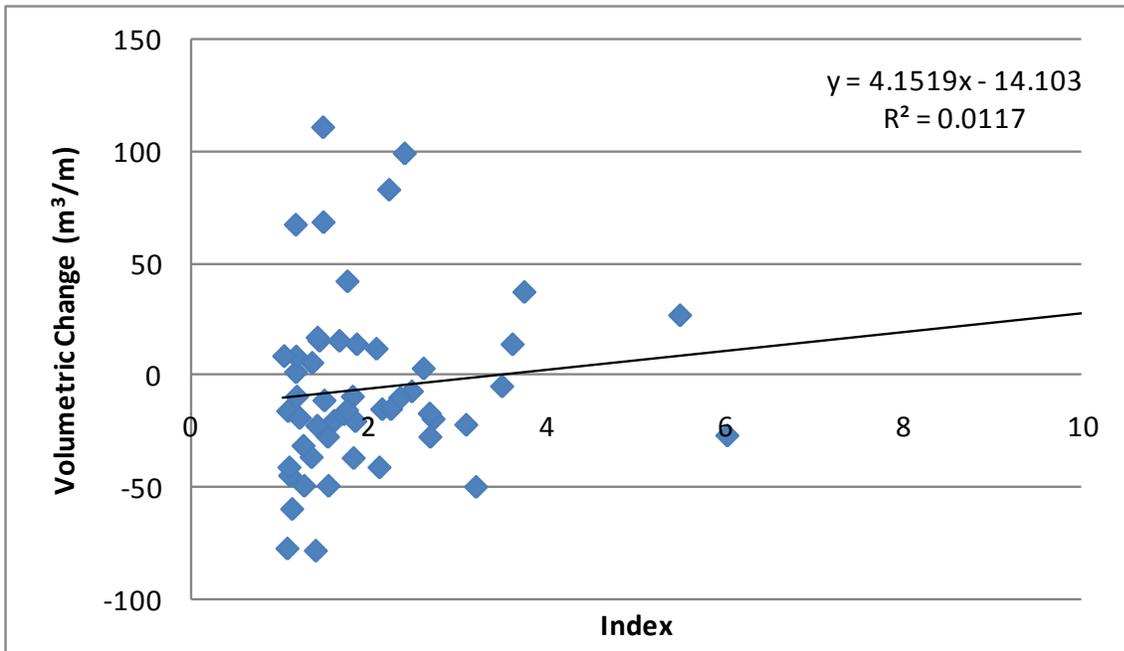


Figure 34- Relationship between profile 62 volumetric change and the event index.

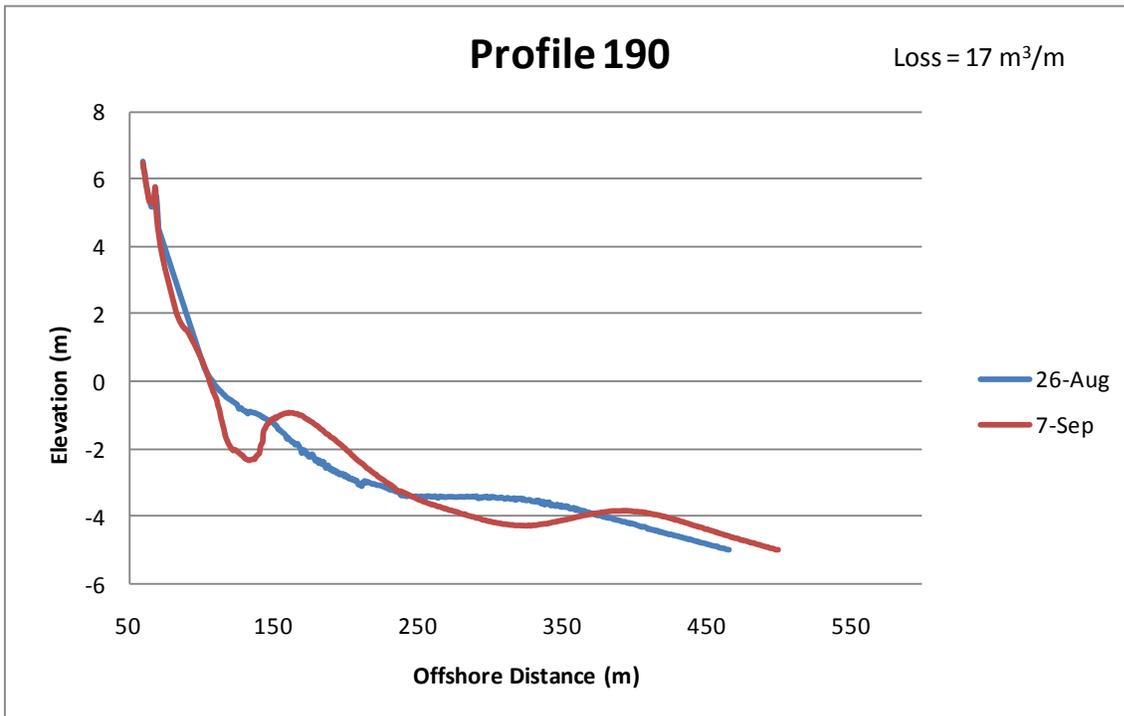


Figure 35- Evident onshore-offshore exchange of sediment after the passing of an event.

The volumetric change analysis (Chapter 4) also suggests there are cases where the expected transfer of sediment from the subaerial beach to the subaqueous zone occurs (Figure 35). However, there is still no relationship between the volumetric change and storm index for either the subaerial or subaqueous zones (figure 36A & B).

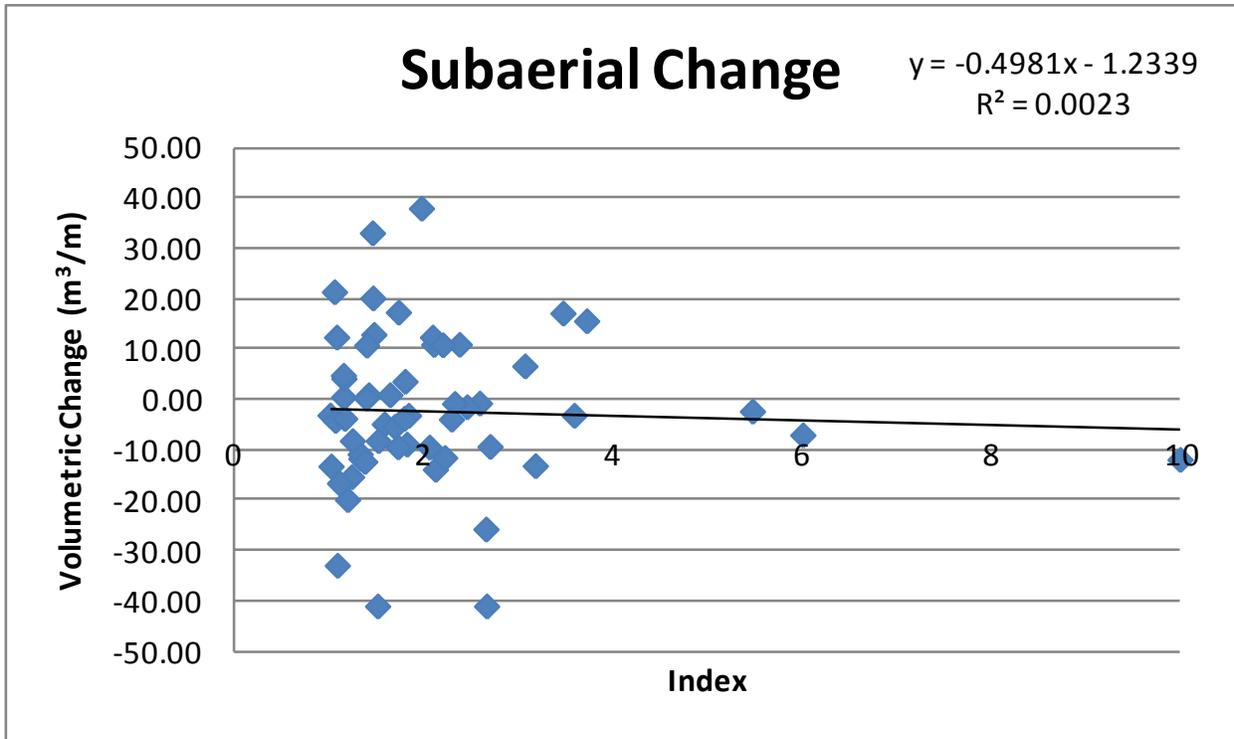
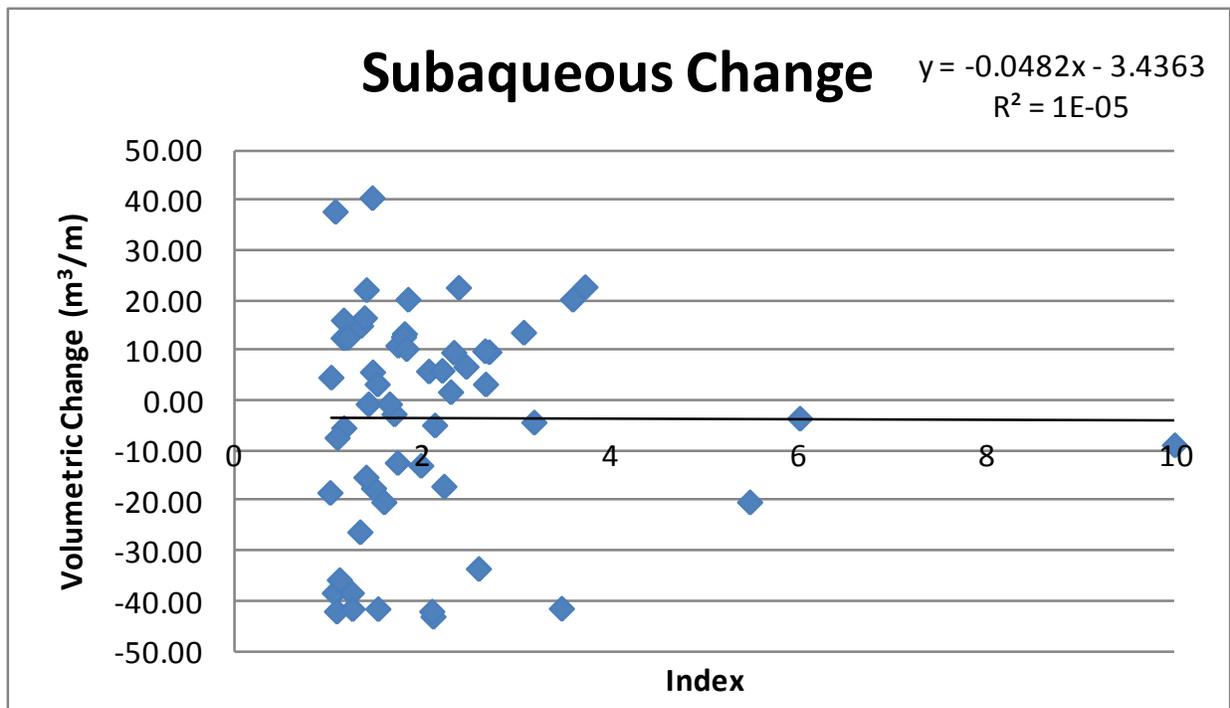


Figure 36A- Relationship between subaerial beach change and the index.



36B-Relationship between subaqueous change and the index.

A series of different regressions were performed to understand some of the event components with regards to volumetric change. The variables that made up the index, significant wave height, significant wave period, duration, and energy, were related to volumetric change to understand which variables might have a larger impact on the change. Storm tide was also used as a variable because Zhang et al (2002) concluded that storm tide, the combination of the storm surge and astronomical tide, was the most important factor in determining beach change. Figure 37 shows that yet again there is a rather small relationship between the index variables and volumetric change out to the 5m depth. Only 2.8% of the variation in volumetric change to the 5m depth is explained by significant wave height, significant wave period, event duration, and the storm tide. The average volumetric change was also related to the energy of the event

and the storm tide and still only 1.5% of the variation in volumetric change is explained by the energy and the storm tide.

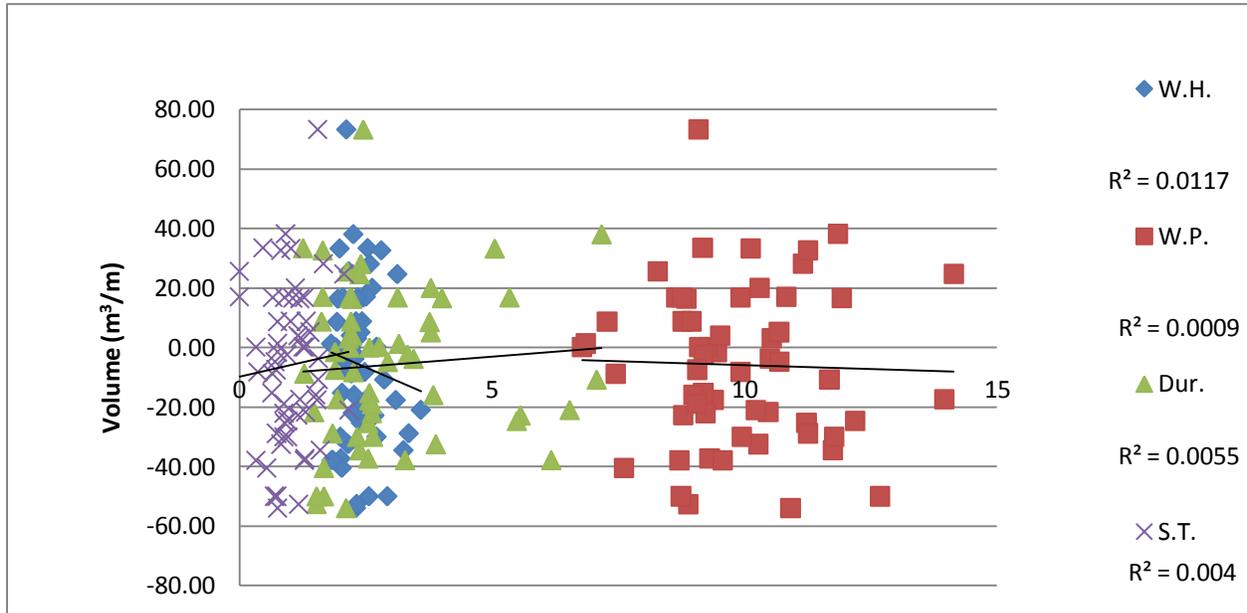


Figure 37- Index variables vs Total avg volumetric change.

With regard to significant wave period, it is also interesting to point out that when looking at the distribution of wave periods within the data set there are two distinct groups. More than half of the events had significant wave periods below 11 seconds. General wave theory claims that wave period can signify erosive or depositions waves. Zhang et al. (2002) concluded that offshore storms needed to be considered as they tend to bring large amounts of sediment to the beach. Wave period was regressed with volumetric change to understand how short vs long period waves can affect the subaerial or subaqueous change on the profile.

Figure 38 shows the relationships between short and long period waves and associated subaerial and subaqueous changes. The relationships, although not great, are better than any other previous relationship relating to volumetric change. There is a direct relationship between

wave period and subaerial volume change, with 20% of the variation in volumetric change explained by wave period. This coincides with general theory that longer period swell waves can transport sediment stored in the offshore bar and deposit it back onto the beachface. There is an inverse relationship between wave period and subaqueous volumetric change. Long period waves produce volumetric loss in the subaqueous portion of the profile as a result of the transfer of sediment from the bar to the beach. Despite the fact that these relationships do conform to the models of storm-induced beach change, the weak relationships suggest that the nature of change is more complex than the simple onshore-offshore transfers that the models depict. It is clear from this analysis that the profiles need to be examined not only in a 2-D aspect but also in the 3-D aspect to account for the alongshore exchange of sediment between the profiles. The alongshore exchange of sediment will be examined in the next section.

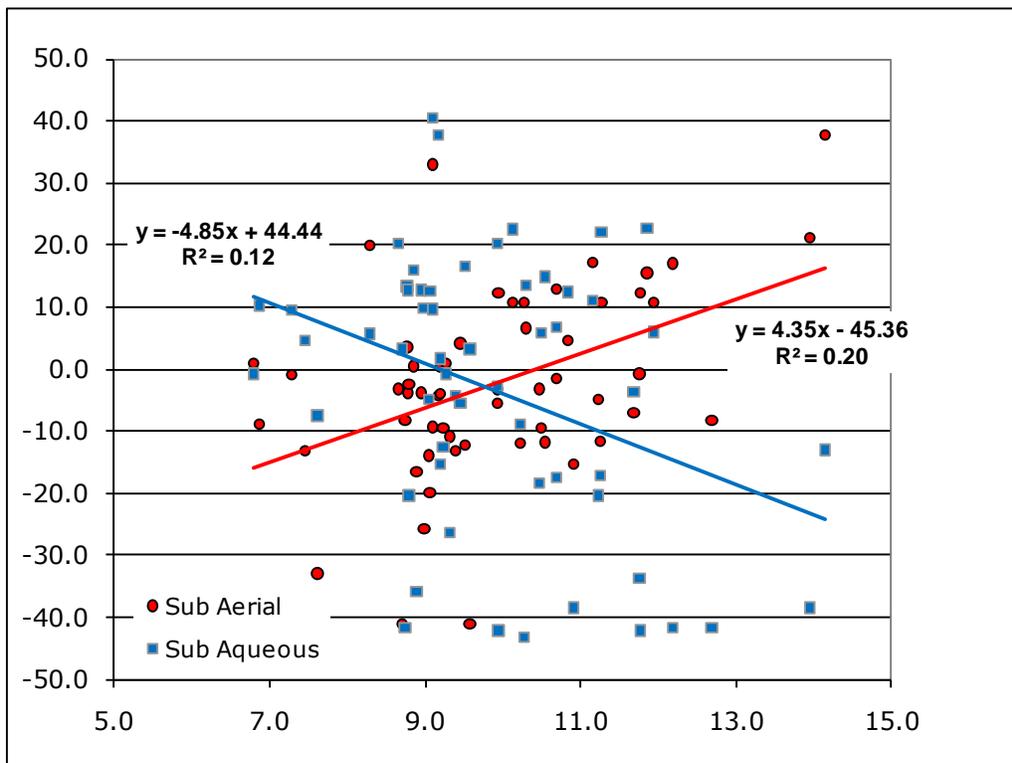


Figure 38- Relationship between subaerial/subaqueous change and wave period.

It is generally recognized that storm activity has a seasonal pattern. The East Coast experiences northeasters during the winter, some hovering offshore for days at a time increasing both the water levels and wave heights (Dolan & Davis, 1991). The fall is often dominated by hurricanes that approach the East Coast from the south-southeast. Birkemeier et al. (1999) created plots to show the distribution of storms in their data set. The majority of events occurred between October and February. This shows a distinct seasonality in storm energy. Birkemeier et al. (1999) and Lee et al. (1998) suggest that individual storms are not independent entities when relating to volumetric change, but that it is storm clustering that produces the significant changes to the beach. This concept was investigated by assessing whether there were any discernable groups of storms within the dataset. Figure 39 shows that a few distinguishable groups are present in the data but most of these groups extend over long periods of time. No distinct groups of high energy storms are apparent between 1997-2007. One possible reason for the lack of distinguishable storm clusters is the fact that 2m was used as the threshold for determining events while Birkemeier et al. (1999) and Lee et al. (1998) use 4m as a threshold for establishing events. There is difficulty in establishing which storms within these groups are playing the dominant role in volumetric change because it was discovered that the smaller events in this dataset are often responsible for large volumetric changes. The lack of clusters within the dataset would suggest that either these 11 years did not exhibit storminess as did the datasets examined by Birkemeier et al. and Lee et al. or that the inclusion of small events prohibits evident groupings of high energy storms.

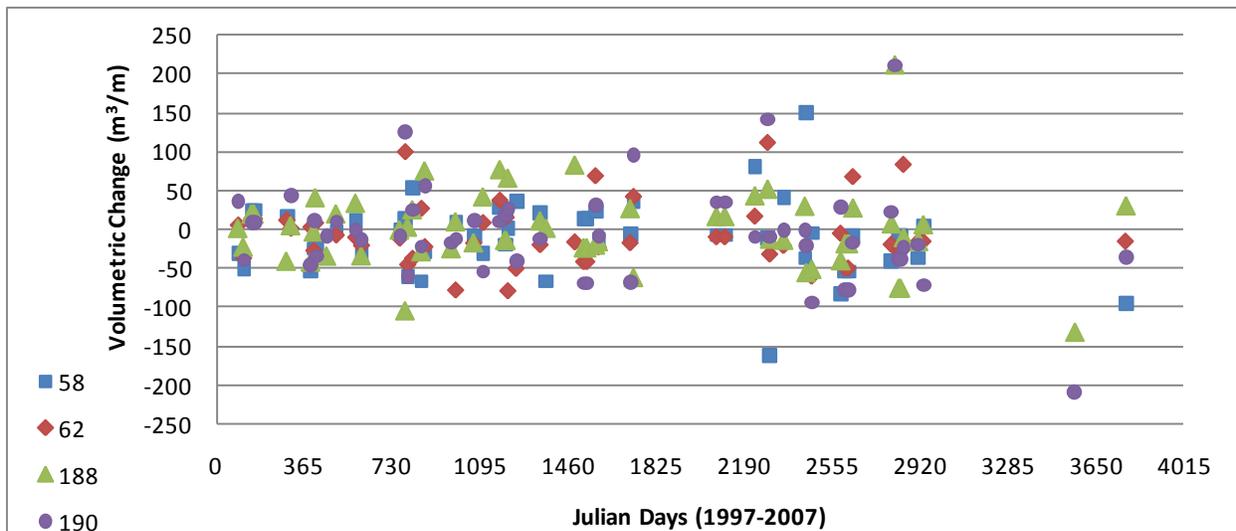


Figure 39- Storm clustering for 1997-2007 events.

The lack of relationship between the associated variables and average volumetric change out to the 5m depth highly suggests that other components, such as alongshore transport of sediment, are contributing to these changes on the beach face. This brings into question the conclusions of other research where wave height, duration, and storm tide are the most important variables in producing volumetric change, as these studies urged these variables as most important in producing change to the beach (Dolan & Davis, 1992; Lee et al., 1995,1998; Birkemeier et al., 1999; Zhang et al., 2001). List & Farris (1999) concluded that large variations in shoreline positions can be attributed to small storms and this is apparent in the profiles analyzed here. The largest average volumetric displacement and gain occurred with events with an index between 1.0-1.9! Wolman & Miller (1960) concluded that moderate magnitude and frequency events causes the most change. For this case at Duck, it was the low magntiude events causing the significant changes to the profiles.

Even though past studies used greater wave heights, wave height in this project had very little effect on the volume. When regressing wave height on volumetric change a mere 1.3% of the variation in volumetric change is explained by these varying wave heights. Although this relationship is very weak it does not disprove that small waves, in addition to other natural forces, can cause changes to the beach. Using the index to predict volumetric change on the beachface at Duck, at this point, is not adequate. Dynamic processes such as wave angle, which determines alongshore currents, should be integrated into the index to better predict the associated landscape change.

Another reason for the lack of relationship between the index and average total beach change is the fact that the profiles were truncated at the 5m depth for consistency when analyzing the volumetric change. Larson & Kraus (1994) explained that the profiles at Duck have a depth of closure at 8m, meaning that there is practically no volumetric change past the 8m depth. Perhaps because the profiles were truncated at the 5m depth the sediment loss between the 5m depth and the 8m depth would prove to be valuable to the relationship to beach change.

The next sections further examines the relationships between the profiles in attempt to understand the alongshore exchange of sediment seen between profiles.

Relationships between the profiles

After examining the changes along the profiles up to the 5m depth, it was observed that change was happening between the dune to the the 1m depth and the 1m depth to the 5m depth. Change in the profile either occurred along the beachface, along the subaqueous part of the profile (-1m to -5m), or happened along both parts in some situations. Examination of the

relationship between subaerial and subaqueous changes (changes) shows again little to no relationship (Figure 40).

This is extremely interesting in that generally one would assume, as suggested by Bascom (1959) and Komar (1976), that sediment would be eroded from the subaerial portion of the profile and deposited along the subaqueous portion of the profile. Less than 1% of the variation in the subaqueous volumetric change is explained by the subaerial change. Yet individual profiles change in different ways. All this reinforces the idea that alongshore transport must be a significant component of storm-wave beach interaction.

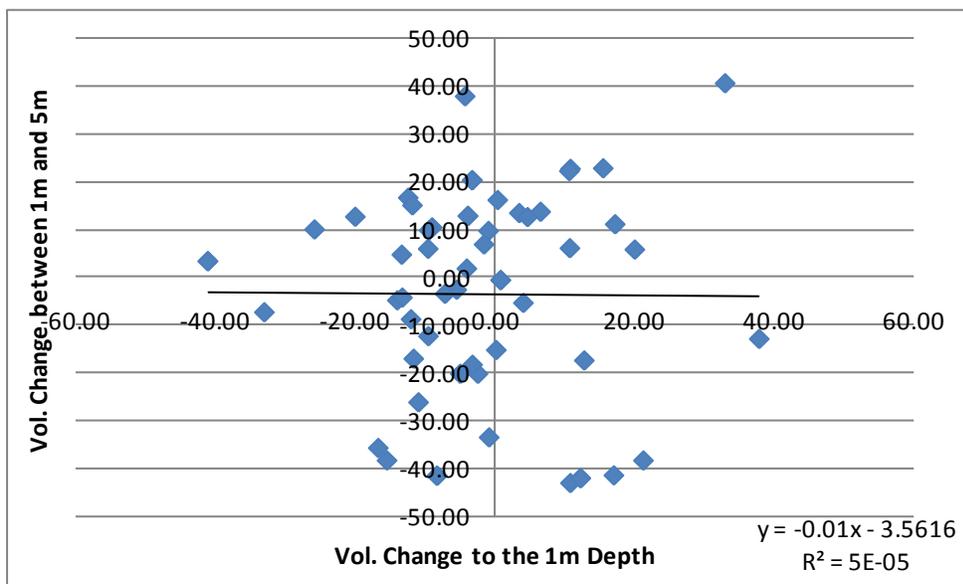


Figure 40- Relationship between subaerial and subaqueous volume change.

Despite the lack of relationship between subaerial and subaqueous change evident in figure 38, a closer look at the distribution reveals some potentially significant findings. The events can be assigned to one of four groups based upon the sediment budget characteristics of the subaerial and subaqueous parts of the profile. Thus group 1 consists of events where there was volumetric gain along both portions of the profile; group 2 consists of events where there

was volumetric loss in the subaerial portion but volumetric gain in the subaqueous portion of the profile; group 3 consists of events where there was volumetric loss in both portions of the profile; and group 4 consists of events where there was gain along the subaerial portion of the profile but loss along the subaqueous portion of the profile. Considering the 4 groups as separate datasets, it becomes evident that different relationships exist for each condition (Figure 41). The events with volumetric gain in both portions of the profile (group 1) have a relatively good relationship ($R^2 = 0.29$). It is interesting that when dividing events into these groups, group 1 consists of low magnitude events, the highest index event being a 3.7. Most of the events above an index of 1 fall within group 2, dominated by erosion in the subaerial and deposition in the subaqueous portions of the profile. This relationship is the standard profile/storm interaction (Bascom, 1959; Komar, 1979). It too has a direct relationship between subaerial and subaqueous change, although the R^2 is only 0.16. Group 3, where volumetric loss in both portions of the profile occurs, demonstrates a slight indirect relationship ($R^2 = .03$) in that as the subaerial loss decreases the subaqueous loss increases. The index 10 event falls within group 3 as well as an index 6 and index 5.5 event. This relationship seems to indicate the complexity within the system at Duck with regards to large magnitude events.

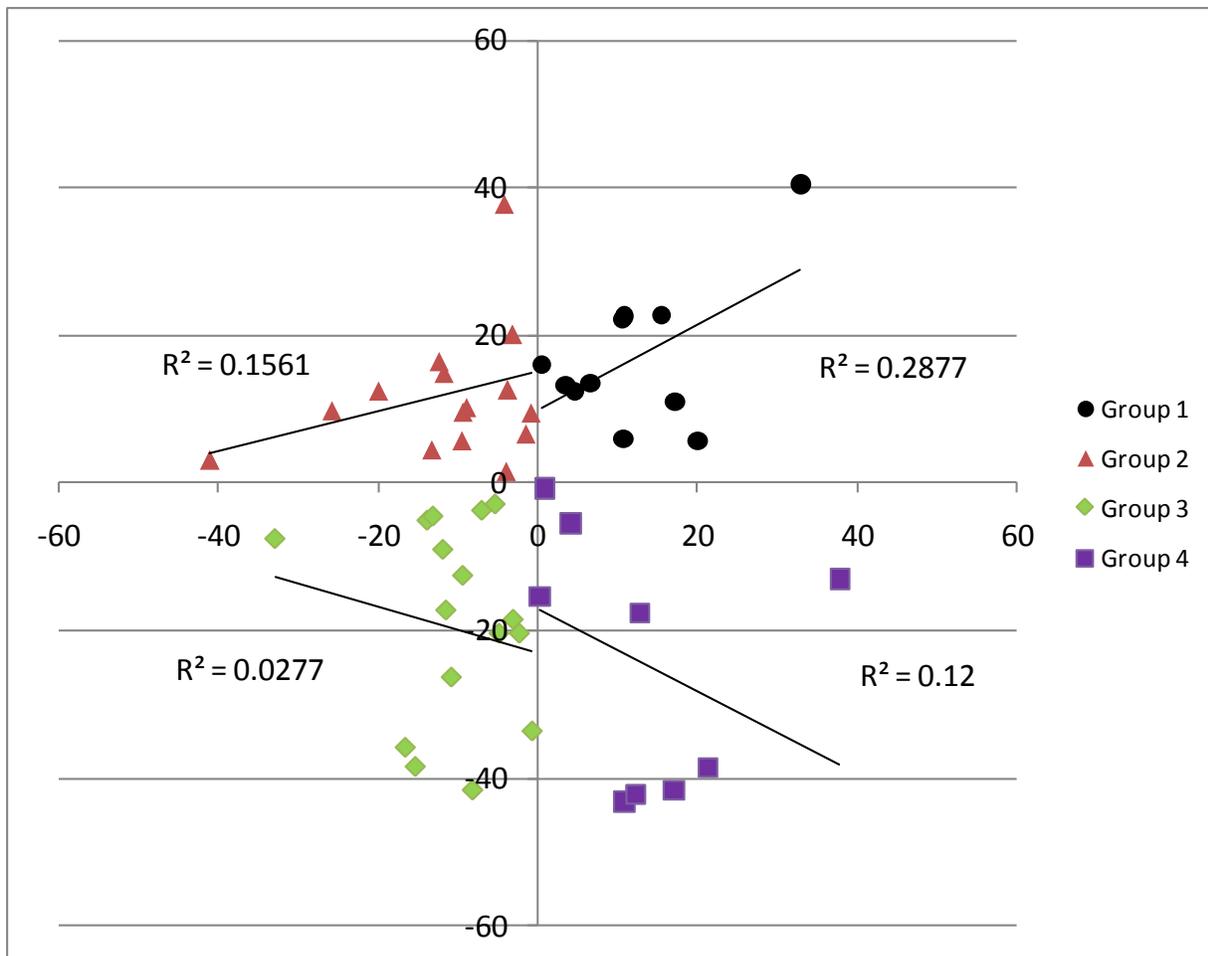


Figure 41- Relationship between subaerial and subaqueous portions of the profile according to associated volumetric change group (1-4).

Morton et al. (1994) explain that there are large variations between profile responses to large events and the Duck profile data supports this. These large variations in profile recovery imply that the alongshore component of sediment transfer needs to be considered, and this can be accomplished by comparing volumetric losses and gains between profiles 58 and 62. These lines were chosen over the other lines, 188 and 190, because they exhibit much larger differences in volumetric change. One would assume that as profile 58, the farthest North at Duck, would gain in volume after the passing of an event so would profile 62 which is only 90m south of 58. This is not the case for some of the profiles after an event. In Figure 42 the orange line represents a

perfect relationship between profile 58 and 62 in that one would expect both profiles to act in unison; as profile 58 gains sediment profile 62 would also gain sediment and vice versa. But, as evidently shown through this analysis, nature does not act perfectly. Volumetric changes corresponding to profile 58 and 62 were then plotted according to this perfect relationship (red and blue dots). The volumetric changes are scattered about the perfect relationship. The standard deviation of volumetric change was taken for both profiles then averaged (43 m^3) to understand how the volumetric changes of each profile deviated from this perfect relationship. The purple and green lines represent one standard deviation, plus or minus 43 m^3 , from the perfect relationship. 17 of the total 59 events had more than a $43.3 \text{ m}^3/\text{m}$ difference in volume between line 58 and 62. These events were examined in further detail in attempt to further understand these differences.

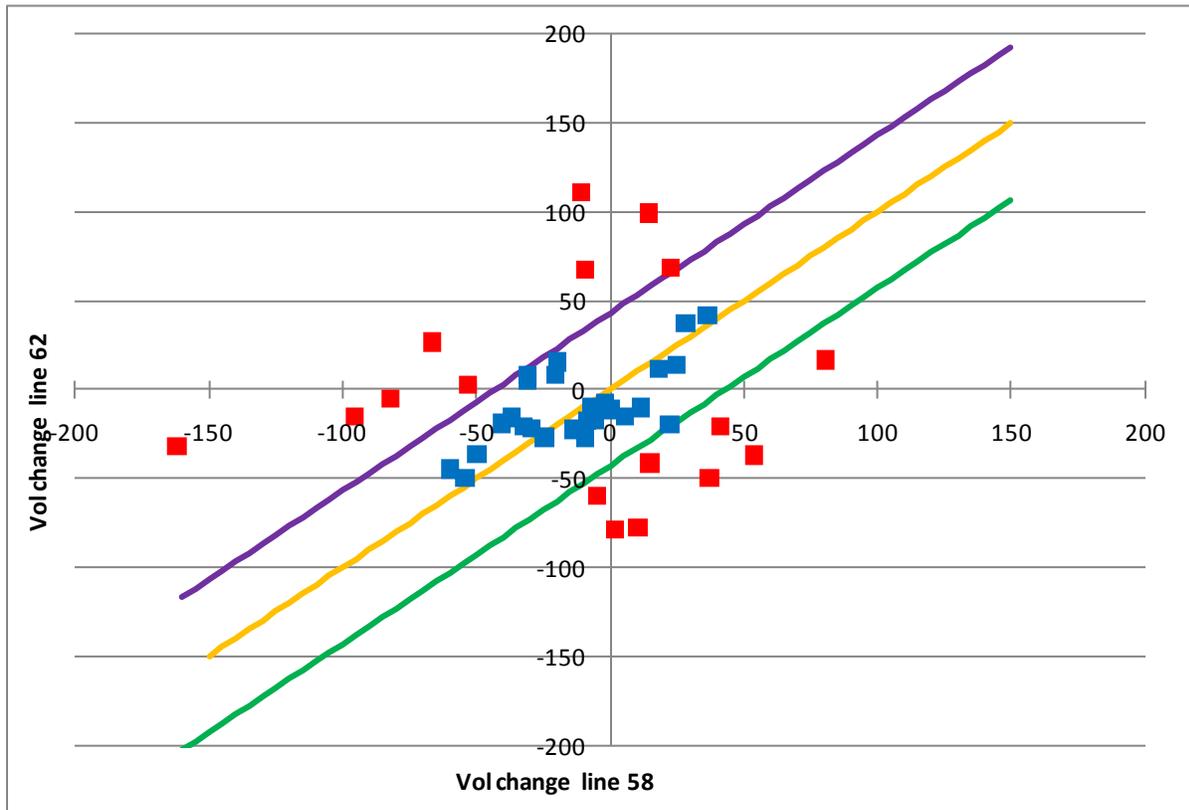


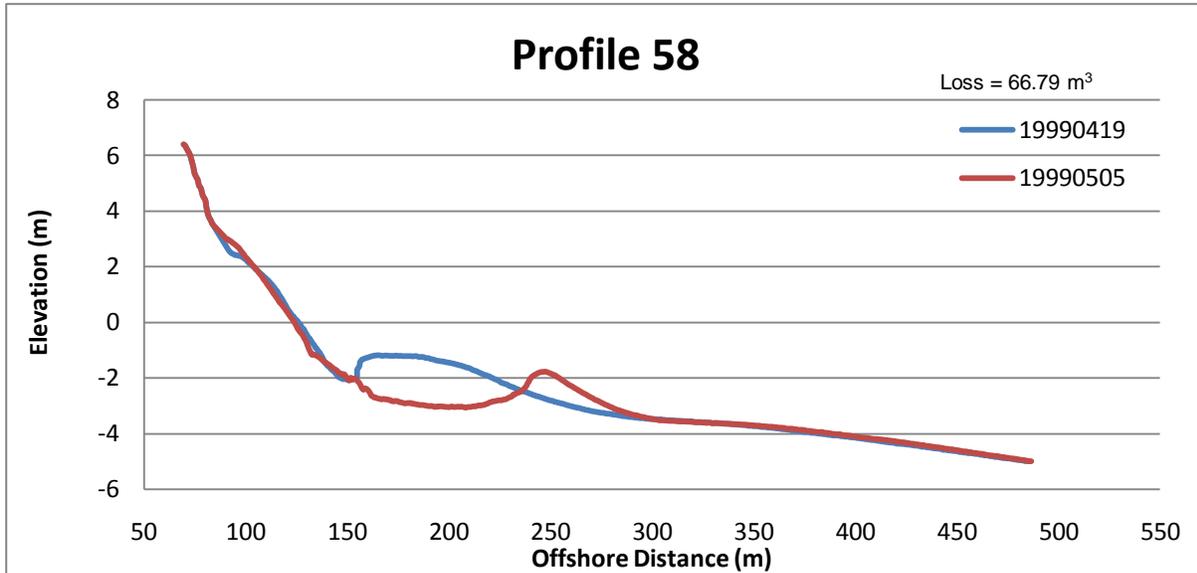
Figure 42- Standard deviation of event volumes for line 58 and 62.

Table 6 shows the 17 events that fell outside of these deviation lines. The event with the largest difference ends on April 21, 2003 with a difference of 130 m³/m between line 58 and 62. Even though the difference between the profiles is great both profiles are still losing sediment although it would be expected that profile 62 would lose a greater amount of sediment if profile 58 lost about 162 m³/m. The event after April 27, 2001 had the least difference, 45 m³/m, in volumetric change. This difference is not however that surprising because as sediment is eroded from line 58 that sediment could be deposited along profile 62 making it appear to gain more sediment. What is interesting to point out is that out of these 17 events that had differences greater than 43.3 m³/m, 11 of them had an index between 1.0-1.9, 3 had an index between 2.0-2.9, 2 had an index between 3.0-3.9, and 1 had an index between 5.0-5.9. This will further be explored.

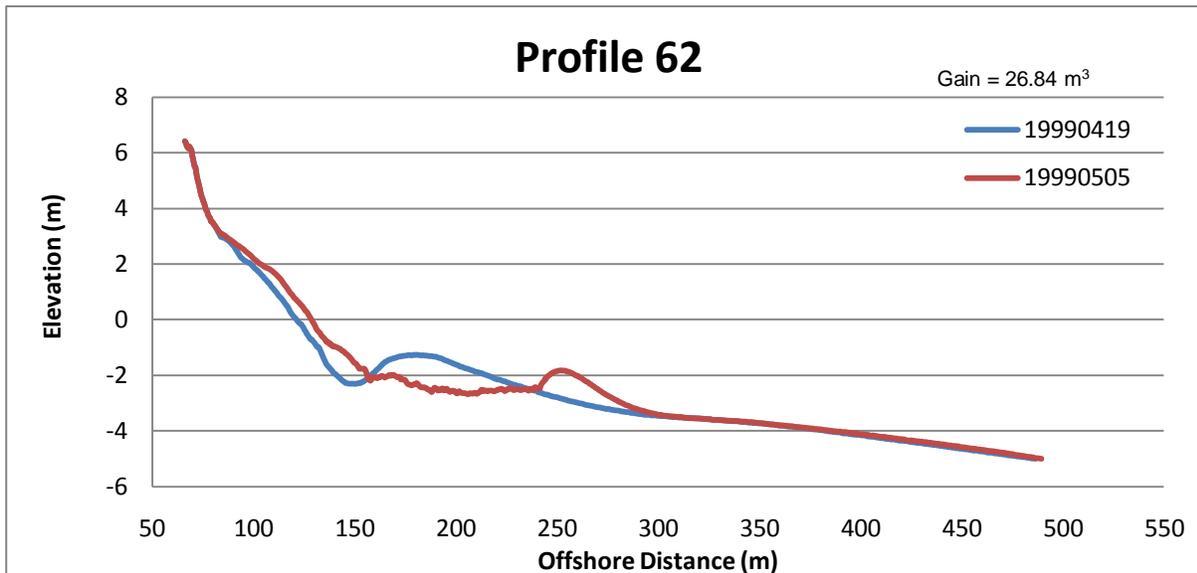
Event Date	58 Vol. Change	62 Vol. Change	Difference	Index
1/30/1998	-53.25	3.03	56.28	2.60
2/26/1999	14.27	99.23	84.96	2.39
3/28/1999	53.70	-37.04	-90.74	1.81
5/4/1999	-66.79	26.84	93.63	5.48
9/23/1999	10.42	-77.50	-87.93	1.07
4/27/2000	1.72	-78.46	-80.19	1.39
5/31/2000	36.99	-49.92	-86.91	3.19
3/9/2001	14.72	-41.21	-55.93	1.09
4/27/2001	22.68	68.47	45.79	1.47
2/18/2003	80.40	16.86	-63.55	1.41
4/12/2003	-10.66	110.95	121.62	1.47
4/21/2003	-161.94	-31.56	130.38	1.25
6/17/2003	41.32	-20.57	-61.89	1.83
10/12/2003	-4.79	-59.82	-55.03	1.12
3/31/2004	-9.10	67.36	76.45	1.16
2/9/2005	-81.98	-4.96	77.02	3.48
5/9/2007	-95.44	-15.15	80.30	2.23

Table 6- Differences between profiles 58 and 62 after corresponding events.

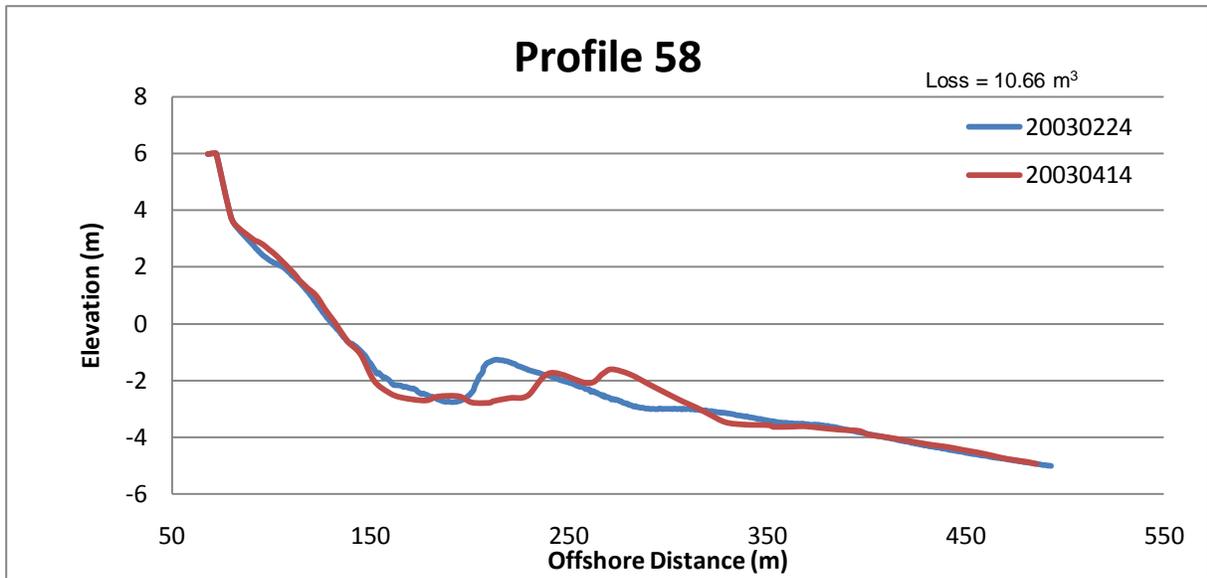
Profiles of these differences were plotted out to visualize these differences between the lines. The events with the three greatest and three least differences were plotted. Figure 43 A-F shows the the three events with the greastest differences between line 58 and 62 in volumetric change.



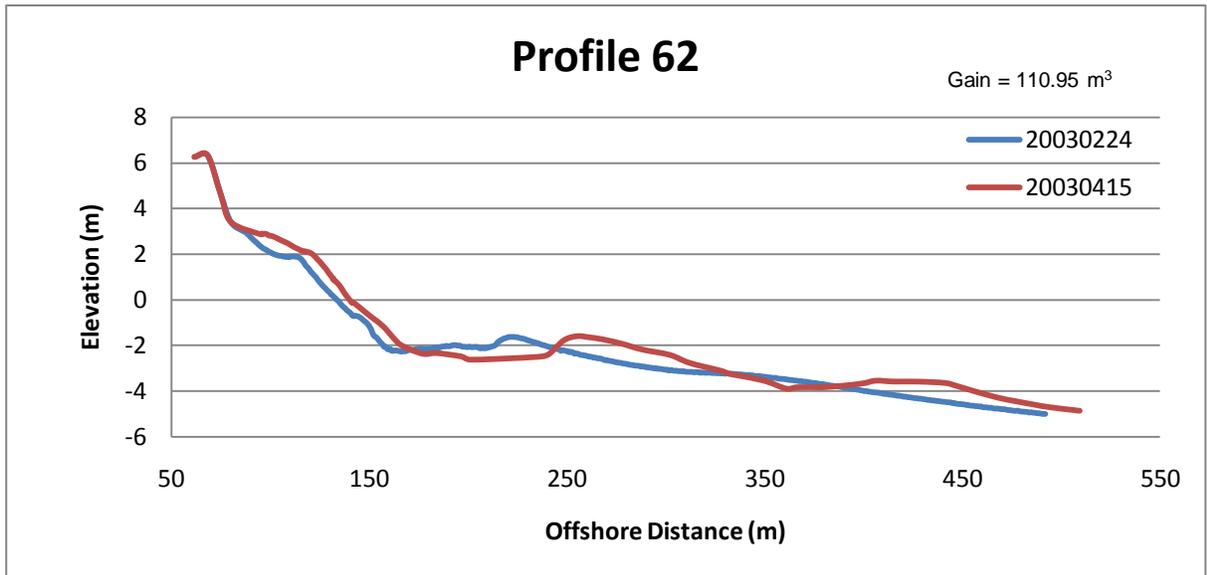
A



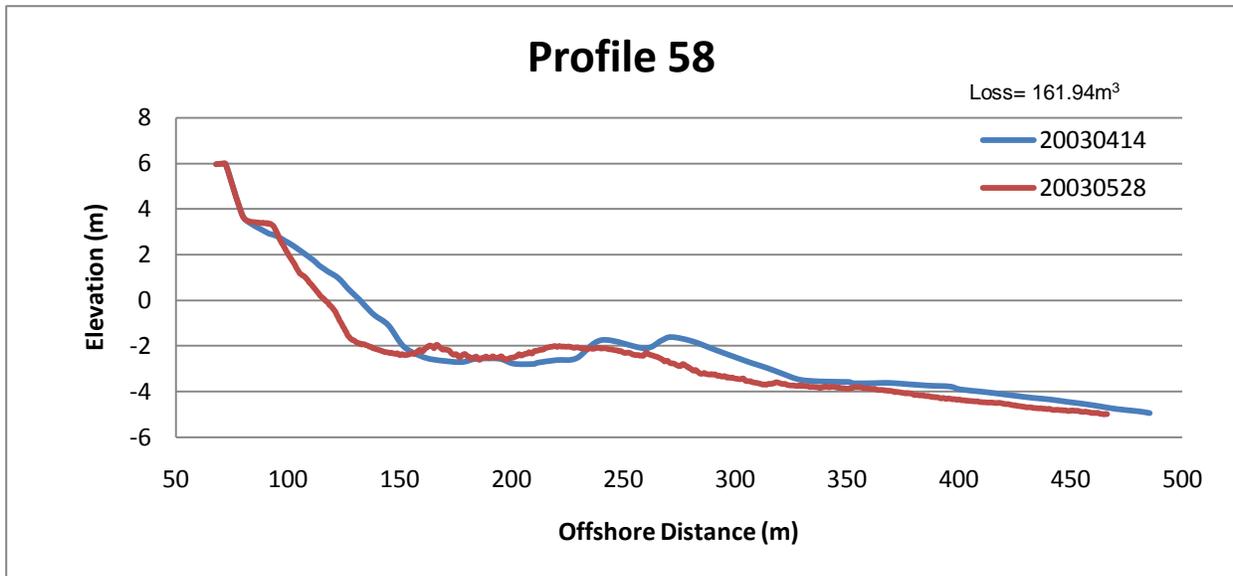
B



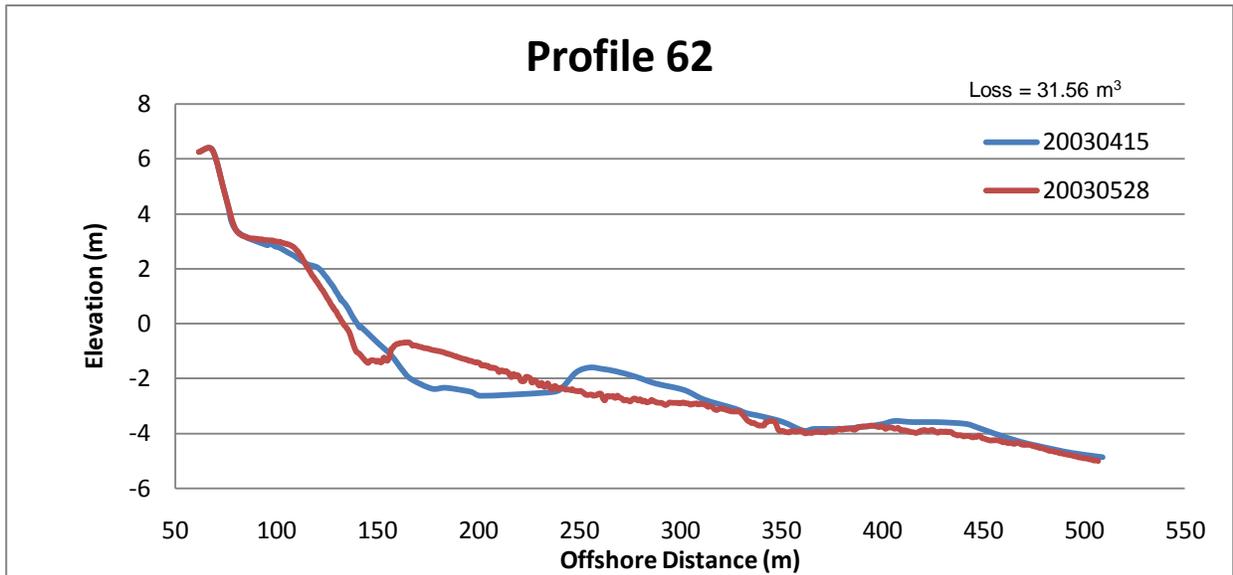
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Figure 43- A-F, profiles with the greatest differences in volumetric change after corresponding events.

43A & 43B show the profiles before and after the event that ended on May 4, 1999. The beachface remained just about the same for line 58. The inner bar that was present just around 200m at the 1m depth eroded completely and was deposited as a smaller and steeper bar about 50m offshore. There was a loss of about 67 m³/m along this profile. For line 62 a small amount

of sediment was deposited along the beachface, extending to the 2m depth. The bar present before this event did erode but not as severely as line 58 and was deposited about 60m further offshore. Line 62 actually gained about 27 m³/m. It is possible that longshore transport played a role in eroding the sediment from line 58 and depositing it along the beachface at line 62. However, it is interesting that this event had an index of 5.4, had a significant wave height of 2.6m, a significant wave period of 8.79 seconds, and lasted for almost 6 days. These conditions may have created a stronger longshore current to deposit the sediment onto profile 62. It would be expected that there would be a direct relationship between the volumetric change at line 58 and 62 because of these conditions but this of course was not the case.

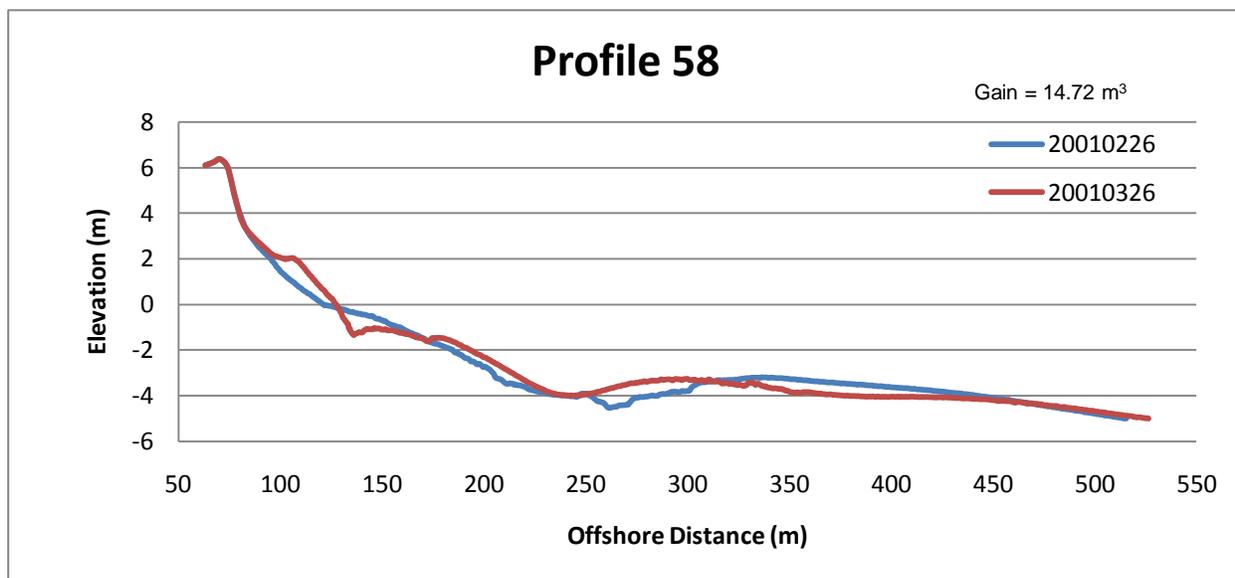
For the event that ended on April 12th 2003 (Figure 43 C & D) major differences in the profiles are evident at first glance. The volume difference for this event was about 121 m³/m. For line 58 the beachface remained relatively the same after the passing of the event. The profile before the event had a bar at the 1m depth with gradual slope that extended down to the 3m depth and to about 300m offshore. After the passing of the event the bar that was previously at the 1m depth eroded back to the 250m offshore mark and down to the 2m depth. This new bar had two peaks with a slightly steeper slope after the second peak. Line 58 lost around only 11m³/m after the passing of the event. For profile 62, there was a very tiny bar close to the 2m depth and had a gradual slope down to the 5m depth. After the event the profile grew on the beachface and the very small bar eroded below the 2m depth and then was deposited as a bigger bar around the 250m offshore mark. A small bar also formed just above the 4m depth around the 400m offshore mark. Profile 62 gained close to 111 m³/m while profile 58 only lost about 11 m³/m. Longshore transport may explain part of the deposition along profile 62 but there was a significant amount of sediment deposited, most of which is probably not coming from profile 58.

The index for this storm was a mere 1.4 which may suggest a “quieter” period for deposition along profile 62.

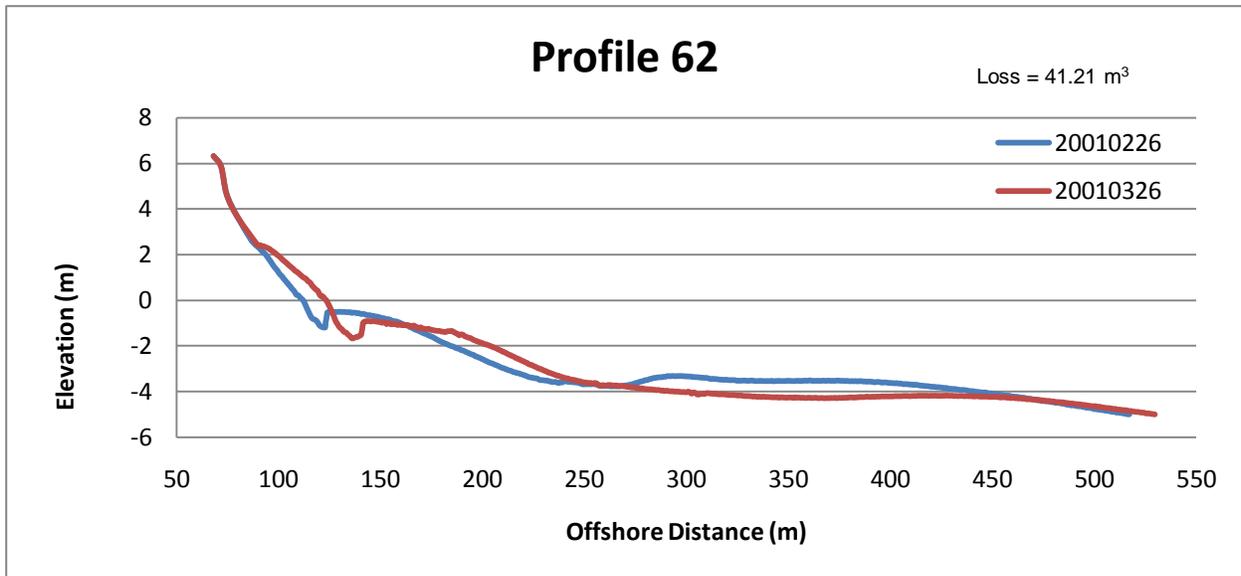
After the April 21st 2003 storm, profile 58 lost 162 m³/m (Figure 43 E & F)! The profile before the storm had a large bar between the 200m and 300m offshore mark. The bar had two different ridges at the 2m depth. The slope after the outermost bar was steep but then gradually extended out to the 5m depth. After the passing of the event a small ridge formed on the beachface with two bars on the upper shoreface. The first most inner bar was very small located at the 2m depth and the second was slightly larger but also located at the 2m depth. The slope after the outermost bar was much more gradual out to the 5m depth. Profile 62 only lost 32 m³/m. The small ridge that was present on the berm before the event actually migrated landward on the berm after the event’s passing. Before the event there was a large bar present around the 2m depth with a rather steep slope that extended down to the 4m depth which then flattened out then extended down to the 5m depth. After the event this bar eroded some and migrated landward, located at the 1m depth. The slope gradually extended to almost the 4m depth. Longshore transport may have deposited the eroded sediment from profile 58 onto profile 62. This may partly explain why profile 58 lost 162 m³/m while profile 62 only lost 32 m³/m. The index for this event was again a mere 1.25 which could have also contributed to the deposition along profile 62 because the event was relatively low in magnitude.

The events with the least differences between profiles 58 and 62 have also been examined to establish whether they too behave in the same manner as the events with the greatest differences. Figure 44 A-F shows the before and after profiles for the events with the least differences between 58 and 62. These profiles were also chosen because they exert some usual

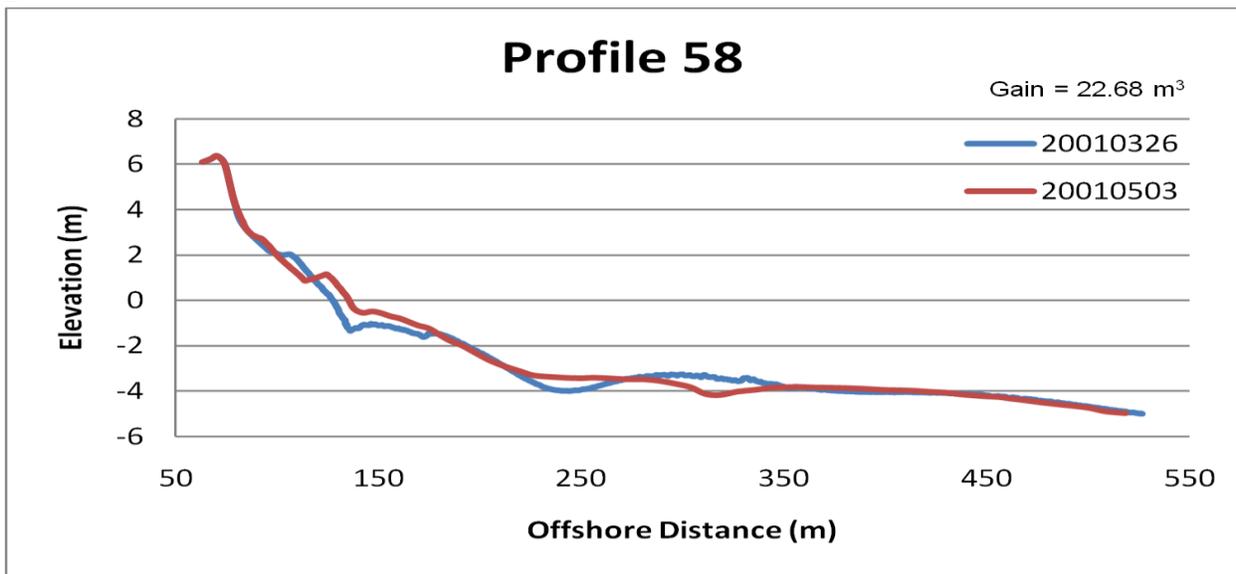
behaviors. A & B represent 58 and 62 for the event that ended on March 9th, 2001. It is interesting that on profile 58 the berm grew after the passing of the storm and a small new bar formed around the 1m depth. The bar that was located about 350m offshore at the 3m depth migrated landward to the 300m offshore mark but remained at the 3m depth. Profile 58 gained 14.72 m³/m of sediment. Profile 62, however, lost about 41 m³/m of sediment. When comparing to the trends of the other profiles one would assume that profile 62 would gain in sediment. Sediment was deposited along the berm which forced the bar that was present before the storm to migrate seaward to the 150m offshore mark at the 1m depth. Before the event there was also a very broad bar around the 3m depth which completely eroded down to the 4m depth. Clearly, longshore transport in this instance did not cause profile 62 to gain in sediment. The index for this event was only 1.09. The lower energy of this event may have allowed for the deposition along profile 58 but it is surprising that 62 eroded as much as it did.



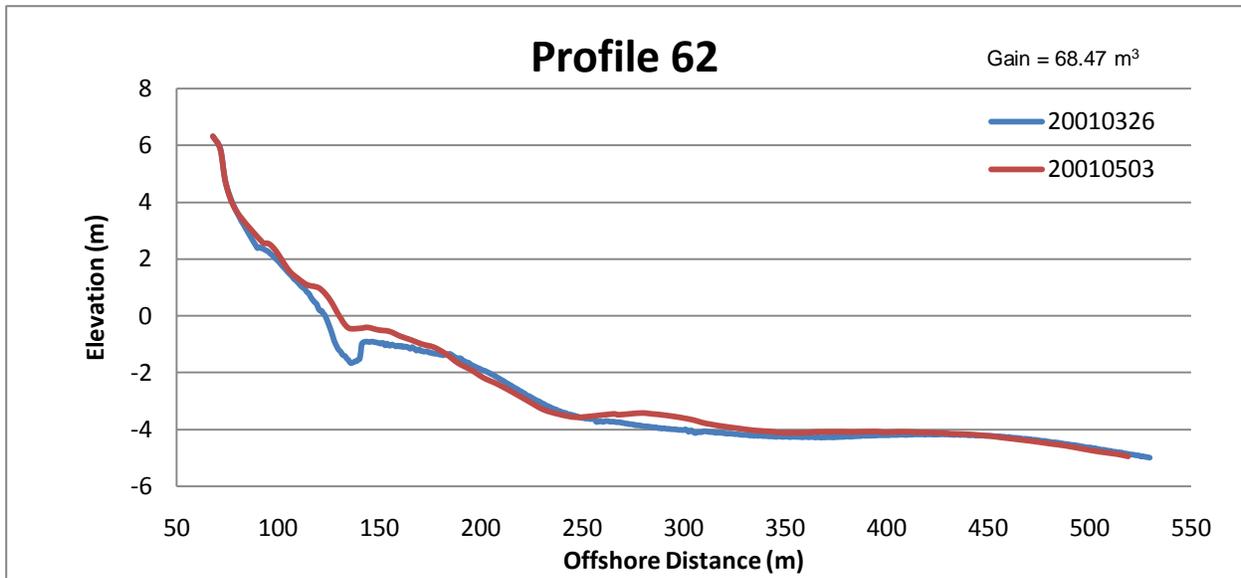
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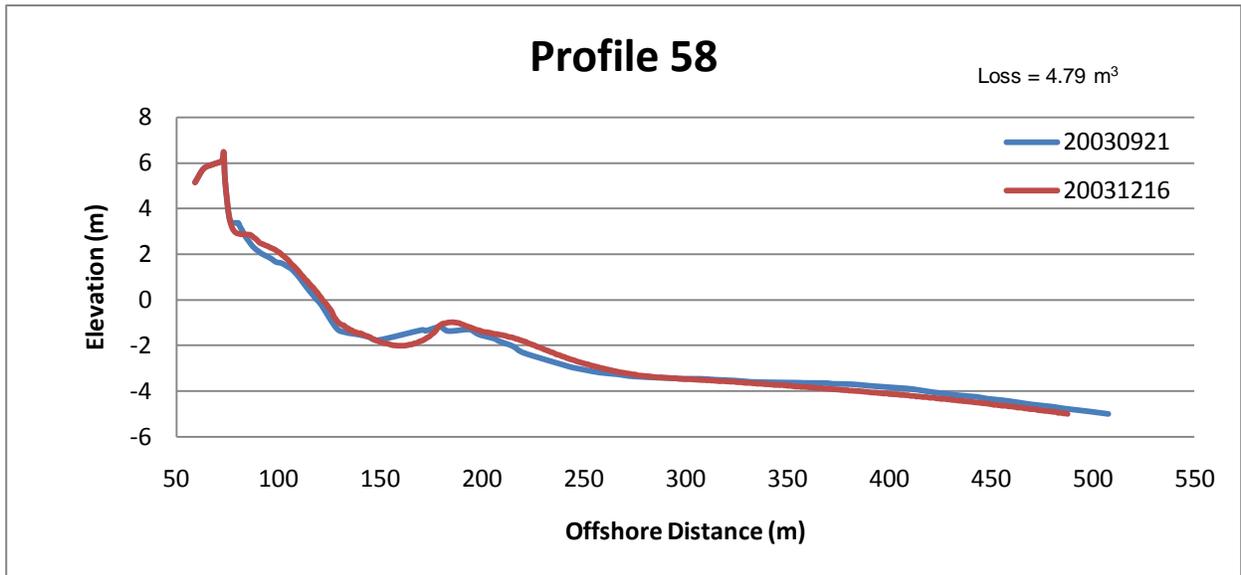
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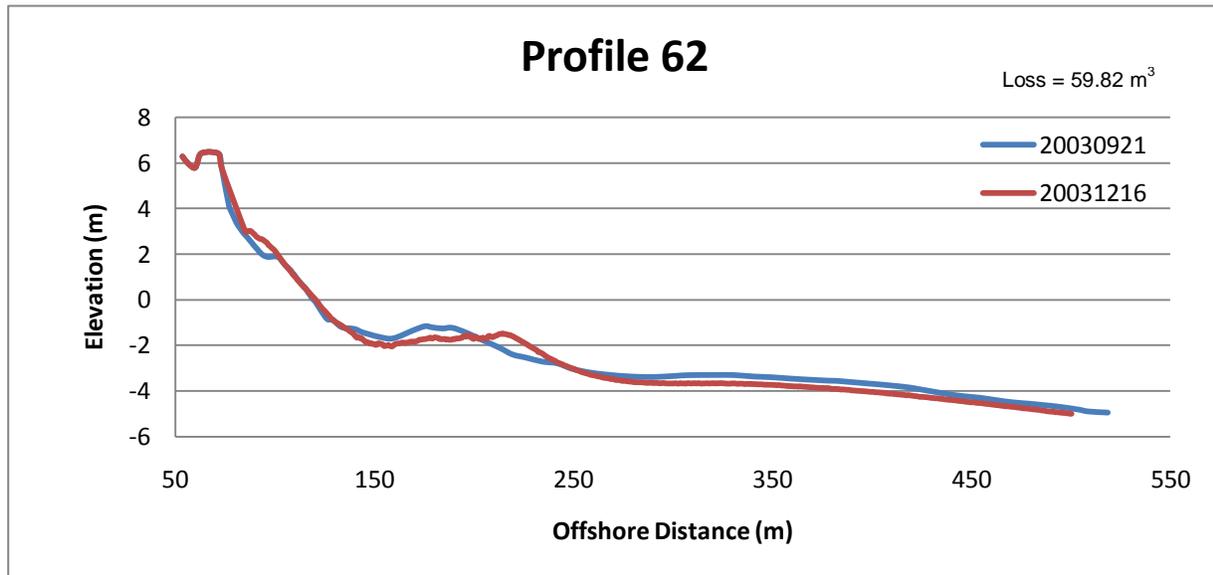
C



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Figure 44A-F- Events with the least differences between profiles 58 and 62.

After the event that ended on April 27, 2001 profile 58 gained close to 23 m³/m. Figure 44 C shows the majority of the gain occurred on the berm where a ridge that was present before the event grew slightly in size and migrated seaward. The profile also grew between the 0m depth to the 2m depth. The broad bar located around the 3m depth before the event eroded leaving behind a small trough near the 4m depth with little change out to the 5m depth. Profile 62 gained about 68 m³/m of sediment (Figure 44D). This also contradicts the trends of the greatest difference events. Very little change occurred after the passing of the event. Before the event there was a small trough located around the 1m depth that filled in with a very broad and small bar forming close to the 4m depth. It seems interesting that as profile 58 gained sediment so did profile 62, no obvious source for the sediment gain along profile 62 is evident.

The event that ended on October 12, 2003 caused little change in the both profiles (Figure 44 E & F). The most important thing to point out is the fact that profile data was available on the 21st of September but not again until the 16th of December. Because almost 2 months passed after the event a considerable amount of profile recovery may have occurred. Profile 58 only lost about 5 m³/m with the most change in the profile at the bar located at the 1m depth. Before the storm the bar was broad with a gradual slope extending out to the 5m depth. After the event the bar narrowed developing a steeper slope that extended out to the 5m depth. Profile 62 surprisingly lost 60 m³/m. The bar that was present before the event flattened down to the 2m depth with loss of sediment 300m-500m offshore between the 4 and 5m depth. Most of the profiles remain stable between this depth so it interesting that even with 2 months recovery time after the event the profile changed at this depth. The index for this event was close to 1. No other significant events occurred between this time frame meaning low energy existed after the event providing the beach with the proper conditions for recovery.

On these profiles little change occurs beyond the 4m depth. Birkemeier et al. (1999) concluded that wave heights must be greater than 4m to produce any changes to the uppershore face, 500m offshore or more. Because not all of the profiles extended past the 5m depth, for consistency issues, any depths past the 5m depth were not considered. The crest of the dune to the 5m depth was the most active part of the profile, especially between the 1m and 5m depth. Birkemeier et al (1999) and Lee et al. (1998) only consider profiles 62 and 188 as they extend at least to the 8m depth. These profiles are suitable for investigating factors contributing to uppershore face change but they neglect any sort of relationships between adjacent profiles, 58 & 62 and 188 & 190.

Lee et al. (1995) discovered that the inner bar was highly mobile under all wave conditions and moved offshore, and sometimes became the outerbar. This was seen in the 1997-2007 profiles (figures 22 & 24) ; these were not included in the Lee et al. (1995) study. Even the smallest of the events produced a change in the inner bar. For example, the event that ended on September 23, 1999 with an index of 1.06 produced changes to the inner bar (Figure 27). Even though these changes are more subtle, they did occur contributing to the idea that not only large but small events produce change to the beach.

The existing relationships, or lack thereof, between the index and volumetric change, and between the profiles would suggest the inclusion of the alongshore sediment transport component as initially mentioned by Morton et al. (1994). In order to do this wave angle can be considered because the angle of the wave dictates the generation of an alongshore current. Also, considering a different study site in which the beach would be protected from alongshore currents could better clarify the relationship between the index and volumetric change. Wright & Short (1984) stated that the morphology of the beach was also dictated by wind speeds and previous beach state. By taking into consideration previous beach a net change of the profile may be assessed which might better reflect the actual response of the beach to one particular storm.

These initial findings would suggest that it would be useful to examine all of the profiles available from the FRF at Duck. The Army Corps also conducts profiles once a month extending across the entire beach. Although these profiles are only conducted once a month they would give a better estimate of beach change after an event. One complication of using this monthly data would be to have multiple events occur in between months making it extremely

difficult to decipher which event played the most dominant role in producing volumetric change. No previous studies have used the monthly profiles for storm/beach change analysis but these profiles should be considered for future research.

CHAPTER SIX: CONCLUSIONS AND FUTURE POTENTIALS

This research attempted to use a common geomorphology principle of frequency/magnitude to first explore the range of magnitude events that occurred at Duck, North Carolina between 1985-2007 and to second relate the events to profile change to make some conclusions about different magnitude events producing change. The goal was to provide geomorphologists with the basis for creating an index based on total wave energy for an event and to relate each magnitude of the index to the volumetric change of the beach. Being able to predict the associated beach change in terms of event magnitude would greatly assist engineers in sediment budgets for beach nourishment projects. This research presented a new approach to linking landscape change through a frequency/magnitude analysis. Referring back to specific research questions for this project:

1. Can a storm event be defined according to a designated threshold through a frequency/magnitude analysis and classified according to energy?

This analysis adequately demonstrates that using a partial-duration series analysis along with the frequency/magnitude principle small wave events at Duck, North Carolina contribute to profile change. The event energy equation used in this project proved to be more valuable than in past research as it adds a time component, allowing for a calculation of the number waves hitting the beach during the duration of the storm thus determining the total energy expended on the beach. A total of 530 events had significant wave heights of 2m or greater or a duration of at least 42000 seconds (about 12 hours). The index was created based on the largest total event energy. Because 43% of the events were under an index of 0.5 and 72% of all the events were under an index of 1 further filtering allowed for an examination of the events above 1 (146). The

largest magnitude event ended on September 5, 1999 and coincided with Hurricane Dennis. Different combinations of wave heights and durations could produce the same index values and when plotted with the actual events, the index lines were slightly under predictive of the actual events as averaged conditions (wave period and water density) were used to develop the index lines. When considering the Weibull analysis, as part of traditional partial duration series analysis, Weibull is an adequate fit to the actual data. A RMSE of 3.3% was derived indicating that Weibull will predict within a 3.3% probability of an event of a given magnitude (index) to occur when compared to the actual probability. Using a threshold of 2m and duration of at least 12 hours proved useful for the inclusion of both small and large events.

With regard to the second research question:

2. Is there a measurable relationship between overall beach change and energy of storms?

The relationship between the index and total average volumetric change was practically zero. Individual profile analysis revealed that there was no relationship between the index and volumetric change. Because of the clear onshore-offshore exchange of sediment occurring along individual profiles the subaerial and subaqueous change were regressed upon the index. Yet again, there was still no relationship. The lack of relationship between the index and volumetric change strongly implies that the alongshore component of sediment transport to be considered. For future work, the angle of the incoming waves needs to be incorporated into the total wave energy equation in order to adequately account for the alongshore component.

When considering significant wave period for each event, the relationship increased with regard to examining subaerial and subaqueous change. As the significant wave period increased subaerial volume also increased coinciding with general wave theory that long period swell waves transport the sediment stored in the offshore bar and deposit it along the upper portion of the profile. Wave events with short period waves produced subaqueous volume decrease, which again reaffirms the need to examine the alongshore component to sediment transport.

When relating these findings to the concept of frequency/magnitude, these particular events disprove the conclusion of Wolman & Miller (1960) that beach profile sediment is mostly transported by events of moderate frequency/magnitude. It was found that the lower index events were causing the most displacement of sediment with regard to the total average volumetric change to the 5m depth. It was extremely interesting to find that the largest event, which coincided with Hurricane Dennis in 1999, produced very little total average volumetric change to the profiles.

These findings indicate the need for several factors to be considered for future research. One, it is clearly evident that the alongshore component of sediment transport be incorporated into the total wave energy equation. By including the wave angle a better assessment can be made about volumetric change and relating the change to the event index. Two, the inclusion of the monthly profile data would provide more accurately assessed total average volumetric change along the beach. There are two disadvantages to considering the monthly profiles. More than one event can hit the beach in a month, making it difficult to determine which event had a greater impact on the change. Also, although there are 24 profiles surveyed monthly, providing a better volumetric change average, a month may allow the beach to recover after the passing of an

event before the next surveys are conducted. The temporal scale of one month may be too long to assess beach change after an event. But nonetheless, considering these additional profiles may deem valuable to assessing the total average volumetric change.

And third, Larson & Kraus (1994) concluded that the profiles at Duck have a depth of closure at the 8m depth in which no change to the profile occurs past this depth. Not all of the profiles from 1997-2007 extended to this depth resulting in the truncation at the 5m depth for consistency. But, every profile that does extend to the 8m depth should be considered as the additional 3 m^3 of volume may also improve the relationship between the index and total average change.

Although this study does not agree with the findings of previous research, it does reiterate the importance of the geomorphic power of small events in producing landscape change. If the index is indeed improved with future research it will benefit planners and beach nourishment managers because it will allow for predicting the probability of beach change with regards to an event of a given magnitude.

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