Spatial and Temporal Evaluation of Dune, Beach and Nearshore Bar Interactions

Cape Cod, MA

by

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Coastal features and processes interact with each other, producing complex patterns of shoreline changes in different beach segments. Coastal dune systems have been studied in detail, looking at their evolution through time, sediment budget and aeolian processes but few researches have combined the studies of the processes that occur in the nearshore with changes in the dune systems. This research explores how the foredune changes are not only affected by beach width and wave/wind conditions, but also by the formation of sandbars in the nearshore and by changes in beach orientation. This study focuses on a 14.6km shoreline section in the Province Lands Dunes area of Cape Cod National Seashore, an area characterized by wide to narrow beach segments containing dunes and foredune features. Dynamics along the coast are not homogeneous. Beach segments are exposed to different wind/wave regimes and therefore have different energy conditions. The effect of shoreline orientation is examined by dividing the study area into five zones each with a different shoreline trend. This research relies on GIS and remotely sensed data sources to quantify and describe shoreline changes. Orthophotography from the 1951-2012 and 2001-2012 period was collected from various sources and digitized in order to compare changes in the coastal features throughout the years. Patterns of dune, shoreline and nearshore bar changes were quantified using DSAS extension in ArcGIS

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Spatial and Temporal Evaluation of Dune, Beach and Nearshore Bar Interactions at Cape Cod, Massachusetts

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Chapter 1: Introduction

The beach and dune system is one of the most dynamic geomorphic environments, changing constantly due to the continual influx of energy from waves, currents and winds. As a result, it is an ideal venue for research of process-form relationships (Sherman and Bauer, 1993). Coastal dune systems have been studied in detail by coastal geomorphologists, who have examined how dune growth and development are directly related to a source of sand supply (Hesp, 1988; Psuty, 1992; Anthony et al., 2006), the characteristics of wind flow across dune systems (Arens, 1996; Frank, A.J. and Kocurek, G., 1996; Walker, 1999; Hesp, 2002; Walker and Nickling, 2002; Delgado-Fernández, 2010, Miot da Silva and Hesp, 2010), rates of aeolian transport (Arens, 1996; Van Dijk et al., 1999; Walker, 1999; Delgado-Fernández, 2010; Ellis et al., 2012; Sherman and Li, 2012) and patterns of erosion and deposition (Gares, 1988; Sapre and Chancey, 1990; Psuty, 1992; Sherman and Bauer, 1993; Hesp, 2002; Forman et al., 2008; Ritcher et al., 2011).

At the same time, researchers have dealt with a wide range of issues associated with beach systems including wave propagation and refraction (Hallermeier, 1980; Peregrine, 1983; Bowen and Huntley, 1984; Herbers and Burton, 1997; Esteves et al., 2006; Ribas et al., 2011), longshore currents (Thornton and Guza, 1986; Moore et al., 2003) and instantaneous and long-term beach response (Short and Hesp 1982, Wright and Short, 1984; Sallenger et al., 1985; Houser et al 2008). The sub-aqueous portion of the beach profile also plays a significant role in affecting the beach response (Aagard et al., 2007) and thus must be considered a part of the shorefront system. Coastal features and processes interact with each other, producing complex patterns of shoreline changes in different beach segments (Esteves et al. 2006). A particular beach segment may show alternate areas of erosion and accretion next to each other at one time and have opposite trends another time. The interrelationship between the dune, beach and nearshore, while recognized, has received only limited attention on the part of coastal researchers (Davidson-Arnott, 1988; Hesp, 1988; Aagard et al., 2007, Aagard et al.,. 2012). Researchers know and recognize there is a relationship between the nearshore processes and dune systems (Aagaard et al., 2007), but not many of them have gone into details of how these processes take place.

The orientation of the coastline plays an important role on how waves and currents affect the beach. Changes in beach orientation of as little as five to ten degrees influence the angle at which wind and waves approach the beach (Esteves et al 2006). If the approach angle to the beach changes, alongshore sediment transport direction and magnitude will change, that might result in greater erosion when wave energy increases or deposition when the energy decreases (Esteves et al. 2006; Pérez-Sánchez 2009). Dune systems are also influenced by beach orientation which causes significant variations in the available onshore wind energy and potential of sediment transport (Delgado-Fernández, 2010; Miot da Silva and Hesp 2010).

Nearshore bars are essentially reservoirs of sand that promote beach growth and protect beaches and, by extent, dune systems from possible erosion (Moore et al. 2003; Grunnet and Ruessink 2005). It can therefore be hypothesized that sandbars are an integral component of the beach-dune system by directly influencing the morphology of each individual component. The presence of one or more well-developed offshore bars would cause waves to break further offshore, reducing the amount of energy that would be expended on the beach and having a positive influence on the beach budget.

Thus it is logical to conclude that foredunes located in areas where sandbars can be found during longer periods of time will present less erosion than in areas where bars are absent or show no erosion.

There is a need to understand how the coastal system's different components interact with each other (Short and Hesp, 1982; Hesp, 1988; Aagaard, 2007). This research focuses on long- (1952-2012) and short-term (2001-2012) changes in the three components of the shoreline systems: beach, dune and nearshore bars. Such a simultaneous approach has not been applied to shoreline systems before; previous research focuses on beach-dune interactions or nearshore-beach interactions. Long and short-term components of this research describe decadal and/or yearly patterns of erosion or accretion at Province Lands, Cape Cod. Further study analyzes the interactions between the shoreline, duneline, and nearshore bars, and how they have varied through time. Aerial imagery provides a source of information to digitize and calculate changes in the shoreline features. The results are highly influenced by the frequency of flights available and the quality of the imagery obtained. The early flights, which are used for the long-term study, occurred about once a decade. The temporal duration between photos presents limitations when studying coastal systems since it may be too long a time interval to accurately examine the interactions between the 3 systems, (shoreline, duneline and nearshore bars) because they may respond to changes more quickly than a 10 year interval would show. The shorter-term study benefits from more frequent flights and better image quality, which allows more detailed analysis to be conducted for the period of 2001-2012.

The Outer Cape Cod shore is primarily affected by waves coming from an east-northeast direction. It can also be hypothesized that segments of the beach oriented to the north-east have narrower beaches and exhibit/display foredune erosion because they may not have the protection of continuous parallel and transverse nearshore bars. This also means that dynamics between nearshore, beach and dunes are not homogeneous along the shoreline. Therefore, it will be possible to identify connections between the changes that occur in the dune systems, beach and bar system.

This research is designed to determine the patterns of change in each of the three components of the shoreline system within both long-term and short-term time frames, whether there are identifiable correlations in the changes that occur in each of the three components and whether orientation plays a role in the patterns of changes and interactions that occur between the three components. The research will focus in looking at the morphological variables present and affecting the study area instead of looking at casual mechanisms present. The questions addressed by this research project are:

1) What are the temporal and spatial distributions of the shoreline features and how do changes in one influence the changes in the others?
    a) Is there are relationship between bar development and beach width? Is there a relationship between distance to the bar and beach change?
    b) What is the relationship between changes in dune morphology and the characteristics of the beach and the bars? In particular, is there a relationship between foredune accretion/erosion and beach width?
    c) Are interactions between nearshore, beach and dune systems homogeneous along the shoreline? Due to their orientation, size and position sand bars protect the beach from waves (Moore et al., 2003), therefore, are eroding dunes more common in areas with no sand bar formations?
    d) Are there discernible patterns between each decade/year?

2) What is the effect of shoreline orientation on the interactions between nearshore, beach and dune?
    a) Will segments of shoreline oriented in a particular direction present more accretion/erosion than segments oriented in a different direction?

Province Lands, Cape Cod, Massachusetts provides an excellent venue to conduct this research because the configuration of the shoreline allows the effects of orientation to be examined within a single shoreline system. Also, field and aerial inspection shows that this is a dynamic coastal system where the bars, beach and dune components seem to be undergoing rapid changes overall and those changes seem to be different at different areas of along the shore. Finally, Province Lands is part of the Cape Cod National Seashore program since 1961 and, therefore, has excellent long and short term sources of data available needed to complete this study.

Chapter 2: Literature Review

Nearshore Sandbars

The surf zone is one of the most complicated regions in coastal studies, where waves, and alongshore and rip currents move sediments into complex features including sand bars, troughs and rip channels (Alexander and Holman, 2004). A sand bar is a dynamic sandbody that has its long axis approximately parallel with the currents, which can change its features in response to changing wave conditions (Olariu et al. 2012; Wijnberg and Kroon 2002; Moore et al. 2003; Sallenger and Howd 1989). Nearshore or wave formed-bars are commonly located in both the intertidal and subtidal domains of sandy beaches (Wijnberg and Kroon 2002). They exist under a wide range of hydrodynamic regimes, ranging from swell-dominated to storm-dominated wave environments and from microtidal to macrotidal wave regimes (Wijnberg and Kroon 2002). Nearshore bars are essentially reservoirs of sand and are able to modify the response of beach to variable wave conditions (Davidson-Arnott, 1988; Grunnet and Ruessink 2005; Mariño-Tapia et al., 2007). They promote beach growth and protect beaches (Wijnberg and Kroon, 2002; Grunnet and Russink, 2005). Beach width varies seasonally and temporally due to sediment exchange between the beach and the nearshore bars (Davidson-Arnott, 1988). Wijnberg and Kroon (2002) explain that sand bars cause shallow waves to break, reflect and refract generating complex flow fields, including asymmetric oscillatory flow, undertow, horizontal cell circulation, edge waves, and swash-backwash motion. The local tidal range and wave climate of the area determines the frequency with which sand bars will develop and will be affected by these types of flow fields (Wijnberg and Kroon, 2012).

Greenwood and Davidson-Arnott (1979) developed a nearshore and intertidal bar classification consisting of six bar types. These were differentiated by using different criteria related to the description of the physical/locational characteristics and the processes that control bar formation. The variables were location, slope, amount of wave energy needed to create and maintain the bar formation and in what tidal range conditions can they be found. This classification was later revised by Wijnberg and Kroon (2002) who maintain the same bar types and variables as Greenwod and Davidson-Arnott (location, slope and wave energy) but revised the tidal range in which each bar type formed.

Wijneberg and Kroon (2002) add that the positioning of the bar on semiprotected or open coasts reflects water depth characteristics and the typical flow regime for the location. Slip face ridges, for example, are intertidal bars with well-defined elongated features that tend to line up with the general shoreline configuration (Greenwood and Davidson-Arnott, 1979; Wijnberg and Kroon, 2002). These types of ridges are cut by small rip channels and may migrate onshore at rates on the order of 10 meters per day (Short 1985; Kroon, 1994; Wijnberg and Kroon, 2012). On the other hand low amplitude ridges are also intertidal bars but without a slip face. They occur in a cross shore sequence parallel to the shoreline and remain apparently static (Wijnberg and Kroon, 2012). Many only respond to movements of the still water level migrating with the spring-neap tidal movement (Orford and Wright, 1979).

Wijnberg and Kroon (2002) further explain that a nearshore morphodynamic system consists of three components: water motion, sediment transport and morphology. The nearshore morphodynamic system receives energy in the form of waves, winds and tides, which influence the flow field in the nearshore zone that is in turn controlled by the nearshore morphology. This flow field induces sediment transport, which will result in bathymetric change if a transport gradient exists (Bowman and Goldsmith 1983; Wijnberg and Kroon 2002; Moore et al. 2003). Landward migration of bars from the nearshore is also possible, and as result one or more sand bars may appear temporarily in the intertidal zone of the coast during processes of migration (Davidson-Arnott 2010).

There is ongoing debate on the mechanisms that govern nearshore bar formation and development. The majority of research on this topic refers to sand bars on semi-protected and open coast beaches (Bowman and Goldsmith 1983; Wijnberg and Kroon, 2002; Moore, 2003; Mariño-Tapia, 2007; Davidson-Arnott, 2010). Although these beaches may be sheltered from large waves from certain directions, they are all exposed to, at least, moderate to high wave conditions in one direction. The position of bars on semi-protected and open coasts varies with water depth characteristics, which in turn influences the typical flow field regime for that particular location (Wijnberg and Kroon 2002).

Two types of bar formations can be observed occurring in gentle slopes: multiple parallel bars and transverse bars. Short and Hesp (1982) explain that parallel sandbars are normally found in dissipative beaches characterized by high wave energy, a wide surfzone and gentle nearshore slopes. Multiple parallel bars are straight to undulating features that are often oriented parallel to the shoreline. In some cases they can also be found at an angle with the shoreline. Any change in orientation of this type of bar system relative to the shoreline is accompanied by a striking change in bar morphology (Konicki and Holman 2000; Wijnberg and Kroon 2002; Moore et al. 2003; Ribas and Kroon 2007). Bar morphology and their alignment, both along the shoreline and through time, suggest that the mechanism responsible fot the formation and persistence of the bars is controlled by bathymetry, specifically by the break in shoreface slope (Moore et al., 2003). Those breaks in shoreface slope affect the tidal drainage across the bar crests with different orientations relative to the shoreline. According to Moore et al. (2003) where bars are diagonal to the shoreline tidal drainage can occur between the bars, but where the bars are parallel to the shoreline tidal drainage must occur across the bars causing them to break and create interconnections between the bars. In order for transverse bars to form, they need small tidal range environments, small nearshore slopes and low wave energy, although Konicki and Holman (2000) found that transverse bars can also form in intermediate energy environments.

Due to their location, nearshore bars serve as protection for the beach against wave action and therefore are subject to episodic changes in response to storm and non-storm related wave activity incident to the beach (Houser and Greenwood, 2007). Location of the bars varies depending on the force of wave energy they are subjected to. When wave energy is small, bars move slowly onshore; they move more rapidly when waves are large and surfzone circulation is strong (Wright and Short, 1984; Alexander and Holman, 2004; Houser and Greenwood, 2007; Coco et al., 2014). In other words, increased wave heights often result in offshore bar migration, while lower wave energy promotes onshore migration. Studies reveal that transport varies nonlinearly with instantaneous oscillatory velocity (Houser and Greenwood, 2007), this means that more sediment is transported by larger onshore-directed velocities during a storm (strong gusts generating large waves in a shorter time period) than by longer duration events with smaller offshore-directed velocities (Bowen, 1980).

In a 2000 study conducted in Skallingen, Denmark, Houser and Greenwood (2007) observed that sediment eroded from the foredune and upper foreshore during major storm surges was deposited in the through area and slope of the nearshore bars, causing them to migrate onshore and attach themselves to the lower foreshore. This process allowed the beach to recover after the storm because some of the lost sediment in the foredune and shoreface area was returned to the beach by currents and by the welding of the bars augmenting the sediment volume of the beach and dunes (Houser and Greenwood, 2007; Aagard et al 2012; Anthony, 2012). The state of the nearshore area not only controls the sediment delivery to the beach and dunes, but it also governs the sediment supply characteristics and grain size distribution, which are crucial components of aeolian processes and of the resulting forms of the subaerial beach (Bauer, 1991; Sherman and Bauer, 1993). These dynamics demonstrate the importance of nearshore bars during storm events in protecting the shoreline and in the recovery process by adding sand to the beach and dune sediment supply.

Beach-Dune Interactions

Wave and longshore current dominated beaches and wind-dominated dunes are systems that interact and adjust mutually and therefore must be considered to be coupled systems. (Psuty, 1988; Psuty, 1989; Sherman and Bauer, 1993). Sediment exchanges between beach and dune environments are dominated by complex feedback mechanisms that have consequences for the evolution of the beach-dune system. The morphodynamics of the beach affect beach-dune sediment exchanges by influencing aeolian processes through three primary controls: beach slope, grain size distribution and beach width (Sherman and Bauer, 1993; Gares, 1988; Short and Hesp, 1982). The beach slope influences aeolian sediment transport rates by altering the wind field and the surface shear-stress distribution on the subaerial area of the beach (Rasmussen 1989; Gares 1988; Sherman and Bauer, 1993).

Dune sediment supply rate is dependent on the spatial and temporal deposition across the beach. Wave and current initiated deposition allows the beach to increase in width (Hesp, 1982).

Fetch length across the beach controls the amount of sand available to be moved by winds of particular velocities (Psuty, 1989; Bauer, 2009). Bauer and Davidson-Arnott (2002) explain that the fetch effect is a manifestation of a downwind saltation cascade through which particles in transport increase exponentially, presuming constant wind stress. Delgado-Fernandez (2010) developed a contextualization of the fetch effect and other factors causing temporal and spatial equilibrium and disequilibrium in coastal systems (Table 1).

Table 1. Factors causing temporal and spatial equilibrium and disequilibrium in coastal systems (Delgado-Fernandez, 2010)

	Transport systems	Time	Space
Equilibrium			
(transport rate in equilibrium with applied stresses	Transport-limited (surface provides unlimited grains)	Steady flow	Dry, non-cohesive and uniform sediment; flat surface
	Supply-limited (surface ability to supply grains is limited)	Steady flow	Homogeneous moisture, bonding agents, roughness elements, particle size and sorting, slope, etc.
Disequilibrium			
(transport rate variable and in disequilibrium with wind field)	Transport limited (surface has potential to provide unlimited grains)	Unsteady flow, wind ramp-up/down	Fetch effect, boundary layer development
	Supply limited (surface ability to supply grains is limited)	Spatial and temporal variations of supply-limiting factors (moisture, crust, topography, etc.) flow and fetch	

Delgado-Fernandez (2010) explains that the disequilibrium between the wind flow and sediment transport rate may occur in time, in space or in both time and space and that the fetch effect is a case of a disequilibrium situation that occurs spatially. There is a positive relationship between the increasing wind velocity, fetch distance, saltation height, and the vertical and horizontal flux (Dong et al., 2004; Delgado-Fernandez, 2010).

In 1992 Psuty created a conceptual model that explains beach/dune interactions based on their equilibrium and disequilibrium dynamics based solely on sediment budget. Psuty's (1992) conceptual model of beach/dune interaction and the resulting dune form is based on the sediment budget status of the beach and adjacent foredune relative to the expected characteristics of the back-shore morphologies (Table 2). The conceptual model combines positive, steady state and negative beach budget with the same characteristics in dune budget resulting in nine morphological features.

Table 2. Relation between sediment budget, beach status and foredunes. From Psuty 1992 and modified by Sherman and Bauer 1993.

Beach budget	**Dune budget**	**Morphology**
Positive	Positive	Beach or dune ridges
Positive	Steady state	Indeterminate
Positive	Negative	Blowouts and deflation hollows
Steady state	Positive	In situ dune growth
Steady state	Steady state	Indeterminate
Steady state	Negative	Blowouts and deflation hollows
Negative	Positive	Dune growth and onshore migration
Negative	Steady state	Indeterminate
Negative	Negative	Dune erosion and washover

This model conceptually separates the positive and negative sediment budget of the foredunes from that of the beach. The combined sediment budgets result in the development of a typical dune morphology. Although it provides an excellent model to help understand beach/dune interactions, it does not take into consideration nearshore processes that may take place in the coastal landscape.

Other classifications have been created in order to explain beach/dune morphodynamics by integrating the beach, dune systems and nearshore processes. Short and Hesp (1982) created a classification of beach/dune morphologies (table 3) to illustrate the range of complex combinations of beach-dune interactions taking into consideration the morphodynamic state of the beach. The table demonstrates that there is a positive relationship between wave-energy environments, modal morphodynamic state of the beach and the size and form of subaerial sand bodies (Short and Hesp 1982; Hesp 1988).

Table 3. Beach Morphodynamics: wave, beach and dune interactions. Modified from Short and Hesp, 1982 and Sherman and Bauer 1993.

Morphodynamic beach state	Frequency	Type of dune scarping	Potential aeolian transport	Foredune size	Wave height	Modal beach state
Dissipative	Low	Continuous scarp	High	Large	6.5’	Parallel Bar(s), wide, low gradient
Intermediate	Moderate	Scarps in rip embayments	High	Large	2-2.5m	Rips, crescentic bars
			Moderate	Low	1.5-2m	
			Low	Small	1-1.5m	
Reflective	High	Foredune scarping; small blowouts	Low	Small	1m	Barless steep beachface cusps

Short and Hesp (1982) provide an explanation of the nature and morphology of the dune systems and compare it with the nearshore characteristics of the beach. Dissipative beaches occur in response to high wave conditions combined with an abundant supply of medium to fine sand. They have a wide low gradient beach face and present shore-parallel sand bars. Also, dissipative beaches characterized by high wave energy that tend to flatten the surfzone gradient, this in turn affect the variations in dune volume (Hesp, 1988). This means that in a dissipative beach dune volume variations are a product of wave induced sediment transport (Hesp, 1988; Bauer and Davidson-Arnott, 2002; Bauer et al., 2009). Intermediate beach states occur between fully dissipative and fully reflective beaches. This beach state can exhibit low to high gradients and store potentially active sediment in the surfzone as crescentic/transverse bars. Reflective beaches form in response to low modal wave conditions, have high gradients and are barless (Short and Hesp, 1982).

These characteristics and dynamics between the nearshore, beach and dune system are important in determining the system's response to storm events. Many factors should be taken into account when estimating storm impact to the coastal system (Anthony, 2012; Almeida et al., 2012), including: height and extent of the foredune relative to storm surge level (Thieler and Young, 1991; Judge et al., 2003; Houser et al. 2008), pre-existing shoreline conditions and their vulnerability (Wright and Short, 1994), storm characteristics or group events (Dolan and Hayden, 1981; Ferreira, 2005), shoreline orientation and nearshore circulation (Strikazzi et al., 2000) and swash processes (Holman, 1986; Sallenger 2000). During storm events, wave induced dune erosion removes sediments from the dunes and returns them to the surf zone (Sherman and Bauer, 1993). If the dune volume is sufficient to add sediment to the nearshore bars during a storm, then beach erosion and shoreline retreat are minimized (Nordstrom and Gares, 1990; Sherman and Bauer, 1993). It is important to add though that when loss of sediment from the dune increases or dune volume is insufficient to withstand storm surge, probability of breaching and overwash is increased (Nordstrom and Gares, 1990; Sherman and Bauer, 1993).

Beach width is also an important factor that is directly related to the characteristics of the dune field and their ability to resist damage from storms (Gares and White, 2005; Claudino-

Sales, 2008; Houser et al., 2008). Wider sections of the island provide more space for dune development and especially the more storm resistant established dunes (Claudino-Sales et al., 2008). It is important to take in consideration spatial variation in beach morphology and width when considering shoreline response to a storm since it is probable that the shoreline response will be mirrored by the dune morphology (Houser et al., 2008). Houser et al. (2008) suggest that these variations in morphology and width may lead to similar variations in the supply of sediment and vegetation growth. For example, in an area that was breached the recovery of the dune system can be limited by the presence of moisture and lag deposits (Houser et al., 2008).

Dunes

Dunes are an important coastal feature because they serve as natural protection against wave attack and are essentially a reservoir for storage of sand against storm waves (Nordstrom et al. 1982; Short, 1988; Psuty 1993; Aagaard et al. 2007; Armaroli et al., 2013). Their growth and shape are directly related to the existence of a source of sand that can be moved by the wind and to wind flow characteristics. Thus, dune growth depends on the occurrence of strong onshore winds that can transport sand from its source on a beach, which ideally would be wide and dry (Short and Hesp 1982; Gares, 1988; Hesp 2002; Houser et al. 2008).

Hesp (2002) defines foredunes as shore-parallel dune ridges formed on top of the backshore by aeolian sand deposition within vegetation. Lower plant canopies reduce the airflow and transport (Hesp, 2002). Wind velocities experience rapid deceleration upon reaching plants, local acceleration around the plants and flow separation behind the plants (Nickling and Davidson-Arnott, 1990; Hesp, 2002). An increase in plant height and density promotes dune height increases and dune length decreases (Van Dijk et al., 1999; Hesp, 2002; Armaroli et al., 2013). Hesp (2002) adds that plant density and distribution also varies seasonally, it is low or absent during the winter and high in the spring. Therefore seasonal growth rates strongly influence patterns of sand transport and deposition on foredunes (Hesp, 2000).

Foredunes can be classified as incipient or established. Incipient foredunes are new or developing dunes that gradually grow on the backbeach at the foot of the foredune. There is active exchange of sediment between the foredune and the beach. The form and orientation of the foredune reflect the beach as a source of sediment and the interaction of wave and wind processes. In areas with strong alongshore transport of sediment, coastal foredune forms develop in a particular spatial sequence that is related to the gradient of the alongshore sediment supply (Short and Hesp 1982; Psuty 1992). Hesp (2002) argues that sand transport is reduced significantly landward from the leading edge of vegetation. He continues to say that the greater deposition at the leading edge produces asymmetric incipient foredunes with the short slope facing seaward.

Generally, variables such as tidal range, beach width, humidity, wave energy, grain size, sediment budget and sea-level change have been suggested as having some control in dune development (Short and Hesp 1982; Sherman and Bauer 1993; Hesp 2002; Judge et al. 2003; Delgado-Fernandez 2010). Understanding dune activity through the two components of sand availability and wind transport capacity provide a more holistic and comprehensive characterization of dune systems. There are some researchers that understand that other variables should also be considered when studying dune development. Aagaard et al. (2007) argue that there is growing evidence that shows that coastal dune initiation and growth is probably linked to both an increased onshore sediment supply caused by increased storm surge activity and possibly by the onset of sea level rise. Aagaard et al (2007) suggest that a novel explanation of enhanced sediment supply might be a consequence of storm activity and nearshore bar migration onshore, which add mechanisms to be considered in coastal dune location and development. This means that the dune system will have the imprint of medium term surf zone beach behavior and will in part depend on the sediment supplied by the nearshore system. Over the years wave-induced sand transport provides the largest volume of sediment for dune formation (Short and Hesp 1982; Hesp 1988).

Dunes systems are subject to erosion during high water conditions associated with storms. The erosion potential of the dune system is determined by storm surge, wave height and storm duration (Judge et al.; 2003; Gares and White, 2005; Caudino-Sales et al., 2008). Under storm conditions, the dune may hold, leaving an erosion scarp but successfully protecting what is behind it (Nordstrom and Gares, 1990; Sherman and Bauer, 1993, Claudino-Sales et al., 2008). The dune may ultimately fail by repeated undercutting during a storm, pulling the sediment from the dune to the beach face and to the nearshore. Overtopping may also occur and completely overwashing a dune, pushing sediment landward (Judge et al. 2003; Hesp 2002). The ability of coastal dunes to recover and their morphological response to the next storm depends on the availability of sediment from the overwash or beach widening, aeolian transport (Gares and White, 2005; Houser et al. 2008; Anthony, 2013). In addition, the presence of vegetation, especially dense shrub vegetation, increases the ability of the dune to resist erosion (Judge et al. 2003; Claudino-Sales et al., 2008).

This review of the available literature reflects how complex are each of the coastal features that this research seeks to study. The shoreline, duneline and nearshore bars are each subject to numerous variables that affect their development through time and each coastal feature has a unique response to these changes. This research goal is to understand how these different responses from each of the coastal features affect one another and to learn if the changes occur at similar rates and time scales.

Chapter 3: Study area

Geomorphology of Cape Cod

This study was conducted at Cape Cod National Seashore located in southeastern Massachusetts. Cape Cod was product of glaciation during Wisconsin period (Fisher and Leatherman, 1987). Approximately 80,000 years ago, ice sheets began to flow from Hudson Bay and Labrador southward into what is now New England reaching as far south as Cape Cod and Long Island. The advancing ice sheets delivered significant amounts of sediment to the terminus where it was deposited in extensive moraines. These moraines became the backbone of many of the features that dominate the southern New England shoreline today, including Cape Cod (Mague, 2012).

The east facing shoreline of Outer Cape Cod consists of a barrier island and spit complex to the south, a coastal bluff segment in the center, and an accretionary spit system to the north (Giese et al., 2007). Dune systems dominate most of the northern and southern extremities of Outer Cape Cod's coastal landscape. The northern spit section is the result of sediment being transported alongshore from the source, which are the bluffs in the middle section. This sediment is then deposited in the northern section and manifests itself as a series of shore parallel dune ridges, the older ones located furthest inland. The dunes, composed of medium to coarse sand formed parallel with the shore, in response to the dominant winds from the north and north-east (Forman et al., 2008). The sediment accreted in this location was reworked by northerly winds that then resulted in the creation of a series of nested parabolic dunes that trend in a southward direction. In the southern most part of the parabolic dune field, the trailing arms of the parabolics that trend in a northerly direction create the foredune system that lines the beach.

Through the years, these dune systems, along with the beach and wetlands and other coastal features of the landscape, have been subject to the geomorphic and ecologic processes that have shaped the terrain to what it is observed today. Each coastal feature has played its part in shaping Cape Cod and each feature has played and still plays an important role in the dynamics of each of the components of this particular coastal area. In keeping with its management philosophy, the US National Park Service focuses on preserving the original character of the shoreline as well as its unique coastal, glacial and dune landscape. As a result, there are no jetties, groins or seawalls along the shoreline, and vehicular access is limited, which presents itself as an ideal venue to conduct this long term and short term study.

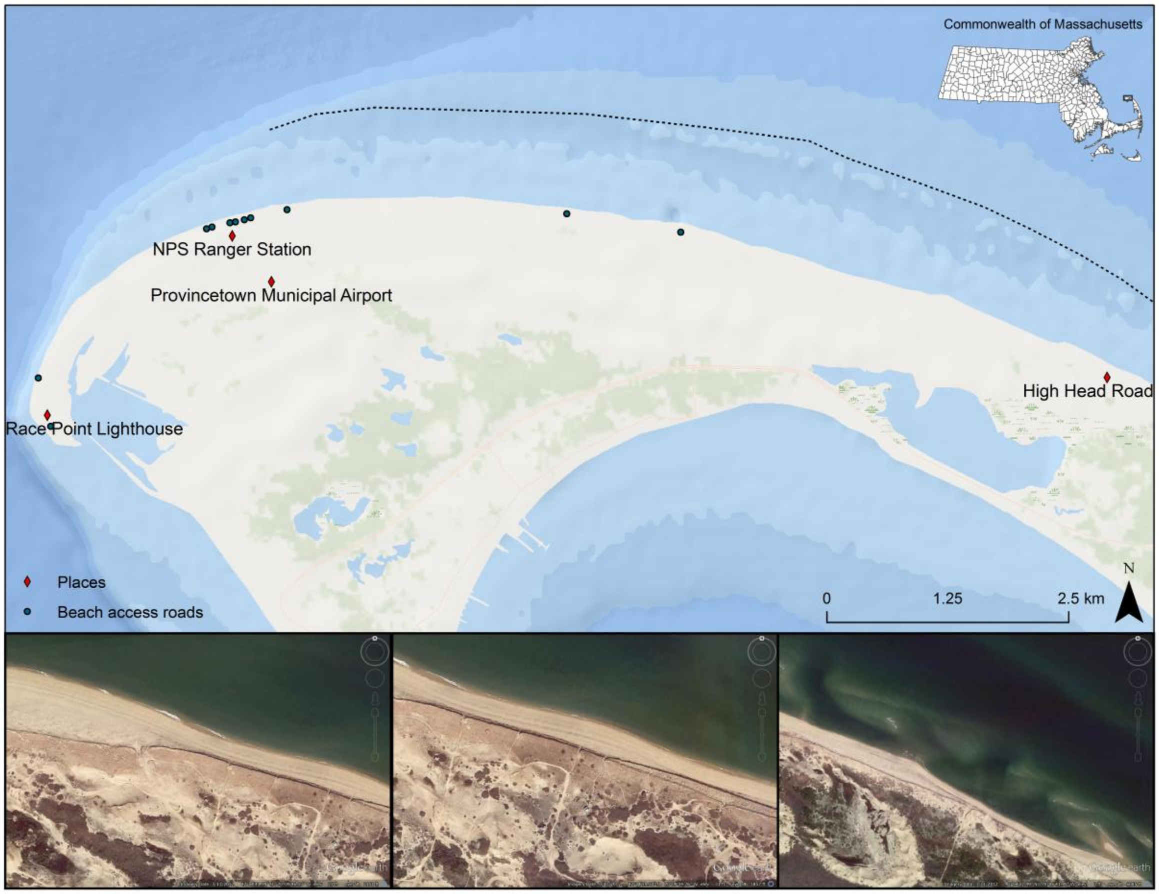

Figure 1: Study area Province Lands, Cape Cod National Seashore. Figure 1a shows the variability in beach width within short distance. Figure 1b illustrates the presence of dune ridges. Figure 1c the shows the presence of nearshore bars between the shoreline and Peaked Hill Bar. ESRI base map, Google Earth Imagery.

The focus of this study is on a 14.6 km long segment of the north-east coast of Province Lands, Cape Cod located between High Head Road and Race Point (figure 1). This area was shaped by changes in sea level during the Holocene period (Giese et al., 2007). Deposition of sediment brought by littoral currents and waves continue to shape the coastline at Race Point and Provincetown Hook. In this area, the beach varies from wide to narrow segments and contains dunes and foredune features. The Province Lands coastline is also characterized by a series of nearshore sand bars that seem to form parallel and transverse to the coastline. The recurved nature of the spit provides an opportunity to examine the role of shoreline orientation in the development of the bar-beach-dune system.

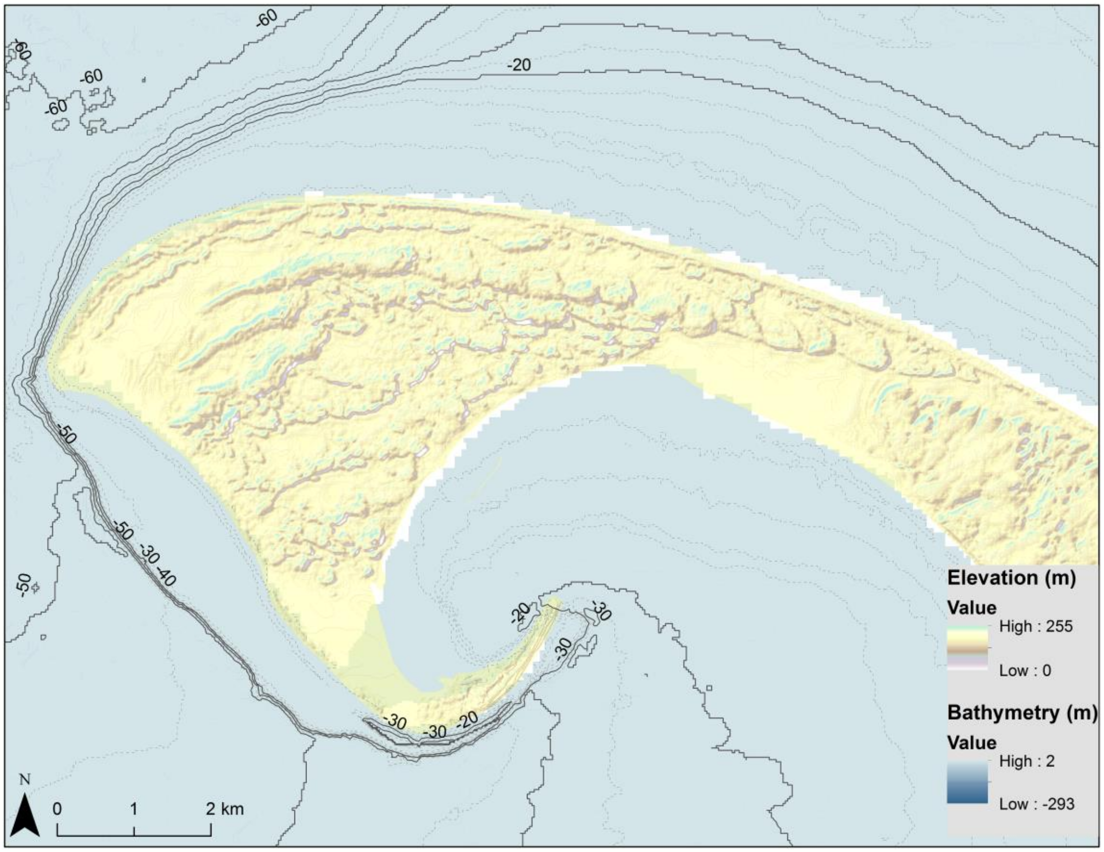

Figure 2: Elevation and bathymetry of Province Lands Cape Cod, MA. The Shaded Relief layer (1:5,000) and Bathymetry raster layer were obtained from the Massachusetts Office of Geographic Information (MassGIS).

Wave energy is highly variable at the study area and around the entire Cape Cod shoreline. Previous studies show that east, northeast waves predominate in Cape (Department of Earth Sciences Boston University, 2007). The variability of the angle of approach of the wave is due to changing shoreline orientations, fetches and offshore bathymetry, which differs greatly from one area to another. The variability of the bathymetry along the coast at Province Lands can be observed in figure 2. At Race Point, depth increases rapidly, reaching 20 meters within 50 meters of the beach and 50 meters deep within 200 meters of the shoreline. The bathymetry of the area to the east of Race Point shows a more gradual change in depth, reaching 10 meters within 800-900m from the shoreline.

Wind patterns also play an important role in the wave dynamics of the area. A ten year wind record (1949-1959) obtained by the Department of Earth Sciences at Boston University from the Logan Airport in Boston shows that the dominant winds in the area come from the northeast while the prevailing winds, those with the longest duration, come from the northwest (Department of Earth Sciences Boston University, 2007).

Chapter 4: Methods

This research contains two analyses of the interactions and changes between the shoreline, duneline and nearshore bars: a long-term or decadal analysis from 1952 to 2012 and a short-term analysis from 2001 to 2012. The behavior of each component of the system may occur a time scale different from the others. Each system may not move parallel to each other at common time intervals and time lags may exist between the changes in one system and those in the others. Analyzing the interactions and changes at two different time scales permits a more comprehensive understanding on how and when system changes take place. The long- term study, which focuses on decadal changes, may not capture responses that occur in time periods shorter than a decade. The availability of aerial images taken about two years apart during the 2000s presents an opportunity to look at the relationships between the different changes in each system at a greater detail.

Data collection and pre-processing

The long-term and short-term analysis of changes in the bar-beach-dune system relies on the existence of aerial photographic imagery dating from 1952 to present from several sources including the USDA Data Gateway, the Massachusetts Office of Geographic Information Systems (MassGIS), NOAA's Digital Coast web portal and the Map Collection at University of Massachusetts at Amherst (Table 4). All the imagery used in this study was acquired over the summer months, a period of low wind speeds and limited wave action, conditions that minimize errors due to seasonal and post-storm variability (Moore, 2000; Leatherman, 2003).

Table 4. Available data

Date	**Resolution**	**RMS*/ horizontal accuracy**	**Source**
Long term study			
07/25/1952	1:20,000	0.9	UMASS at Amherst
09/20/1970	1:20,000	0.6	UMASS at Amherst
03/26/1985	1:20,000	0.5	NOAA Digital Coast
Summer 1994	1:7,000	Not available	MassGIS
Summer 2003	1m	+/- 3m	USDA Data Gateway
Summer 2012	1m	+/- 6m	USDA Data Gateway
Short term study			
April 2001	1:2,500	Not available	MassGIS
Summer 2003	1m	+/- 3m	USDA Data Gateway
April 2005	1:5,000	Not available	MassGIS
Summer 2008	1m	+/- 5m	USDA Data Gateway
Summer 2010	1m	+/- 5m	USDA Data Gateway
Summer 2012	1m	+/- 6m	USDA Data Gateway

*RMS refers to the root mean square error calculated when georeferencing the imagery.

The images were first rectified and corrected using ERDAS Imagine v. 2013 in order to eliminate distortions and displacements caused by perturbations in the geometric relationship between image and object space (Moore, 2000). Ground control points obtained from a 1972 USGS topographic map were used to rectify aerial photographs from 1952 and 1970; the rest of the imagery was already rectified. Following recommended practice (Thieler and Danforth, 1994; Moore, 2000), 8-10 ground control points, consisting preferably of cultural features, were used to rectify each image. However, it became necessary to use less reliable features such as sand roads and obvious vegetation formations as control points because the study area is mostly undeveloped, with few cultural features. The use of these less reliable ground control points could substantially affect mapping accuracy (Thieler and Danforth, 1994; Moore, 2000). After rectification, the images were assembled into a mosaic using a polynomial Geometric Model order 1, Lambert Conformal Conic projection, GRS 1980. The resampling method used was

Nearest Neighbor where the values of the output cells are determined by the nearest center on the input grid.

Digitization of features

Three shoreline features were digitized on the mosaics: the bars; the shoreline; the dune line. The features were digitized at a scale of 1:2,000, which is considered the smallest usable scale for shoreline mapping (Thieler and Danforth, 1994; Moore, 2000; Schupp et al., 2005).

Following previous practice (Moore, 2000; Leatherman, 2003; Parker, 2003), the high water mark (also known as the wet/dry line) was used to represent the shoreline. Some concerns about the use of the wet/dry line as a shoreline marker have been raised because displacement of the line due to wave, tide or wind effects can approach several meters (Thieler and Danforth, 1994). However, low resolution imagery often makes it difficult to identify other more stable features, as was the case with the 1952 and 1971 imagery used in this study. The use of imagery collected over the summer season reduces the errors associated with using the wet/dry line (Leatherman, 2003).

The second feature to be digitized was the duneline. Although it would preferable to use a geomorphic feature such as the dune crest or dune toe, it was difficult to identify these on the imagery used here, which was not available in a form that facilitated stereographic representation. It was decided to use the vegetation line to represent the dune line, assuming that it fluctuates with changes in the dune (Zuzek et al., 2003).

Digitizing the nearshore bars represented the greatest challenge for a number of reasons. First, the occurrence of sunglint off the water on the images affected the identification of sand bars. Second, although color differences associated with water depth could be used on some images to identify shallower areas, the tide state changes these color differences rendering reliance on color to identify sand bars somewhat questionable. In the end, color changes in the recent imagery in combination with the pattern of breaking waves visible in the imagery were relied on to identify the approximate location of nearshore bars (Plant and Holman, 1997; Alexander and Holman, 2004).

The digitization of the shoreline was done in ESRI ArcMap. The aerial photograph sets were imported into the GIS. Separate layers were created for each of the three coastline features and each layer contained the lines traced from the different sets of imagery.

Accounting for orientation

Because one of the issues being assessed in this study is shoreline orientation, it was necessary to divide the shoreline into sections with different orientations. A In order to determine changes in orientation alongshore, it was determined that transects should be established perpendicular to the shoreline at 300m intervals. The orientation of each transect was then calculated using the linear directional mean tool available in ArcMAP. This tool calculates a trend for a set of line features measured by calculating the average angle of the lines. The orientation is calculated as a compass angle, clockwise from due north. Afterwards, a value of 180 was added to the result of compass angle values to be able to plot them into a line graph to identify locations (specific transect number) where a distinct change in orientation occurs. Five distinct shoreline orientation zones were identified (Figure 3). Each zone varied in length and had a mean orientation that was quite distinct from the others (Table 5)

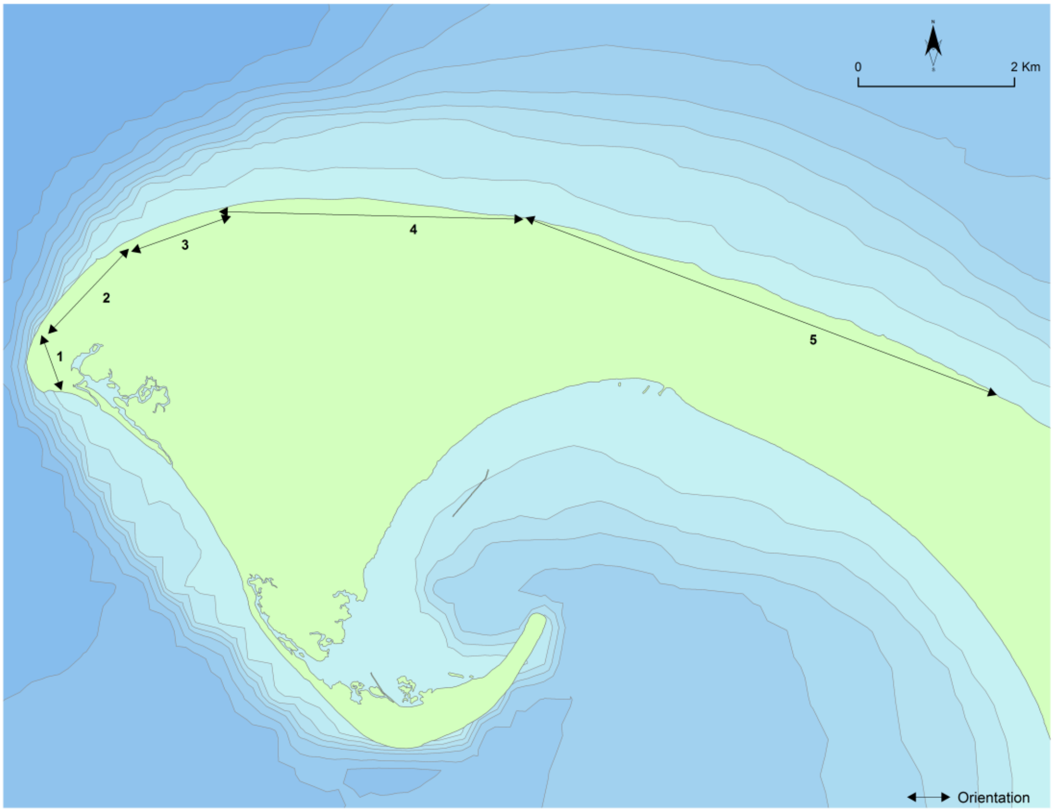

Figure 3: Five zones identified based on orientation.

Table 5. Details of each zone

Zone	Orientation	Length	Number of transects
1	236.85 SW	0.75km	15
2	310.59 WNW	1.49km	30
3	336.29 NW	1.35km	27
4	359.64 N	3.89km	77
5	18.95 NE	64km	128

Because each zone varies in length, it was decided to select a 1km area of interest within each zone in order to compare the changes and interactions in each zone,. Each area of interest was located in the center of each of the 5 orientation zones (Figure 4). The different zone lengths meant that in some cases (zones 2 and 3), the area of interest included nearly the entire zone whereas in others (zones 4 and 5) the areas of interest comprised only a small part of the zone. Zone 1 was so short, that the area of interest was shorter than the desired width (Table 5)

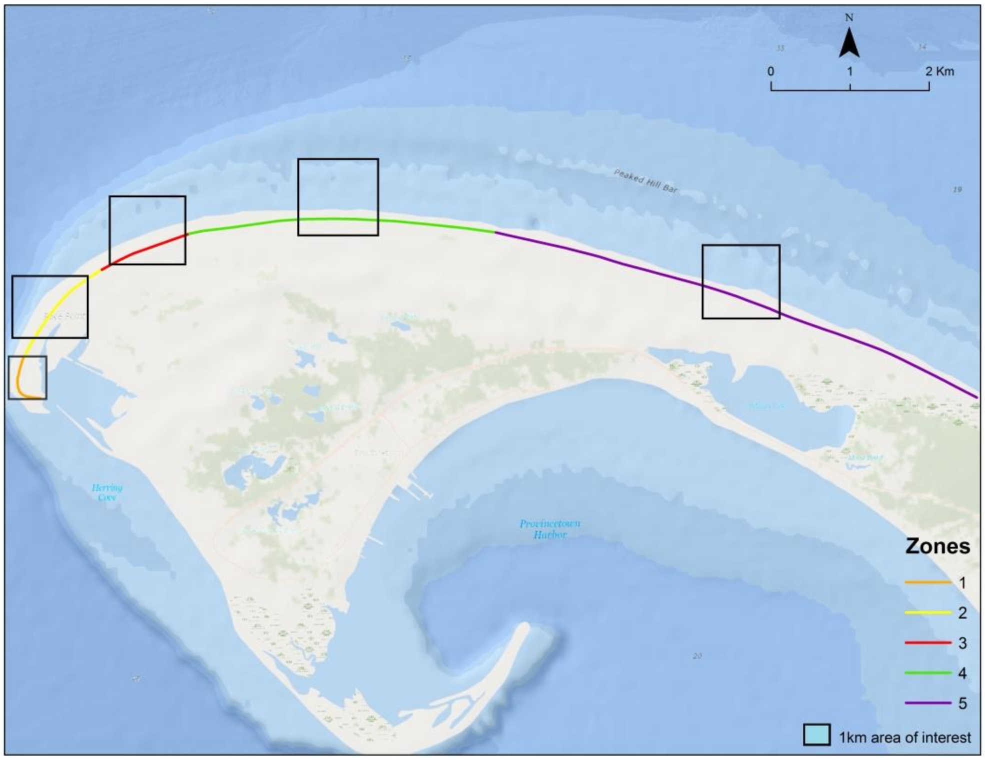

Figure 4: Areas of interest within the five shoreline zones.

DSAS Calculations

Digital Shoreline Analysis System (DSAS) version 4.3 was used to collect the data for each of the three shoreline features. DSAS is an ArcGIS extension created by the USGS for calculating shoreline change. In order to quantify changes in the positions of the three shoreline features, a baseline was drawn within 10 meters of the oldest dune line (1952) (Fletcher et al. 2003). The baseline was created following the recommendations provided in the Digital

Shoreline Analysis System (DSAS) Guidelines, where each segment must be placed entirely offshore or onshore (in this case, onshore) and parallel to the shorelines (Thieler et al. 2009).

Transects for each AOI in each zone were cast onshore at 50m spacing (20 transects per AOI) at a length of 1,000m to make certain that the permanent storm bar, Peaked Hill Bar, was included in the calculations. The intersection parameter was set for farthest intersection. Choosing farthest intersection instructs DSAS to use the last intersection between transect and shoreline measurement location when calculating change statistics. The casting method was a smoothed baseline cast, which is used to orient transects along curved sections of the baseline. Finally, the uncertainty value for the calculations was left at default as +/- 4.4m.

DSAS uses the baseline to calculate rate of change statistics for a time series of shorelines (Himmelstoss, 2009; Thieler et al. 2009). DSAS computes the shoreline rates of change using four methods: end point rate, simple linear regression, weighted linear regression and least median squares (Thieler and Danforth, 1994; Brass, 2009; Thieler et al. 2009). The goal of this software is to facilitate the shoreline change calculation process and to provide rate of change information and the statistical data necessary in order to establish the reliability of the calculated results.

The calculations performed with DSAS were:

- End Point Rate (EPR): calculates the rate of change between the oldest and most recent shoreline by dividing the distance between them by the years elapsed between the two. Its major advantage is the ease of computation and minimal requirement of only two shorelines (Thieler et al., 2009). The major disadvantage of this calculation is that it ignores additional information when more data is available. This may cause that changes of erosion or accretion magnitude or cyclical trends may be missed (Thieler et al., 2009).

- Shoreline Change Envelope (SCE): is the distance between the shoreline farthest from and closest to the baseline at each transect. This calculation represents the total change in shoreline movement for all available shoreline positions regardless of their dates.
- Net Shoreline Movement (NSM): it reports the total distance between the oldest and most recent shoreline for each transect.

Chapter 5: Results

Decadal Study: 1952-2012: Relationship between variables

In Zone 1, both the shoreline and duneline experienced erosion along the south-facing shoreline (as the spit curves) while transects that face west and northwest experienced accretion, although at different rates (figure 5). Transect 2, 4 and 9 are outliers in this area. Transects 2 and 9 showed higher accretion rate at the duneline, while transect 4 showed lower erosion rate at the duneline.

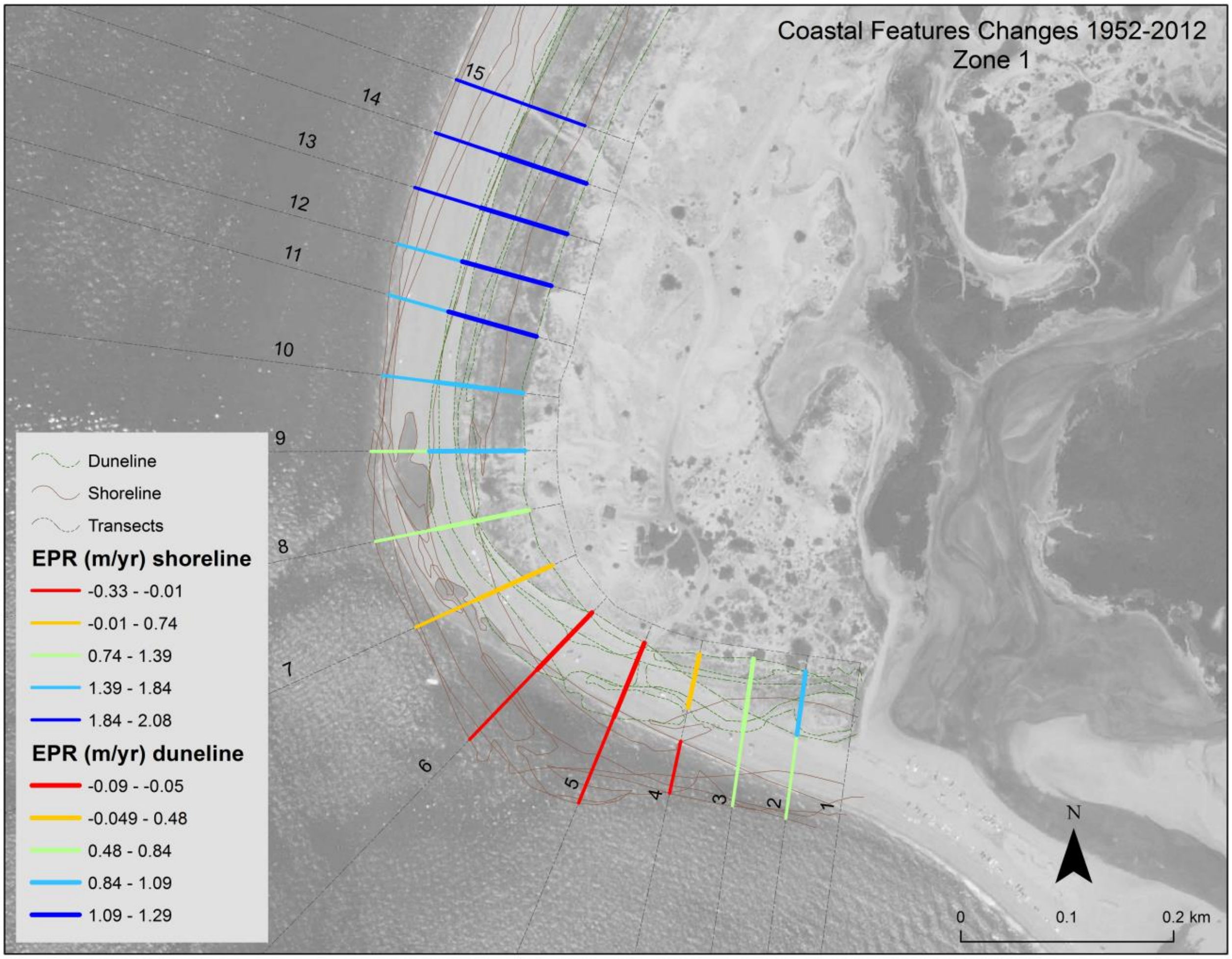

Figure 5: Relationship between variables at zone 1. Reds indicate erosion, while blues indicated accretion.

At Zone 2, both variables in this AOI showed accretion in all 19 transects. Transects 15 to 18 showed the most accretion with an accretion rate of more than 2.13 m/yr. Transects 9 to 12 show a higher accretion rate at the duneline than at the shoreline. Transects 19 to 22 showed higher accretion rate at the shoreline than at the duneline.

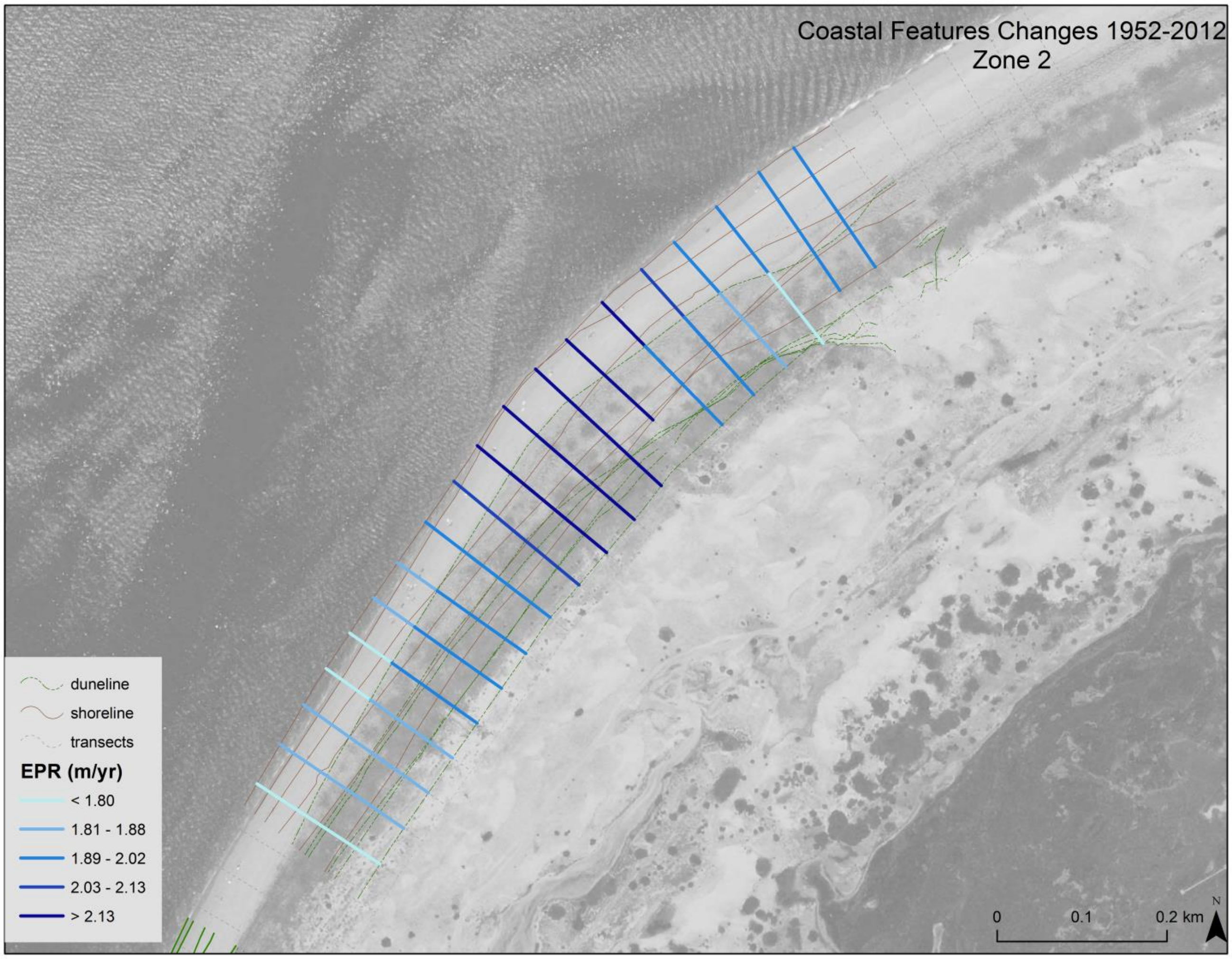

Figure 6: Relationship between variables at zone 2. Reds indicate erosion, while blues indicated accretion.

In zone 3, all variables in this AOI showed accretion. Transects 10 to 15 showed the highest rate of accretion for both the duneline and the shoreline, while the bars show the lowest rate of movement closer to the shoreline, which means that the bars in this area are at their farthest point from the shoreline. Transects 20 to 24 show the lowest accretion rate for the shoreline, while the nearshore bars are at their closest point from the shoreline. The lowest accretion rate at the duneline was in transects 5 and 6.

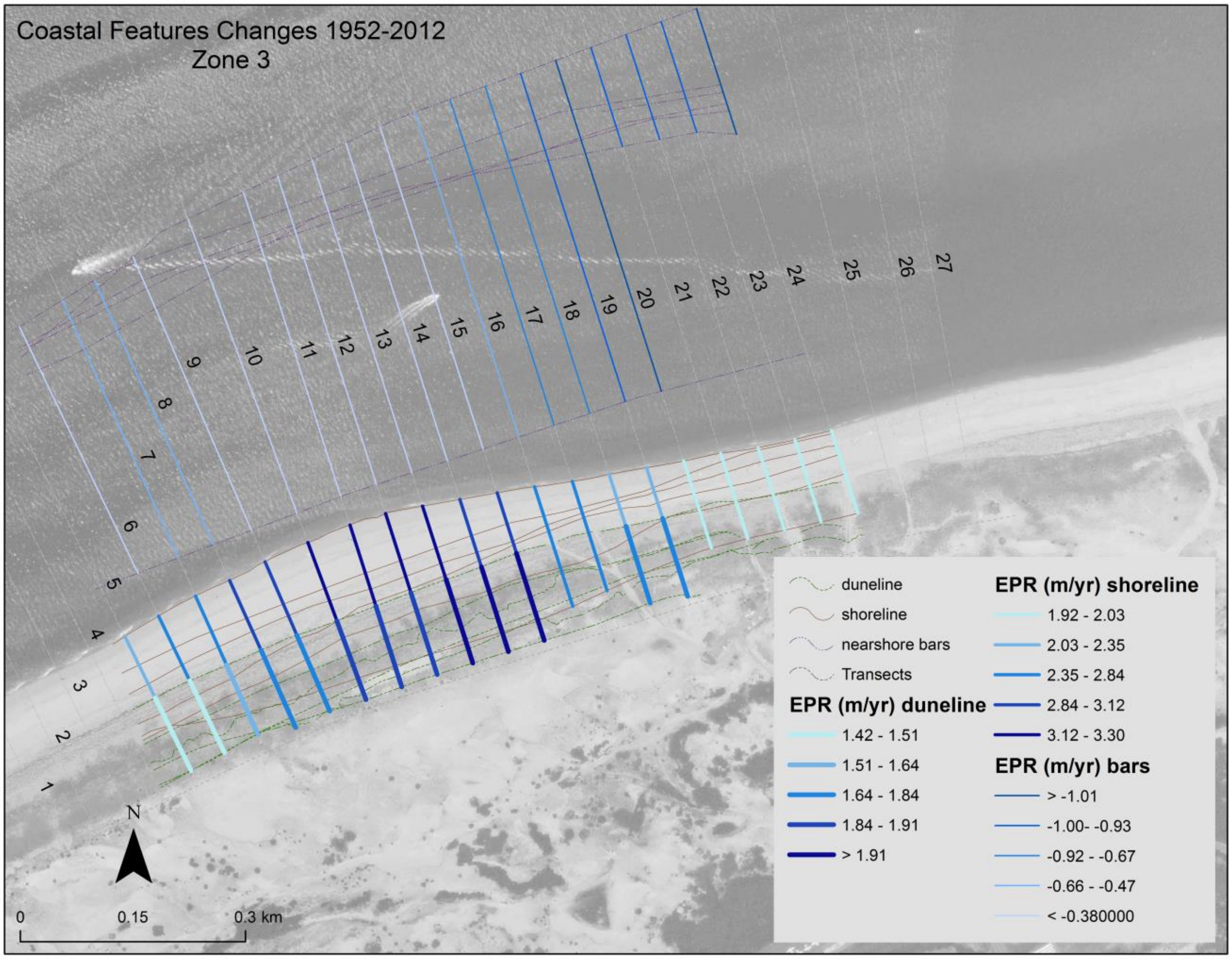

Figure 7: Relationship between variables at zone 3. Reds indicate erosion, while blues indicated accretion.

In zone 4, the shoreline and duneline show erosion along the entire AOI. Transects 31 to 33 show the lowest erosion rates for the duneline with -0.20 m/yr or less, while at this point the nearshore bars are at their closest point from the shoreline. Transects 41 to 43 show the lowest erosion rate for the shoreline, at this point the nearshore bars are at their farthest point from the shoreline. Transects 43 to 48 show the highest erosion rate for the duneline, while 46 to 48 also show the highest erosion rate for the shoreline.

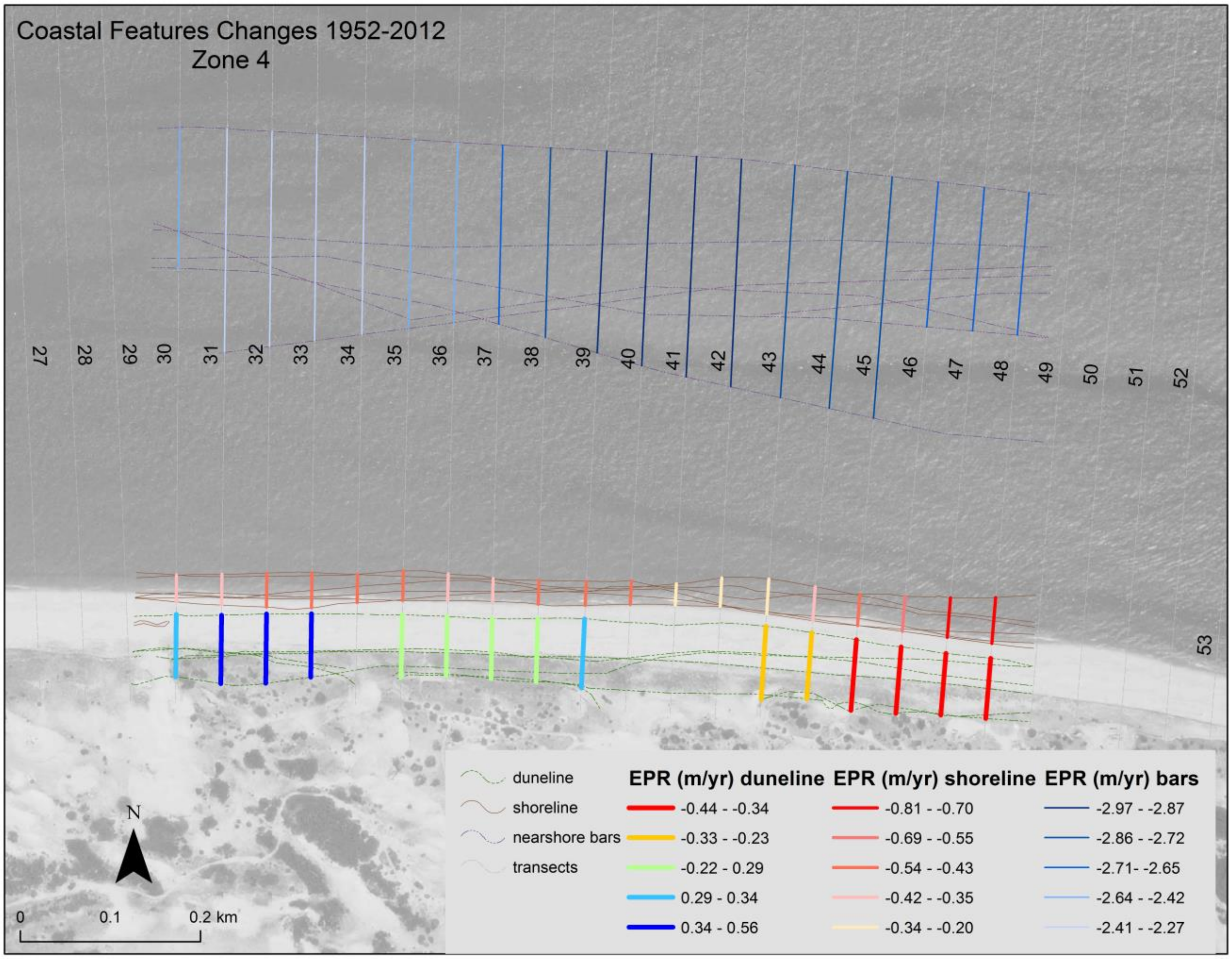

Figure 8: Relationship between variables at zone 4. Reds indicate erosion, while blues indicated accretion.

Zone 5 transects showed erosion for both the shoreline and the duneline. Transects 56 to 59 showed the lowest erosion rates for the duneline, while transects 73 and 74 showed the highest erosion rates. Transects 61 to 63 showed the highest erosion rate for the shoreline, while transects 73 and 74 had the lowest erosion rate. When looking at the nearshore bars transects 64-68 show the bars at their farthest point from the shoreline, while to the east and west of those transects the bars are at their closest point to it.

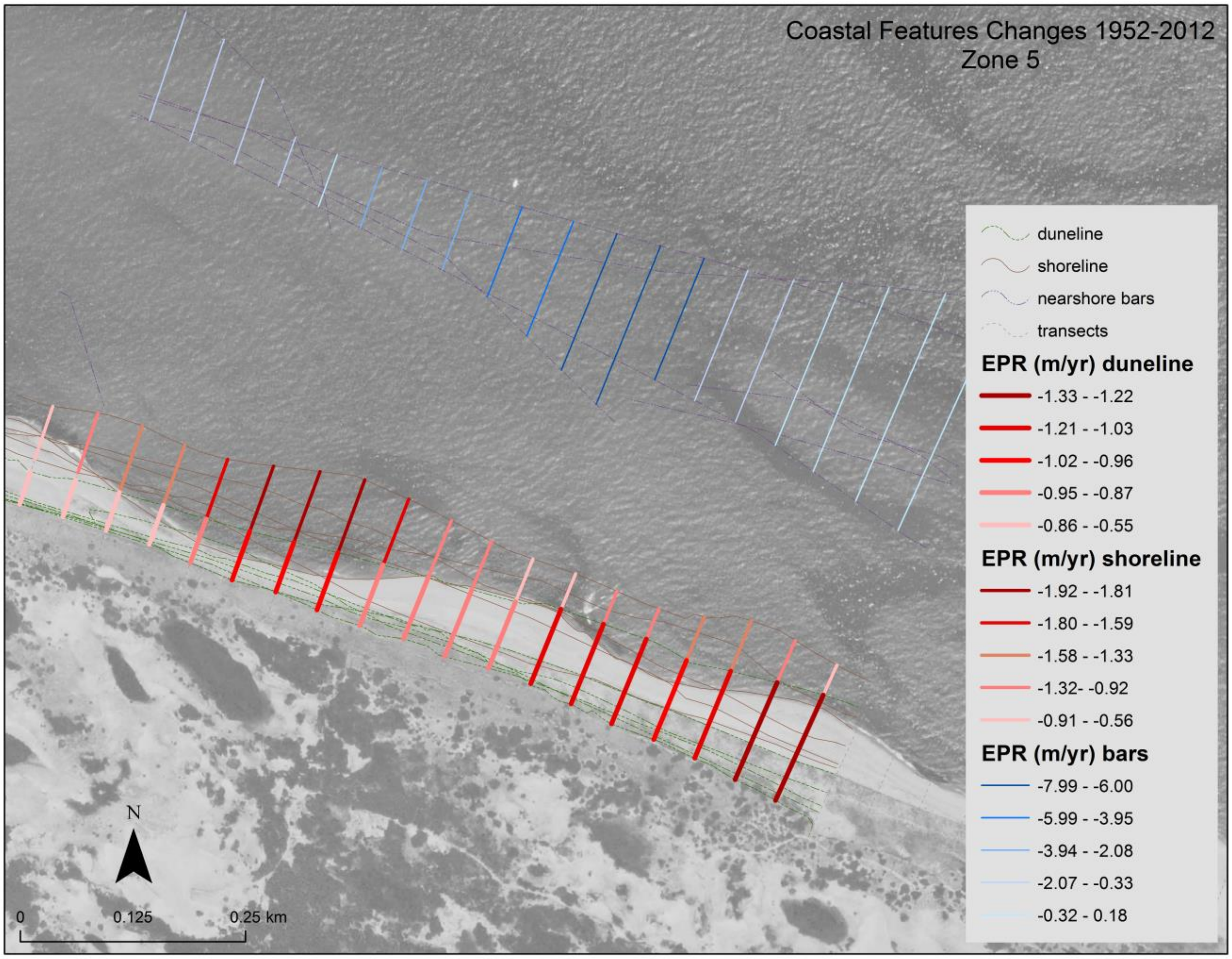

Figure 5: Relationship between variables at zone 5. Reds indicate erosion, while blues indicated accretion.

DSAS results for the period showed that zones 1, 2 and 3 showed significant shoreline accretion while zones 4 and 5 showed erosion. Table 6 shows the net shoreline movement and shoreline change envelope for each shoreline. Between 1952 and 2012 zone 1 accreted 1.168 m/yr, a total of 70 meters. Zone 2 accreted 122 meters, with an EPR of 2.037 m/yr. Zone 3 accreted 2.626 m/yr, about 157 meters between 1952 to 2012. Zone 4, on the other hand eroded almost 27 meters in a 60 year period at a rate of 0.455 m/yr. Zone 5 also showed erosion, between 1952 and 2012 the shoreline eroded 75 meters at a rate of 1.247 m/yr.

The results for duneline changes showed accretion for all areas of interest except for zone 5 which showed erosion. As described in table 6 the duneline accreted 48 meters in zone 1 at a rate 0.810 m/yr and zone 2 showed approximately 125 meters of growth at a rate of 2.083 meters. Zone 3 accreted at a rate of 1.802 m/yr a total of 108 meters in the 60 year period, while zone 4 showed the lowest accretion rate at 0.09 m/yr which amounts to almost 5 meters between 1952 and 2012.

Nearshore bars were identified only in zones 3, 4 and 5. In all cases DSAS results showed the bars moving closer to the shoreline between the years studied. The bars in zone 3, which are located parallel to the shoreline, moved 0.64 m/yr, about 37 meters between 1952 and 2012. At zone 4 the bars showed the highest movement rate, 2.639 m/yr, a total of 158 meters in the 60 year period studied. The bars at zone 5 also showed a significant movement rate at 2.092 m/yr, moving approximately 57 meters closer to the shoreline.

Table 6. Average changes by zone for the period 1952-2012.

	EPR (meters/yr)	NSM (meters)	SCE (meters)
Shoreline			
Zone 1	1.168	70.006	103.394
Zone 2	2.037	122.108	140.334
Zone 3	2.626	157.432	157.432
Zone 4	-0.445	-26.738	33.737
Zone 5	-1.247	-74.76	103.528
Duneline			
Zone 1	0.810	48.472	77.954
Zone 2	2.083	124.840	125.394
Zone 3	1.802	107.958	111.751
Zone 4	0.099	4.669	72.413
Zone 5	-2.092	-56.34	76.221
Nearshore Bars			
Zone 1*	----	----	----
Zone 2*	----	----	----
Zone 3	-0.645	-36.832	352.260
Zone 4	-2.639	158.149	214.774
Zone 5	-2.092	-56.998	143.111

**No nearshore bars where identified in zones 1 and 2.*

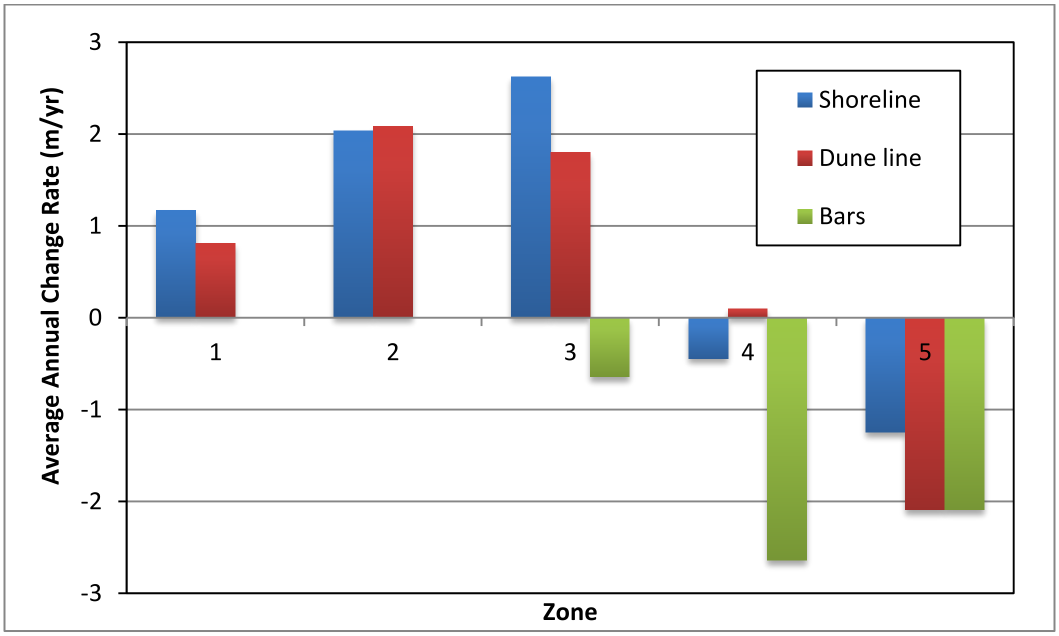

Figure 10: Comparison between average annual change rate of the shoreline duneline and nearshore bars.

ANOVA: Accounting for orientation

A one-way ANOVA analysis was conducted to determine if orientation plays a significant role in the changes present in the coastal variables. One-way ANOVA analysis is useful for determining significant differences in means scores on the dependent variable exist across two or more groups. The assumptions of analysis of variance are: observations between and within samples are random and independent, the observations in each category are normally distributed and/or the population variances are assumed equal for each category. There were six dependent variables in this analysis: shoreline change, duneline change, nearshore bar, beach width, dune-bar distance and shoreline-bar distance. The independent variable was the zone number. For this analysis the null hypothesis states that there is no difference between the variables due to orientation.

The data did not meet the assumption of homogeneity because it had a significance value higher than 0.05 (table 7). The assumption of homoscedasticity uses the Levene's test to state that the variances of the responses could be equal if the significance is greater than 0.05 and that only a sampling variation was observed. Since the data violated the assumption it is said to be robust and therefore instead of looking at the ANOVA significance values (table 8) it was necessary to look at the Robust Test of Equality of Means (table 9).

The ANOVA results showed that the variables of shoreline change, duneline change, beach width, dune-bar distance and shoreline bar distance had significant ($p < 0.001$) F values which means that in those cases the null hypothesis was rejected and that there is a difference between the variables based on orientation. The only variable that did not have a significant result was nearshore bar change; its F value significance was .783.

Table 7. Test of Homogeneity of Variances: 1952-2012

Variables	Levene statistic	df1	df2	Sig.
Shoreline Change	40.816	4	375	.000
Duneline Change	3.782	4	375	.005
Bar Change	19.940	2	198	.000
Beach Width	.569	4	451	.685
Shoreline-bar distance	22.071	2	243	.000
Dune-bar distance	14.764	2	243	.000

Table 8. ANOVA results: long term study

Variables	Sum of squares	df	Mean Square	F	Sig.
Shoreline Change					
Between groups	132306.77	4	33076.69	31.275	.000
Within groups	396601.32	375	1057.604		
Total	528908.09	379			
Duneline Change					
Between groups	74208.592	4	18552.45	18.673	.000
Within groups	372575.07	375	9993.534		
Total	446783.66	379			
Bar Change					
Between groups	11849.50	2	5924.747	.245	.783
Within groups	4793596.4	198	24210.08		
Total	4805445.9	200			
Beach Width					
Between groups	15930.802	4	3982.700	5.233	.000
Within groups	343273.68	451	761.139		
Total	359204.49	455			
Shoreline-bar distance					
Between groups	338606.53	2	169303.3	15.459	.000
Within groups	2661219.5	243	10951.52		
Total	2999826.1	245			
Dune-bar distance					
Between groups	399224.26	2	199612.1	20.041	.000
Within groups	2420281.9	243	9960.008		
Total	2819506.2	245			

Table 9. Robust test of equality means: 1952-2012

Variables	Statistic	df	df2	Sig.
Shoreline Change				
Welch	70.055	4	177.664	.000
Brown-Forsythe	35.001	4	243.118	.000
Duneline Change				
Welch	20.792	4	181.134	.000
Brown-Forsythe	18.665	4	324.919	.000
Bar Change				
Welch	.240	2	116.464	.787
Brown-Forsythe	.226	2	93.250	.798
Beach Width				
Welch	5.399	4	218.788	.000
Brown-Forsythe	5.269	4		.000
Shoreline-bar distance				
Welch	8.887	2	139.921	.000
Brown-Forsythe	14.025	2	129.736	.000
Dune-bar distance				
Between groups	12.309	2	144.396	.000
Within groups	18.428	2	142.878	.000

Short term scale study: 2001-2012: Relationship between variables

The duneline in zone 1 shows significant erosion between transects 5 to 8. The shoreline shows the highest erosion rate at transect 5. The shoreline has accreted from transects 7 to 15. The shoreline at transects 2 to 5 shows significant erosion, while transects 11 to 15 show the highest rate of accretion.

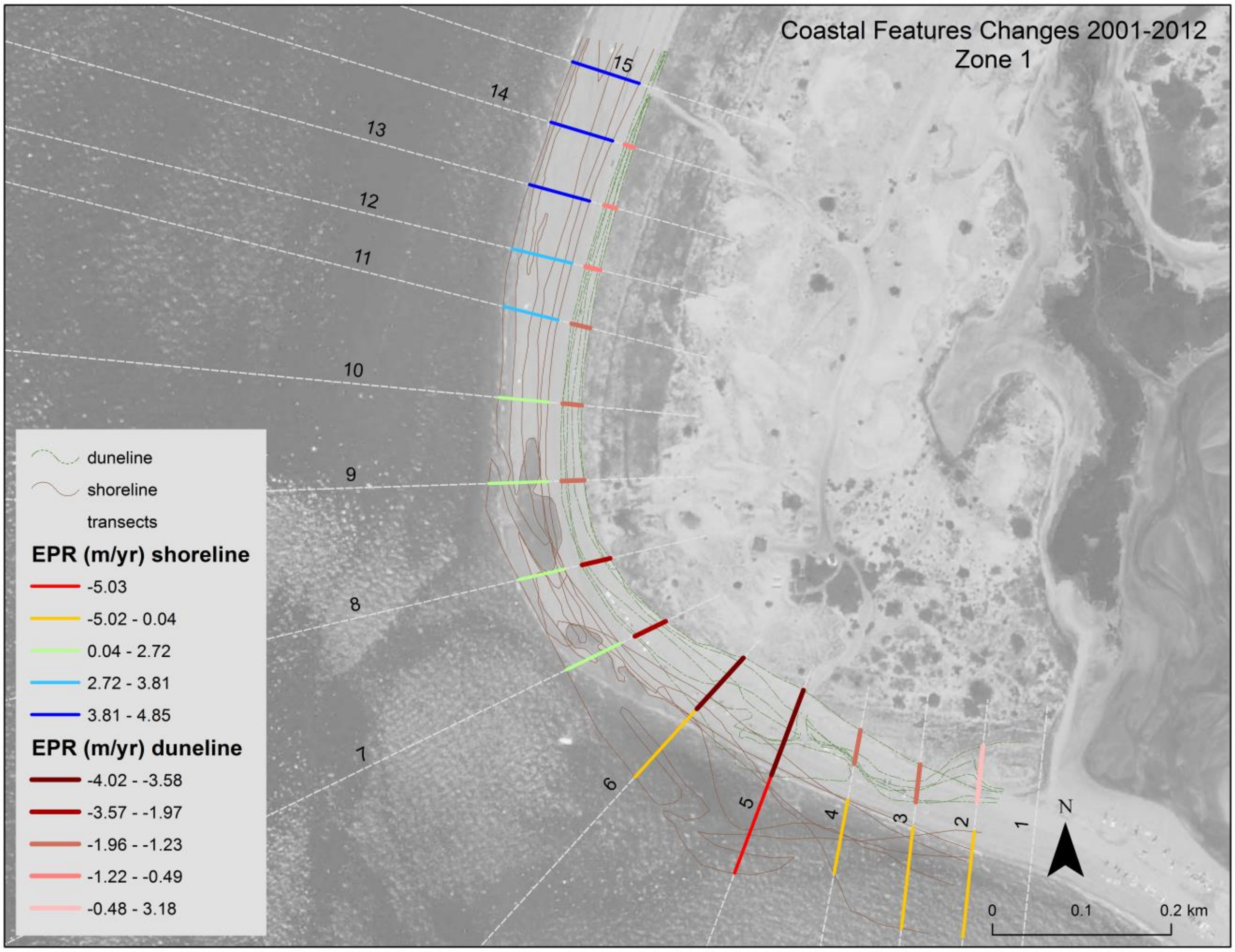

Figure 6: Relationship between variables at zone 1. Reds indicate erosion, while blues indicated accretion.

In zone 2, the shoreline and duneline at zone 2 both show accretion. Transects 9 to 22 show the duneline with a high rate accretion rate of more than 3 m/yr. As for the shoreline significant accretion rates of more than 3 m/yr are only found in transects 22 and 23. Transects 5 to 11 have the lowest accretion rates for the shoreline. In this AOI the duneline is accreting at a higher rate than the shoreline.

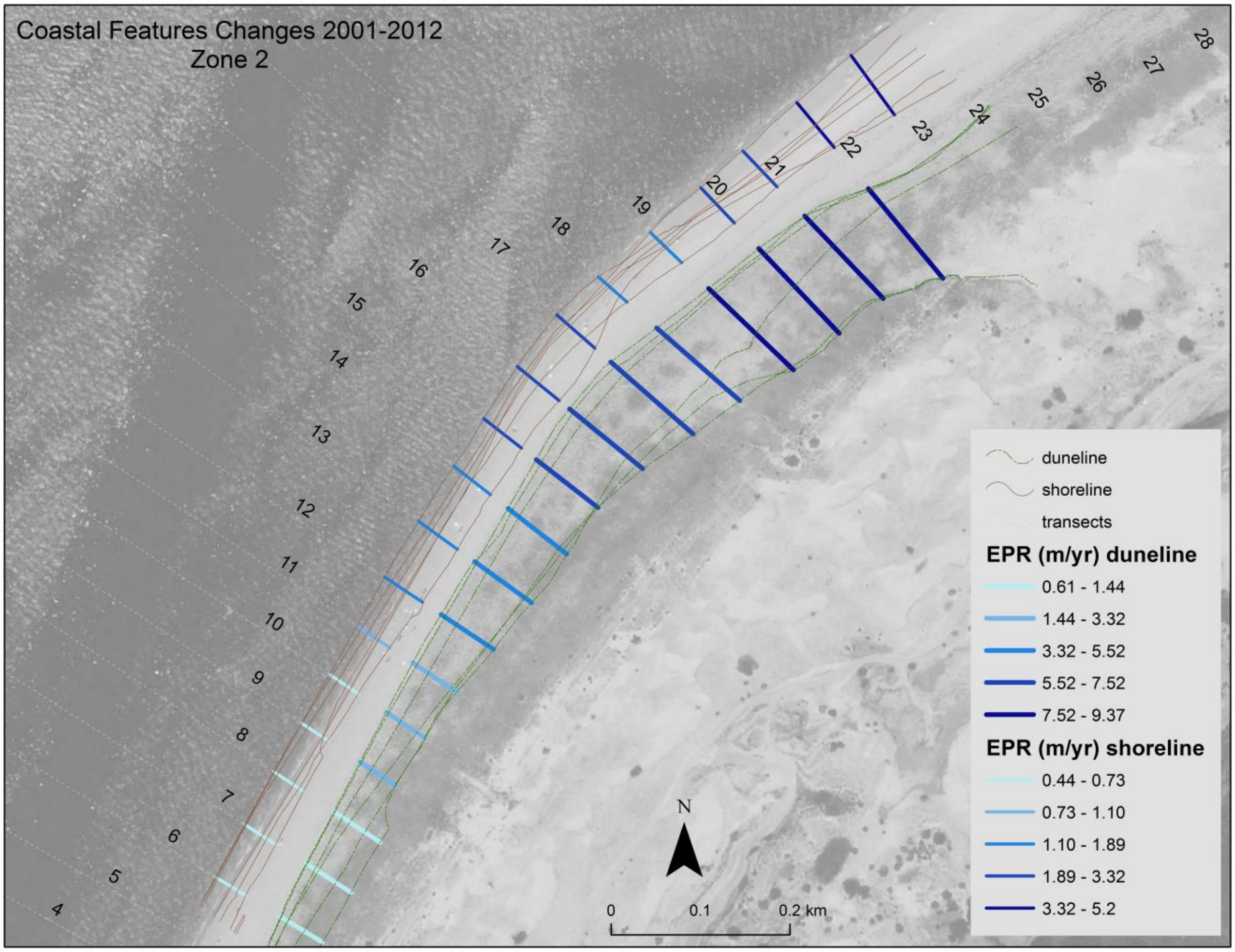

Figure 7: Relationship between variables at zone 2. Reds indicate erosion, while blues indicated accretion.

Both the shoreline and duneline at zone 3 show accretion. The transects to the east, 5 to 15, show the highest accretion rate for both variables at more than 5.71 m/yr. At this particular site the nearshore bars are at their closest point to the shoreline. The lowest accretion rate for the duneline is between transects 18 to 20 at less than 2.5 m/yr while the lowest accretion rate for the shoreline extends from transect 19 to 24. This area of low accretion for the shoreline and duneline corresponds to the area where the nearshore bars are at their farthest pint from the shoreline.

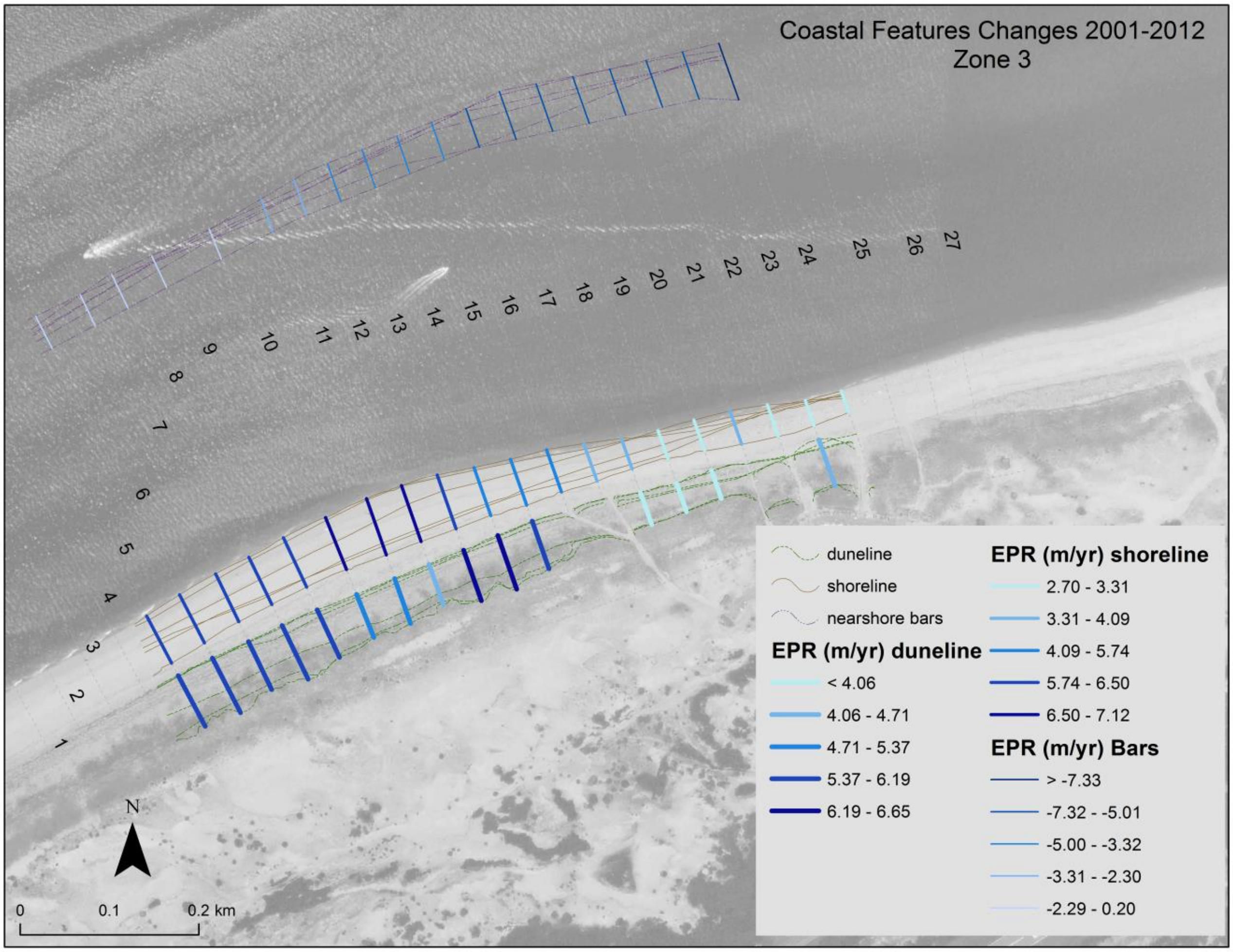

Figure 8: Relationship between variables at zone 3. Reds indicate erosion, while blues indicated accretion.

Zone 4 presents a different pattern from the other areas. In this case the duneline and shoreline rates of erosion and accretion are opposite. To the east of the study area, transects 30 to 37, the duneline presents erosion, while the shoreline presents the highest accretion rates for the entire AOI. The nearshore bars in this area, which are characterized by a crescent shape, are at their farthest point from the shoreline. While to the west of the study area, transects 42 to 48, the shoreline presents the erosion rates between 0.16 to 0.45 m/yr while the duneline is accreting between 0.53 to 1.63 m/yr. The bars in the western part of the shoreline are at their closest point to the shoreline.

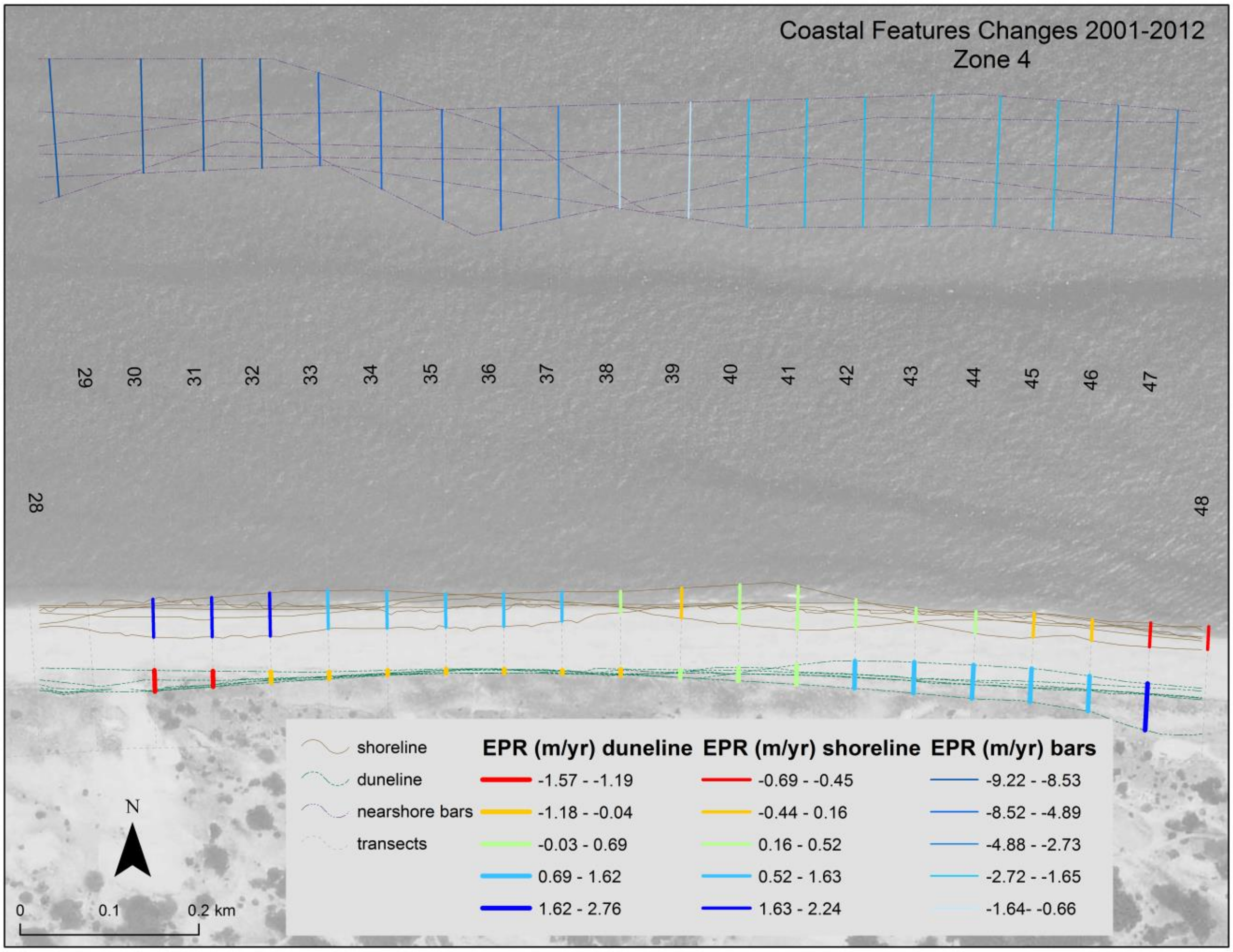

Figure 9: Relationship between variables at zone 4. Reds indicate erosion, while blues indicated accretion.

Zone 5 has the most interesting pattern of all the study area. The shoreline is characterized by a series of cusps separated by very narrow concave beach segments. Therefore the shoreline shows high accretion rates were the cusps are present (transects 56-57, 65-68, 74) and high erosion rates in the concave spaces in between. The duneline on the other hand shows high erosion rates in the eastern part of the AOI regardless of the presence of cusps or not, although the highest erosion rates are found in transects 60 and 61 were the beach is at its most narrow point. To the west of the AOI the duneline shows high accretion rates even though the shoreline show some of its highest erosion spots between transects 69 and 72. The nearshore bars in this have an “S” shape and overall they seem to be moving closer to the shoreline the farther west they move.

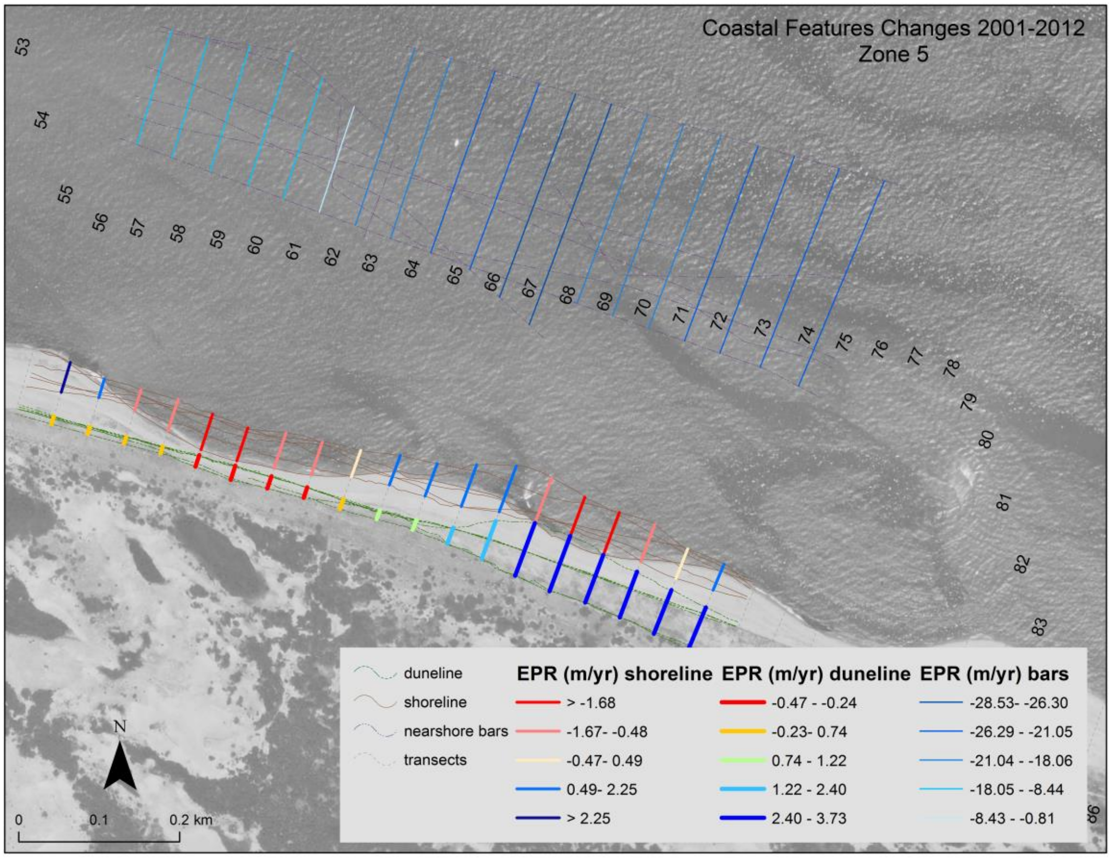

Figure 10: Relationship between variables at zone 5. Reds indicate erosion, while blues indicated accretion.

DSAS results for the short term study show accretion in all AOIs shorelines from 2001 to 2012. As table 7 shows, zone 1 accreted 16 meters at a rate of 1.46 m/yr. The shoreline at zone 2 accreted approximately 23 meters at a rate of 2.026 m/yr. Zone 3 showed the highest accretion rate at 5.08 m/yr, growing about 57 meters in the 10 year period studied. The shoreline at zone 4 accreted approximately 9 meters at rate of 0.805 m/yr. Zone 5 showed the lowest accretion rate in the entire study area with a rate 0.056 m/yr, a total growth of less than a meter.

The duneline for the short term study show erosion only at zone 1, while zones 2, 3, 4 and 5 show accretion. The duneline at zone 1 receded approximately 16 meters at a rate of 1.31 m/yr. At zone 2, the duneline shows the highest accretion rate of 5.338 m/yr, growing 60 meters in a ten year period. Zone 3 has similar numbers, with the duneline accreted also 60 meters at a slightly lower rate of 5.299 m/yr. Zone 4 has the lowest accretion rate at 0.263 m/yr, growing just about 3 meters between 2001-2012.

As it happened with the long term study nearshore bars were only identified in zones 3, 4 and 5. In all three AOIs the bars appear to be moving closer to the shoreline. The bars at zone 3 is moving at a rate of 3.605 m/yr. The bars located at zone 4 moved at a rate of 4.341 m/yr, while the bars at zone 5 have moved at the highest rate of 17.213 m/yr.

Table 10. DSAS results 2001-2012. (Results were averaged)

	EPR (meters per year)	NSM (meters)	SCE (meters)
Shoreline			
Zone 1	1.458	16.322	62.676
Zone 2	2.026	22.761	22.761
Zone 3	5.080	57.105	60.255
Zone 4	0.805	8.981	26.358
Zone 5	0.056	0.626	47.789
Duneline			
Zone 1	-1.318	-15.7	28.749
Zone 2	5.338	60.106	60.106
Zone 3	5.299	59.607	60.007
Zone 4	0.263	2.967	15.455
Zone 5	1.525	17.286	33.641
Nearshore Bars			
Zone 1	----	----	----
Zone 2	----	----	----
Zone 3	-3.605	-39.674	57.084
Zone 4	-4.341	-37.884	102.256
Zone 5	-17.213	-18.465	47.950

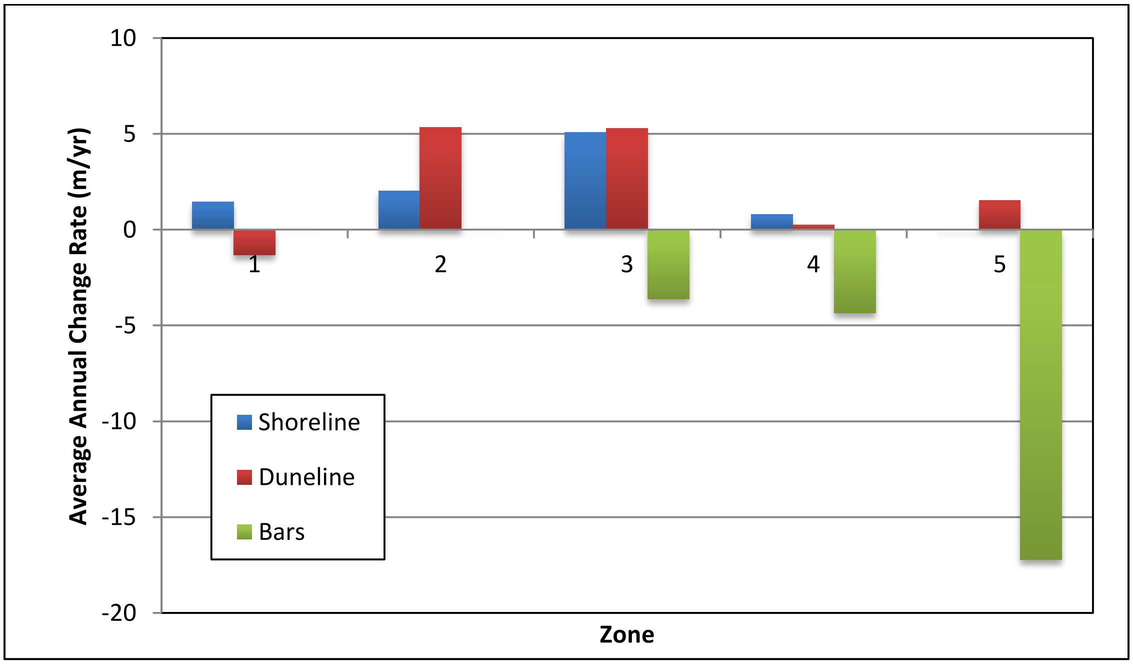

Figure 16: Comparison between variable changes

ANOVA: Accounting for orientation

As it occurred with the long-term data, the short-term data did not meet the assumption of homogeneity because the variables had a significance value higher than 0.05 (table 12). Since the data violated the assumption it is said to be robust and therefore instead of looking at the ANOVA significance values (table 13) it was necessary to look at the Robust Test of Equality of Means (table 14).

The ANOVA results showed that all variables, shoreline change, duneline change, bar change, beach width, dune-bar distance and shoreline bar distance had significant ($p < 0.001$) F values which means that in those cases the null hypothesis was rejected and that there is a difference between the variables based on orientation.

Table 11. Test of Homogeneity of Variances: 2001-2012

Variables	**Levene statistic**	**df1**	**df2**	**Sig.**
Shoreline Change	23.978	4	435	.000
Duneline Change	13.745	4	400	.000
Bar Change	52.893	2	249	.000
Beach Width	14.520	4	481	.000
Shoreline-bar distance	34.842	2	291	.000
Dune-bar distance	45.065	2	326	.000

Table 12. ANOVA results: short term study

Variables	Sum of squares	df	Mean Square	F	Sig.
Shoreline Change					
Between groups	4483.555	4	1120.889	2.388	.000
Within groups	204216.04	435	469.462		
Total	208699.59	439			
Duneline Change					
Between groups	13476.727	4	3369.182	11.302	.000
Within groups	119242.755	400	298.107		
Total	132719.482	404			
Bar Change					
Between groups	31677.851	2	15838.92	.959	.385
Within groups	4110491.16	249	16507.99		
Total	4142169.01	251			
Beach Width					
Between groups	93086.397	4	23271.59	19.877	.000
Within groups	563135.993	481	1170.761		
Total	656222.390	485			
Shoreline-bar distance					
Between groups	608340.11	2	304170.0	79.893	.000
Within groups	1107900.73	291	3807.219		
Total	1716240.84	293			
Dune-bar distance					
Between groups	423524.644	2	211762.3	53.069	.000
Within groups	1300855.83	326	3990.355		
Total	1724380.48	328			

Table 13. Robust test of equality means: 2001-2012

Variables	Statistic	df	df2	Sig.
Shoreline Change				
Welch	5.636	4	196.985	.000
Brown-Forsythe	2.083	4	200.967	.084
Duneline Change				
Welch	12.914	4	184.191	.000
Brown-Forsythe	11.613	4	333.315	.000
Bar Change				
Welch	.623	2	144.240	.538
Brown-Forsythe	.934	2	92.417	.397
Beach Width				
Welch	24.662	4	222.481	.000
Brown-Forsythe	18.977	4	286.442	.000
Shoreline-bar distance				
Welch	175.550	2	180.106	.000
Brown-Forsythe	82.260	2	175.282	.000
Dune-bar distance				
Between groups	107.765	2	192.056	.000
Within groups	49.233	2	166.205	.000

Chapter 6: Discussion

Relationship between variables

Results show that Province Lands coastal features are extremely dynamic. No clear decadal patterns that explain the coastal features behavior could be identified. Each zone dynamics differ from one another and the dynamics within each zone, at the 1km AOI, varied greatly.

Each zone showed a different pattern when looking at the interactions between the shoreline, dune and nearshore bars. Zone 1 showed accretion in both variables, dunes and shoreline in the northern transects and erosion in the southern transects (figure 5). This is an interesting case due to the fact that the alongshore current in this area moves from north to south (Fisher and Leatherman, 1987). It would be expected that more sediment is lost in the northern part of the AOI and being deposited in the southern end of the spit. It could be possible that the current is stronger in that area and its moving the sediment further south into Provincetown Harbor or nearby areas.

Zones 2 and 3 both show accretion in the shoreline and duneline. The variables appear to be also accreting at very similar rates. Also these two areas of interest have the widest beaches in the study area with mean widths of 70.68 and 77.79 meters (figure 17) respectively. In zone 3, where parallel nearshore bars are first identified, the areas that show higher accretion rates in both variables are areas where the nearshore bars are moving closer to the shoreline (figures 18 and 19). Therefore it is possible that the bars in this area are protecting the shoreline from the predominant waves from the north- north east. This type is characterized by large fordunes with high potential of aeolian transport and parallel bars.

Zone 4 on the other hand shows that the shoreline and duneline are eroding at similar rates, especially the transects to the west. The bars in this area are crescentic. To the east of the study area where the bars are closer to the shoreline, the erosion rates for the duneline and shoreline are lowest than to the west where the bars are farther away from the shoreline (figure 8 and 14). Zone 5 also shows the shoreline and duneline eroding, with the duneline eroding at a higher rate than the shoreline, this patterns is consistent across the AOI regardless of the proximity of the nearshore bars. This zone also had the narrowest beach in the study area with a width 60.79 meters.

Similar dynamics where observed in the short-term study. The short-term study showed some interesting results when looking at the interactions between the variables. In some instances the patterns observed between the variables in the short-term study differ from those observed in the decadal study.

Zone 1 showed the shoreline accreting to the north and eroding to the south, as it did in the decadal study (figure 11). The duneline on the other hand is accreting at a lower rate, than the decadal study suggested, and in some transects showing erosion at rate between 1 and 2.99 m/yr.

The AOI at zone 2 showed both variables, shoreline and duneline, accreting, same pattern as the long-term study. This time though, duneline is accreting at a rate of 5.338 m/yr much faster than the shoreline rate of 2.026 m/yr. Zone 3 also shows similar accretion patterns as the decadal study with the transects to the west accreting at a lower rate than those to the east. The nearshore bars also have behaved in a similar fashion. Transects to the east shows the bars at their closest point to the shoreline while the transects to the west have the bars at their farthest point from the shoreline.

Zone 4 has some different patterns in the short-term study, not present in the decadal study. While in the long-term study both variables were eroding along the AOI, the short-term analysis shows some areas of accretion in the shoreline and duneline. The shoreline is accreting to the east, between transects 30 to 37 (figure 14). It is especially interesting that transects 30 and 31 show the point of highest accretion rate in the shoreline, while they are also the points with the highest erosion rate for the duneline. To the east of the AOI the patterns invert, with transects 45 to 47 showing the highest erosion rate for the shoreline while at this same point the duneline has its highest accretion rate. These differences may be due to a time lag component, the duneline recovers or destabilizes at a slower rate than the shoreline. The nearshore bar patterns are similar to those in the decadal study were the transects to the west are at their closest point to the shoreline while the transects to the east are at their farthest point from the shoreline.

Finally, zone 5 also shows different patterns of interactions between the variables between the two studies. While the long term study showed both variables eroding, the short term study shows some areas of accretion in both the shoreline and duneline. The cusps areas observed in figure 15 show accretion, while the concave areas in between show erosion. The duneline shows erosion to the west of the AOI and high rates of accretion in the transects to the east. The nearshore bars also show a somewhat different pattern with the transects located to the east being at their closest point to the shoreline.

This short term study during the 2001-2012 decade, also shows that the Province Lands coast follows expected spit dynamics with zone 5 and 1 showing erosion while zones 2, 3 and 4 show accretion. Some interesting results are that although zone 4 is oriented directly north where it is subject to receive strong wave action, the presence of crescent shape bars are protecting the shoreline and duneline. Another interesting result is that once again, just as it happened in the decadal study, the duneline in zone 5 shows accretion while the shoreline erodes.

Coastal Storms

One of the problems with the kind of analysis presented here is that it is difficult to relate the observed morphological changes to the factors that produce them. The coastal features in question respond to wave and wind processes that may have produced the observed landform changes within days prior to the photographic surveys, or within a year or two. One way of determining what factors may be responsible for the landform responses is to examine weather records for the intervals between the aerial surveys. The record for strong nor'easters found for this study only went back as far as 1985. For the long-term study it was found that 16 hurricanes or tropical systems and 6 major snow storms or nor'easters affected the region between 1985 and 2012 including Hurricane Bob, strongest hurricane to hit the Northeast since 1960, the "Perfect Storm" 1991 (10 weeks apart between the hurricane and the nor'easter) and "The Storm of the Century" 1993. These events, summarized in table 15 caused high winds and strong storm surge that affected millions of dollars in damage and severe coastal erosion in Massachusetts.

Although no specific details were found on the extent of damages to the coastal area of Province Lands, it is imperative to understand that the frequency of occurrence of these atmospheric events and their strength play an important role on the dynamics of this coastal region. These events cause significant beach and dune erosion, as well as changing the normal movement of the nearshore bars, even creating temporal storm bars (Houser and Greenwood, 2007).

Table 14. Important atmospheric events between 1950-2012

Year	Name	Details
1985	Strong cold front	A strong cold front generated 17 tornadoes across the Northeast and 100mph+ winds across the region.
1985	Hurricane Gloria	Category 2 hurricane, although it did not make landfall in Massachusetts, generated 90-120mph winds and significant storm surge.
1991	Hurricane Bob	Category 2 hurricane and first to make landfall in New England since 1960. In Massachusetts, 150mph gusts were registered and sustained winds of more than 100mph. In the Cape the airport anemometers registered 1 minute of 110mph sustained winds. It generated storm surge between 6-12ft above normal.
1991	Hurricane Grace/Henri	Category 1 hurricane generated wind gusts of 77mph over Cape Cod causing severe coastal erosion to an area that was already affected a few weeks before by Hurricane Bob.
1991	"Perfect Storm" / The Halloween Storm	A weak extratropical low combined with a strong cold front just 10 weeks after Hurricane Bob to generate strong winds and record breaking 15ft storm surge in the area for 3 days. Offshore waves heights varied between 40 to 70ft.
1992	"Downslope Nor'easter"	A category 2 in the Kocin-Uccellini Northeast Snowfall Impact Scale, this nor'easter caused heavy damage to the coast of Massachusetts due to a high surf up to 30ft.
1993	"Blizzard of 1993"/ "Superstorm" / "Storm of the Century"	For 3 days this nor'easter generated winds comparable to a category 4 hurricane and a storm surge between 8-12ft.
07/2001	Tropical Storm Allison	Passed south of the New England coast as a subtropical storm causing minor damages.
09/2002	Hurricane Gustave + non-tropical system	The interaction between these two systems caused strong winds that affected the coastal areas of New England.
09/2003	Hurricane Isabel	Caused strong surf in the New England area
10/2003	Remnants Hurricane Kate	The interactions between the hurricane and a high pressure area produce 1 meter surge.
08/2004	Tropical Storm Hermine	Made landafall near New Bedford, Massachusetts making minimal damage because of gusty winds.
08/2005	Remnants Hurricane Katrina	Caused wind damage across Vermont, New Hampshire and Massachusetts.
09/2005	Tropical Storm Ophelia	Brings to Massachusetts gusty winds and heavy rainfall.
07/2006	Tropical Storm Beryl	Made landfall on Nantucket generated 3m storm surge and gusty winds
11/2007	Hurricane Noel	Affected coastal Massachusetts as an extratropical hurricane with hurricane force wind gusts up to 89moh and sustained winds of 59mph. Cape Cod was also affected by heavy rainfall, high seas and coastal flooding.
08/2009	Hurricane Bill	Passed offshore of New England causing very heavy surf and gusty winds over coastal Massachusetts.
08/2009	Tropical Storm Danny	Passed over coastal Massachusetts as an extra tropical storm bringing gusty winds up to 60mph across the coast.
11/2009	Hurricane Ida	After affecting the northeast gulf coast as a tropical storm, it redeveloped of the coast of North Carolina as a strong nor'easter causing severe beach erosion and strong winds across New England area.
09/2010	Hurricane Earl	Passed 90 miles offshore, but still brought heavy rainfall, large waves and tropical storm force gusts to Cape Cod. Strongest wind gusts were recorded near Hyannis Massachusetts of 58 mph and sustained winds between 29-35 mph.

Effects of orientation

The ANOVA statistical analysis showed that orientation plays a significant role in the changes that occur in the coastal features, both within the groups and between the groups. Depending on the angle of orientation of each AOI the interactions between the variables differed. In zone 1, segment of the beach oriented south-west, both the dune and the shoreline present accretion. In this instance the shoreline is accreting at a faster rate than the duneline. Zone 2, oriented west-northwest, again both variables show accretion but this time the duneline is eroding at slightly faster rate than the shoreline. Zone 2 is characterized by having the widest beach in the area for the short-term study and 3rd widest in the long term study, with an average width of 82 meters and 70 meters respectively (figure 17).

Zone 3, oriented northwest, presents accretion at the shoreline and duneline, the shoreline accreting at a faster rate, while the bars move closer to the shoreline. As discussed previously this particular zone is characterized by parallel bars, that exert some amount of protection against strong waves or swells during high wind events or storms. Zone 3 1km AOI is also the 2nd widest beach in the system in the short-term study and the widest in the long term study, with an average width of 70 meters and 77 meters respectively (figure 17). The distance between the dune and bars and beach and bars only varied slightly between the long and short-term study (figures 18 and 19). Figure 18 shows that the duneline and bars at zone 3 more distant from each other than those in zone 4 and 5. Same situation is showed in figure 19 where the shoreline and the bars have a distance between them of approximately 464 meters.

Zone 4, characterized my crescentic bars and oriented directly north, shows significant erosion in the shoreline, while there is accretion in the duneline. The bars in this area are also moving closer to the shoreline. For the long-term study, this AOI presented the 2nd widest beach with 72 meters while in the short-term study it is the narrowest beach in the study with 45 meters (figure 17). The bars at this area where at their closest point from the shoreline and duneline than at any other area (figure 18 and 19). The half-moon shape of the cresentic bars may be contributing to the different dynamics identified in this area, sometimes interfering with the alongshore currents that supply sediment to the beach.

Finally, zone 5, oriented to the northeast, presents erosion in both the shoreline and duneline, while the bars are also moving closer to the shoreline. The long-term study showed this area as being the narrowest in Province Lands with 60 meters, while the short term width only varied 4 meters of accretion (figure 17). This zone is characterized by erratic "S" shape bars difficult to identify in some instances and that in particular occasions seem to be attached to the shoreline. Again, as discussed in zone 4, the proximity of these bars to the shoreline, may be affecting the continuous flow of alongshore sediment in the area, cutting the sediment supply received by the beach.

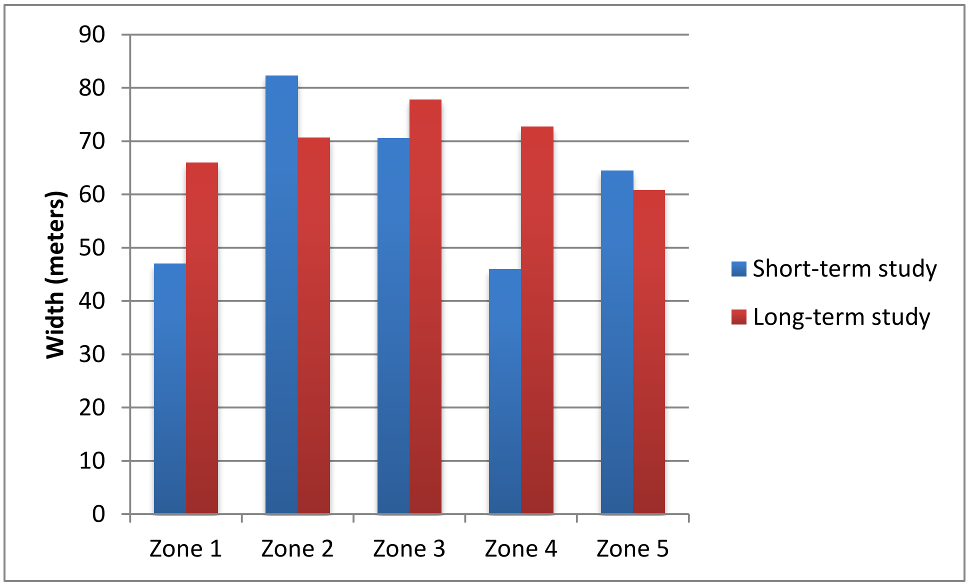

Figure 17: Beach width changes, Province Lands, Cape Cod

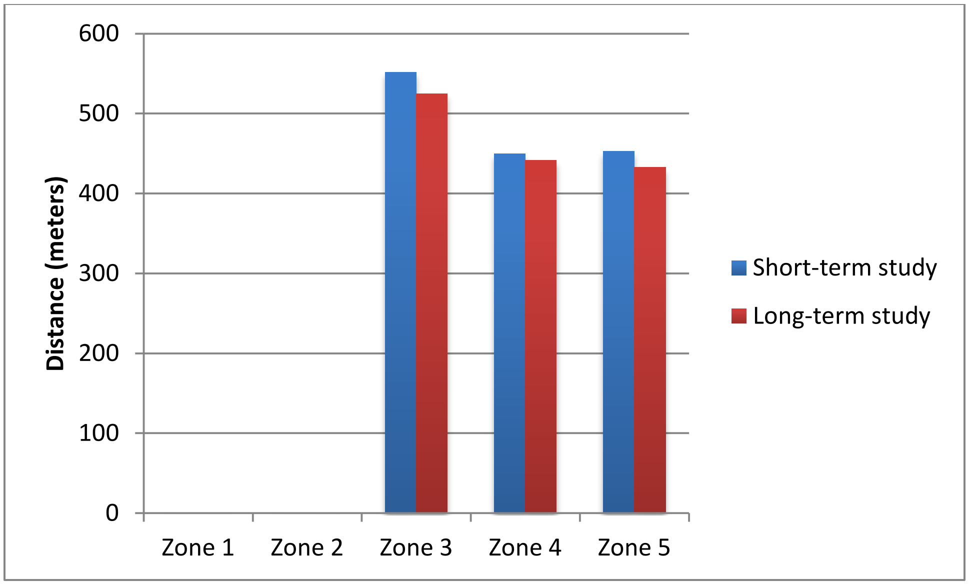

Figure 118: Dune-Bar distance, Province Lands, Cape Cod

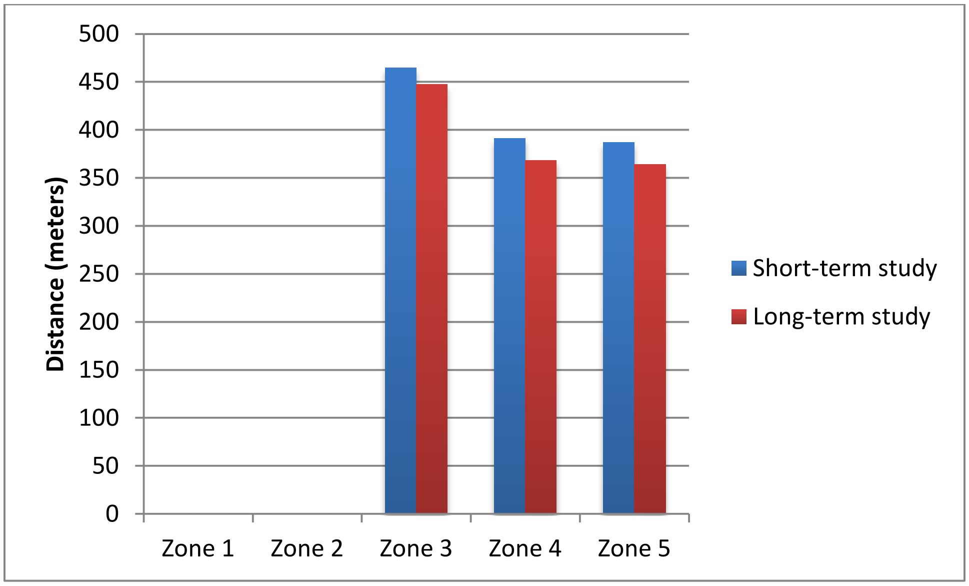

Figure 12: Beach-Bar distance, Province Lands, Cape Cod

Chapter 7: Conclusion

The Province Lands shoreline area is extremely dynamic, each zone behaved differently from one another and even the 1km AOIs showed 2 to 3 different trends each. The beach-dune interactions were what was expected except in zone 5 where the duneline is accreting while the shoreline erodes in both the long and short-term studies. It appears that the proximity of the nearshore bars does not necessarily meant that the shoreline and dunes are better protected from storm surge, although the shape of the bars may have an effect on the ability to protect the shoreline. Based in the results, the parallel bars identified in zone 3 seem to be providing better protection to the shoreline, making it one of the widest beaches in the study area. The cresentic bars located in zone 4 and the "S" shaped bars in zone 5 move more erratically do to the waves and currents experienced in the area and therefore are not as effective in protecting the coastline. Also, as discussed previously their shape and movement may be interfering with the normal sediment flow in the area

Different relationships between the morphologic units emerge when the time intervals between the photographs are shorter. With the second data set a pattern emerges and predominates in each zone: as the nearshore bars move further away from the shoreline, both the shoreline and duneline show accretion.

There are several differences in the shoreline response between the decadal and the bi-annual study. Whereas in the decadal study zones 1, 2, and 3 showed shoreline accretion while zones 4 and 5 showed shoreline erosion, in the short term study all zones showed accretion. By looking at the imagery and data available, zone 5 is one of the most active in the study area, and although it showed some accretion in the short term study, the rate is very low (0.05 m/yr) and does not signify stabilization of the shoreline. Continuous evaluation of this zone will determine if indeed the area will start stabilizing and accrete or will continue the pattern of erosion observed in the decadal study.

Looking at the duneline, the trends are similar in both the short-term and long-term, except in zone 1 which shows accretion in the decadal scale and erosion at the shorter time scale. The accretion rate for the duneline in zone 1 was 1 m/yr at the decadal time frame and for the shorter time scale the erosion rate of 1.552. This is an interesting result because the erosion rate for the duneline is significantly higher for the duneline than for the shoreline. The difference comes because in the shorter time scale study zone 1 is narrower than the shorelines digitized for the decadal study.

The ANOVA analysis revealed that orientation does play a significant role in the changes observed in the study area. As discussed previously, different shoreline orientations result in differences in the amount and force and energy coming from waves and wind that a particular segment of beach may receive. Identifying difference in orientation is therefore important when studying coastal and understanding its dynamics and patterns.

This research has several limitations. Due to the nature of the data, there were time gaps that are important to coastal environments. Seasonal changes are not taken into account and it was not possible to quantify how storms and wave events affect the dynamics in the coastal area. Also, the relationship between the three variables could not be statistically tested in the decadal study due to the time gaps and the amount of variables that affect them in a 10yr period. Finally, this research does not take into account the time lags that elapse between the changes in each of the features.

Although there is overall idea of what are the rates of erosion/accretion in a coastal region, it is clear that within small segments of the shoreline important changes and dynamics are also taking place and are lost when looking at the bigger picture. Both studies show how dynamic the Province Lands coastal features are, which makes conservation and management of the area much more difficult. It is clear that the nearhore bars are an important component of the coastal system that provide protection to the shoreline, affect alongshore sediment transport and are sediment reservoirs, which in turn affect the shoreline and duneline dynamics. Therefore, studying all coastal features, dunes, shoreline and nearshore bar, together instead of separating them is a challenge but brings better understanding of the coastal area allowing to create better projects or ideas for protection and management of our coastal resources.

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