

ABSTRACT

Beach and dune volume changes, a sediment transport model, and a morphometric model were used to investigate dune development and to understand the influence of beach and dune morphology on dune accretion rates on South Padre Island, Texas. Dune volumes were calculated using lidar-derived digital elevation models for the years 2000, 2005, and 2009. Dune volume between the years 2000 and 2005 increased throughout the study area, averaging $3.5 \text{ m}^3/\text{m}/\text{yr}$, although there was large alongshore variability ($-13.6 \text{ m}^3/\text{m}/\text{yr}$ to $30 \text{ m}^3/\text{m}/\text{yr}$). Minimal dune erosion occurred from 2000-2005, making the 2000-2005 dune volume changes a good estimate of the long-term aeolian accretion rates. In contrast, dune volume changes from 2005-2009 are not a good estimate of long-term accretion rates because most areas experienced storm surge erosion averaging $-8.3 \text{ m}^3/\text{m}/\text{yr}$. The dune accretion average from 2000-2005 is in good agreement with the results of the sediment transport model that coupled a locally measured wind velocity time series and a semi-empirical aeolian transport relationship. The morphometric model shows that dune accretion rates are influenced by the present dune morphology and beach width. From calculation of profile volume and estimates of dune accretion rate by dune type (washover terrace, dune terrace and dune ridge) it was determined that a washover terrace would require 43 years to develop into a foredune ridge, if the space, vegetation and sediment supply are available. Due to the shoreline retreat rate and hurricane frequency, overwash will continue to be a recurrent process shaping South Padre Island.

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INTRODUCTION

Beaches and dunes are a valuable part of the coastal environment because they hold a major portion of the barrier island sediment budget, serve as a buffer against storm surge and waves, provide habitat for various species, recreational space, as well as an aesthetic quality to the coast. This study is focused on foredune accretion and morphological change for developed, nourished areas and non-developed areas on South Padre Island (SPI), Texas. Dune morphological development results from the interaction between the beach and dune environment (Psuty, 1988), for this reason these are both analyzed in this study. South Padre Island is a transgressive barrier. The shoreline at SPI has been retreating as a result of decreased sediment supply and as response to sea level rise. Long-term shoreline retreat on SPI, ranges from 2.5-4 meters per year (Morton and Pieper, 1975), and because of this beach nourishment is practiced in developed sections of the island. Beach nourishment contributes to the sediment budget of the beach, which in turn, can contribute sediment to the development and growth of dunes. Volumetric change analysis of beaches and dunes was performed using lidar derived Digital Elevation Models (DEMs) for the years 2000, 2005 and 2009. Although a large number of studies of beach-dune systems, few have been conducted on South Texas beach-dune systems and furthermore, studies that compare natural beaches to developed and nourished beaches are lacking.

Purpose and Objectives

The main goal of this project was to gain a better understanding of the beach and dune dynamics on developed, nourished and natural dune systems on South Padre Island (SPI), TX. The determination of the cumulative effect that beach nourishment has on foredune accretion rates was of particular interest. The objectives of this study were to:

1. Map and characterize the morphology of the beach and dune environments.
2. Calculate the volume change for the time periods 2000 to 2005, 2005 to 2009 and 2000 to 2009.
3. Estimate the net sediment transport rate from wind data using available transport models.
4. Investigate the controlling factors in foredune accretion with a linear regression model.

Hypothesis

Because SPI experiences high rates of long term shoreline change ranging from 2.5-4 m/yr (Morton and Pieper, 1975), most beaches will experience a net loss of volume in the beach environment. Because the beach is a primary source for dune sediment, I hypothesized that dune volume change will increase more per unit length in nourished sections. Dune height and topography varies alongshore SPI, and varying rates of dune accretion are expected as dune height and topography affect the frequency of exposure to storm surge (Ritchie and Penland, 1988; Sallenger, 2000) and experience different shear velocities (Hsu, 1977; McAtee and Drawe, 1981; Svasek and Terwindt, 1974).

Previous studies that have used sediment transport models show that the models overestimate the transport rates, as compared to measures sand transport or deposition (Arens, 1997; Bennett and Olyphant, 1998; Davidson-Arnott and Law, 1996). Overestimation of sediment transport models has been attributed to various beach conditions including sand moisture, beach width, the occurrence of shell material on the sand surface, the angle of wind approach and frequency, and amount of precipitation. Since SPI is not considered to have fetch-limited conditions (Houser and Mathew, 2011) and is located in a semi-arid climate, sediment transport models might provide a close estimate of actual rate of transport providing more insight than wind data alone. Meteorological data from a single location used in computing sediment transport applies to the entire study area, therefore, the potential sediment transport for all beaches will be equal, but the actual transport can be affected by a number of beach parameters, as mentioned previously. The regression model was used to further understand the effect of various beach and dune morphological parameters on sediment deposition.

Table 1. *Measured sand transport or aeolian deposition from the literature*

Author/date	Location	Method	Sediment Transport/ Deposition
Aagaard et al. 2004	Denmark	Topographic Profiles	6-7.5 m ³ /m/yr
Illenberger and Rust 1988	Alexandria, South Africa	Dune migration	31 m ³ /m/yr
Inman, Ewing, and Corliss 1966	Baja California, Mexico	Dune migration	23 m ³ /m/yr
Davidson-Arnott and Law 1996	Lake Erie, Canada	Measured elevation changes	2.6 – 10.3 m ³ /m/yr
Christiansen and Davidson-Arnott 2004	Denmark	Measured Elevation changes	9 m ³ /m/yr
van der Wal 2004	Netherlands	Topographic Profiles	9-14 m ³ /m/yr
Anthony, Vanhee, and Ruz 2006	North Sea Coast of France	Topographic surveying electronic station	3-11 m ³ /m/yr

Table 1 summarizes various studies of sediment transport and deposition.

Sediment transport has been estimated from dune migration rates, from volumetric changes estimated from topographic changes, and measured from sand collection in sediment traps. The transport/deposition values found on Table 1 have been modified to m³/m/yr for comparison. From this table, reasonable expectations for sediment transport ranges from 2.6 m³/m/yr up to 31 m³/m/yr. Areas that are dry and experience dune migration have significantly larger sediment transport rates, similar rates might apply to certain active-dune sections of SPI.

Relevance of the Study

Beaches and dunes are a valuable part of coastal communities because they are a buffer against storm surge, and provide recreational, ecological, and aesthetic qualities to the coast. Beaches are popular vacation destinations, such that, coastal states receive approximately 85% of all tourist-related revenue in the United States. California beaches alone, have more than twice the tourist visits than all 388 National Park Service properties combined (Houston 2008). Increased coastal population, climate change, and sea level rise contribute to the increased rate of beach erosion. Beach erosion poses a threat to the infrastructure and tourism revenue of coastal communities because it reduces the width of the recreational beach and increases the risk of damage during storm events. Assessment and an understanding of the beach and dune systems, therefore, are important for coastal community planning.

Management of coastal environments should be based on the best possible understanding of coastal dynamics, their current state, their susceptibility to change, the scales at which they operate, and the possible direction and magnitude in which they are likely to change. This study provides a better understanding of the beach-dune system of developed beaches and un-developed beaches, the alongshore variation of morphological change, and the foredune accretion rates which contribute to the understanding post-storm dune recovery. The results of this study add to the knowledge base of beach-dune interaction studies and may help in the future development of conceptual or numerical models of coastal processes and evolution.

Literature Review and Background

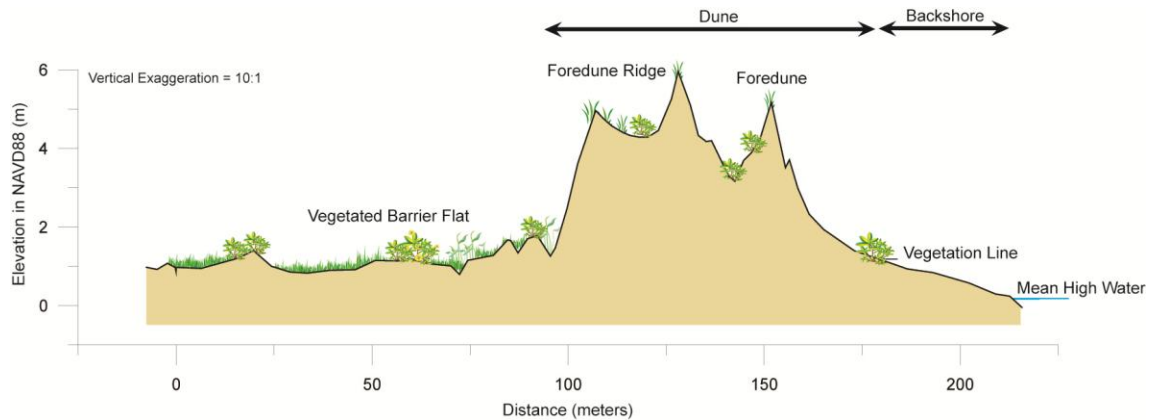


Figure 1. The beach/dune system in this study is composed of the backshore, the foredune and the foredune ridge.

The following section describes the beach-dune system (Figure 1), the scales at which these environments change (Figure 2), and the factors that control coastal dune morphology (Figure 3). The beach-dune system is composed of sub-environments that are modified by different processes and include the foreshore, primarily modified by marine processes, the backshore, influenced by marine processes as well as aeolian processes, the foredune complex, mostly modified by aeolian processes and lastly, vegetated barrier flats, which are not in contact with marine processes and least modified by aeolian activity. The environments to be considered in this study are the backshore and the foredune complex. The foredune complex is composed of incipient dunes, foredunes, foredune ridge and secondary dunes (if these are in active exchange of sediment with the foredune). Volumetric analysis is not performed on the foreshore in this project because the strip of beach from the mean high-tide line to the mean-low tide line is very narrow and is seldom captured during the collection of airborne lidar. In

addition, the features associated with the foreshore are modified at a relatively small time-scale compared to the research time span (Figure 2) and are less relevant in the interpretation of the results.

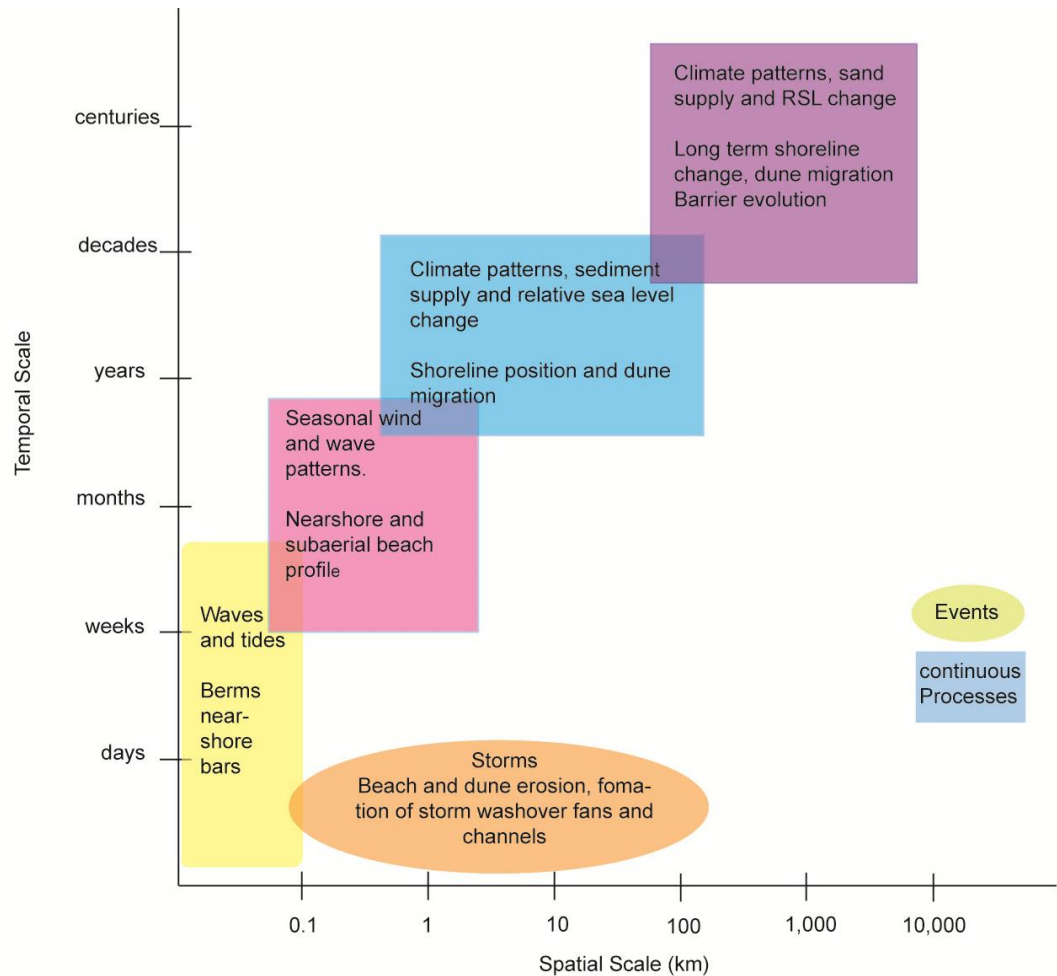


Figure 2. Shown above are the spatial and temporal scales of coastal variation and sediment redistribution. The squares are continuous processes or modes of sediment transport and the features they modify. The ovals represent episodic events.

Coastal Dunes

Coastal dunes are geomorphic features formed by the accumulation of windblown sand. They are primarily recognized for their protection against storm surge, but are also important sediment storage areas for barrier islands, and serve as habitat to various plants and animals. Current research on coastal dunes is concerned with beach-dune interactions, since the formation and modification of dunes depends on the morphology and characteristics of the beach environment (Aagaard et al., 2004; Bauer and Davidson-Arnott, 2003; Houser, Hapke, and Hamilton, 2008; Saye et al., 2005; Sherman and Bauer, 1993; Short and Hesp, 1982; van der Wal, 2004). The factors that influence dune morphology (Figure 3) are presented in the following sections and will be discussed. Wind patterns, wave patterns, tidal cycles, sediment supply, and changes in sea level are all forcing mechanisms responsible for directly or indirectly shaping the dune environment. The forcing mechanisms just mentioned, are examples of continuously operating processes that gradually deposit and remove sediments in a range of temporal frequencies from seconds to thousands of years (Figure 2). Episodic events, such as hurricanes and storms, create elevated water levels and are accompanied by strong winds and large waves causing large-scale beach and dune volumetric changes. Vegetation type and cover are ecological factors that effectively trap and hold sand, important for dune growth and stability. Lastly, human modification and activities can affect the sediment budget and the beach and dune morphology through various activities

The magnitude of sediment transport from the beach to the dune is related to the average wind speed and direction. The relationship between wind speed and sediment transport has been extensively investigated and there are a number of models available (Bagnold, 1941; Hsu, 1977; Lettau and Lettau, 1978) for the calculation of sediment transport from wind data. Sediment transport will be discussed in more detail in a later section.

The Subaerial Beach. The subaerial beach is the source of sediment for dune formation and the buffer between dunes and the destructive forces of waves and currents. For these reasons, the beach is an essential component in dune morphological studies. The rate of sediment transport to the foredune is limited by several beach morphological characteristics, for example beach width, beach height, moisture, sediment grain size, and beach microtopography. This project analyses the effect of some of these beach characteristics to foredune accretion for SPI using a statistical model.

Beach width is one characteristic found to be most important to the rate of sediment transport from the beach to the dune (Christiansen and Davidson-Arnott, 2004; McLean and Shen, 2006; Davidson-Arnott and Law, 1990; Saye et al., 2005). Wide beaches promote higher sediment transport rates as a result of the fetch effect. The dominant form of sediment transport is through saltation (Bagnold, 1941). Saltation (Figure 4) begins as eddies of turbulent wind lift sand grains off the surface of the beach. Once lifted, the sand grains are carried forward by the wind flow and the momentum of the falling grains initiates the movement of more sand grains. This process continues ejecting sand grains from the sand surface in an exponential manner, until the wind is fully saturated and the saltating grains carry all the vertical momentum flux of the wind.

This transition from zero to the maximum transport (Figure 5) is termed the fetch effect (Bauer and Davidson-Arnott, 2003). Higher wind speeds require a larger fetch to achieve full sediment transport, as illustrated in Figure 5. Davison-Arnott and Law (1990) found that for onshore winds just above the threshold speed of sand movement (~ 5.6 m/s), a 15-m beach width is needed to reach the maximum sediment flux. For onshore winds of 8.5 m/s, a 30-m beach width is needed to reach maximum sediment flux. This implies that although the wind speed needed to move sediment onto the dunes is available, the amount of sand that will reach the dune may be limited by narrow beaches. Wider beaches also provide increased protection against wave runup, thus reducing the amount of dune erosion (Christiansen and Davidson-Arnott, 2004; van der Wal, 2004)

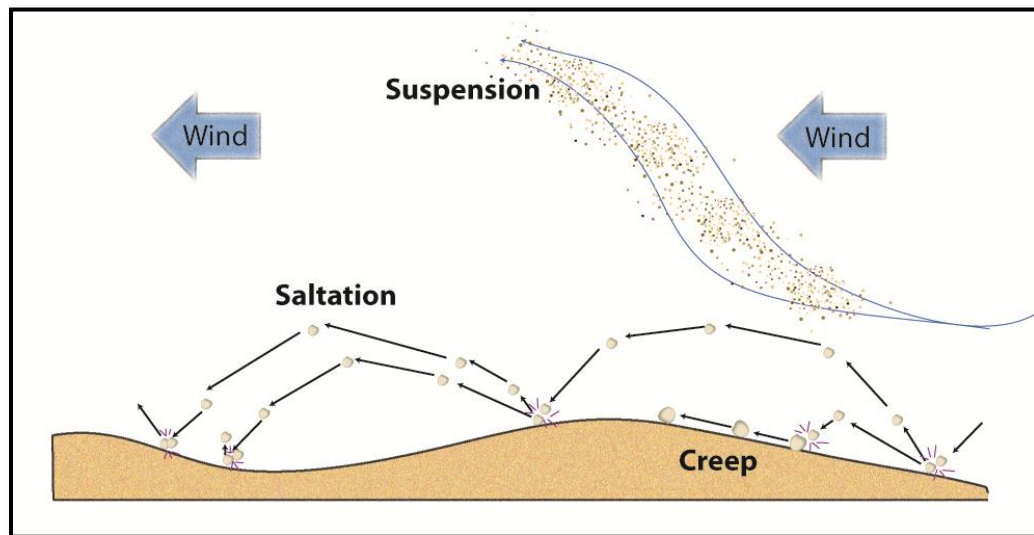


Figure 4. Primary modes of sediment transport are creep, suspension and saltation.

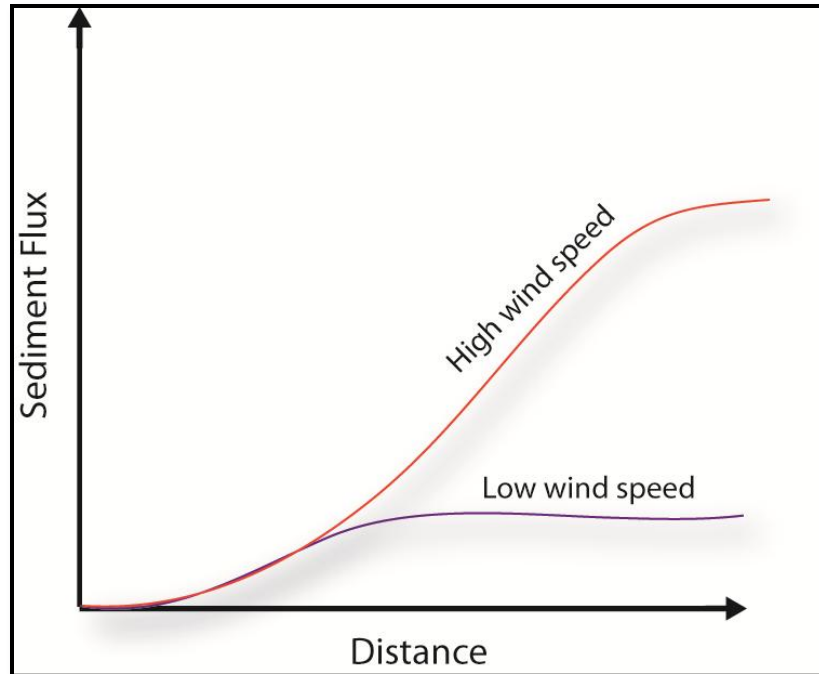


Figure 5. This graph illustrates the increase in sediment flux with distance across the beach from the shoreline

Beach height is also a controlling factor to sediment transport. Topographically low beaches are closer to the water table and may have sediments that are moist, and therefore cohesive. Cohesive sediments increase the threshold velocity of the sand surface and thus reduce the sediment transport rate (Houser, 2009). Dissipated beaches have the greatest potential for landward transport of sand and are more likely to form large foredunes, as observed by Short and Hesp (1982) on Australian beaches. A dissipative beach is generally flat and wide, maximizing sand transport. This is in contrast to reflective beaches which have berms, runnels and a steep shoreface that disturb the wind flow fields. Beaches on SPI vary alongshore from dissipative to intermediate (Houser and Mathew, 2011) and this may affect the rate of sediment transport or pattern of foredune accretion along the study area.

As previously mentioned moisture on sand makes the sediments more cohesive and may increase the threshold wind velocity necessary to initiate saltation. Moisture on the beach is caused by high reach of the tidal range, precipitation, and low evaporation. Backshore moisture is not considered to be a limiting factor to dune accretion on SPI because of the semi-arid conditions of the study area. But beach moisture associated with tropical-storm precipitation is important when considering higher wind velocities associated with storm events in sediment transport modeling (Arens, 1997).

Beach Sediment Supply. Another constraint on sediment transport from the beach to the dunes is the availability of sediments. The sediment supply of a barrier island is limited by the relative rise in sea level and the resulting shoreline retreat (Brunn, 1962) and by the dimension of the beach environment. Figure 6 illustrates Psuty's (2004) model which relates the beach sediment budget to dune morphology. According to this model, assuming constant wind, if there is a highly positive sediment budget, a series of abandoned, low elevation, foredune ridges will occur. Rapid shoreline progradation and seaward displacement of the beach profile prevents the continued growth of a single foredune ridge. As sediment supply decreases, so does the rate of beach progradation, allowing more time for the landward sediment transport to contribute to foredune accretion. Maximum foredune development, according to this model, occurs when the beach budget is slightly negative. A largely negative beach sediment budget, in contrast, results in erosion of the beach and increases the rate of landward migration of the beach and dune environments. Narrow beaches expose foredunes to wave action and scarping, destabilizing the foredune. The initiated foredune destabilization will lead to a foredune morphology dominated by blowouts, washovers or sandsheets. Along SPI, there are

localized differences in sediment budget, this is reflected in the alongshore variability of shoreline retreat rates from south to north.

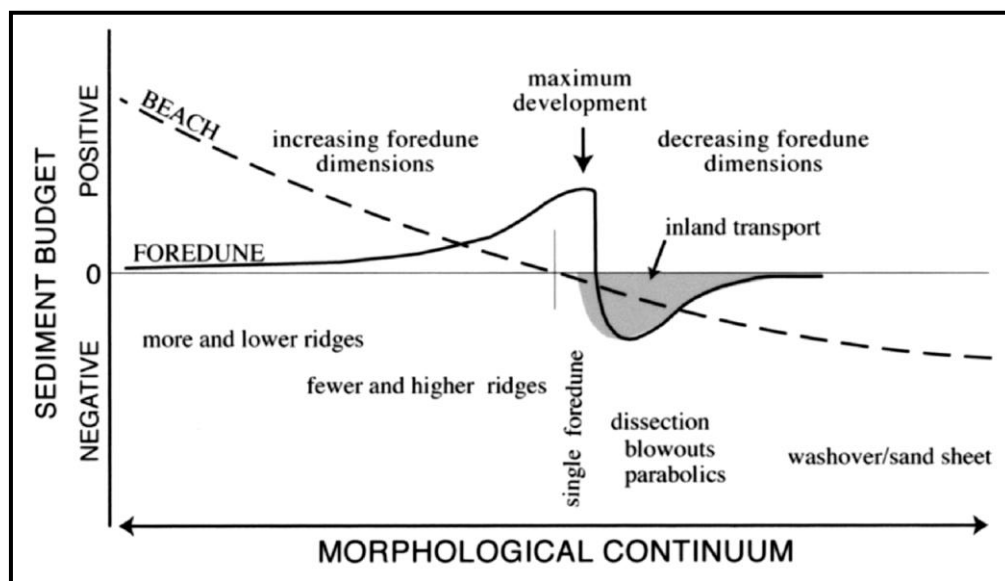


Figure 6. Psuty (2004) model showing the relationship between the beach sediment budget (dashed line), and the dune sediment budget (solid line), and resulting dune morphology.

Forcing Factors. The forcing factors that directly or indirectly modify dune morphology include wind, waves, tides, sea level, and precipitation (Figure 3). All these factors supply, remove, or transfer sand between the beach and dune systems.

The rate of sediment exchange between the beach and nearshore determines the backshore width and availability of sand for landward transport and foredune accretion. One mode of transport of sand from the beach is through longshore currents. As waves approach the shoreline at an angle, they create a net current that carries sand alongshore. Longshore transport increases as the relative angle between the wave approach and the shore increases.

Waves can affect dune morphology directly and indirectly. Dune scarping by waves is a direct influence to dune morphology. Scarping occurs when elevated water conditions allow wave runup to reach the dune. Indirectly, waves work with alongshore currents to remove and transport sediments from the beach and nearshore environments. Also, wave height and type determine the dimensions and slope of the beach.

Lastly, precipitation indirectly influences dune morphology by decreasing sediment transport potential. Wet sand has less potential of being transported, than dry sand. In addition, precipitation increased the vegetation cover, which reduces the aeolian transport rate and increases sediment accumulation. In this study, the effect of waves and precipitation will be considered in the context of storm events and as these might influence the morphology of the beach and dunes at the time of lidar data collection.

Seasonal variation in the direction and magnitude of wind, currents, wave energy or the occurrence of storm events results in beach/dune morpho-dynamic cycles (Aubrey, 1979; Davis and Fox, 1972). Seasonal beach erosion and accretion patterns have been widely documented and are attributed to seasonal changes in wave energy or water levels (Arens, 1997; Aubrey, 1979; Davidson-Arnott and Law, 1990). Seasonal fluctuations in precipitation and shifts in wind direction alter the rate and of aeolian transport and may result in significant changes in the sediment budget (Arens, 1997). Seasonal patterns should be taken into consideration when comparing data collected in different seasons.

Ecological Factors. Vegetation type and cover directly affects dune morphology by influencing the location and pattern of sand deposition. Vegetation reduces wind stress to the bare surface of the sand, preventing erosion and trapping sediment. Because of this,

foredune vegetation is important for the development and morphological stability of dunes. Dune scarping, trampling, grazing or motor vehicle traffic can result in localized vegetation loss and initiate the development of small scale blowouts or troughs. Blowouts alter the wind flow dynamics, and accelerate wind velocity causing the blowouts to expand (Hesp, 2002). Hesp (1988) suggested a morpho-ecologic classification of dunes based on the vegetation cover and dune stability (Figure 7). The morpho-ecologic stage of the current coastal environment is important when considering the effects of storms and dune recovery or the effects that climate change can have on dune landscape.

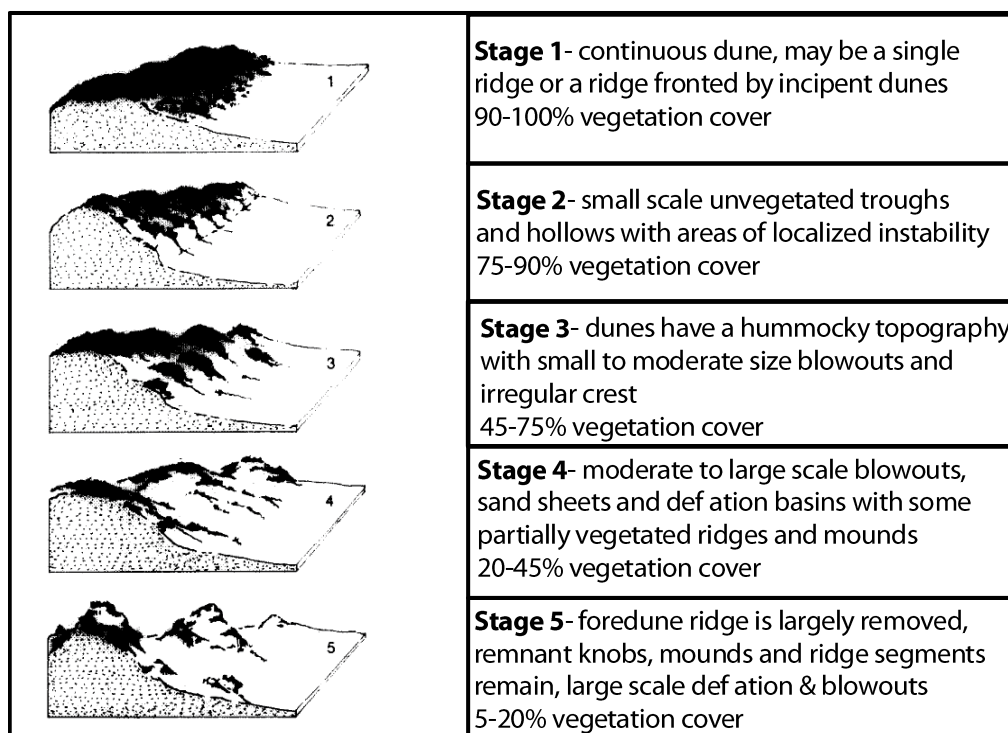


Figure 7. Hesp's (1988) morpho-ecologic foredune model

Anthropogenic Influence. Coastal structures, beach nourishment, beach scraping, dune building efforts, sand mining, and other forms of mechanical removal of sand, are all anthropogenic activity that can directly influence the development and evolution of coastal dunes. Anthropogenic activity can also alter dune morphology indirectly, by modifying the type and abundance of vegetation (Figure 3).

Coastal structures alter the aerodynamic wind flow across the backshore and limit the space available for the landward migration of coastal environments. In a study conducted on Fire Island, NY, it was found that the sand transport rate across a 1-km length of dune crest was reduced by houses build directly on the ground as well as by houses elevated on stilts (Nordstrom and McCluskey, 1985). Landward sediment transport is further decreased if sand fences are present. As a result, sand accumulates in close vicinity to the structure or sand fencing and the depositional pattern differs from natural dune accretion pattern and dimensions. Sand not transported landward of the dune crest is subject to erosion and loss to the alongshore transport system during storm events. Landward sediments transport is a necessary process in landward barrier migration, as it supplies sand to the backbarrier environments. Furthermore, in transgressive barriers or eroding beaches, man-made structures impede the landward migration of beach and dune environments. The loss of these environments is accompanied with the loss of native beach and dune vegetation and the interruption of plant succession process (Feagin, Sherman, and Grant 2005).

Human, vehicular and mechanical traffic, all have a direct and indirect effect on beaches and dunes. Vehicular and pedestrian traffic affect the beach and dune environments indirectly by altering the microclimate of the area (e.g. soil moisture and

temperature) and directly by reducing the density of vegetation, and presence of embryo dunes (McAtee and Drawe, 1981). Beach scraping directly affects dune dimensions, as it consist of the mechanical placement of sand from the lower parts of the beach to the dune toe (Bruun, 1983). Beach scraping is practiced on SPI as a form of maintenance (removal of sargassum) and also as a way to strengthen the primary dune ridge by supplementing its volume. Some studies have suggested that beach scraping increases sediment transport (Conaway and Wells, 2005) perhaps because of the reduced topography or the expanded foreslope surface area.

Beach nourishment is a soft-engineering solution used for shoreline stabilization. Sand placed directly on the beach or the nearshore advances the shoreline seaward and increases the local sediment budget of the area. This increased sediment budget may provide extra material for dune building. In addition, a wider beach provides greater protection to foredunes from minor storm surges and wave run-up, and can increase the potential transport of sand to the foredune since fetch will be longer (Van der Wal, 2004).

Storms Events. Storms are a major contributor to the present and future morphology of barrier islands on the Gulf Coast and East Coast of the U.S. because of the potential, large-scale magnitude of sediment redistribution that can occur in a relatively short period of time (Houser, Hapke, and Hamilton, 2008; Morton, 1979; Stone et al., 1997). Foredune survival or destruction during a storm depends on pre-storm dune morphology, vegetation cover and the intensity and frequency of storm events (Houser, Hapke, and Hamilton, 2008; Morton, 2002; Ritchie and Penland, 1990; Sallenger, 2000). The level of morphological change to the dune environment from storm surge is determined by the relative height of the foredune to the storm surge elevation (Sallenger,

2000) as shown in Figure 7. From the figure, the possible impacts that storm surge can have on a dunes are swash (dune toe erosion), collision (dune scarping), overwash or inundation. Overwash is the flow of water and sediment over the crest of the beach that does not directly return to the water of water where it originated (Donnelly, Kraus, and Larson 2011). The washover deposits can accumulate on the backshore or as far back as the lagoon, on the landward side of the barrier. Washover processes maintain the barrier-island subaerial sand budget and width as a response to sea level rise, shoreline erosion and to large storm events (Dolan and Godfrey, 1973; Hosier and Cleary, 1977; Stone et al., 2004). Storm events that occurred during the study period will be considered in the interpretation of observed beach and dune volume changes.

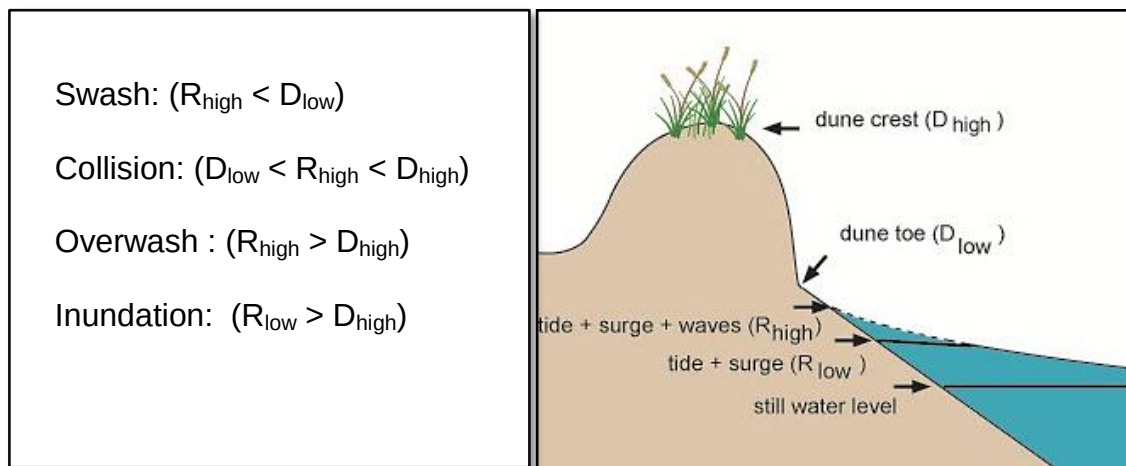


Figure 8. Right: The four impact regimes are defined: Swash, collision, overwash and inundation. Right: Sketch representing dune toe (D_{low}), dune crest (D_{high}), tide and surge water level (R_{low}) and water levels from Sallenger (2000) storm impact scale model.

Dune morphology on a storm dominated, transgressive barrier like SPI is highly determined by the rate of recovery from, and frequency of storm events. A conceptual model developed by Ritchie and Penland (1988) for the barrier islands of south Louisiana, relates storm return period to subaerial sediment budget as shown on Figure 9. After a storm event, the beach and dune recover volumetrically and morphologically with the aid of re-established vegetation. Beach and dune recovery continues until the occurrence of the next storm event.

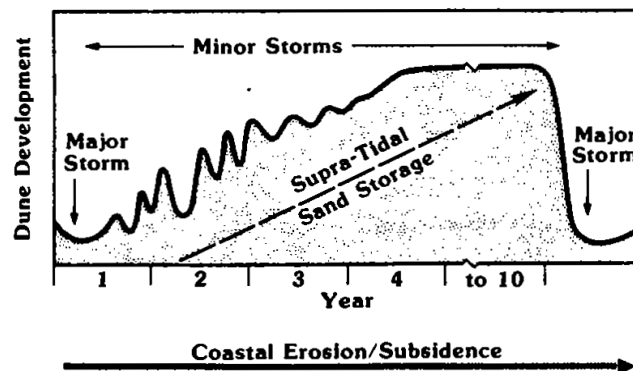


Figure 9. Ritchie and Penland (1988) generalized conceptual model of sand dune development for the southern Louisiana coast. Note that storm return periods are different for all sections of the Gulf of Mexico coast.

Climate. Lastly, climate variability has an effect on the morphology of beaches and dunes on a temporal scale of years to decades (Figure 2). Various climatic conditions are accompanied by different atmospheric and oceanographic patterns of winds, waves, precipitation, temperature, and intensity and frequency of storm activity. Various modes of climatic variability that might affect geomorphic processes include the El Nino Southern Oscillation, North Atlantic Oscillation, Atlantic Multidecadal Oscillations, among others. The individual modes and interaction between them can affect regional climate patterns for years (Viles and Goudie, 2003), causing drought, extreme heat, or increased storm condition. These climatic variations are important to the south Texas region because they control the extent and density of the vegetation cover and hence the stability of backshore and dune environments (Price and Gunter, 1942) and can also affect the character of plant communities (Miller, Gornish, and Buckley, 2010).

Climatic change will increase pressure on the beach and dune ecosystem with increased temperatures and decreased precipitation. In the last 100 years, temperatures derived from the instrumental record (1906-2005) show a linear increase of 0.74°C , as reported by the IPCC's Fourth Assessment Report (Christensen et al., 2007). Future-climate model, Hadley Centre Model or HadCM2 (Field et al., 2000), predicts an increase of 1.5°C along the Texas coast, which can increase the July heat index from 5° to 10°C . Furthermore, precipitation is expected to decrease in the southern Texas coast which can reduce soil moisture and decrease the vegetation cover. In addition to these effects, other ecosystem changes can result from changes in runoff, reduced freshwater input, and well as increased evapotranspiration rates (Twilley et al., 2001).

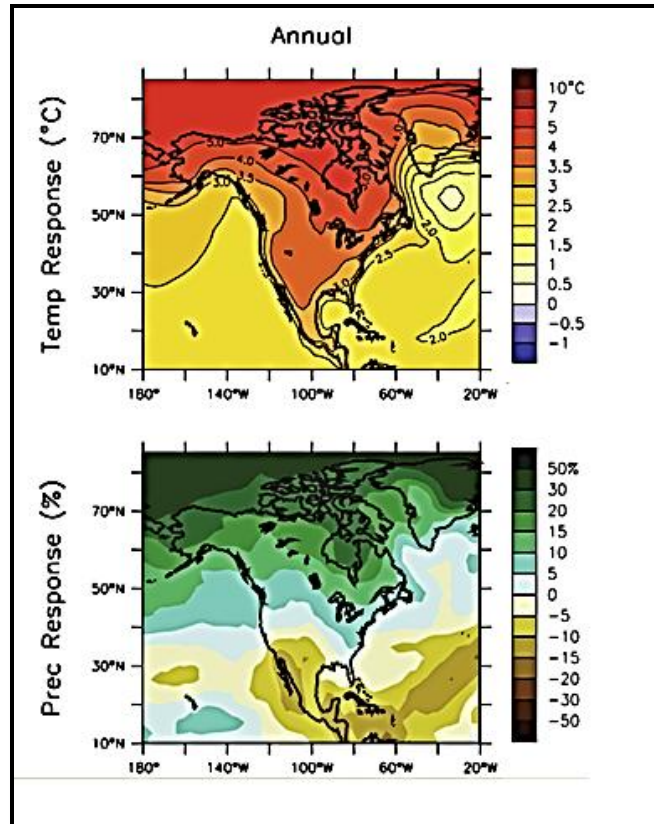


Figure 10. HadCM2 models the average annual temperature and precipitation change from 2080-2099 as compared to 1980-1999 values. Figure from Christensen et al (2007).

STUDY AREA

South Padre Island is a sandy retrogradational barrier located on the southernmost tip of Texas. The island is approximately 60 km long and extends from Brazos Santiago Pass north to Port Mansfield Channel. This study is focused on the southernmost 30 km of the island (Figure 11). The northern 20 km of the island are not developed and the southern 10 km are developed. The following sections will describe the geologic history, vegetation, climate, wind, waves, sea-level changes, and storms of SPI.



Figure 11. Study site location

Geologic Setting

SPI originated from sediments eroded from the Rio Grande delta roughly 3,400 to 1,900 years before present (Brown and Hartmann, 1980). At this time, the sediment supply of the once-prograding Rio Grande River delta diminished causing the delta to subside and erode. The sand of the eroding delta was reworked by waves and tides to form offshore shoals. These shoals began to coalesce and transgress landward to form a peninsula attached to the Rio Grande deltaic headland. Continued sediment transport and northward spit-accretion resulted in the formation of Padre Island. Since 1957, Padre Island has been split into North Padre Island and South Padre Island by Mansfield channel. To this day, the barrier island continues its landward transgression.

SPI is a wave-dominated barrier prone to overwash with dunes that vary in size and distribution (Davis, 1994). The island narrows from north to south from 8 km near Mansfield channel to approximately 1 km at the narrowest sections. The barrier is approximately 3-5 m in height (not including dunes) and its deposits extend to a depth of 3 m below sea level (Morton, 1994). The sand that makes up the island is mostly composed of quartz and sanidine, and the most abundant heavy minerals (60%) are hornblende and pyroxene (Bullard, 1942). Grain sizes range from 0.18 to 0.21 mm with a mean of 0.195 mm (Kraus, Prouty, and Sommerfeld, 1996). Sediment supplied by the littoral currents originates from the erosion of updrift beaches. Previously, the major source of sediment was supplied by the Rio Grande River. The Rio Grande's sediment load has diminished over the Holocene epoch due to climatic changes and continued to decrease over historical time due to the building of dams (Morton and Pieper, 1975).

The main processes that have shaped SPI are sea level changes, wave activity, and wind; all these agents redistribute sand amongst the island's geoenvironments.

Geoenvironments on SPI include the nearshore, beach, foredunes, secondary dunes, backbarrier flats, washover fans, washover channels, inlet channel, tidal deltas, and marshes. There are approximately 20 washover areas in the 30-km long study site where remnant scour channels remain and provide site for ephemeral/seasonal wetlands on the island.

Located on the southern end of the island is Brazos Santiago Pass. Brazos Santiago Pass is a microtidal inlet that connects the lower Laguna Madre to the Gulf of Mexico. Before dredging and the construction of the jetties, the inlet supported an ebb-tidal delta that extended from 3 to 7.5 m below sea level, had a maximum extension of approximately 1 km into the Gulf, and had a flood delta with a maximum thickness of 4.5 m (Morton, 1994). This inlet is protected by a set of jetties completed in 1935. Following construction of the jetties, sand of the ebb-tidal delta was eroded and transported onshore by the altered wave refraction and tidal current pattern and deposited approximately 2 million m³ of sand along the beach adjacent to the northern jetty (Morton, 1994). This channel is currently dredged to 44 ft depth and 300 ft width by the U.S. Army Corp of Engineers. The material dredged from this channel has been used to nourish the beaches of South Padre Island since 1989 (Aidala, Burke, and McLellan, 1992).

Dunes

The foredune system on South Padre Island is fragmented and has variable topography that can be describes as ranging from a stage 3 to a stage 5 of Hesp's morpho-ecologic model (Figure 7). The secondary dune system is composed of low hummocks, approximately 2 to 4 m in elevation. In the northern sections of the island there are large, un-vegetated transverse dunes. These mobile dunes supply sand to the lagoon margins of the island to form extensive wind-tidal flats. Foredunes and their remnant dune-knobs are from 4-9 m tall and even higher in a few locations. Breaks in the dune system occur as a result of overwash processes.

In the developed southernmost 10 km of the island, dunes are low (ranging from 2-4 m) and backed by seawalls that protect local property. These dunes are under the influence of anthropogenic activities such as beach fill, mechanical modification, re-vegetation, placement of sand fences, and the segmentation of dunes by beach access corridors. Coppice mounds are relatively absent in this area with the exception of push-up dunes, where scraped sand and sargassum are pushed up to the existing dune as part of beach maintenance.

Vegetation

Vegetation on SPI varies by geoenvironment (Figure 12). Table 2 presents a summary of the most common vegetation found on the backshore and foredunes, secondary dunes and backbarrier flats, and wetland environments of SPI. Wetland environments correspond to areas that are periodically flooded by tides or precipitation. These wetlands occur at the margins of tidal flats, along relic washover channels, as well as within some secondary dunes and vegetated flats (Judd and Lonard, 2009). The list of vegetation was developed from field observation in addition to published data (Judd and Lonard, 2009; Judd, Lonard, and Sides, 1977; Judd et al., 2008). Species names follow Richardson (2002).

Vegetation cover is important in the backshore for the development of incipient dunes and at the foredune for stability. In SPI secondary dunes and vegetated flats have greater vegetation cover than the foredune and backshore environment. Because foredunes have lower vegetation cover they experience a greater rate of topographic change when compared to the other environments (Judd et al., 2008).

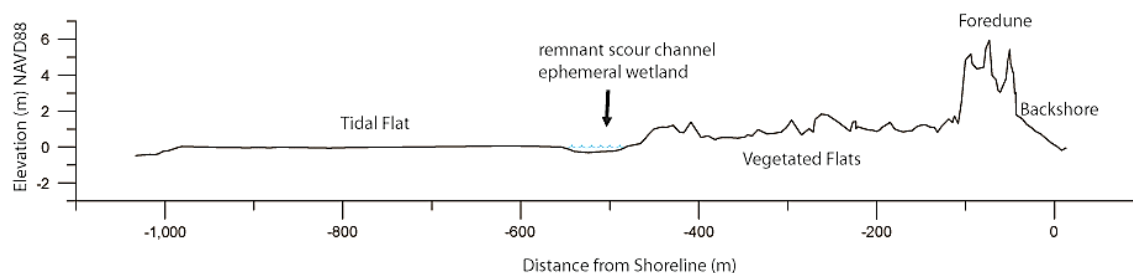


Figure 12. Vegetation type and cover vary in SPI according to the geoenvironment they occur on. Above is an illustration of various environments found on SPI.

Table 2. Vegetation found on SPI by summarized by geoenvironment

	Species	Common Name
Backshore/ Foredune	<i>Uniola paniculata</i>	Sea Oats
	<i>Panicum amarum</i>	Bitter Panicum
	<i>Schizachyrium scoparium</i>	Seacoast Bluestem
	<i>Heterotheca subaxillaris</i>	Camphor weed
	<i>Sesuvium portulacastrum</i>	Sea Purslane
	<i>Machaeranthera phyllocephala</i>	Camphor Daisy
	<i>Croton punctatus</i>	Gulf Croton
	<i>Ipomea pes-caprae</i>	Railroad Vine
	<i>Ipomea imperati</i>	Beach Morning Glory
Secondary Dunes and Backbarrier Flats	<i>Schizachyrium scoparium</i>	Seacoast bluestem
	<i>Eragrostis secundiflora</i>	Red Lovegrass
	<i>Paspalum monostachyum</i>	Gulfdune Paspalum
	<i>Dichromena Clorata</i>	White-top Umbrella Grass
	<i>Iva texensis</i>	Texas Marsh Elder
	<i>Heterotheca subaxillaris</i>	Camphor weed
	<i>Solidago sempervirens</i>	Seaside Goldenrod
	<i>Machaeranthera phyllocephala</i>	Camphor Daisy
Wetland Environments	<i>Gaillardia pulchella</i>	Indian Blanket
	<i>Spartina patens</i>	Marshay Cordgrass
	<i>Fimbristylis castanea</i>	Fimbristylis
	<i>Scirpus pungens</i>	Bulrush
	<i>Scirpus maritimus</i>	Saltmarsh Bulrush
	<i>Typha domingensis</i>	Cattails
	<i>Monanthochloe littoralis</i>	Shoregrass
	<i>Batis maritima</i>	Turtleweed/Vidrillo
	<i>Borrichia frustenscens</i>	Sea Ox-eye daisy
	<i>Salicornia sp</i>	Glasswort

Climate

Vegetation cover and dune stability is highly dependent on the regional climate. SPI is located in a subtropical, semi-arid climate zone (Dahl et al., 1974). This area experiences hot summers and mild winters. The average temperature for the research period was 23.6°C and the monthly averages from the years 2000 to 2009 are shown in Figure 13. The average yearly rainfall for the south Texas coast is 66 cm and because of the high summer temperatures, yearly evaporation rates are high, ranging from 58.5 to 79 cm (Brown and Hartmann, 1980). Figure 14 shows average monthly evaporation and precipitation rates obtained from the Texas Water Development Board for state quadrangle 1110 corresponding to Cameron, Willacy, and part of Kennedy counties. Precipitation is seasonal, occurring during the months of active tropical storm activity from June to November. Yearly evaporation exceeds precipitation year round (Figure 14). This pattern of evaporation and precipitation is an average derived from the historical record starting in 1940, but there are wet years and dry years depending on global climate patterns. Overall, precipitation and evaporation rates are important since they control soil moisture and hence the vegetation-cover of the region.

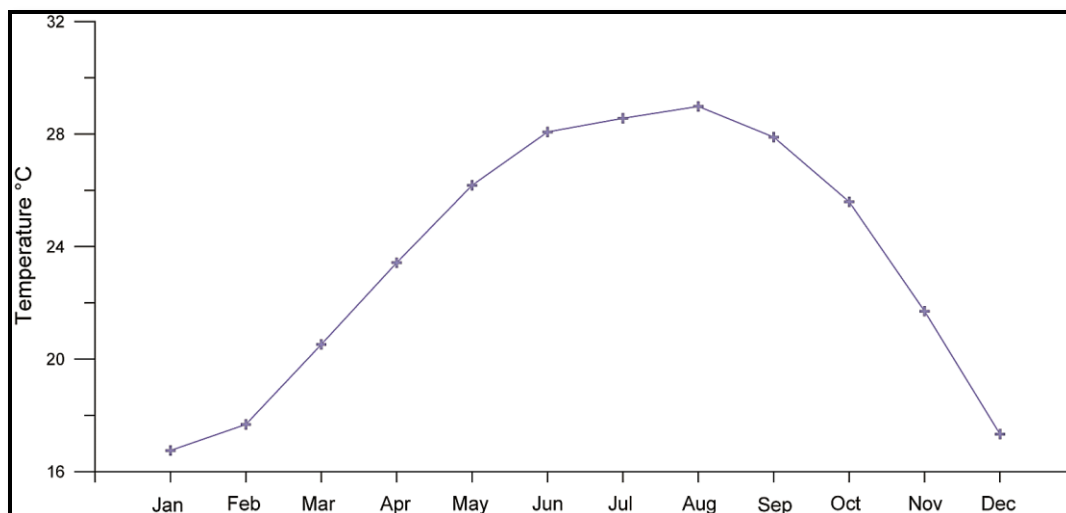


Figure 13. Monthly average temperature for Port Isabel, Texas. Data obtained from meteorological station # 87797701 available at <http://lighthouse.tamucc.edu/TCOON/HomePage>

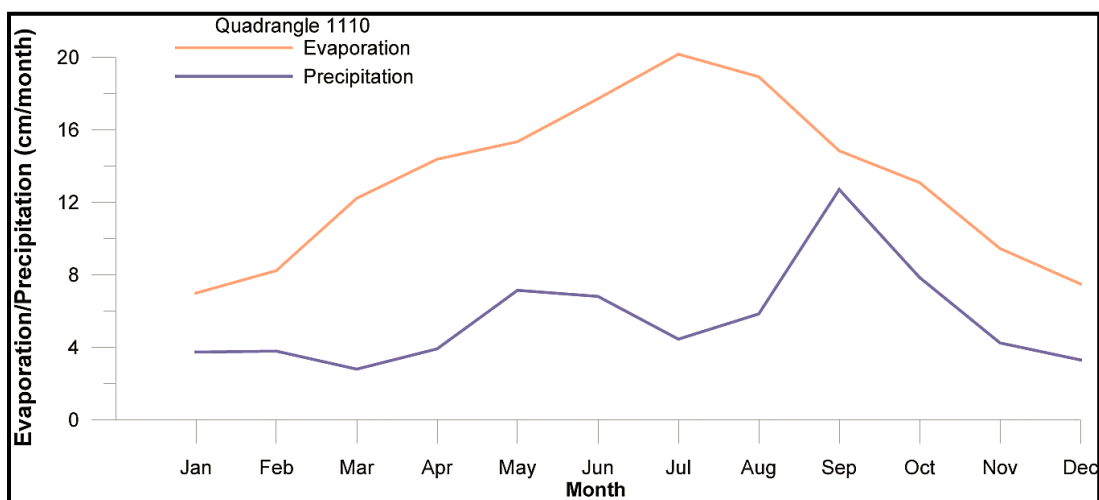


Figure 14. Monthly averages for evaporation and precipitation for the state quadrangle 1110, which includes Cameron, Willacy, and part of Kennedy Counties. Data from the Texas Water Development Board found at <http://midgewater.twdb.state.tx.us/Evaporation/evap.html>

Wind, Waves, and Tides

Predominant winds for the study period were from the southeast (Figure 15) with an average speed of $5.3 \text{ m}\cdot\text{s}^{-1}$. In the spring and summer months, the wind direction is almost exclusively from the southeast and in the winter months the winds become bimodal with a large frequency of wind approaching from the north-northwest.

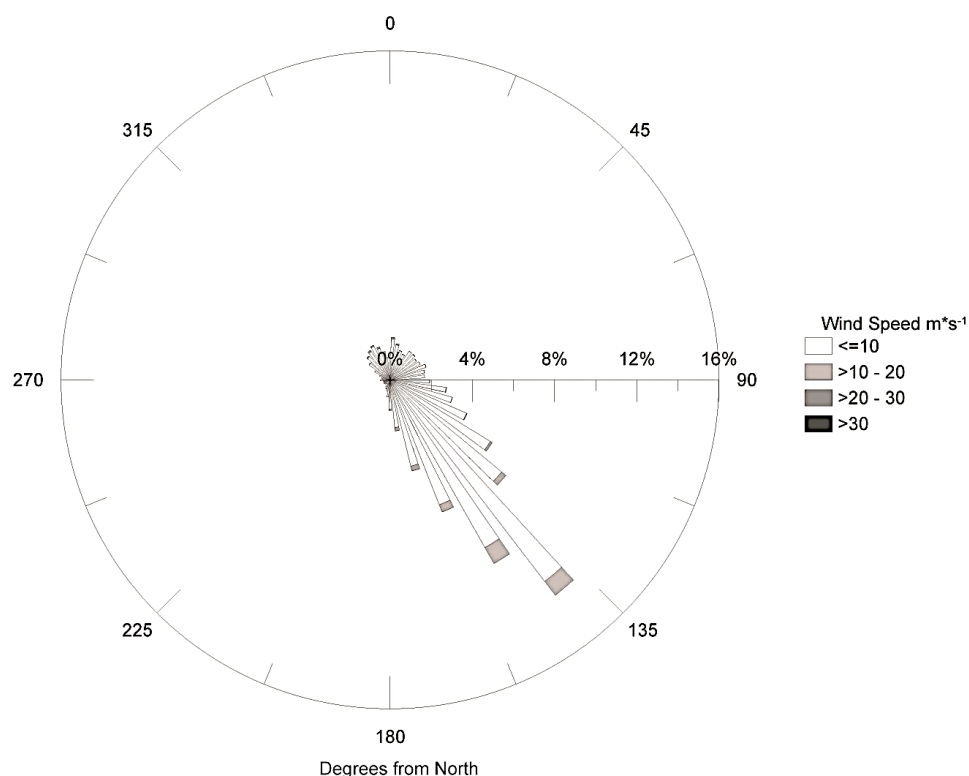


Figure 15. Wind frequency for South Padre Island (2000-2009)

The prevailing winds are also the driver of the wave trains that approach the beach. Wave approach is most frequently from the southeast (Figure 16). The significant wave height is 1.49 m and mean-peak wave period is 6.8 seconds (Kraus, Prouty, and Sommerfeld, 1996). The average monthly wave height is greater in the winter months

(December and January) averaging 1.7 m and 1.2 m in the summer months (July-September). Gross littoral drift is estimated to be 270,000 m³/yr, the net drift is to the north at a rate of approximately 92,000 m³/yr (Heilman, Darnell, and Mahoney, 2006)

South Padre Island has semidiurnal tides and a tidal range of 0.38 m as calculated from the difference between MHW and MLW from NOAA station #8779750. Tide levels are on average highest in September-October and lowest in January-February.

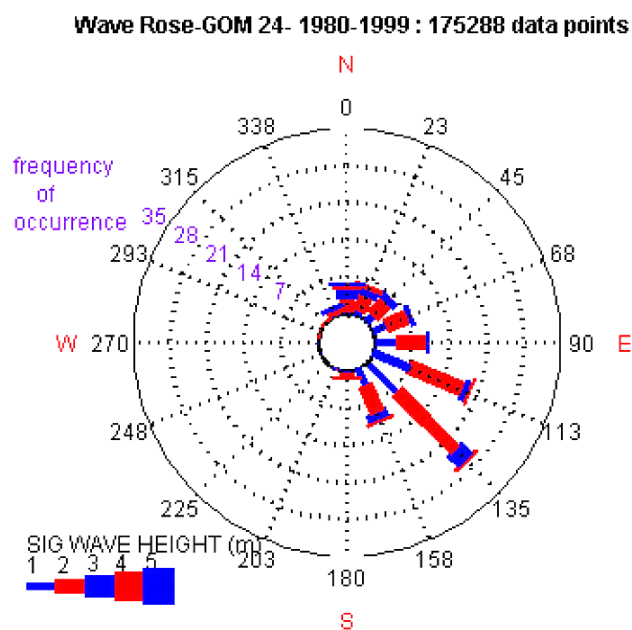


Figure 16. Significant wave height and frequency of direction of approach. Graphic from the USACE Wave Information Studies (WIS) site for station number 73024 located at Lat 26.42 and Lon -97.00. Available at <http://frf.usace.army.mil/wis2010/hindcasts.shtml>

Sea-level and Shoreline Change

Regional sea-level changes are caused by the global sea-level trend and local and regional geologic factors. According to tide gauge records (Figure 17), the rate of relative sea-level trend for SPI is 3.48 mm/yr (Zervas, 2009) with a 95% confidence interval of ± 0.75 mm/yr. This rate is based on monthly mean sea level data from 1958-2006. Sediment compaction contributes to the relative sea level rise of this region. The Texas coastal plain developed from the accumulation of estuarine, alluvial, marine and coastal sediments over the last 150 million years. The coastal plain can have sediment packages that are on the order of 10-15 km thick. With time, sediments compact causing a negative vertical displacement of the land. The rate of compaction contributes 0.5mm/yr to relative sea-level rise of the South Texas coast (Montagna, Gibeaut, and Tunnell, 2007).

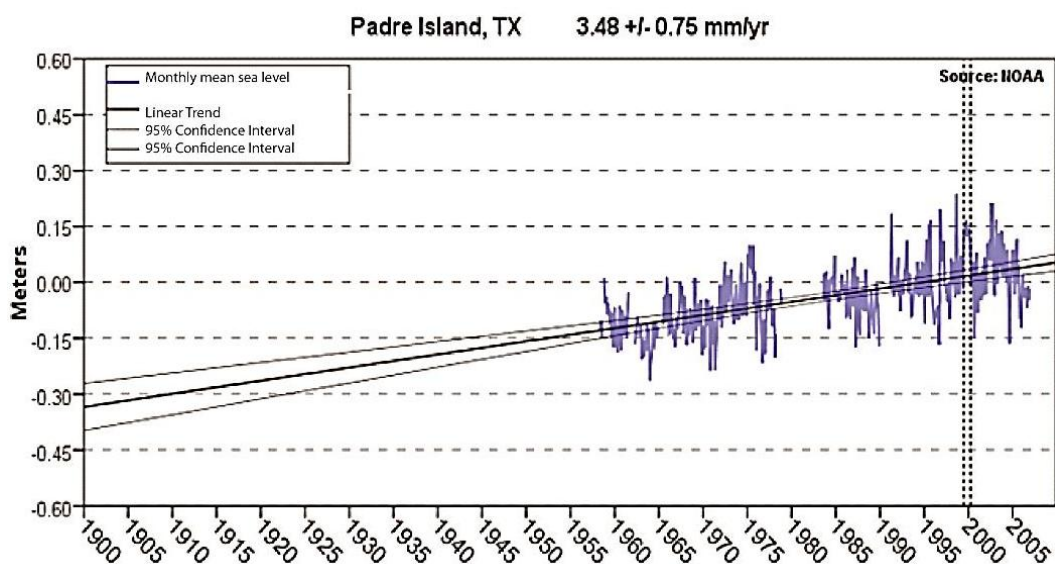


Figure 17. Sea level trend (black line) and upper and lower 95% confidence interval (gray lines). The blue line represents the mean sea level with the average seasonal cycle removed. Graph obtained from NOAA tides and currents website at <http://tidesandcurrents.noaa.gov/sltrends/sltrends.shtml>.

Long-term rise in sea level progressively shifts the energy of waves landward causing shoreline retreat (Brunn, 1962). Shoreline retreat is also caused by storm events and changes in sediment budget. According to the 2009 Texas Coastal Erosion Planning and Response (CEPRA) report, 92% of the shoreline from Mansfield cut to Rio Grande River (South Padre Island) is critically eroding. Critical erosion is defined as a long-term shoreline retreat rate of 2 ft or more per year. SPI as a whole has been retreating since the late 1800's (Morton and Pieper, 1975) as a result of global sea level rise and a decreased sediment budget. Historical shoreline change rates for SPI average -2.47 m according to Shoreline Change Project data from the Bureau of Economic Geology (BEG) available from <http://www.beg.utexas.edu/coastal/download.php>. Shoreline change rates vary alongshore for the study area (Figure 18). The developed portion of the island experiences the least amount of long-term shoreline erosion, and in some areas accretion, if these have been nourished. Erosion rates increase northward to as high as -5.6 m/yr.



Figure 18. Variation of shoreline change rates for the study area.

Beach Nourishment

Beach nourishment on SPI began in 1988. The first nourishment events used sand dredged from Brazos Santiago Pass to construct a nearshore berm. This berm had an initial volume of 170,000 m³ and was placed 1.5 km north of the jetty, from 0.5 to 1.2 km offshore, with the use of a hopper dredge (McLellan, 1990). The berm sand was re-worked by nearshore processes and re-distributed through the littoral system, eventually nourishing the beach and nearshore. Berm construction events occurred in 1988, 1990 and 1995 (McLellan et al., 2009). In 1997, the nourishment approach changed from construction of a nearshore-berm to placing the sand directly on the beach.

From 1997 to 2009, approximately 2,000,000 m³ of sand dredged from Brazos Santiago Pass were used to nourish portions of SPI beaches. Most of the nourishment events for the time period of this study, took place between station 180-250 (Figure 19 and Table 3). Beach nourishment is designed to supplement the beach and nearshore to the depth of closure. In SPI the depth of closure is 20 to 25 ft corresponding to distance of approximately 750 m offshore from Mean Low Tide (Heilman, Darnell, and Mahoney, 2006). For storm events with recurrence intervals of 10, 20, and 50 years, the depth of closure extends to 23, 28, and 36 ft respectively, as calculated from Hallenmeier's equation (Heilman, Darnell, and Mahoney, 2006). The fill that is placed on the beach evolves over time from the initial construction-profile to the design-profile as sand is redistributed by waves and tides (Figure 20). Occasionally, dune nourishment is practiced by placing a berm in front of the dune to provide a buffer against long-term erosion.

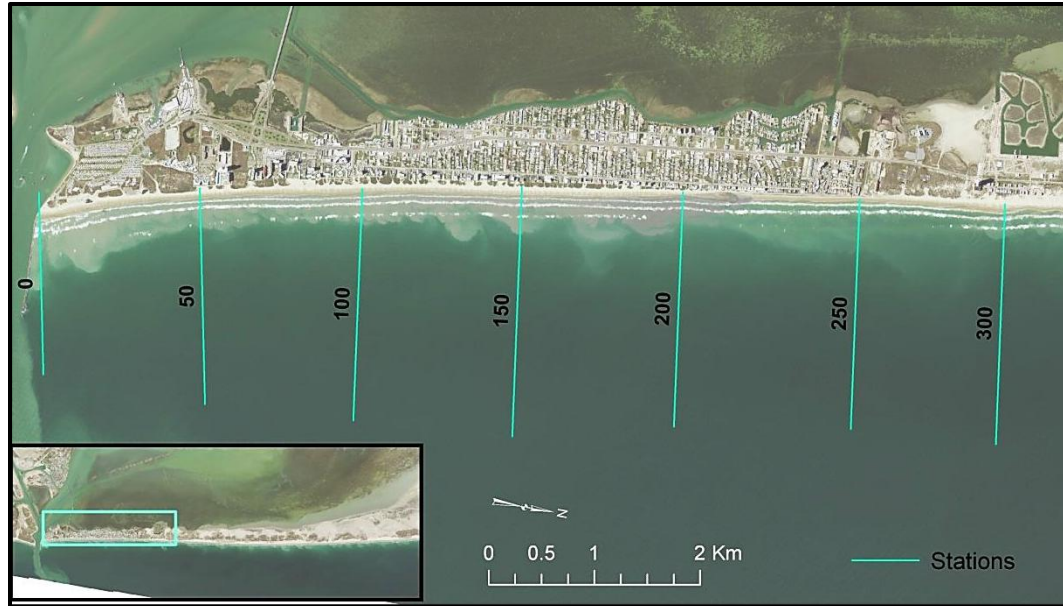


Figure 19. Map of the developed portion of South Padre Island. Most of the beach nourishment during the study period was placed between stations 180-250

Table 3. *Beach nourishment from dredged material (Heilman et al., 2009)*

Date	Volume m ³	Placement Limits	Length (m)
February 1997	373,952	Station 182+29 to 242+29	1,829
February 1999	378,276	Station 80+00 to 120+00	1,219
December 2000	295,883	Station 206+00 to 238+00	975
December 2002	253,091	Station 184+00 to 218+00	1,036
January 2005	37,491	Station 9+30 to 30+00	640
January 2005	175,052	Station 182+00 to 213+00	945
March 2007	54,318	Sta 226+00 to 261+00 (beach)	1,067
		Sta 181+00 to 253+00 (dunes)	2,195
March 2008	76,455	Station 224+00 to 260+00	1,097
February 2009	311,040	Station 208+40 to 255+00	1,433
Total	1,955,559		

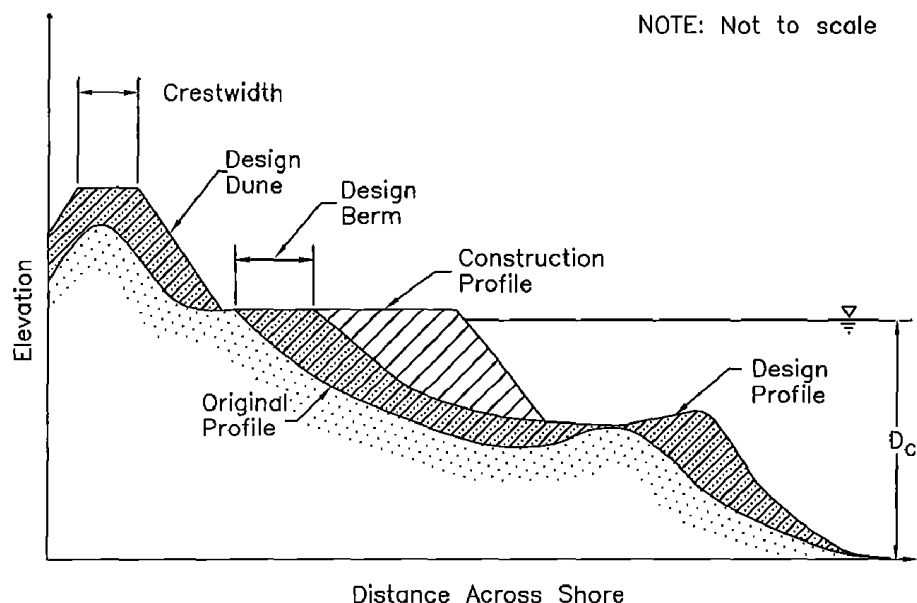


Figure 20. The beach nourishment design seeks to supplement the profile to the Depth of Closure (D_c). Sand is placed directly on the beach and modified to the construction profile; this sand is slowly re-worked by waves and tides and distributed to meet the final design profile. This figure was obtained from Heilman and Kraus (1996)

Hurricanes and Tropical Storms

The Texas coast experiences an average of 0.8 hurricanes per year (Morton and Pieper, 1975; Roth, 2000). Major storms that had an effect on the study area are shown in Table 4 and Figure 21. Hurricane Emily and Dolly both occurred during the study period and may have an effect on the results. Of the storms listed in Table 4, hurricane Allen and Beulah had the highest storm surge recorded for the study area of approximately 2.5 m and 6 m respectively (Giardino, Isett, and Fish, 1984; Roth, 2000), as well as the highest peak wave heights of 7.3 and 7.5 m (Kraus, Prouty, and Sommerfeld, 1996). These storm conditions resulted in the development of 40 washover channels after Allen and 30 after Beulah.

Table 4 *Major storms since 1960*

Date	Storm	Category at Landfall
September 1961	Carla	Hurricane – 4
September 1967	Beulah	Hurricane – 5
August 1970	Celia	Hurricane - 3
August 1975	Caroline	Hurricane - 3
July 1978	Amelia	Tropical Storm
August 1980	Allen	Hurricane - 3
June 1993	Arlene	Tropical Storm
August 1999	Bret	Hurricane – 4
July 2005	Emily	Hurricane - 3
July 2008	Dolly	Hurricane – 1

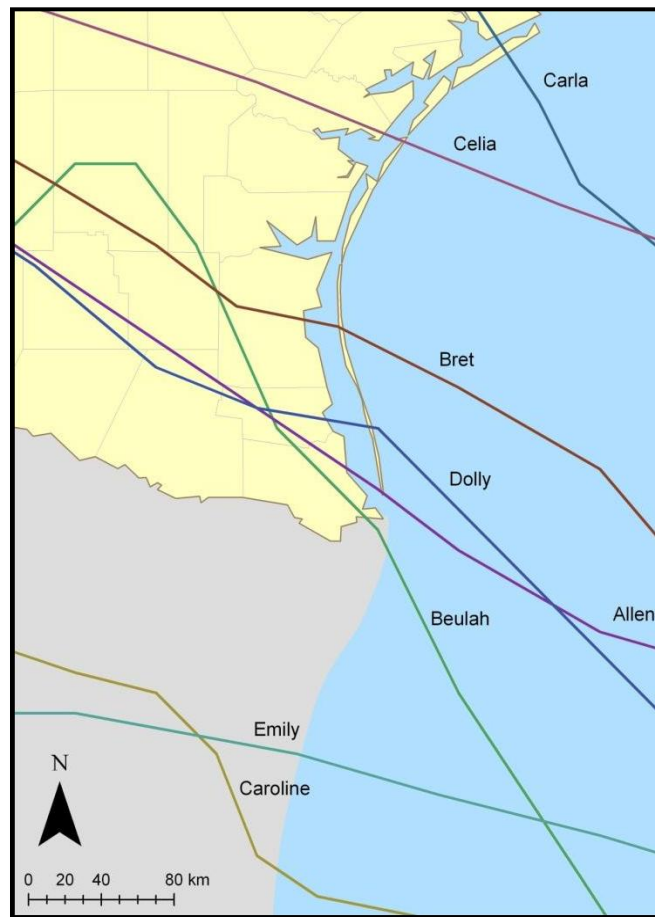


Figure 21. Major storms since 1960. Data obtained from NOAA National Hurricane Center (<http://www.nhc.noaa.gov/>).

METHODS

To better understand the beach and dune system on SPI, this project focused on building a sediment budget for the beach-dune environment and performed quantitative analysis of dune accretion rates to dune and beach metrics. The sediment budget consisted of calculating volume change for the beaches and dunes and an estimation of the onshore aeolian sediment flux.

Table 5. *Data sources*

Year	Data Type	Source
2000	DEM (August)	BEG
2005	DEM (August)	BEG
2009	DEM (February)	BEG
2009-2010	Beach and dune topographic surveys	TAMUCC
2000-2009	Wind data	TCOON
1995	DOQ	USGS
2004	DOQ	TNRIS-USDA
2009	NAIP imagery	TGLO

Data used in this project are lidar-derived DEMs for the years 2000, 2005, and 2009, beach profile data collected from Summer 2009-Fall 2010, digital imagery for years 1995, 2004, and 2009, and wind speed and direction data for the time period of 2000 to 2009 (Table 5). All coordinate values are based on national datums. The horizontal coordinates are referenced to the North American Datum of 1983 (NAD83) and the vertical coordinates are referenced to the North American Datum of 1988 (NAVD 88), as required by the standards of the Federal Geographic Data Committee (1988). All distances and heights are expressed in meters.

The Sediment Budget Approach

According to Rosati (2005), there are five steps in producing a sediment budget, 1.) create a conceptual budget 2.) delineate the sediment budget cells 3.) identify sediment budget pathways 4.) estimate volume changes, and 5.) estimate sediment fluxes. In a sediment budget, the volumetric differences in a study cell must equal the rate of change represented in the following equation (Rosati 2005):

$$\sum Q_{source} - \sum Q_{sink} - \Delta V + P - R = residual$$

Equation 1

Q_{source} and Q_{sink} are the sources and sinks that contribute to the sediment volume of the cell, ΔV is the net change in volume within the cell, and P and R represent the volume of material placed or removed from the cell, respectively.

Figure 22 displays the conceptual model explaining the relationship between the beach and dune sediment budget. The sediment sources for the beach environment come from sand transported onshore, from alongshore aeolian transport, and from any sand mechanically placed on the beach (e.g. beach nourishment). Sediment sinks corresponding to the beach are landward aeolian transport to dunes, alongshore transport away from the beach cell, and offshore sediment transport. Sediment sources for the dune cells come from landward sediment transport from the beach, alongshore aeolian transport, and from sand placed directly on the dunes. Sediment lost from the dune

environment can be transported landward to the backbarrier environments (sink) by aeolian or by washover processes, as well as seaward if eroded by wave activity.

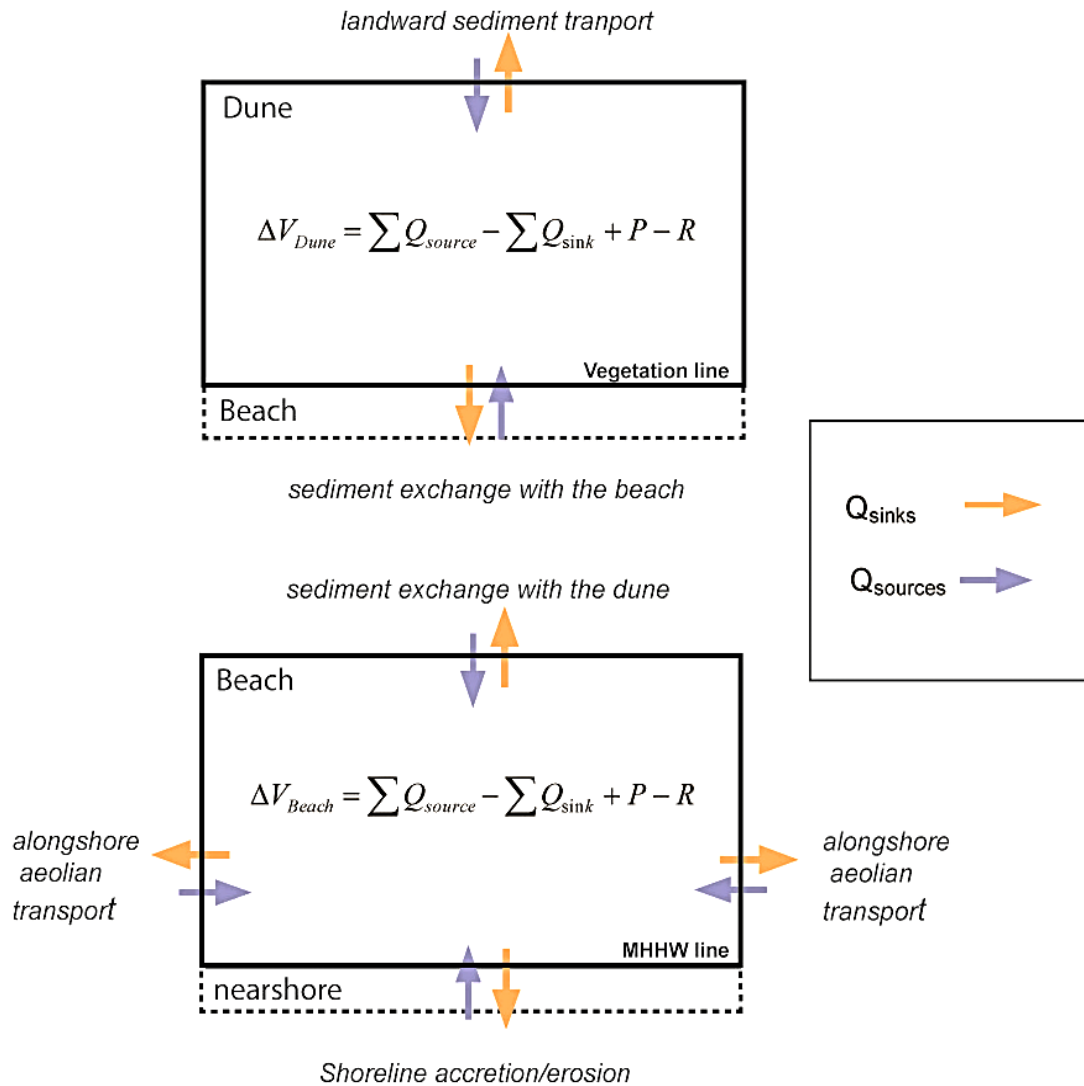


Figure 22. Conceptual sediment budget for beaches and dunes

Beach and Dune Budget Cells

The beach and dune cells used for volume calculations were created from a set of contours, a manually digitized landward dune boundary, and a set of shore-perpendicular transects. Using these boundaries the study area was split into 120 cells, 60 beach and 60 dune cells, each 500-meters in alongshore length. A 500-m length was chosen to achieve a detailed pattern of beach and dune accretion/erosion, while cancelling noise in volume calculations. Additionally, 500-m corresponds to one of shorter wavelengths of shoreline rhythms that occur on SPI.

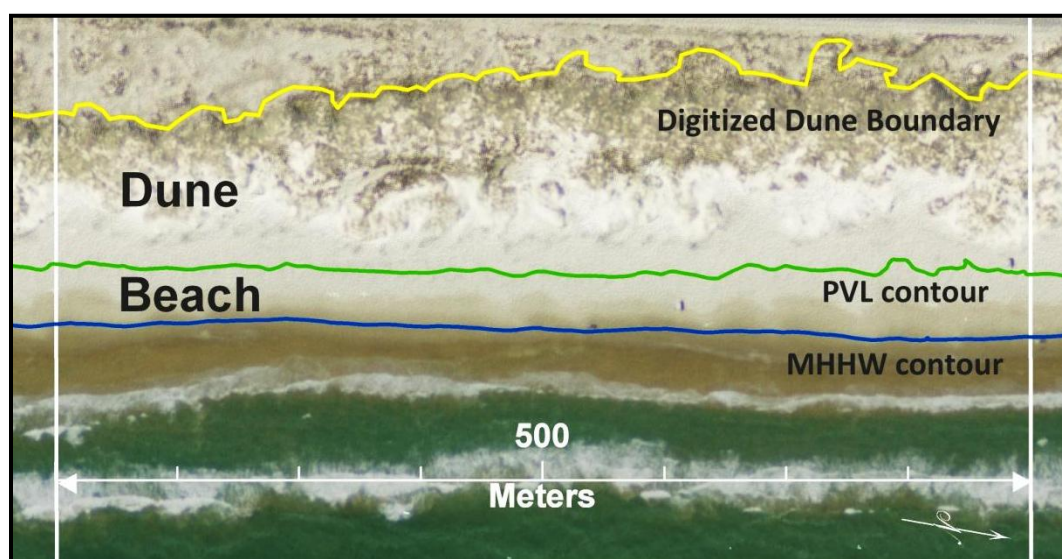


Figure 23. Aerial view of beach and dune boundaries. Each cell is 500-m in alongshore length. The beach environment is bounded by the MHHW and PVL contour and the dune environment is bounded by the PVL contour and a manually digitized dune boundary line.

The cross-shore boundaries for the beach and dune environments are the Mean Higher High Water (MHHW) line as the seaward beach boundary, the potential vegetation line (PVL) as the beach landward boundary and the dune seaward boundary,

and a manually digitized line as the landward foredune boundary (see Figure 23). Tidal datum values were obtained from the National Oceanic and Atmospheric Administration (NOAA) Tides and Currents website (<http://tidesandcurrents.noaa.gov>) for station #8779750 (Figure 24) . This station was operational from June 1, 1956 to May 5, 1994 and was located in Brazos Santiago Pass. Although this tide gauge is no longer operational, it is the closest ocean-side tide gauge whose datum values are in accepted status for the latest tidal epoch for SPI. Contours based on tidal datums are referenced to the geodetic datum NAVD88. The NAVD88 height above the station datum for the NOAA station 8779750 is 0.854 m (Figure 25), for the MHHW is 0.175 m and for the PVL is 1.192 m.



Figure 24. Tidal datums used in this study were obtained from the NOAA tide station #8779750 located within the Brazos Santiago Pass at the southern end of South Padre Island.

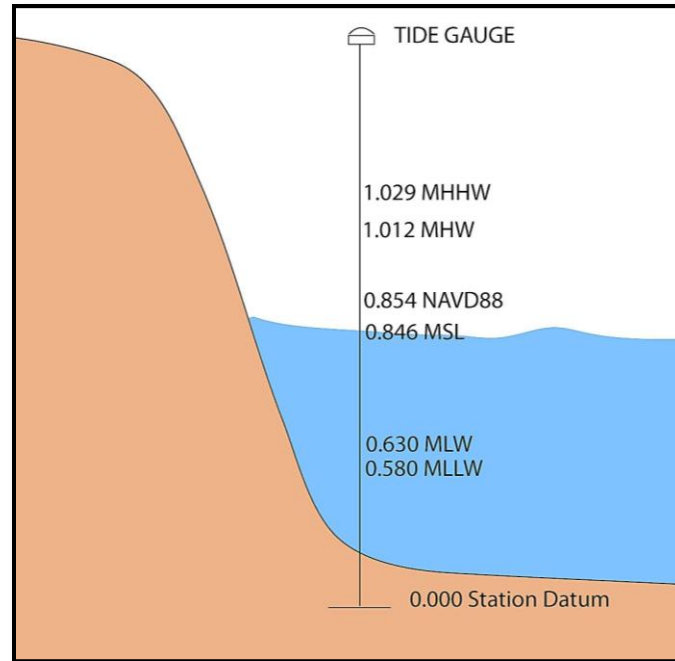


Figure 25. Tidal datums of NOAA station 8779750 Padre Island, Brazos Santiago Pass, Tx (figure not to scale).

The PVL contour value follows Gibeaut and Caudle (2009) and is equal to 1.2 m above MSL. They determined that 1.2 m above mean sea level is the lowest elevation at which vegetation can grow a continuous cover from statistical analysis of long-term beach profile elevation data of natural dunes along the Texas coast. When compared to aerial imagery, the actual vegetation line and the PVL do not necessarily correspond to one another (Figure 23). The actual vegetation line in areas of transgressive dunes is located behind the dune features on the vegetated barrier flats. In areas where the foredune feature is vegetated, the PVL is usually located seaward of the actual vegetation line. Since the purpose of the PVL is to separate the marine-dominated beach and aeolian-dominated dune environments, and because of the erratic nature of the natural

vegetation line, it was considered the best method for this study to use the PVL contour as a representative boundary of the seaward-most location where vegetation may occur.

The foredune complex boundary was digitized using ArcGIS 9.3.1 from aerial imagery, a DEM (reclassified to show elevation above 2m), raster data representing the topography aspect from west, northwest, and southwest, a raster representing height differences between two time periods to identify areas of significant sediment, and a shapefile of the PVL contour. For a detailed foredune mapping criteria refer to appendix A. The ArcGIS smooth line function was used on all contours to simplify the line (with a moving path tolerance of 5m).

Sediment Budget Pathways

Sediment budget pathways describe the significant sediment transfers between cells in a sediment budget. These may be simple to define through general knowledge of the area or through aerial or topographic mapping, but estimating the magnitude of the transport is be more difficult (Rosati 2005). Figure 26 illustrates the possible pathways of sediment transport that can occur on SPI.

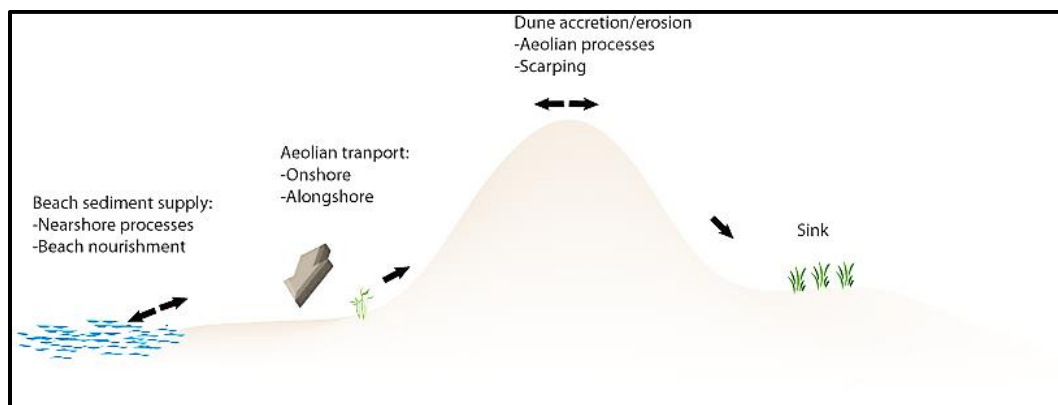


Figure 26. Sediment budget pathways.

Beach and Volume Change Calculation

Lidar and Digital Elevation Models. The primary data sources for this study are DEMs derived from airborne topographic lidar. Lidar surveys make it possible to collect dense topographic data over a large geographic region, making this technology increasingly utilized for coastal research studies and coastal management applications (Gares, Wang, and White, 2006; Gutierrez et al., 2001; Kratzmann and Hapke, 2008; Robertson et al., 2004; Sallenger et al., 2003; Stockdon, Doran, and Sallenger, 2009; Stockdon et al., 2002; White and Wang, 2003).

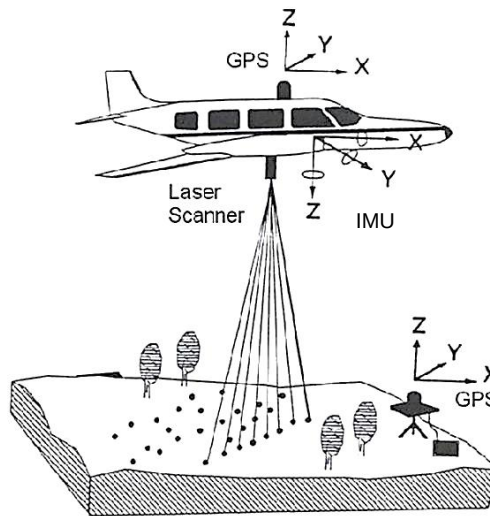


Figure 27. Lidar data collection system.
 Picture obtained from
<http://slvg.soe.ucsc.edu/unvis.html>.

Lidar is an active remote sensing technology (Figure 27) used to calculate the elevation of the ground surface with the use of plane-mounted laser transmitters, kinematic global positioning system (GPS), and an inertia measurement unit or IMU

(Jensen, 2007). The GPS is used to track the exact location of the aircraft at the instant that the laser pulse is transmitted and received. The IMU measures the roll, pitch, and yaw of the aircraft and is used for adjustment of position and elevation calculations. Ground GPS stations provide a correction to the GPS position recorded from the plane (National Oceanic and Atmospheric Administration Coastal Services, 2008). Post processing of lidar data integrates information from the lidar sensor, IMU, ground GPS, and airborne GPS to develop elevation values for specific x,y locations (Jensen, 2007). Elevation values are collected in Height Above Ellipsoid (HAE), and then converted to NAVD88 using the Geoid99 model.

The 2000 and 2005 lidar data was collected by the Bureau of Economic Geology (BEG) at The University of Texas at Austin (UT) as part of the Texas shoreline change project. These surveys collected topographic data from the shoreline to an extent 300 m landward from the beach, for the entire Texas coast. The 2009 lidar survey was collected by the BEG at UT in collaboration with the Harte Research Institute (HRI) at Texas A&M Corpus Christi, and has a study area that covers the lower 30 km of SPI. The 2009 survey area extends cross the width of the barrier island, from the Gulf of Mexico to the Laguna Madre. All surveys were collected using the same equipment and procedures describe in Gutierrez et al. (2001). The DEMs created from the lidar point data have a 1m x 1m cell size and a horizontal accuracy of 0.01-0.03 m, well within the 1 m resolution. Vertical accuracy is from 0.01-0.5 m with a root mean square error (*RMSE*) <0.095 m as derived from comparing lidar points with ground-surveyed points on roads.

Elevation Bias Determination and Correction. Three types of error that can occur in measurements and observations of ground elevation data are gross error, systematic error, and random errors (Lo and Yeung, 2006). Gross errors are usually mistakes that can be detected by independent checks. Systematic errors result from bias in the measurements, mechanical defects, or changing of environmental conditions. The effects of systematic error are cumulative and therefore were addressed in this study. Truly random errors are the inconsistencies in measurements that are left after eliminating gross and systematic error. Random errors tend to be small and normally distributed, and because some of the errors are positive and some are negative their cumulative effect is close to zero.



Figure 28. Digitized points for determining elevation bias between lidar DEMs.

The systematic error was assessed through a comparison of elevation values between all three DEM datasets. A geographic file containing points (Figure 28) placed on broad flat concrete surfaces such as roads, seawalls, and parking lots, was used to extract elevation values from all three datasets (2000, 2005 and 2009). The elevation

differences between DEMs were calculated using the 2000 DEM as the reference elevation. The mean error (Z_m) and $RMSE$ were calculated as shown in Equation 2 and Equation 3 for the years 2005 and 2009.

$$Z_m = \frac{\sum_{i=1}^n (z(reference)_i - z(sample)_i)}{n}$$

Equation 2

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (z(reference)_i - z(sample)_i)^2}{n}}$$

Equation 3

The elevation differences for 2000-2005 were from -0.124 to 0.161 with a Z_m of 0.010 m. Elevation differences between the 2000 DEM and 2009 DEM ranged from -0.305 to -0.013 with a Z_m of -0.150 m. The $RMSE$ values for 2000-2005 and 2000 to 2009 are 0.055 and 0.162, respectively.

The systematic error observed in the 2009 DEM was corrected by applying Z_m (-0.15 m) to the elevation values. Once the elevation bias was adjusted, elevation differences were recalculated between the 2000 to 2009 DEMs, resulting in a $RMSE$ of 0.063m.

Extracting Beach and Dune Volume from DEMs. Elevation statistics were calculated for the years 2000, 2005, and 2009, for all cells, 60 beach and 60 dune cells (see Appendix B and G). The results contain the min, max, range, mean, standard deviation, and sum value of elevation for each cell. The sum represents the addition of the elevation value of every pixel (1x1 m) within a polygon and therefore the volume above NAVD88. Volume for each cell was normalized by dividing the volume by the length of the cell (500 m), and is represented as m^3 per m. The volume of sand held within the defined boundaries for each year (see Figure 29) was compared for the years 2000 to 2005, 2005 to 2009 and 2000 to 2009.

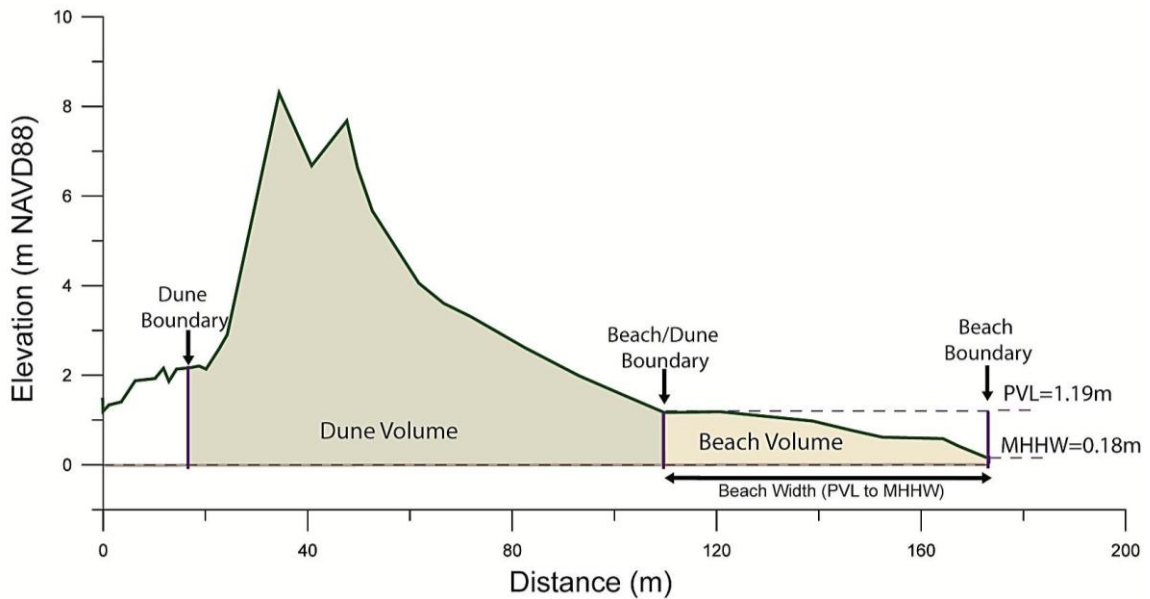


Figure 29. Boundaries for beach and dune volume estimation.

Sediment Transport

Calculating the rate of aeolian sand transport is an important step in the development of a beach/dune sediment budget (Hsu, 1988). Potential sediment transport from the beach to the dune was calculated using wind speeds above threshold velocity for beach sand, without taking into account the unconstructive influence of fetch, beach slope, moisture, temperature, and vegetation cover (Arens, 1997). There is a myriad of sediment transport equations, all of which were derived using different methods and assumptions. Common inputs to all equations are wind shear velocity, grain size, gravity, air density, and some coefficient. These coefficients are empirically derived and because these coefficients account for violations of the model assumptions, and because beaches are all different, Sherman et al. (1998) suggests that a model that works in one location might be ineffective in another. Model assumptions are: 1.) unidirectional wind field, 2.) turbulent flow that is uniform and steady, 3.) uniform sediment size and composition, and 4.) dry sediment that occurs on a flat unobstructed horizontal surface (Sherman et al., 1998). To find the best transport equation to model the sediment movement observed in our study area, a comparison was made between two of the most widely used models, Bagnold (1941) and Hsu (1973).

Theoretical Background. Sediment movement occurs as the wind transfers momentum to the sediment, resulting in sediment suspension, saltation, or creep (Figure 4). Saltation is the predominant form of transport, accounting for 75-80% of the total weight of sand moving past a fixed point per second (Bagnold, 1941). The force exerted on the sand surface by the wind is shear stress τ (Equation 4), which is a function of the air density ρ (approximately 1.22 kg m^{-3}) and shear velocity u_* .

$$\tau = \rho u_*^2$$

Equation 4

The Logarithmic Wind Profile. The transfer of momentum to the surface of the sand is related to the vertical distribution of the wind profile and the surface roughness Z_0 (Sherman and Hotta, 1990). Assuming turbulent flow, the distribution of wind velocity varies logarithmically with the height above the surface (Bagnold, 1941; Hsu, 1973)(Bagnold 1941, 44), as follows:

$$u_z = \frac{u_*}{\kappa} \ln\left(\frac{Z}{Z_0}\right)$$

Equation 5

where u_z is the mean horizontal wind velocity for a given height Z , u_* is the shear velocity, and κ is Von Kármán's constant (≈ 0.4). Surface roughness Z_0 , also called aerodynamic roughness length, corresponds to the elevation at which wind speed drops to zero.

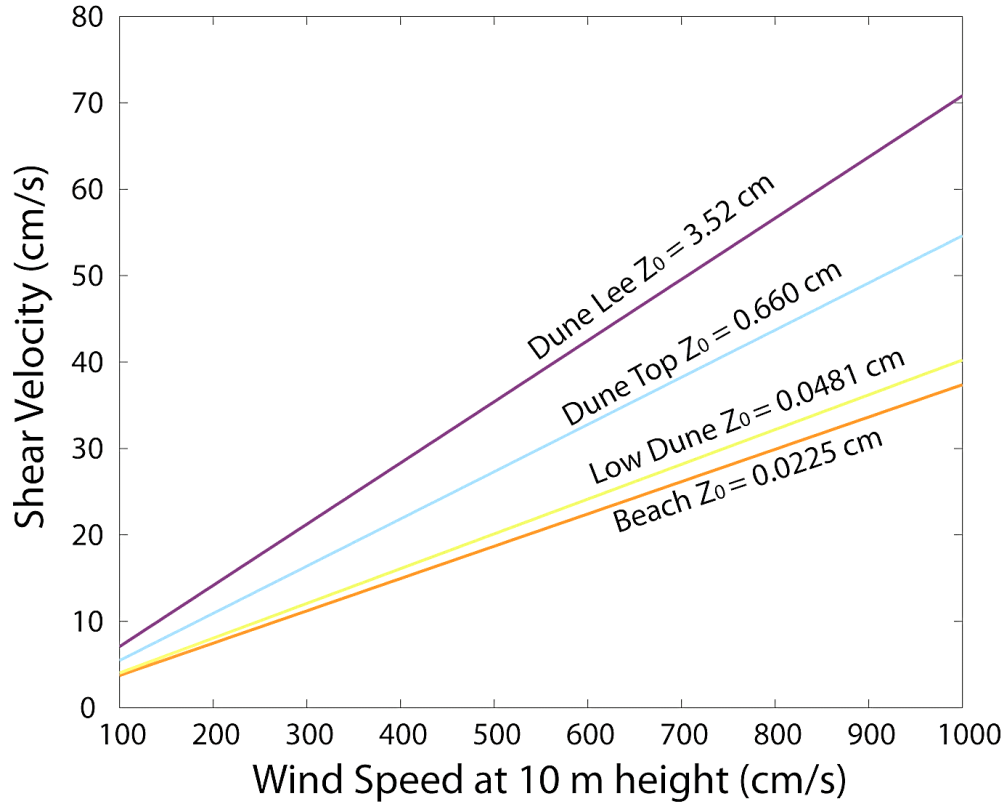


Figure 30. The relationship between shear velocity u_* and the wind velocity at 10m height for various coastal environments. Surface roughness values were obtained from Hsu (1977) and shear velocity was calculated using Equation 6.

Surface roughness varies for different coastal settings (Hsu, 1977). Figure 30 shows the effect of various Z_0 values on shear velocity for wind speeds ranging from 100 to 1,000 cm/sec at a height of 10 m. Z_0 values were derived by Hsu (1977) from field experiments that tested the transfer of momentum from the atmospheric surface boundary layer to the sediment surface. Hsu's data was collected over a variety of coastal environments in Texas, Florida, and Ecuador. From his results, it is found that an approximate roughness length for beaches is 0.0225 cm, and because it is of particular interest in this study to find the rate of transport from the beach to the dune, this is the

value used in this study for estimating shear velocity. The logarithmic wind profile equation (Equation 6) can be modified and used to estimate shear velocity as follows:

$$u_* = k * u_z / \ln\left(\frac{Z}{Z_0}\right)$$

Equation 6

Threshold Shear Velocity. For noncohesive sediment beds, sediment movement begins only after shear stress surpasses a certain threshold (u_t). Hunter and Richmond (1988) suggested a threshold velocity of $500 \text{ cm}\cdot\text{s}^{-1}$ for North Padre Island. Since field measurements of threshold velocity were not conducted in SPI, the threshold velocity values used in this study will follow that of Hunter and Richmond (1988).

Sediment Transport Models. Sediment transport models used in this study are from Bagnold (1941) and Hsu (1971). For both models, aeolian sediment transport q is expressed in $\text{g}\cdot\text{cm}^{-1}\text{s}^{-1}$ and is related to a cubic shear velocity component u_*^3 , gravity g ($980 \text{ cm}\cdot\text{s}^{-2}$), and mean grain size d (0.195 cm). Bagnold's (1941) sediment transport equation is represented by Equation 7:

$$q = C \sqrt{\frac{d}{D}} \frac{\rho}{g} u_*^3$$

Equation 7

In addition to the previous variables mentioned, this equation uses air density ρ (approximately equal to $0.0012 \text{ g}\cdot\text{cm}^{-3}$), an empirical coefficient related to sediment size

distribution C , and a reference grain diameter D equal to 0.025 cm. The empirical coefficient C , may have the values of 1.5 for nearly uniform sand, 1.8 for naturally graded sand such as that found on dunes, and 2.8 for sand with a wide range of grain sizes (Bagnold 1941). For this study a value of 1.8 was used.

Lastly, Hsu's (1988) sediment transport equation (Equation 8) has all the same basic variables including a cubic shear velocity component u_*^3 , gravity g , and mean grain size d . In addition, Hsu's equation uses a coefficient K , equal to $e^{-0.42+4.9d} \cdot 10^{-4}$. For a grain size $d=0.195$ mm, $K=1.71 \times 10^4$.

$$q = K \left[\frac{u_*}{(gd)^{1/2}} \right]^3$$

Equation 8

Wind Data. Wind speed and direction measurements used to estimate sediment transport were obtained from the Texas Coastal Ocean Observation Network (<http://lighthouse.tamucc.edu/TCOON/HomePage>) for the South Padre Island Coast Guard Station #87797481 (blue flag on Figure 31). The measurements are taken at 10 m above MSL and consist of wind speed in m/s and directions in degrees from north. Data was obtained for the time period of August 2009 to October 2010 for short-term sediment transport comparison and from August 2000 to February 2009 for long-term sediment transport estimation.

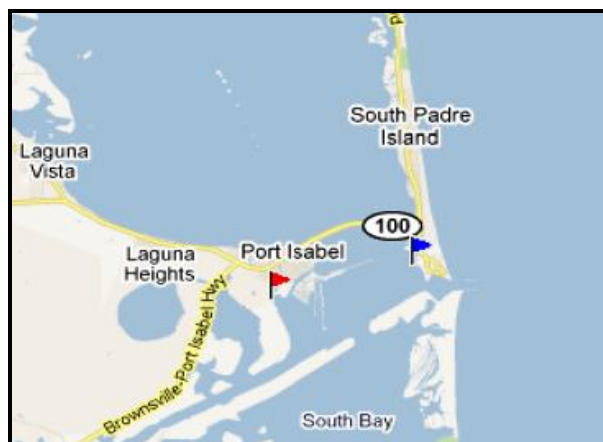


Figure 31. TCOON station #87797481 located on South Padre Island (blue flag).

For the time period of August 2009 to October 2010, one-hour averages were calculated from six-minute measurement intervals. The hourly averages help minimize data gaps and provide more accurate representation of the wind record for that hour. For the time period of August 2000 to February 2009, data was downloaded at one-hour intervals due to the large amount of data required, and it was assumed that each record is a good representation of the wind conditions for the entire hour. Each year of wind data had data gaps of approximately 200 to 350 missing hours. One large gap occurred from August 17, 2007 to August 13, 2008 and because this is a considerable gap, data was supplemented by wind speed and direction data from the Port Isabel station (red flag on Figure 31).

Field Data. To determine if either of the two sediment transport models would be useful for predicting the potential sediment transport from the beach to the dune environment for a time span of 8.5 years, the short-term sediment transport was calculated and compared to observed changes of beach profiles collected in the summer of 2009, spring 2010, and fall 2010.

Beach profiles were surveyed at 10 locations in the study area (Figure 32) by means of a level-and-transit method using a Sokkia SCT6 Total Station. Surveys were conducted in July/August 2009, April 2010, and October 2010.



Figure 32. Benchmark location for beach profiles

Volume change for observed profiles was calculated using the Regional Morphology Analysis Package (Rmap). Rmap is part of the Coastal Engineering Design and Analysis System (CEDAS) software. CEDAS incorporates 11 coastal design and analysis products developed by the Engineer Research Development Center (ERDC) of the Coastal and Hydraulics Laboratory (see: <http://chl.erdc.usace.army.mil/cedas>). This software provides tools for the manipulation, analysis, visualization, and archiving of shoreline position and beach profile data. Rmap's Cut/Fill function was used in this study to calculate the volume change between profiles. The results are presented in a table and graphical form, as seen in Figure 33. Volume change is calculated from the intersections between profiles, for each intersection cell, and for the total profile (Batten and Kraus, 2004). Sand transported from the beach to the dune environment is most likely collected at the dune toe (Figure 33), or the area extending from PVL to the first dune crest. For all profiles and volume change reports see appendix D.

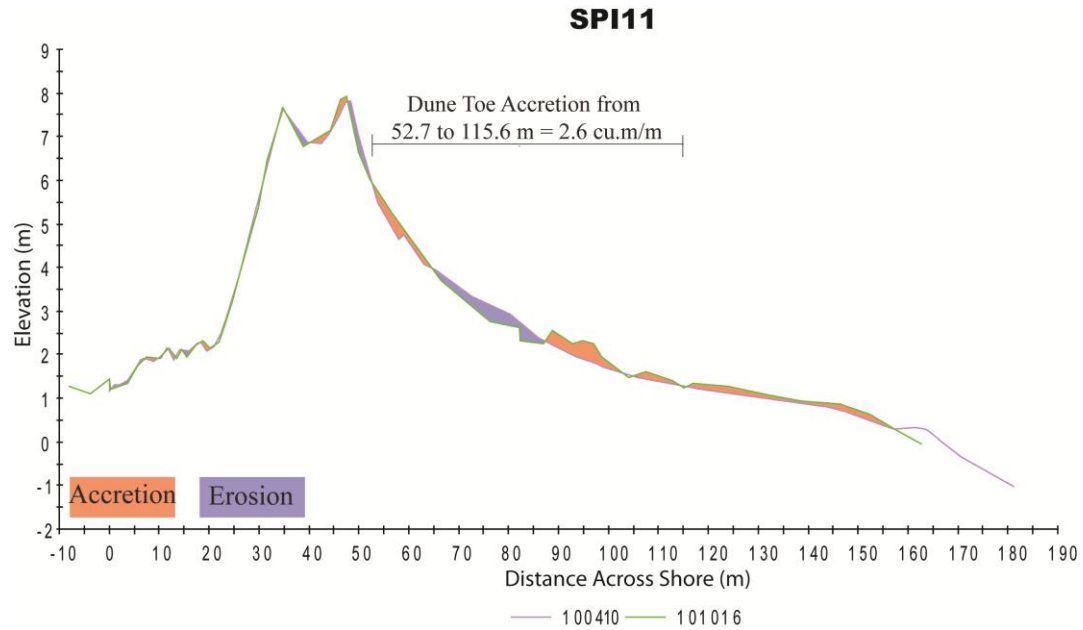


Figure 33. Example of a beach profile with cut/fill results. The orange areas represent accretion and purple areas represent erosion. In this profile the dune toe accumulation extends from 52.7 m to 115.6 m across shore.

Sediment Transport Calculations. All calculations were performed using Matlab software (see appendix C for script sample). First, the wind data files (Excel format) are read in Matlab. Wind speed was converted from m/s to cm/s and attached to a new column on the data matrix. These wind speeds were then used to calculate shear velocity using Equation 6, for each 1 hour record. Wind speeds were indexed using a logical operation to separate data that did not meet threshold velocity. Wind speeds greater than 5 m/s were given an index value of 1, and wind speeds under 5 m/s were given an index value of 0. This vector of ones and zeros was multiplied with the shear velocity results so that any wind speed of 5 m/s or less yields a shear velocity of 0, and therefore a transport value of 0. Next, using the calculated shear velocity, sediment transport was calculated for each hourly record using Hsu's (Equation 8) and Bagnold's (Equation 7) formulas.

Each record was treated as a vector with the magnitude of the potential sediment transport and direction from north. All records were added to find the resultant vector for the various time periods. The resultant vector was multiplied by 3600 sec/hr to obtain a total transport in g/cm length of beach. This transport, expressed in weight of sand, was converted to volume of sand per meter of beach width for comparison with the profile and DEM results. To convert from weight to volume, the total transport was multiplied by the bulk density of sand of 1410 kg/m^3 . The bulk density value used in this study was obtained by averaging the results obtained by McAtee and Drawe (1981). Their work compared the microclimate of various sections of the beach with varying levels of human disturbance in North Padre Island. McAtee and Drawe (1981) measured soil and atmospheric temperature, soil salinity, evaporation, bulk density of sand, and local wind speeds. Their sampling was done in various environments including the foreshore, backshore, dune crest, and back barrier flat. The bulk density results for the backshore environment ranged from 1.32 to 1.48 g/cm^3 , and averaged 1.41 g/cm^3 .

Lastly, the resultant vector was decomposed into onshore and alongshore components. These components were calculated by multiplying by the cosine and sine of the resulting vector angle relative to the shoreline orientation angle. The shoreline orientation was calculated for SPI for 1 km sections with the ArcGIS extension “Tool for Graphics and Shapes” (Jenness, 2011). The shoreline orientation for the lower 30 km of SPI varies from 345.4° to 353.7° , and the average orientation of 350.1° was used.

Beach and Dune Characteristics of Interest.

Beach characteristics collected for statistical analysis are average beach height, beach width, beach slope, and MHHW and PVL rates of change. These characteristics were compared with dune volume changes through a linear regression model.

Beach width, slope and height were calculated from DEMs. Average beach height was taken as the average elevation between the PVL and the MHHW for each section. The average beach width was measured from the PVL and MHHW lines. Slope was measured from the PVL to the MHHW line in degrees downhill (0° - 90°). For detailed methods refer to appendix C. Statistical analysis was performed using R statistical software (R Development Core team, 2009). Steps performed to complete the regression analysis are found in appendix D.

RESULTS

Alongshore Characterization of Beaches and Dunes at South Padre Island

Each 500-m section of the study area was characterized by their primary-dune form using a modified version of Ritchie and Penland's (1988) model. Dunes in the developed portion of the island were grouped together (16 sections) as these dunes are all bounded by seawalls and mechanically modified. Dunes in non-developed areas were classified as washover terrace, dune terrace, dune ridge or active (Figure 34).

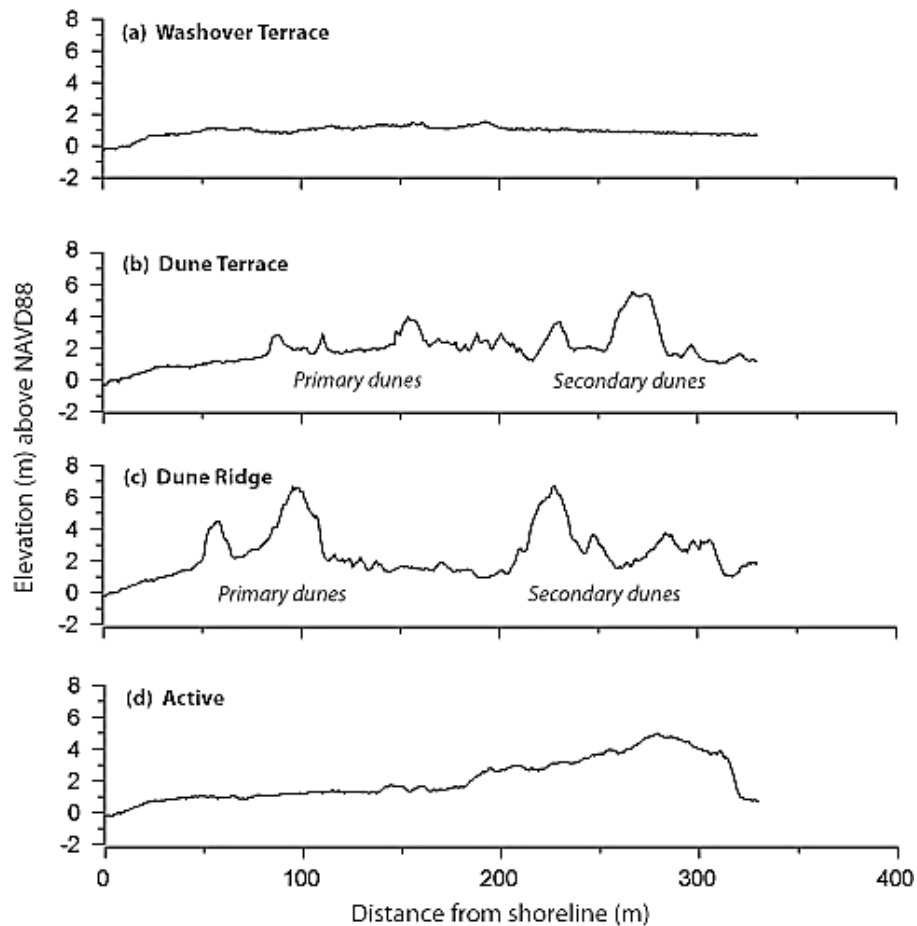


Figure 34. Dune types used in this study are washover terraces (a), dune terraces (b), dune ridges (c) and active dunes (d). Developed dune type not shown.

Washover terraces (Figure 34.a) have topography of less than 2 m in height and lack vegetation. Washover terraces are mostly found in the northern 10 km of the study area (sections 43, 47, 54-55 and 57-58 of Figure 35). Dune forms found on washover terraces are ephemeral and constantly reshaped by the wind and because of their low elevation these areas experience the highest frequency of overwash (Ritchie and Penland, 1988) reinforcing the topography of the area. The lack of vegetation causes dispersed sections of deflation. The degree of wind deflation is controlled by the water table or shell lag.

Dune terraces (Figure 34.b) have a higher topography than washover terraces, from 2-3 m in height. Incipient dunes form as sand is trapped by vegetation and accumulates into mounds. These low mounds do not form a continuous complex and therefore experience some degree of overwash penetration at their lowest points (Ritchie and Penland, 1988). Dune terraces become unstable and transgressive if the vegetation cover diminishes.

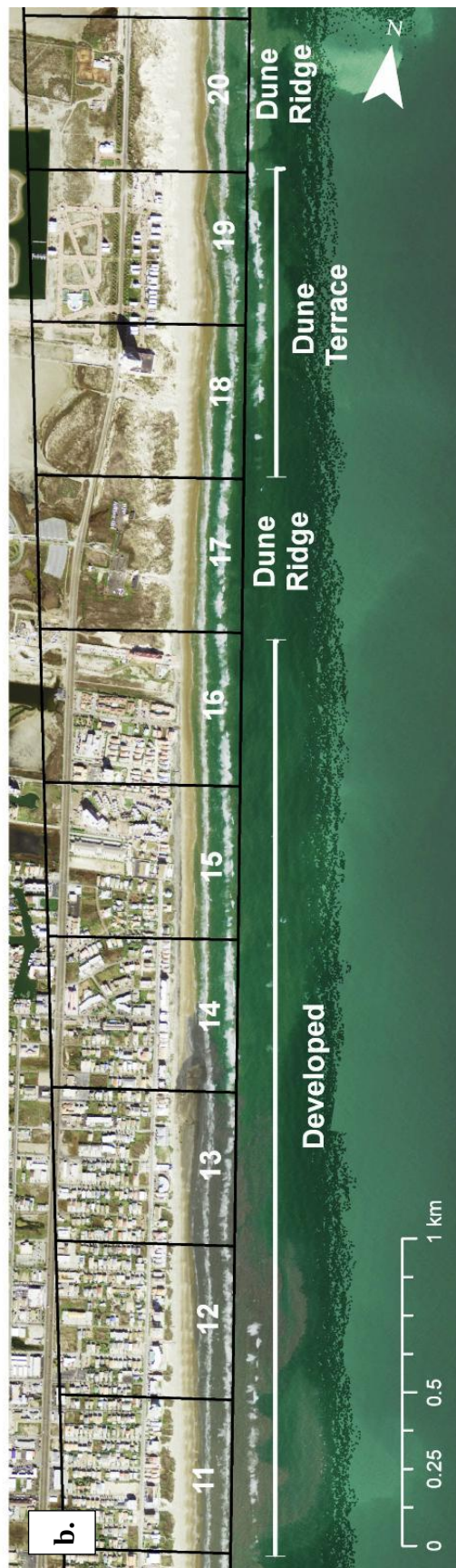
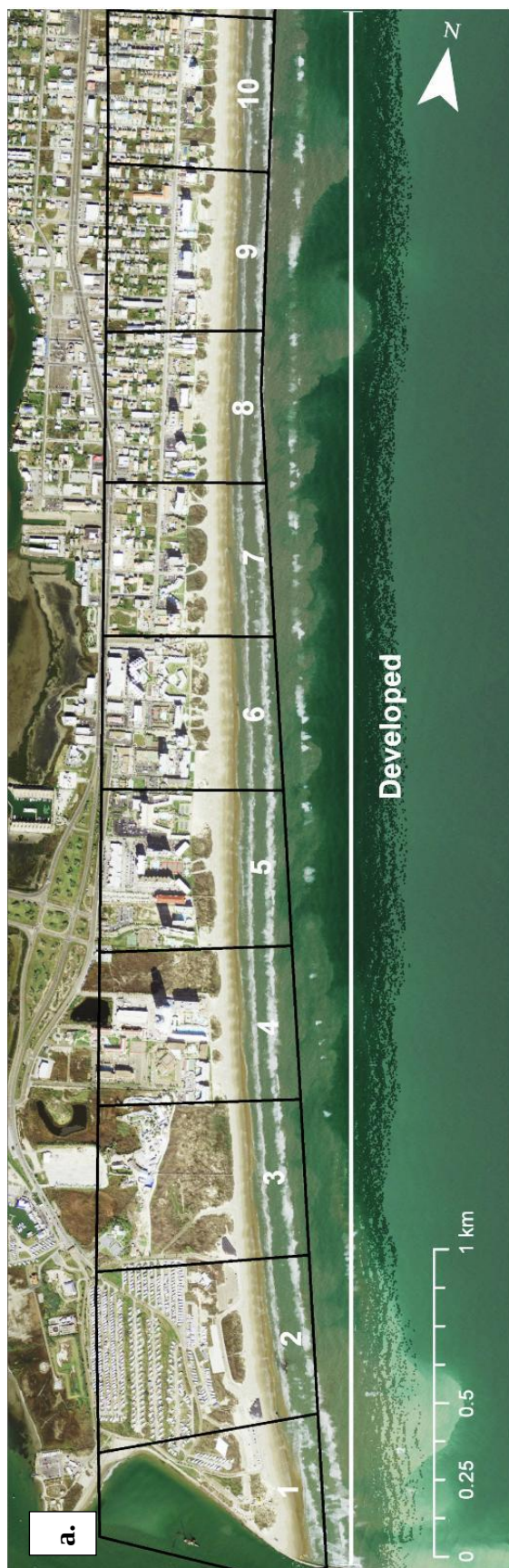
Dune ridges that occur on South Padre Island are best described as Stage 3 dunes from Hesp's (1988) morpho-ecologic model (Figure 7). These dune complexes have a hummocky topography, with some small to medium scale blowouts. Vegetation cover varies with seasonal precipitation and ranges from 30-75% cover. The height of these dune ridges ranges from 5-7 m and in some locations the height can exceed 9 m.

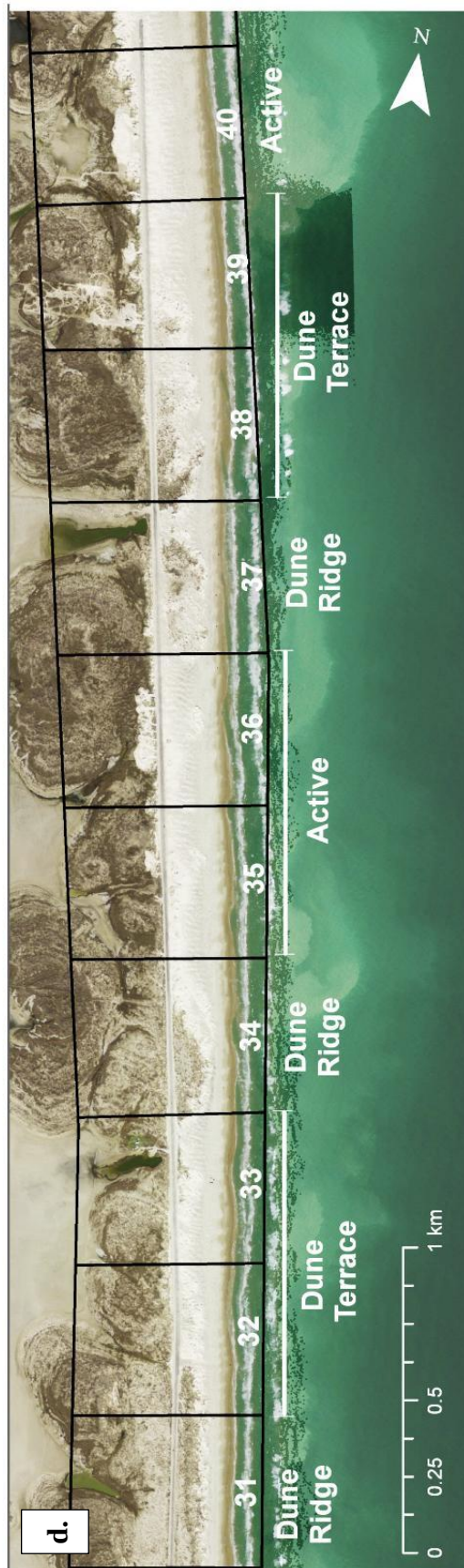
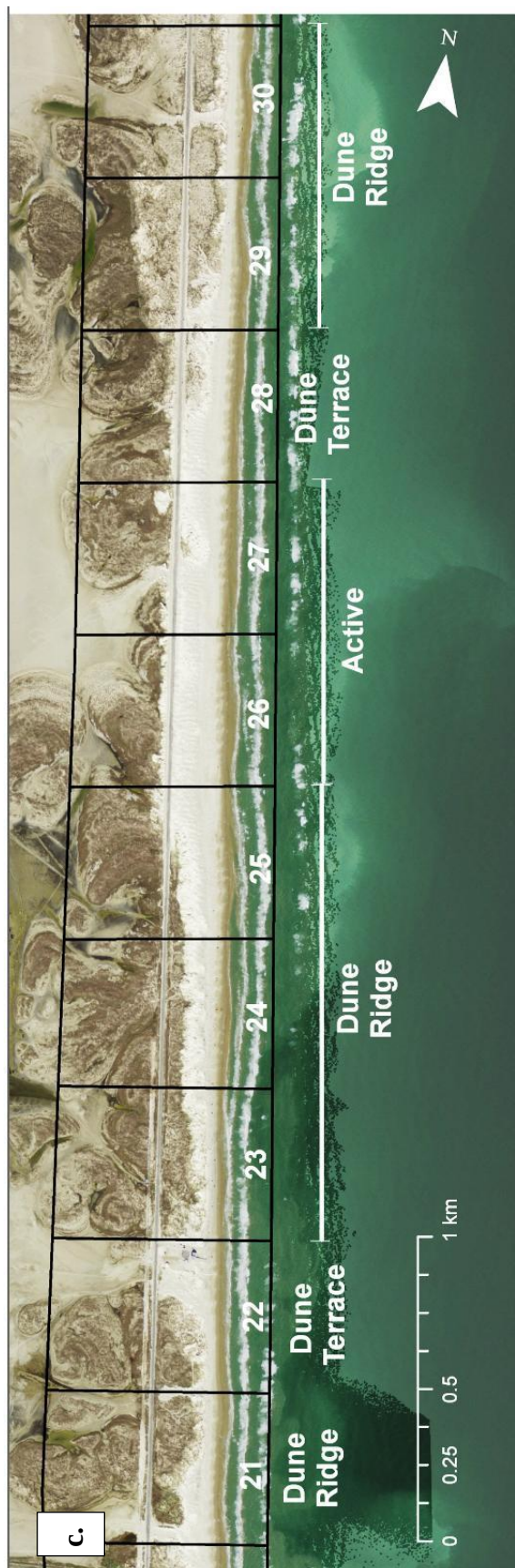
There are two types of active or transgressive dunes on SPI. One type of active dunes are low, 2-3 m barchans formed by downwind movement of sand over un-vegetated to semi-vegetated areas. These areas have similar elevation to dune terraces

but vegetation is not present to trap sand. The second type of active dunes are taller, 6-9 m, transverse dunes that migrate landward over vegetated backbarrier flats (sections 41-42, 49-51 and 56 on Figure 35). These dune features have migrated landward between 15 m and 50 m from 2005 to 2009 (rate of 4-14 m/yr).

Of the 60 sections, 15 are classified as developed, 12 as active, 18 as dune ridge, 8 as terraces and 6 as washover terraces (Figure 35). The relative occurrence of each of these dune forms will vary with precipitation, changes in sediment supply, and intensity and frequency of storms.

Figure 35. Dune type map of the study area for section 1-20 on pg 64 and 21-40 on pg 65 and 41-60 on pg 66.







Changes in Budget Cell Boundaries

Beach and dune boundaries on SPI have migrated landward over the study period. Dune landward boundaries are most stable on dune terraces and dune ridges, but have been migrating landward on active dune types. Changes to the position of the MHHW and the PVL from 2000 to 2009 are shown in Figure 36. The overall pattern is similar to long-term erosion rates, increasing northward. An exception is washover terraces which experience high rates of seaward (positive) PVL movements. Developed areas are the only sections to have a seaward movement of the MHHW, reflecting the effect of beach nourishment.

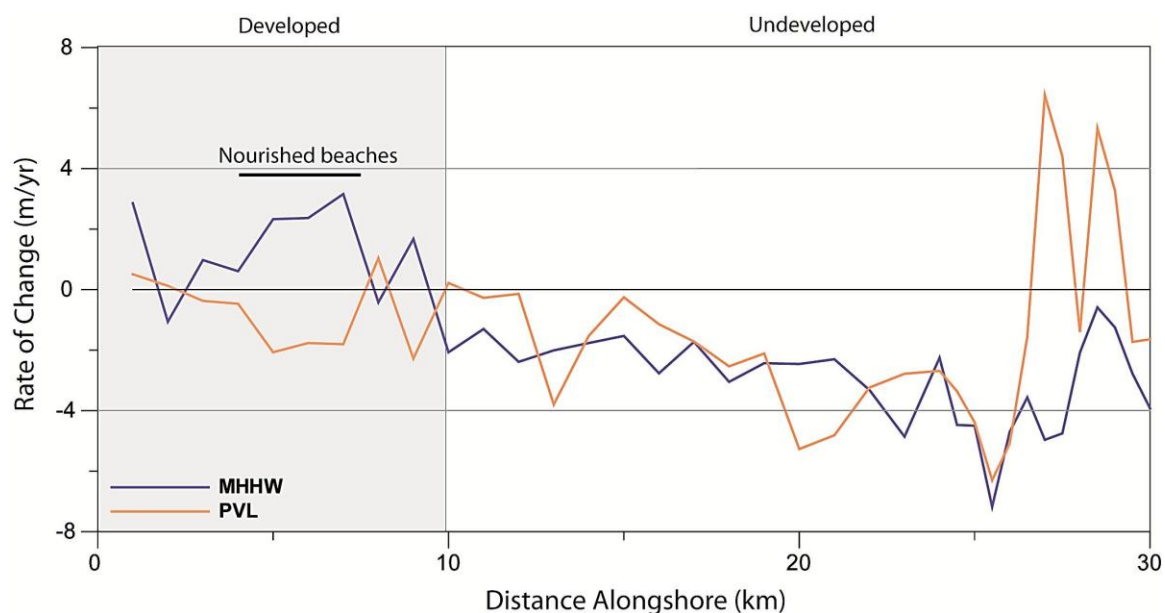


Figure 36. MHHW and PVL change rate from 2000 to 2009 in m/yr

Beach and Dune Volume Change

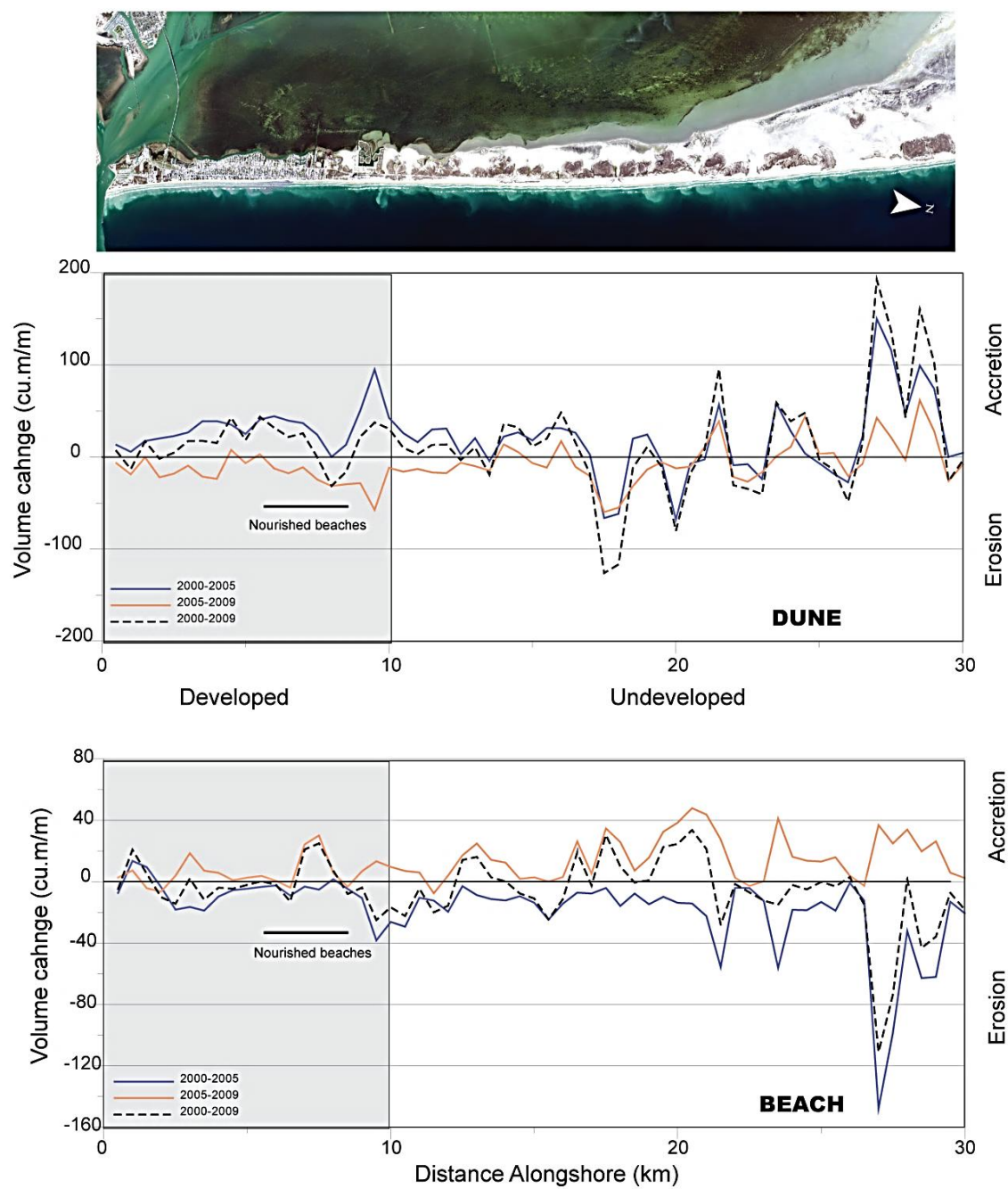


Figure 37. Beach (bottom) and dune (top) volume changes.

The total beach volume above NAVD88 held between the MHHW and PVL (Figure 29) varied for the 3 DEMs. For the entire study area the beach volume was 1.3 million m^3 of sand in 2000, 800,000 m^3 in 2005 and 1.2 million m^3 in 2009. Table 6 contains beach and dune volume changes for the 3 DEMs. From 2000 to 2005 the average beach volume change for all beaches was $-18.41 \text{ m}^3/\text{m}$ reflecting the 2005 post-storm beach conditions. Nourished and developed beaches experienced less volumetric loss ($-2.32 \text{ m}^3/\text{m}$ and $-9.5 \text{ m}^3/\text{m}$) from 2000 to 2005, compared to undeveloped beaches ($-23.58 \text{ m}^3/\text{m}$). The beach volume in 2009 was greater than in 2005, but less than the beach volumes of the year 2000; Net beach volume change from 2000 to 2009 was $-5.67 \text{ m}^3/\text{m}$. The exception was nourished beaches which experienced a $6.77 \text{ m}^3/\text{m}$ gain in volume, reflecting the nourishment event of 2009. The difference in beach volume between the 2000 and 2009 DEM may be related to seasonal variations in nearshore conditions.

Table 6. *Average normalized volume change for beach and dune compartments. Results are summarized by year and beach type.*

	2000-2005 (m^3/m)		2005-2009 (m^3/m)		2000-2009 (m^3/m)	
All (n=60)	-18.41	21.88	12.73	-8.32	-5.67	13.57
Developed (n=20)	-7.24	30.97	6.02	-17.29	-1.21	13.68
Not developed (n=40)	-23.58	17.67	15.84	-4.16	-7.74	13.51
Nourished (n=8)	-2.32	27.29	10.03	-15.70	6.77	10.64
Not nourished(n=52)	-20.19	21.28	13.03	-7.50	-7.59	14.02
Not nourished Developed (n=12)	-9.50	32.67	4.17	-18.03	-7.02	15.89
Not Nourished Not Developed (n=40)	-23.58	17.67	15.84	-4.16	-8.05	13.51

Most beach-volume changes observed between 2000 and 2009 are related to the difference in nearshore conditions, since the 2000 lidar data was collected in August and the 2009 was collected in February. One exception are beaches associated with washover terraces which experienced significantly greater beach volume loss, as well as the largest range of values (-15 to -115 m³/m). Since beach volume was calculated between the PVL and MHHW the volume within this environment is fairly constant, with the exceptions of washover areas which have experienced rapid accretion and seaward-movement of the PVL (see Figure 36), this seaward movement of the PVL resulted in a smaller beach area in 2009 than in 2000, thus reflecting large negative beach volume change.

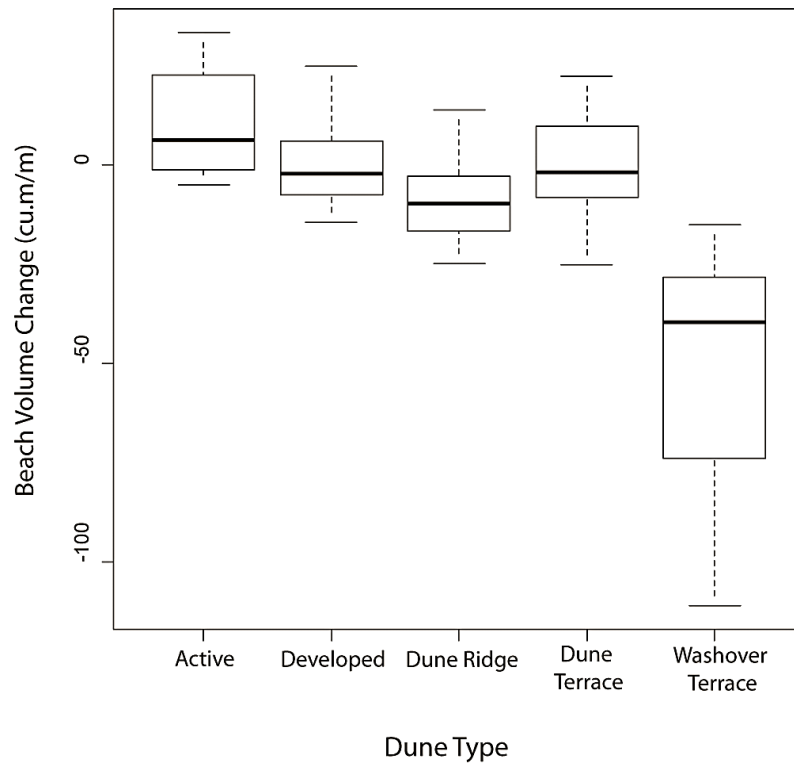


Figure 38. Beach volume change from 2000-2009 by dune type. Box plots represent 1st and 3rd quantiles, the bars represent the extent of outliers and the bold bar is the median.

During the study period, the dune environment held a total volume that ranged from 10.5 to 11 million m^3 of sand. From 2000 to 2005 most sections of the study area experienced dune accretion (Table 6). Nourished beaches had greater dune volume change ($27.29 \text{ m}^3/\text{m}$) than non-developed beaches ($17.67 \text{ m}^3/\text{m}$), but developed non-nourished beaches experienced even greater dune accretion ($32.67 \text{ m}^3/\text{m}$). From 2005 to 2009 most dunes experienced erosion. In this case, un-nourished, developed areas experienced the greatest dune volume loss ($-18.03 \text{ m}^3/\text{m}$), followed by nourished beaches ($-15.70 \text{ m}^3/\text{m}$). Dune-volume loss was lower for undeveloped areas and averaged $-4.16 \text{ m}^3/\text{m}$. Dune erosion from the 2008 hurricane season is reflected in the 2009 DEM, where dunes lost 38% loss of the dune volume gained from 2000-2005. This percent is larger for developed, nourished areas (61%) compared to undeveloped areas (19%).

Dune volume change and depositional pattern varied by dune form reflecting the degree of relative influence from marine and aeolian processes. From 2000 to 2009, the greatest dune accretion was observed in washover terraces (Figure 39), which had a mean of $124.74 \text{ m}^3/\text{m}$. This large increase of dune volume reflects aeolian accumulation, the gain in dune area from PVL movement seaward, as well as wave run-up, overwash-accumulation from the 2008 hurricane season. The aeolian-sand deposits in washover areas occur along the flanks of the washover as rim accumulation, as referred to by Ritchie and Penland (1990). Ritchie and Penland explained that the presence of debris and vegetation along the flanks of the washover channel helps traps wind transported sand and results in rim accumulation.

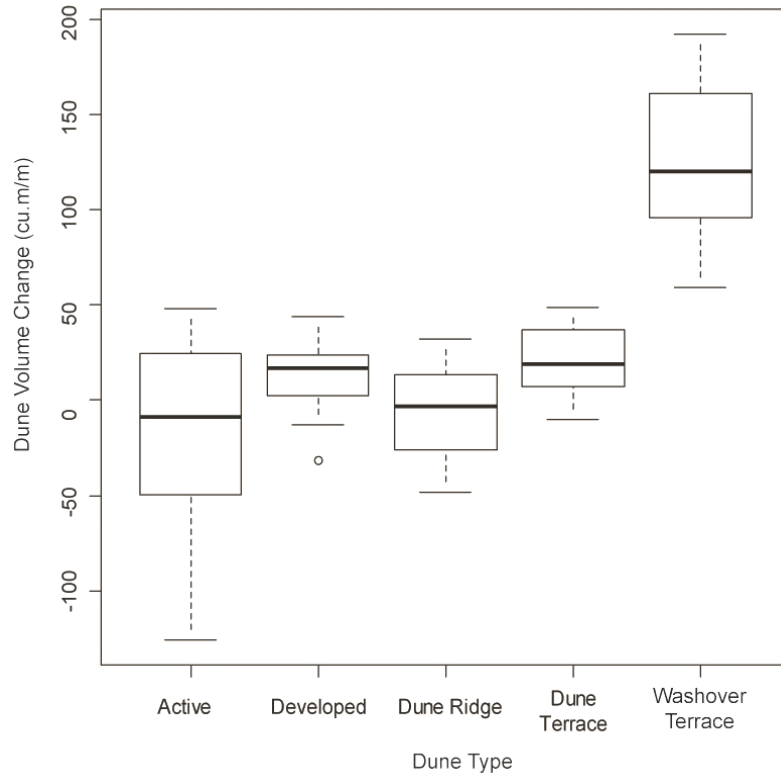


Figure 39. Dune volume change from 2000-2009 by dune type. Box plots represent 1st and 3rd quantiles, the bars represent the extent of outliers and the bold bar is the median.

Dune terraces and developed sections experienced positive dune volume change over the study period, and had mean of $20.47 \text{ m}^3/\text{m}$ and $13.53 \text{ m}^3/\text{m}$, respectively. Dune terraces had an overall increase in elevation as wind-transported sand deposits around vegetation forming nebkas or incipient dunes approximately 100-200 m landward of the shoreline (Figure 34). Dune ridge areas and active areas both had a decrease in volume from 2000 to 2009 of $-4.81 \text{ m}^3/\text{m}$ and $-19.01 \text{ m}^3/\text{m}$, respectively. Dune volume loss in dune-ridge areas resulted from dune scarping. In active-dune sections, the dune volume change resulted from aeolian processes, hence the volume change ranged from $+67 \text{ m}^3/\text{m}$ to $-126 \text{ m}^3/\text{m}$ in active dune sections.

Sediment Transport

Two models were considered for estimation of the potential sediment transport for the region, Hsu (Hsu 1973) and Bagnold (1941). The cumulative results of the transport models were compared to sand deposition at the seaward toe of the dune, as observed from profiles measured along South Padre Island (Figure 32). These profiles were collected in July/August 2009, April 2010 and October 2010. Dune toe and profile volume change are shown in Table 7. Cumulative results from the transport models were converted from g/cm/s to m^3/m for comparison to beach profile and DEM volume change results. Table 8 presents the cumulative onshore component from the two sediment transport models and the average dune toe accumulation for each of the time periods.

Comparison of Sediment Transport Models

From August 2009 to April 2010 Hsu's model results in a cumulative transport of 9.8 m^3 of sand in a direction of 304.2° from north. This vector is composed of an onshore component equal to 6.8 m^3 and alongshore component equal to 7.1 m^3 . Results calculated from Bagnold's model are similar and have a cumulative vector of 9.5 m^3 in a direction 304.2° from north. The observed dune toe deposition for various beach profiles (Table 7) from summer 2009 to spring 2010, ranged from $-18.1 \text{ m}^3/\text{m}$ to $12.53 \text{ m}^3/\text{m}$ and had an average of $2.2 \text{ m}^3/\text{m}$. The potential transport falls within the range of the observed volume changes.

Table 7. *Dune volume changes estimated from beach profile surveys*

	Site	Description	Profile 1	Profile 2	Dune toe accumulation (m ³ /m)	Total dune volume change (m ³ /m)
Summer 09 / Spring 10	SPI01	developed	8/25/2009	4/11/2010	0.20	0.20
	SPI02	developed	7/15/2009	4/11/2010	6.82	6.82
	SP115	dune-ridge, traffic	8/23/2009	4/10/2010	3.57	2.79
	SPI08	dune ridge, scraped, traffic	8/25/2009	4/11/2010	0.38	9.54
	SPI09	dune-terrace active	7/14/2009	4/11/2010	5.80	4.91
	SPI11	dune ridge	8/24/2009	4/10/2010	6.37	4.99
	SPI12	washover dune ridge,	7/13/2009	4/11/2010	12.53	5.35
	SP106	fragmented	7/15/2009	4/9/2010	-18.05	74.61
Spring 10 / Fall 10	SPI01	developed	4/11/2010	10/16/2010	5.20	5.20
	SPI02	developed	4/11/2010	10/16/2010	-1.33	-1.33
	SP115	dune-ridge, traffic	4/10/2010	10/17/2010	1.04	1.24
	SPI08	dune ridge, scraped, traffic	4/11/2010	10/17/2010	-5.49	-14.86
	SPI09	active	4/11/2010	10/17/2010	-3.73	-0.65
	SPI11	dune ridge	4/10/2010	10/16/2010	2.64	1.85
	SPI01	developed	8/25/2009	10/16/2010	3.89	3.89
	SPI02	developed	7/15/2009	10/16/2010	5.53	5.53
Summer 09 / Fall 10	SP115	dune-ridge, traffic	8/23/2009	10/17/2010	4.52	4.32
	SPI08	dune ridge, scraped, traffic	8/25/2009	10/17/2010	-3.06	-4.72
	SPI09	active	7/14/2009	10/17/2010	-3.40	0.56
	SPI07	active	8/23/2009	10/16/2010	3.90	0.68
	SPI11	dune ridge	8/24/2009	10/16/2010	6.86	8.55

From April 2010 to October 2010 the cumulative potential transport from Hsu's formula was $25.2 \text{ m}^3/\text{m}$ in a direction 324.9° from North. The onshore component was $22.8 \text{ m}^3/\text{m}$ and alongshore component was $10.7 \text{ m}^3/\text{m}$. Bagnold's formula resulted in similar results. The total transport volume was a vector of $24.4 \text{ m}^3/\text{m}$ in a direction 324.9° from north. The onshore component was $22.1 \text{ m}^3/\text{m}$. The observed dune-toe accumulation ranged from $-5.5 \text{ m}^3/\text{m}$ to $5.2 \text{ m}^3/\text{m}$ with an average of $-0.2 \text{ m}^3/\text{m}$. For this time period, the potential transport values fall outside the measured values. The results from April to October are larger than those from August to March due to the variation in wind direction. The fall and winter months have a significant input from north/northwest winds that reduce the influence of the south/southeast winds (Figure 40). In addition, during the summer of 2010 south Texas was impacted by a hurricane and a couple of tropical storms. Storm surge associated with these events caused some dune scarping; half of the profiles from the spring 2010- fall 2010 survey (Table 7) experienced erosion during this time.

Table 8. *Comparison of results from sediment transport models (onshore component) to measured values.*

	Results of Sediment Transport Models (m^3/m)		Measured (m^3/m)
	Hsu (1977)	Bagnold (1941)	Average dune toe accumulation
summer 09-spring 10	6.8	6.6	2.2
spring 10- fall 10	22.8	22.1	-0.2
summer 09-fall 10	29.7	28.7	2.6

The total potential transport from August 2009 to October 2010 using Hsu's formula resulted in a vector with magnitude of 34.6 m^3 in a direction 319.2° from north. The onshore component is $29.7 \text{ m}^3/\text{m}$ and alongshore component of $17.8 \text{ m}^3/\text{m}$.

Similarly, Bagnold's model resulted in a vector of $33.4 \text{ m}^3/\text{m}$ in a direction 319.2° from north. The onshore component is $28.7 \text{ m}^3/\text{m}$ and alongshore component is $17.2 \text{ m}^3/\text{m}$. Observed dune toe accumulation changes ranged from $-3.4 \text{ m}^3/\text{m}$ to $6.9 \text{ m}^3/\text{m}$ and an average of $2.6 \text{ m}^3/\text{m}$. Therefore over the 9 month period the potential transport is more than 10 times the observed.

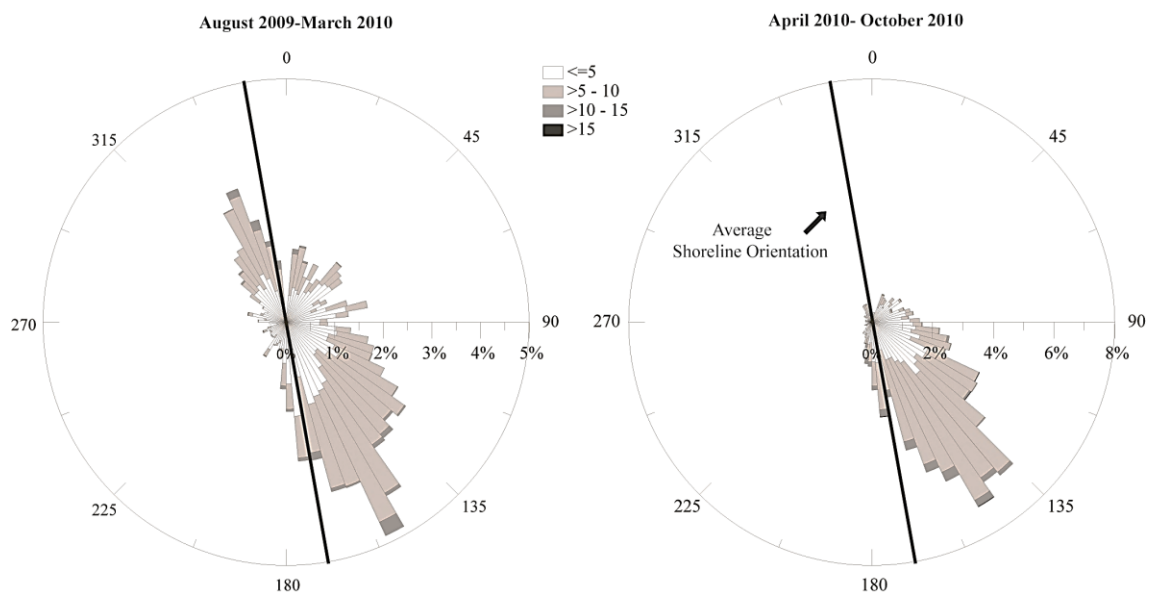


Figure 40. Wind rose associated with the time periods Aug 2009- Mar 2010 and Apr 2010 – Oct 2010

Both the Hsu (1977) and Bagnold (1941) sediment transport models produce similar results, and because the differences between the models are smaller than the alongshore variability, it doesn't matter which of the formulas is used to estimate potential transport. The overall sediment transport potential for the time period of 2000 to 2009 was computed and the results represent the higher limits of transport.

Sediment transport for the study period

For the whole time period (August 2000 to February 2009) the resultant vector was $116.4 \text{ m}^3/\text{m}$ in a direction 303.7° from north. The onshore and alongshore components of the resulting vector are similar in magnitude, $80.3 \text{ m}^3/\text{m}$ and $84.2 \text{ m}^3/\text{m}$, respectively. This value falls within the range of dune volume change observed from the DEMs ($-126 \text{ m}^3/\text{m}$ to $193 \text{ m}^3/\text{m}$), for the time period of 2000 to 2009. Averaged over the 8.5 year period, potential onshore transport is approximately $9.4 \text{ m}^3/\text{m}/\text{yr}$. Over the length of the study area (30 km), this calculated rate of potential onshore transport results in $280,000 \text{ m}^3$ of sand that can potentially move from the beach to the dune environment each year. This value is assuming that the onshore component of the wind is the only component that provides sand to the dunes, which is not always the case (Bauer and Davidson-Arnott 2003). Other studies show that oblique winds have a significant and at times a larger influence in sediment transport (Nordstrom and Jackson, 1993; Udo, 2009).

Quantitative Analysis

Beach morphometric parameters derived from the DEMs were analyzed to find their relationship with the observed dune volume change from 2000-2009. Figure 41 shows the alongshore pattern of various beach characteristics including average beach width, average beach height, average beach slope, and shoreline orientation. Beach width, measured as the horizontal distance between MHHW and PVL, ranged from 24.5 to 85.8 m and averaged 47.9 m. Average beach height from MHHW to PVL ranged from 0.67 to 0.83 m and averaged 0.74 m. Average slope of the beach ranged from 3° to 3.7° and averaged of 3.6° . Lastly, shoreline orientation for the study area ranged from 353.7° to 340.8° from north and averaged 349.8° . Toward the northern end of the island the shoreline orientation begins to increasingly deviate west as the island approaches the flank of the Holocene Rio Grande delta. This shoreline orientation pattern does not correspond to the alongshore pattern of dune volume change but is inversely correlated with the alongshore pattern of long-term shoreline change rate.

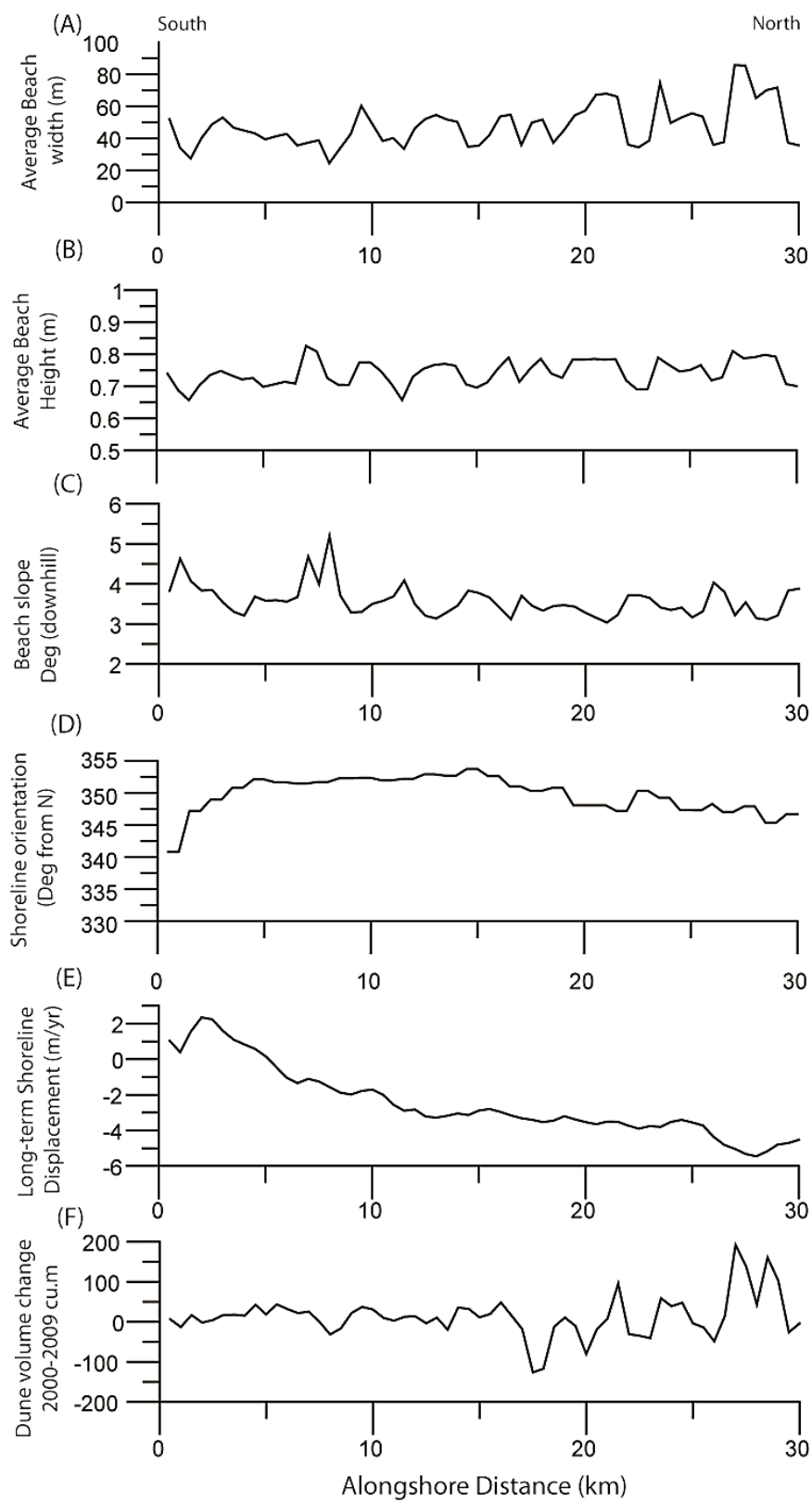


Figure 41. Alongshore variation in selected beach and shoreline characteristics along South Padre Island

The beach characteristics were compared graphically for each dune type as shown in Figure 42. Dune volume change shows a correlation of 0.55 (Pearson) with the average beach width and a smaller correlation of 0.30 with average beach height. The widest beaches are found on washover areas and these beaches are generally the ones with highest average height. The two sections with the largest beach height correspond to nourished beaches. Sections that have the lowest beach width and height are dune ridges, followed by developed unnourished beaches. Average beach slope shows a slight negative correlation of -0.23 with dune volume change. The highest average beach slope is found on developed nourished beaches. Of the non-developed dune types, dune ridges have the highest average slope (3.7°) and the active dune types have the lowest mean slope (3.26°), followed by washover terraces (3.29°).

In addition to the previously mentioned parameters, other factors considered in the quantitative analysis include long-term shoreline change rate (the average for each section from Shoreline Change Project data from B.E.G. available from <http://www.beg.utexas.edu/coastal/download.php>), MHHW and PVL change rates (from 2000 to 2009) and dune type. Using stepwise backwards regression to find significant correlations, it was found that the significant parameters which explain the variation in dune volume change are beach width and dune type (see Table 9 and Appendix D for more information on the regression analysis).

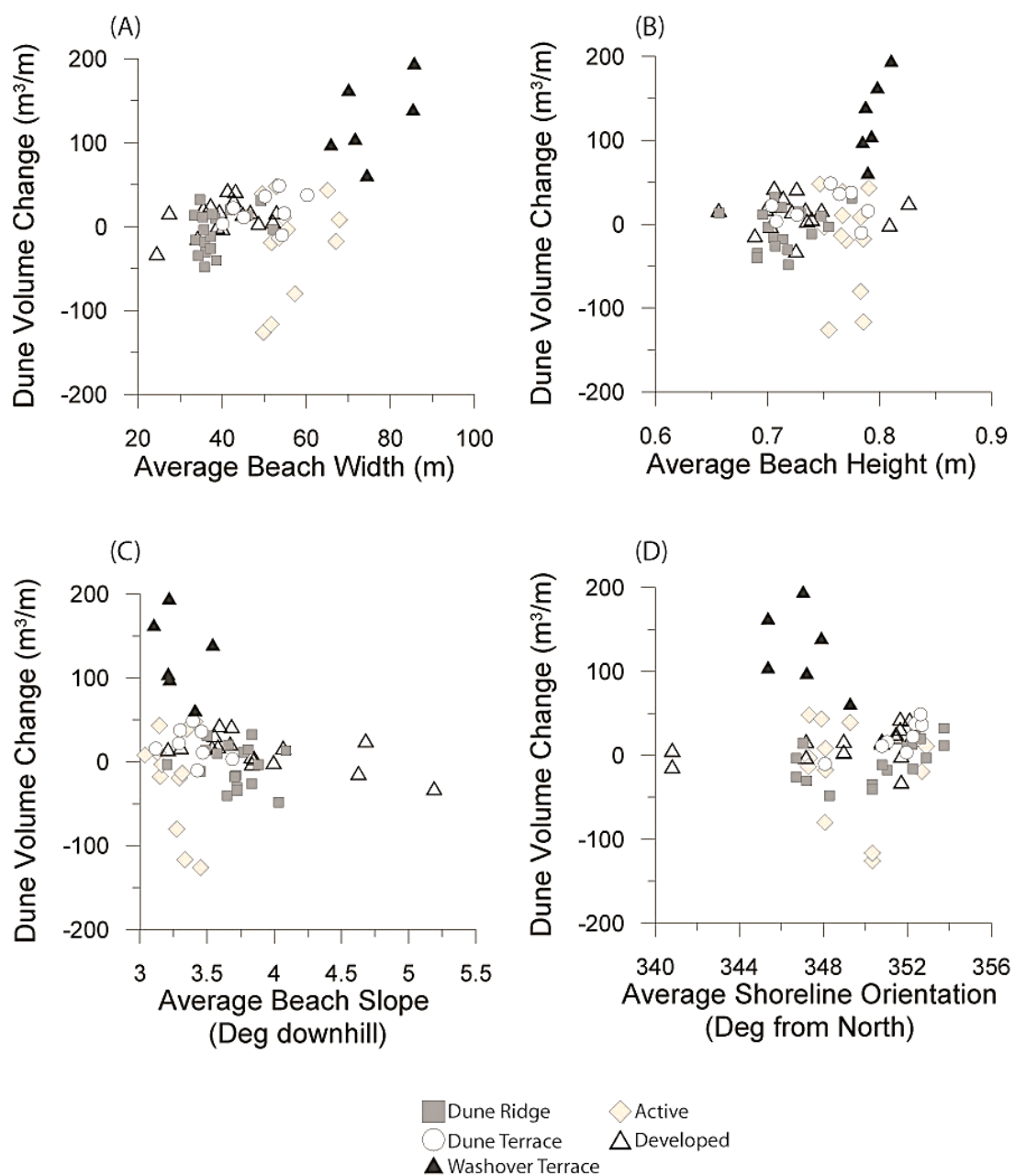


Figure 42. Comparison of beach characteristics and dune volume changes.

The final regression model was a generalized least-squares model. This type of model was chosen being that variance among the variables was unequal. The final model includes beach width, dune type and a variance structure for dune type, and is in the form of:

$$\text{Dune Vol Change} = \text{Dune type} + \text{width} + \text{residual}$$

The various equations that represent the dune environments previously described are shown in Table 9. The intercept reflects the difference in dune volume changes observed (Figure 43) with washover terraces having the highest baseline. The relationship between beach width and dune volume change is the same for all dune types.

Table 9. *Regression equations for dune volume change at SPI according to dune type where D equals dune volume change*

Model	Variance
<i>Active</i>	
$D = -85.01 + 1.17 \text{ width}$	$\text{residual}_{i\text{Active}} \sim N(0, 54.76^2)$
<i>Developed</i>	
$D = -33.97 + 1.17 \text{ width}$	$\text{residual}_{i\text{Developed}} \sim N(0, 17.56^2)$
<i>Dune Ridge</i>	
$D = -49.87 + 1.17 \text{ width}$	$\text{residual}_{i\text{Dune Ridge}} \sim N(0, 22.65^2)$
<i>Dune Terrace</i>	
$D = -38.16 + 1.17 \text{ width}$	$\text{residual}_{i\text{Dune Terrace}} \sim N(0, 17.21^2)$
<i>Washover Terrace</i>	
$D = 36.33 + 1.17 \text{ width}$	$\text{residual}_{i\text{Washover Terrace}} \sim N(0, 40.21^2)$

To address the violation in homogeneity of variance, the model used a variance structure that allowed variance to differ by dune type. It is important to adjust for heterogeneity to attain reliable p-values. The standard deviation for the developed group is 17.56, for dune ridge is 22.65, 17.21 for dune terrace, 54.79 for active, and 40.21 for washover terrace. A hierarchical partitioning method was used to confirm the model results, From this procedure it was found that the model's overall r-square is between 0.5-

0.65, indicating this model explain less than 65% of the dune volume variation. Figure 43 shows the relationship of beach width and dune volume change per dune type.

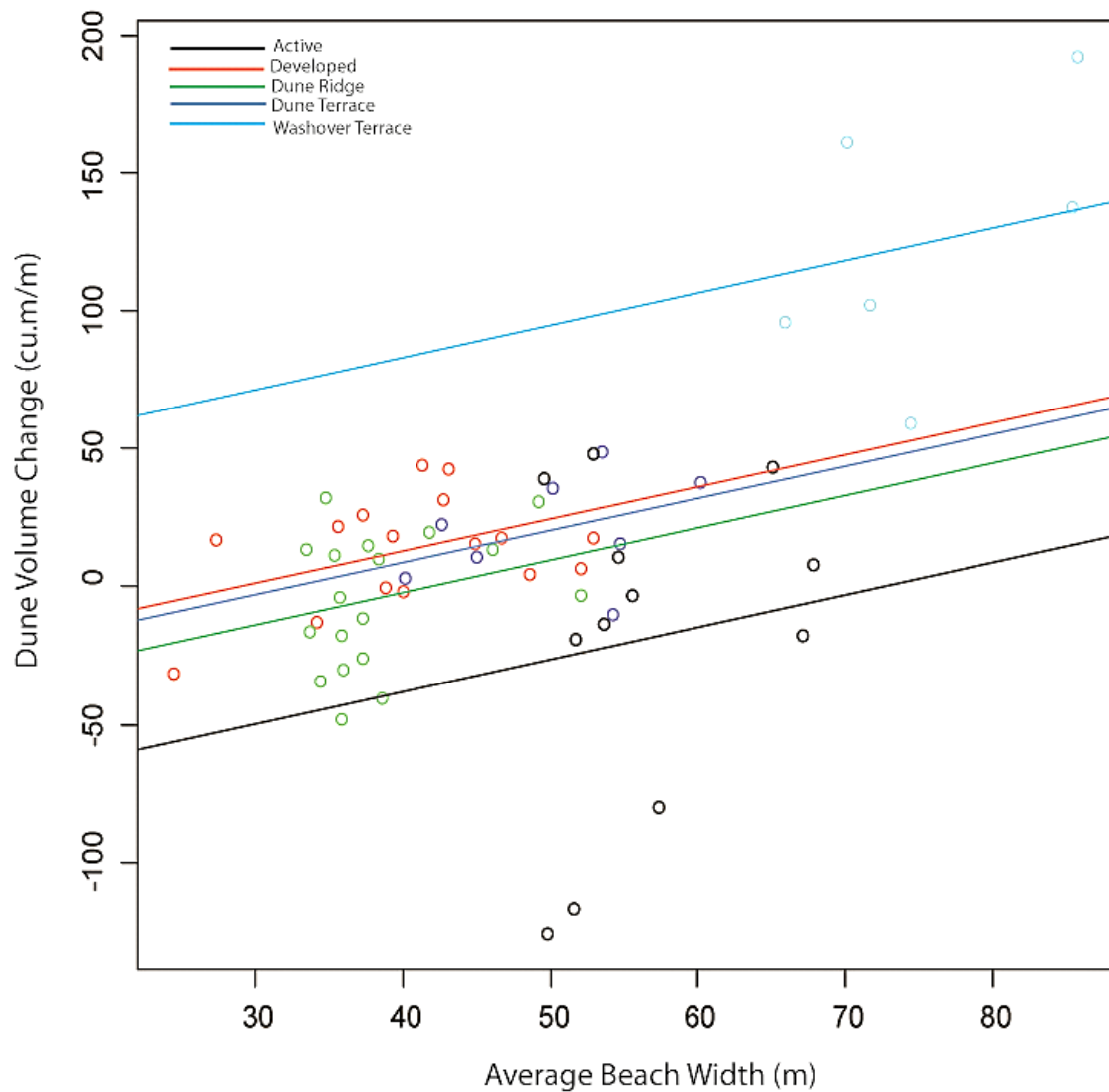


Figure 43. Regression results by dune type. Although the various dune types have different y-intercept values, the slope is the same for all dune types.

DISCUSSION

The main goal of this study was to gain insight into the beach and dune dynamics on SPI, Texas. Of particular interest, was to find what effect beach nourishment has on foredune development. It was found that dune volume changes from 2000 to 2005 are the best estimate of foredune accretion for the study area. Calculations of potential transport concur with the rates of foredune accretion on the undeveloped portion of the island for the time period of 2000-2005. Lastly, foredune accretion rates vary for various dune types as well as certain beach morphological parameters, mainly beach width, height, and slope.

Dune Accretion Rates on South Padre Island

Results from DEMs

By analyzing the results and the storm surge record for the research period, it was found that dune aeolian accretion rates for the time period of 2000 to 2005 are more representative than those of 2005 to 2009. Marine processes had an impact on the dune volume observed on the 2009 DEM. Calculated beach volumes reflect the wave conditions of the weeks prior to the lidar surveys. The 2000 and 2009 datasets reflect the conditions of a fair-weather accretional beach. The 2005 dataset however, represents conditions of an eroded beach from recent storm-surge conditions.

Two storms that had an impact on the beach and dune volume change results are Hurricane Emily in 2005 and Hurricane Ike in 2009. Between 2000 to 2005 the highest storm surge elevations were observed during Hurricane Claudette in 2003 (surge of 0.5-

0.9 m) and Emily in 2005 with a surge of 0.7-0.8 m. The impacts of Hurricane Claudette are not apparent in the 2005 DEM because the beach and dunes recovered by 2005.

Figure 44 shows the storm surge associated with Hurricane Emily for 3 different tide gauges: Port Isabel (PTISAB), South Padre Island (SPICGS), and Bob Hall pier (BOBHAL) in Corpus Christi. The Bob Hall pier tide gauge was included because it is the closest open ocean tide gauge to the study area. The two tide gauges near SPI are located within the Laguna Madre and may not represent the effect of waves on the surge elevation on the ocean side of the island. From the comparison of the 2000 and 2005 DEMs, the erosion and deposition pattern revealed that the surge associated with Emily caused beach erosion along the island, but the surge was not high enough to scarp dunes.

From 2005 to 2009, aside from Hurricane Rita in September 2005, the storms that reached a surge elevation greater than .5 m were Hurricane Dolly (July 2008) and Ike (October 2008). From the comparison of the 2005 and 2009 DEM, it was found that dune erosion and scarping was most likely a result of Hurricane Ike storm surge (Figure 45), which ranged from 0.8-1.3 m.

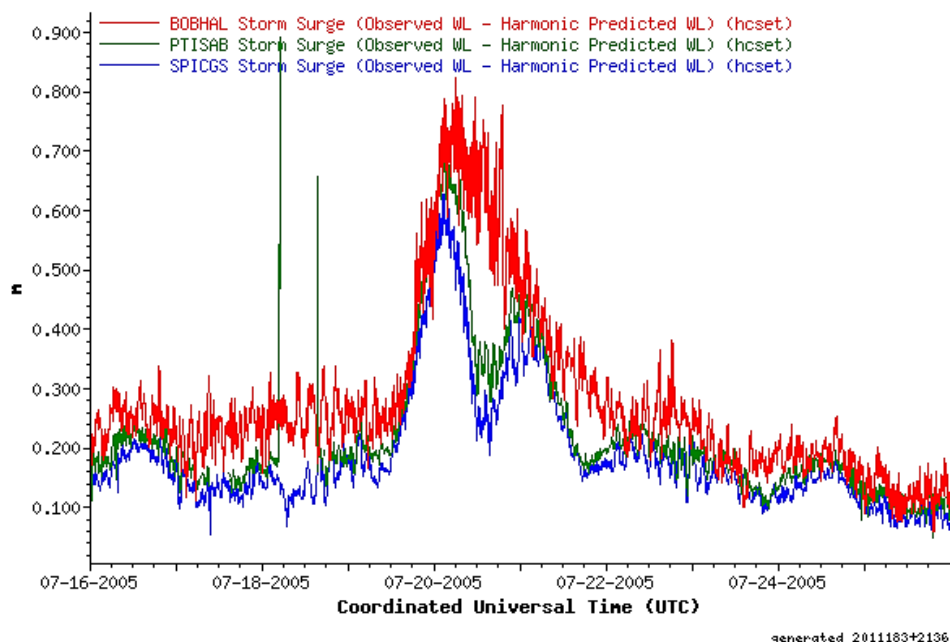


Figure 44. Storm surge associated with Hurricane Emily (2005) in m above NAVD88 as recorded at 3 area tide gauges.

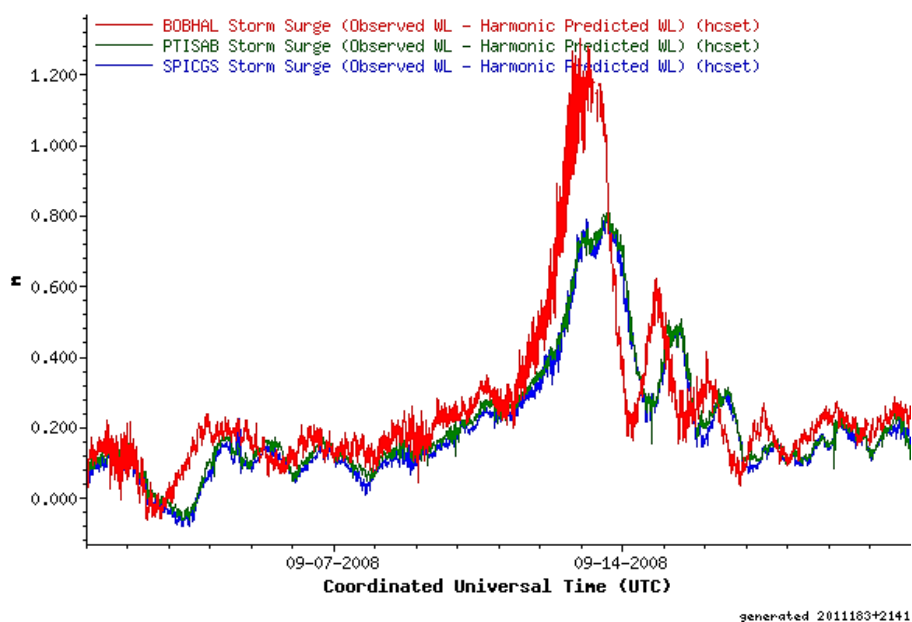


Figure 45. Storm surge associated with Hurricane Ike (2008) in m above NAVD88 as recorded at 3 area tide gauges.

Dune accretion rates on South Padre Island ranged from -13.6 to 30 m³/m/yr and averaged 4.4 m³/m/yr. The average accretion rate was greater for dunes in developed areas (6.2 m³/m/yr) than undeveloped areas (3.5 m³/m/yr). Because of the potential modification and influence human activity may have on dune accretion, the average of the undeveloped areas should be taken as a reasonable rate for accretion through natural aeolian processes rather than the average of all sections of the study area.

Results from Sediment Transport Model

Aeolian sediment transport calculations resulted in cumulative transport volumes that do not match the observed foredune volume changes. This has been attributed to the storm conditions that occurred during the time period. High wind speeds that contribute a large portion of the modeled sediment transport volume, are usually coupled with rain which increases sediment surface cohesion and hence sediment threshold velocity. In addition, storm surge and waves that are associated with these storms often erode the dunes. Therefore, most transport model results will prove to be an overestimation of dune volume change.

To find the possible range of error associated with aeolian sediment transport models in the study area, the results were compared to volume changes measured by ground surveys during the period of August 2009 to October 2010. The results of two different models, Hsu (1977) and Bagnold (1941), proved to be similar and the differences among the results for different dune types are much larger than the differences between the models. Model results obtained for the time period between the summer of 2009 to spring of 2010 are within the range of observed dune toe deposition

values calculated from beach profile data (Appendix D). However, the results from the spring 2010 to fall 2010 did not compare to the observed dune volume changes. The potential transport for the time period of August 2000 to February 2009 was an onshore component of $22.8 \text{ m}^3/\text{m}$, yet, the observed differences ranged from -5.5 to $5.2 \text{ m}^3/\text{m}$ and average close to 0.

These discrepancies between modeled and observed volume changes are attributed to the storm conditions that affected the study area during the 2010 hurricane season. Although there were high speeds and onshore-directed winds, the sediment transport may have been impeded by rain. During the month of June 2010 alone, the study area experienced from 20 to 38 cm of rain, and because the relationship between wind speed and sediment transport is not linear but cubed, the high wind speeds associated with storms contribute significantly to the total sediment transport model results. In addition, half of the profiles which were used to calculate dune toe accumulation (see appendix E) for comparison with the model results, experienced erosion caused by storm surge and waves associated with Hurricane Alex (June 2010). Figure 46 is a graph representing the storm-surge elevation during Hurricane Alex. Storm surge ranged from 1 to 1.2 m and caused minor erosion on some parts of the study area.

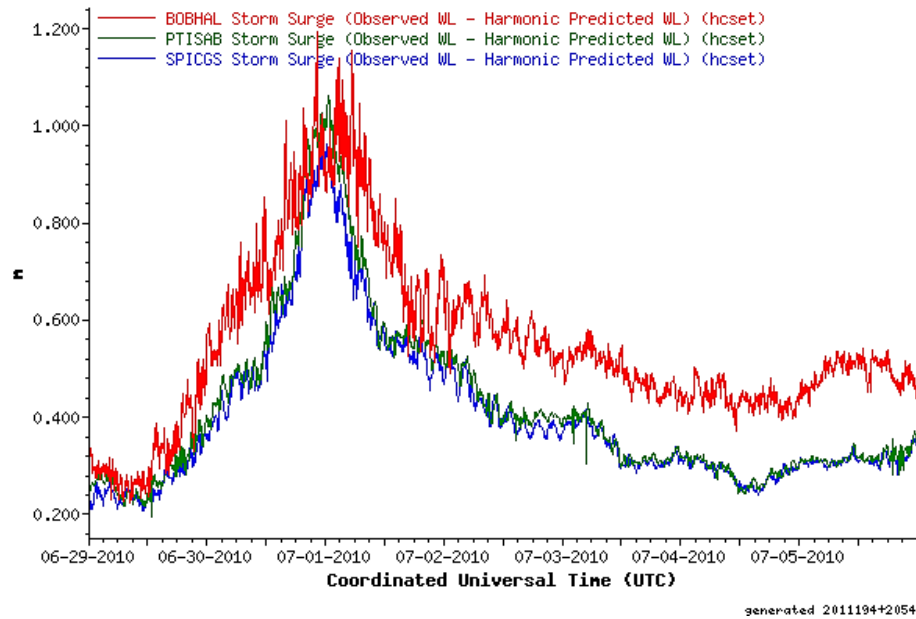


Figure 46. Storm surge associated with Hurricane Alex (2010) in m above NAVD88 from 3 area tide gauges.

Because of dune erosion from storm events in 2008, the sediment transport results for the time period of 2000 to 2009 do not compare to dune volume changes observed from the DEMs. Dune accretion rates derived from the dune volume differences for the period of 2000 to 2005 are considered more representative of aeolian processes because dune storm erosion did not occur or was minimal. Using Hsu's (1977) model to calculate sediment transport for the time period between August 2000 and August 2005, it was found that the resultant vector is $36.6 \text{ m}^3/\text{m}$ in a direction of 286.8° from north. The onshore component of this vector is equal to $16.44 \text{ m}^3/\text{m}$. Over a 5 year period (2000 to 2005), therefore, the yearly onshore-directed transport rate averaged $3.3 \text{ m}^3/\text{m}/\text{yr}$. Observed accretion rates from 2000 to 2005 (Table 6) averaged $21.9 \text{ m}^3/\text{m}$ or $4.4 \text{ m}^3/\text{m}/\text{yr}$. Developed and non-developed areas had different measured averages of $31 \text{ m}^3/\text{m}$ ($6.2 \text{ m}^3/\text{m}/\text{yr}$) and $17.7 \text{ m}^3/\text{m}$ ($3.5 \text{ m}^3/\text{m}/\text{yr}$), respectively. The transport model

results for 2000 to 2005 are most comparable to the rate of observed dune accretion of undeveloped areas.

The rate of sediment transport is affected by sediment supply, precipitation, beach morphology (fetch and slope), and wind conditions. Low sediment supply, high shoreline retreat rates, and high rates of landward migration of the beach and dune environment prevent the study area from having a higher rate of foredune development than what has been measured in this study. Shoreline retreat observed from 2000 to 2009 resulted in an average beach volume change of $-11.9 \text{ m}^3/\text{m}$, as calculated from the change in MHHW position. Over this 9 year period, the beach lost an average of $1.4 \text{ m}^3/\text{m}$ of sand a year, and over the length of the study area, the total amount of sand lost to shoreline retreat was $42,000 \text{ m}^3/\text{yr}$.

Because of the semi-arid conditions, SPI sediment transport is usually not limited by precipitation, with the exception of active hurricane seasons. Limited beach fetch can affect the development of full sediment transport. According to a study by Davidson-Arnott & Law (1990) for wind speeds of 5.5 m/s (similar to the average wind speed of the study area), a 15-m wide beach is needed to achieve full sediment transport. The average beach width for SPI is 48 m and ranges from 25 to 85 m, therefore, this area is not a fetch-limited system. Another limiting factor and source of uncertainty in modeling sediment transport is determining the wind speed threshold and surface roughness. These values were not measured in this study; instead the values used were found in the literature for similar settings.

Effect of Beach Nourishment on Dunes

The comparison of DEMs show that from 2000 to 2005 dune accretion rates were higher in the area of beach nourishment than in undeveloped areas. Yet comparison with the 2009 DEM shows that volumetric loss was much higher on nourished and developed areas than on natural dunes after the 2008 Hurricane Ike storm surge. Dune accretion results concur with those of van Der Wal (2004) along the Dutch North Sea, where she found that dune accretion rates increased after beach nourishment. Van Del Wal suggested that the increased beach width enhanced transport. Furthermore, she suggested that nourished beaches provide more protection from dune toe erosion associated with high wave runup when compared to non-nourished beaches, but this was not the case on SPI where dune volume change is closely related to the beach width. Average beach width from 2000-2009 is 20 m lower for nourished beach sections than the average of undeveloped beaches (see variation in beach width in Appendix B and Appendix G).

Greater dune accretion on the developed portion of SPI than on non-developed portions is mostly related to beach management practices like beach scraping, dune fencing, dune nourishment, and re-vegetation. Sand scraped from Park Road 100 is at times used to nourish beach and dune areas along the most critically eroding segments of the beach. According to the 2009 CEPRA report, during the 2008-2009 funding cycle, approximately 76,500 m³ of sand were used to nourish the beach and dune in critically eroding sections of SPI (Texas General Land Office, 2009), which were the same areas nourished with sand from dredge material. From 2000 to 2005, 724,000 m³ (Heilman et al., 2009) of dredged sand was placed on the beach (Table 3) along a 1000 m stretch from station 182-238 (Figure 19), corresponding to sections 14 and 15. The sum of these

nourishment activities is $800,500 \text{ m}^3$ or approximately $800 \text{ m}^3/\text{m}$. Of this amount, a portion of the sediment builds the beach wider, a portion builds the nearshore profile, and in time, a fraction is transported from the dry beach to the dune system. The measured volume change that contributed to the seaward expansion of the beach (MHHW change) for section 14 and 15, as observed from the comparison of the shoreline in 2000 to the shoreline of a recently nourished beach in 2009, was approximately $30,000 \text{ m}^3$, and normalizing by the shoreline length equals $30.0 \text{ m}^3/\text{m}$ or 4% of the total beach nourishment volume per meter of beach. The amount of sand that was incorporated into the dunes in the same sections totaled $20,076 \text{ m}^3$ from 2000 to 2005 or $20.1 \text{ m}^3/\text{m}$ which is 3% of the total nourishment volume per meter of beach. The other 93% corresponds to sand that builds the forebeach and nearshore below NAVD88 as well as sand that is transported alongshore out of the nourish-placement area where it may contribute to the beach and dune sediment budget of downdrift beaches. Overall, nourishment increases storm protection by increasing the beach width and nearshore profile and by contributing to the sediment budget needed for foredune accretion. It is found that nourished beaches that have dunes provide more flooding protection to upland areas than nourished beaches without dunes (Clark, 2005). Would the dunes in developed areas on SPI provide the protection against storm surge that is needed? The survival of barrier-island dunes from a storm impact depend on the distance from the storm landfall, width of the barrier and dune field, elevation of the dunes, density of vegetation, the frequency of storm impacts, and storm intensity and duration (Claudino-Sales et al., 2008; Houser et al., 2008; Morton & Sallenger, 2003; Pries et al., 2010). Peak surge elevation values and recurrence intervals for SPI (Heilman and Kraus, 1996) are presented in Table 10. Most dunes on the

developed portion of the beach are 3 to 4-m tall and provide flood protection for a 100-year storm. There are some sections that have narrow dunes (parts of section 12-13 and 15-16 on Figure 35). The only thing that cannot be address without modeling, are the effects that wave activity and storm duration will have on dune volumes. If the surge is prolonged for hours or days, dune width becomes important along with dune height.

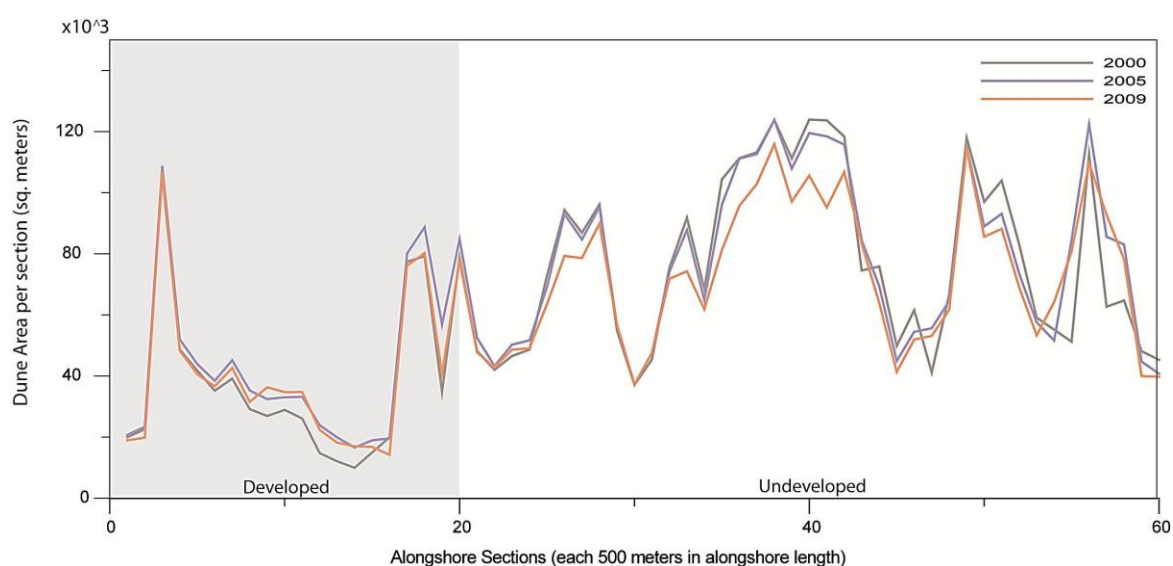


Figure 47. Area of dune sections along the study area.

Figure 47 shows the dune area for each 500-meter alongshore section. In the developed portion of SPI, most dunes have area of less than $40,000 \text{ m}^2$, resulting in dune widths of generally less than 80 m. Table 11 shows reports of volumetric losses resulting from hurricane storm surge at various locations in Florida, Louisiana and Texas. For storm surge greater than 3 m, reported beach/dune erosion ranged from 30 to $125 \text{ m}^3/\text{m}$ and shoreline retreat from 15-35 m. The average profile on the developed portion of SPI holds $31 \text{ m}^3/\text{m}$ of sand above NAVD88 in the beach environment and $210 \text{ m}^3/\text{m}$ in the

dune environment. Beach/dune profile lengths are 120 m on average (40 m average beach width and 80 m approximate dune width). Based on storm-surge levels we can expect to see on South Padre (Table 10) and typical amounts of volumetric loss and shoreline retreat distances (Table 11), the South Padre beach/dune system can provide upland protection for a storm surge with a 100 year return period.

Table 10. *Storm surge recurrence interval from Heilman & Kraus (1996)*

Recurrence Interval (yr)	Peak Surge (m) Above NAVD88
2	0.51
5	1.10
10	1.55
20	1.99
50	2.48
100	2.83
200	3.16
500	3.63

Table 11. *Literature reporting volumetric losses and shoreline retreat from various storm events.*

Author	Location	Storm	Storm Surge	Volumetric losses	Shoreline Retreat
Clark (2005)	Pensacola Beach, Fl	Hurricane Ivan (2004)	3 - 4 m	50-125 m ³ /m	
Clark (2005)	Avalon St Park, Fort Pierce, Fl	Hurricane Frances (2004)	3.5 m	-	15-18 m
Morton et al (1995)	Galveston, Tx	Hurricane Alicia (1983)	3.9 m	51-73 m ³ /m	15 m
Houser et al (2008)	Santa Rosa Is, Fl	Hurricane Ivan (2004)	3.2 m (peak)		35 m
Zhang et al (2005)	Florida	Hurricane Floyd (1999)	0.75 m	-0.2 m ³ /m (dunes) <-18 m ³ /m (beach)	-
Stockdon et al (2009)	Horn Island, La	Hurricane Gustav (2008)	1.37 m (max=3 m)	34 m ³ /m (beach)	-13 m

Beach and Dune Morphological Relationships

Graphical and statistical analyses were conducted to find the relationships between foredune accretion and beach and dune characteristics. The final model resulted in a mixed-effect linear model including dune type and beach width. Although these are the two predictors that explain most of the variation, they are not the only important ones.

During the exploratory phase of the quantitative analysis, a number of relationships were found for beaches. Important to mention are the relationships between height and width (correlation=0.7), width and slope (-0.7), and slope and nourished beaches (0.6). And although there is some correlation between dune volume change and beach height, slope, and orientation, these were not incorporated in the final model because they did not help explain enough of the variation and did not result to be significant. The reason that a model with less variable has a higher p-value than a model with more variables, in this case is collinearity. Collinearity or multicollinearity occurs when predictor variables are correlated amongst themselves making it difficult to accurately estimate the regression parameters and to separate how much variation in the response is associated with each predictor (Gotelli and Ellison, 2004). To assess the impact of collinearity, the Variance of Inflation Factor (VIF) was calculated. The VIF index measures the increase in variance (and therefore standard error) for each predictor, compared to what the variance would be if that predictor were not correlated with the others. Results of the VIF show that some of the highest collinearity occurs with beach width and height.

Because not all predictors should be part of the final model, it is important that the main predictors are. The main predictors are those that have a major explanatory contribution to the model. To understand how much each predictor contributes to the explanation of the variance associated with dune volume change, a hierarchical partitioning method was used. Hierarchical partitioning takes the proportion of variation explained by a full model and determines how much of that variation is uniquely explained by each predictor (Quinn and Keough, 2002). The results are shown on Table 12 and Figure 48. From Table 12, the independent R^2 is the contribution made by that predictor that is not duplicated by the others and the joint R^2 is the contribution that the predictor makes that is duplicated by the others. From Table 12, a full model can explain 64% of the variation in dune volume change (Total R^2_{full}). In addition, most of the variation is explained by dune type (total $R^2=0.576$) and beach width (total $R^2=0.300$). The next highest is beach height, which can explain 9% of the variation, but of that 9%, 5% (Joint $R^2= 0.054$) can be explained by other predictors. In a full model, 62.6% (Independent R^2 / Total R^2_{full}) is explained by the dune type and 24.7 % is explained by beach width (Figure 48).

Table 12. *Results from Hierarchical Partitioning method*

	Independent R^2	Joint R^2	Total R^2
height	0.035	0.054	0.089
width	0.159	0.141	0.300
shoreline	0.006	0.009	0.015
slope	0.026	0.027	0.053
Nourished	0.005	-0.004	0.000
Dune type	0.403	0.173	0.576
orientation	0.011	0.005	0.017
Total R^2_{full}	0.644		

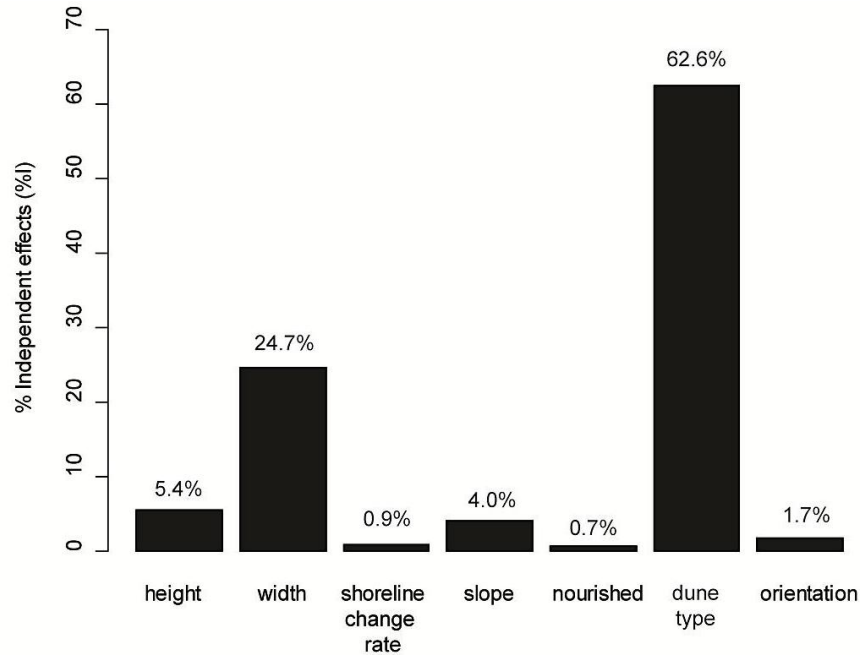


Figure 48. Percent of the independent explanatory power (Independent R^2 to Total R^2_{full}) of various predictors considering a full regression model.

For the hierarchical partitioning method it was found that 62.6% of the variation in dune volume change is explained by dune type and in most cases the contribution of predictors that is already explained by other variables is higher (joint R^2) than the individual contributions (Independent R^2). This is because different dune types have characteristic beach width, height, and slope making it redundant, therefore, to add these to the model if the variation is already addressed by dune type. If dune type were not incorporated in the regression model, the model's total R^2 drops to 0.4. In a model where dune type is excluded beach width explains 69% of the variation, beach height 14%, and beach slope 9%. Yet, dune type adds a significant amount of explanatory power to the model (20%) and addresses variation not explained by the other predictors. This suggests that, of the beach characteristics, width has the strongest influence on dune accretion followed by height and slope, but so does the existing dune morphology.

Barrier Evolution and Washover Recovery

The landscape of SPI is composed of various sediment storage compartments, all of which are part of the barrier island sediment budget. The sediment budget of SPI is limited, and most of the sand in the system is reworked by external forcing mechanisms. The barrier sand is in constant rearrangement among the various geoenvironments including the beach, dunes, washover fans, and wind tidal flats (Figure 49). The formation of washover fans, landward migration of transverse dunes, and shoreline retreat are primary responses of the barrier island to storms and sea level rise.

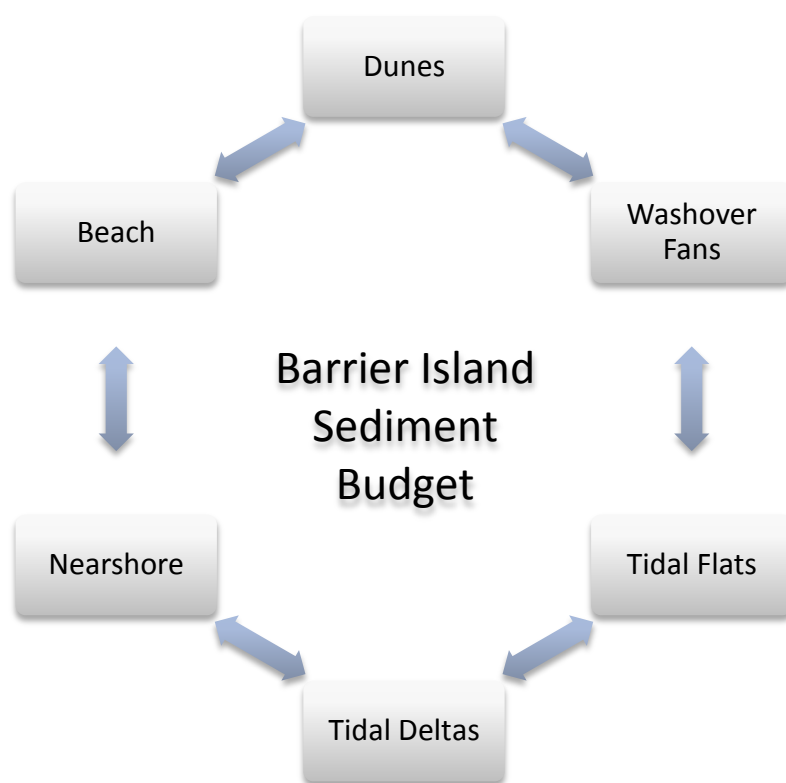


Figure 49. Barrier island sediment budget consists of a transfer of sand between various depositional environments such as beaches, dunes, washover fans, tidal flats, and the nearshore.

Foredunes on SPI are ephemeral features that range in morphology from small coppice mounds to a semi-continuous ridge. These are, at times, completely eroded by storm surge and the sand is redistributed to washover fans or to the nearshore. Foredunes reestablish their form, if the space, vegetation, and sediment supply is available. The barrier island nucleus, as previously described by Andrews (1970), is composed of vegetated foredunes, secondary dunes and vegetated barrier flats. The barrier island nucleus is the most stable feature on this barrier island. The barrier-nucleus fragments are separate by washover channels. As part of the recovery process, these channels slowly reduce in width as vegetation on the peripheral edges of barrier-nucleus traps sand and accrete in concentric ridges. Vegetation propagates laterally and the washover channel recovers topographically, with the exception of remnant freshwater ponds in the place of deeply incised channels. The foredune recovers landward of the barrier island nucleus and in front of the recovered washover channel. Foredune recovery occurs through a series of geomorphic stages consisting of washover terrace, dune terrace, and dune ridge.

Succession from a washover to dune ridge occurs if vegetation is present to stabilize the sand volume within 100-m of the shore, and if accretion is not limited by foredune erosion. Although an area may recover volumetrically, the foredune-ridge morphology may not occur if vegetation is not present. Unvegetated dunes become transgressive and shift the bulk of sand landward as transverse dunes, migrating over the remnant barrier nucleus, or alongshore as migrating sief dunes. The length of the cycle is related to the dune accretion rate for this region and successful completion of the cycle depends on the occurrence of large storm events.

This study has shown that foredune accretion varies alongshore as does the beach and dune morphology. Beach width and slope, which are closely related to the concurrent dune morphology, and the dune morphology in itself affect the rate of accretion. From 2000 to 2005 washover terraces accreted at a rate of $18 \text{ m}^3/\text{m}/\text{yr}$, dune terraces at a rate of $6.5 \text{ m}^3/\text{m}/\text{yr}$ and dune ridges at a rate of $2.3 \text{ m}^3/\text{m}/\text{yr}$ (see figure 50). Profile configuration and volume above NAVD88 for various profile types are shown in Figure 50 and Table 13. The volume difference between the washover terrace and dune terrace is $360.2 \text{ m}^3/\text{m}$. The washover recovery rate is $18 \text{ m}^3/\text{m}/\text{yr}$, therefore it is estimated that it would take approximately 20 years for this volumetric recovery to occur. The volume difference between the dune-terrace and dune-ridge profiles is $146.3 \text{ m}^3/\text{m}$. Because the dune-terrace accretion rate is $6.5 \text{ m}^3/\text{m}/\text{yr}$, it would take approximately 22.5 years for a dune terrace to accrete to a dune-ridge type. In total, it would take approximately 42.5 years for a washover to recover to a foredune ridge of 6.5 m in elevation.

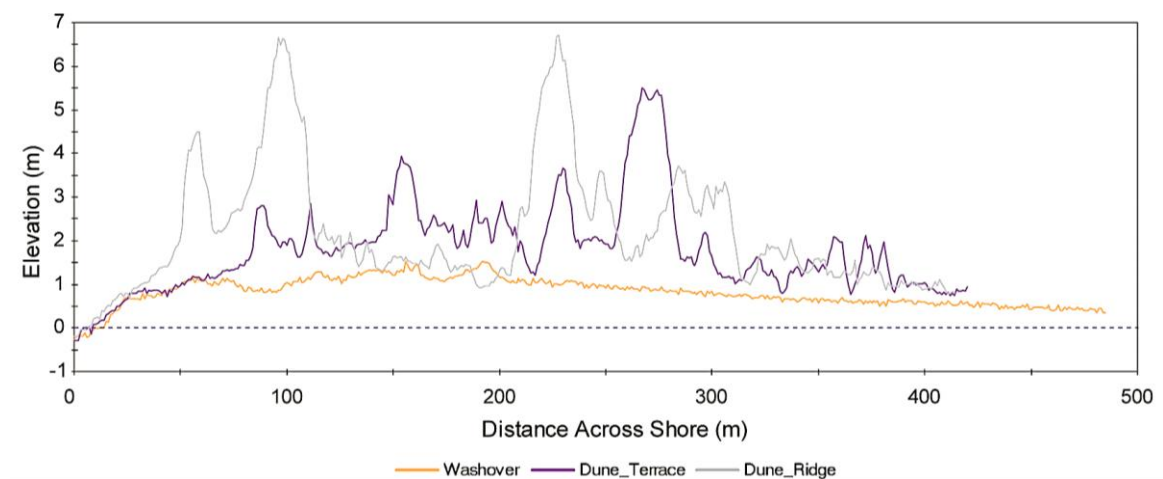


Figure 50. Comparison of a typical profile of various dune types at different stages of foredune washover-recovery.

Table 13. *Profile properties*

Profile	Accretion rate cu.m/m/yr	Profile Length (m)	Volume (cu. m/m)
Washover	18	485	397.01
Dune Terrace	6.5	420	757.18
Dune Ridge	2.3	414	903.51

Dune recovery can occur only if erosion from storm surge does not occur. The last major storm to occur on SPI was Hurricane Allen in 1980. Allen created a storm surge of approximately 2.5 m (Giardino, Isett, and Fish, 1984) and caused 38 breaches from Brazos Santiago pass to the Mansfield cut. According to the statistical modeling of storm surge return periods by Kraus & Heilman (1996) (Table 10), 2.5 m surge has a return period of approximately 50 years, this suggest that recovery of a washover to a foredune ridge can occur. The current topography of the island suggests that smaller storm surge reinforce the low topography of certain washovers, inhibiting recovery. Yet, review of aerial imagery from the 1950's, 1970's, and 2000's confirmed that some areas have experienced washover-recovery to a dune ridge. The limiting factors that determine if a washover will recover are unclear and not addressed in the present study.

CONCLUSION

The goal of this study was to gain a better understanding of the beach and dune dynamics on South Padre Island, Tx. In particular, to determine the effect that beach nourishment has on foredune accretion rates. The main objectives accomplished were mapping of the beach and dune environment, calculating change in volume for the beach and dune environment using DEMs from the years 2000, 2005 and 2009, estimating the potential sediment transport using wind data and existing sediment transport models, and determining the relationship between various beach and dune parameters to dune volume change.

It was found that the dune volume change from 2000 to 2005 provides the best estimate of the dune accretion rates on SPI because the area did not experience any dune erosion from storm surge during that period. The measured accretion rate for undeveloped beaches for the time period of 2000 to 2005, was comparable with sediment transport model results using Hsu's (1977) formula. The sediment transport rates calculated for the time period of 2000 to 2009 overestimated the amount of sand volume change when compared to the DEM results for the same time period. This discrepancy is attributed to dune volume losses resulting from storm surge related to Hurricane Ike (2008).

Comparing the dune volumes between nourished and unnourished beaches shows that beach nourishment is beneficial to dune accretion because it widens the beach, providing a buffer against wave runup and a supply of sand for foredune accretion. It was found that approximately 4% of the total beach nourishment volume contributes to the

widening of the beach, and approximately 3% of the total volume is incorporated into the dunes. Although the dunes in the developed portion of the study area are narrow compared to the natural dune systems on SPI, their average width, height and volume should be able to provide significant protection during a storm surge of 3 m associated with a 100-year return period. However, it is recommended that breaks in the dune system used for public access be restored to avoid water channeling and inundation of nearby areas.

From the statistical analysis and regression model it was found that beach width is correlated with dune accretion rates. However, correlations exist among various beach characteristics, mainly beach width, height and slope. Beach width explains a major portion of the variation in dune volume change, second to dune type. Dune type varies alongshore SPI and reflects various stages of dune recovery and stability.

Barrier dune morphology on SPI reflects various levels of storm washover recovery. Washover recovery can take approximately 42.5 years if progress is not impeded by further erosion. Given a 50-year, 2.5-m storm-surge return period, dune recovery may occur along SPI, although, it is unclear why some areas experience full recovery and others preserve their washover morphology. Washover and dune recovery will continue to be a persistent process on SPI and is important for the redistribution of available sediments in a barrier island system undergoing sea-level rise.

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APPENDIX A

Landward Dune Boundary Mapping Criteria

- **Elevation-** The elevation of foredunes and dune ridges must be higher than that of the beach and back beach which are exposed to tidal inundation. The average beach height on the Texas coast is 1 m. Foredune height varies along the Texas coast. On Galveston Island and South Padre Island, dunes may be low as 2-3 m (R. A Morton & McGowen 1980). Elevation values greater than 2 m were visualized using a reclassified DEM.
- **Aspect-** Aspect is derived from the DEM and is used to identify sloping surfaces and slope direction. Aspect is a visual aid for identifying the backslope of foredune features. It is also helpful for identifying the edges of seawalls.
- **Orientation-** Features included in the foredune complex are those that are parallel to the coastline.
- **Proximity and Clustering-** Dune features in close proximity or connected to the main foredune are included in the foredune complex.
- **Exclusion of man-made structures-** Any structure, other than dune walk-overs, situated within the foredune complex is excluded.
- **Overwash areas-** The landward boundary of washover areas is mapped as a contour line with an elevation equal to that of the PVL (1.192 m NAVD88)
- **Dune dynamics-** Areas of significant sediment exchange with the beach and dune environment were included in the foredune complex.
- **Vegetation cover-** For the case of highly dynamic areas, if there is a secondary dune feature landward of a segmented, non-vegetated active dune, the dune line may be placed behind the second dune feature if it is vegetated and more stable.

APPENDIX B

Methods for extraction of beach characteristics

Average beach height

To find the average beach height, first three shapefiles are made using the boundaries of MHHW and PVL polygons sections representing the upper beach for the years 2000, 2005 and 2009. These shapefile are used to perform zonal statistics on the corresponding DEM. This function returns various statistics including the mean elevation for each of the sections. This mean value is used as the mean height for that year. Average beach height varied for the 3 years (see Figure 51) but the alongshore pattern is similar. Average beach height is much lower in 2005, this is most likely the result of the increased wave activity and angle of approach from the high storm activity of that year (HDR|Shiner Moseley 2007). The mean beach height for all three years is used for the quantitive analysis.

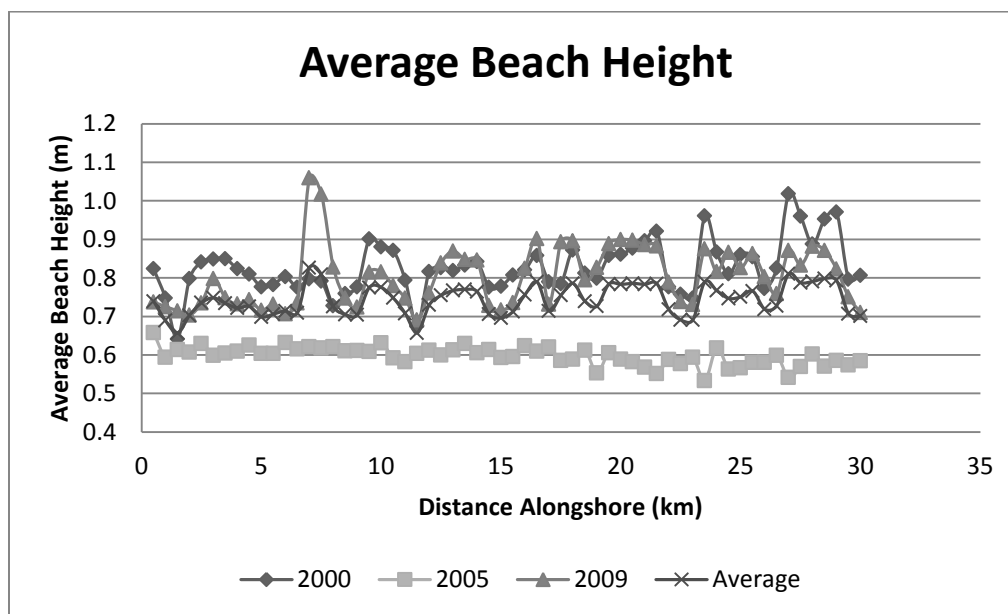


Figure 51. Alongshore variation of average beach height for years 2000, 2005, 2009, and the average for whole time period.

Average beach width

Average beach width was measured for each of the DEMs as the distance between the PVL and MHHW contours. Beach width was measured every 50 meters and then averaged for each 500 m sections. The following procedure was repeated for the years 2000, 2005 and 2009. For statistical analysis the average of for all three years is used (see Figure 53). Steps taken in calculation of the beach width:

1. Create a point shapefile using ET Geowizards ArcGIS extension function “create station points”. Using this function points are created on the PVL contour every 50 meters (orange points on Figure 52).
2. Next, shore-perpendicular lines were cast from station points to an offshore baseline. This is done with another ET Geowizards function “perpendicular to polylines” (Figure 52).

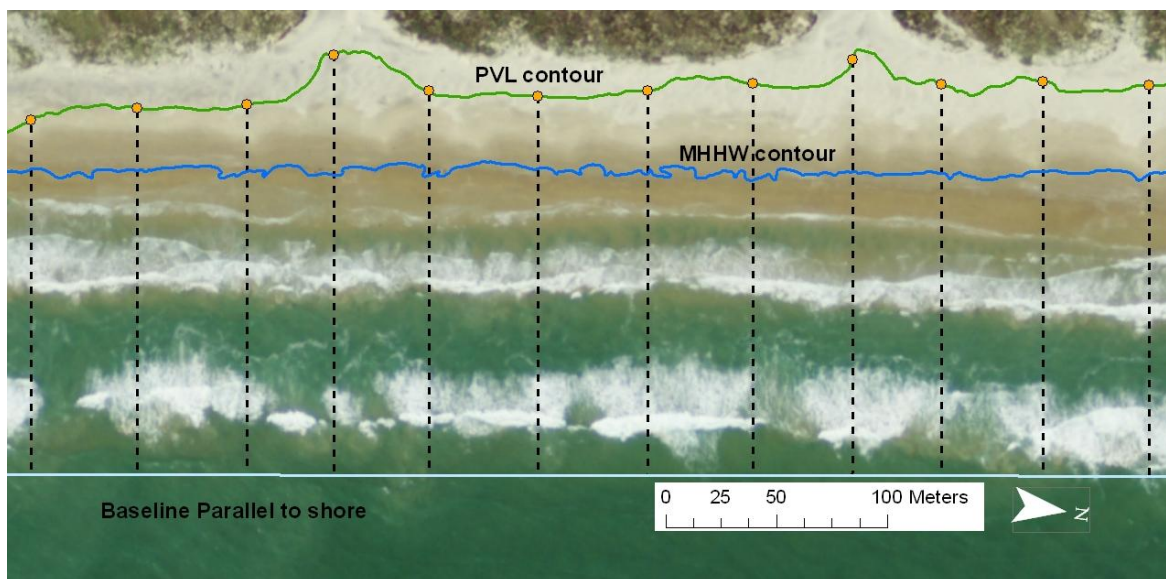


Figure 52. Beach width in this study is measured from the PVL to MHHW

3. To make a line representative of the beach width the shore perpendicular lines are split with the MHHW contour using ET Geowizards function called “split polyline with layer”.
4. The shapefile that includes the split perpendicular lines and is edited manually, deleting unnecessary lines. Unnecessary lines are those that extend from the MHHW to the offshore baseline (Figure 52).
5. Once the remaining line are those that represent beach width, a field is added to the shapefile, called “length”. The length was directly calculated on the shapefile attribute table by using the “calculate geometry” option.
6. Finally the length of all the beach width lines was averaged for each of the 60 sections the Spatial Join tool.
 - a. The shapefile that contains all the 60 sections is the target feature and the shapefile with the beach width lines is the join feature.
 - b. Once the output feature class has been specified, the join operation is set one to one- this means that we want to maintain the same number of rows found in our “sections” shapefile. Since more than one feature fall within each section the length results will be aggregated as the mean of all lengths found within each polygon section.
 - c. Under the field map of join features, specify the merge rule for the column “length” as the mean.
 - d. The match options will be specified as “contains”, therefore the mean of all lines contained within a polygon will be used to calculate the mean length for each section.

- e. Finally, validate the results for of the table join. Select random section polygons and compare the average of the length of all the beach width lines that are contained by that section with the join output.

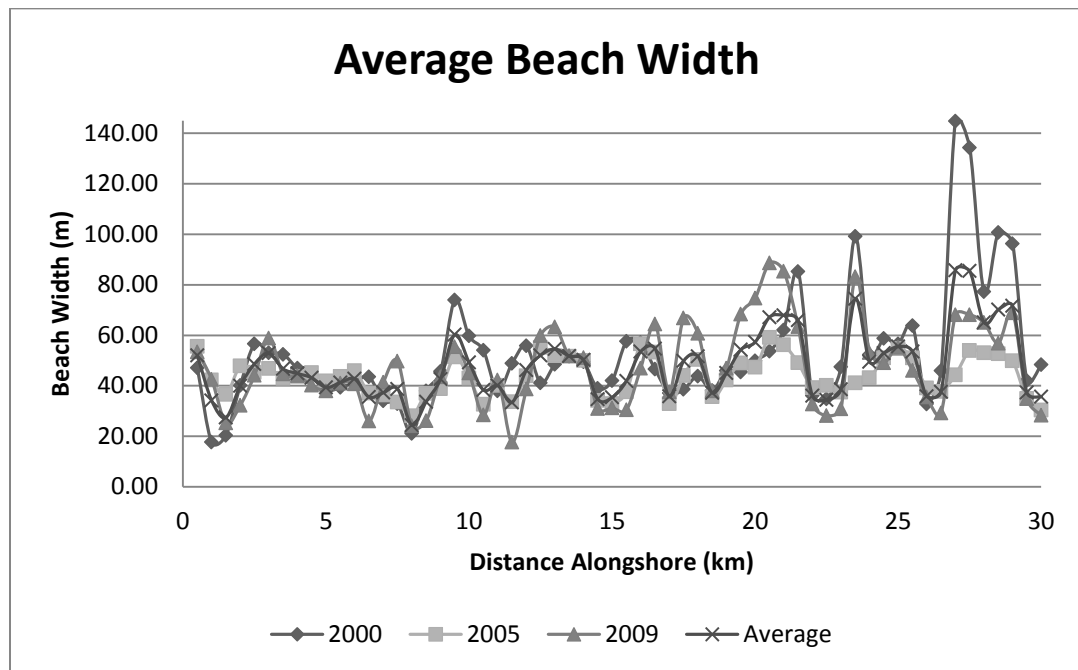


Figure 53. Longshore variation in beach width for years 2000, 2005, 2009 and the average.

Beach Slope

Beach slope as is calculated for the years 2000, 2005 and 2009 (Figure 54). Calculations are made using the same lines used for beach width every 50 m. For each year, an average slope is calculated by creating a spatial join with the polygon section shapefile. For statistical analysis the average slope for all three years is used. The steps taken in calculating slope are as follows:

1. Slope calculations used the same line representing the beach width from the PVL to MHHW.
2. A point shape file with points on every meter along each of the beach width lines was created using ET Geowizards ArcGIS extension function “create station points”.
3. This shapefile was then used to extract the elevation values at each meter from the DEM of the same year using the “Extract Values to Points” tool.
4. Next, this point shapefile was converted to a Polyline (Z) shapefile. This line is 3-dimensional and will reflect the changes in elevation from the MHHW to the PVL.
7. Using the “PolylineZ Characteristics” tool from ET Geowizardsm, a number of measurements of this line can be extracted, for example the 3D length of the line, Max and Min height, distance up/downhill, and max slope. In this case we are interested in slope downhill which is measured in degrees (from 0 to 90). Output precision is set to 3 numbers after the decimal place.
8. Finally the slope of all the beach width polyline Z lines was averaged for each of the 60 sections the Spatial Join tool.

- a. The shapefile that contains all the 60 sections is the target feature and the shapefile with the beach slope lines is the join feature.
- b. Once the output feature class has been specified, the join operation is set one to one.
- c. Under the field map of join features, specify the merge rule for the slope column, “Av_S_Down” as “mean”.
- d. The match option will be specified as “contains”.
- e. Finally, validate the results for of the table join. Select random section polygons and compare the average of the slope of all the beach slope lines that are contained by that section to that of the join output.

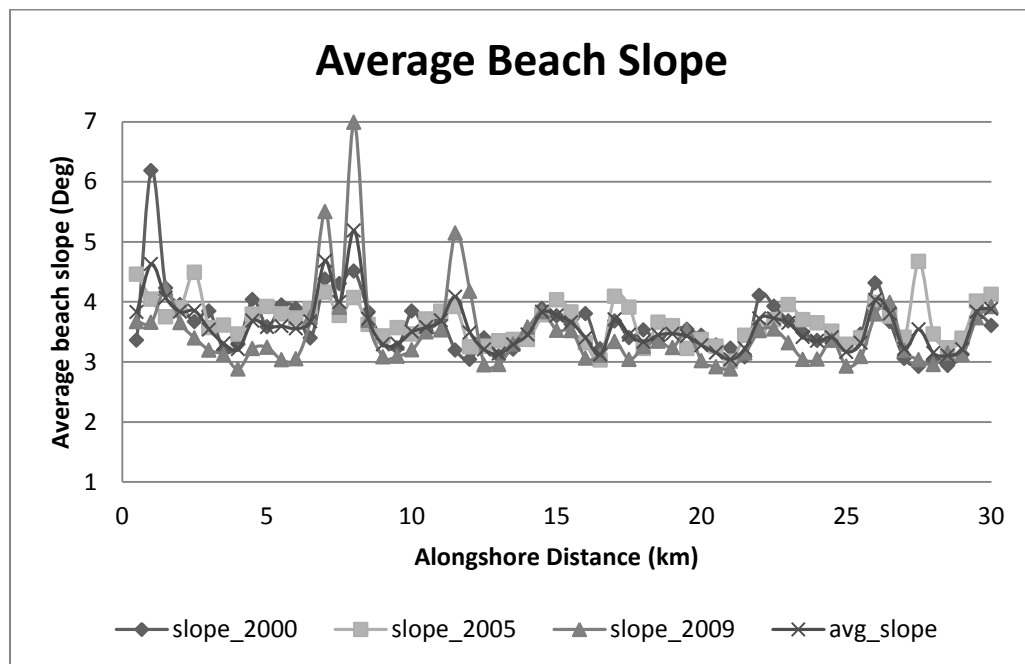


Figure 54. Alongshore variation in beach slope for years 2000, 2005, 2009 and average

Shoreline Orientation

The line orientation was manually drawn, parallel to the beach from aerial photography. Each line followed a 1 km and was drawn for the 30 km research area. These are same lines that were used as the offshore-baselines used to calculate the beach width. The orientation of the line is calculate using the ArcGIS extension “Tools for Graphics and Shapes” (Jenness 2011) which calculates an azimuth in degrees clockwise from North (Figure 55).

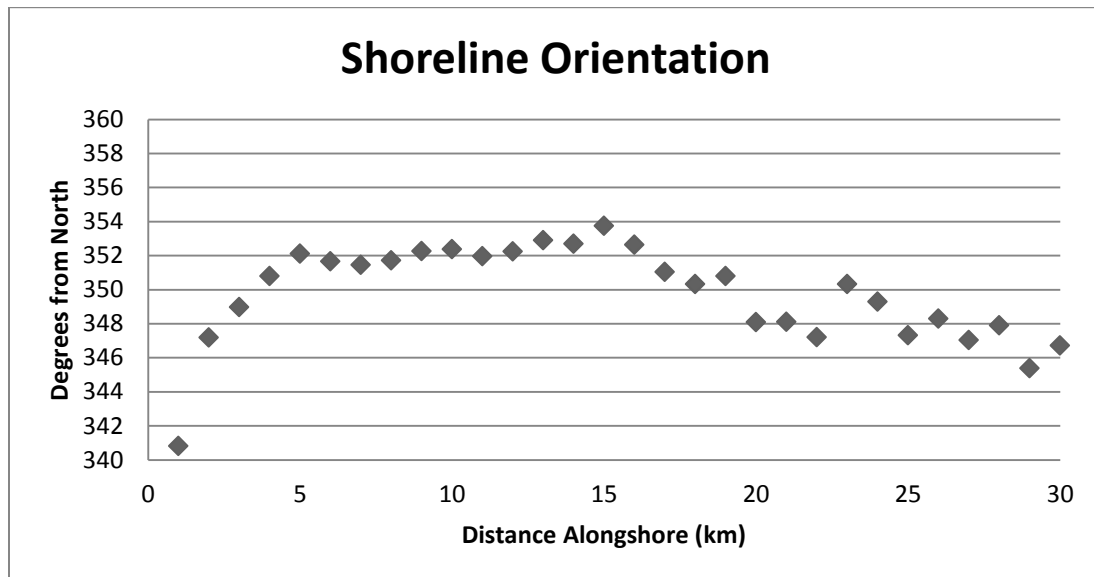


Figure 55. Alongshore variation in shoreline orientation.

Steps in Data Analysis

1. Read data into R. Data is saved on a CSV format.
2. Visual analysis of using pair plot from AED package (Zuur et al. 2009) is used to find possible relationships among variables and decide if any transformations are necessary.
3. Find correlation and variable of inflation factor to identify collinearity among variables. Collinearity makes it difficult to estimate the regression parameters accurately (Faraway 2005) and might reduce the significance value. The variance is a measure of the impact of collinearity among variables and although there is not a formal value that determines collinearity the relative values and the knowledge of our data will help us decide if collinearity is present.
4. To analyze the different variables and their statistics by dune type a summary report can be generated using the psych package (Revelle 2009) function “describe.by”.
5. Select appropriate linear model using backwards and stepwise regression. Beginning with a fully saturated model that includes all possible variables and begin with eliminating variables with the highest p-value greater than $\alpha=0.01$, one at a time. Possible interactions between variables will also be tested. Mixed effects models are evaluated using the nlme package (Pinheiro et al. 2009).
6. Check and address violation of model assumptions.

APPENDIX C

Script for Calculation of Sediment Transport

This script reads excel files containing hourly averages of wind direction and speed. Wind speed is converted to shear velocity using the logarithmic wind profile formula. This shear velocity is then used to calculate transport using Hsu's and Bagnold's sediment transport formulas. Wind velocities that are below the threshold velocity value will have a transport value of 0. Finally, the resulting drift potential is calculated from the magnitude of transport and direction using vector summation. Results are in g*cm and converted to cu.m/m. The resultant vector is then decomposed to onshore and alongshore components.

%This procedure is repeated for the following time periods:

- August 2009 to April 2010
- April 2010 to October 2010
- Total from August 2009 to October 2010

Calculating shear velocity

This section reads wind data from excel file and uses wind speed to estimate shear velocity in cm per sec. Any shear velocity measurement less than the threshold velocity is given a value of 0.

```
Aug_Apr = xlsread('08_09_03_10_1hr_avg.xls'); % reads excel file from directory
```

%Variables

```
%Hsu_K=e^(-0.42+4.9d)*10^-4      % where d = mean grain size
Hsu_K = 1.71*(10^-4);
Z0= 0.0225;                        % beach surface roughness (from Hsu, 1973)
Aug_Apr(:, 5)= Aug_Apr(:, 3)*100; % horizontal wind velocity in cm/s
uz= Aug_Apr(:, 5);                 % assign wind velocity to uz
Z= double(10*100);                 % elevation of wind speed measurement in cm
vonKarman= 0.4;                    % von Karman's constant
```

```
%shear velocity calculation Hsu (1973):
```

```
Shear_velocity_hsu = (vonKarman .* (uz)) / (log(Z / z0));
```

```
Aug_Apr(:, 6)= Shear_velocity_hsu;
```

```
% after Hunter and Richmond (1988), threshold velocity for transport = 5 m/s
```

```
index = Aug_Apr(:, 3) > 5; % Index wind speed greater than 5 m/s
```

```
Shear_velocity_t = Aug_Apr(:, 6) .* index; % any wind speed < 5 yield 0 transport
```

```
Aug_Apr(:, 7)= Shear_velocity_t; % attach to the Aug_Apr matrix
```

Calculating sediment transport using Hsu's equation

In this section Hsu's equation is used to estimate the magnitude of sediment transport for each hourly wind speed. A resultant vector is calculated by converting the magnitude and wind direction to orthogonal components. The cumulative sum of the components is calculated then converted back to magnitude and direction. The resulting magnitude is multiplied by 3600 sec/hr to obtain a magnitude in g/cm, this is then converted to cu.m/m by multiplying by the bulk density of sand.

% Variables

```
g= 980; % gravity in cm/s
```

```
d= 0.0195; % mean grain size cm
```

```
Hsu_q = Hsu_K .* ( Aug_Apr(:, 7) ./ (( g * d )^(1/2)))^3;
```

```
% Hsu_q is sediment transport in g/cm/s
```

```
Aug_Apr(:, 8) = Hsu_q; % attach to matrix
```

```
% Vector sum of potential drift
```

```
% Note this section requires the function files (md2en and en2md)
```

```
%md2en - Converts geographic velocity components to East and North components
% input is magnitude (Hsu q) and direction (wind)
```

```
[east,north] = md2en(Aug_Apr(:,8),Aug_Apr(:,4)); % call the function
Aug_Apr(:,9) = east; % attach east components
Aug_Apr(:,10) = north; % attach north components
% Sum of components
Aug_Apr(:,11) = cumsum(Aug_Apr(:,9)); % running sum of x
Aug_Apr(:,12) = cumsum(Aug_Apr(:,10)); % running sum of y
```

```
% function [mag,dir] = en2md(east,north)
% Converts orthogonal velocity components back to magnitude and direction
```

```
[magnitude,direc] = en2md(Aug_Apr(:,11),Aug_Apr(:,12)); % call the function
Aug_Apr(:,13) = magnitude; % attach magnitude
Aug_Apr(:,14) = direc; % attach direction
```

```
% now the we have a sediment transport rate in g/cm/s for each hourly average
% and is summed into a resultant vector = 38.44 mag and 124.15 degrees
```

```
% Multiply the sum vector by 3600 sec/hr
```

```
total = 38.44 * 3600; % total g/cm of beach
```

```
% Convert to cubic m per m length
```

```
Cu_m_m_total= (total * 1/10 * (1/1410)) % (10g/cm in 1 kg/m) * bulk density of sand
```

```
% From Aug to April a total of 9.88 cubic meters per meter of beach of
% tranport @ 121.4 degrees. This is the last value from the Magnitude and
% direction columns.
```

```
% For onshore transport multiply by the cosine of the wind angle relative to shore
% normal. Average shoreline orientation is 9.9 degrees.
```

```
relative_angle= 124.15 + 9.9           % of tranport vector and shoreline
```

```
% get x and y components:
```

```
u= Cu_m_m_total * [cosd(relative_angle), sind(relative_angle)];
```

```
onshore_alongshore_tranport=u
```

```
%u = -6.82 and 7.05
```

```
Cu_m_m_total =
```

```
9.8145
```

```
relative_angle =
```

```
134.0500
```

```
onshore_alongshore_tranport =
```

```
-6.8239    7.0540
```

Calculating sediment transport using Bagnold's equation

In this section Hsu's equation is used to estimate the magnitude of sediment transport for each hourly wind speed. A resultant vector is calculated by converting the magnitude and wind direction to orthogonal components. The cumulative sum of the components is found then converted back to magnitude and direction. The resulting magnitude is multiplied by 3600 sec/hr to obtain a magnitude in g/cm, this is then converted to cu.m/m by multiplying by the bulk density of sand.

%Same procedure with Bagnold's model:

```

C_bagnold= 1.8;      % empirical coefficient related to
                      % sediment size distribution - naturally graded

d= 0.0195;          % mean grain size in cm
D= 0.025;           % reference grain size cm
air_den= 0.0012;     % in g/cm3 air density equal apprxx 1.22 kg*m^-3
g= 980;             % gravity in cm*s^-1

Bagnold_q= (C_bagnold*(sqrt(d/D))*(air_den/g))*Aug_Apr(:, 7).^3;
Aug_Apr(:,15)= Bagnold_q;

[east,north] = md2en(Aug_Apr(:,15),Aug_Apr(:,4)); % call the function
Aug_Apr(:,16) = east;
Aug_Apr(:,17) = north;
Aug_Apr(:,18) = cumsum(Aug_Apr(:,16));           % running sum of x
Aug_Apr(:,19) = cumsum(Aug_Apr(:,17));           % running sum of y

[magnitude,direc] = en2md(Aug_Apr(:,18),Aug_Apr(:,19));
Aug_Apr(:,20) = magnitude;                       % attach to matrix
Aug_Apr(:,21) = direc;                           % attach to matrix

% now we have a sediment transport rate in g/cm/s for each hourly average
% and is summed into a resultant vector = 36.56 mag and 124.15 degrees
% multiply the sum vector by 3600 sec/hr
total = 36.56 * 3600;                            % total g/cm of beach

```

```
Cu_m_m_total= (total * 1/10 * (1/1410)) % total in cubic m per m length
```

```
% From Aug to Apr a total of 9.33 cubic meters per meter of beach of
```

```
% transport @ 124.154 degrees
```

```
%
```

```
% Separating to Onshore/Alongshore components
```

```
% Average shoreline orientation is 9.9 degrees
```

```
relative_angle= 124.15 + 9.9 % of transport vector and shoreline
```

```
% get x and y components:
```

```
u= Cu_m_m_total * [cosd(relative_angle), sind(relative_angle)];
```

```
onshore_alongshore_transport= u
```

```
% -6.49 and 6.71
```

```
Cu_m_m_total =
```

```
9.3345
```

```
relative_angle =
```

```
134.0500
```

```
onshore_alongshore_transport =
```

```
-6.4901      6.7090
```

APPENDIX D

R Code for Statistical Analysis

This script reads csv file containing all the beach and dune characteristics. This section includes steps in data exploration and in multiple stepwise regression.

```
beach<-read.csv("stats_method2_2.csv") #read data
names(beach)

#Rename columns
colnames(beach)<-c("section","B_vol_ch","D_vol_ch", "height", "width", "shoreline", "slope",
                  "MHHW_change", "PVL_change","Nourished", "Dune_type", "orientation")

# Data Exploration

library(AED)
pairs(beach[,c(2:12)], lower.panel=panel.cor,upper.panel=panel.smooth2,diag.panel=panel.hist)

#check collinearity and the Variance of Inflation factors

vifs<-corvif(beach [,c(2:9,12)])

#average beach width has the highest VIF correlates with dune volume change

# for report of various variable statistics by group

library(psych)
describe.by(beach,D_type)

##Begin with an overfull model with no interactions

overfull.beach.model<-lm(D_vol_ch ~ width + Dune_type + height + Nourished + shoreline +
                        orientation + slope, data=beach)
summary(overfull.beach.model)

##Plots are made to view variation of the model residuals

op=par(mfrow=c(2,2))
plot(overfull.beach.model)
op=par(mfrow=c(3,3))
plot(resid(overfull.beach.model)~beach$width, xlab="Width", ylab="residuals")
plot(resid(overfull.beach.model)~beach$Dune_type, xlab="Dune Type", ylab="residuals")
plot(resid(overfull.beach.model)~beach$height, xlab="Height", ylab="residuals")
plot(resid(overfull.beach.model)~beach$Nourished, xlab="Nourished", ylab="residuals")
```

```
plot(resid(overfull.beach.model)~beach$shoreline, xlab="Shoreline Change", ylab="residuals")
plot(resid(overfull.beach.model)~beach$orientation, xlab="orientation", ylab="residuals")
plot(resid(overfull.beach.model)~beach$slope, xlab="Slope", ylab="residuals")
```

Method for exploration and selecting a variance structure for slope and dune type. This method uses restricted maximum Likelihood (REML) for better estimation of for unbiased estimated of variance

```
library(nlme)
full.model<-gls(D_vol_ch ~ width + Dune_type + height + Nourished + shoreline
               + orientation + slope, data=beach, method="REML")
full.model_varpower<-glis(D_vol_ch ~ width + Dune_type + height + Nourished + shoreline
               + orientation + slope, data=beach,varPower(form=~slope), method="REML")
full.model_varExp<-glis(D_vol_ch ~ width + Dune_type + height + Nourished + shoreline
               + orientation + slope, data=beach,varExp(form=~slope), method="REML")
full.model_varIdent<-glis(D_vol_ch ~ width + Dune_type + height + Nourished + shoreline
               + orientation + slope, data=beach,weights=varIdent(form=~1|Dune_type),
               method="REML")
Full.model_comb<-glis(D_vol_ch ~ width + Dune_type + height + Nourished + shoreline
               + orientation + slope,
               data=beach,weights=varComb(varPower(form=~slope),varIdent(form=~1|Dune_type)),
               method="REML")

anova(full.model, full.model_varpower,full.model_varExp, full.model_varIdent,
Full.model_comb)
```

#best variance structure is var comb, but var_ident may also work

```
plot(resid(Full.model_comb)~beach$slope, xlab="slope", ylab="residuals")
```

#####

#Refit with Maximum Likelihood method

```
Full.model_comb<-glis(D_vol_ch ~ width + Dune_type + height + Nourished + shoreline
               + orientation + slope,
               data=beach,weights=varComb(varPower(form=~slope),varIdent(form=~1|Dune_type)),
               method="ML")
summary(Full.model_comb)

op=par(mfrow=c(2,2))
plot(full.model_varIdent)
hist(resid(full.model_varIdent), xlab= "residuals", main="normality")
```

#Model selection method- backwards regression that removes non-significant variables
summary(Full.model_comb)

#least significant is shoreline change rate

```

model.1<-glms(D_vol_ch ~ width + Dune_type + height + Nourished
              + orientation + slope,
data=beach,weights=varComb(varPower(form=~slope),varIdent(form=~1|Dune_type)),
method="ML")
summary(model.1)
anova(Full.model_comb,model.1)

```

#remove slope (and its associated variance structure)

```

model.2<-glms(D_vol_ch ~ width + Dune_type + height + Nourished
              + orientation, data=beach,weights=varIdent(form=~1|Dune_type), method="ML")
anova(model.1, model.2)
anova(model.1)

```

#Although the AIC is lower for model one the anova of model.1 show that slope is not a
#significant variable nor is height

```
summary(model.2)
```

#remove height

```

model.2.2<-glms(D_vol_ch ~ width + Dune_type + Nourished
               + orientation + slope,
data=beach,weights=varComb(varPower(form=~slope),varIdent(form=~1|Dune_type)),
method="ML")
anova(model.1, model.2, model.2.2)

```

#nourished not significant

```
summary(model.2.2)
anova(model.2.2)
```

#removing slope again

```

model.2.3<-glms(D_vol_ch ~ width + Dune_type + Nourished
               + orientation, data=beach,weights=varIdent(form=~1|Dune_type), method="ML")
anova(model.2.2, model.2.3)

```

AIC better for model.2.2 log likelihood test reject the null if the value of this stat is too small-

```
anova(model.2.3)
```

#nourished not significant

```

model.3<-glms(D_vol_ch ~ width + Dune_type + orientation,
              data=beach,weights=varIdent(form=~1|Dune_type), method="ML")
anova(model.2, model.3)

```

AIC # similar for both but BIC better for model.3

```
anova(model.3)
summary(model.3)
```

#model 3 try removing orientation to see if it's a better model or not

```
model.4<-glm(D_vol_ch ~ width + Dune_type,
             data=beach,weights=varIdent(form=~1|Dune_type), method="ML")
anova(model.3,model.4)
anova(model.3)
```

#model 3 lowest AIC

my problem with this model is that beach width shows such a high correlation but also is
associated with a high VIF
#In an attempt to understand how much each predictor contributes to the understanding of Y- I
will use the method of hierchial partitioning which takes the proportion if variation of Y
explained by the full model and determine how
#much of that R-square each predictor is responsible for

```
library(hier.part)
hier.part(beach$D_vol_ch, beach[,c(4:7, 10:12)], gof = "Rsqu", barplot = TRUE)
```

```
op=par(mfrow=c(2,2))
plot(width~Dune_type)
plot(width~slope)
plot(width~height)
plot(width~orientation)
```

so there is relationships with width and other variables,
being that dune type and width are so important maybe they can work together
#lets look at a co-plot of the relationship of beach width and dune vol change by dune type

```
coplot(D_vol_ch~width | factor(Dune_type), data=beach)
```

#If the relationship between width and dune volume is not the same for all dune types so
perhaps an interaction will work better
#test an interaction

```
model.5<-glm(D_vol_ch ~ width * Dune_type + orientation,
             data=beach,weights=varIdent(form=~1|Dune_type), method="ML")
anova(model.3, model.4, model.5)
```

#Model5 better than model 4 but not better than model 3

```
anova(model.5)#interaction not significant
```

#interaction not significant

```
summary(model.4)
```

```
## orientation will not be included as the amount of explained variance is not enough
### check model assumptions
```

```
final_model<-glS(D_vol_ch ~ width + Dune_type ,
  data=beach,weights=varIdent(form=~1|Dune_type), method="REML")
summary(final_model)
p=par(mfrow=c(2,2))
plot(final_model)
hist(resid(final_model), xlab= "residuals", main="normality")
```

```
#check homoscedasticity
```

```
plot(resid(model_7)~beach$Dune_type, xlab="Dune Type", ylab="residuals")
plot(resid(model_7)~beach$orientation, xlab="orientation", ylab="residuals")
plot(resid(model_7)~beach$width, xlab="width", ylab="residuals")
final_model<-glS(D_vol_ch ~ width + Dune_type ,
  data=beach,weights=varIdent(form=~1|Dune_type), method="ML")
```

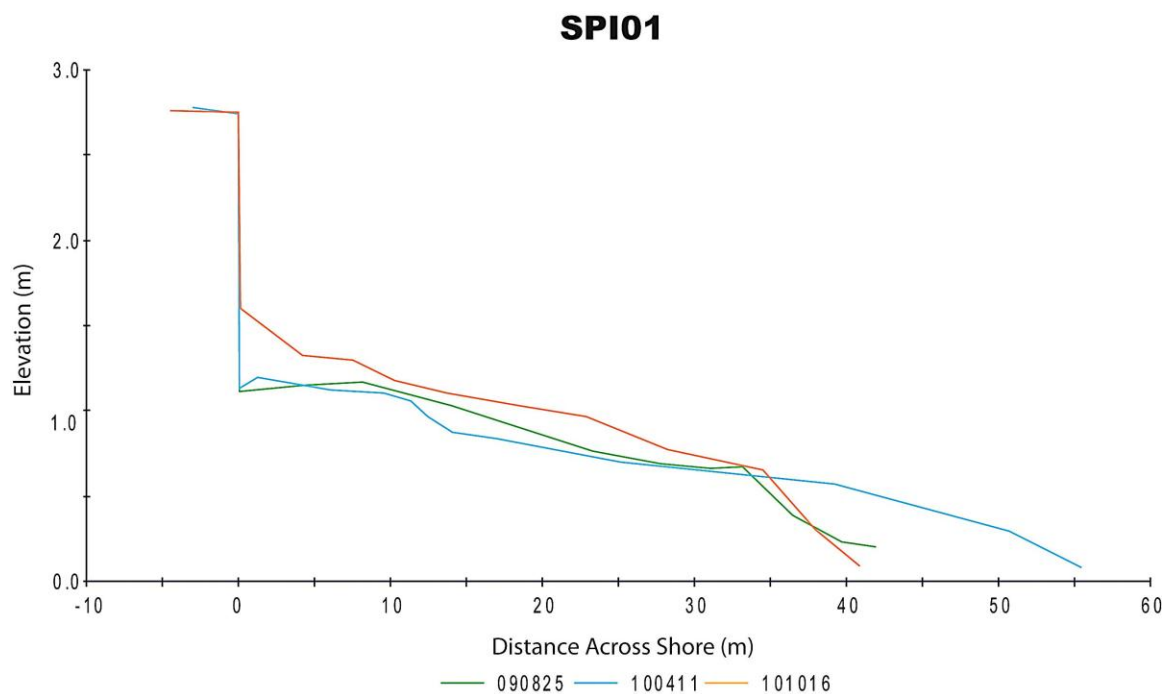
```
#plot of final model
```

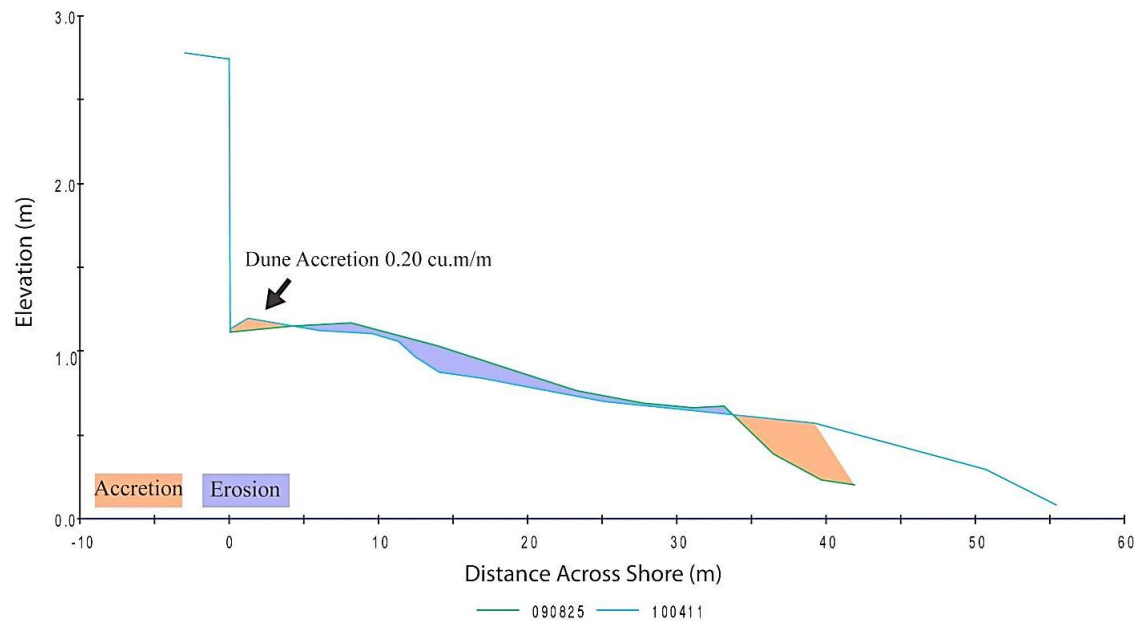
```
plot(D_vol_ch~width, col=Dune_type)
abline(a=-85.01, b=1.17)
abline(a=-33.97, b=1.17)
abline(a=-49.87, b=1.17)
abline(a=-38.15, b=1.17)
abline(a=36.33, b=1.17)residuals")
```

APPENDIX E

Beach Profiles for Dune Accretion Calculations

The following section contains graphs of profiles collected from the summer 2009 to the Fall of 2010 and cut/fill results obtained from Rmap. The lines are represented by their collection date as YYMMDD. Volume change was calculated among profiles. Dune toe accretion was used for comparison with the sediment transport model results. Dune toe accretion has been highlighted in the cut/fill reports.

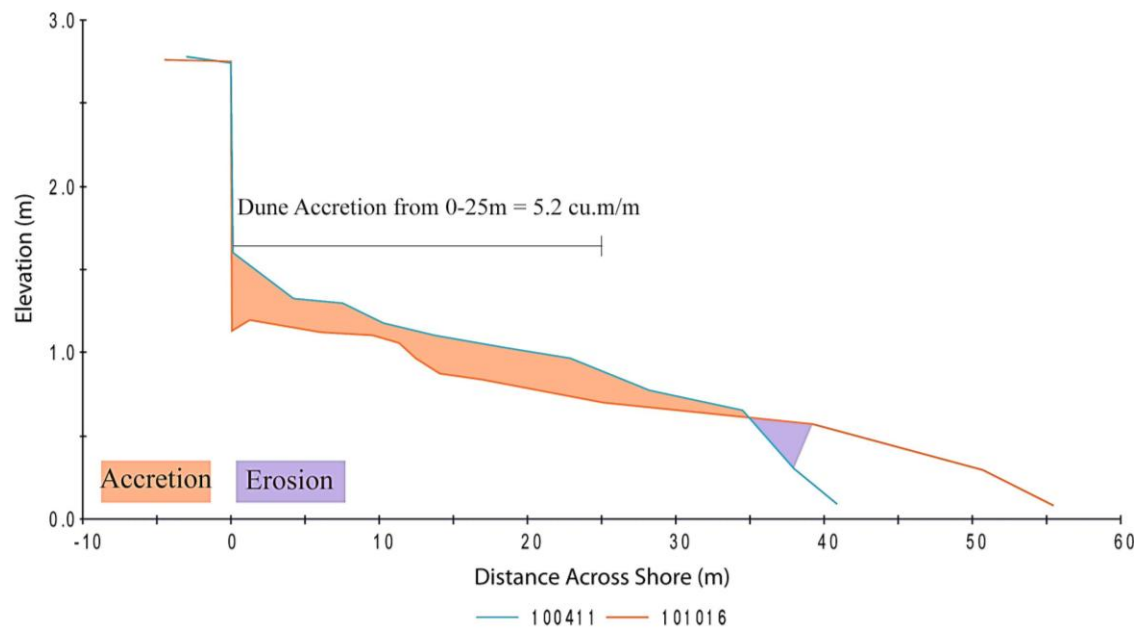


SPI01**SPI01 Cut Fill Report**

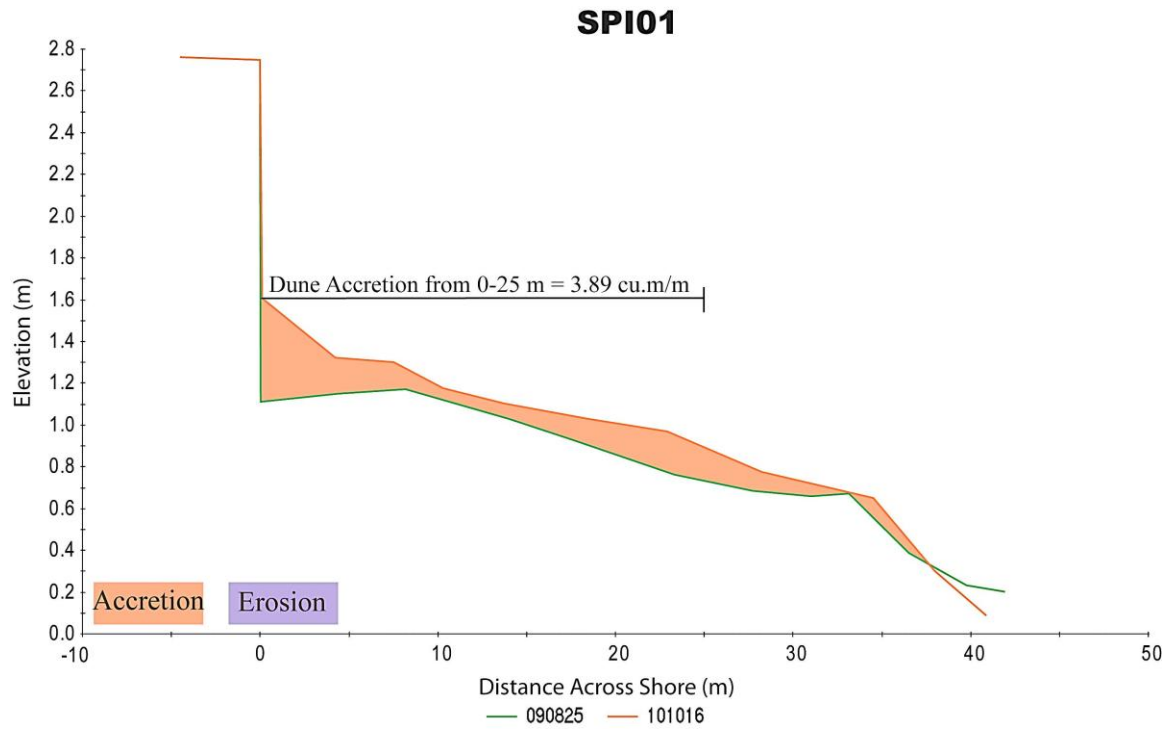
Profile 1:	090825
Profile 2:	100411

Cell Changes

Cell #	Ending Distance(m)	Ending Elevation(m)	Cell Volume (m ³ /m)	Cumulative Volume (m ³ /m)	Gross Volume (m ³ /m)
1	4.28	1.15	0.204	0.204	0.204
2	33.79	0.62	-1.627	-1.423	1.831
3	41.89	0.2	1.805	0.382	3.637

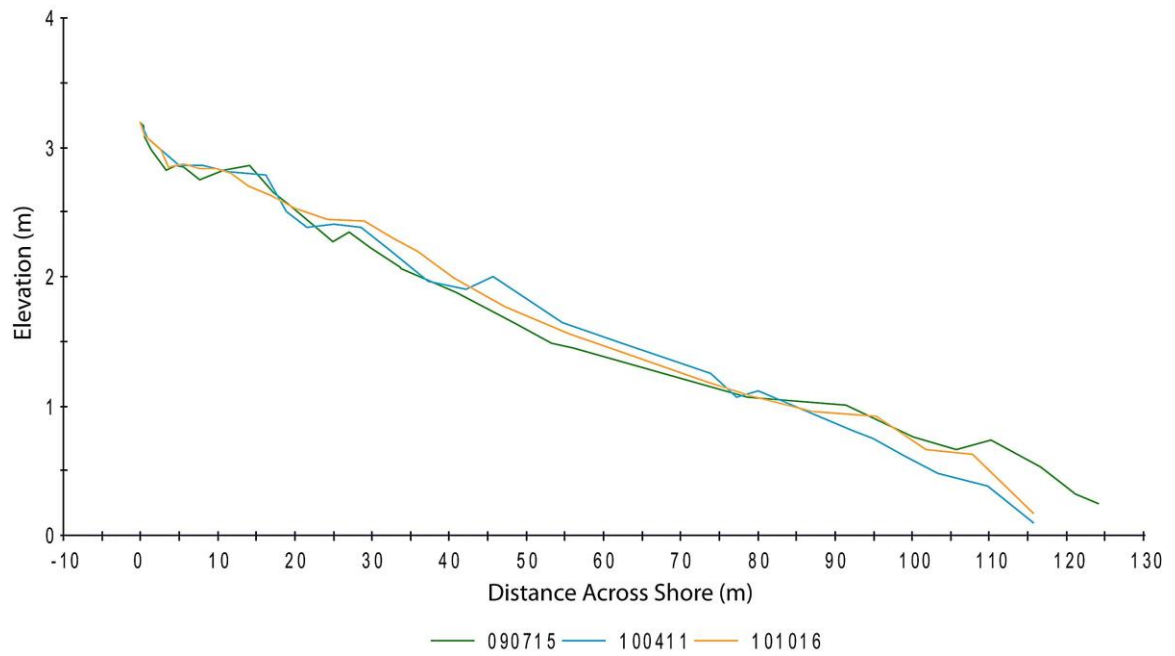
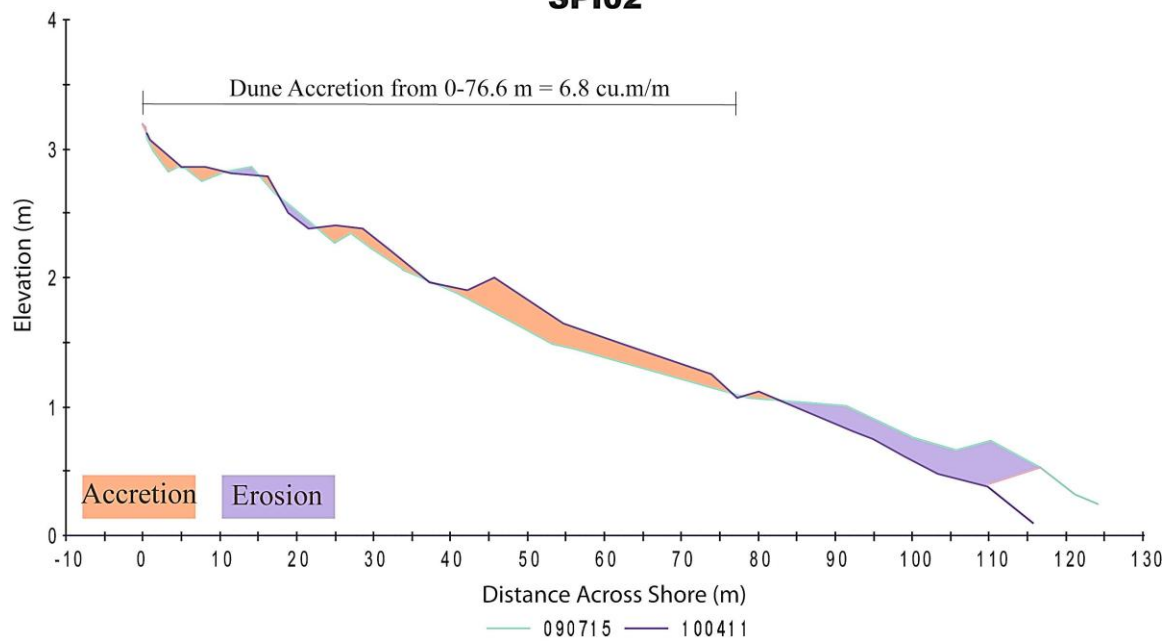
SPI01**SPI01 Profile Comparison Report**

Profile 1:	100411
Profile 2:	101016
XOn:	0.00 m
XOff:	25.00 m
Volume Change:	5.205 cu. m/m



SPI01 Profile Comparison Report

Profile 1:	90825
Profile 2:	101016
XOn:	0.09 m
XOff:	25.00 m
Volume Change:	3.886 cu. m/m

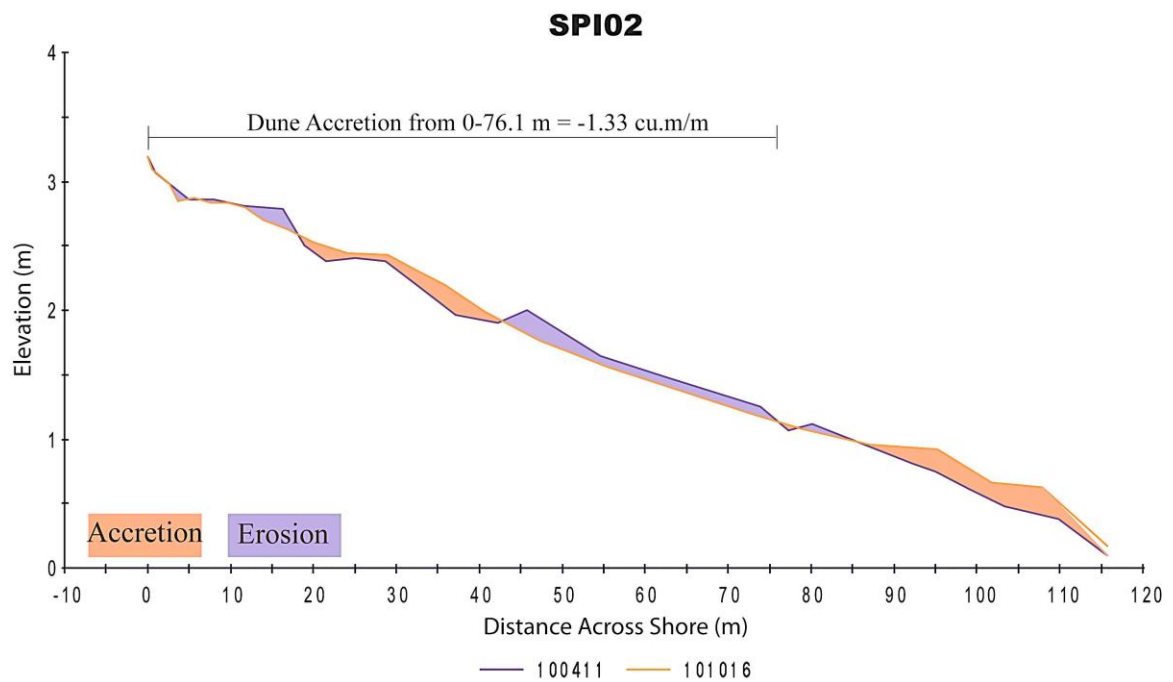
SPI02**SPI02**

SPI02 Cut/Fill Report

Profile 1:	090715
Profile 2:	100411

Cell Changes

Cell #	Ending Distance(m)	Ending Elevation(m)	Cell Volume (cu. m/m)	Cumulative Volume(cu. m/m)	Gross Volume (cu. m/m)
1	0.46	3.14	-0.009	-0.009	0.009
2	10.57	2.82	0.624	0.615	0.634
3	15.22	2.79	-0.178	0.437	0.812
4	17.75	2.62	0.095	0.533	0.907
5	22.5	2.39	-0.239	0.294	1.146
6	36.66	1.99	1.05	1.344	2.195
7	38.06	1.95	-0.009	1.335	2.204
8	76.64	1.1	5.481	6.815	7.684
9	78.07	1.08	-0.019	6.797	7.703
10	82.76	1.05	0.133	6.93	7.837
11	115.65	0.56	-7.052	-0.122	14.889

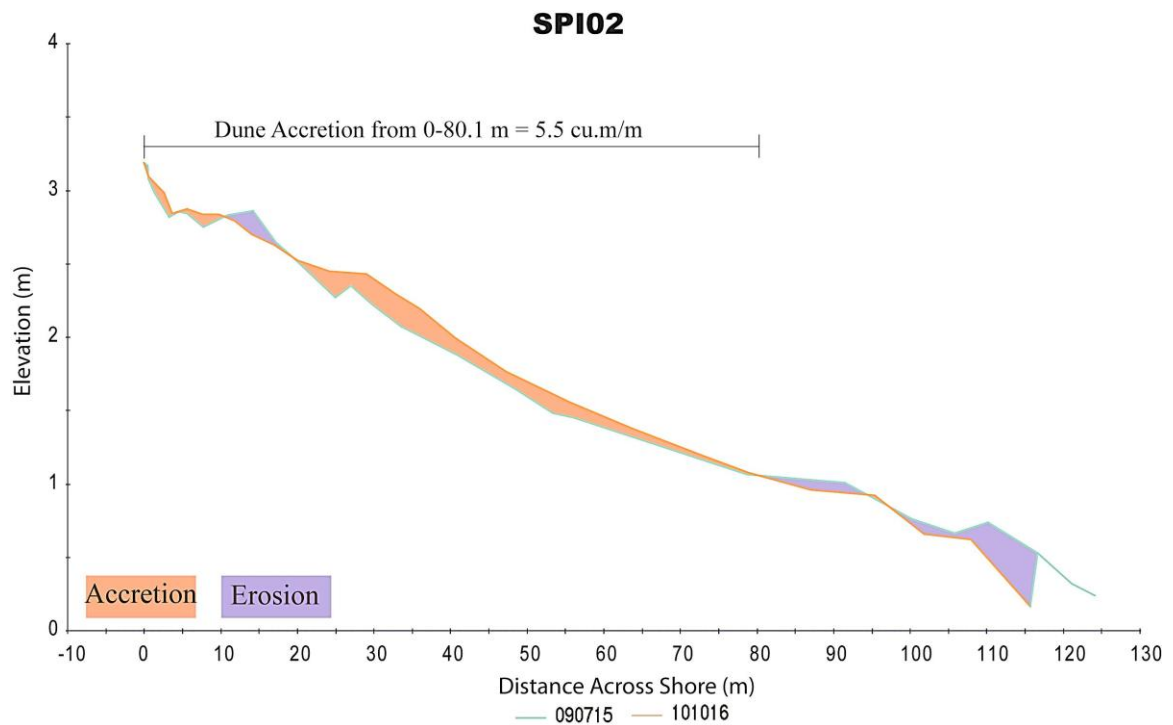


SPI02 Cut/Fill Report

Profile 1:	100411
Profile 2:	101016

Cell Changes

Cell #	Ending Distance(m)	Ending Elevation(m)	Cell Volume (cu. m/m)	Cumulative Volume (cu. m/m)	Gross Volume (cu. m/m)
1	0.78	3.08	-0.007	-0.007	0.007
2	2.62	2.98	0.013	0.006	0.02
3	4.9	2.86	-0.093	-0.087	0.113
4	6.38	2.86	0.012	-0.075	0.125
5	18.01	2.59	-0.537	-0.612	0.662
6	42.76	1.92	2.182	1.57	2.844
7	76.11	1.13	-2.9	-1.33	5.744
8	78.49	1.09	0.053	-1.278	5.797
9	84.99	0.99	-0.177	-1.454	5.974
10	115.65	0.09	3.967	2.512	9.94

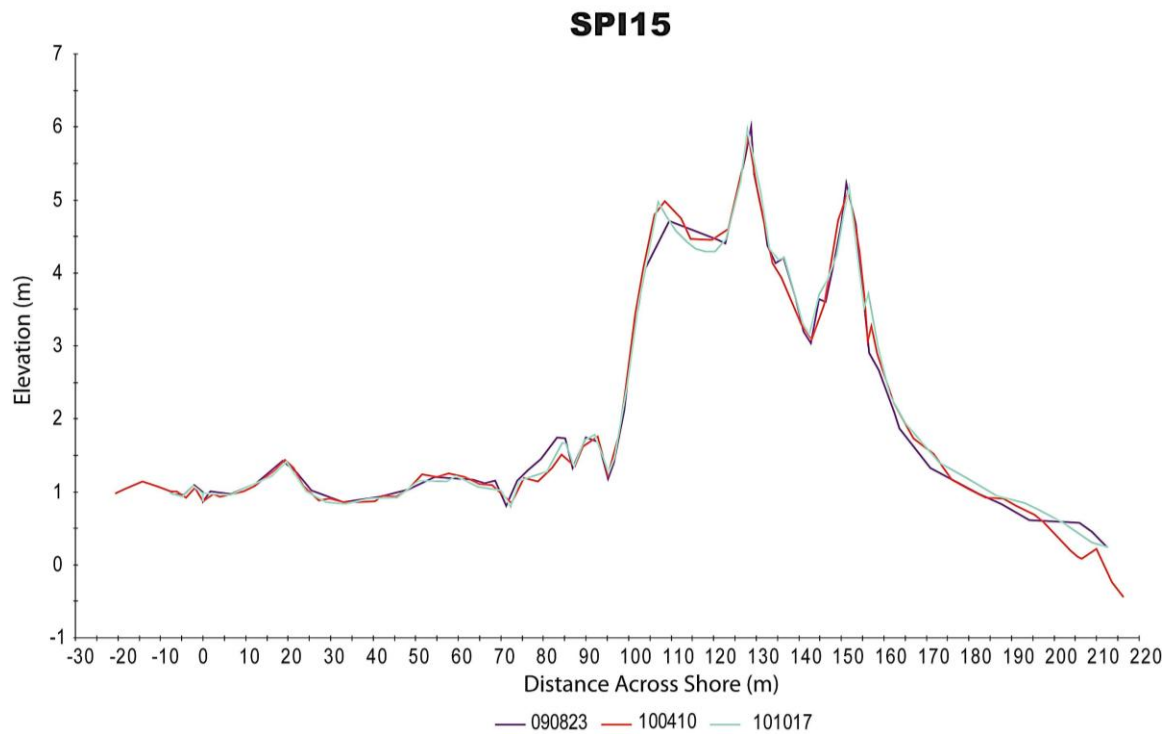


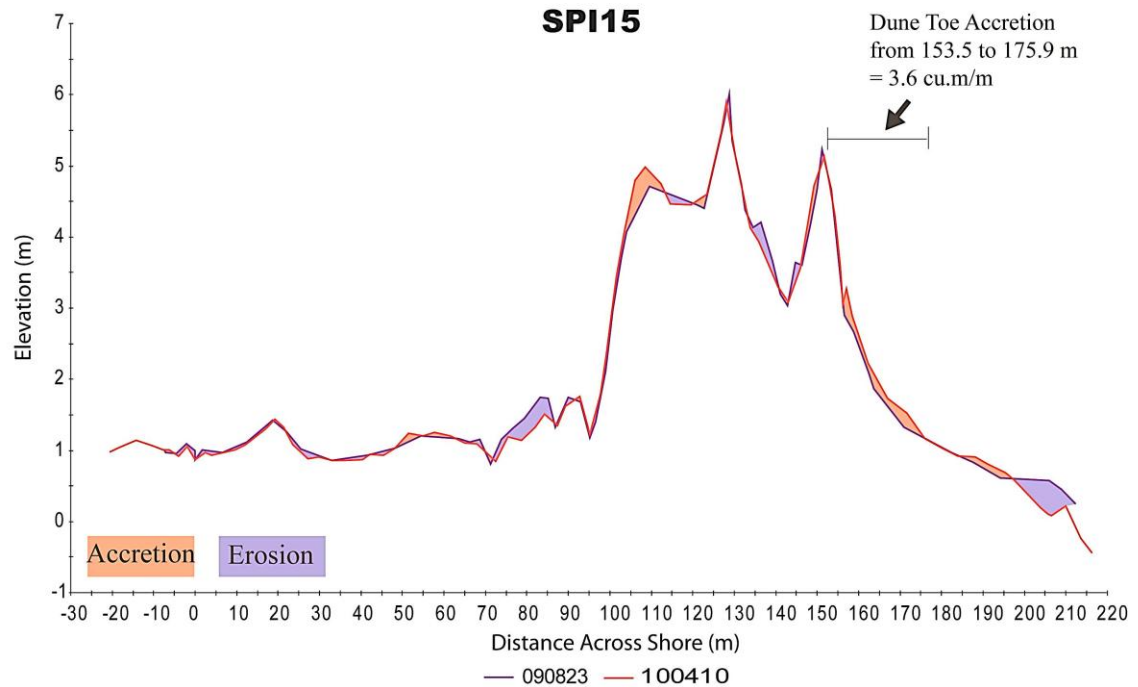
SPI02 Cut/Fill Report

Profile 1:	090715
Profile 2:	101016

Cell Changes

Cell #	Ending Distance(m)	Ending Elevation(m)	Cell Volume (cu. m/m)	Cumulative Volume (cu. m/m)	Gross Volume (cu. m/m)
1	0.52	3.09	-0.014	-0.014	0.014
2	10.49	2.82	0.508	0.495	0.522
3	19.64	2.53	-0.591	-0.096	1.113
4	80.14	1.06	5.631	5.535	6.744
5	94.14	0.93	-0.593	4.942	7.337
6	97.38	0.84	0.044	4.986	7.381
7	115.71	0.56	-2.621	2.365	10.002





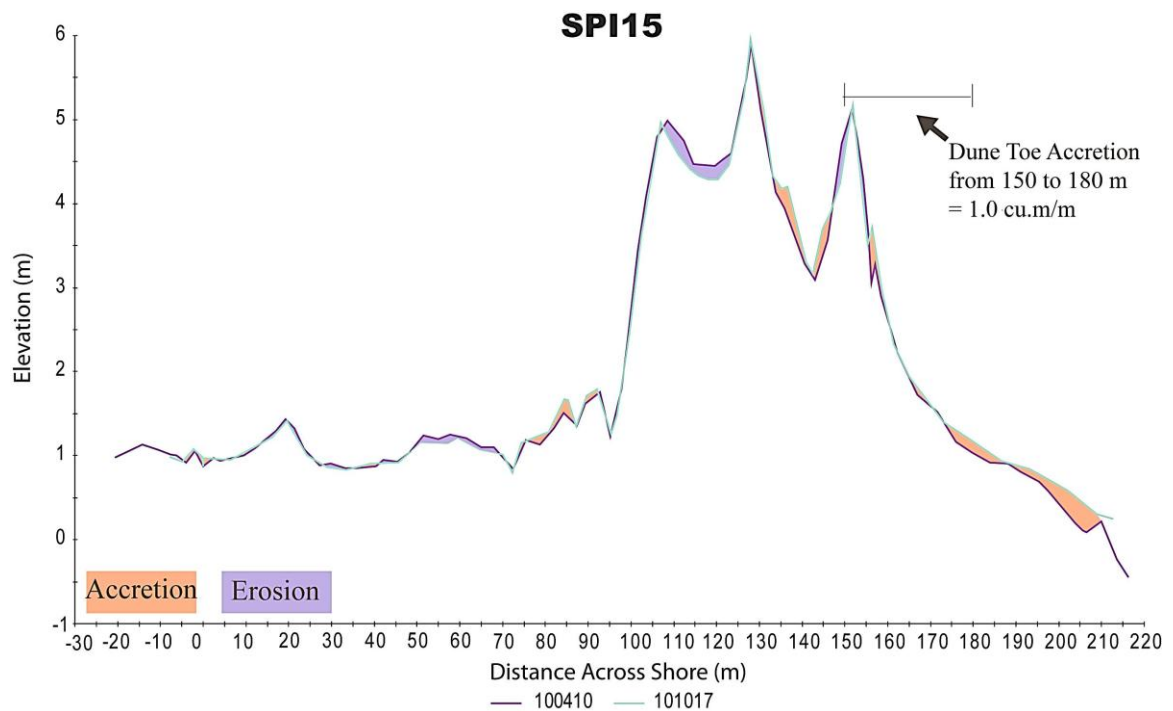
SPI 15 Cut/Fill Results

Profile 1:	090823
Profile 2:	100410

Cell Changes

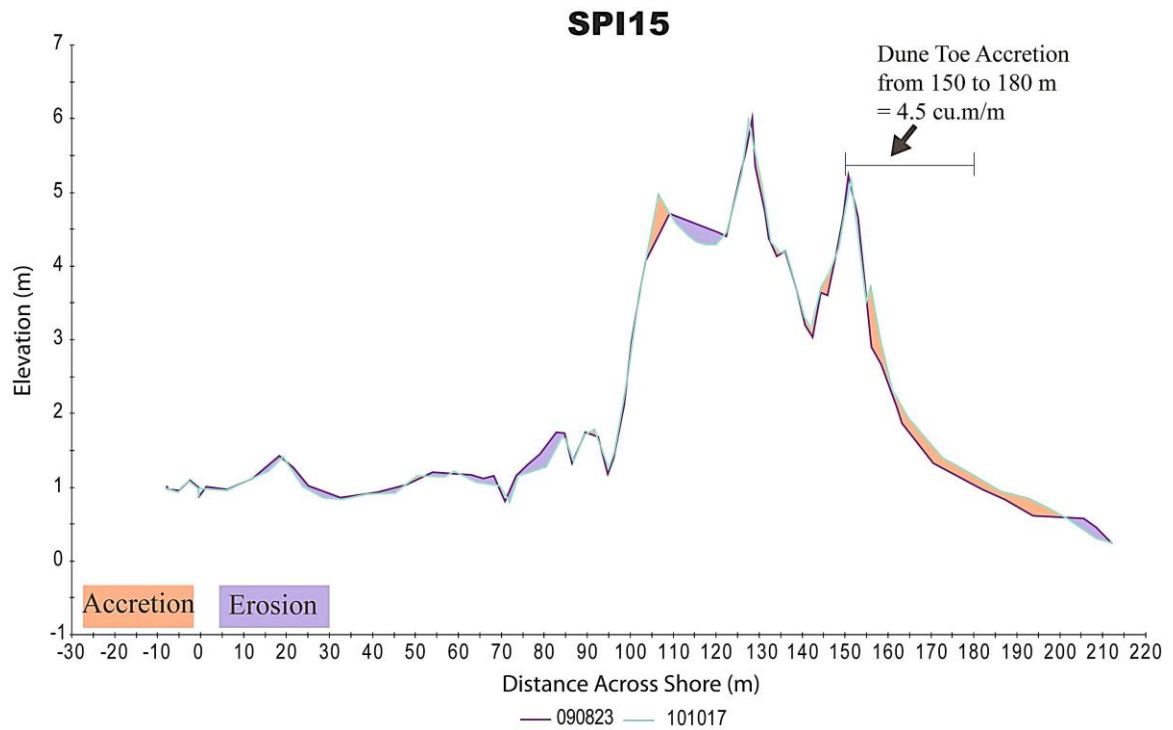
Cell #	Ending Distance(m)	Ending Elevation(m)	Cell Volume (cu. m/m)	Cumulative Volume(cu. m/m)	Gross Volume (cu. m/m)
1	-4.95	0.95	0.073	0.073	0.073
2	18.96	1.41	-0.842	-0.769	0.915
3	21.95	1.27	0.094	-0.675	1.009
4	32.48	0.86	-0.481	-1.156	1.49
5	33.03	0.86	0.001	-1.156	1.491
6	41.72	0.93	-0.218	-1.374	1.709
7	42.7	0.94	0.005	-1.369	1.714
8	48	1.03	-0.15	-1.519	1.864
9	62.72	1.17	0.663	-0.856	2.527
10	69.92	0.99	-0.239	-1.094	2.765
11	71.8	0.88	0.097	-0.997	2.863
12	86.51	1.4	-3.015	-4.012	5.878
13	87.19	1.37	0.022	-3.99	5.899
14	91.47	1.71	-0.214	-4.204	6.113

15	113.33	4.63	3.625	-0.579	9.737
16	120.25	4.47	-0.525	-1.105	10.263
17	128.25	5.85	0.387	-0.717	10.65
18	129.53	5.37	-0.221	-0.938	10.871
19	129.96	5.23	0.007	-0.931	10.878
20	131.95	4.65	-0.045	-0.976	10.923
21	133.18	4.3	0.051	-0.925	10.974
22	140.89	3.26	-1.366	-2.291	12.34
23	143.09	3.11	0.093	-2.198	12.433
24	146.06	3.61	-0.394	-2.592	12.828
25	150.54	4.95	0.8	-1.793	13.628
26	151.59	5.12	-0.093	-1.886	13.721
27	153.03	4.75	0.019	-1.866	13.74
28	153.47	4.6	-0.006	-1.873	13.746
29	156.1	3.11	0.372	-1.501	14.118
30	156.17	3.07	-0.001	-1.502	14.119
31	175.88	1.18	3.199	1.698	17.318
32	184.76	0.91	-0.132	1.566	17.45
33	197.19	0.6	0.884	2.45	18.333
34	212.12	0.26	-4.122	-1.672	22.455



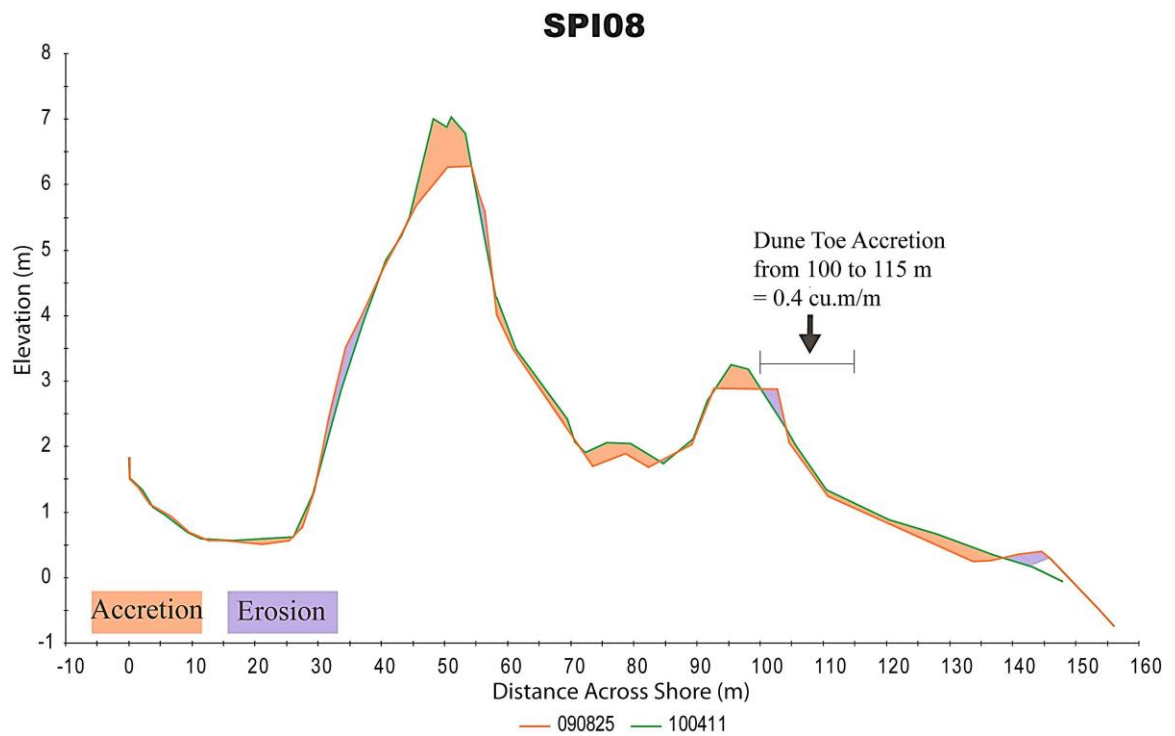
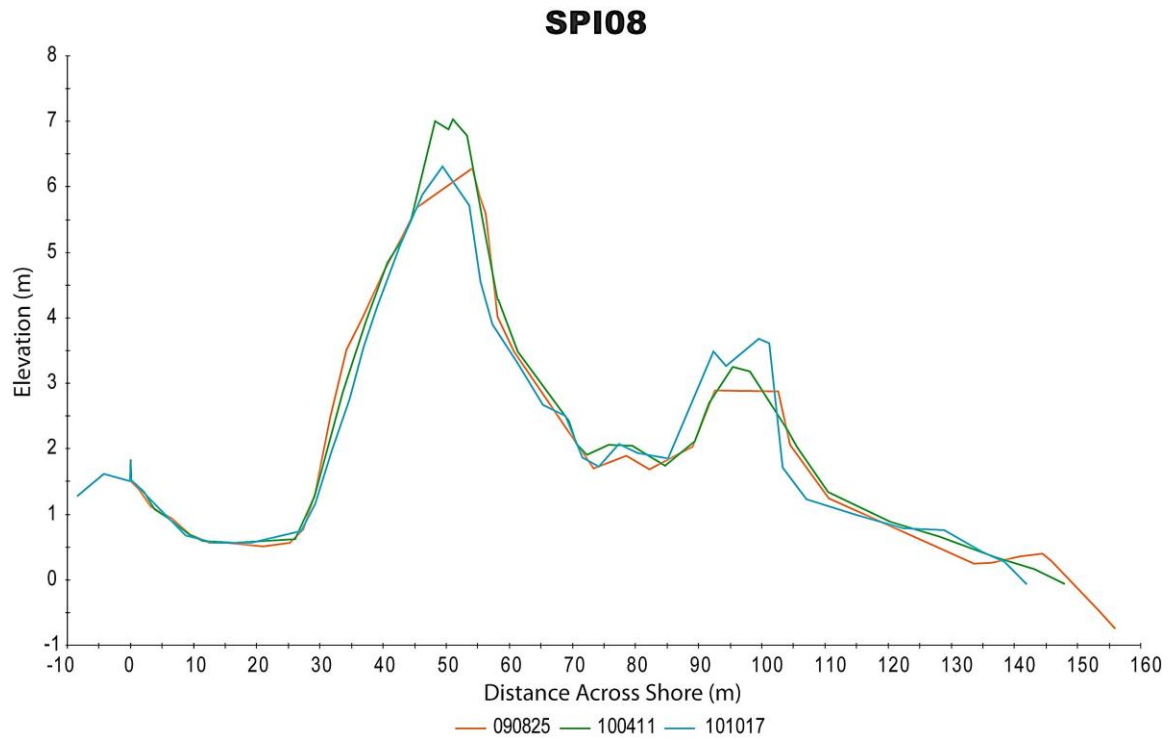
SPI15 Profile Comparison Report

Profile 1:	100410
Profile 2:	101017
XOn:	150.00 m
XOff:	180.00 m
Volume Change:	1.041 cu. m/m



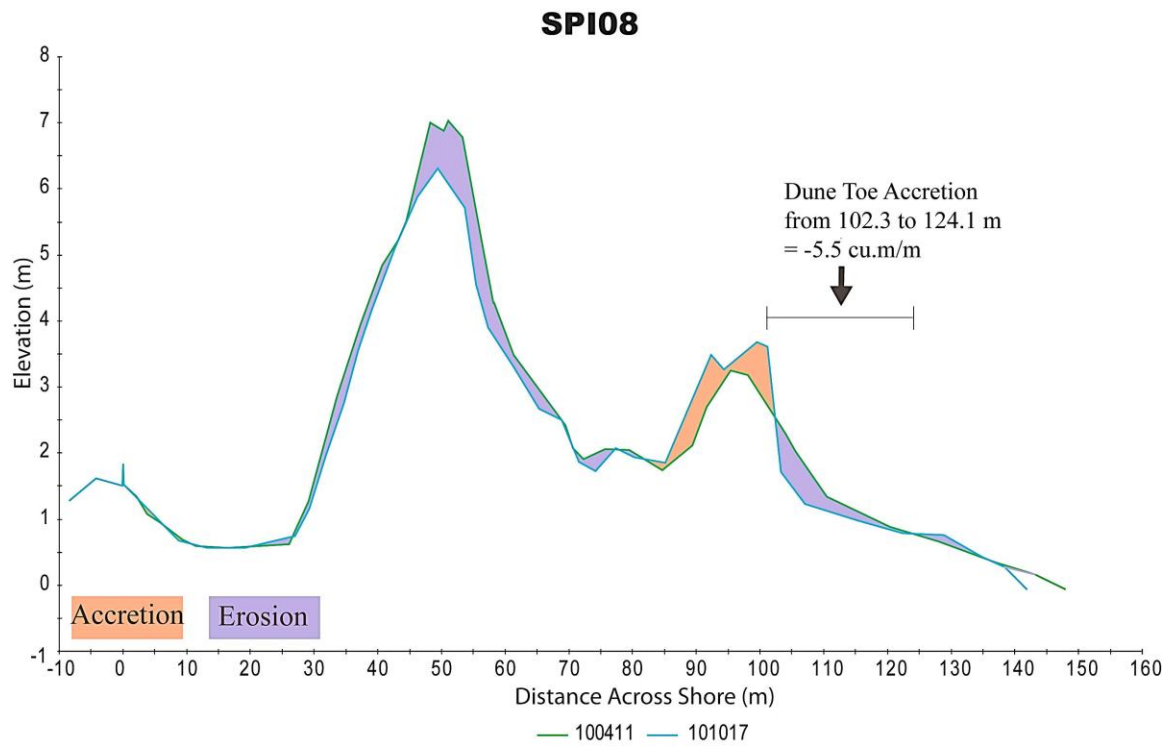
SPI15 Profile Comparison Report

Profile 1:	090823
Profile 2:	101017
XOn:	150.00 m
XOff:	180.00 m
Volume Change:	4.521 cu. m/m



SPI08 Profile Comparison Report

Profile 1:	090825
Profile 2:	100411
XOn:	100.00 m
XOff:	115.00 m
Volume Change:	0.376 cu. m/m

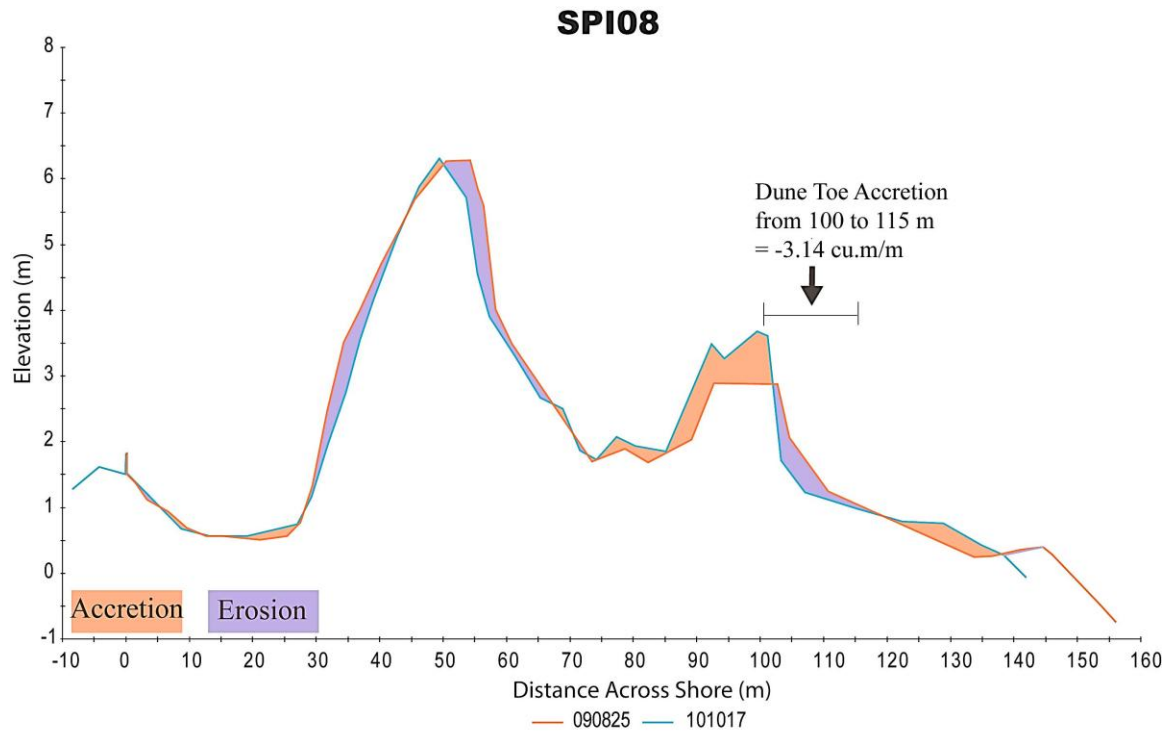


SPI08 Cut/Fill Report

Profile 1:	100411
Profile 2:	101017

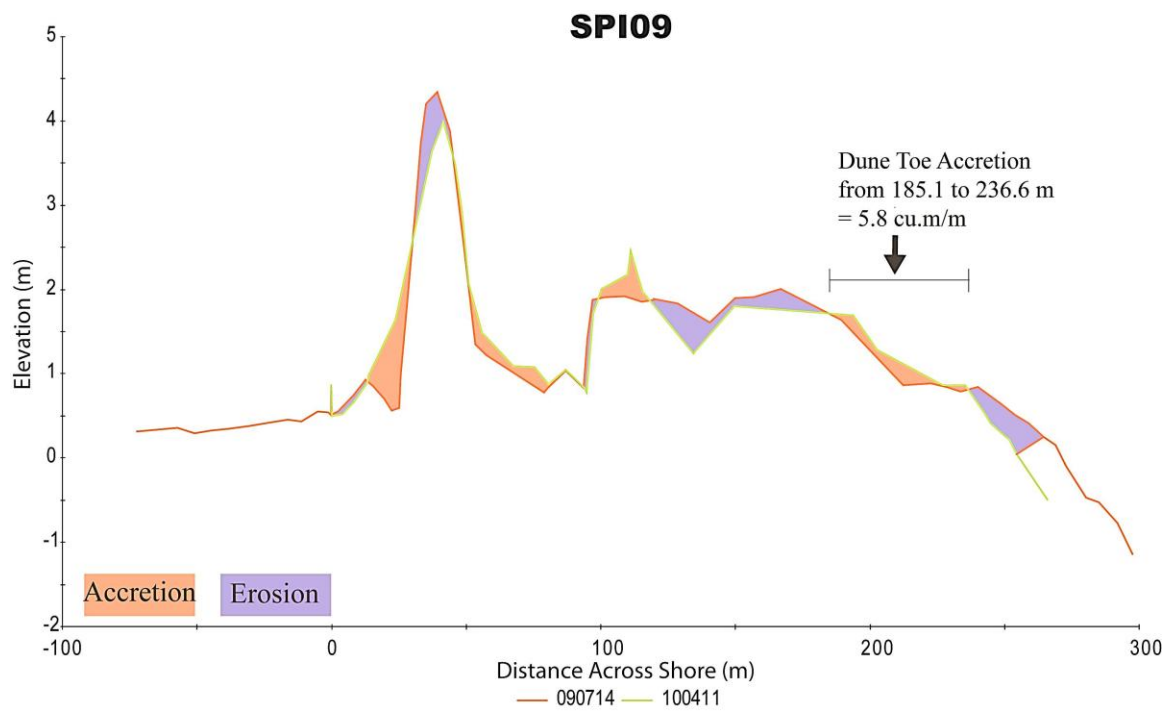
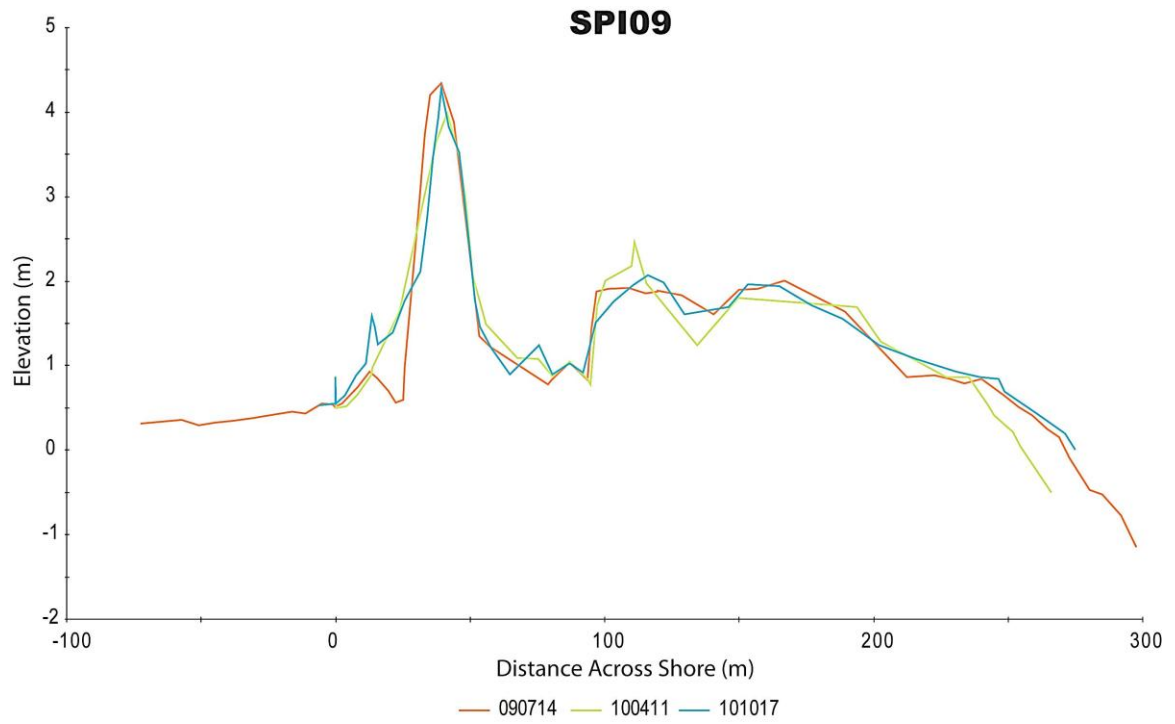
Cell Changes:

Cell #	Ending Distance(m)	Ending Elevation(m)	Cell Volume (cu. m/m)	Cumulative Volume (cu. m/m)	Gross Volume (cu. m/m)
1	1.57	1.38	-0.006	-0.006	0.006
2	2.08	1.34	0	-0.006	0.006
3	6.68	0.88	0.183	0.177	0.189
4	10.81	0.62	-0.095	0.081	0.285
5	12.1	0.59	0.008	0.089	0.292
6	15.64	0.57	-0.034	0.055	0.326
7	17.45	0.57	0.005	0.06	0.331
8	19.61	0.58	-0.009	0.051	0.341
9	26.57	0.73	0.352	0.403	0.692
10	77.16	2.05	-17.756	-17.354	18.448
11	77.83	2.05	0.007	-17.347	18.455
12	81.66	1.92	-0.145	-17.492	18.6
13	102.34	2.54	8.21	-9.282	26.81
14	124.09	0.78	-5.491	-14.774	32.301
15	135.09	0.42	0.63	-14.144	32.931
16	141.86	0.2	-0.527	-14.671	33.459



SPI08 Profile Comparison Report

Profile 1:	90825
Profile 2:	101017
XOn:	100.00 m
XOff:	115.00 m
Volume Change:	-3.057 cu. m/m

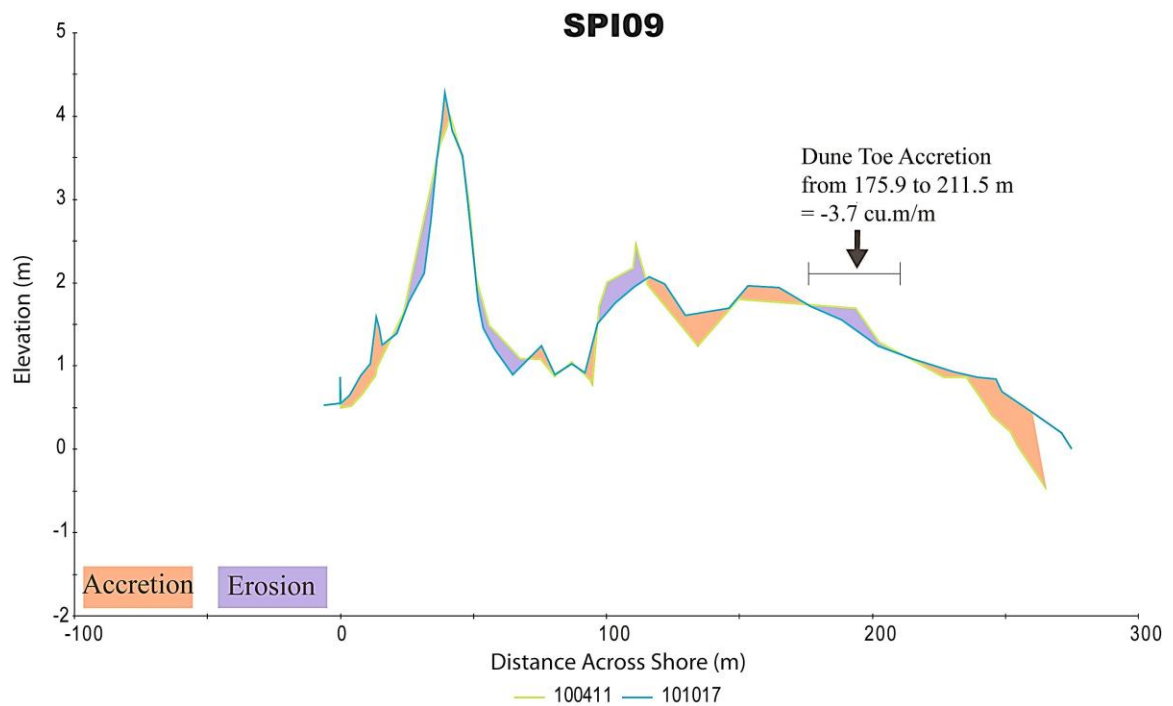


SPI09 Cut/Fill Report

Profile 1:	090714
Profile 2:	100411

Cell Changes:

Cell #	Ending Distance(m)	Ending Elevation(m)	Cell Volume (cu. m/m)	Cumulative Volume (cu. m/m)	Gross Volume (cu. m/m)
1	13.37	0.91	-0.96	-0.96	0.96
2	30.27	2.61	10.373	9.412	11.333
3	45.14	3.57	-6.528	2.885	17.86
4	93.35	0.84	6.019	8.904	23.88
5	99.14	1.89	-1.589	7.315	25.469
6	118.17	1.87	3.949	11.264	29.418
7	185.12	1.71	-12.186	-0.922	41.604
8	236.61	0.81	5.836	4.914	47.44
9	266.01	0.22	-11.669	-6.755	59.109

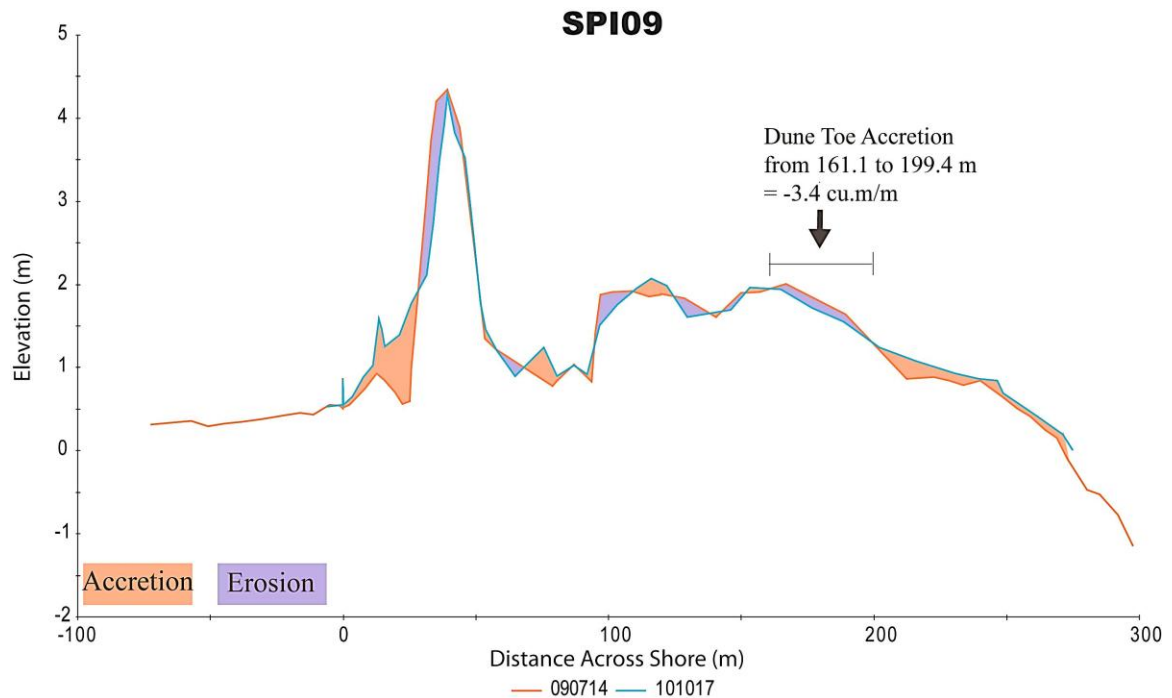


SPI09 Cut/Fill Report

Profile 1:	100411
Profile 2:	101017

Cell Changes:

Cell #	Ending Distance(m)	Ending Elevation(m)	Cell Volume (cu. m/m)	Cumulative Volume (cu. m/m)	Gross Volume (cu. m/m)
1	19.11	1.34	4.182	4.182	4.182
2	36.36	3.51	-4.753	-0.572	8.935
3	41.2	3.96	1.021	0.449	9.956
4	44.99	3.59	-0.218	0.231	10.174
5	46.29	3.39	0.019	0.25	10.193
6	70.49	1.08	-4.177	-3.928	14.37
7	82.82	0.94	0.902	-3.025	15.272
8	89.61	0.97	-0.086	-3.111	15.358
9	96.71	1.51	1.224	-1.887	16.582
10	114.79	2.05	-5.013	-6.9	21.596
11	175.85	1.74	9.971	3.072	31.567
12	211.46	1.13	-3.726	-0.655	35.293
13	266.01	-0.49	15.233	14.578	50.526

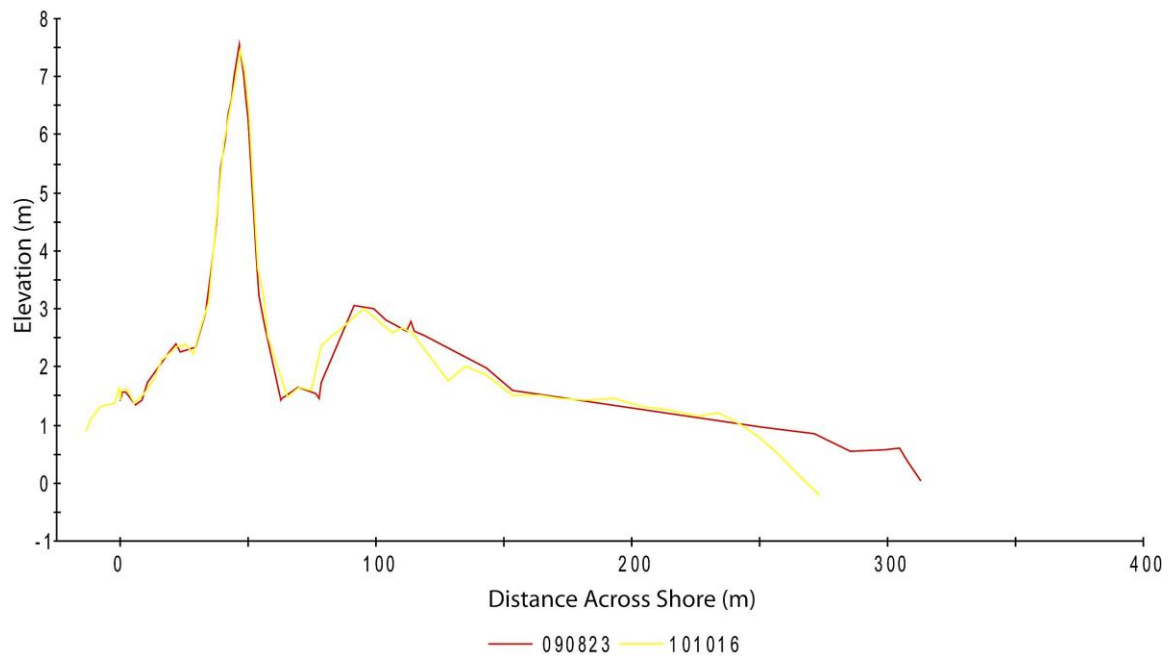
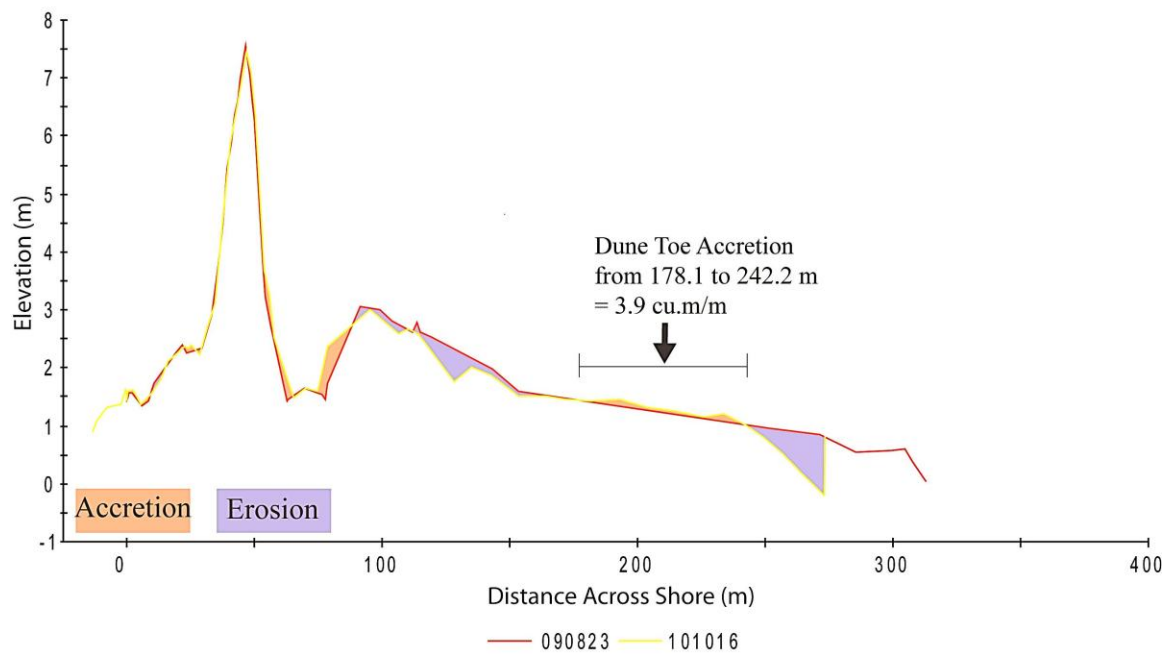


SPI09 Cut/Fill Report:

Profile 1:	090714
Profile 2:	101017

Cell Changes:

Cell #	Ending Distance(m)	Ending Elevation (m)	Cell Volume (cu. m/m)	Cumulative Volume (cu. m/m)	Gross Volume (cu. m/m)
1	-2.43	0.54	-0.044	-0.044	0.044
2	28.38	1.94	12.109	12.065	12.153
3	45.11	3.58	-8.953	3.111	21.107
4	50.41	2.19	0.41	3.521	21.517
5	52.35	1.66	-0.072	3.449	21.589
6	57.53	1.22	0.304	3.753	21.893
7	67.97	1	-0.91	2.843	22.803
8	85.93	1	2.899	5.742	25.702
9	88.25	0.99	-0.014	5.727	25.716
10	94.44	1.23	0.448	6.175	26.163
11	109.12	1.92	-2.617	3.558	28.781
12	124.4	1.86	1.813	5.37	30.594
13	138.22	1.65	-1.426	3.945	32.019
14	142.73	1.68	0.123	4.068	32.143
15	151.59	1.9	-0.465	3.604	32.608
16	161.12	1.95	0.357	3.961	32.965
17	199.42	1.3	-3.403	0.558	36.368
18	274.7	-0.19	8.648	9.206	45.015

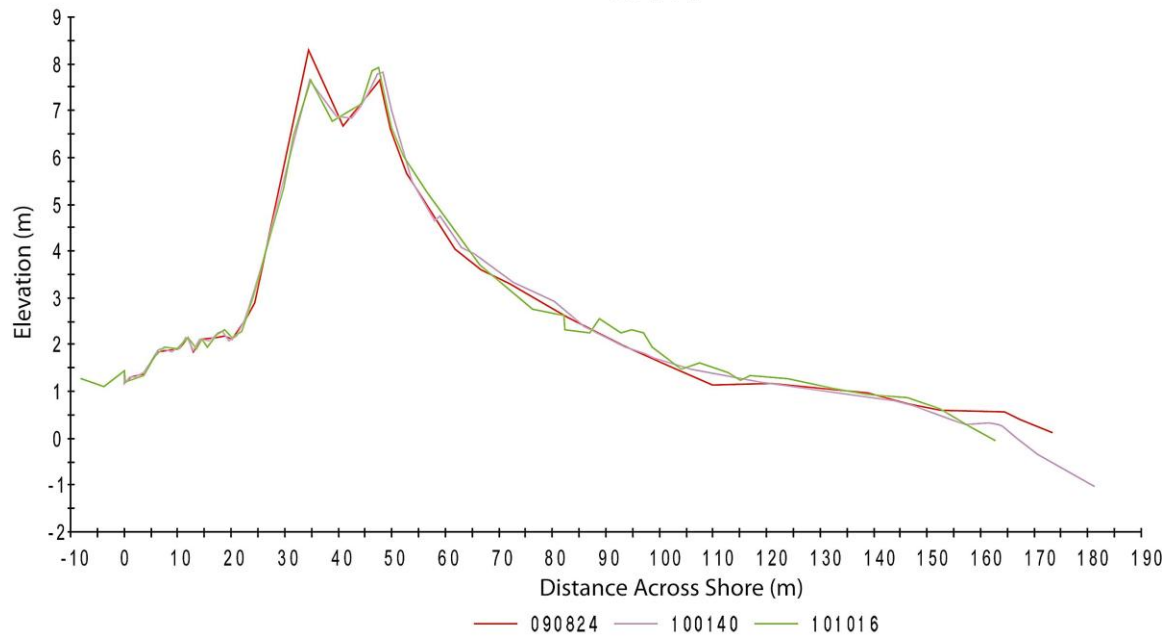
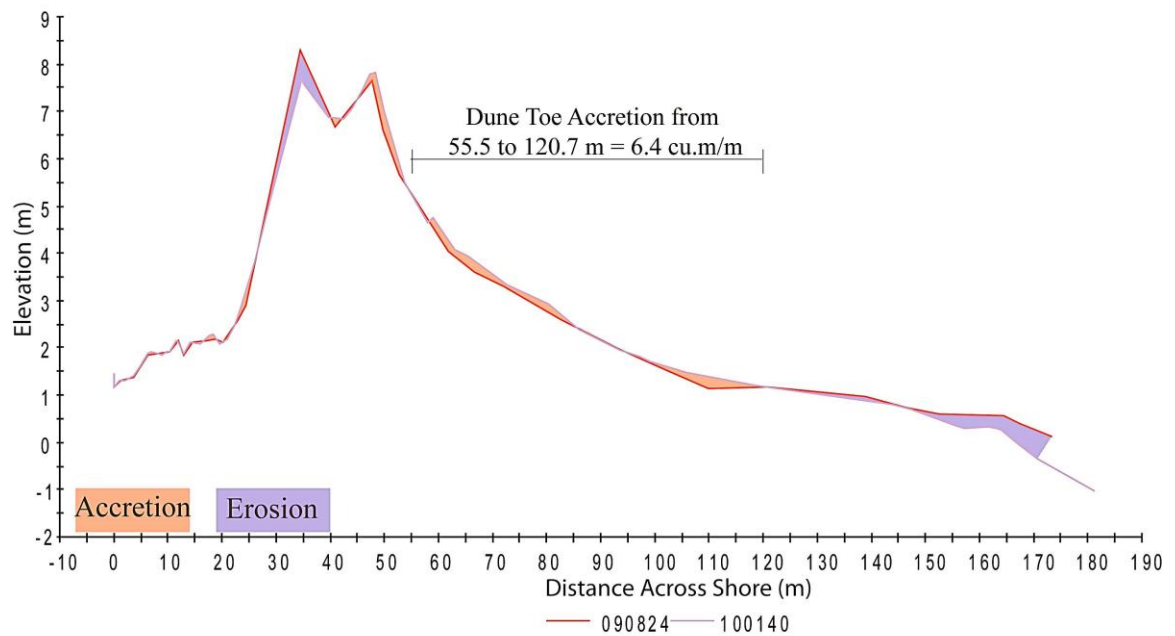
SPI07**SPI07**

SPI07 Cut/Fill Report

Profile 1:	90823
Profile 2:	101016

Cell Changes:

Cell #	Ending Distance(m)	Ending Elevation(m)	Cell Volume (cu. m/m)	Cumulative Volume (cu. m/m)	Gross Volume (cu. m/m)
1	9.34	1.55	0.477	0.477	0.477
2	14.8	1.98	-0.369	0.108	0.846
3	18.97	2.24	0.144	0.252	0.99
4	22.09	2.36	-0.067	0.185	1.057
5	27.08	2.3	0.346	0.531	1.403
6	28.95	2.33	-0.075	0.456	1.477
7	33.08	2.91	0.107	0.563	1.584
8	39.85	5.64	-0.543	0.02	2.127
9	43.87	6.77	0.15	0.17	2.277
10	46.66	7.42	-0.316	-0.146	2.593
11	65	1.51	4.631	4.484	7.223
12	69.78	1.65	-0.075	4.41	7.298
13	88.51	2.76	5.037	9.446	12.335
14	109.98	2.67	-2.4	7.046	14.735
15	111.87	2.63	0.007	7.053	14.742
16	178.07	1.44	-10.276	-3.223	25.018
17	242.17	1.02	3.901	0.678	28.919
18	273	0.81	-14.574	-13.896	43.492

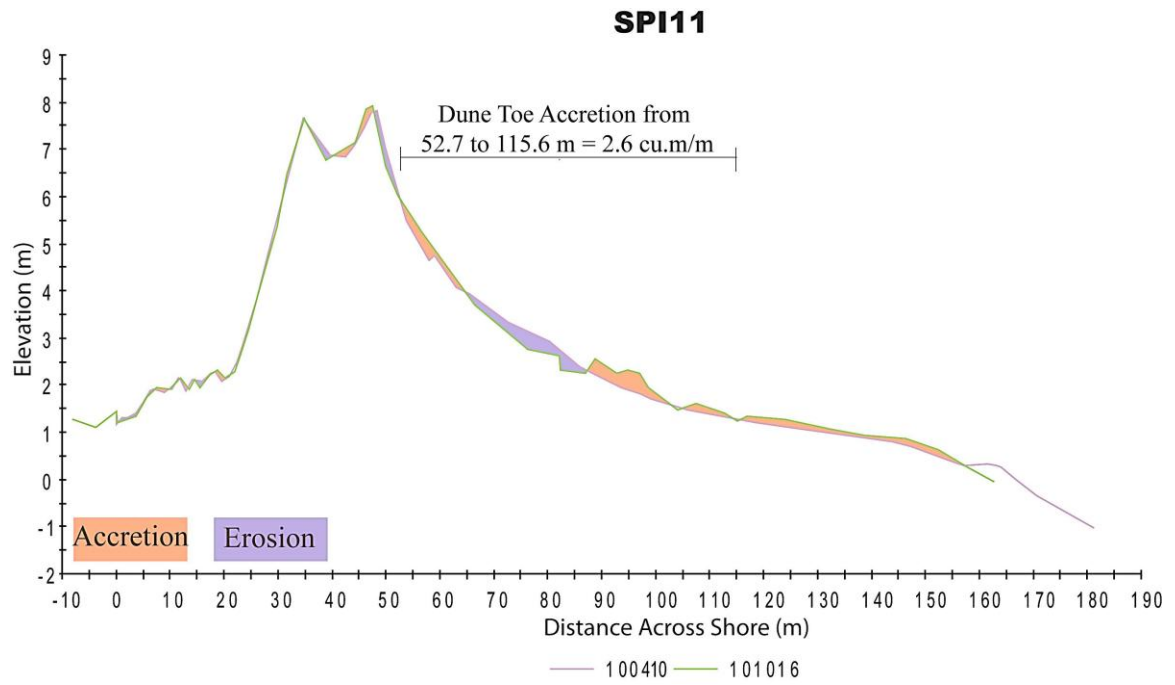
SPI11**SPI11**

SPI11 Cut/Fill Report

Profile 1:	090824
Profile 2:	100140

Cell Changes:

Cell #	Ending Distance(m)	Ending Elevation(m)	Cell Volume (cu. m/m)	Cumulative Volume (cu. m/m)	Gross Volume cu. m/m)
1	0.31	1.21	-0.01	-0.01	0.01
2	1.12	1.31	0.001	-0.009	0.012
3	3.21	1.37	-0.051	-0.06	0.063
4	8.12	1.88	0.084	0.024	0.147
5	9.42	1.9	-0.021	0.004	0.167
6	10.2	1.91	0.007	0.011	0.175
7	10.5	1.95	-0.001	0.01	0.176
8	11.78	2.12	0.029	0.038	0.205
9	12.59	1.95	-0.011	0.028	0.216
10	14.44	2.11	0.078	0.105	0.293
11	16.59	2.14	-0.052	0.053	0.346
12	19.02	2.18	0.153	0.205	0.498
13	20.02	2.13	-0.028	0.177	0.526
14	20.5	2.16	0.007	0.184	0.533
15	22.12	2.45	-0.04	0.144	0.572
16	26.91	4.24	0.713	0.857	1.285
17	40.11	6.86	-4.818	-3.961	6.103
18	42.16	6.85	0.196	-3.765	6.299
19	44.76	7.22	-0.104	-3.869	6.403
20	55.54	5.16	2.484	-1.385	8.887
21	58.25	4.68	-0.076	-1.461	8.963
22	85.28	2.44	3.962	2.501	12.924
23	93.98	1.93	-0.104	2.398	13.028
24	120.71	1.17	2.589	4.987	15.617
25	173.26	0.13	-8.869	-3.881	24.486

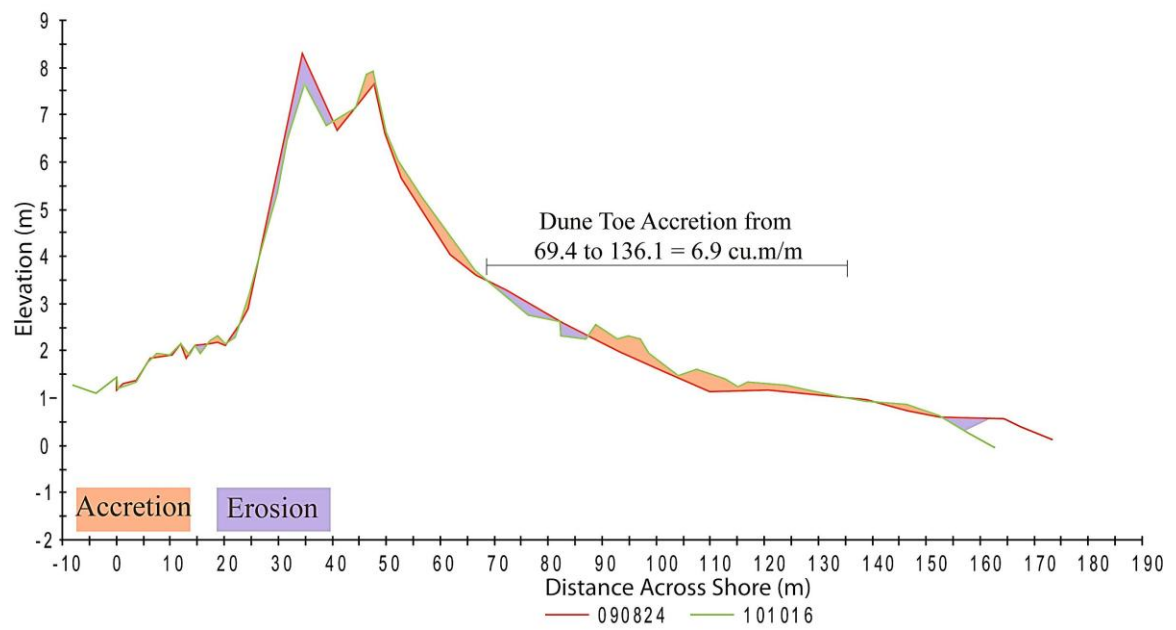


SPI11 Cut/Fill Report

Profile 1:	100140
Profile 2:	101016

Cell Changes:

Cell #	Ending Distance(m)	Ending Elevation(m)	Cell Volume (cu. m/m)	Cumulative Volume (cu. m/m)	Gross Volume (cu. m/m)
1	0.32	1.21	0.02	0.02	0.02
2	7.02	1.9	-0.268	-0.248	0.288
3	9.52	1.91	0.11	-0.138	0.398
4	10.01	1.91	-0.006	-0.144	0.403
5	10.94	2.03	0.018	-0.126	0.421
6	11.75	2.12	-0.014	-0.141	0.436
7	13.23	1.94	0.103	-0.038	0.538
8	14.37	2.11	-0.069	-0.107	0.607
9	14.63	2.11	0.003	-0.104	0.61
10	18.09	2.27	-0.189	-0.293	0.799
11	20.86	2.19	0.128	-0.166	0.927
12	30.59	5.82	-0.737	-0.903	1.664
13	34.45	7.52	0.351	-0.552	2.015
14	34.72	7.63	-0.002	-0.554	2.017
15	35.74	7.47	0.024	-0.53	2.041
16	40	6.86	-0.344	-0.874	2.385
17	47.83	7.8	1.034	0.16	3.419
18	52.74	5.93	-1.189	-1.029	4.608
19	64.82	3.98	2.407	1.378	7.015
20	87.28	2.3	-4.835	-3.457	11.85
21	103.07	1.57	4.076	0.619	15.925
22	104.71	1.51	-0.038	0.581	15.963
23	114.68	1.28	1.039	1.62	17.003
24	115.55	1.26	-0.013	1.607	17.016
25	157.23	0.31	4.415	6.023	21.431
26	162.7	0.31	-0.981	5.042	22.412

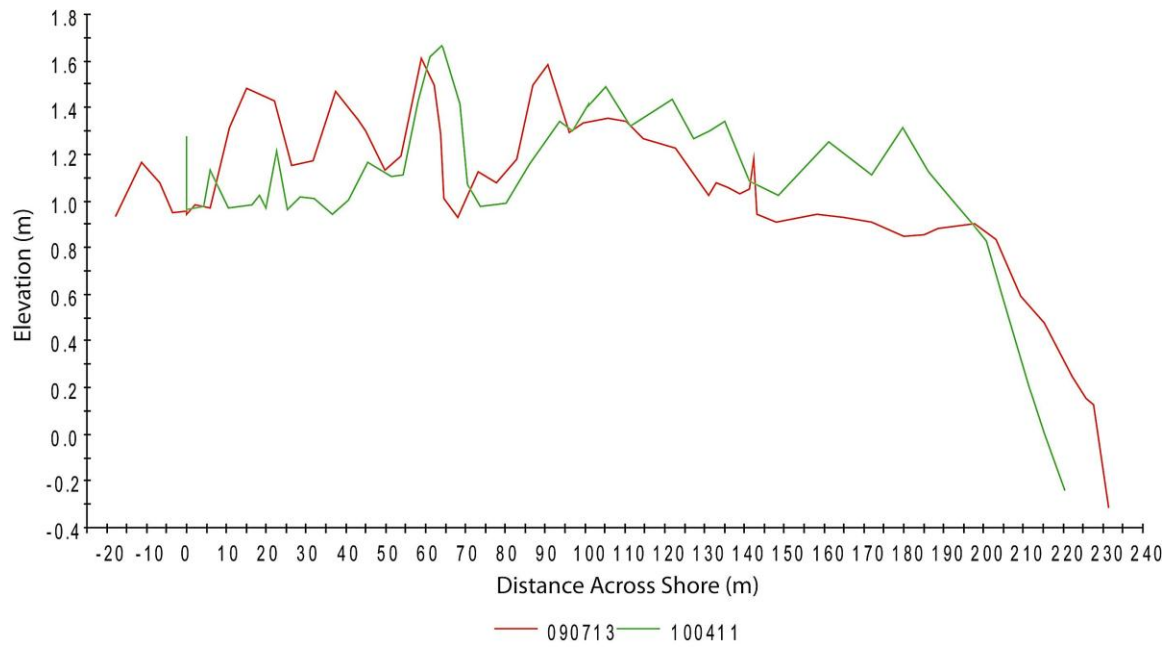
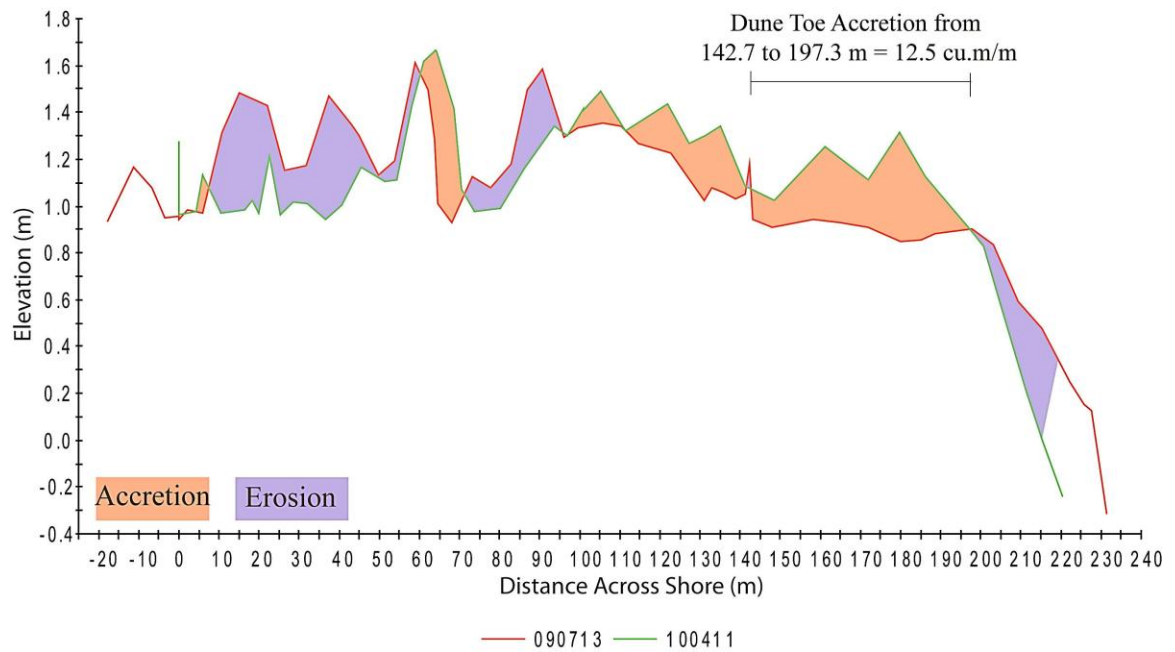
SPI11

SPI11 Cut/Fill Report

Profile 1:	90824
Profile 2:	101016

Cell Changes:

Cell #	Ending Distance(m)	Ending Elevation(m)	Cell Volume (cu. m/m)	Cumulative Volume (cu. m/m)	Gross Volume (cu. m/m)
1	0.32	1.21	0.009	0.009	0.009
2	5.48	1.71	-0.235	-0.226	0.244
3	5.7	1.74	0.001	-0.225	0.245
4	6.74	1.86	-0.02	-0.245	0.265
5	9.72	1.9	0.111	-0.134	0.376
6	9.88	1.9	0	-0.134	0.376
7	13.38	1.92	0.143	0.009	0.519
8	14.18	2.07	-0.012	-0.003	0.532
9	14.55	2.12	0.003	-0.001	0.534
10	16.9	2.15	-0.221	-0.222	0.755
11	20.51	2.17	0.24	0.018	0.995
12	22.96	2.61	-0.207	-0.189	1.202
13	26.51	4.02	0.449	0.26	1.652
14	40.08	6.86	-5.095	-4.835	6.747
15	69.36	3.44	6.527	1.692	13.274
16	87.37	2.32	-2.686	-0.994	15.96
17	136.06	0.99	9.544	8.55	25.504
18	140.08	0.93	-0.05	8.501	25.554
19	152.84	0.59	0.823	9.323	26.376
20	162.7	0.58	-3.028	6.295	29.404

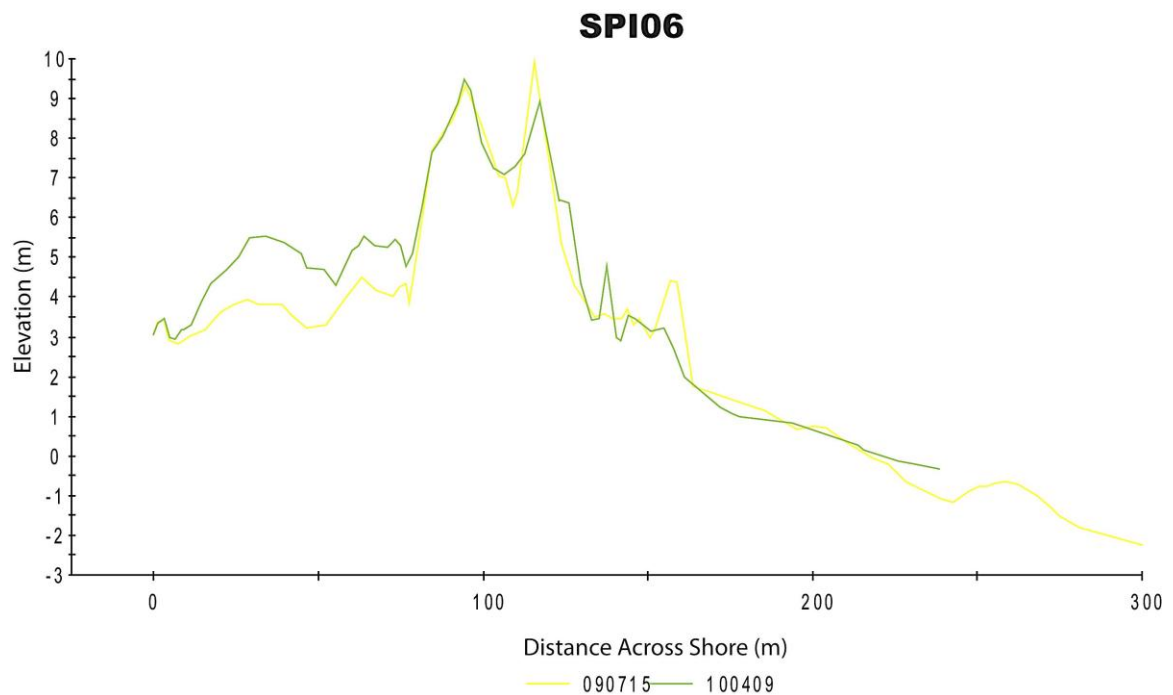
SPI12**SPI12**

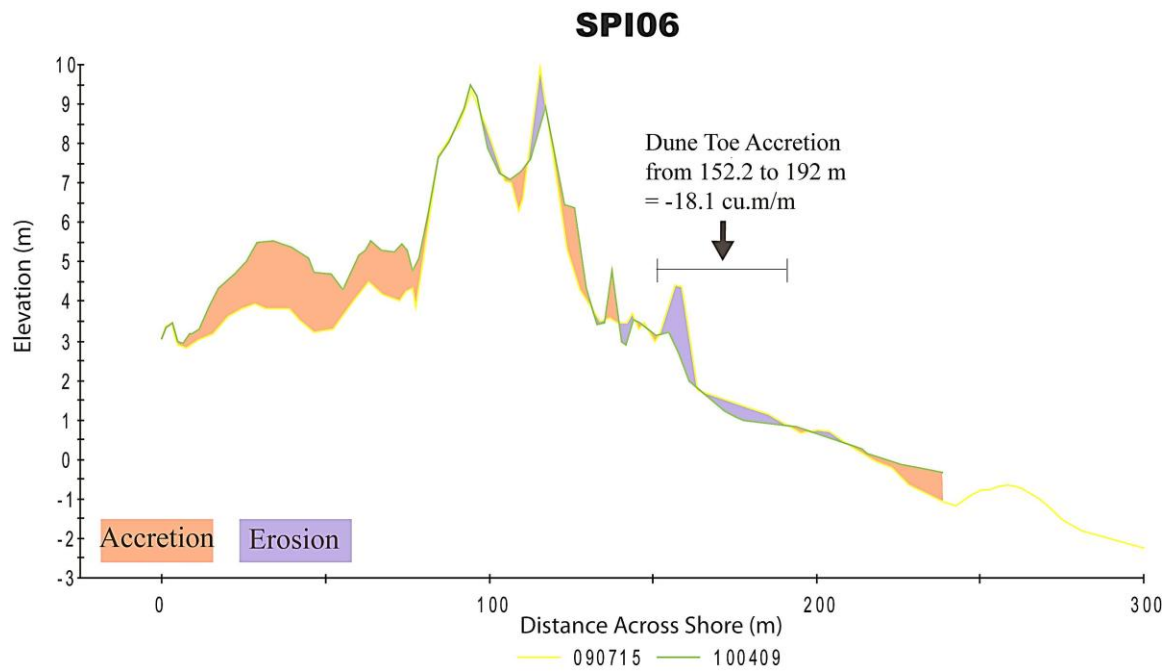
SPI12 Cut/Fill Report

Profile 1:	90713
Profile 2:	100411

Cell Changes

Cell #	Ending Distance(m)	Ending Elevation(m)	Cell Volume (cu. m/m)	Cumulative Volume (cu. m/m)	Gross Volume (cu. m/m)
1	1.36	0.97	0.018	0.018	0.018
2	4.1	0.98	-0.02	-0.002	0.037
3	7.45	1.07	0.26	0.258	0.297
4	60.24	1.57	-13.165	-12.907	13.462
5	71.34	1.05	3.807	-9.1	17.268
6	95.7	1.31	-4.012	-13.112	21.281
7	96.68	1.3	0.007	-13.105	21.288
8	96.97	1.31	0	-13.106	21.288
9	141.62	1.08	5.985	-7.121	27.273
10	142.74	1.07	-0.057	-7.177	27.33
11	197.31	0.9	12.528	5.35	39.857
12	226.17	0.15	-9.688	-4.338	49.545





SPI06 Cut/Fill Report

Profile 1:	90715
Profile 2:	100409

Cell Changes

Cell #	Ending Distance(m)	Ending Elevation(m)	Cell Volume (cu. m/m)	Cumulative Volume (cu. m/m)	Gross Volume (cu. m/m)
1	1.85	3.39	-0.015	-0.015	0.015
2	84.45	7.67	84.074	84.06	84.089
3	89.29	8.33	-0.28	83.78	84.368
4	97.31	8.77	1.108	84.888	85.476
5	104	7.22	-1.524	83.364	87
6	111.76	7.5	3.268	86.632	90.269
7	118.03	8.55	-4.264	82.368	94.533
8	131.69	3.78	9.414	91.782	103.947
9	135.48	3.54	-0.357	91.425	104.304
10	139.62	3.47	2.541	93.965	106.845
11	144.64	3.51	-1.777	92.188	108.622
12	146.72	3.39	0.16	92.348	108.781
13	148.46	3.3	-0.085	92.262	108.867
14	152.19	3.18	0.395	92.658	109.262
15	163.84	1.76	-11.701	80.956	120.964
16	164.36	1.75	0.006	80.963	120.97
17	191.98	0.83	-6.357	74.606	127.327
18	197.54	0.71	0.262	74.868	127.589
19	210.43	0.35	-1.331	73.536	128.92
20	238.45	-1.05	8.594	82.13	137.514

APPENDIX F

Beach and Dune Volume Change Data

	2000-2005		2005-2009		2000-2009	
section ID	Beach	Dune	Beach	Dune	Beach	Dune
1	-7.36	13.20	2.59	-6.58	-4.78	6.62
2	13.50	5.70	7.28	-18.75	20.77	-13.05
3	9.35	17.41	-4.34	-0.33	5.01	17.07
4	-3.65	20.22	-6.48	-22.02	-10.13	-1.79
5	-18.27	22.72	3.80	-18.12	-14.48	4.60
6	-16.51	26.75	18.47	-9.41	1.96	17.33
7	-18.94	38.88	7.13	-21.26	-11.81	17.62
8	-9.70	38.99	5.74	-23.73	-3.97	15.26
9	-5.57	35.13	0.88	7.66	-4.69	42.78
10	-4.63	24.99	2.51	-6.55	-2.13	18.44
11	-3.43	40.72	3.70	3.02	0.27	43.73
12	-2.55	44.24	0.51	-12.49	-2.04	31.75
13	-9.10	39.52	-3.93	-17.67	-13.03	21.85
14	-3.23	36.85	24.19	-11.12	20.96	25.73
15	-5.20	24.22	30.09	-24.40	24.89	-0.18
16	1.54	0.18	5.60	-31.53	7.15	-31.36
17	-4.75	13.26	-3.30	-29.51	-8.05	-16.25
18	-10.70	50.52	6.77	-28.35	-3.93	22.16
19	-38.28	94.97	13.24	-57.44	-25.04	37.54
20	-26.29	42.62	9.55	-11.75	-16.74	30.86
21	-29.38	25.91	6.96	-15.93	-22.42	9.98
22	-10.52	16.11	5.95	-12.93	-4.57	3.18
23	-12.42	29.94	-7.60	-16.74	-20.02	13.20
24	-19.64	30.94	3.93	-17.44	-15.71	13.50
25	-2.98	2.98	17.07	-6.23	14.09	-3.25
26	-8.78	20.45	24.85	-9.96	16.06	10.49
27	-11.41	-4.54	14.16	-14.73	2.75	-19.27
28	-12.27	22.19	12.40	13.78	0.13	35.97
29	-9.54	26.82	1.78	5.41	-7.76	32.23
30	-13.76	18.04	2.75	-6.55	-11.02	11.49
31	-24.75	31.52	0.03	-11.51	-24.72	20.01
32	-14.37	31.31	2.95	17.27	-11.41	48.58
33	-7.18	26.40	26.19	-10.70	19.01	15.70
34	-7.77	2.89	5.10	-20.66	-2.68	-17.77
35	-4.15	-66.25	34.66	-59.78	30.51	-126.03
36	-15.87	-61.69	25.77	-54.93	9.90	-116.62

37	-7.78	20.01	7.13	-31.67	-0.65	-11.66
38	-14.75	24.49	15.60	-13.51	0.85	10.98
39	-9.92	-4.82	32.48	-5.52	22.56	-10.34
40	-13.85	-67.97	38.39	-12.26	24.54	-80.23
41	-14.24	-7.19	47.84	-10.48	33.60	-17.67
42	-22.43	-2.58	43.71	10.68	21.29	8.10
43	-55.69	56.96	27.53	38.88	-28.16	95.85
44	-4.06	-8.92	2.48	-21.59	-1.58	-30.52
45	-4.20	-7.76	-2.84	-26.80	-7.04	-34.56
46	-12.60	-23.96	0.26	-16.51	-12.34	-40.46
47	-56.21	58.36	41.11	0.85	-15.10	59.21
48	-18.37	28.04	16.14	10.92	-2.23	38.96
49	-18.66	3.87	13.60	44.09	-5.06	47.96
50	-13.28	-6.85	13.10	3.55	-0.18	-3.30
51	-18.95	-18.19	15.82	4.54	-3.13	-13.65
52	-0.90	-27.50	3.81	-20.82	2.91	-48.32
53	-12.38	22.10	-2.71	-7.50	-15.09	14.60
54	-147.96	150.04	36.82	42.55	-111.15	192.58
55	-98.66	116.17	24.84	21.29	-73.82	137.47
56	-32.17	46.55	33.90	-3.41	1.72	43.14
57	-62.88	99.29	19.68	61.54	-43.20	160.83
58	-62.12	74.24	26.24	28.26	-35.88	102.50
59	-13.13	0.04	5.82	-26.00	-7.31	-25.96
60	-20.54	4.55	2.33	-8.23	-18.21	-3.68

APPENDIX G

Beach and Dune Data Characteristic Data

ID	Dune Vol Change 2000-2009	Avg Beach Height	Avg Beach Width	Avg Long-term Shoreline Change	Avg Beach Slope	Shoreline Orientation	Nourished	Dune Type
1	6.62	0.74	52.04	1.04	3.83	340.81	Y	Developed
2	-13.05	0.69	34.18	0.39	4.63	340.81	Y	Developed
3	17.07	0.66	27.40	1.56	4.07	347.18	N	Developed
4	-1.79	0.70	40.04	2.35	3.83	347.18	N	Developed
5	4.60	0.74	48.65	2.24	3.85	348.97	N	Developed
6	17.33	0.75	52.95	1.59	3.54	348.97	N	Developed
7	17.62	0.73	46.69	1.10	3.31	350.79	N	Developed
8	15.26	0.72	44.87	0.84	3.21	350.79	N	Developed
9	42.78	0.73	43.17	0.59	3.68	352.11	N	Developed
10	18.44	0.70	39.35	0.17	3.58	352.11	N	Developed
11	43.73	0.71	41.29	-0.43	3.59	351.66	Y	Developed
12	31.75	0.71	42.74	-1.05	3.56	351.66	Y	Developed
13	21.85	0.71	35.54	-1.34	3.67	351.46	Y	Developed
14	25.73	0.83	37.26	-1.10	4.68	351.46	Y	Developed
15	-0.18	0.81	38.76	-1.26	4.00	351.71	Y	Developed
16	-31.36	0.73	24.45	-1.56	5.19	351.71	Y	Developed
17	-16.25	0.71	33.68	-1.87	3.72	352.26	N	Dune ridge
18	22.16	0.70	42.66	-1.98	3.29	352.26	N	Dune terrace
19	37.54	0.77	60.26	-1.79	3.30	352.38	N	Dune terrace
20	30.86	0.78	49.26	-1.70	3.50	352.38	N	Dune ridge
21	9.98	0.75	38.36	-1.99	3.58	351.96	N	Dune ridge
22	3.18	0.71	40.09	-2.55	3.69	351.96	N	Dune terrace
23	13.20	0.66	33.39	-2.89	4.09	352.23	N	Dune ridge
24	13.50	0.73	46.13	-2.82	3.49	352.23	N	Dune ridge
25	-3.25	0.75	52.07	-3.22	3.20	352.9	N	Dune ridge
26	10.49	0.77	54.56	-3.28	3.14	352.9	N	Active
27	-19.27	0.77	51.74	-3.18	3.29	352.69	N	Active
28	35.97	0.76	50.20	-3.04	3.46	352.69	N	Dune terrace
29	32.23	0.71	34.71	-3.14	3.83	353.74	N	Dune ridge
30	11.49	0.70	35.37	-2.88	3.77	353.74	N	Dune ridge
31	20.01	0.71	41.84	-2.79	3.66	352.63	N	Dune ridge

32	48.58	0.76	53.53	-2.96	3.40	352.63	N	Dune terrace
33	15.70	0.79	54.74	-3.15	3.12	351.04	N	Dune terrace
34	-17.77	0.71	35.83	-3.32	3.70	351.04	N	Dune ridge
35	-126.03	0.75	49.82	-3.41	3.45	350.33	N	Active
36	-116.62	0.79	51.62	-3.53	3.34	350.33	N	Active
37	-11.66	0.74	37.25	-3.45	3.45	350.79	N	Dune ridge
38	10.98	0.73	45.08	-3.20	3.47	350.79	N	Dune terrace
39	-10.34	0.78	54.25	-3.38	3.43	348.08	N	Dune terrace
40	-80.23	0.78	57.29	-3.54	3.28	348.08	N	Active
41	-17.67	0.79	67.12	-3.65	3.15	348.1	N	Active
42	8.10	0.78	67.87	-3.51	3.04	348.1	N	Active
43	95.85	0.79	65.92	-3.52	3.22	347.21	N	Washover terrace
44	-30.52	0.72	36.01	-3.73	3.72	347.21	N	Dune ridge
45	-34.56	0.69	34.35	-3.90	3.72	350.33	N	Dune ridge
46	-40.46	0.69	38.61	-3.76	3.65	350.33	N	Dune ridge
47	59.21	0.79	74.46	-3.80	3.41	349.28	N	Washover terrace
48	38.96	0.77	49.53	-3.52	3.35	349.28	N	Active
49	47.96	0.75	52.94	-3.41	3.41	347.32	N	Active
50	-3.30	0.75	55.51	-3.55	3.17	347.32	N	Active
51	-13.65	0.77	53.59	-3.72	3.32	347.29	N	Active
52	-48.32	0.72	35.83	-4.36	4.03	348.29	N	Dune ridge
53	14.60	0.73	37.60	-4.81	3.81	347.04	N	Dune ridge
54	192.58	0.81	85.73	-5.04	3.22	347.04	N	Washover terrace
55	137.47	0.79	85.43	-5.32	3.54	347.91	N	Washover terrace
56	43.14	0.79	65.09	-5.45	3.15	347.91	N	Active
57	160.83	0.80	70.09	-5.18	3.11	345.37	N	Washover terrace
58	102.50	0.79	71.65	-4.79	3.21	345.37	N	Washover terrace
59	-25.96	0.71	37.26	-4.71	3.83	346.71	N	Dune ridge
60	-3.68	0.70	35.66	-4.52	3.88	346.71	N	Dune ridge