# RATE OF POST-HURRICANE BARRIER ISLAND RECOVERY

A Thesis

by

BRIANNA MARIE JOSEPH HAMMOND

Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

| | |
|---|---|
| Chair of Committee, | Chris Houser |
| Committee Members, | Michael Bishop |
| | Rick Giardino |
| Head of Department, | David Cairns |

August 2015

Major Subject: Geography

# ABSTRACT

Barrier island foredunes are key indicators of the rate of island transgression, in which small dunes exhibit rapid transgression through washover and breaching, and large dunes exhibit controlled transgression in response to sea level rise. Recent evidence suggests that the largest foredunes at Santa Rosa Island, Florida and Galveston Island, Texas exhibit sigmoidal recovery patterns over an approximately 10 year time period, and that high and low islands vary alongshore in a pattern that is reinforced if there is a sufficient recovery period. This study examines the resiliency of Assateague Island National Seashore, MD through its ability to return to its pre-storm condition following a hurricane.

The primary hypothesis of this study is that the rate of recovery of each examined parameter at ASIS will exhibit a sigmoidal pattern as seen at Santa Rosa Island, and that recovery rates will vary alongshore due to high and low island areas. Foredune elevation data from 2000 and 2005 was compared and categorized into recovery periods based on the temporal difference between impactful storm surges and the 2005 elevation data. Morphometric parameters including dune crest, height, volume, and toe were extracted and used to characterize recovery. Logistic curves were modified to represent the growth patterns of each parameter and recovery was examined with respect to high and low island sections. The rates of recovery from this study were compared with the results of a previous at Santa Rosa Island, FL. Results from this study support recovery patterns identified in previous studies. Evidence also suggests that low dunes at Assateague Island cease to recover and that there is a limit to the growth of the smallest dunes. Land managers can use this knowledge as a resource in the preparation for and response to hurricanes, specifically as it relates to varying levels of vulnerability alongshore.

# DEDICATION

This thesis is dedicated to my parents, Steve and Charlotte Hammond, who pushed me to pursue a graduate degree and supported me during my time at Texas A&M University.

# ACKNOWLEDGEMENTS

I would like to thank my advisor and committee chair, Dr. Chris Houser, for the incredible opportunities for my development of skills and knowledge provided to me during my time at Texas A&M University. I would also like to thank my committee members, Dr. Bishop and Dr. Giardino, for their time and feedback throughout the course of this research. Special thanks to Dr. Cheryl Hapke, an ex officio committee member, for her guidance and support over the past year.

I would like to extend my sincere appreciation to my friends and colleagues, and to the department faculty and staff for making my time at Texas A&M University a great experience. I especially would like to thank my coastal geomorphology research cluster peers, Sarah Trimble, Phil Wernette, Brad Weymer, Patrick Barrineau, Peggy Flores, and Tess Rentschlar. I also want to extend my gratitude to my primary support team and best friends, Shelby Young, Luci Pounders, and Jamie Turner. Thanks also go to my NSBE family, especially the 2012-2013 Region II Executive Board members.

Finally, special thanks to my parents and sister for their encouragement and inspiration, to my grandparents for their support, and to my fiancé for his optimism, patience, and love.

# TABLE OF CONTENTS

Page

ABSTRACT .......... ii

DEDICATION .......... iv

ACKNOWLEDGEMENTS .......... v

TABLE OF CONTENTS .......... vi

LIST OF FIGURES .......... viii

LIST OF TABLES .......... x

CHAPTER I INTRODUCTION, BACKGROUND, AND STUDY SITE .......... 1

- Introduction .......... 1
- Background .......... 4
- Identification of Study Site .......... 16

CHAPTER II METHODOLOGY .......... 26

- Introduction .......... 26
- Acquisition of Imagery .......... 26
- Pre-Processing .......... 27
- Casting Transects with DSAS .......... 30
- Dune Extraction and Analysis .......... 30
- Dune Classification and Recovery .......... 32

CHAPTER III RESULTS .......... 38

- Introduction .......... 38
- Changes in Parameters .......... 38
- Ensemble Averaging .......... 43
- Alongshore Variability .......... 53

CHAPTER IV DISCUSSION .......... 55

- Profile Recovery .......... 62
- Alongshore Variability .......... 67

  Implications and Future Work ........ 69

CHAPTER V CONCLUSION ........ 72

REFERENCES ........ 74

## LIST OF FIGURES

Page

Figure 1 Example sediment budget along a barrier island chain in North Carolina, retrieved from Pierce (1968)................................................................5

Figure 2 Logistic recovery curve results from Houser *et al.* (2015) with data points from Morton *et al.* (1994) and Priestas and Fagherazzi (2010).........................9

Figure 3 Dune-beach-bar relationship of sediment transport obtained from Psuty (2004)..........................................................................................................10

Figure 4 Equilibrium (ball and cup) diagram representing high and low island states as it relates to a threshold (Houser et al. 2015)...............................................12

Figure 5 Four stages of recovery, obtained from Morton et al. (1994). Stage 4 can take 10 years or more to occur after a storm event.........................................15

Figure 6 Map of Assateague Island National Seashore (ASIS) study site with the 2010 elevation dataset overlaid. ASIS is a barrier island off the coast of southern Maryland. The blue triangle north of ASIS represents Ocean City, MD. ........19

Figure 7 Wind direction data for Assateague Island (WindFinder 2015). .......................22

Figure 8 Re-projected elevation datasets for years 2000, 2005, 2008, and 2010 collected from NOAA's Digital Coast. ............................................................28

Figure 9 Transects cast from offshore via DSAS tool. While each transect was the same for each year alongshore, datasets varied in island width. ......................31

Figure 10 Sample profile from 2005 dataset showing parameter definitions dune toe, dune height, and dune crest (left to right). The dashed line and red arrow represent the extraction method of dune toe...................................................32

Figure 11 Extracted dune toe and dune crest elevation on ASIS in 2000. Storm surges shown are associated with all storms between 2000 and 2005, affecting the recovery period of each transect. .....................................................................35

Figure 12 Extracted dune toe and dune crest elevation on ASIS in 2005. Storm surges shown are associated with the single storm occurring between the 2005 and 2008 datasets, affecting the recovery period of each transect. .........................35

Figure 13 Change in $D_C$ represented by quartiles and years of recovery with modified logistic curves overlaid. .........................................................................41

Figure 14 Change in $D_H$ represented by quartiles and years of recovery, with modified logistic curves overlaid. ....................42

Figure 15 Change in $D_V$ represented by quartiles and years of recovery, with modified logistic curves overlaid. ....................42

Figure 16 Change in $D_T$ represented by quartiles and years of recovery. ....................43

Figure 17 Ensemble average of transects in each quartile for years 2000 and 2005, where A) is Quartile 1, B) is Quartile 2, C) is Quartile 3, and D) is Quartile 4. ....................44

Figure 18 Quartile 1 recovery for Year 0 (A), 1 (B), 2 (C), and 5 (D). Values along each Y axis represent Elevation (m), and the X axis represents Cross-shore Distance (m). ....................46

Figure 19 Quartile 2 recovery for Year 0 (A), 1 (B), 2 (C), and 5 (D). Values along each Y axis represent Elevation (m), and the X axis represents Cross-shore Distance (m). ....................48

Figure 20 Quartile 3 recovery for Year 0 (A), 1 (B), 2 (C), and 5 (D). Values along each Y axis represent Elevation (m), and the X axis represents Cross-shore Distance (m). ....................50

Figure 21 Quartile 4 recovery for Year 0 (A), 1 (B), 2 (C), and 5 (D). Values along each Y axis represent Elevation (m), and the X axis represents Cross-shore Distance (m). ....................52

Figure 22 High and low island areas along ASIS. This graphic shows the location alongshore of first and fourth quartile groups as it relates to change in dune height. ....................54

Figure 23 Logistic curves with Houser *et al.* (2015) data from Santa Rosa Island, Fl. The recovery rate (r) for Quartile 4 is 0.8. ....................59

Figure 24 Logistic curve showing average Quartile 4 recovery values at ASIS, assuming a maximum $D_C$ value of 2.11 m (averaged from De Stoppelaire *et al.* 2004) and r = 0.26. ....................60

Figure 25 Combination of data points from this study (ASIS), Houser *et al.* (2015), Priestas and Fagherazzi (2010), and Morton *et al.* (1994). ....................60

# LIST OF TABLES

Page

Table 1 This table shows the categories and dates of recent coastal storms affecting ASIS. Not all storms listed were incorporated in this study, due to small surge elevations. ....................25

Table 2 Display of dataset characteristics. ....................29

Table 3 Hurricane dates, categories, and storm surges affecting ASIS. ....................34

Table 4 Recovery rates (r) for dune crest, dune height, and dune volume, represented by *n* in the equation used by Houser *et al.* (2015). ....................41

# CHAPTER I

# INTRODUCTION, BACKGROUND, AND STUDY SITE

## *Introduction*

In 2012, Hurricane Sandy displaced the residents of roughly 100,000 Long Island homes, significantly altering the lives of many and resulting in billions of dollars of damage (Crichton 2012). Major coastal storms, like superstorm Sandy, are often destructive to human lives and the mainland topography. This will be even more significant as storms are projected to continue to increase in frequency and magnitude (Goldenberg *et al.* 2001; Emanuel 2005). Barrier islands are critical landforms in the protection of a mainland by absorbing energy produced by hurricanes, such as erosive waves, overwash penetration, and wind (Coastal Barrier Resources Act; Leatherman 1979b; Guo 2014). This protective role is evidenced through witnessing the deterioration of a barrier island. For example, the Chandeleur Islands in Louisiana continue to be reduced as a result of insufficient recovery time between storms, and lack of sediment supply. The impact caused by storms in the Gulf of Mexico are minimized for coastal communities in this area because waves are forced to break at the island rather than on the mainland, thus eroding and drowning the offshore landscape. Whereas this is not a typical barrier island system, it is an example of the destruction that can be caused by storms and the ability for coastal formations to be inundated in a short amount of time if not properly nourished.

Understanding the dynamics of these coastal features provides information for improved recovery plans and prediction of barrier island resiliency. This knowledge is valuable in the evaluation of future risk as it pertains to hurricanes and barrier islands. For example, information about the rate of recovery of foredunes may be used by land managers in the identification of areas that may be more easily breached during future storms or that require specific care as it relates to renourishment and growth of vegetation. Similarly, this information can be useful to homeowners when deciding where to purchase or build a house (Anderson 2013). The response and recovery patterns of a barrier island influence the long-term condition of the landscape. Slow recovery rates may result in degradation of the island as a whole after several storm occurrences, whereas a fast recovery rate may contribute to the lastingness of the site, even as storms continue to cause an impact. This variance can maintain the condition of varying portions of the island. Some areas with low dunes may continuously be impacted and overwashed, reinforcing its low island condition, whereas high island areas are less susceptible to overwash and have a greater ability to grow in both height and width. It is essential to gain knowledge about which area is most susceptible to damage and the timescale of recovery in that same area to preserve both human lives and wildlife.

Remotely sensed data can be used to produce information about coastal processes and the causes for specific patterns of response. For instance, vegetation data can produce an idea about rates of growth and spatial variability, which is a contributing factor to dune growth. Current research demonstrates a need to quantify the volumetric and topographic characteristics to understand the resiliency of a barrier island. Whereas many studies focus on quantifying one specific parameter as it relates to dune recovery, this study is an evaluation of a variety of variables and their pattern of change (Fisher *et al.* 1974; Psuty 1992; Roman and Nordstrom 1988; Hapke and Richmond 2000; Durán and Moore 2013; Houser 2013). Studies also indicate that knowledge of a variety of morphometric variables provides a better understanding of the rate of recovery in the complex situation of barrier islands protecting the mainland (Sallenger 2000; Roelvink *et al.* 2009; Houser 2013). To date, no study has accomplished the quantification of an array of geomorphometric parameters, aside from changing dune height, to achieve a detailed understanding of recovery patterns contributing to barrier island resiliency. This thesis addresses these items through an evaluation of Assateague Island National Seashore on the coast of Maryland. Results are compared to the recovery curve developed by Houser *et al.* (2015) in which the change in dune height was represented by a sigmoidal curve. This study quantifies the recovery rate of Assateague Island National Seashore, MD after a hurricane, using the following parameters: dune crest elevation, dune height, dune volume, and dune toe elevation.

The primary hypothesis of this study is that the rate of recovery of each examined parameter will exhibit a sigmoidal pattern as seen in Houser *et al.* (2015). Recovery rates will vary alongshore at Assateague Island National Seashore, and high and low island areas will be evident, similar to the alongshore variability observed on Santa Rosa Island in northwest Florida. To test this hypothesis, two objectives must be completed:

1. Identify study site and obtain multitemporal elevation data.

2. Quantify change in dune height, dune toe elevation, dune slope, and dune volume to identify the rate of recovery over a 5-year period.

It remains unknown whether barrier islands in various geographic locations experience similar recovery patterns and timelines following storm events. This thesis will help determine whether a similar pattern exists compared to what is seen in previous studies.

### *Background*

Storm events are powerful enough to alter barrier island morphology through a variety of sediment transport processes. Hurricanes are categorized based on wind speed using the Saffir-Simspon Hurricane Scale, where 74-95 miles per hour represents a Category 1 hurricane and 157 miles per hour represents a Category 5 hurricane (Dolan and Davis 1992). These wind intensities contribute to changes in wave height, influencing the effect that the ocean has on a barrier island. Aeolian processes transport sediment and storm surges can breach the island or transport sand away from the shoreline. Where $S_s$ is storm surge elevation and $D_C$ is dune elevation, overwash occurs when $S_s > D_C$ and has the potential to move sediment towards the part of the island closest to the mainland. This washover deposition contributes to island migration, which may eventually lead to the welding of the island to the mainland. Lateral, or longshore, transport of sediment is another function that is critical to erosion and accretion on a barrier island landscape. Assateague Island experiences a north to south longshore current in which sediment is both eroded and deposited; the jetty just south of Ocean

City restricts the deposition of sand at the northern end of the island, which is being eroded more quickly than the southern portion (Leatherman 1979a). Figure 1 shows a sample sediment budget demonstrating areas of sediment loss and gain on a barrier island. Offshore and alongshore resources provide nourishment while other features and processes, such as inlets and overwash, erode sediment from the island. This does not include cross-shore loss (eroding away from the shoreline), or any loss that is also sustained as a result of the alongshore current. However, overarching sediment budget interactions between the ocean and an island are demonstrated in this illustration.

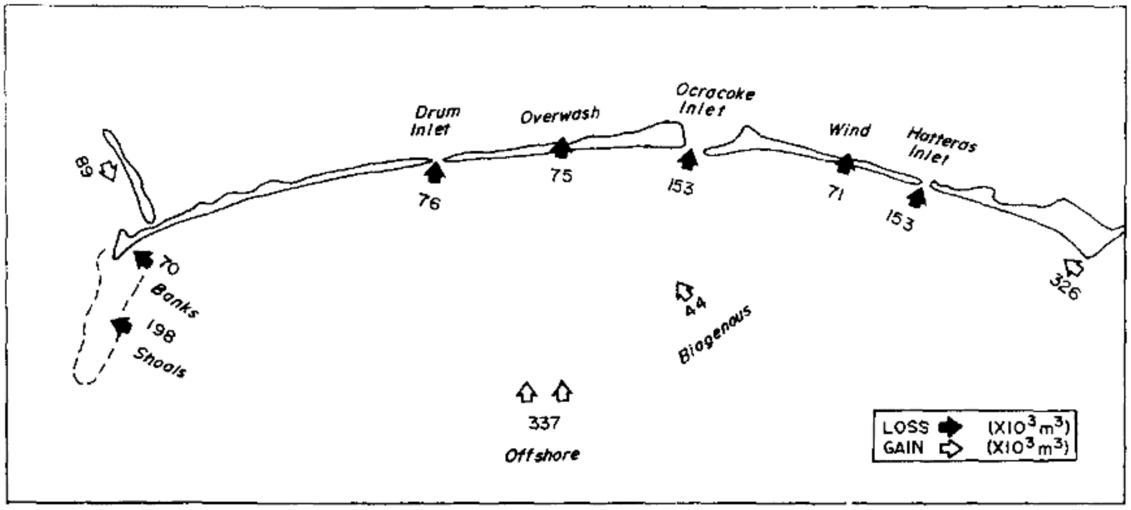


**Figure 1** Example sediment budget along a barrier island chain in North Carolina, retrieved from Pierce (1968)

Assateague Island National Seashore, MD is no exception to these processes, and is frequently affected by hurricanes of all categories in addition to tropical storms. Even weak hurricanes can cause these damaging occurrences if dunes are small or absent, posing a threat to wildlife and human inhabitants through exposure to submerged areas, ecosystem devastation, economic damages, or destruction of infrastructure resulting in injuries or death (Pielke *et al.* 2008; Houser and Hamilton 2009). Barrier islands act as barricades to the mainland, and are often effective in the mitigation of disaster. Leatherman (1979a) emphasizes the effect of barrier island dune systems as a stabilizing effect that prevents overwash and breaching. When examining overwash patterns and effects at Assateague Island, it was found that this process is effective in maintaining island width "*within the limits of 120-215 meters*" (Leatherman1979a). However, severe storm events can result in significant storm surges causing damage to both the island and the mainland.

Sallenger (2000) suggests four impact levels representing the magnitude of storm impact on barrier islands. Impact Level 1, the 'swash' regime, is representative of wave runup confined to the shore. Because this area erodes during the storm and recovers following the storm, there is assumed to be no net change in sediment supply associated with Level 1. Impact Level 2 is identified as the 'collision' regime. In this instance the waves force net erosion, resulting from runup that exceeds the threshold of the base of the foredune ridge. Impact Level 3 may contribute to landward sediment transportation, potentially causing landward migration of the island. This impact level, identified as the 'overwash' regime, is characterized through wave runup that overtops the berm and/or foredune ridge. Finally, Impact Level 4, the 'inundation' regime, describes an instance in which the storm surge completely and continuously submerges the barrier island.

Sediment is transported net landward, and evidence suggests that the quantity and distance of this migration is greater than that seen in the ‘overwash’ regime. These scales of impact represent the erosive and depositional behavior of varying storm intensities, and provide information about what might occur as a result of these storms (Sallenger 2000). Though the forces contributing to these regimes are dynamic, it is possible to parameterize them. Stockdon *et al.* (2006) notes that the magnitude of a swash regime is dependent only on offshore wave height and period, while runup (primarily related to the collision and overwash regimes) is dependent on significant wave height and time-mean setup processes. On Assateague it can be inferred that the gentle slope does not impact the swash regime and supports a greater runup magnitude. Assateague Island most typically experiences ‘swash’ and ‘collision’, in which case the storm surge does not breach the foredune. However, historic storm events and the permanent jetty just north of the island have influenced its landward migration. As overwash events continue to occur and the northern end of the island is starved of sediment, the island will continue to transgress through a positive feedback system.

Previous studies have shown that beaches and dunes on barrier islands have demonstrated a sigmoidal curve in their rate of recovery in which the recovery gradient peaks in the middle of the time scale (Hugenholtz and Wolfe 2004; Houser *et al.* 2015). Overall recovery of dunes in returning to pre-storm conditions takes 10 years or more (Houser *et al.* 2008; Houser *et al.* 2015). Identified primarily by the regeneration of foredune elevation, recovery is dictated by the severity of the storm and the time interval between storms. Beach and dune quantification using LiDAR, bathymetry, and profiles derived from these technologies, offers evidence of alongshore and across-shore variation (Houser and Hamilton 2009). Houser *et al.* (2015) identifies the vulnerability of a barrier island through the relationship between the water level and the coastal geometry, primarily as it relates to the height and extent of an island's foredunes. This growth model, originally presented as a vegetation recovery model by Hugenholtz and Wolfe (2005), is:

$$\mathrm{N_t} = \frac{\mathrm{KN_o}}{(\mathrm{K} - \mathrm{N_o})^{-\mathrm{n}} + \mathrm{N_o}}$$

where *N* is a system attribute (i.e. dune height), t is the time elapsed since the last disturbance, *n* is the rate of growth (represented by *r* in this thesis), $N_o$ is the initial position or height of the attribute (t = 0), and *K* is the upper boundary (asymptote) of dune growth (Hugenholtz and Wolfe 2005; Houser *et al.* 2015). This equation quantifies the condition of a specific attribute at a given point, and is applied in this study to the parameters $D_C$ (dune crest), $D_H$ (dune height), and $D_V$ (dune volume). The results of this equation when applied to dune recovery at Santa Rosa Island, FL contributed to a sigmoidal recovery curve seen in Figure 2 (Houser *et al.* 2015).

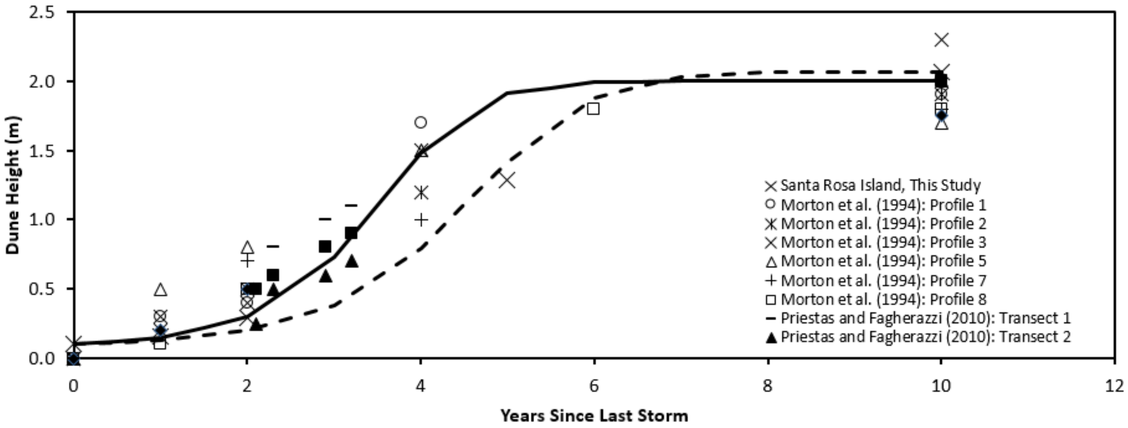


**Figure 2** Logistic recovery curve results obtained from Houser *et al.* (2015) with data points from Morton *et al.* (1994) and Priestas and Fagherazzi (2010).

Following the erosive impacts that a storm may cause, an island's recovery rate is dependent upon the ability to return to its equilibrium state. Processes contributing to this recovery may include alongshore migration of sediment through waves, revitalization of dune vegetation, landward migration of nearshore bars, and aeolian sediment transfer from the beach to the recovering dunes (Houser *et al.* 2015). Barrier islands along the Gulf of Mexico and in the mid-Atlantic witness storm surge impact nearly every year, thus experiencing some level of vulnerability. This study examines a variety of parameters, including dune height, to quantify the rate of change, taking each of these recovery processes into consideration.

Coastal fordunes vary over space and time as a result of the dynamic nature of the adjacent beach, which also contributes to the complexity of forms (Psuty 1992). Hesp (2002) discusses incipient foredunes as being formed primarily through aeolian forcing interacting with barriers such as vegetation, driftwood, or flotsam. Obstructions such as these slow the wind transporting sediment, resulting in deposition of material. Different species, density, and distribution of vegetation contribute to variability in the morphology of foredunes along shore. Studies have shown that continuous beach propagation also contributes to the formation of multiple dunes. Aeolian transport rates vary based on beach type, resulting in dissipative beaches exhibiting large fordunes (Short and Hesp 1982; Durán and Moore 2013). Other influencing controls on sediment availability and transport to foredunes include beach width, seasonal variations, wind direction, and water table heights. Houser *et al.* (2008) identifies nearshore morphology as a key factor in the alongshore variability of dunes, particularly as it relates to transverse ridges and island width. Bathymetric features such as these strongly influence the interaction of waves with the beach, impacting the sediment supply to renourish the beach and dunes following a storm event. Figure 3 shows the dune-beach-ocean relationship in which the offshore bar nourishes the beach, the beach nourishes the dune, and vice versa (Psuty 2004). This fundamental morphological process is the basis of coastal sediment exchange and the formation of onshore and nearshore features.

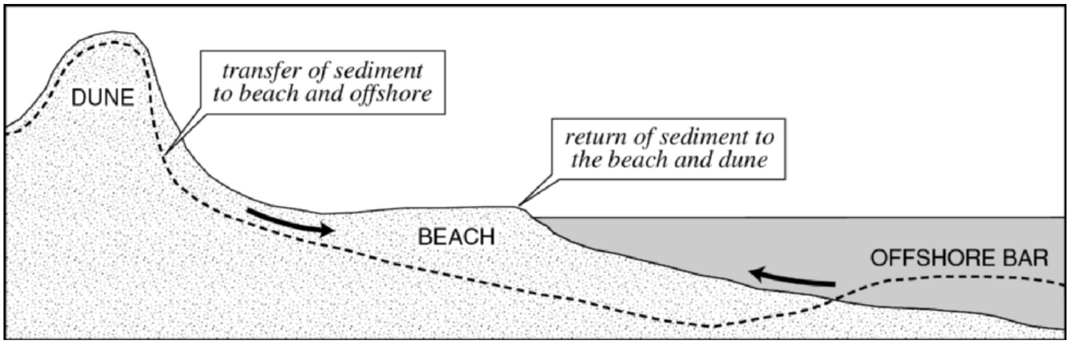


**Figure 3** Dune-beach-bar relationship of sediment transport obtained from Psuty (2004).

The effectiveness and functionality of barrier islands are dependent upon dune ability to recover to pre-storm elevation following a disturbance. Elevation change is a fundamental identifier of barrier island recovery after a storm event, as analytical capabilities demonstrate the erosional and depositional patterns of an area (Houser and Hamilton 2009). Observation of pre- and post-storm conditions at a site allow for an understanding of the direction and magnitude of sediment movement. Several factors that affect dune formation in a coastal environment include vegetation and anthropogenic impact, which may alter the anticipated relaxation trend of an area. Vegetation has proved to be a critical component of dune recovery and stability, especially on barrier island landscapes in many studies (Fisher *et al.* 1974; Morton *et al.* 1994; Hesp 2002; Houser *et al.* 2015). Durán and Moore (2013) discuss that foredune growth eventually becomes limited "*by a negative feedback between wind flow and topography*". It is suggested that the amount of sand in a dune system, and thus the maximum size of a foredune, is controlled primarily by "*plant zonation*" (Durán and Moore 2013). Figure 4 demonstrates an island state using an equilibrium diagram, where there are two equilibrium states of "high island" and "low island". The ball starts in the high island state of equilibrium, but moves to an unstable state as it crosses a threshold; in this case, the threshold is representative of a storm event. With a sufficient period of nearshore, beach, and dune recovery, the ball will move back towards the high island state. However, if the storm reduces the vegetation within a dune system and erodes the dune itself, or if there is insufficient time to recover before another storm event occurs, it will move into a low island state. Over time, the equilibrium state may return to high island if overwash does not continue to affect the area, and if the revitalization of vegetation and sediment availability exists in the system. If overwash and storms continue to impact a low island area, the state of equilibrium will be reinforced over time.

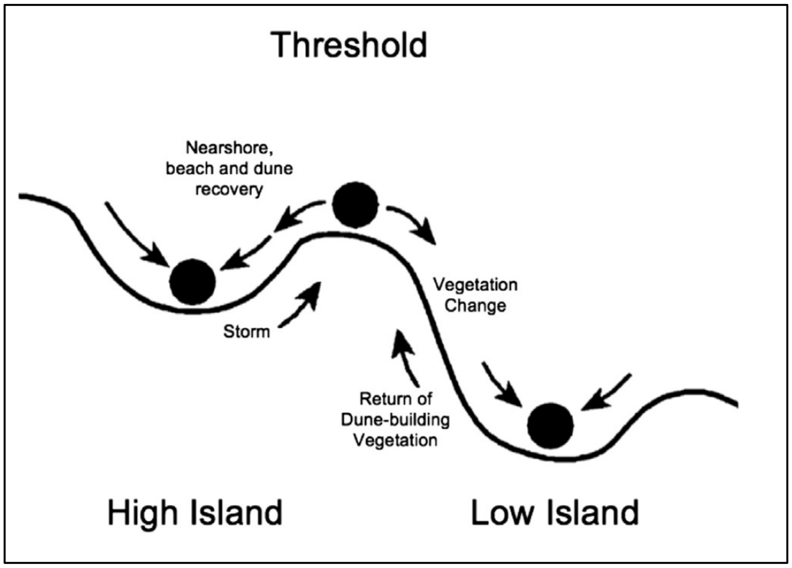


**Figure 4** Equilibrium (ball and cup) diagram representing high and low island states as it relates to a threshold (obtained from Houser *et al.* 2015).

Morton *et al.* (1994) discuss four stages of recovery as it pertains to beach resiliency (see Figure 5): (1) rapid forebeach accretion, (2) backbeach aggradation, (3) dune formation, and (4) dune expansion and vegetation recolonization. Stage 1 is characterized by a steep forebeach, and can last between several months to a year; this stage is common among sandy beaches and is relatively rapid in comparison to some other recovery stages. Stage 2 begins at the second post-storm summer because the elevations “must exceed the limits of flooding produced by normal spring high tide” prior to the significant accumulation of sand (Morton *et al.* 1994). Stage 3 is dependent upon the amount of aeolian transport and the presence of back beach vegetation to limit the transport; this phase is characterized as taking several years. Stages 2, 3, and 4 are gradational because of these limiting factors. Stage 4 differs from stage 3 in that the dunes are “taller, wider, continuous, and more densely vegetated” (Morton *et al.* 1994). As the last phase, stage 4 can take more than 10 years to occur. Despite this model primarily relating to anthropogenic-limited sites, aspects can be applied to other beach locations in projecting recovery patterns. This recovery pattern was studied on Galveston Island, TX, and results showed that “only two of seven profile sites experienced complete recovery” in total sand volume as a result of the areas being undeveloped (Morton *et al.* 1994). Areas with anthropogenic forcing experienced forebeach recovery similar to undeveloped beaches, but backbeach and dune recovery was impeded due to infrastructure, especially houses and filled lots, restricting deposition (Morton *et al.* 1994). Assateague Island is mostly undeveloped, and thus allows for the backbarrier to become renourished. Volumetric data can produce a greater understanding of spatial variance within a coastal environment, and may offer information regarding the health of an island. Houser *et al.* (2015) supports this timeline, showing that recovery of large dunes on Santa Rosa Island, FL also takes approximately 10 years.

Alongshore variability in dune response to storm events is reflected in current coastal geomorphology research. For example, narrower portions of Assateague experience more washover, resulting in a different recovery pattern than that of wider portions. Furthermore, any significant morphological features offshore likely contribute to the variation identified along the island (Houser *et al.*, 2008; Houser and Hamilton, 2009; Weymer *et al.* 2013). Sediment shifted away from the island during a hurricane generally returns to the shoreline over the course of several years as a result of the complex system of longshore and cross-shore currents and oscillation, and contributes to the revival of the dunes and shoreline (Morton *et al.* 1994; Houser *et al.* 2008). This lag is controlled by nearshore bathymetric characteristics, the erosion of antecedent geology, and the presence of nearshore transgressive sand deposits (Schwab *et al.* 2014).

Predominant factors contributing to the variability in the morphology of dunes at Assateague include anthropogenic activity and overwash. As a national seashore, Assateague Island experiences effects of visitors driving along the beach and promoting alterations in the beach and dune morphology. A recent study by Houser *et al.* (2013) examines the impacts of driving on Assateague's beaches, based on more than 2 million visitors per year interacting with approximately 26 kilometers of drivable beach. Results suggest that while driving on the beach does not "*lead to a loss of sediment from the beach-dune system*," this activity may contribute to the susceptibility of the scarping and overwash of foredunes. Additionally, driving on the beach following a storm event limits the ability of vegetation and foredune recovery (Houser *et al.* 2013).

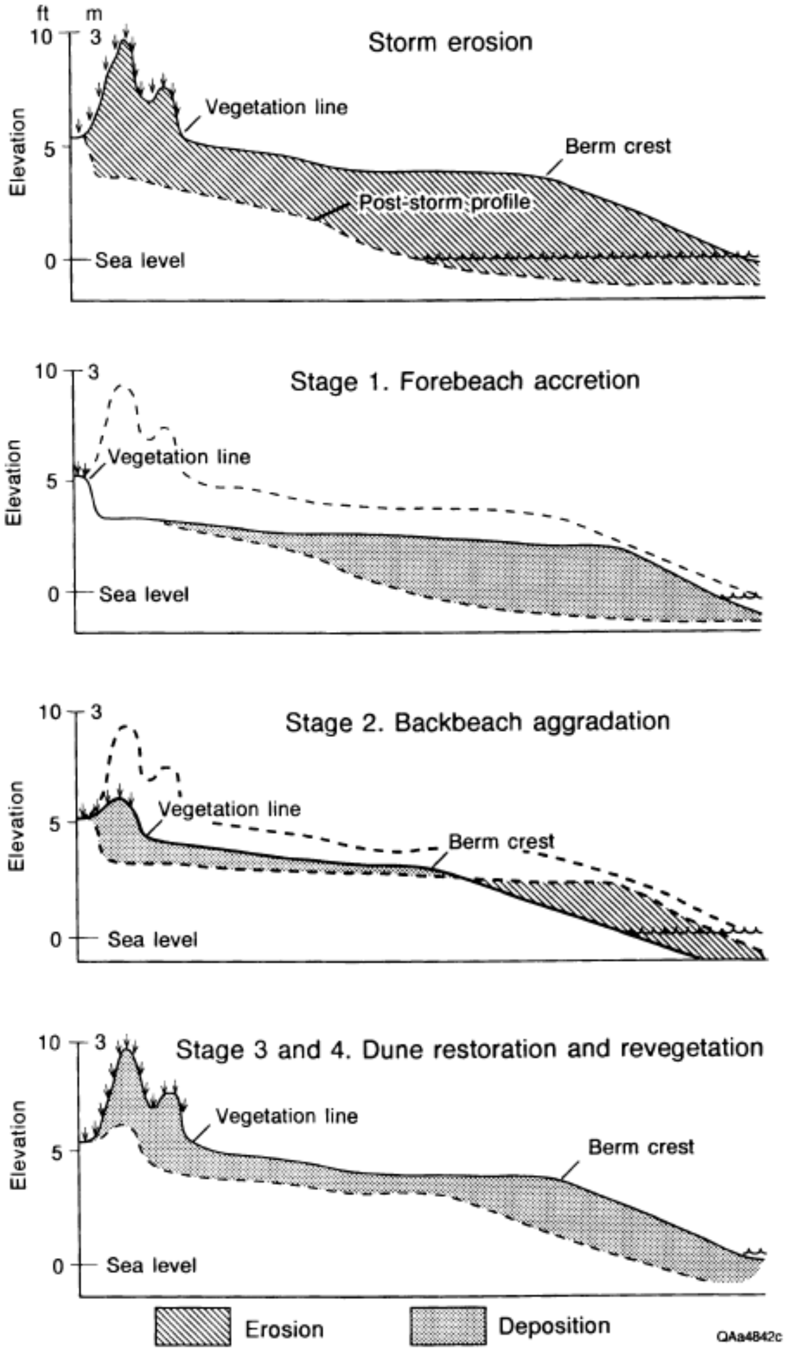


**Figure 5** Four stages of recovery, obtained from Morton *et al.* (1994). Stage 4 can take 10 years or more to occur after a storm event.

Foredune vulnerability to overwash events is another significant variable in a barrier island's morphology. Houser (2013) identifies successive overwash occurrences as the primary reinforcement of alongshore variation in dune morphology. The topography and near-shore bathymetry are complex variables that significantly influence the impact of a storm. Overwash is a critical component of the morphology on Assateague Island, and has been examined in multiple studies. Fisher *et al.* (1974) identifies the fan areas as being ultimately stable, but records the slight recession of the dune line at the northern end of the island after two years and at least four storms causing overwash. Overwash material is eroded and transported back to the beach by the predominant northwest winds. Studies on Assateague Island National Seashore have shown that non-vegetated areas act as "*temporary reservoirs*" for the overwashed sediment that will eventually be redistributed to the beach and dunes (Leatherman 1976). Storm events causing overwash contribute to the transgression of the island, and will continue to do so as future storms impact the landscape.

### *Identification of Study Site*

Identifying a study site was the initial step of this research process. This step was heavily reliant on data availability; the scarcity of raw LiDAR data available to the public made it a challenge to find appropriate elevation data for multiple years at a sufficient resolution. Another limiting factor was finding barrier islands that have been recently affected by storms, but has also had a period of time to show some recovery patterns. Several locations considered include Fire Island, NY, Assateague Island, MD, Matagorda Island, TX, the Outer Banks, NC, and Santa Rosa Island, FL. These barrier islands share characteristics including dune elevation, storm frequencies, and anthropogenic forcing. Assateague Island National Seashore was ultimately selected based on the availability of remotely sensed over a period of nearly 20 years, the frequency and magnitude of storms affecting the area, the availability of literature to establish a working knowledge of the morphology of the landscape, and the ability to collect storm surge data.

## Background

Established in 1962, Assateague Island National Seashore (ASIS) is a barrier island jointly managed by the National Park Service, the U.S. Fish and Wildlife Service, and the Department of Natural Resources. The purpose statement of this national park is: "*Assateague Island National Seashore was established to protect and preserve Assateague Island and its surrounding waters, to give the public opportunities to enjoy outdoor recreation, and to appreciate and learn about associated natural and cultural resources*." (NPS 2002). The national seashore is located across two state boundaries (Maryland and Virginia), and is often associated with neighboring Chincoteague Island, Virginia. Assateague Island is comprised of 48,000 acres of land just south of Ocean City, MD and is separated from the mainland by Newark and Chincoteague Bays. Over 2 million tourists visit the park every year to enjoy the scenery and explore the island, with more than 91 million visitors recorded since 1967; this number of visitors contributes to the funding eligibility of ASIS over time (Stats Report Viewer). At its widest point, the island measures approximately 3 kilometers across. The area being analyzed, shown in Figure 6, is less than 40 kilometers in length, and was selected based on data availability and extent.

Hurricanes and tropical storms impact the mid-Atlantic coast nearly every year, and sometimes multiple times per year. In the 20th century, at least 12 high magnitude storms occurred and impacted Assateague Island through wind gusts, rain, and increased wave heights (Schwartz 2014). Frequency of these high magnitude coastal storms can vary from less than one year to greater than a decade. One large storm hit the area in 1933, overwashing the area and creating an inlet between Assateague Island National Seashore and what is now Fenwick Island. Wright and Short (1984) identify a relationship between beach state and environmental conditions, in which the breaker height, wave period, and sediment fall velocity are considered; over time, this relationship establishes an equilibrium condition. Storm magnitude and frequency influences this environmental beach state parameter and can describe the impact that the 1933 storm had on Maryland's shore (Wright and Short 1984). This impact resulted in a decision by land managers to develop a jetty just downdrift from Ocean City, MD that has been maintained since its completion in 1935 (Mackintosh 1982). Ultimately, the limited sediment availability to be deposited along the Assateague shoreline has resulted in the rapid transgression of the northern part of the island (Leatherman 1976). Since the establishment of this infrastructure, Assateague has migrated approximately 1 km to the west due to the lack of available material around the jetty to be transported southward (Houser *et al.* 2013).

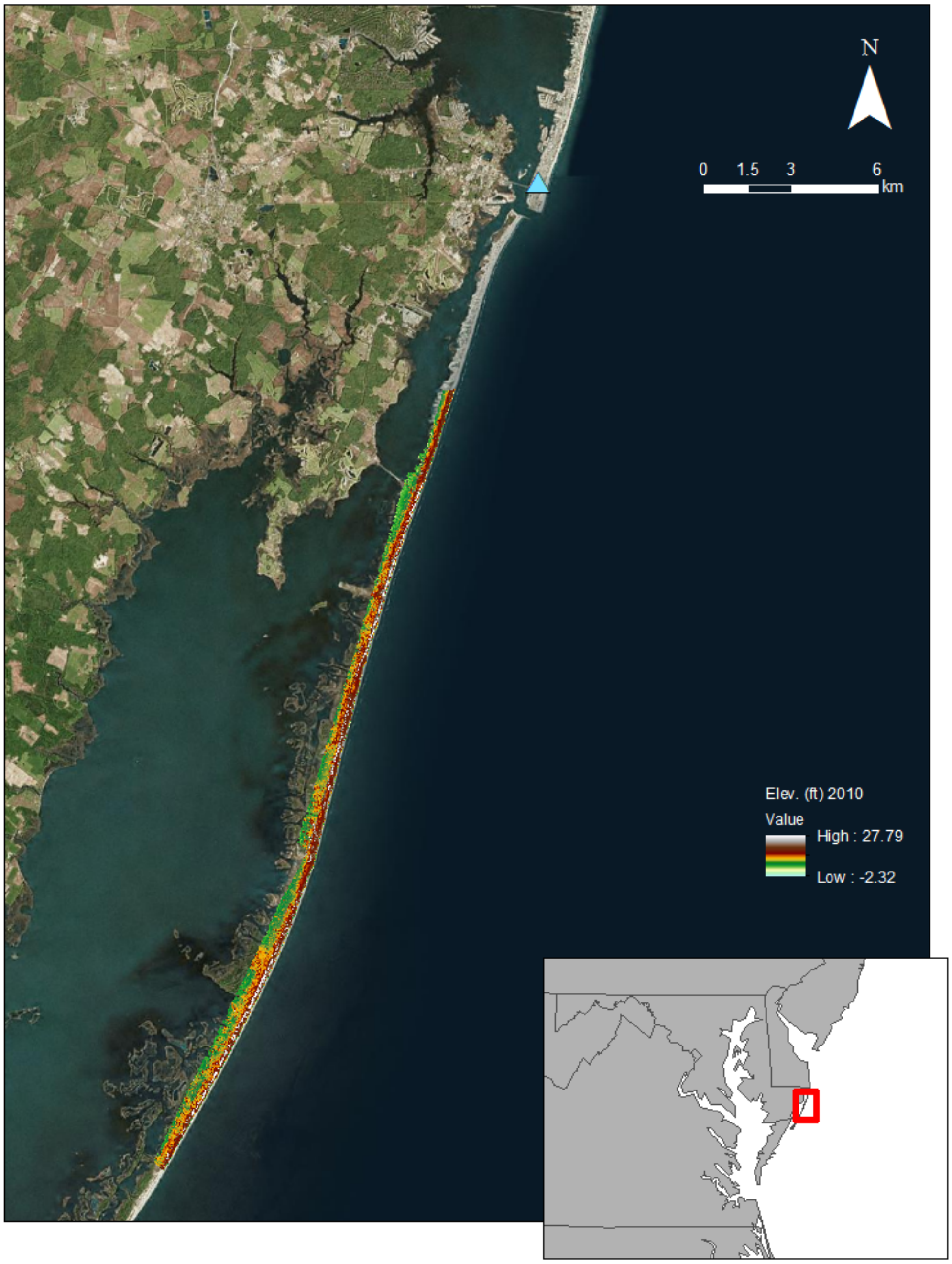


**Figure 6** Map of Assateague Island National Seashore (ASIS) study site with the 2010 elevation dataset overlaid. ASIS is a barrier island off the coast of southern Maryland. The blue triangle north of ASIS represents Ocean City, MD.

## Overwash and Sediment Budget

While the northern part of the island is transgressing rapidly, the entire length of Assateague is transgressing through the redistribution of sediment to the landward side of the island through washover. However, this movement landward has been somewhat stabilized through sediment renourishment, such as the establishment of a low foredune and one-time beach-widening project (Houser *et al.* 2013). Fisher *et al.* (1974) discusses the fan areas as being ultimately stable, but records the slight recession of the dune line at the northern end of the island after two years and at least four storms causing overwash. Washover material is eroded and transported back to the beach by the predominant northwest winds. Studies on Assateague Island National Seashore have shown that non-vegetated areas act as "*temporary reservoirs*" for the overwashed sediment that will eventually be redistributed to the beach and dunes (Leatherman 1976). Smaller particle sizes are transported from the nearshore bar or beach to the dune or backshore portion, and then captured by the vegetation in the area. Fisher *et al.* (1974) identifies the smallest grain size as the particles on the dune (0.20 mm), the second smallest as those on the overwash fan (0.25 mm), and the largest as those particles on the beach (0.30 mm). Storm events causing overwash contribute to the transgression of the island, and will continue to do so if storm magnitude and frequency increases (Goldenberg *et al.* 2001; Emanuel 2005).

Assateague Island National Seashore cross-shore and alongshore profiles can change drastically in response to storm events. The mean elevation of the island is 2 meters above sea level, with dunes reaching up to 10 meters in elevation (Nature &

Science 2014). Overwash and aeolian processes, interaction with wildlife, and vegetation are several key characteristics that heavily influence dunes through sediment transportation, stabilization, deposition, and erosive forcing at ASIS. Beach state may vary temporally as a result of changes in each of these parameters (Wright and Short 1984). According to the USGS, "*tidal range is ranked microtidal (<1 m) coasts are very high vulnerability and macrotidal (>6 m) coasts are very low vulnerability*" as it relates to sea-level rise (Pendleton *et al.* 2004, 5). Assateague is characterized by a 1-2 m tidal range, demonstrating a high vulnerability to inundation in respect to this natural hazard (Pendleton *et al.* 2004). Average yearly wind direction is predominantly South-Southwest, and ranges from 10 to 40 miles per hour on a typical day, influencing sediment transport and the development of the beach and dunes. This is shown in Figure 7, where the island is oriented from SW/SSW to NNE. Typical daily tide heights range from -1 to 0.5 feet relative to sea level (WindFinder 2015).

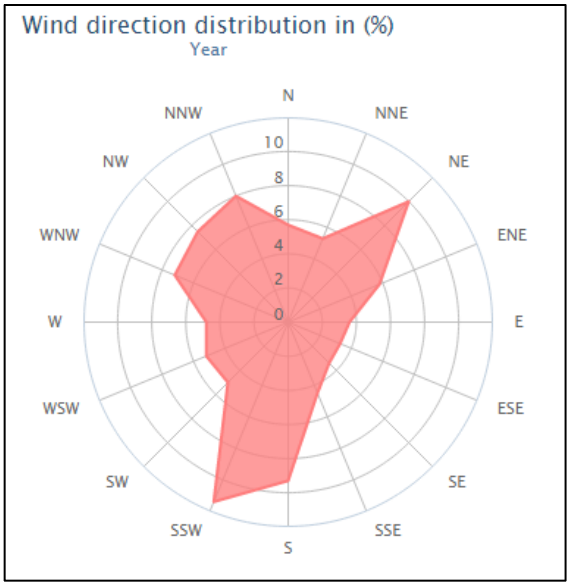


**Figure 7** Wind direction data for Assateague Island (WindFinder 2015).

## Vegetation

A diversity of environments throughout the island results in less than 1% of the beach landscape being classified as vegetated (Nature & Science 2014). Fleshy, thick-skinned plants are located on the beach and low dunes, preventing erosion through aeolian influences. Roman and Nordstrom (1988) identify the dominant species on large dunes at the southern end of the island as *Ammophila* and *Solidago sempervirens* (Seaside Goldenrod); lower, discontinuous dunes are "*sparsely vegetated*" with *Ammophila breviligulata* (American Beachgrass), a stabilizing entity. Their study determines the presence of a critical threshold for erosion rates, "beyond which vegetation does not recover" (Roman and Nordstrom 1988). This suggests that past a certain point of overwash and/or scarping, the island will fail to achieve dune buildup as it was able to do in the past (Roman and Nordstrom 1988). These relationships can be discussed in terms of "high" and "low" dunes, in which a high island is more likely to exhibit strong recovery patterns during a post-storm period and a low island cannot recover before it is impacted by another storm. Thus, it is typical that high islands and low islands maintain these characteristics over time (Houser and Hamilton 2009). In the case of a low island, the landscape may experience rapid transgression and eventually weld to the mainland beach.

Vegetation and dune health on ASIS is also impacted by the island's wildlife population. Assateague's wild horse population is a unique element of the park that draws many visitors. However, the grazing by these horses has been documented as a significant influence on dune formation and erosion (De Stoppelaire *et al.* 2004). Results from this study suggest that "in order to maintain the natural processes that historically occurred on barrier islands", the horse population must be reduced, or larger fenced areas must be established to prevent grazing (De Stoppelaire *et al.* 2004). This wildlife population is one that does not commonly exist on other barrier islands, and thus poses a unique additional variable to consider in the maintenance and stability of the island.

## Wildlife and Recreation

In addition to being known by tourists for its 37 miles of beaches and population of feral horses, Assateague is also known for the wildlife and recreational activities supported in the area. Occupants of this national seashore include snakes, rodents, crabs, deer, and seasonal birds. Offshore wildlife includes seasonal fish and infamous Maryland blue crabs. Tourists may visit the Maryland portion of the island year round to enjoy the landscape. Popular activities include bicycling, camping, hiking, canoeing and kayaking, and shell collecting. Assateague Island also allows over-sand vehicles along 12 miles of beach in Maryland and a small stretch of beach in Virginia; the rest of the beach is undisturbed by vehicles. Results from Houser *et al.* (2013) suggest that driving on this beach ultimately increases the vulnerability of the island through decreased foredune crest elevations. This is primarily a result of vehicles crushing existing vegetation and limiting seaward growth of the vegetation (Houser *et al.* 2013). Many visitors also participate in swimming and surfing, surf fishing, and shellfishing (Plan Your Visit 2014). The Assateague Island Visitor Center is located on the mainland, but transportation infrastructure extends to the island itself for the convenience of campers and hikers at the northern end. This influences the sediment budget and presence of vegetation at the end of the island, and is the area of ASIS that experiences the most anthropogenic forcing.

## Storm History

Located on the east coast of the United States, Assateague Island's shoreline is constantly reconstructed through storm events as well as everyday aeolian and wave dynamics. Recent storm events include Hurricanes Sandy (2012), Irene (2011), Earl (2010), Hurricane Hanna (2008), Hurricane Ernesto (2006), and Tropical Storm Barry (2007). Storm events such as these have the ability to significantly impact the distribution of sediment in an area based on pre-existing morphology. Table 1 shows the dates and categories of the storms between datasets. The surge associated with these storms influence the recovery ability of the foredunes on ASIS.

Table 1 This table shows the categories and dates of recent coastal storms affecting ASIS. Not all storms listed were incorporated in this study, due to small surge elevations.

| Date | Storm or Data | Category |
|---|---|---|
| 8/19-30/1998 | Hurricane Bonnie | 3 |
| 8/24-9/7/1999 | Hurricane Dennis | 2 |
| 9/7-19/1999 | Hurricane Floyd | 4 |
| 10/13-24/1999 | Hurricane Irene | 2 |
| 9/14-21/2000 | Hurricane Gordon | 1 |
| 9/14-29/2002 | Hurricane Isidore | 3 |
| 9/6-20/2003 | Hurricane Isabel | 5 |
| 8/24-9/10/2004 | Hurricane Frances | 4 |
| 9/2-24/2004 | Hurricane Ivan | 5 |
| 9/13-29/2004 | Hurricane Jeanne | 3 |
| 7/4-10/2005 | Hurricane Dennis | 4 |
| 8/24- 9/1/2006 | Hurricane Ernesto | 1 |
| 8/25-9/5/2010 | Hurricane Earl | 4 |
| 8/21-30/2011 | Hurricane Irene | 3 |
| 10/22-11/2/2012 | Hurricane Sandy | 3 |

# CHAPTER II

# METHODOLOGY

## *Introduction*

Light Detection And Ranging (LiDAR) elevation data was used to identify changes in foredune height and volume at Assateague Island National Seashore using cross shore transects at regular 20 m intervals alongshore, and GIS tools available through the USGS and ESRI ArcGIS ArcMap and ArcCatalog interfaces. A total of 5,824 transects were extracted for the years 2000, 2005, 2008 and 2010. The 2000 and 2005 datasets were interpreted in this study.

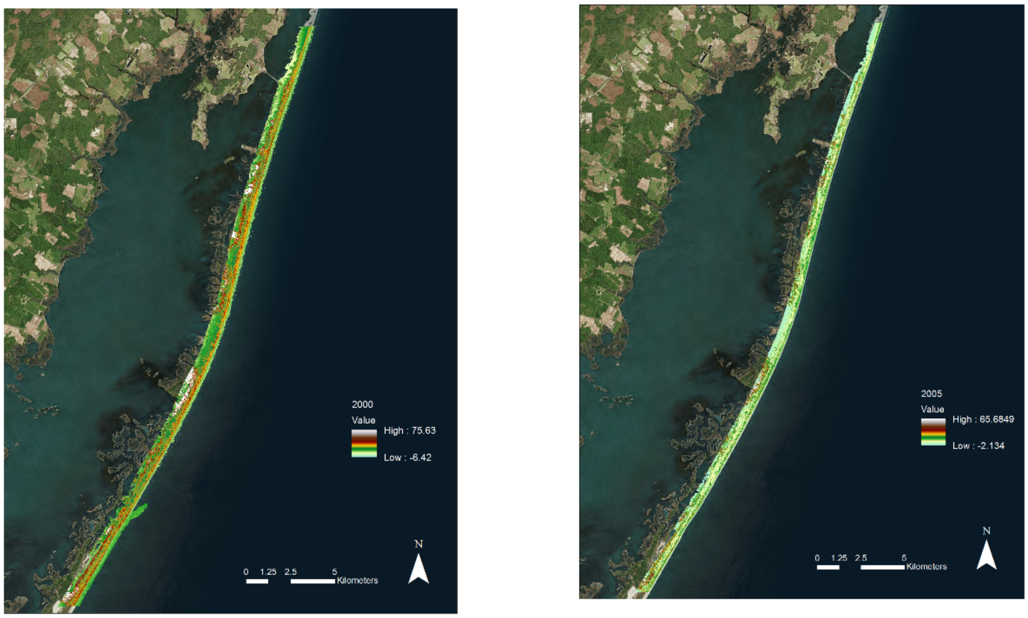
## *Acquisition of Imagery*

While there is a variety of data viewers and datasets available for downloading online, not every system contains historical data, nor data for every coastal area. NOAA Digital Coast is a free resource available to the public that offers a multitude of multitemporal data formats for coastal areas in the United States. This online tool hosts benthic, demographic, economic, land cover, weather, and many other data types, and is encouraged to be used by coastal communities and land managers. LiDAR digital elevation models at Assateague Island National Seashore were downloaded for the years 2000 and 2005 using NOAA Digital Coast; data for 2008, 2010, and 2012 was also available through this site, but not analyzed in this study. While the website called these files “LiDAR”, suggesting they were formatted in .las or .laz format, they were not raw

LiDAR files as expected. Rather, these DEMs were in .tif format and were DEMs already built from raw LiDAR by the organizations that had collected the data, including the U.S. Geological Survey (USGS, 2000 and 2008), the National Oceanic and Atmospheric Administration (NOAA, 2000), the National Aeronautics and Space Administration (NASA, 2000 and 2008), and the Army Corps of Engineers (USACE, 2005, 2010, and 2012). Figure 8 shows the spatial extent for each dataset obtained and Table 2 shows the characteristics of each dataset including dates, technology, organization, and cell size.

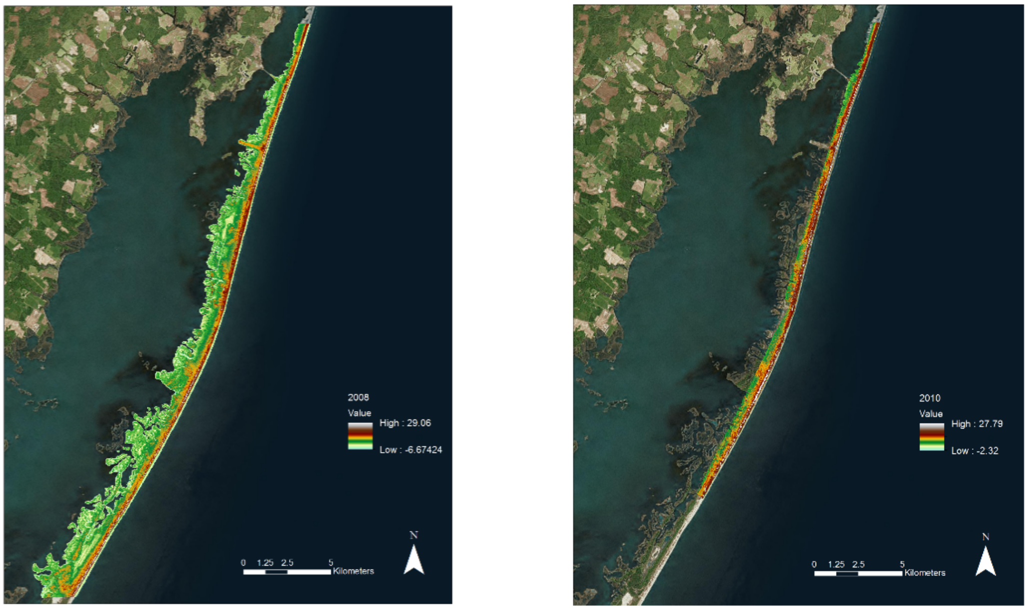
### *Pre-Processing*

Upon the acquisition of raster data from Digital Coast, the data was reprojected into the Maryland State Plane projection in ArcMap 10.2.2. Because there was no projection initially associated with the data, it was necessary to ensure that it would correspond to a basemap layer and typical Maryland projection for appropriate geographic display and any potential georeferencing purposes. Following the re-projection, any years that had multiple tiles were mosaicked in ArcCatalog 10. 2.2, providing data continuity for the casting of transects.



2000 dataset.

2005 dataset.



2008 dataset.

2010 dataset.

**Figure 8** Re-projected elevation datasets for years 2000, 2005, 2008, and 2010 collected from NOAA's Digital Coast.

**Table 2** Display of dataset characteristics.

| Dates Collected | Sensor Name | Resolution | Organization (s) | Project Name | Accuracy (Horizontal/ Vertical) |
|---|---|---|---|---|---|
| 9/20 - 11/2/2000 | Airborne Topographic Mapper (ATM) II | 3.089 m | NOAA, USGS, NASA | Airborne LiDAR Assessment of Coastal Erosion (ALACE) Project for the US Coastline | +/- 0.8 / 0.15 m |
| 8/24 - 11/26/2005 | SHOALS-1000T | 2.065 m | USACE | 2005 US Army Corps of Engineers (USACE) National Coastal Mapping Program Topo/Bathy Lidar: Delaware, Maryland, New Jersey, New York, North Carolina and Virginia | +/- 0.75 / 0.2 m |
| 3/24 - 3/25/2008 | Experimental Advanced Airborne Research Lidar (EAARL) | 2.062 m | USGS, NPS, NASA | 2008 USGS/NPS/NASA Experimental Advanced Airborne Research Lidar (EAARL): Assateague Island National Seashore | +/- 1.0 / 0.15 m |
| 9/23 - 9/25/2010 | Compact Hydrographic Airborne Rapid Total Survey (CHARTS) | 2.072 m | USACE | 2010 US Army Corps of Engineers (USACE) Joint Airborne Lidar Bathymetry Technical Center of eXpertise (JALBTCX) Lidar: Maryland- September (Post-Hurricane Earl, Topo) | +/- 0.75 / 0.2 m |
| 11/9 - 11/11/2012 | Optech Gemini LiDAR Sensor | 1.030 m | USACE | 2012 USACE Post Hurricane Sandy Topographic LiDAR: Virginia and Maryland | +/- 0.304 / 0.143 m |

### *Casting Transects with DSAS*

Contours were cast in the cross shore direction using the ArcMap Digital Shoreline Analysis System (DSAS) extension developed by the USGS (Thieler *et al.* 2009). The contours for this project are based on the 2008 data, in which ArcMap was used to derive contours and identify the 0 foot contour to establish sea level. This base contour was pulled 100 meters offshore from the 2008 dataset shoreline. A cross shore distance of 500 meters was established for each transect to ensure the collection of any bathymetry and foredune elevations. Transects were cast 20 meters apart, creating a total of 1,456 transects along the island (see Figure 9); the 2010 DEM was the limiting dataset because it had the shortest alongshore distance. More than 5,800 elevation transects were manually extracted in ArcMap for 2000, 2005, 2008, and 2010. Approximately 220 transects were selected at a time, plotted using the Profile Graph tool in the 3D Analyst toolbar, and exported as X and Y points in .xls format.

### *Dune Extraction and Analysis*

Following the formatting of the 5,824 transects in Excel, dunes were extracted and the following dune parameters were identified: dune crest elevation ($D_C$), dune toe elevation ($D_T$), and dune height ($D_H$). Sallenger (2000) defines $D_C$ as the "elevation of the highest part of the 'first line of defense'", or the maximum elevation of the foredune. $D_T$ is simply defined as the "elevation of the base of the dune" (Sallenger 2000). The difference between these two elevations is defined as $D_H$.

To capture the dune in each profile, the dune toe and dune "heel" were identified. In most instances, the dune toe is identified at the first major inflection point. Each dune was evaluated by drawing a line from the dune crest to the berm and identifying the farthest point from that line (see Figure 10). Dune "heel" was identified using the same methodology on the landward side of the foredune. Following this manual extraction of each foredune, the dune toe and crest elevations were identified.

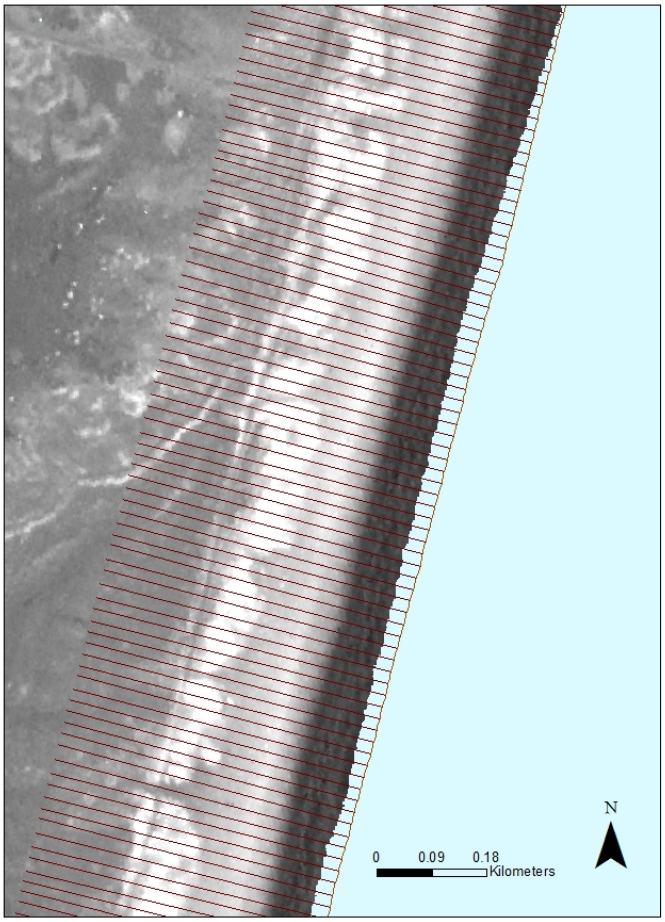


**Figure 9** Transects cast from offshore via DSAS tool **(**Thieler *et al.* 2009). While each transect was the same for each year alongshore, datasets varied in island width.

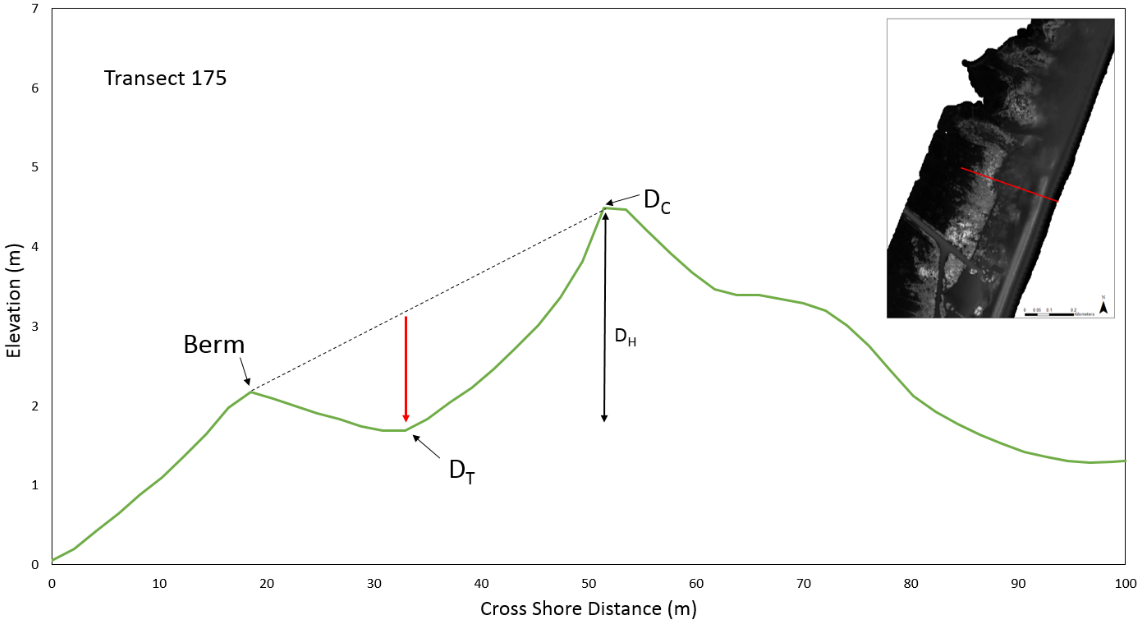


**Figure 10** Sample profile from 2005 dataset showing parameter definitions dune toe, dune height, and dune crest (left to right). The dashed line and red arrow represent the extraction method of dune toe.

*Dune Classification and Recovery*

Upon completing the foredune extraction for every transect, each dune was classified into a regime (Sallenger 2000) based on the storm surge of each storm event where $R_{HIGH}$ is the elevation of the storm surge. Sallenger (2000) describes these impact regimes as incorporating swash, taking into account astronomical tides, storm surge, and vertical height of wave runup values (see Table 3; Figures 11 and 12). Because swash, runup, and tides were not incorporated in the storm surge data acquired in this study, the impact regimes used in this study are not direct representations, but rather modeled and named after those described by Sallenger (2000). The swash regime is characterized by a storm surge elevation less than or equal to the elevation of the dune toe ($R_{HIGH}/D_C = D_T/D_C$) and is characterized by erosion of beach sediment and scarping along the dune toe area. The collision regime occurs when a surge elevation is greater than that of the dune toe, and less than or equal to that of the dune crest ($R_{HIGH}/D_C > D_T/D_C$). As a result, the dune slope can change drastically during a storm event, and may be scarped in this regime. In the overwash regime the surge elevation exceeds the foredune crest elevation ($R_{HIGH} > D_C$), where the critical threshold is $R_{HIGH}/D_C = 1$ (Sallenger 2000). This regime is frequently seen at Assateague (Fisher *et al.* 1974), and contributes to washover fans and sediment deposition on the landward side of the dune.

Storm surge was estimated from buoy data was from the Tide and Current database managed by NOAA (see Table 3); the data used was that collected by the buoys closest to ASIS. An active buoy at Ocean City captured data from a majority of storm surges under consideration, and is geographically the closest historical data available to Assateague Island National Seashore. In several instances, data was collected at both Ocean City, MD (north of the island) and Wachapreague, VA (south of the island), allowing for two data points to be used in the classification of transects via Excel; this is represented by a sloped line between the alongshore locations of these two buoys, rather than the otherwise horizontal line (representing data from a single buoy only) in Figures 11 and 12.

**Table 3** Hurricane dates, categories, and storm surges affecting ASIS.

| Date | Storm Events | Datasets | Category | Storm Surge (m) |
|---|---|---|---|---|
| 8/19-30/1998 | Hurricane Bonnie | | 3 | 1.05 |
| 8/24-9/7/1999 | Hurricane Dennis | | 2 | |
| 9/7-19/1999 | Hurricane Floyd | | 4 | |
| 10/13-24/1999 | Hurricane Irene | | 2 | |
| 9/14-21/2000 | Hurricane Gordon | | 1 | |
| ***9/20-11/2/2000*** | | ***LiDAR Data Set 2000*** | **-** | |
| 9/14-29/2002 | Hurricane Isidore | | 3 | 1.10 |
| 9/6-20/2003 | Hurricane Isabel | | 5 | 1.10 – 2.16 |
| 8/24-9/10/2004 | Hurricane Frances | | 4 | 1.60 |
| 9/2-24/2004 | Hurricane Ivan | | 5 | 1.73 |
| 9/13-29/2004 | Hurricane Jeanne | | 3 | 1.73 |
| 7/4-10/2005 | Hurricane Dennis | | 4 | 1.63 |
| ***8/24-9/8/2005*** | | ***LiDAR Data Set 2005*** | **-** | |

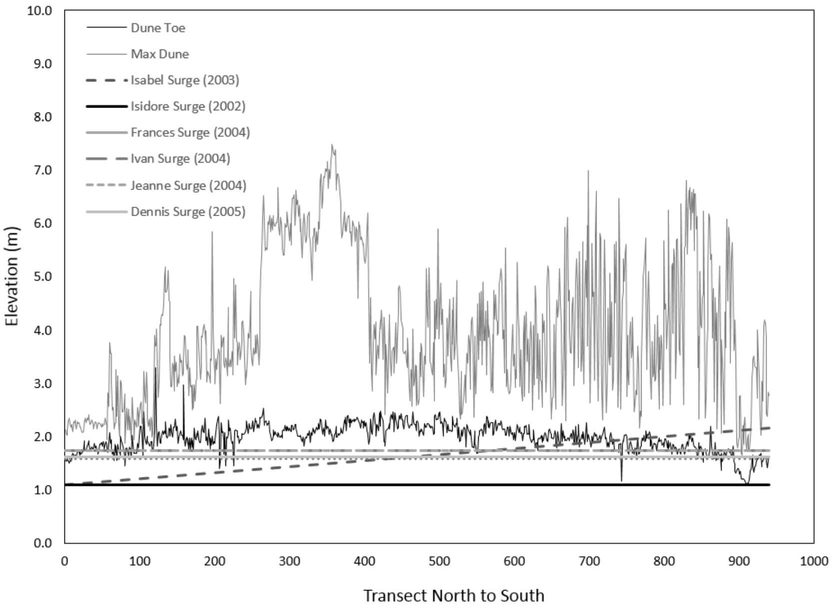


**Figure 11** Extracted dune toe and dune crest elevation on ASIS in 2000. Storm surges shown are associated with all storms between 2000 and 2005, affecting the recovery period of each transect.

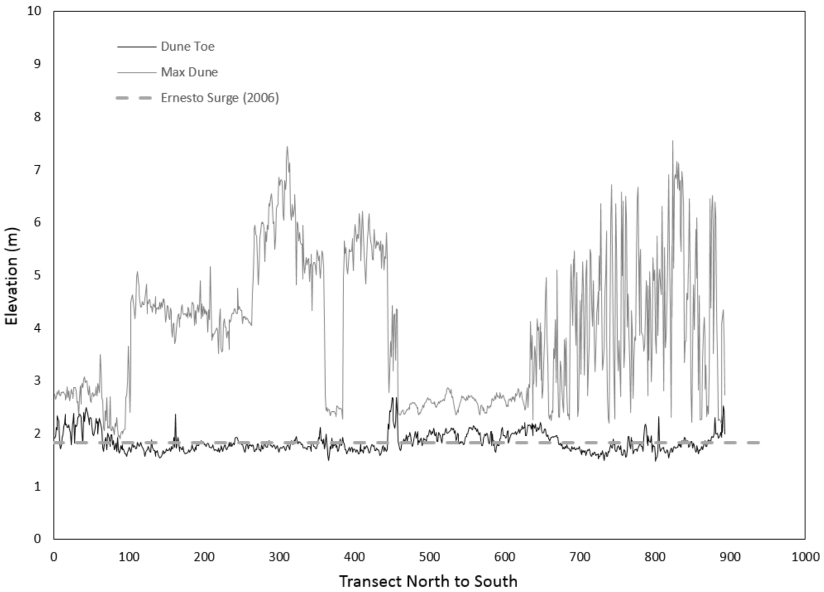


**Figure 12** Extracted dune toe and dune crest elevation on ASIS in 2005. Storm surges shown are associated with the single storm occurring between the 2005 and 2008 datasets, affecting the recovery period of each transect.

Recovery periods were identified as the amount of time since a Collision or Overwash regime impacted a given profile. Transects with a greater $D_H$ elevation in 2000 than in 2005 were not analyzed because they represented profiles in which dunes did not recover; this left a total of 370 transects to analyze. The maximum recovery period possible between 2000 and 2005 is 5 years, which is shown if transects that experienced a Swash regime for each storm event. A Collision or Overwash regime is representative of a transect experiencing some type of disturbance, and thus the recovery period may be "reset" if either regime occurs. If Collision or Overwash occurred over a transect during Hurricane Dennis in July 2005 before the 2005 LiDAR dataset was collected (in August), the recovery period was less than one year. Alternatively, if a transect experienced one of these damaging regimes during an earlier storm but experienced a Swash regime in 2003, 2004, or 2005, other values would be assigned to the recovery period of the transect. Specifically, the dates of each storm event were compared to the 2005 LiDAR; a calculation of the difference in months was conducted, resulting in the following possibilities for recovery period: 0.083 years (1 month), 0.917 (11 months) years, 1.917 years (23 months), and 5 years.

Dune height ($D_H = D_C - D_T$) was calculated for transects in years 2000 and 2005 and then subtracted to show the change in $D_H$ between the two LiDAR dates. These values ranged between approximately -2.5 feet and more than 8 feet. Each recovery timeframe was then broken into quartiles and grouped to analyze recovery patterns of differing dune types; thus the first quarter of each recovery period created the First-Quartile, or lowest values in each section, and so on. Dune volume was calculated by finding the area under each dune profile and multiplying that value by a width of 1 m; these values were also displayed in quartiles.

# CHAPTER III

# RESULTS

## *Introduction*

Dune morphometry extraction was successfully completed for the years 2000 and 2005 using elevation profiles captured using the DSAS tool as described in Chapter II: Methodology. A total of 1,086 transects had no dune, or the dune crest elevation decreased or exhibited no change during the recovery period. These profiles were not included in the analysis because there was no vertical growth or recovery to analyze in these cases and this study is not examining erosion. Rather it is identifying growth in $D_C$ and changes in $D_H$, and $D_V$, and $D_T$ where growth exists. The remaining 370 transects that were evaluated varied in location across the island. Logistic curves were created for the change in parameters seen in the 370 transects using the equation used by Houser *et al.* (2015) and presented in Chapter I. This allowed the comparison of the recovery curves for ASIS to those developed in previous studies. Because of the time between LiDAR dataset, the options for the number of years of observed recovery are 0.08 (1 month), 0.92 (11 months), 1.92 (23 months), and 5.00 (5 years), represented by Y0, Y1, Y2, and Y5 respectively.

## *Changes in Parameters*

Between 2000 and 2005, average dune elevation ($D_C$) across Assateague Island increased from 3.8 m to 4.4 m, while average dune toe elevation ($D_T$) decreased, from

1.9 m to 1.8 m. Average recovery of dune height ($D_H$) over the span of Assateague Island during this time period was approximately 0.71 m, but varied in magnitude alongshore. Minimum values of change in $D_H$ fall around -0.75 m, with maximum values of approximately 3 m. Changes in $D_C$ range from slightly greater than 0 m to approximately 2 m of growth. Volumetric change for the 370 transects under consideration is nearly all positive, with less than 10 negative values due to varying dune width and dune height; $D_V$ values range from -200 $m^3$ to more than 1,000 $m^3$.

Quartiles were used to identify rates differences in recovery rates between large height and small height dunes. The first quartile demonstrates the smallest values within each recovery period, while the fourth quartile exhibits the largest values. Greater dune height corresponds to greater dune elevation, and a greater change in dune height between 2000 and 2005 appears to relate to a greater dune height. Thus, Quartile 1 is representative of low island areas, while Quartile 4 is representative of high island areas. Each parameter under consideration was split into quartiles to determine whether growth rates aligned with the sigmoidal curve equation. When evaluating change in $D_V$, the 5-year recovery averages are less than the 2-year recovery averages, which may suggest a loss in dune extent. Changes in dune crest elevation over time at each transect shows a similar logistic recovery pattern to the dune height parameter discussed in Houser *et al.* (2015), especially in the rate of change in the third and fourth quartiles. In general, recovery in early years is limited, but the gradient of recovery dramatically increases between 3 and 5 years before reaching a point of diminishing return. Logistic curves were developed through the modification of variables in this equation and applying the equation to each quartile to understand the rate of recovery for each dune height variety. Thus, four logistic curves exist for each parameter (see Table 4). The variables adjusted for each curve include: initial point, rate of change, and maximum recovery point. This logistic curve was modified for parameters $D_C$, $D_H$, and $D_V$ (see Figures 13, 14, and 15).

Sigmoidal patterns vary between these parameters, particularly when comparing maximum growth rate periods. $D_C$ recovery (Figure 13) shows the greatest growth rate between 2 and 3 years, where the slowest growth rate is between 0 and 1 year. The recovery curve for $D_H$ (Figure 14) appears to have a gentler increase over time when compared to the logistic recovery curve representing change in dune crest elevation. This curve demonstrates a maximum growth rate between 1 and 3 years of more than 1 m. In comparison to the recovery curves of $D_C$ and $D_H$, $D_V$ (Figure 15) exhibits a much gentler logistic pattern over time. With a maximum growth rate between 0 and 2 years, each quartile reaches its 5-year growth extent at least one year before other parameters. $D_T$ values (see Figure 16) indicate an inverted sigmoidal pattern for each quartile that cannot be represented by the logistic recovery rate equation applied to the other parameters. However, it appears that the maximum rate of change occurs between 1 and 2 years, suggesting a period where the dune is developing in extent.

**Table 4** Recovery rates (r) for dune crest, dune height, and dune volume, represented by *n* in the equation used by Houser *et al.* (2015).

| | DC | DH | DV |
|---|---|---|---|
| **Quartile 1** | 0.65 | 1.5 | 1.6 |
| **Quartile 2** | 0.8 | 0.2 | 2 |
| **Quartile 3** | 0.8 | 1.1 | 1 |
| **Quartile 4** | 0.8 | 0.7 | 0.8 |

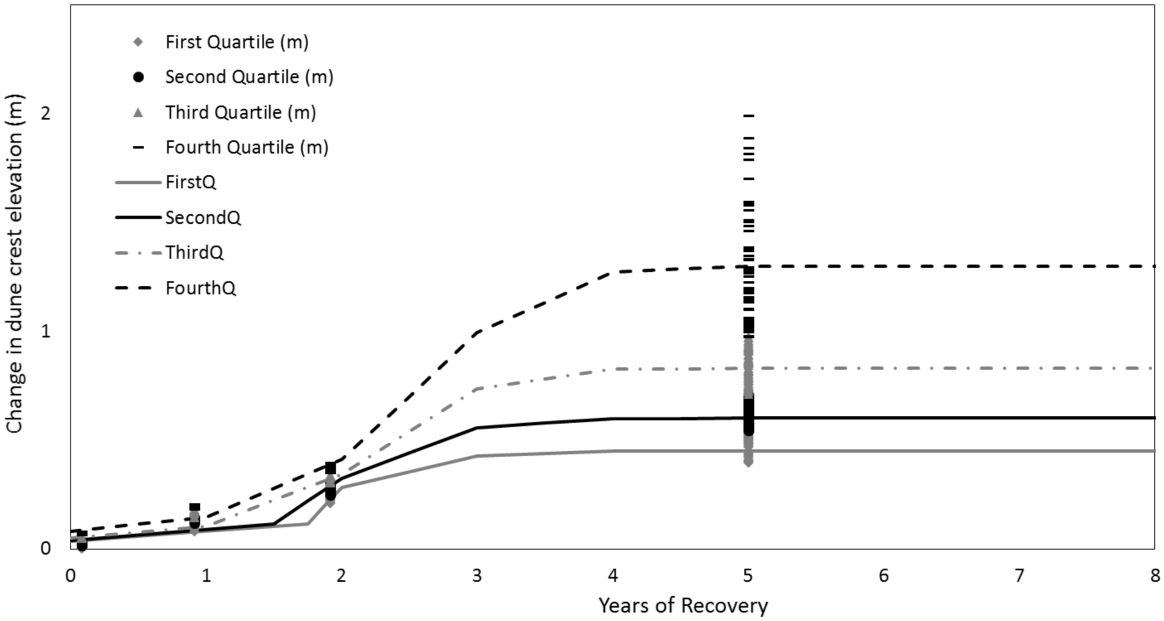


**Figure 13** Change in $D_C$ represented by quartiles and years of recovery with modified logistic curves overlaid.

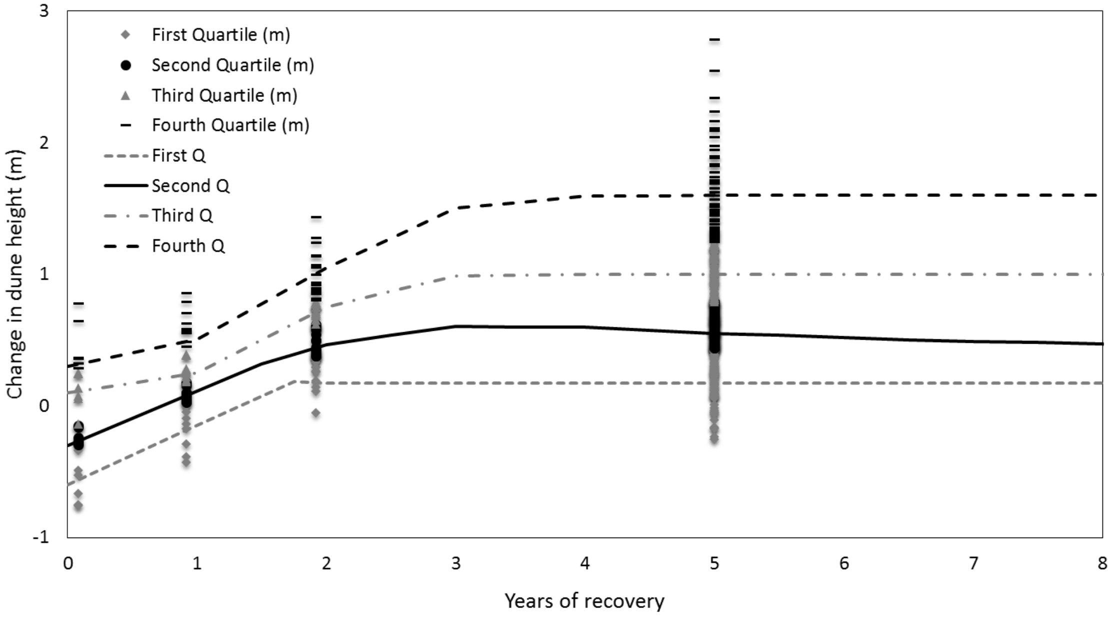


**Figure 14** Change in $D_H$ represented by quartiles and years of recovery, with modified logistic curves overlaid.

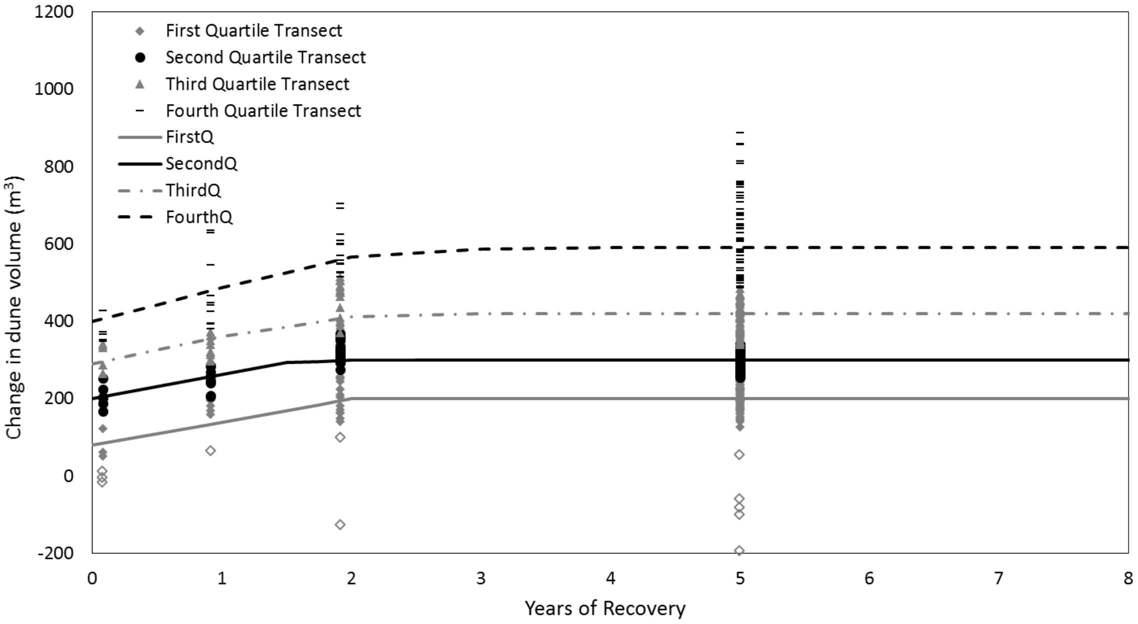


**Figure 15** Change in $D_V$ represented by quartiles and years of recovery, with modified logistic curves overlaid.

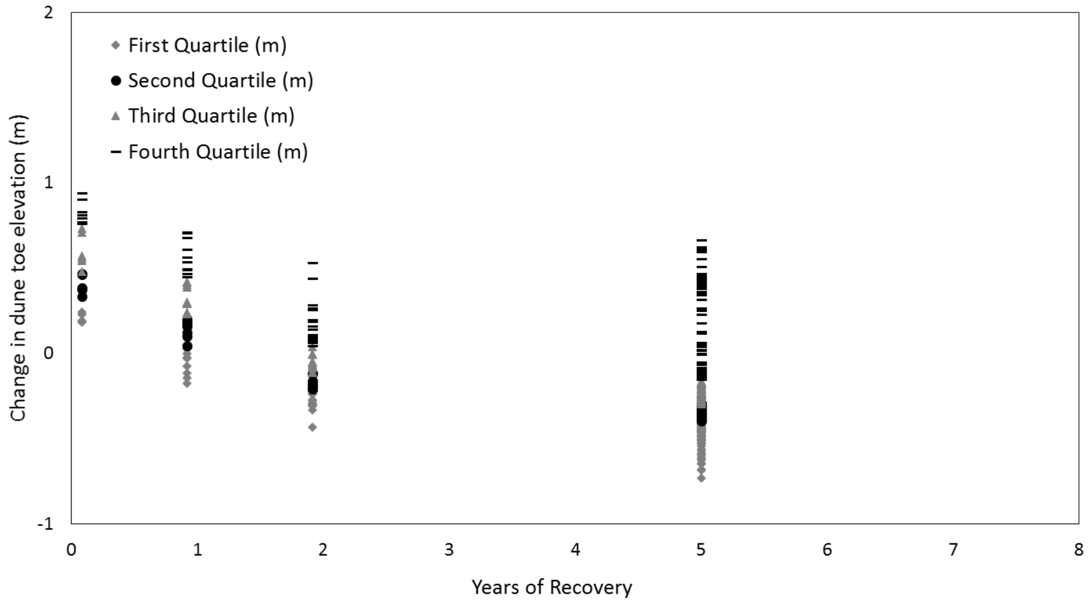


**Figure 16** Change in $D_T$ represented by quartiles and years of recovery.

*Ensemble Averaging*

Ensemble averages of transects from each period were calculated for each quartile to better characterize the processes behind the recovery observed at ASIS between 2000 and 2005. This analysis offers a general explanation for the characteristics of dune growth in each quartile (see Figure 17). Quartile 1 demonstrates sediment accretion on both the seaward and landward side of the dune, and exhibits some vertical dune growth of approximately 0.2 m. Quartile 2 shows a similar pattern of sediment accumulation, but with less erosion along the backbeach portion. Quartile 3 depicts nearly 0.5 m of vertical growth in some areas, with greater accretion along the backbeach than what is seen on the seaward side of the dune. Quartile 4 demonstrates a great amount of change, with nearly 1 m of accumulation in some areas. This average of transects shows little sediment buildup on the seaward side of the dune, a large vertical increase, and great backbeach growth. Each representation of recovery for a given quartile differs from the others, with an overall increase in both $D_C$ and $D_V$. Average $D_T$ varies among quartiles as well. The morphological changes seen in each quartile between 2000 and 2005 suggest that a variety of processes contribute to dune redevelopment through accretion and erosion.

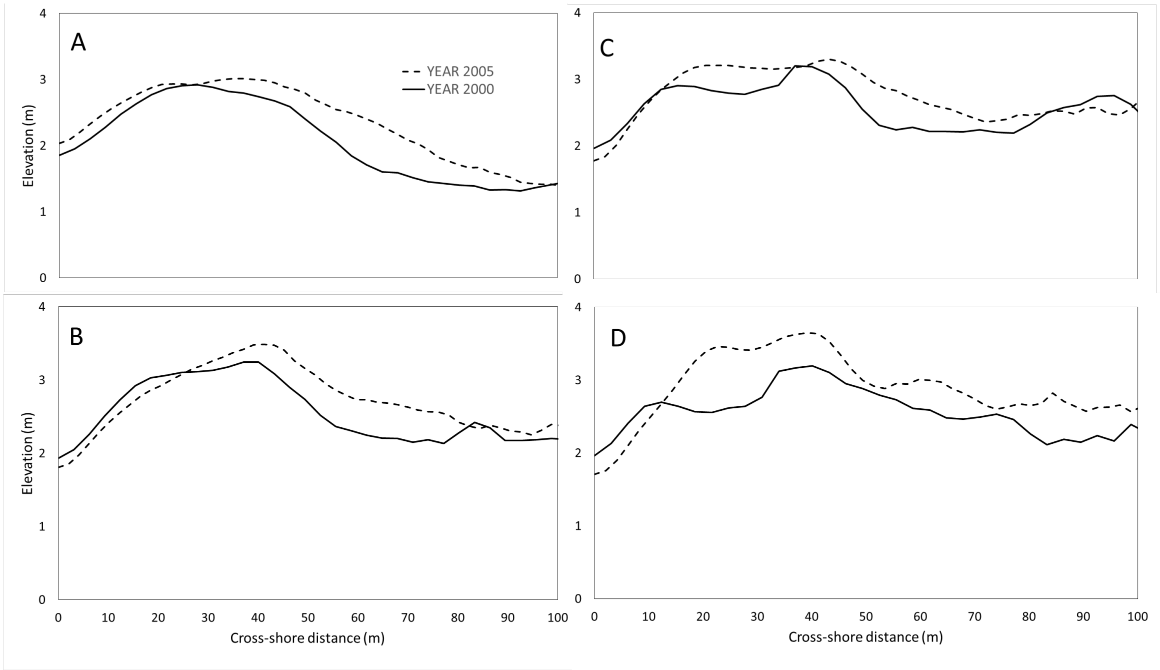


**Figure 17** Ensemble average of transects in each quartile for years 2000 and 2005, where A) is Quartile 1, B) is Quartile 2, C) is Quartile 3, and D) is Quartile 4.

In addition to the ensemble averages of quartiles, transects within each $D_H$ quartile were organized by recovery period, based on the date and magnitude of storm surges. For example, Quartile 1, Year 0 (Q1Y0) represents an ensemble average of transects that were relatively low change in height over less than one year of recovery. Conversely, Quartile 4, Year 5 (Q4Y5) transects represent recovery of more developed "5 year" dunes with a large growth in $D_H$.

### Quartile 1

The highest dune seen in the first quartile, or average of low island profiles, is about 4 m in elevation in Q1Y2. Dunes of this size exhibited an overall decrease in $D_H$ between 2000 and 2005. Transects categorized in Q1Y0 represent areas of the island that were impacted most recently by a storm event in comparison to other years of recovery (Figure 18). These profiles exhibit accretion on the seaward side of the dune. A greater 2005 $D_T$ value was observed for both Q1Y0 and Q1Y1 by approximately 1 m and 0.5 m respectively. Transects in this category show an average dune that transgressed landward with minor vertical growth, and an extended seaward dune slope in comparison to the shorter, steeper dune slope seen in 2000. A similar recovery pattern is seen profile Q1Y2, which shows accretion on the backshore, and a slight landward migration of the dune crest. Transects with the greatest recovery period, Q1Y5, demonstrate volumetric growth through the accumulation of sediment along the backshore area of the dune, between 50 and 100 m cross-shore. The cross-shore distance of each set of 2000 transects ranges between 20 and 30 m while the location of the 2005 recovery curves show dunes at approximately 18 m (Q1Y0), 43 m (Q1Y1), 42 m (Q1Y2), and 20 m (Q1Y5).

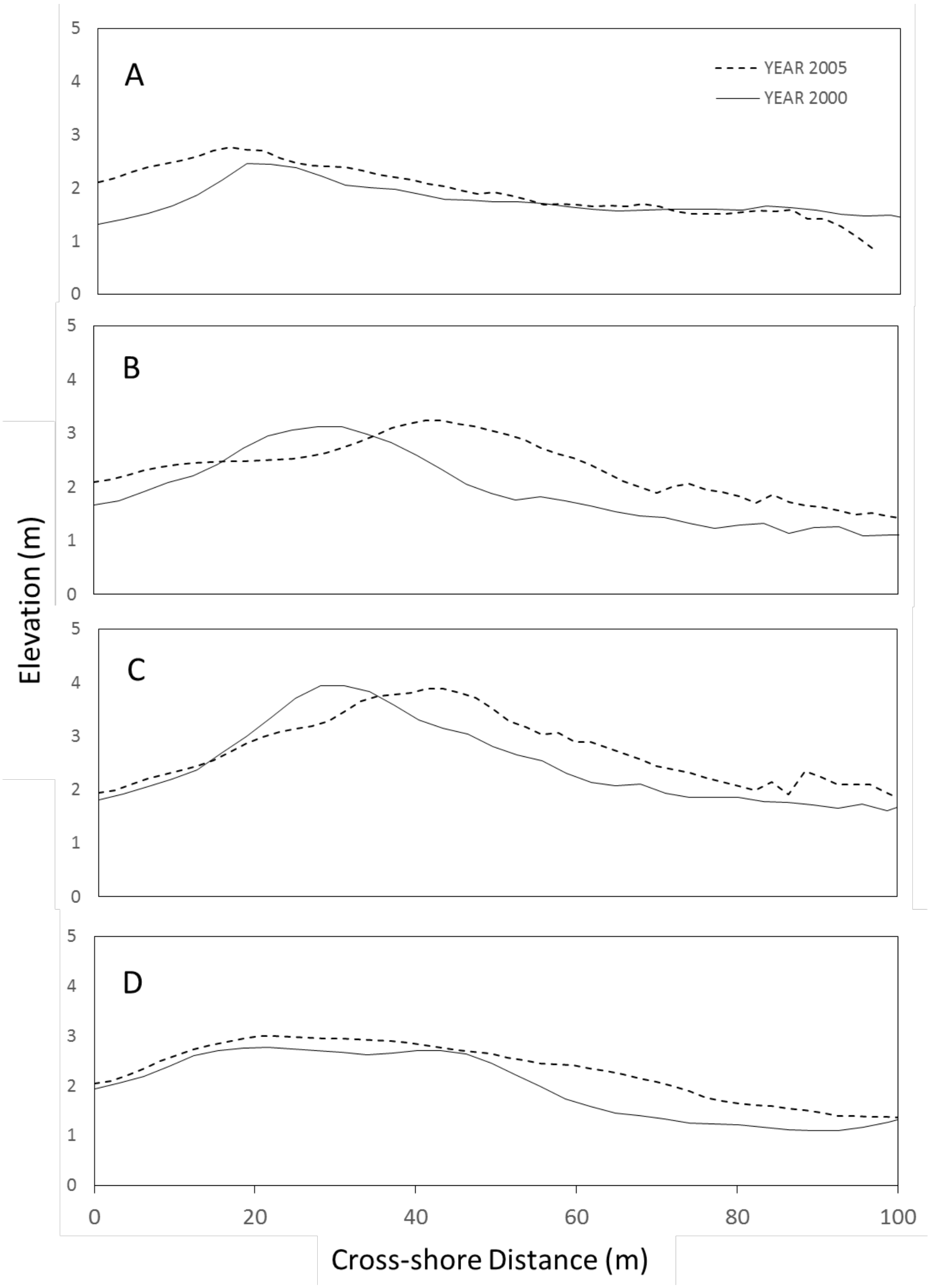


**Figure 18** Quartile 1 recovery for Year 0 (A), 1 (B), 2 (C), and 5 (D). Values along each Y axis represent Elevation (m), and the X axis represents Cross-shore Distance (m).

### Quartile 2

Several morphological changes between 2000 and 2005 in the second quartile average profiles show similarities to those in Quartile 1 (Figure 19). Specifically, Q2Y0 also shows approximately 0.5 m of sediment accretion sediment on the seaward side of the profile, which differs from what is seen in the in Q1Y0 ensemble average of nearly 1 m between 2000 and 2005. Q2Y1 shows a landward migration of the dune and a vertical increase of approximately 0.2 m, similar to that seen in the Q1Y1 average transect; Q2Y2 exhibits some of these characteristics as well. While the change in $D_C$ for 23 months is not as large as that seen in recovery time of 11 months, the transgression of the dune results in a gentler seaward slope than what is reflected in the 2000 dataset. Between the 2000 and 2005, Q2Y5 shows a decreased $D_T$ of more than 0.3 m and a very similar average dune shape at a slightly greater magnitude represented by accumulation of sediment along the backshore side of the dune. Each ensemble average in Quartile 2 migrated landward between 2000 and 2005. Specifically, dune crest position moved from 40 to 60 m (Q2Y0), 30 to 50 m (Q2Y1), 25 to 45 m (Q2Y2), and 40 to 46 m (Q2Y5).

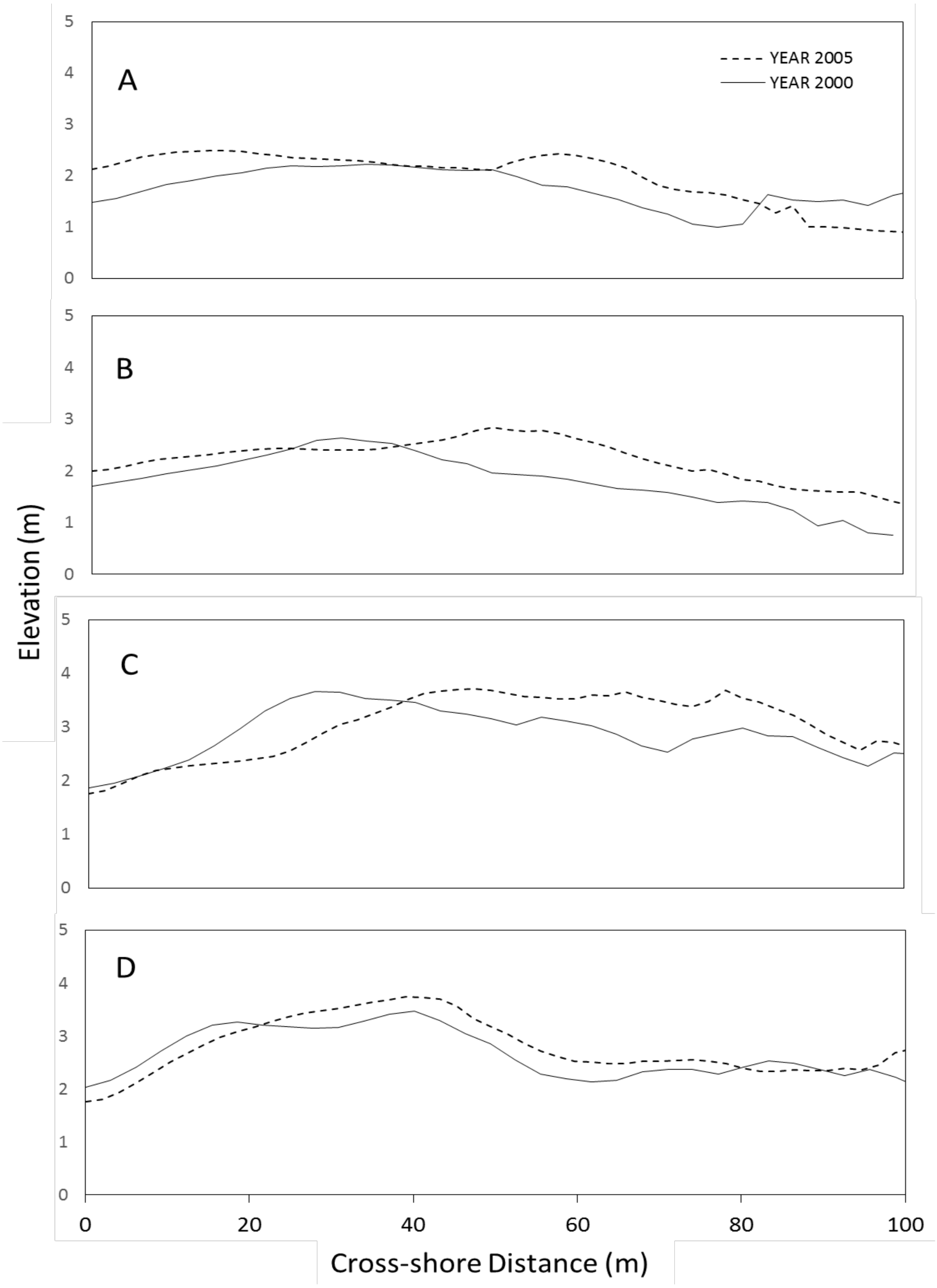


**Figure 19** Quartile 2 recovery for Year 0 (A), 1 (B), 2 (C), and 5 (D). Values along each Y axis represent Elevation (m), and the X axis represents Cross-shore Distance (m).

### Quartile 3

Recovery transects in quadrant three vary from what is observed in Quartiles 1, 2, and 4 (Figure 20). Q3Y0 demonstrates more than 1 m of accretion of sediment in the backshore, reflecting dune transgression since 2000. Additionally, there is nearly 0.5 m of accumulation along the seaward portion of the dune. $D_T$ increases by approximately 0.4 m between elevation datasets in both Q3Y0 and Q3Y1 profiles. With this increase in dune elevation on each side of the dune, an increase in $D_V$ also occurred between 2000 and 2005. Nearly one year of recovery results in an average dune that has grown volumetrically both seaward, developing a berm, and landward. Sediment deposition on the landward side of the dune caused a gentler slope, with the crest of the 2005 dune located landward of the 2000 dune position. Q3Y2 exhibits an overall vertical increase in dune elevation and the development of a stoss slope. Finally, Q3Y5 displays a slightly eroded $D_T$ and accumulation along the backshore section, resulting a wider spatial distribution of sand along the average transect. This distribution shows one dune rather than two features, located at approximately 12 and 40 m cross-shore, seen in the 2000 ensemble average transect. Similar to those average profiles in Quartile 2, the crest positions in 2005 are landward from those in 2000 in all but Q3Y2. These migrations are represented by changes in cross-shore position from approximately 20 to 53 m (Q3Y0), 20 to 15 m (Q3Y1), 25 to 45 m (Q3Y2), and 12 to 20 m (Q3Y5).

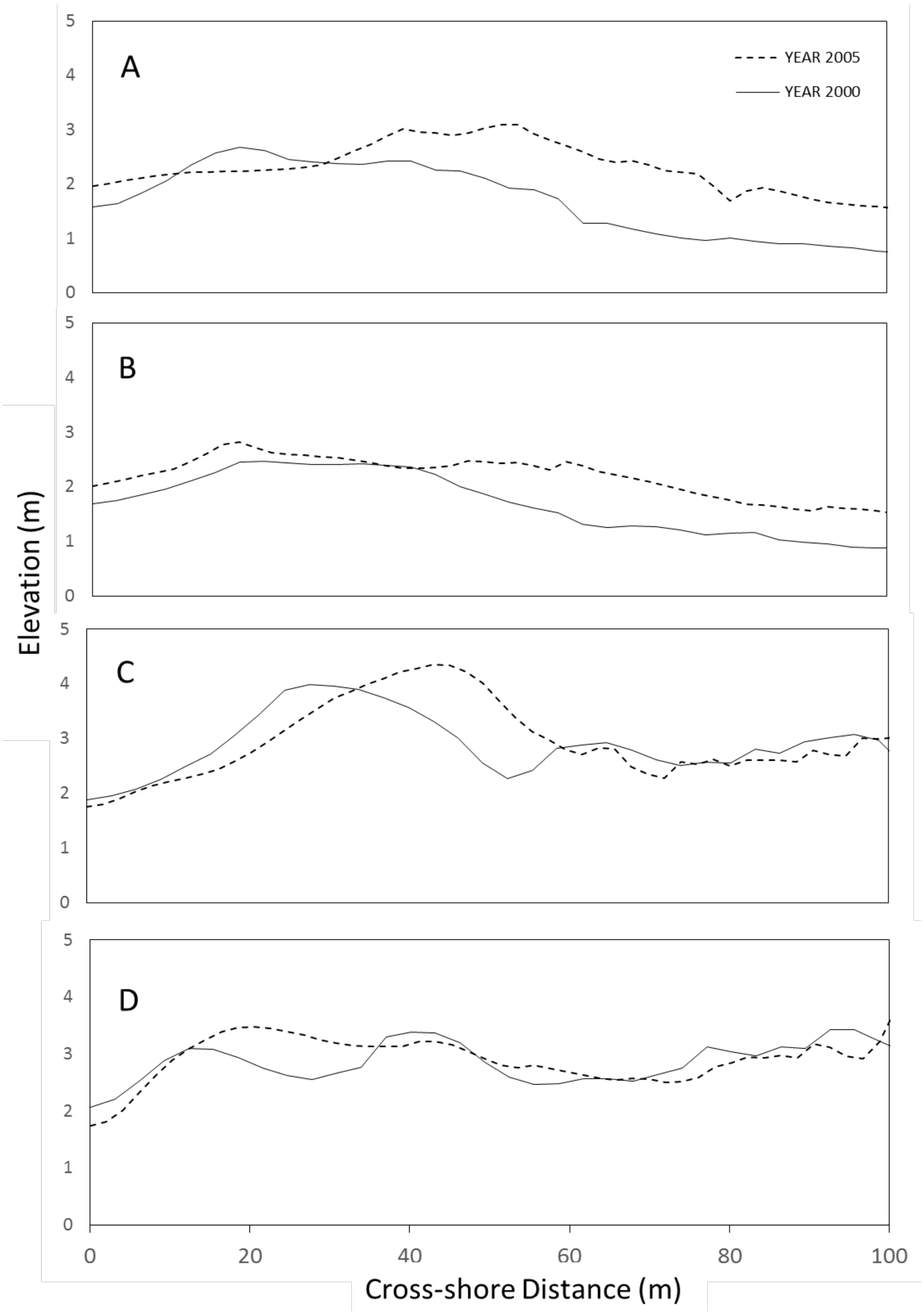


**Figure 20** Quartile 3 recovery for Year 0 (A), 1 (B), 2 (C), and 5 (D). Values along each Y axis represent Elevation (m), and the X axis represents Cross-shore Distance (m).

### Quartile 4

The fourth quartile, or high island transects, represents dunes that have had the greatest change in dune height (Figure 21). Ensemble averages of $D_C$ in this quartile reach more than 4 m in elevation, with changes in $D_H$ of more than 2 m. When compared with the average of transects in 2000, Q4Y0 demonstrates the development of a berm on the seaward side of the dune. Q4Y1 shows similar accretion landward of the 2000 dune, and small vertical growth. This average transect also shows some erosion on the seaward side of the dune, with $D_T$ at a nearly identical elevation in each year. Nearly 2 years of recovery show a landward migration of the dune as landward growth and a well-developed stoss slope. The average of transects with the greatest period of recovery, Q4Y5, shows a slightly decreased $D_T$ and a large volumetric increase, particularly between 15 and 30 m cross-shore. This growth is seen landward of the seaward-most feature in the 2000 dataset. Recovery patterns in this quartile are similar to those seen in others, with greater volumetric increase seen in transects with long-term recovery periods. In respect to the cross-shore location movement in $D_C$, between 2000 and 2005 positions have shifted from 31 to 17 m (Q4Y0), 40 to 55 m (Q4Y1), 25 to 38 m (Q4Y2), and 10 to 20 m (Q4Y5).

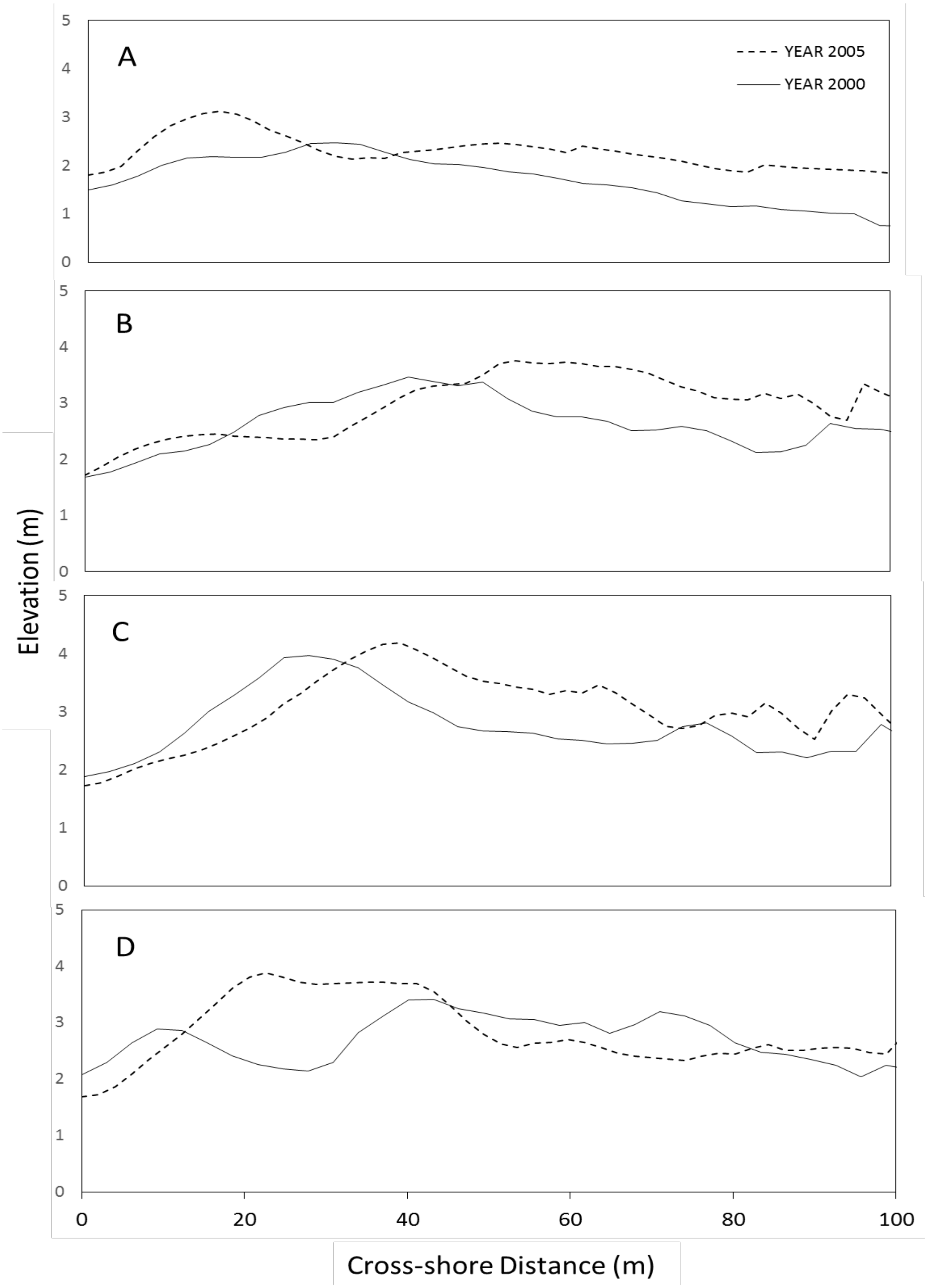


**Figure 21** Quartile 4 recovery for Year 0 (A), 1 (B), 2 (C), and 5 (D). Values along each Y axis represent Elevation (m), and the X axis represents Cross-shore Distance (m).

### *Alongshore Variability*

In addition to examining transects based on $D_H$ quartiles, spatial variability was also considered. Specifically, high and low island areas (Quartiles 1 and 4) were mapped to gain a better understanding of the types of processes that might be affecting these different sections of Assateague Island. Groups were characterized by identifying areas within Quartiles 1 and 4 with 10 to 30 consecutive points where less than one-third of the points outside of the quartile under consideration are present. High and low islands were found to be grouped and alternating alongshore as seen in Figure 22. This map shows the change in dune height and the corresponding locations along Assateague Island National Seashore of each identified cluster. Transects in groups A, C, and E (low island areas) demonstrate a smaller change in dune height of -1.0 to -0.5 m, while transects in groups B and D (high island areas) exhibit a larger change between 1 and 3 m in dune height. Groups A and B are spatially dense (approximately 30 transects in each group over 1 km) towards the northern end of the island, while group C consists of 17 transects that span nearly 10 km across the middle of the study section. Groups D and E, located at the southern end of the island, are more sparsely distributed than A and B, but are considerably more condensed than group C, at alongshore areas of approximately 1.5 and 2.0 m respectively.

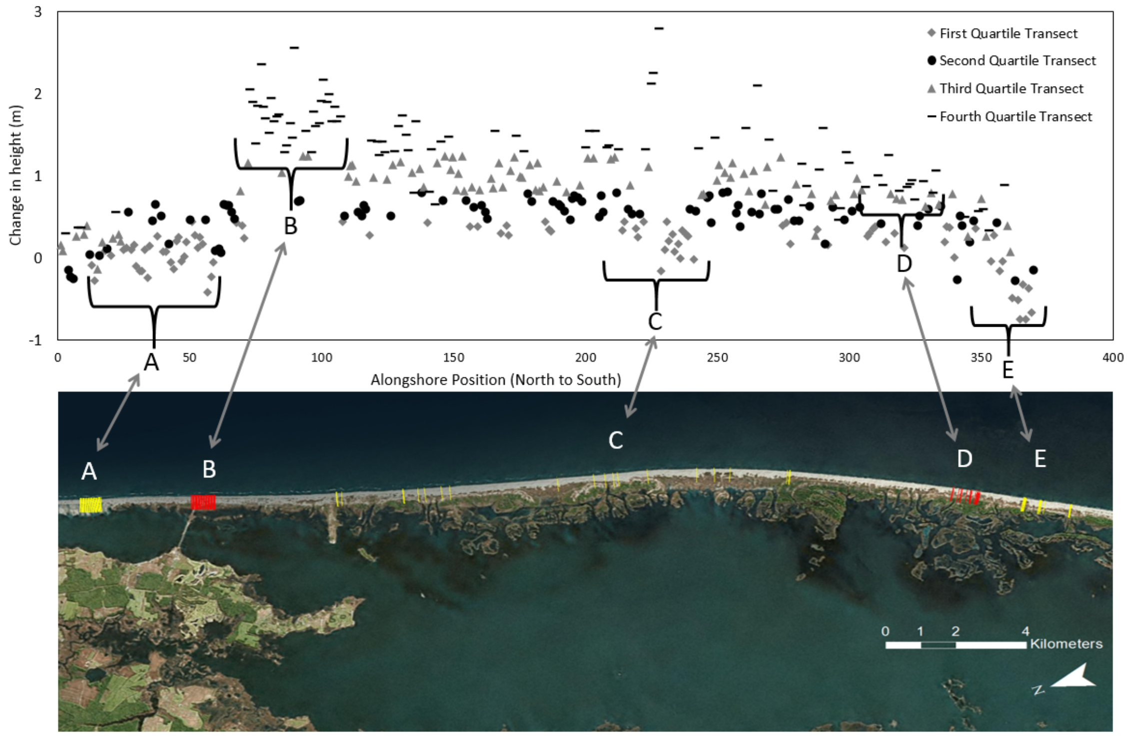


**Figure 22** High and low island areas along ASIS. This graphic shows the location alongshore of first and fourth quartile groups as it relates to change in dune height.

# CHAPTER IV

# DISCUSSION

Coastal resilience is defined as "*a measure of the [coastal] system's capacity to respond to the consequences of perturbation*" (Klein *et al.* 1994). Barrier island recovery from disturbances such as elevated storm surge is a key indicator of the island's resiliency, and thus its ability to adjust to changes in sea-level through moderated transgression, as well as protect the mainland and provide a habitable environment to flora and fauna (NPS 2002; Leatherman 1979b; Durán and Moore 2013; Guo 2014). Moreover, these changes alter what has been identified as the natural state of the nearshore morphology. Foredunes are particularly important in the discussion about barrier island resiliency because they control the rate of island transgression and are the first line of defense to beach and nearshore disturbances, both anthropogenic and natural. Controlled transgression is characteristic of areas with high dunes, while rapid transgression through washover and breaching occurs in areas of low dunes. High and low island areas alongshore have shown iterative patterns on Santa Rosa Island, FL, in which processes impacting the morphology of the landscape promote a consistent spatial variability between spaces with high and low dunes (Morton 2002; Houser *et al.* 2008; Houser and Hamilton 2009). Specifically, Weymer *et al.* (2013) suggests that storm impact varies because of the pre-existing morphology and that beach-dune recovery "*may represent a reinforced process*" where high island areas remain large and low island areas remain small over time. Therefore, the inability for a dune to recover may force it from a high to a low dune.

Previous studies have shown that the recovery of a barrier island to its pre-storm state is sigmoidal, showing peak growth rates around 3 or 4 years, during the backbeach and dune restoration phase (Houser *et al.* 2015). The primary hypothesis of this study is that the rate of recovery of each examined parameter at ASIS will exhibit a sigmoidal pattern as seen in Houser *et al.* (2015), and that recovery rates will vary alongshore due to high and low island areas. Whereas previous studies have examined changing dune height, this present study is an assessment of a wider range of morphometric parameters. Furthermore, in comparison to Houser et al (2015), most recovery values in this study did not begin at a 0 value because elevation data from 2000 was not collected immediately following a hurricane with a large storm surge as observed in Florida (Houser *et al.* 2015). This factor increased the complexity of the research design and interpretation of results, because a sequence of changes for individual dune profiles is not available and each transect on ASIS was disturbed as apparent in the recovery.

Results of this thesis suggest that not all parameters demonstrate the same recovery rates or patterns, and that variability of recovery alongshore exists. Recovery rates at Assateague Island were evaluated by four dune parameters: dune crest ($D_C$), dune height ($D_H$), dune volume ($D_V$), and dune toe ($D_T$). Parameters were obtained through the manual extraction of dunes from 1,456 cross shore transects and elevation data from the years 2000 and 2005. Results suggest that a variety of processes are responsible for the redistribution of sediment leading to incipient dune growth and backshore and berm development. There is also evidence of high and low island recovery variability alongshore, contributing to the idea that large dunes exhibit a faster rate of recovery than smaller dunes; raw values of this change show a recovery period of approximately 0.4 m change over 2 years for small dunes in Q2, whereas large dunes (high island transects) show a 4-year recovery period to grow more than 1 m. This is supported by the variation in r-values for $D_C$, where low island areas had a recovery rate of 0.65 and high island areas had a recovery rate of 0.8.

The change in $D_C$ is consistent with the pattern and magnitude of points identified by Houser *et al.* (2015). Values captured by the Santa Rosa study primarily align with the third and fourth quartile logistic curves from this thesis. Specifically, the average Santa Rosa value for zero years of recovery falls along both the third and fourth quartile curves for ASIS, one year of Santa Rosa recovery falls along the fourth quartile ASIS curve, two years of recovery at Santa Rosa intersects with the second quartile ASIS curve, and finally, the average value of five years of recovery at Santa Rosa falls at 1.3 m, intersecting the fourth quartile ASIS dataset (see Figure 23). In both studies the peak rate of recovery (r) occurs between 3 and 4 years after a storm event. This suggests that Assateague Island National Seashore dunes recover at approximately the same rate as Santa Rosa Island, FL. Initial recovery is limited due to a lack of sediment available for dispersal, after a storm event erodes material away from foredunes, the beach, and the bar. Recovery of the foredune primarily relies on availability of sediment for the beach and backshore, as well as the ability for vegetation along the backshore to be renourished (Leatherman 1979a; Houser and Hamilton 2009). Dune recovery on

Assateague between 2000 and 2005 may be a result of "*the landward migration of the nearshore bars and recovery of the profile volume*" (Houser *et al.* 2015). According to Houser *et al.* (2008), high island areas experience a faster rate of sediment return to the beachface as a results of landward migration of the nearshore bars. However, without ASIS bathymetric data, it is unknown what nearshore mechanisms influence the recovery on this barrier island. Houser *et al.* (2015) identified more rapid recovery (approximately 2 years) for small dunes in comparison to large dunes (approximately 6 years); initial results from this thesis exhibit a small dune recovery around 2 years and a large dune recovery of about 5 years.

Because the current dataset does not provide pre-storm elevation values to determine the presence of a relationship between dune height and recovery period at ASIS, values describing the initial condition must be obtained. De Stoppelaire *et al.* (2004) presented dune elevations between 1997 and 2000 at Assateague Island, ranging from 1.55 m to 3.36 m above mean sea level. Specifically, elevations were collected from several unfenced plots in locations representative of this study's high island dunes. These elevations in 2000 were 1.57 m, 2.74 m, 2.83 m, 1.84 m, and 1.55 m from north to south at Plots 1 to 5 respectively (De Stoppelaire *et al.* 2004). This suggests that the fourth quartile values may not represent the maximum height of the foredunes, and that the period of recovery may extend past 5 years at some areas. Figure 24 demonstrates a modified logistic curve, using average point values from Quartile 4 and assuming a maximum dune elevation of 2.1 m, averaged from the values provided by De Stoppelaire *et al.* (2004). While a range of hurricanes impacted Maryland between 1990 and 2000, Hurricane Bob was the most impactful in August of 1991, with storm surges of approximately 3.7 m (Beyers and Jordan 1991). As a result, elevation data from 2000 is assumed to be a 9-year recovery. This modified curve has an r value of 0.28, and is very similar to the curve observed by Houser *et al.* (2015), from Pensacola, FL. Figure 25 demonstrates this curve in comparison to several other studies from Texas and Florida (Morton *et al.* 1994; Priestas and Fagherazzi 2010; Houser *et al.* 2015).

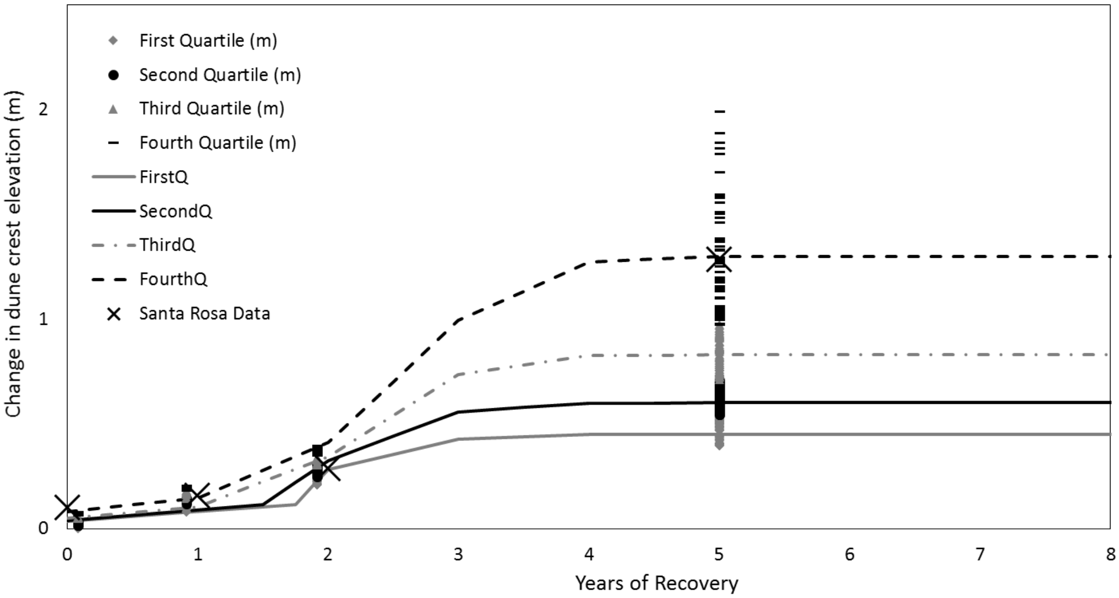


**Figure 23** Logistic curves with Houser *et al.* (2015) data from Santa Rosa Island, Fl. The recovery rate (r) for Quartile 4 is 0.8.

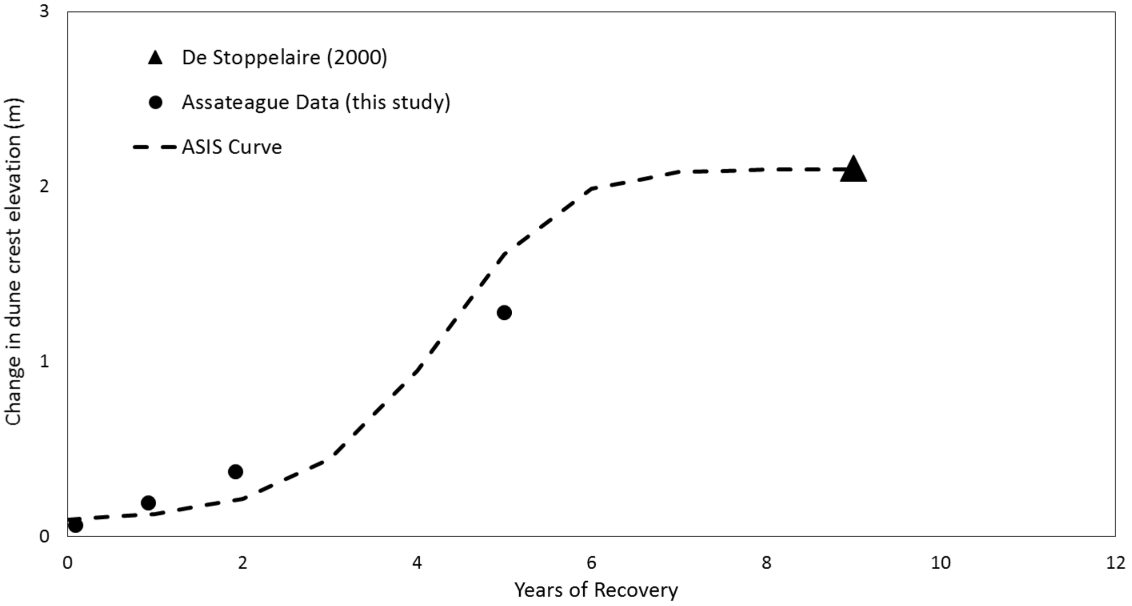


**Figure 24** Logistic curve showing average Quartile 4 recovery values at ASIS, assuming a maximum $D_C$ value of 2.11 m (averaged from De Stoppelaire *et al.* 2004) and r = 0.26.

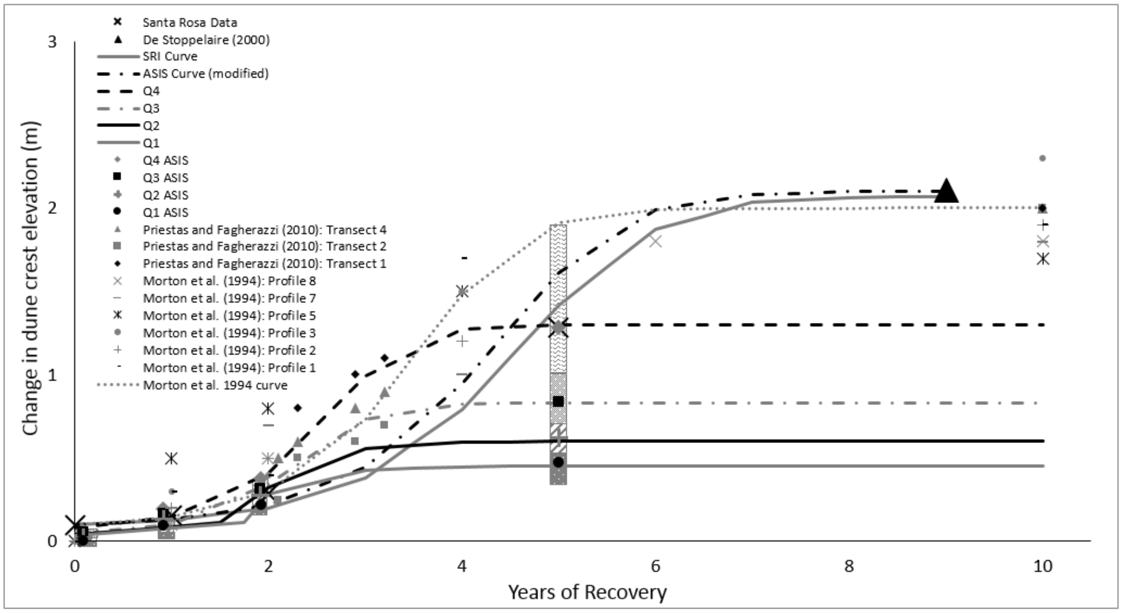


**Figure 25** Combination of data points from this study (ASIS), Houser *et al.* (2015), Priestas and Fagherazzi (2010), and Morton *et al.* (1994).

Dune volume did not demonstrate a sigmoidal response as hypothesized and observed for the dune height. Rather, the distribution across years of recovery and quartiles was a lower magnitude logistic curve that was nearly linear. This suggests that the development of dune width proceeds at a different growth rate than $D_C$ and $D_H$. Assateague's volume curve (see Figure 15 in Chapter III) is similar to that seen at Santa Rosa, where a relationship between vegetation growth and $D_V$ is identified (Houser *et al.* 2015). However, the volume curve developed in this thesis represents a change of volume while Houser *et al.* (2015) offers a curve demonstrating total volume. More specifically, results from Houser *et al.* (2015) show that as vegetation reaches its maximum, the volume growth slows, suggesting that vegetation revitalization relies on sediment deposition. This buildup of vegetation contributes to growth in $D_H$, which shows logistic growth. The inverted sigmoidal curve representing $D_T$ also contributes to the growth in $D_H$, such that as $D_T$ decreases, $D_H$ increases.

Results show a redistribution of sediment that leads to incipient dune growth and backshore and berm development, caused by a variety of processes. Assateague is susceptible to "*sediment-charged surges*" and overwash deposition during storm events (Leatherman 1976). In a 1974 field study of ASIS, overwash and storm surge were found to be the most significant factors in data transport during a storm and in some instances the washover values matched the amount of eroded sediment from the berm (Leatherman 1976). Additionally, it is argued that the backshore and dunes supply the material for washover, contributing to the landward migration of foredune elevation profiles (Leatherman 1976). This pattern is visible in the 11-month recovery period in quartiles 1, 2, and 3, as seen in Chapter III. Additionally, as described by Morton *et al.* (1994), the initial recovery stage is forebeach accretion, and is apparent in Y0 profiles, less than 1 month after Hurricane Dennis where each quartile, except Quartile 3, shows seaward deposition. Quartile 3 instead shows landward migration, possible as a result of washover. Following this stage, the backbeach and dune are restored primarily as a result of aeolian forces and the development of vegetation. Finally, dune expansion and vegetation recolonization exhibits taller dunes with greater extents and more surrounding vegetation; in this study, this stage is indicative of 5-year dunes (Morton *et al.* 1994). Results also show high and low island recovery variability alongshore, including measurements of dunes with a large $D_H$ exhibiting a slower rate of recovery than dunes with a smaller height. This pattern is characteristic of form reinforcement through process (Houser *et al.* 2008; Weymer *et al.* 2013; Houser *et al.* 2015). Growth rates also varied between parameters and between quartiles.

## *Profile Recovery*

### **Forebeach Accretion**

Recovery patterns were identified using ensemble averaging, supporting an understanding of the processes behind the quantitative changes discussed above. With the exception of the average profile in the third quartile, one month of recovery (Y0) across transects exhibited sediment deposition seaward of the dune from a storm event. Specifically, this accretion was likely a result of the storm surge associated with Hurricane Dennis of 1.6 m, which impacted Assateague Island just over a month prior to the collection of the 2005 LiDAR dataset. This suggests the deposition of material through storm events with little time for redistribution before the 2005 elevation data was captured. Similar post-storm profiles have been characterized by seaward accretion, documented in previous studies at Galveston Island, TX and Santa Rosa and St. George Islands, FL (Morton *et al.* 1994; Houser and Hamilton 2009; Priestas and Fagherazzi 2010). The changes between 2000 and 2005 profiles reflect the presence of sand deposits on the landward side of the dune for the same reason of limited time for sediment transport. For example, in Q4Y0 (see Figure 21, panel a), the backshore portion of the dune profile was developed due to this accumulation of sand. This backshore accretion also suggests overwash, transporting sediment over the dune, pushing material landward. Meanwhile, for the same recovery period, Quartile 3 (see Figure 20) demonstrates evidence of seaward erosion of the dune and landward transport of material where some points have increased in elevation by more than 1 m, also suggesting washover.

### Backbeach and Dune Restoration (Y1)

Approximately one year (Y1) following a hurricane, transects in each quartile showed landward migration of the dune suggesting that aeolian influences impacted the sediment originally deposited seaward of the dune towards the backshore (Morton *et al.* 1994). In addition to the transportation of material, there is also volumetric growth of the profiles. This is as a result of the elevation increasing on both the seaward and landward side of the 2000 dune. Quantitative and spatial changes observed in profiles of 11 and 23 months of recovery in Quartile 2 (Q2Y1 and Q2Y2) suggest an increase in the presence of vegetation along the backshore at each set of transects, similar to what is exhibited in Q1Y1 and Q1Y2 average profiles. It can be argued that dunes in this area may not have been severely impacted by the Hurricane Dennis storm surge, because overwash and scarping will limit the ability of the establishment of vegetative cover (Leatherman 1979a). Less than one year of recovery showed an increase in $D_T$ elevation by approximately 0.3 m in Quartiles 1, 2, and 3. $D_T$ in Quartile 4 did not change, but shows the development of a berm. This increase in dune height (decrease in $D_T$ and growth of $D_C$) may be a result of overwash or scarping and the redistribution of sediment along the seaward portion of the dune over time (Houser 2013).

### Backbeach and Dune Restoration (Y2)

Nearly two years of recovery is associated with the development of smooth and gentle stoss slopes that have migrated landward signifying the recovery of vegetation on the dune and backshore (Morton *et al.* 1994). Dune migration seen in each quartile from approximately 30 to 40 m cross-shore (see panel B in Figures 18, 19, 20, and 21 in Chapter III) suggests a revitalization of the vegetative population on the dune and backshore area, similar to that seen after nearly one year of recovery. This vegetation acts as a blockade and slows wind enough to deposit any sediment being transported, contributing to the accumulation of sediment and the growth of dune extent and volume. An increased accumulation of sediment caused by the presence of vegetation, also observed in “Year 1”, is consistent with previous coastal dune studies at other locations in Texas and Florida (Morton *et al.* 1994; Morton 2002; Houser and Hamilton 2009;

Priestas and Fagherazzi 2010; Houser *et al.* 2015) . Dune toe elevation decreased in Quartiles 2, 3, and 4 by approximately 0.1 m; Quartile 1 $D_T$ increased by approximately 0.1 m. These slight changes suggest further redistribution of sediment to the dune and backshore areas of the profile.

## Dune Expansion and Vegetation Recolonization (Y5)

Transects experiencing the longest recovery period of 5 years demonstrate well-developed dunes that exhibit growth in extent, height, and volume. It can also be assumed that dunes observed by De Stoppelaire *et al.* (2004) exhibited similar characteristics. Despite an absence of vertical growth in Q1Y5, the landward expansion of the average dune profile suggests the presence of vegetation, resulting in considerable development over the course of 5 years (Morton *et al.* 1994). This recovery period in Quartile 4 also shows a sizeable change of approximately 1 m in $D_C$ between the years 2000 and 2005. Because these dunes have experienced limited overwash events, it is likely that aeolian influence is the primary force in the development of "5-year" dunes. Furthermore, the nearshore morphology of one or more bars may also strongly affect the build-up of sediment on the beach, and, as a result, on the foredune (Houser *et al.* 2015). Although these dunes demonstrate patterns of substantial recovery, it is unknown whether additional recovery time would result in further growth of $D_H$ and $D_V$, or whether a 5-year recovery period is the time needed for the island to return to its pre-storm equilibrium state.

The recovery seen at ASIS can be described using the model presented by Morton *et al.* (1994), and is consistent with the current understanding of high and low islands (Houser *et al.* 2008; Houser *et al.* 2015). As evidenced by the results of this study and by conclusions within the current literature, high dunes recover at a slower rate than low dunes and maintain that variability over time. The cause of this variation is based on presence of vegetation, nearshore bathymetry and sediment availability, pre-existing morphology (equilibrium state of the dunes), and storm surge heights (Morton *et al.* 1994; De Stoppelaire *et al.* 2004; Houser *et al.* 2008; Houser and Hamilton 2009; Durán and Moore 2013; Houser *et al.* 2015). Many of these factors are dependent upon the others; for example, the presence of vegetation is controlled by the frequency and magnitude of overwash events, which is linked to the pre-existing morphology. Because overwash is a fundamental process at ASIS, the reiteration of high and low island areas is especially apparent (Leatherman 1976; Leatherman 1979a). Small island areas are continuously susceptible to breaching and overwash; as a consequence, elevation stays small. However, high island areas are at risk of erosion and a reduction in elevation; a reduction in elevation can increase the vulnerability and decrease the resiliency of large dunes. As suggested in Houser *et al.* (2015), if the frequency and magnitude of storm increase, thereby reducing the amount of time for dunes to recover, a barrier island has the potential to become a low island, representing a new state of equilibrium. At Assateague, this state might be characterized by washover channels or a reduction of dune size from approximately 2.0 m to 1.0 m or less. If tourism continued in its current capacity, Assateague would became a low island as a result of the impact of driving on the beach. This activity causes loosening sediment and destruction of vegetation, and would in turn promote erosion and eventually island inundation during a storm (Houser *et al.* 2013). Additionally, the current rate of transgression caused by the Ocean City jetty would greatly increase due to increased washover and the transport of sediment from the north end of the island to the south end. A transition of ASIS from a high island to low island state would result in significant implications have as it relates to resiliency and storm impact on the mainland.

### *Alongshore Variability*

Previous studies have argued that dunes aligned with transverse ridges are supply limited, while those aligned with swales are transport limited; however, washover potential and storm frequency may be as important as the nearshore morphology because of the loss of sediment in the backbeach, limiting supply (Houser and Hamilton 2009; Houser *et al.* 2015). Results from a recent study at Santa Rosa Island, FL indicate that areas with small dunes demonstrate slow recovery as a result of moisture from overwash and a lag in sediment availability, as opposed to locations with well-developed dunes where sediment is transported to the shoreface during a storm. Thus, subsequent storm surges will impact these low island areas and may reinforce alongshore variability in dune type and recovery (Morton 2002; Houser *et al.* 2008). Similarly, a correlation between beach type and foredune size has been observed, where small dunes are found on steep, reflective beaches, and foredunes nearly 10 times the height of those found on reflective beaches are located on dissipative beaches; variation in beach type is another characterizing factor of alongshore variability in high and low islands and the recovery of those locations (Durán and Moore 2013).

In this study, large $D_H$ values occur in transects with a large $D_C$; quartiles used in the ensemble averages were broken up by magnitude of change in $D_H$. High island (Quartile 4) areas and low island (Quartile 1) areas varied in groups alongshore, with three low island areas and two high island groups, as seen in Figure 22 in Chapter III. First quartile values showed a change in dune height of approximately 0.5 m or less, and fourth quartile values under consideration changed 1 m or more. This suggests that the 1.6 m storm surge from Hurricane Dennis impacted low island dunes by either eroding the dune crest or depositing sediment around the dune toe. Ensemble averages (see Figure 17) show increased $D_T$ values for the first quartile, contributing to the negative, or small positive, $D_H$ values between 2000 and 2005. Conversely, Quartile 4 values represent large increases in $D_H$. Also as a result of the storm surge associated with Hurricane Dennis at ASIS, these larger dunes experienced erosion of the dune toe, seen in ensemble averages C and D in Figure 21. Previous studies suggest that the alongshore variability present on Assateague Island will be reinforced over time, especially if hurricanes increase in frequency and magnitude (Goldenberg *et al.* 2001; Houser *et al.* 2008; Houser and Hamilton 2009; Priestas and Fagherazzi 2010; Houser *et al.* 2015). Figure 22 exhibits several areas where high dunes are adjacent to low dunes. This may be a result of lateral erosion where overwash decreases dune height within a space over time. Low island areas that have been breached may continue to expand alongshore because of this erosive process, affecting high island areas and potentially resulting in the entire island to become low.

### *Implications and Future Work*

Results from this study can be used to produce predictive models for other barrier islands along the Atlantic coast, especially as climate change discussion continues to be at the forefront of the scientific community. While it is disputed whether or not hurricane magnitude and frequency will rise in the coming years, recent studies have modeled an increase in the frequency and magnitude of storms by the end of the 21st century (Goldenberg *et al.* 2001; Pielke *et al.* 2005; Knutson *et al.* 2008; Bender *et al.* 2010). As a result, mitigation and preparatory strategies should be considered; evaluating the response and recovery of barrier islands is a critical aspect when considering how this change will affect coastlines in the United States and elsewhere (Goldenberg *et al.* 2001; Pielke *et al.* 2005). Other disturbances, such as driving on the beach and the presence of wild horses on the landscape, also present an opportunity for dune recovery studies such as this (De Stoppelaire *et al.* 2004; Houser *et al.* 2013).

This study creates the opportunity for further research to be conducted both at Assateague Island National Seashore and elsewhere regarding barrier island recovery following hurricanes. As a result of limited elevation data available publicly and the effect of storm surges over time at ASIS, this thesis only examines recovery of up to 5 years. In order to fully understand the recovery rate of this island in comparison to what has been identified at Santa Rosa Island, FL, a study should be conducted with 10 years or more of elevation data. Other variables should also be considered, including dune width and fetch length. Additionally, raw LiDAR data would benefit future work on this topic, in order to apply algorithms for effectively and practically extracting morphometric parameters. Furthermore, bathymetric data should be obtained and compared to features onshore to enhance the information surrounding the mechanisms that contribute to the recovery rate of the island. Specifically, the integration of onshore and nearshore elevation data would produce new knowledge regarding high and low islands, as well as spatial and temporal variation in reaction and relaxation. Such a study would enhance the understanding of reinforced patterns, and would be valuable in predicting future storm impact both at Assateague and along the Atlantic coast.

This thesis is only the second study to develop a recovery curve, providing a basis for further morphometric research as it relates to barrier island recovery. An understanding of the one-dimensional morphometry on this landscape is required before a two-dimensional tactic is introduced. For example, additional parameters may be considered in respect to both the longshore and cross shore, and onto the beach. Furthermore, the results from this study support previous literature and suggest that foredune morphometry is a fundamental representative of island growth. Using this thesis and previous research as a basis to understanding post-storm barrier island recovery, a more sophisticated multi-dimensional approach could be utilized in the future to incorporate additional surficial and subsurface data. A more composite analysis may produce information, not only about spatial recovery patterns, but also about the mechanisms behind this recovery. This analysis may be especially relevant when evaluating recovery at different barrier islands. When comparing the results of this study to those from Houser *et al.* (2015) and Morton *et al.* (1994), some variation can be seen where Santa Rosa Island recovered slower than Assateague Island, which recovered slower than Galveston Island. One hypothesis for these differences in recovery rate is beach type. Specifically, because Galveston is a dissipative beach, the recovery curve suggests a rapid recovery of a wide beach with a gentle slope, providing sediment nourishment to the dune system. Santa Rosa Island and Assateague Island are both characterized by intermediate beaches, demonstrating alongshore variability in recovery and a variety of wave heights and energies (Short and Hesp 1982). A study evaluating a reflective beach would likely show a different recovery curve based on the morphology of the beach, dunes, and nearshore features. This additional context could provide an understanding about how other barrier islands recover from storm impacts throughout the Atlantic region of the U.S. and the Gulf of Mexico.

# CHAPTER V

# CONCLUSION

As barrier islands transgress with sea level rise through storm impacts, there is a need for sediment and vegetation to recolonize so that dunes can recover in height and extent (see Figure 7). This thesis examines storm impact and recovery, and the information can be used to aid land managers and coastal engineers in making decisions. The primary conclusions of this thesis are:

- Dune recovery on Assateague Island National Seashore follows the model described by Morton *et al.* (1994), where forebeach accretion occurs post-storm, followed by backbeach and dune restoration, and concludes with dune expansion and vegetation recolonization.
- Quartile 4, representative of high dunes, demonstrate average recovery rates at ASIS comparable to those observed at Santa Rosa Island, FL by Houser *et al.* (2015). With an estimated pre-storm dune elevation of approximately 2.1 m, a sigmoidal curve with an r-value of 0.26 is representative of foredune growth at Assateague, as shown in Figure 25.
- Sigmoidal patterns between 1 month and 5 years of recovery characterized $D_C$ and $D_H$, and an inverted sigmoidal curve characterized $D_T$. Change in $D_V$ was represented by very small r-values, showing a logistic curve very different from those observed for the other parameters.

- High and low island areas were identified and exhibited recovery characteristics representative of alongshore variability seen in previous studies (Houser *et al.* 2008; Houser and Hamilton 2009; Durán and Moore 2013; Weymer *et al.* 2013; Houser *et al.* 2015). Specifically, high island portions of ASIS experienced a longer recovery period, while low island areas had a greater potential for overwash and recovered quickly.

# REFERENCES

Anderson, J. 18 May 2013. "Rebuilding the Coastline, but at What Cost?" *The New York Times*. Web. <http://www.nytimes.com/2013/05/19/nyregion/rebuilding-the-coastline-but-at-what-cost.html?pagewanted=all&_r=0>.

Bender, M. A., Knutson, T. R., Tuleya, R. E., Sirutis, J. J., Vecchi, G. A., Garner, S. T., Held, I. M. 2010. Modeled impact of anthropogenic warming on the frequency of intense Atlantic hurricanes. *Science 327*(5964), 454-458.

Beyers, D., Jordan, M. 20 Aug. 1991. "With a wave, Bob passes by; hurricane skirts thankful coast." *Washington Post*. Web. <http://www.highbeam.com/doc/1P2-1080765.html>.

Chust, G., Galparsoro, I., Borja, Á., Franco, J., Uriarte, A., 2008. Coastal and estuarine habitat mapping, using LIDAR height and intensity and multi-spectral imagery. *Estuarine, Coastal and Shelf Science* 78(4), 633-643.

"Coastal Barrier Resources Act." 19 Dec. 2014. *U.S. Fish and Wildlife Service*. Web. <http://legcounsel.house.gov/Comps/Coastal%20Barrier%20Resources%20Act.pdf>.

"Communities: The U.S. Population Living at the Coast." 14 Mar. 2013. NOAA's State of the Coast. *NOAA*. Web. <http://stateofthecoast.noaa.gov/>.

Crichton, S. 10 Dec. 2012. "Officials: Sandy destroys more than 2,000 LI homes". *Newsday*. Retrieved 4 October 2014. Web. <http://www.newsday.com/long-island/officials-sandy-destroys-more-than-2-000-li-homes-1.4316744>.

De Stoppelaire, G. H., Gillespie, T. W., Brock, J. C., and Tobin, G. A. 2004. Use of remote sensing techniques to determine the effects of grazing on vegetation cover and dune elevation at Assateague Island National Seashore: impact of horses. *Environmental Management* 34(5), 642-649.

Dolan, R., Davis, R. E., 1992. An intensity scale for Atlantic coast northeast storms. *Journal of Coastal Research* 8(4), 840-853.

Durán, O., Moore, L. J. 2013. Vegetation controls on the maximum size of coastal dunes. *Proceedings of the National Academy of Sciences* 110(43), 17217-17222.

Emanuel, K., 2005. Increasing destructiveness of tropical cyclones over the past 30 years. *Nature* 436(7051), 686-688.

Evans, M. W., Hine, A. C., Belknap, D. F., Davis Jr., R. A., 1985. Bedrock controls on barrier island development: west-central Maryland coast. *Marine Geology* 63(1), 263-283.

Fisher, J. S., Leatherman, S. P., Perry, F. C. 1974. Overwash processes on Assateague Island. *Coastal Engineering Proceedings* 1(14).

Goldenberg, S. B., Landsea, C., Mestas-Nuñez, A., Gray, W. 2001. The Recent Increase in Atlantic Hurricane Activity: Causes and Implications. *Science* July 2001, 474-479.

Guo, J. 2 Dec. 2014"The Old Man and the Rising Sea." *Washington Post*. Web. <http://www.washingtonpost.com/news/storyline/wp/2014/12/02/the-old-man-and-the-rising-sea-2/>.

Hesp, P., 2002. Foredunes and blowouts: initiation, geomorphology and dynamics. *Geomorphology* 48(1-3), 245-268.

Houser, C., 2013. Alongshore variation in the morphology of coastal dunes: Implications for storm response. *Geomorphology* 199, 48-61.

Houser, C., Hamilton, S., 2009. Sensitivity of post-hurricane beach and dune recovery to event frequency. *Earth Surface Processes and Landforms* 34(5), 613-628.

Houser, C., Hapke, C., Hamilton, S., 2008. Controls on coastal dune morphology, shoreline erosion and barrier island response to extreme storms. *Geomorphology* 100(3), 223-240.

Houser, C., Labude, B., Haider, L., Weymer, B., 2013. Impacts of driving on the beach: Case studies from Assateague Island and Padre Island National Seashores. *Ocean and Coastal Management* 71, 33-45.

Houser, C., Wernette, P., Rentschlar, E., Jones, H., Hammond, B., Trimble, S., 2015. Post-storm beach and dune recovery: implications for barrier island resilience. *Geomorphology* 234, 54-63.

Hugenholtz, C.,Wolfe, S., 2005. Biogeomorphic model of dunefield activation and stabilization on the northern Great Plains. *Geomorphology* 70, 53-70.

Kana, T. W., 1995. A mesoscale sediment budget for Long Island, New York. *Marine* Geology 126, 87-110.

Keim, B. D., Muller, R. A., Stone, G. W., 2007. Spatiotemporal patterns and return periods of tropical storm and hurricane strikes from Texas to Maine. *Journal of Climate* 20(14), 3498-3509.

Klein, R. J., Smit, M. J., Goosen, H., and Hulsbergen, C. H. 1998. Resilience and vulnerability: coastal dynamics or Dutch dikes? *Geographical Journal* 259-268.

Knutson, T. R., Sirutis, J. J., Garner, S. T., Vecchi, G. A., and Held, I. M. 2008. Simulated reduction in Atlantic hurricane frequency under twenty-first-century warming conditions. *Nature Geoscience* 1(6), 359-364.

Leatherman, S. P. 1976. Barrier island dynamics: overwash processes and solian transport. *Coastal Engineering Proceedings* 1(15).

Leatherman, S. P. 1979a. Migration of Assateague Island, Maryland, by inlet and overwash processes. *Geology* 7(2), 104-107.

Leatherman, S. P. 1979b. Barrier dune systems: a reassessment. *Sedimentary Geology* 24(1), 1-16.

Lentz, E. E., Hapke, C. J., 2011. Geologic framework influences on the geomorphology of an anthropogenically modified barrier island: Assessment of dune/beach changes at Fire Island, New York. *Geomorphology* 126(1), 82-96.

Mackintosh, B. 1982. Assateague Island National Seashore: An Administrative History. Department of the Interior: Washington, D.C. 165p

Morton, R. A., Paine, J. G., Gibeaut, J. C., 1994. Stages and durations of post-storm beach recovery, southeastern Texas coast, USA. *Journal of Coastal Research* 884-908.

Morton, R. A. 2002. Factors controlling storm impacts on coastal barriers and beaches: a preliminary basis for near real-time forecasting. *Journal of Coastal Research* 486-501.

Nature & Science. 2014. NPS. Retrieved December 3, 2014, from nps.gov/asis.

NPS. 2002. Assateague Island National Seashore Long Range Interpretive Plan. Web. <http://www.nps.gov/asis/learn/management/upload/lripscreen.pdf>

Pendleton, E. A., Williams, S. J., Thieler, E. R. 2004. Coastal vulnerability assessment of Assateague Island National Seashore (ASIS) to sea-level rise. *U.S. Geological Survey Open-File Report 2004-1020*. <http://pubs.usgs.gov/of/2004/1020/images/pdf/asis.pdf>

Pielke Jr, R. A., Landsea, C., Mayfield, M., Laver, J., Pasch, R. 2005. Hurricanes and global warming. *Bulletin of the American Meteorological Society* 86(11), 1571-1575.

Pielke, R., Jr., Gratz, J., Landsea, C., Collins, D., Saunders, M., Musulin, R., 2008. Normalized Hurricane Damage in the United States: 1900–2005. *Nat. Hazards Rev*. 9(1), 29–42.

Pierce, J. W., 1968. Sediment budget along a barrier island chain. *Sedimentary Geology* 3(1), 5-16.

Plan Your Visit. 2014. NPS. Retrieved December 3, 2014, from nps.gov/asis.

Psuty, N. P., 1992. Spatial variation in coastal foredune development. Coastal dunes: geomorphology, ecology and management for conservation, Rotterdam: Balkema 3-13.

Psuty, N. P., 2004. The coastal foredune: a morphological basis for regional coastal dune development. Coastal Dunes (pp. 11-27). Springer Berlin Heidelberg.

Priestas, A. M., Fagherazzi, S. 2010. Morphological barrier island changes and recovery of dunes after Hurricane Dennis, St. George Island, Florida. *Geomorphology* 114(4), 614-626.

Roelvink, D., Reniers, A., van Dongeren, A. P., van Thiel de Vries, J., McCall, R., Lescinski, J., 2009. Modelling storm impacts on beaches, dunes and barrier islands. *Coastal Engineering* 56(11), 1133-1152.

Roman, C. T., Nordstrom, K. F. 1988. The effect of erosion rate on vegetation patterns of an east coast barrier island*. Estuarine, Coastal and Shelf Science* 26(3), 233-242.

Rosati, J., 2005. Concepts in Sediment Budgets. *Journal of Coastal Research* 21(2), 307-322.

Sallenger, A. H., 2000. Storm impact scale for barrier islands. *Journal of Coastal Research* 16(3), 890-895.

Schwab, W. C., Baldwin, W. E., Denny, J. F., Hapke, C. J., Gayes, P. T., List, J. H., Warner, J. C., 2014. Modification of the Quaternary stratigraphic framework of the inner-continental shelf by Holocene marine transgression: an example offshore of Fire Island, New York. *Marine Geology* 355, 346-360.

Schwartz, R. 20 Nov. 2014. "Hurricanes and Maryland." *Hurricanes and the Middle Atlantic States*. Blue Diamond Books, Web. <http://www.midatlantichurricanes.com/Maryland.html>

Short, A., Hesp, P., 1982. Wave, beach and dune interactions in southeastern Australia. *Marine Geology* 48, 259-284.

Stats Report Viewer. 2015. National Park Service. Retrieved February 15, 2015. Web. <https://irma.nps.gov/Stats/SSRSReports/Park Specific Reports/Annual Park Recreation Visitation (1904 - Last Calendar Year)?Park=ASIS>

Stockdon, H. F., Holman, R. A., Howd, P. A., Sallenger, A. H., 2006. Empirical parameterization of setup, swash, and runup. *Coastal Engineering* 53(7), 573-588.

Stockdon, H. F., Sallenger, A. H., Holman, R. A., Howd, P. A. (2007). A simple model for the spatially-variable coastal response to hurricanes. *Marine Geology*, 238(1), 1-20.

Thieler, E.R., Himmelstoss, E.A., Zichichi, J.L., Ergul, A., 2009. Digital Shoreline Analysis System (DSAS) version 4.0— An ArcGIS extension for calculating shoreline change: U.S. Geological Survey Open-File Report 2008-1278.

Weymer, B. A., Houser, C., Giardino, J. R. 2013. Poststorm evolution of beach-dune morphology: Padre Island National Seashore, Texas. *Journal of Coastal Research* 31(3), 634-644.

WindFinder. 2015. Wind and weather statistics Assateague Island. Retrieved from February 3, 2015. Web. <http://www.windfinder.com/windstatistics/assateague_island>

Woolard, J. W., Colby, J. D., 2002. Spatial characterization, resolution, and volumetric change of coastal dunes using airborne LIDAR: Cape Hatteras, North Carolina. *Geomorphology* 48(1), 269-287.

Wright, L. D., Short, A. D. (1984). Morphodynamic variability of surf zones and beaches: a synthesis. *Marine Geology* 56(1), 93-118.