Beach Form, Change, and Mangrove Interactions Along Galleon Fish Sanctuary, South Coast Jamaica

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BEACH FORM, CHANGE, AND MANGROVE INTERACTIONS ALONG GALLEON FISH SANCTUARY, SOUTH COAST JAMAICA

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Kayla Marie Geier

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ABSTRACT

Shoreline erosion is a problem around the world that is getting worse as sea level rises and populations expand into coastal areas. It is important to identify areas at the greatest risk for shoreline erosion so environmental planners will have the knowledge and time to mitigate potential resource losses. The Galleon Fish Sanctuary in St. Elizabeth Parish is a 6 km stretch of shoreline along the south coast of Jamaica composed of mangrove forests, sand beaches, and coral reefs. This study assesses shoreline form and composition in the sanctuary in order to provide new information about the relationships between beach topography, vegetation, substrate, and changes in the shoreline position. Beaches were surveyed and other geomorphic characteristics were recorded at 28 sites. Erosion rates for Galleon for the years 2012-2016 were determined using historical aerial photograph analysis and averaged +0.23 m/yr, ranging from -3.0 to 2.6 m/yr. It was found that 32% of the shoreline in the sanctuary was stable, 44% of the shoreline was accreting, and 24% of the shoreline was eroding. Since 2003, 36% of the beaches in Malcolm Bay and 53% of the beaches in Hodges Bay have recovered to their 2003 pre-Hurricane Ivan position. Toppled vegetation, coarse substrate, and active scarps were indicators of erosion. Mangroves in the sanctuary are at risk for erosion, which is a concern because they provide protection to the beaches and swamp ecosystems. A classification system was developed to categorize beaches based on erosion risk.

KEYWORDS: Jamaica, beach erosion, GIS, mangroves, shoreline management

This abstract is approved as to form and content

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Robert Pavlowsky, PhD
Chairperson, Advisory Committee
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CHAPTER 1- INTRODUCTION

Shoreline erosion is a problem that threatens coastal environments, economies, and societies around the world. Human activity and development along the coast can cause and intensify shoreline erosion (Escudero et al., 2014). Natural events such as hurricanes and sea level rise also cause shoreline erosion, and these events are getting worse due to climate change (Leatherman et al., 2000). There are important socioeconomic reasons to protect beaches. In the Caribbean, tourism is one of the largest contributors to the revenue of coastal communities (Gable, 1991; Gable and Aubrey, 1990; Bueno et al., 2008). Coastal regions need to be able to support tourists with the culture and services they expect, including environmental tourism (de Souza Filho et al., 2011, Fonseca et al., 2014). To provide these services, shoreline management must be rooted in effective assessment of beach vulnerability so politicians, planners, and conservationists can use their resources efficiently to protect beaches. However, beach types and geography vary regionally. Therefore, erosion vulnerability assessments must understand the behavior of different beach types in an area because they all respond differently to erosion (Robinson et al., 2012).

Monitoring human and natural rates of shoreline erosion is of interest because they are helpful for planning and managing communities in coastal areas. As of 2011, 40% of the world's population lives within 100 km of the coast, and as of 2014, 10% of the world's population lives 10 m or less above sea level. These numbers will only increase over time (Losada et al., 2011; Silva et al., 2014). Humans cause erosion by building along coastlines and constructing beach protection structures which prevent

natural beach migration (Nordstrom and Jackson, 2013). Building dams and dredging sand also cause shoreline erosion by reducing the sediment supply to beaches.

In general, sand beaches form and change in response to the wave energy in the area and the size and strength of the material on the beach where the waves break (Wright and Short, 1984). Sand transported cross-shore or along the shore forms offshore bars, a foreshore that slopes upwards to the berm, the raised part of a beach formed by the furthest extent of the high tide, and a relatively horizontal backshore behind the berm (Cambers, 1998) (Figure 1). Dunes or cliffs can be found in the backshore. In tropical areas, mangroves may be present on the shore and in coastal wetlands and coral reefs can be found offshore. These features help protect a beach (Ellison and Zouh, 2012; Maragos et al., 1996).

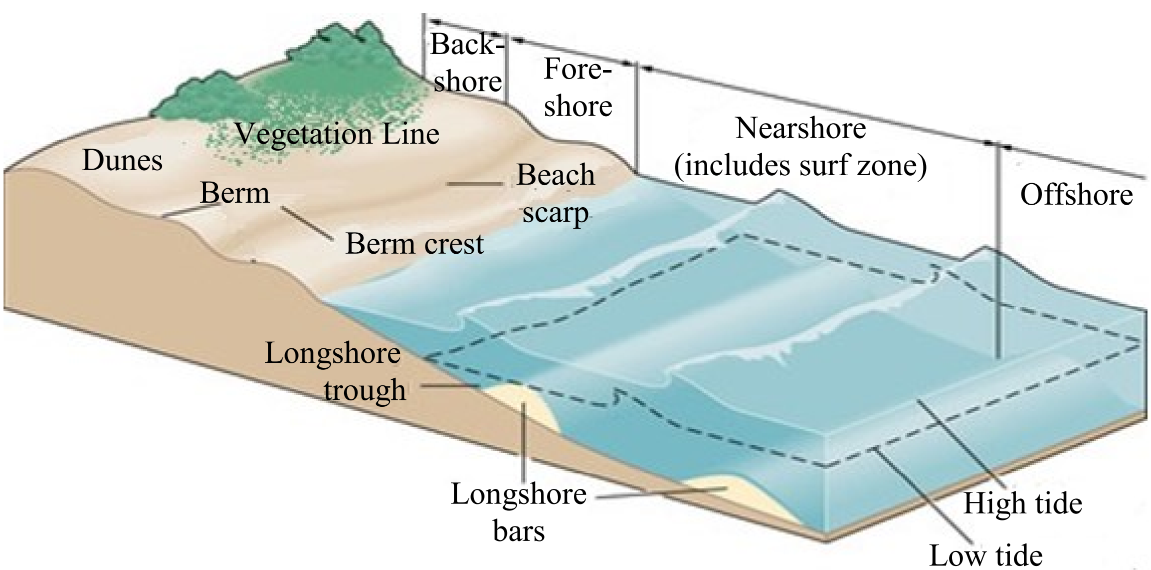

Figure 1: Diagram of a beach profile showing the locations of the backshore, foreshore, and nearshore, as well as beach features such as the berm and beach scarps (Modified from The British Geographer, 2015).

Climate change is creating an even greater need for understanding beaches and how to manage natural erosion, since it contributes to sea level rise and stronger storm systems (Silva et al., 2014). Climate change is causing global sea level to rise rapidly as polar ice caps and glaciers melt (Leatherman et al., 2000). Thermal expansion, which occurs when ocean temperatures increase, causes sea level rise as the same mass of water increases in volume and is responsible for up to half of the sea level rise that has occurred in the past century (Feagin et al., 2005; Leatherman et al., 2000). Since 1970, sea level has risen about 10 cm, and current predictions report that sea level could rise another 0.5 m to 1.6 m globally by 2100 (Robinson et al., 2012). Sea level rise is linked not only to coastal flooding, but to increased erosion as well. Erosion increases because a rise in sea level causes the inundation of low lying areas, allowing wave energy to reach much further inland. Based on this, Leatherman et al. (2000) estimate that for every 10 cm of sea level rise the shoreline will retreat 15 m due to erosion, a 1:150 ratio. This landward migration of coastal environments continues as sea level rises as long as there are no natural or anthropogenic barriers (Linhoss et al., 2015). However, if sea level rises too quickly and beach migration is not able to keep up or there are obstacles to migration, erosion will occur and the coastal area will thin including land available for communities and ecological services (Martins and Pereira, 2014).

Hurricanes and other strong storms can cause intense erosion over a short period of time. Webster et al. (2005) claim that storm intensity and frequency have increased since 1970 and attribute this to climate change. Beaches are greatly modified by storms, causing changes in morphology and grain size (Simeone et al., 2014). Strong storms are associated with waves with greater energy and height, which causes sand to be eroded

from the shore and deposited in offshore bars (Nelson, 1991). Inundation and overwash, which occur when sea water erodes through or overtops the dunes, are also associated with storms (Wang et al., 2006). Wang et al. (2006) investigated the recovery of beaches after a hurricane and found that the foreshore and berm experienced rapid growth within a month after a storm. After 90 days the pre-storm berm height is reached, although the new berm is located further inland. Sand deposited in the offshore bar is gradually redeposited onshore after the storm, driving storm recovery (Nelson, 1991). Wang et al. (2006) confirm that post-storm beach profiles tend to have a gentler slope than pre-storm beach profiles, with steeper angles being restored within a month after a storm as well. Beaches naturally respond to storms, but sea level rise and stronger and more frequent storms will disrupt this natural cycle, causing permanent beach loss (March and Smith, 2012).

Coastal areas act as buffers between the land and sea. They provide protection to the sea from pollution such as agricultural chemical runoff and excessive sedimentation from construction. Coastal areas also protect inland areas from destructive wave energy and coastal flooding. Coastal areas are also important habitats for a variety of wildlife. Sand beaches serve as nesting sites for turtles, mangroves serve as habitats for crocodiles and birds and provide places for fish to lay eggs and young to develop, and coral reefs are homes for many marine creatures (Fish et al., 2005, Ellison and Zouh, 2012; Burke and Maidens, 2006).

In tropical areas, both coral reefs and mangroves help protect shorelines, from erosion. Coral reefs dissipate wave energy before it reaches the shore, which helps reduce erosion (Maragos et al., 1996). This benefit is jeopardized when pollution, sedimentation,

sea level rise, storms, and ocean acidification kill coral reefs (Maragos et al., 1996; Hughes et al., 2010). Mangroves filter nutrients and sediment before they can enter the sea. They also protect the coast by reducing wave energy, anchoring beaches, and reducing storm surge (U.S. Fish and Wildlife Service, 1999; Bell and Lovelock, 2013). In places where mangroves are unsustainably harvested or extensive erosion has occurred, replanting mangroves can help reestablish shoreline protection (Cuc et al., 2015). Therefore, conservation efforts to maintain or restore coral reefs and mangrove forests offer opportunities to protect shorelines.

In Jamaica, which has 895 km of coastline, the need to assess shoreline erosion is especially important (Figure 2). Tourism and fishing are primary sources of income for many coastal towns in Jamaica, both of which are greatly affected by shoreline erosion (Sary et al., 2003; Burke and Maidens, 2006; Oderiz et al., 2014). Beach resorts and ecotourism rely on healthy beaches, coral reefs, and mangroves in order to support the industry (Oderiz et al., 2014, Burke and Maidens 2006). Changes in coastal ecosystems due to beach erosion can lead to a decline in annual fish catches (Sary et al., 2003).

The Galleon Fish Sanctuary is a marine protected area in St. Elizabeth parish that was designated in 2009 (Figure 3). Fish sanctuaries in Jamaica are coastal areas where no fishing is allowed, also known as no-take areas (BREDS- Treasure Beach Foundation, 2016). The Jamaican government established fish sanctuaries to try to reduce the effects of overfishing in Jamaica's coastal waters. The hope is that fish can hatch and grow in the safety of the fish sanctuary and then when they reach maturity they can leave the fish sanctuary, increasing the fish stock outside of the sanctuary where fishing is allowed (BREDS- Treasure Beach Foundation, 2016). The sanctuary must offer good habitats for

Figure 2: Map of the Caribbean. Jamaica is outlined in red (modified from Esri, 2011).

juvenile fish, such as mangroves, coral reefs, and sea grass. In Jamaica, the government approves the sanctuary and offers funding to maintain it, but it is managed by a local community organization or partnership. The Galleon Fish Sanctuary is managed by BREDS- Treasure Beach Foundation, a community group based in Treasure Beach, Jamaica. Fish sanctuaries can help replenish the fish stock in an area, which would be useful for the 2,000 fishermen in the area surrounding Galleon Fish Sanctuary (BREDS-Treasure Beach Foundation, 2016; C-Fish, 2012).

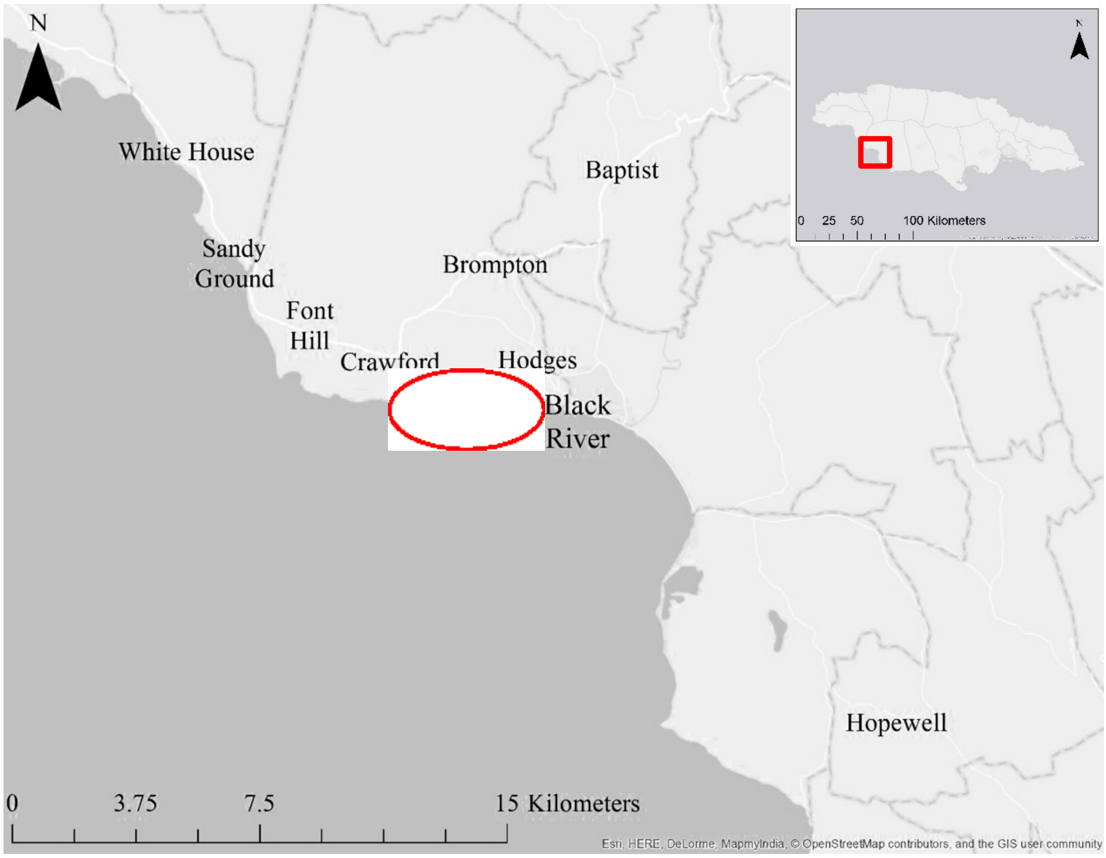

Figure 3: The southwestern part of St. Elizabeth Parish, with Galleon Fish Sanctuary circled in red (Esri, 2011).

The Galleon Fish Sanctuary is also threatened by erosion due to global sea level rise. Sea level rise rates in the Caribbean have averaged about 2.7 mm/yr in the past (Robinson et al., 2012). Zelzer (2015) analyzed shoreline position changes along the Black River Bay, which includes Galleon Fish Sanctuary, in response to Hurricane Ivan, which occurred in September 2004. Erosion rates for the Galleon Fish Sanctuary were calculated for the years 2003-2012 and showed that almost 40% of the shoreline was eroding. Although some of the beach in the sanctuary has recovered since the 2004 hurricane, other areas are recovering more slowly or are eroding.

Objectives

The goal of this thesis project is to gain an understanding of the relationships between beach characteristics and beach change in the Galleon Fish Sanctuary in order to develop a risk map that can be used for efficient monitoring and management of the area. Geomorphic assessments of beach form, vegetation, and sediment or substrate can be used to understand the patterns and causes of beach erosion rates (Hanslow, 2007; Hapke et al., 2011; Miot da Silva, 2008). The results of these assessments can be used by coastal managers to allocate resources efficiently to protect beaches and the people living in the area. In Jamaica, shoreline erosion of the Galleon Fish Sanctuary has the potential to affect ecological productivity and the sustainability of local communities. Assessing how the beaches along the shoreline of the sanctuary respond to erosion can be used to achieve a better understanding of how beach changes, vegetation patterns, and substrate are related to erosion patterns and rates. Developing a risk map based on current erosion rates and erosion indicators for the Galleon Fish Sanctuary will help in the conservation of the area, as resources can be focused to protect areas at the greatest risk for erosion. The objectives of this research project are as follows:

1) Assess topographic shoreline profiles, erosion indicators, and vegetation characteristics along the shore of the fish sanctuary. This information will quantify beach forms and erosion indicators of the beaches at 32 beach sites, including sand beach and mangrove beach sites. Different beach types were analyzed in order to determine how beach morphology responded to erosional forces;
2) Determine the recent rates of shoreline change in Galleon Fish Sanctuary from 2012 to 2016 using satellite images. Compare the recent rates to the historical shoreline change rates from the years 2003- 2012 reported by Zelzer (2015). This is done to evaluate where beach recovery has occurred since Hurricane Ivan and subsequent storms as well as areas where erosion trends are continuing;

3) Determine the relationships among geographic location, erosion or accretion history, and beach morphology to better be able to understand recent and historical beach change and predict future effects; and

4) Evaluate the geomorphic processes and resource threats associated with erosion risk and create an erosion risk map for Galleon. A classification system is developed based on erosion history, substrate resistance and mangrove influence. Classification systems have long been used by beach geomorphologists in their research to more effectively convey their findings (Borges et al., 2014). Recommendations are provided for monitoring and management goals for conservation purposes.

Hypotheses

It is expected that areas with higher rates of erosion will have beach characteristics typically associated with erosion, such as lower beach angles with wide beach widths and low berms, eroded backbeaches, active scarps, toppled vegetation, larger substrate, and overwash deposits (Wang et al., 2006; Hanslow, 2007; Folk et al., 1970; Shipman, 2008). It is also expected that erosional beaches will lack high percentages of ground vegetation, leaf litter, and beach ridges, which are characteristics of stable or accretionary beaches. Mangroves located seaward of the berm erode more quickly than those located landward of the berm (Ellison and Zouh, 2012). Areas protected by coral reefs are predicted to have lower rates of erosion than areas that are not protected by coral reefs. With a lack of recent hurricanes in the area, current erosion patterns are likely caused by sea level rise, human activity, or long-term recovery from past hurricane erosion events.

Benefits

Scientifically, protecting shorelines is extremely important. The protection of coral reefs as marine protected areas is beneficial as long as it is properly managed (Burke and Maidens, 2006). Mangroves and coral reefs provide habitats for fish, and sandy beaches serve as nesting sites for sea turtles (Ellison and Zouh, 2012; Burke and Maidens, 2006; Fish et al., 2005). Mangrove repopulation is also advantageous in areas where it has been unsustainably harvested (Cuc et al., 2015). Coral reefs and mangroves help protect shorelines, so protecting them helps prevent erosion to an even greater extent.

The results of this study will raise the awareness of local authorities to beach erosion problems and the complex pattern of both changing and relatively stable shorelines in their communities. Economically, protecting coastal areas is also very important. Tourism is often one of the largest contributors to the revenue of coastal regions, especially in the Caribbean (Gable, 1991; Gable and Aubrey, 1990; Bueno et al., 2008). Combining tourism and protected coastal features encourages policy makers to take a stand against erosion (Oderiz et al., 2014).

Information about the beach characteristics that indicate erosion will be given to the management of the Galleon Fish Sanctuary so that they can allocate their resources to the most threatened areas along the shoreline. This will help improve the sustainability of the marine protected area as a fish nursery that will improve fishing in the area. Successful management of the fish sanctuary can also help provide the local community with educational, recreation, and occupational services (C-Fish, 2012). Having a good place to fish is also important, especially when it is a way of life for people living near

the coast who need to provide for their families. Creating and maintaining fish sanctuaries can help restore some of the fish populations decimated by overfishing. Coral reefs and mangroves within the sanctuary provide nurseries for young fish to mature. Fishermen in Jamaica have benefitted from fish sanctuaries for this reason.

CHAPTER 2- BACKGROUND

Shoreline management is very difficult if there is no way to assess the vulnerability of a shoreline. Planners and local governments need to understand the risks that threaten development along the coast in order to prevent infrastructure and economic failure. Protection of fragile coastal ecosystems is also important as they act as a natural defense against erosion and serve as a habitat to many organisms. The addition of geomorphologists to management teams ensures that shoreline assessments can effectively address vulnerability to erosion (Alcantara-Ayala, 2002).

Geomorphic Beach Vulnerability Assessments

Many beach vulnerability assessments used for management purposes include geomorphic factors. Murali et al. (2015) determined which beaches along a coastline were at the greatest risk of erosion based on remote sensing data and digital shoreline analysis. They concluded that the rapid erosion in the area is caused by natural and human factors such as storms and dam construction. Borges et al. (2014) developed a Coastal Vulnerability Index (CVI) with a rating scale based on the degree of vulnerability. The vulnerability was determined using remote sensing and field data, and focused on cliff type, storm wave exposure, chance of flooding, and presence of shoreline protection structures. Borges et al. (2014) anticipate that their CVI will be used by coastal management for the purpose of focusing resources on areas that are comparatively more vulnerable. Cambers (1998) outlined which beaches in particular need attention based on their erosion rate. They suggested protecting beachfront property, conserving beaches, or

finding a way to compromise on these two options. Lam et al. (2014) investigated factors that make a shoreline vulnerable to hurricanes, such as exposure, low ability to adapt, and the socioeconomic status of people in coastal areas. From this they developed a weighted index that could be used as a tool to determine where and how to reduce vulnerability by increasing resilience.

Geomorphic assessments can also be used to evaluate erosion risk. In large study areas, such as the 1460 km shoreline of New England and the Mid Atlantic, geomorphic analysis was used to broadly classify beaches as rocky coasts, bluffs with narrow beaches, mainland beaches, and barrier beaches (Hapke et al., 2011). The geomorphic shoreline types were then further broken down based on substrate size, tidal influence, and depositional landforms such as spits and barrier beaches. During the past 25-30 years, 60% of the shoreline in this study area has been experiencing erosion. The classification of the shoreline using the different shoreline form types helped determine which beach types are more susceptible to erosion (Hapke et al., 2011). A variety of geomorphic shoreline indicators can be used to determine the state of a beach. Hanslow (2007) compared the significance of the changes in shoreline position, high water line position, vegetation line position, scarp position, beach volume, and dune volume of a beach in Australia. Vegetation line position yielded more statistically significant trends than shoreline position and high water line position, but if the data is available, scarp position, beach volume, and dune volume are more accurate indicators of erosion and accretion trends. Geomorphic indicators can also be used to determine the effectiveness of protective structures. Shoreline protective structures can cause beaches to narrow, reduce sediment transport, and scour and erode by reflecting wave energy in comparison

to similar beaches without the structures (Shipman 2010). Toppled vegetation, active scarps, and overwash fan deposits indicated this increased erosion. Shipman (2010) recommended softer erosion control in the form of beach nourishment, using vegetation as stabilization, and rip rap such as cobbles or woody debris.

A geomorphic study that classifies shorelines based on its relationship with erosion rate has not been completed in Jamaica. As an important natural resource, the Galleon Fish Sanctuary needs to be protected against hurricanes, sea level rise, and human activities. Understanding the erosion risk for an area allows for the allocation of resources to protect beaches that are more vulnerable to erosion.

Beach Type and Change

Different types of beaches can be found around the world, but they can also be found juxtaposed along a single stretch of shoreline. Being able to identify and understand the characteristics of each type is important for effective shoreline management. Beaches that are in a state of dynamic equilibrium experience a balance between erosional and depositional forces (Passeri et al., 2014). Erosion is driven by higher wave energy reaching further inland. Storms, sea level rise, and human alterations of the shoreline can cause an increase in wave energy, an increase in extent of wave reach inland, or a decrease in sediment supply (Wong, 2003). Accretion occurs in areas of low wave energy or increases in sediment supply (Allen, 1981). There are some sandy beaches that are in a state of dynamic equilibrium or accretion, but most are in a state of erosion. Worldwide, about 70% of the worlds sand beaches are eroding, 10% or less are

accreting, and 20-30% are stable (Wong, 2003). Different variables affect each beach type and determine if and how much the shoreline is eroding.

Sandy Beaches. Sandy beaches provide protection against waves, serve as a habitat for many organisms, and are economically important as tourist destinations (Absalonsen and Dean, 2011). The most seaward part of the beach is the surf zone, the offshore area where breaking waves roll in to shore. The foreshore, the area of the beach between the high tide and low tide marks, is located between the surf zone and the backshore (Cambers, 1998). The backshore is located behind the berm and is where vegetation can start growing. Landward of the backshore is where dunes can form (Cambers, 1998) (Figure 4).

Sandy coastline evolution is driven by the transport of sediment parallel to the shoreline, where it is either deposited or eroded (Absalonsen and Dean, 2011). This

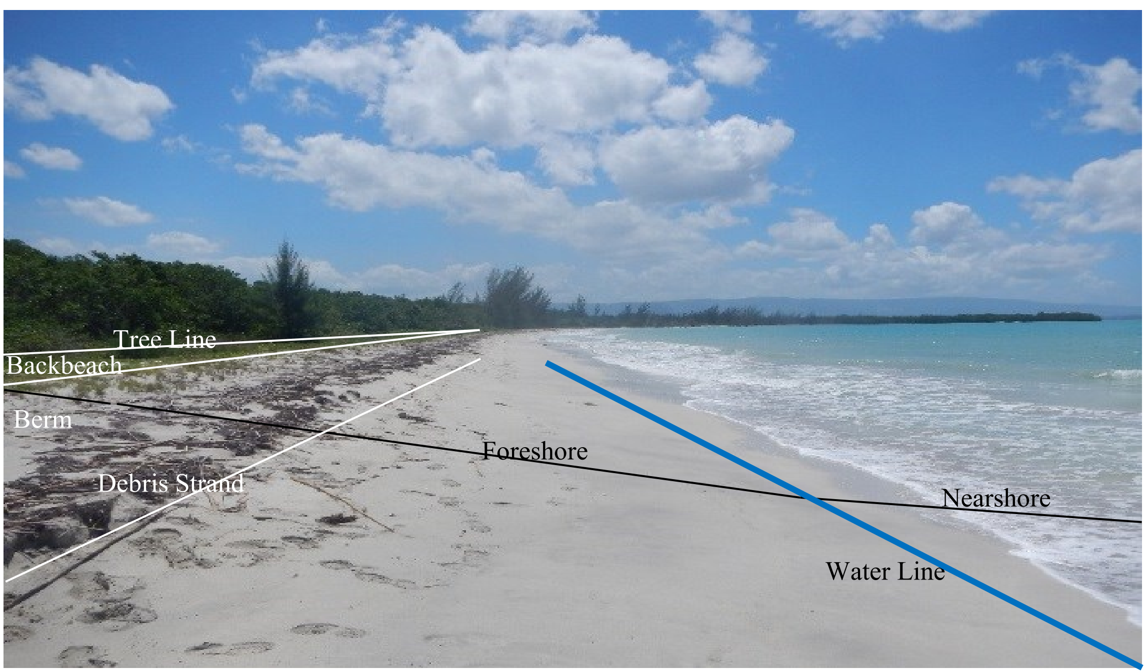

Figure 4: Galleon Fish Sanctuary beach with features labeled.

longshore current is caused by waves breaking at an angle other than perpendicular to the beach. The current can transport large amounts of sediment a long distance in coastal areas if it does not meet with interference. Anything that stops or deflects the longshore current would be considered interference such as beach protection structures like breakwaters, groins, and jetties or natural features such as resistant headlands, and coral reefs, shore parallel barrier islands that protect the shoreline like a natural breakwater.

Wave energy is dependent on how the wave approaches the shore. Waves break when the base of the wave experiences friction on the bed of the shore, which causes the energy of the wave is dissipated (Wright et al., 1991). Beaches can either be dissipative or reflective depending on where waves break on the shore. Dissipative beaches are wide and slope gently and are associated with high wave energy (Wright and Short, 1984; Short and Hesp, 1982). Dissipative beaches also tend to have shore parallel bars and channels. Reflective beaches are steeper and narrower, with waves running up far onto the shore (Wright and Short, 1984). Reflective beaches are associated with low wave energy, and cusps and distinct berms are more common on reflective beaches (Short and Hesp, 1982). Dissipative beaches tend to have large dune systems while reflective beaches have little dune development. The energy of a wave as it breaks onshore is also related to wave refraction. Wave energy is refracted by resistant headlands, causing erosion where waves converge on the headland and along its flanks and deposition in the bays (Razak et al., 2014).

Beach sediment can come from river inputs, offshore sediment deposits, and erosion of the coast. The size of the sediment on a beach is dependent on wave energy and the amount of time it has been transported. In general the greater the wave energy,

the larger the particles deposited on the beach can be. Rivers are the major source of sediment that enters the ocean (Milliman and Meade, 1983). Whether this sediment is transported as suspended sediment or bedload or is deposited depends on wave energy and grain size. Cross-shore sediment transport occurs when sediment is transported from onshore to offshore and vice versa. This is caused by changes in wave energy, which occur seasonally and during strong storms. It is also caused by changes in sea level. Houston (2015) explains how in order for a beach affected by sea-level rise to achieve equilibrium, offshore sediment must be transported onshore by wave energy.

A sediment budget is an analysis of the inputs and outputs of sediment in a system and what drives the sediment to be transported or deposited (Allen, 1981). Sediment budgets can be used to understand changes in the amount of sediment a river delivers to the ocean. This is important because the amount of sediment input from a river determines the amount of sediment that can be deposited on beaches by longshore currents. According to Syvitski et al. (2005), humans have increased the amount of sediment entering rivers by causing sediment erosion, but the overall amount of sediment entering the ocean has decreased due to the construction of dams that trap sediment. Cross-shore sediment transport to and from offshore deposits is also a factor in the amount of sediment on beaches. Sediment is often transported onshore during fair weather or offshore during storms (Wright et al., 1991). Cross-shore sediment transport is also a seasonal occurrence in some locations around the world. In areas where wave frequency and direction change depending on whether it is summer or winter, there are annual cycles of beach accretion and beach erosion as sand is transported onshore and offshore (Aubrey, 1979). Shoreline erosion is also a source of sediment. Sea level rise,

intense and frequent storms, and certain shoreline protection structures such as sea walls and groins all worsen erosion (Nordstrom and Jackson, 2013).

Shoreline retreat of sandy beaches caused by sea level rise is often estimated using the Bruun Rule, an equation that represents the distance a beach profile will shift. This method is fairly inaccurate, as it ignores several important variables (Cooper and Pilkey, 2004). Combining this method with tidal gauge data and historical erosion rates interpreted from aerial photographs helps to makes sea level rise estimates more accurate (Feagin et al., 2004). Absalonsen and Dean (2011) estimate past erosion rates from 1971-2006 in Florida and find an erosion rate between +0.3 to +2.4 m/yr, but this accretion is due to extensive beach nourishment projects. Cambers (1998) reports erosion rates on the Caribbean island of Nevis range from -6.53 to +1.2 m/yr. Robinson et al. (2012) find erosion rates to average -0.41 m/yr in Negril, Jamaica for the years 1991-2008 based on field surveys, aerial surveys and satellite imagery. Any of the human or natural causes of erosion could affect sandy beaches, though the exact cause would depend on the local conditions.

Coral Reef Protected Beaches. Barrier reefs and fringing reefs are typically associated with controlling beach morphology and erosion (Maragos et al., 1996). Barrier reefs are detached from the shore, whereas fringing reefs are adjacent to the shore. Coral reefs grow both upward and seaward depending on sea level. Coral can’t survive above the water and if sea level rises faster than the coral can grow upward, it will die. There are three main types of coral species, including branching coral, massive coral, and encrusting coral (Hughes, 1994). Massive coral and encrusting coral are much more resilient to wave energy than branching coral, while branching forms of coral are more

resistant to sedimentation (Hughes, 1994; Rogers, 1990). A reef is considered healthy if there is a diverse population of coral and fish and a minimal population of algae. If the opposite is true, the reef is considered degraded (Hughes and Connel, 1999). Globally, coral cover has decreased more than 50% since the 1970s (Green et al., 2008). In Jamaica live coral cover has decreased from 50% to 3% between the 1970s and 1990s (Hughes, 1994). Some recovery has occurred, with live coral cover averaging 15% (Creary et al., 2008).

Coral reefs are very beneficial features along tropical coastlines. Coral reefs help to protect beaches from erosion by dissipating wave energy (Maragos et al., 1996). They also reduce the amount of damage caused by hurricanes and storm surge on shore (Burke and Maidens, 2006, Temmerman et al., 2013). Coral that is stressed by bleaching, algal encrustation, rising sea levels, or sedimentation and has low live coral cover is more susceptible to damage by wave energy, which causes the beaches they protect to erode (Maragos et al., 1996; Hughes et al., 2010). Healthy reefs protect beaches from erosion and create systems that are more likely to be close to dynamic equilibrium. Without reefs to protect the beaches, they will erode at rates similar to what is seen in unprotected beaches subject to the many causes of erosion. Coral reefs are also an important habitat for aquatic life. Herbivorous fish and invertebrates such as parrot fish and sea urchins graze on algae, which is beneficial for the coral, and predatory fish then feed on them (Hughes, 1994). Invasive species such as the lionfish upset this balance (Creary et al., 2008).

Coral reefs are important to the economy as fisheries and tourist attractions (Burke and Maidens, 2006). Fish, mollusks, and crustaceans can all be found in reef

environments and are harvested from reef environments to sell and for sustenance (Aiken et al., 2002). Overfishing is a significant problem, depleting many of the large predatory fish populations (Hughes, 1994). Establishing marine protected areas and fish sanctuaries that include reefs within their boundaries can help fish populations grow again by providing a safe place for juvenile fish to mature (Aiken, 2012).

There are many human and natural causes of reef degradation. Excessive sedimentation causes water to become cloudy, which can decrease the amount of light available for photosynthesis, and can bury coral, killing it (Rogers, 1990). Dredging and sediment loaded runoff from areas of human development, construction, and agriculture along shorelines are some of the main sources of sediment entering the ocean. Hurricanes can cause damage to coral reefs because of the increase in wave energy associated with them (Hughes and Connel,, 1999). If hurricanes occur more frequently than coral can recover, the damage done to the coral can be even worse than one large storm in the long term. Algal blooms can be caused by agricultural runoff of fertilizers or by decreases in the number of herbivorous fish (Hughes, 1994; Burke and Maidens, 2006).

Mangroves. Wetlands are areas where frequent inundation causes the soil to be saturated, limiting the vegetation that can grow there (Cambers, 1998). In low lying tropical areas, one of the most common types of coastal wetland is mangrove forests. They are located in the intertidal zone, meaning that during high tide the lower parts of the trees could be submerged in sea water (Bell and Lovelock, 2013). Mangroves cannot survive in pure freshwater and require salinities above 0 but below 40 parts per thousand (U.S. Fish and Wildlife Service, 1999). Mangrove stands are divided into three main types, fringe, basin, and riverine (Schaeffer-Novelli et al., 2000). Fringe and riverine

mangroves are exposed to flowing water, while basin mangroves have standing water (Figure 5).

Mangrove forests grow in a mixture of sand, fine silts and clays, and organics up to a meter above sea level (Ellison and Zouh, 2012; Phan et al., 2015). The health of a mangrove forest depends a lot on the sediment delivered to and within the system. If the sediment is eroded from the seaward boundary of the forest, the mangrove forest will be forced to migrate inland (Ellison and Zouh, 2012). However, mangroves also generate their own sediment in the form of peat and detritus. Mangroves enhance sedimentation by trapping sediment, and efforts to plant more in areas where erosion is occurring helps to stabilize the forests (Cuc et al., 2015). Mangroves filter sediment out of runoff water, which helps prevent excessive sedimentation of coral reefs (Ellison and Zouh, 2012). Wider mangrove forests are better at promoting stability and reducing flooding. These benefits are threatened by sea level rise, subsidence, land loss, and more severe and frequent storms. Sea level rise causes the landward retreat of mangroves, a process known as relocation (Williams et al., 1999). Erosion of mangrove forests can also be caused by the loss or submergence of sediment from around the roots of the mangroves,

Figure 5: Diagrams of the three main types of mangrove forests, fringe mangrove forests, basin mangrove forests, and riverine mangrove forests (Modified from Hensel et al., 2014).

which causes trees to collapse as their roots are weakened. Sand beaches serve as a protective barrier for mangroves just as mangrove roots anchor sand beaches in place. Coastal squeeze occurs when mangroves cannot migrate inland due to the presence of human development or mountains (Schleupner, 2008). This causes the width of the forest to narrow. The erosion of mangrove forests leads to further erosion inland, as healthy, wide mangrove forests dissipate wave energy and significantly reduce wave height (Cuc et al., 2015).

Thampanya et al. (2006) analyzed mangrove forests and sand beaches in southern Thailand at four study sites along the coast, covering a total of about 650 km of coast. While some are expanding, there is a net loss of forest in the area. The erosion rate ranges from -1.6 to -6.7 m/yr, and in areas of accretion, the rate of accretion is 1.0 to 8.9 m/yr (Thampanya et al., 2006). They also found that the sand beaches were experiencing a larger degree of beach change than the mangrove beaches. The eastern coast, which has sand beaches, experienced erosion along 29% of its shoreline and accretion along 3% to 21% of its coastline. The western coast, which has predominantly mangrove beaches, experienced erosion along 11% of its beaches and accretion along 2%-9% of its beaches. Therefore, mangroves provide much more stability to beaches by protecting them against wave energy.

Galleon Fish Sanctuary has sand beaches, mangrove forests, and coral reefs. The presence of these 3 different beach types adds complexity and diversity to the sanctuary. Based on the general trend of erosion found in previous studies, there should be concern that the shoreline of the sanctuary is threatened by erosion due to sea level rise, storms, and human activities.

CHAPTER 3- STUDY AREA

Jamaica is located south of Cuba and west of Haiti in the Caribbean Sea (Figure 2). Jamaica is 236 km in length and ranges from 35-82 km in width, making it the third largest island in the Caribbean (Richards, 2008). The coastline is 895 km in length and has a variety of beach types, including headland embayments, sandy beaches, estuaries, mangroves, coral reefs, and rocky shorelines or cliffs. Jamaica's climate is considered tropical maritime. The southern coast of the island usually receives less rain than the northern coast, with the wettest months from May to June and September to November and the driest months from December to March (Richards, 2008). The average temperature year round is about 27°C (80°F). Hurricanes most frequently occur from June to November. The predominant wind direction is from the east, which helps form the southeast to northwest longshore current found along the south shore of Jamaica (Norrman and Lindell, 2010). Rafted reeds and vegetation cut from the Black River in order to keep the waterway clear for boats wash up on the shore of the Galleon Fish Sanctuary, providing evidence of this southeast to northwest wind and current direction.

The Galleon Fish Sanctuary is located in St. Elizabeth parish just west of town of Black River in southern Jamaica and was established in 2009 (C-Fish, 2012) (Figure 3). It is managed by The BREDS Foundation, which works out of Treasure Beach, Jamaica. The shoreline of the Galleon Fish Sanctuary is relatively undeveloped. Galleon Harbor and is located just south of the western boundary of the sanctuary on the headland. The sanctuary has a shoreline boundary that is about 6 km in length and a seaward boundary that is about 4.5 km in length. There are three main sections of the sanctuary, Malcolm

Bay, Hodges Bay, and Dead-Man Hole, located west to east, respectively (Figure 6). The shoreline of the sanctuary is characterized by sandy beaches along the eastern part of Malcolm Bay, mangrove forests along the western part of Malcolm Bay and along Hodges Bay and Dead-Man Hole, and a resistant headland that separates Malcolm Bay from Hodges Bay. Coral reefs can also be found right offshore of the resistant headland, Hodges Bay, and Dead-Man Hole. The sand beaches in Galleon Fish sanctuary are reflective, characterized by narrow beach widths and the presence of cusps.

Geology and Soils

The geology of southern Jamaica is characterized by a primarily limestone karst landscapes. It is highly fractured because of its location on the northern edge of the Caribbean Plate where it meets the North American Plate (Robinson and Hendry, 2012).

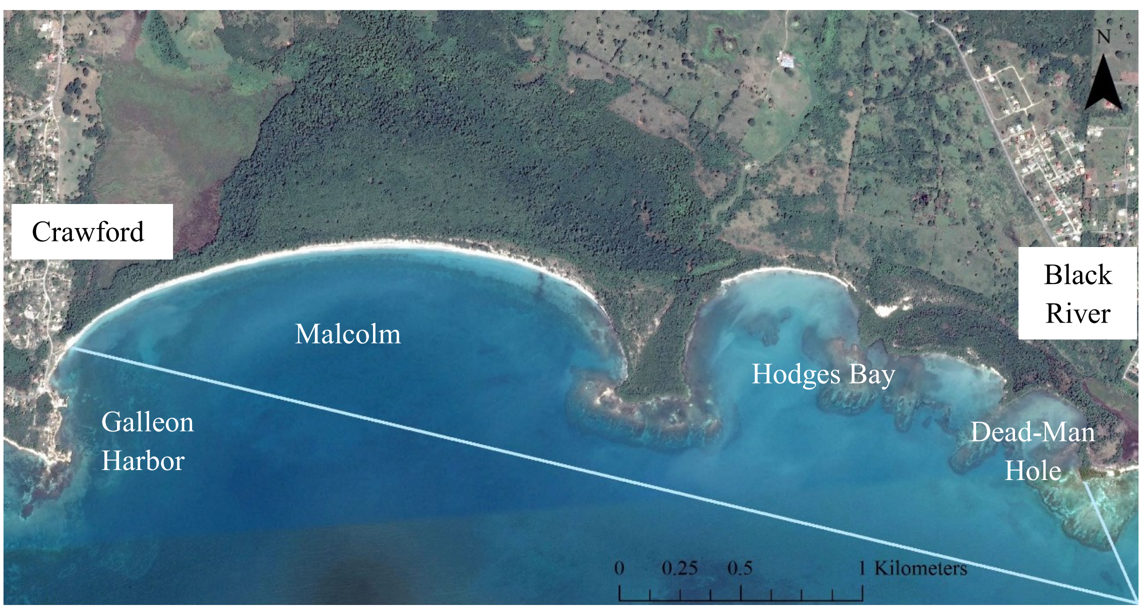

Figure 6: The Galleon Fish Sanctuary with Malcolm Bay, Hodges Bay, and Dead-Man Hole labeled, as well as neighboring towns Crawford and Black River (Google Earth Pro, 2016).

Within the study area, the headlands on either side of each bay are composed of resistant rock (Figure 7). Maps modified from data obtained from MONA Geoinformatics does not specify the rock type. The soil types identified in the study area include the Bonny Gate, Crane, and Mangrove Swamp (MONA, 2001) (Figure 8). The Bonny Gate, located by the Galleon Harbor, is a stony loam rich in aluminosilicates. The Crane soil Institute (2001) show that there is also a non-limestone portion within the study area but type is a Holocene sand sheet found along the shoreline of the sanctuary wherever the Mangrove Swamp soil type is not present. The Mangrove Swamp soil type is a gravelly clay loam, and its distribution matches up well with the land cover of mangrove forests, which can be seen in Figure 9 (MONA, 2001).

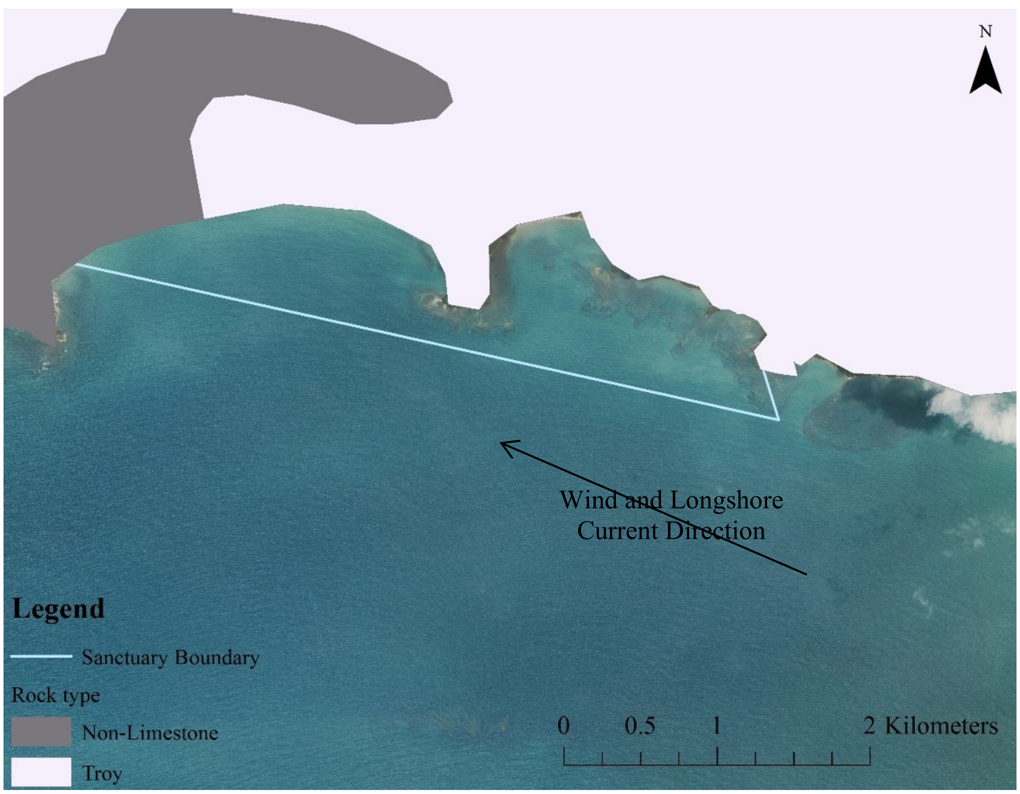

Figure 7: The geology of the coast along Galleon Fish Sanctuary. The western portion is non-limestone. The eastern portion is Troy Limestone (modified from MONA, 2001).

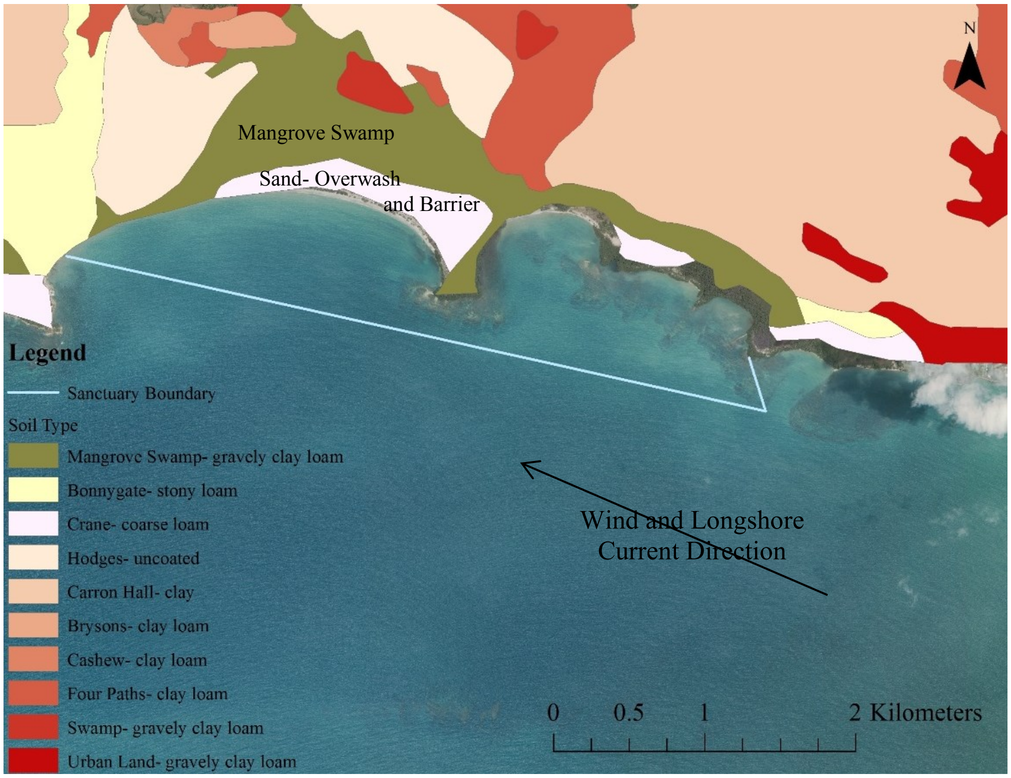

Figure 8: A soils map of the coast along the Galleon Fish Sanctuary. The soil types identified in the study area include the Bonny Gate, Crane, and Mangrove Swamp (modified from MONA, 2001).

Vegetation and Land Cover

The land bordering the Galleon Fish Sanctuary is largely undeveloped (Figure 9). The small town of Crawford is located at the western extent of the sanctuary, and the town of Black River is located at the eastern extent of the sanctuary. Mangrove forests and fields extend at least 1 km inland of the sanctuary's shoreline boundary, if not further. Red mangroves, black mangroves, white mangroves, and buttonwoods are all found along the coast of the sanctuary. A wide variety of other shoreline plants are also present. There are also fields for grazing livestock such as cows and goats. This sustenance farming could cause runoff into the bay to have higher levels of nitrogen and phosphorous.

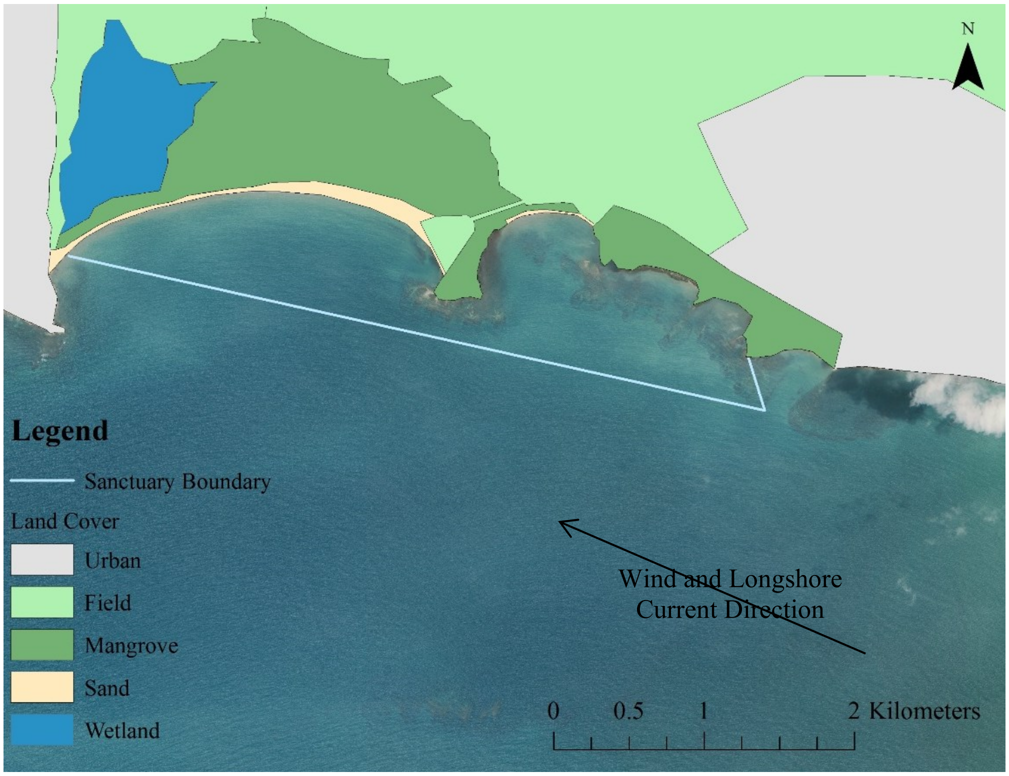

Figure 9: Land cover map of area surrounding Galleon Fish Sanctuary (MONA, 2001).

Sediment System

Sediment deposited along the Galleon Fish Sanctuary may have originated from a variety of sources. Mangroves forests create deposits of peat and detritus. Sediment that has eroded from other beaches or has entered the erosion through fluvial systems can be transported by longshore drift. The longshore drift along the south coast of Jamaica is predominantly east to west, although bays may create a counter current (Norrman and Lindell, 2010). A delineation of the Black River watershed, the mouth of which is located less than 2.5 km east of the Galleon Fish Sanctuary, was used to find the Stream Power Index (SPI) in ArcMap (Dogwiler et al., 2010). The SPI shows where there are high slopes and high flow accumulation in the watershed, indicating higher risk for erosion (Wilson and Gallant, 2000) (Figure 10). Sediment coming from the Black River is most

likely to come from the limestone mountains of the southern part of the cockpit country, assuming it can be weathered, as limestone is resistant to physical weathering alone. This could be deposited on the beaches of the Galleon Fish Sanctuary. Carbonate sediment deposited on the beaches could also be from the coral reefs that border the sanctuary. About 20-40% of the sand in Galleon is carbonate, based on observations made in the field, and is likely from these reef sources. Silica deposits can be found north of the sanctuary, and the mining of this material could cause the deposition of quartz sand on

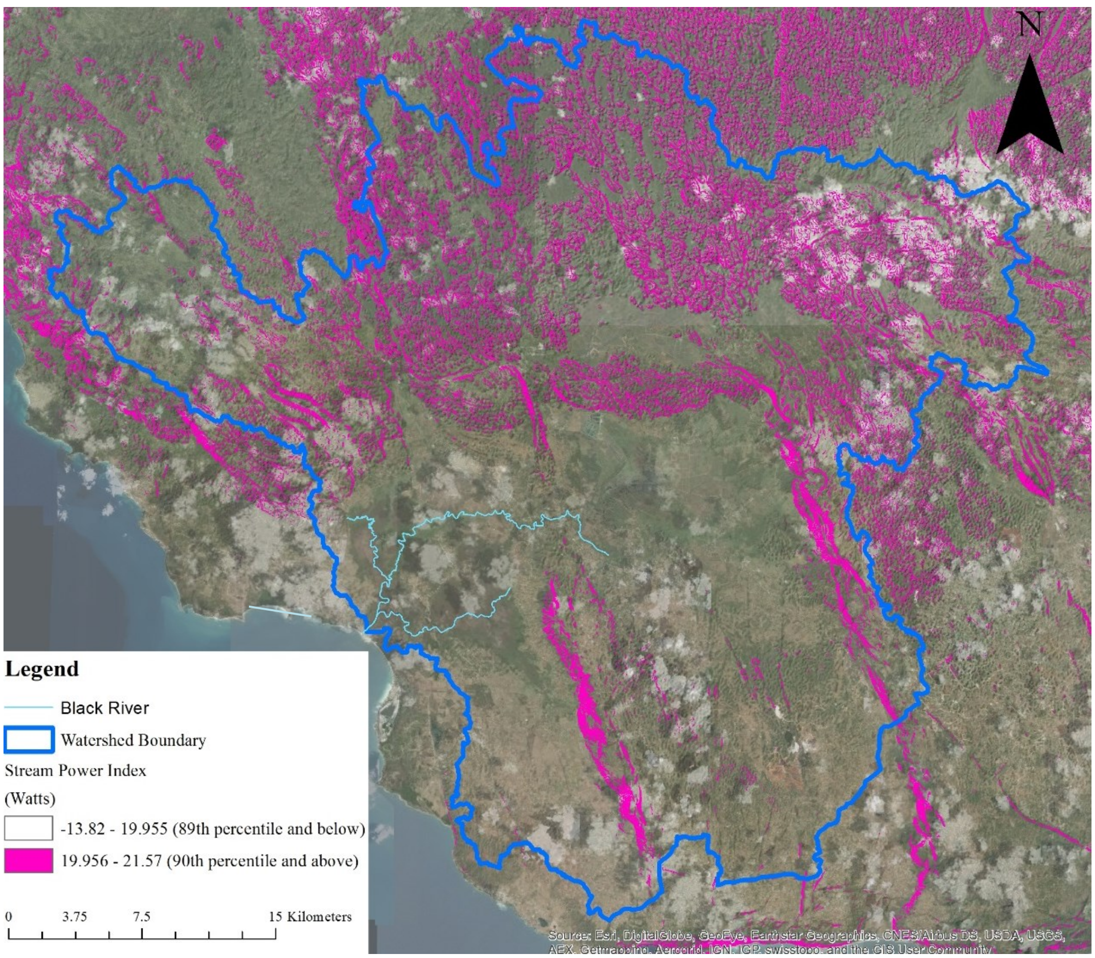

Figure 10: Map depicting delineated watershed of the Black River and the areas with a stream power index at or above the 90th percentile.

the beach if transport between the source and the beach exists (Jackson and West-Thomas, 1994). These deposits have a provenance in the granitic Central, Above Rock, and Blue Mountain Inlier groups. Sediment eroded from these interior mountains was transported by rivers and deposited on the marine shelf before low sea levels exposed them and they were transported by wind and deposited in their current locations.

Hurricanes

Hurricanes can cause extensive damage along shorelines, but beaches usually recover within a few months or years (Wang et al., 2006). However, if there is not enough deposition along a beach or sea level rise outpaces deposition, the damage done by hurricanes can last much longer. In the Caribbean, there are usually about 6 hurricanes and 4 tropical storms per hurricane season (McKenzie, 2012). Since 2004, there have been five tropical storms or hurricanes with a path within 75 nautical miles (138.9 km) of Black River, Jamaica in southwest Jamaica (Office for Coastal Management, 2013). Hurricane Charley was a Category 1 Hurricane with a path along the south coast of Jamaica in August of 2004. Hurricane Ivan, a Category 4 storm, also followed a path south of Jamaica a month later in September of 2004 and caused widespread damage. In Negril, along western Jamaica, there was an average of 16 m of erosion caused by Hurricane Ivan (Robinson et al., 2012). In August of 2007, another Category 4 hurricane, Hurricane Dean followed a path along the south shore of Jamaica (Office for Coastal Management, 2013). The next year, in August of 2008, Hurricane Gustav, which was a tropical storm when it made landfall in Jamaica, took a path just a few kilometers north of Black River. The most recent hurricane within 75 nautical miles of was Hurricane

Sandy in October of 2012. Hurricane Sandy was a Category 1 storm that followed a south to north path on the east side of Kingston, Jamaica, which is located about 110 km directly east of Black River.

Erosion Rates 2003-2012

Previous research done by Zelzer (2015) assessed beach change along 32 km of shoreline from Font Hill to Parottee Point. She determined shoreline erosion rates using IKONOS satellite imagery for the years 2003, 2007, and 2012. The focus was on the erosion and recovery in the area after Hurricane Ivan in 2004. From these erosion rates she predicted the loss of land within the next 10 and 30 years. She found that sand beaches without coral protection had the highest rates of erosion, while resistant limestone headlands and mangroves had the lowest rates of erosion or were stable. Beaches without coral reef protection experienced almost 3.5 times as much erosion as beaches protected by coral reefs. For the years 2003-2012, she found that Malcolm Bay was eroding along 69% of the shoreline and Hodges Bay and Dead-Man Hole was eroding along 31% (Figure 11).

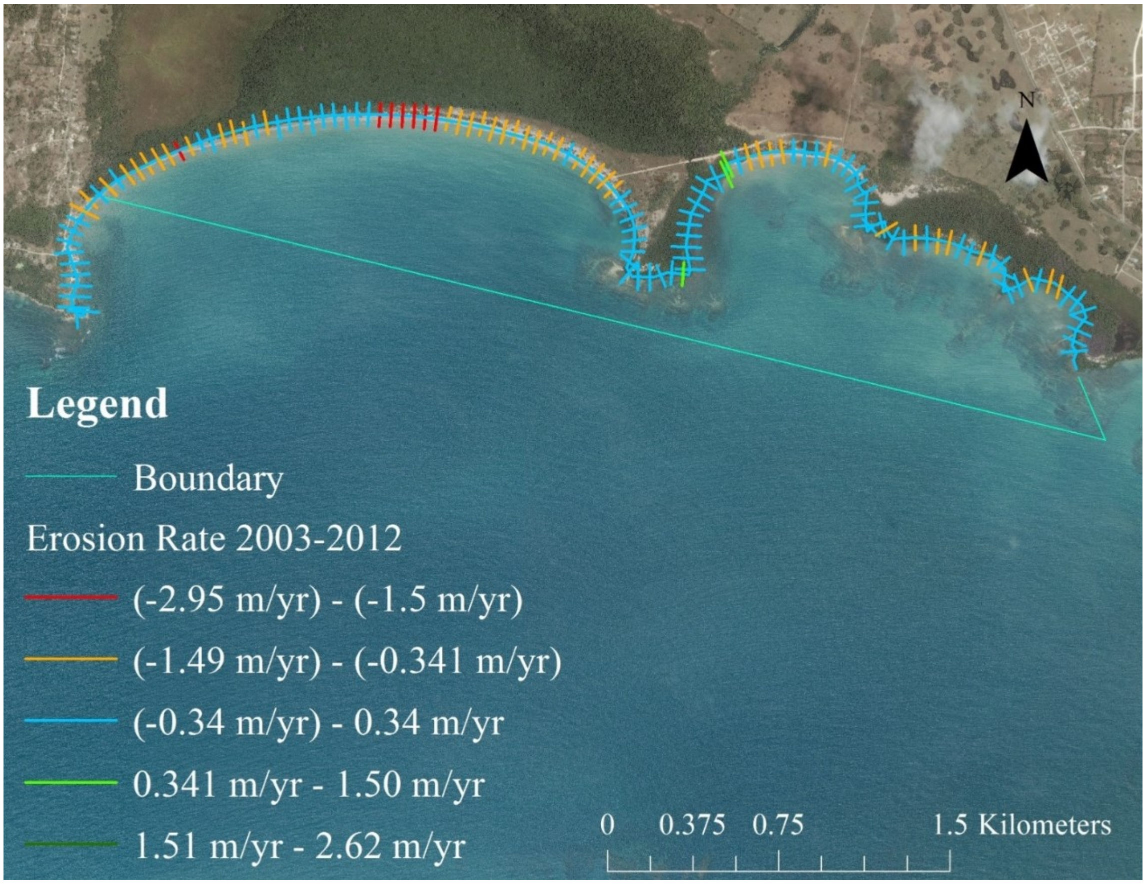

Figure 11: Historical shoreline change rates for 2003-2012 (Zelzer, 2015) Satellite imagery is from 2003 and obtained from The Nature Conservancy (2011).

CHAPTER 4- METHODS

The methods needed to assess beach erosion in Galleon Fish Sanctuary require GIS, field data collection, and data analysis. The sampling design was created to best represent the range of eroding, stable, and accreting beaches occurring along the shoreline boundary of the Galleon Fish Sanctuary. Data collection in the field included surveying the beaches along transects and recording beach properties such as vegetation, beach angle, and substrate. Relationships between beach characteristics and known erosion rates were evaluated using Microsoft Excel descriptive statistics and IBM SPSS linear regression statistics. Significant relationships were used to develop a classification system for beach erosion risk.

Geographic Information Systems

ArcMap 10.2.2 was used to create an interactive field map. A DEM provided elevation information for the study area. The pixel resolution was 30 m^2, with 1 m vertical resolution. The elevation along the shoreline was all 2 m or less below sea level, except for along the headland where a few areas were up to 4 m high. The geology map layer, soils map layer, land cover layer were created using data from the MONA Geoinformatics Institute (2001) (Figures 7, 8, and 9). Satellite imagery was also used to determine land cover (Figure 6).

The erosion rate data from Zelzer (2015) is from the years 2003-2012. Zelzer calculated the changes in vegetation line by digitizing the vegetation line for April 2003, December 2007, and March 2012 and then measuring the distance between the lines. The

historical erosion rate was then calculated by dividing the vegetation line change in meters by the number of years between the photo years. Erosion is indicated by negative beach change rates, accretion is indicated by positive beach change rates (Figure 11). The transects from Zelzer (2015) for Galleon Fish Sanctuary were symbolized based on their beach change rate to represent historical erosion and accretion rates as well as stability.

Recent Erosion Rates

Recent erosion rates were determined for the years 2012 to 2016. The base map used was the March 2012 satellite image from Zelzer, which has a 0.5 m resolution (2015). A satellite image from Google Earth Pro from March 15, 2016 georectified in ArcMap to the 2012 image (Appendix A). This 2016 image has a 1.6 m resolution. The georectification was done at a 1:500 m scale with 9 control points and a 2nd order polynomial transformation (Hughes et al., 2006). The root mean square error of the georectification was 1.04 m. The vegetation line was then digitized for both years, and the distance between the two vegetation lines was calculated at 50 m transect intervals along the transects (Figure 12) (Murali et al., 2015). The transects used for this study are the same transects used for the Zelzer (2015) study so recent erosion rates could be compared to the historical erosion rates. The vegetation line was used for both the Zelzer study and this study because the water line can be difficult to determine in the satellite imagery and is variable due to tides and storms (Hanslow, 2007). The distance of the vegetation line change was divided by 4 because the satellite images were from March 2012 and March 2016. Negative values indicate erosion, or the vegetation line moving inland, and positive values indicated accretion, or the vegetation line moving seaward.

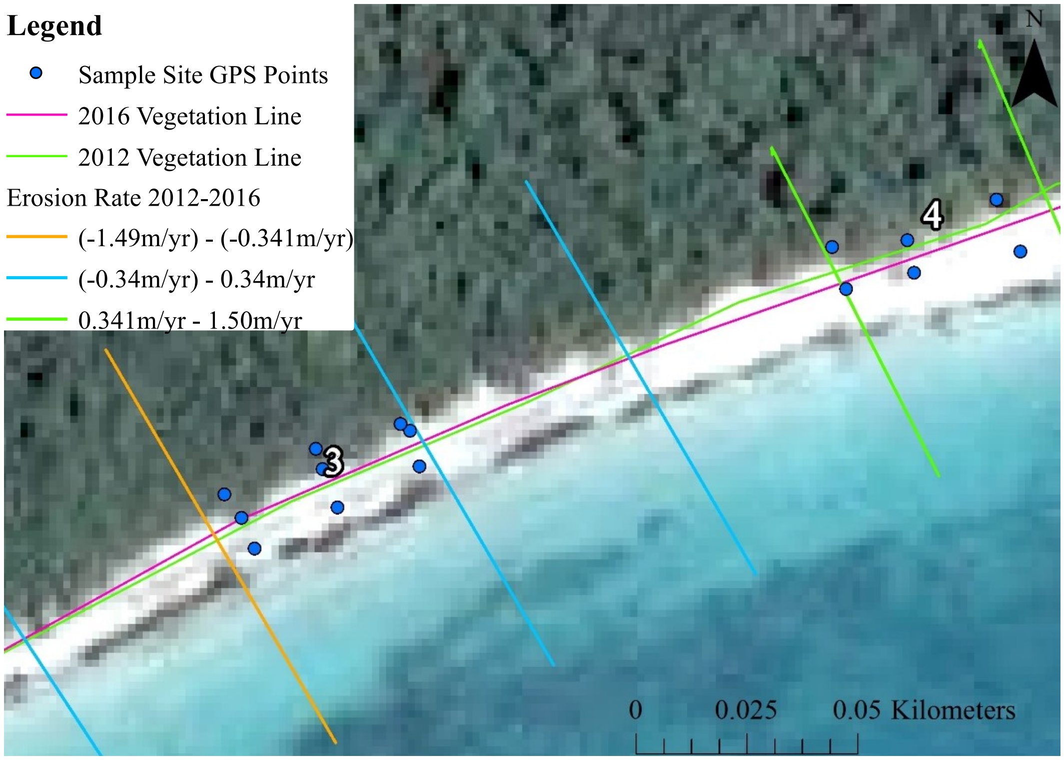

Figure 12: Method used to determine the updated erosion rates for Galleon Fish Sanctuary. The vegetation line for 2012 and 2016 was digitized and the distance between the lines was measured. The base map is from 2016 (Google Earth Pro, 2016).

The test point error for the 2012 and 2016 images was calculated by placing ground control points on the corner of the 6 buildings for each satellite photo year in ArcMap and calculating the distances between points on the same building corners (Hughes et al., 2006). The test point error was found to be 1.36 m, so any change between -0.34 m/yr and +0.34 m/yr was insignificant and considered stable.

The Trimble GPS points from both research trips were added to an ArcMap file. The GPS latitude and longitude data can be found in Appendix B. An erosion rate was assigned to each field beach transect based on the ArcMap layer with the recent erosion rate and the GPS location of the field transects for each sample site. Field transects located between erosion transects were given the average of the erosion rates on either side of it.

Sample Site Selection

Sample sites were chosen to indicate a range of historical erosion rates along the shoreline of the Galleon Fish Sanctuary were well represented (Figure 13). Sample sites were also chosen based on accessibility by boat or walking. There are no sample sites in Dead-Man Hole since mangroves and other vegetation made access difficult. ‘Sample sites were designed to have triplicate transects located 20 m apart. This layout allowed for accuracy and error analyses to be performed. Table 1 shows the characteristics of each sample site.

Field Methods

The first round of field work was completed in January of 2016. Training on how to do a beach survey and perform consistent qualitative assessments took place before data collection began. All measurements and observations were recorded on field sheets at each site (Appendix C). For this study, a sand beach site has a beach berm on the seaward side of the vegetation and a mangrove site has a berm that has retreated into the

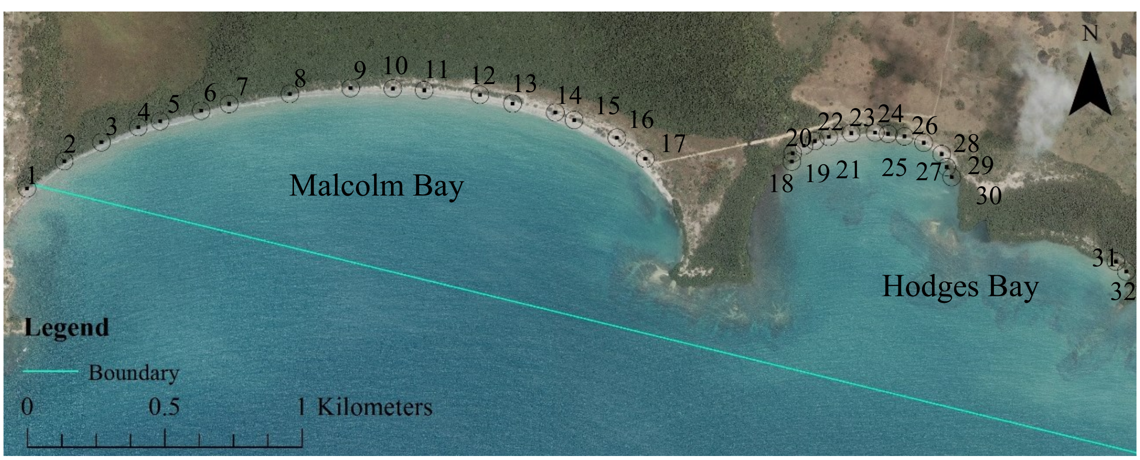

Figure 13: Field sample sites, location based on GPS points. Each sample site had 3 transects.

Table 1: Sample site properties and locations.

Site	Bay	Soil Type	Geology	Land Cover	Historical Beach State	Recent Beach State	Beach Km
1	Malcolm	Bonnygate	Non-Limestone	Sand	Eroding	Eroding	0.45-0.5
2	Malcolm	Mangrove Swamp	Non-Limestone	Sand	Stable	Eroding	0.6-0.65
3	Malcolm	Mangrove Swamp	Non-Limestone	Sand	Eroding	Stable	0.75-0.8
4	Malcolm	Mangrove Swamp	Non-Limestone	Sand	Eroding	Accreting	0.9-0.95
5	Malcolm	Mangrove Swamp	Non-Limestone	Sand	Stable	Accreting	0.95-1.05
6	Malcolm	Mangrove Swamp	Non-Limestone	Sand	Eroding	Stable	1.1-1.2
7	Malcolm	Mangrove Swamp	Non-Limestone	Sand	Stable	Accreting	1.25-1.3
8	Malcolm	Crane	Limestone	Sand	Stable	Accreting	1.45-1.5
9	Malcolm	Crane	Limestone	Sand	Stable	Accreting	1.7-1.75
10	Malcolm	Crane	Limestone	Sand	Eroding	Accreting	1.85-1.9
11	Malcolm	Crane	Limestone	Sand	Eroding	Accreting	1.95-2.0
12	Malcolm	Crane	Limestone	Sand	Eroding	Accreting	2.15-2.2
13	Malcolm	Crane	Limestone	Sand	Eroding	Accreting	2.25-2.35
14	Malcolm	Crane	Limestone	Sand	Eroding	Accreting	2.45-2.5
15	Malcolm	Crane	Limestone	Sand	Eroding	Eroding	2.5-2.55
16	Malcolm	Crane	Limestone	Sand	Eroding	Stable	2.65-2.7
17	Malcolm	Crane	Limestone	Sand	Eroding	Eroding	2.8-2.85
18	Hodges	Mangrove Swamp	Limestone	Mang-rove	Stable	Eroding	4.05-4.1
19	Hodges	Mangrove Swamp	Limestone	Mang-rove	Accreting	Eroding	4.1-4.15
20	Hodges	Mangrove Swamp	Limestone	Sand	Stable	Accreting	4.15-4.2

Table 1. Continued

Site	Bay	Soil Type	Geology	Land Cover	Historical Beach State	Recent Beach State	Beach Km
21	Hodges	Mangrove Swamp	Limestone	Sand	Eroding	Stable	4.2-4.25
22	Hodges	Mangrove Swamp	Limestone	Sand	Eroding	Stable	4.25-4.3
23	Hodges	Mangrove Swamp	Limestone	Sand	Eroding	Stable	4.35-4.4
24	Hodges	Mangrove Swamp	Limestone	Sand	Eroding	Stable	4.45-4.5
25	Hodges	Mangrove Swamp	Limestone	Sand	Stable	Accreting	4.5-4.55
26	Hodges	Mangrove Swamp	Limestone	Sand	Stable	Stable	4.55-4.6
27	Hodges	Mangrove Swamp	Limestone	Sand	Stable	Stable	4.6-4.65
28	Hodges	Mangrove Swamp	Limestone	Sand	Stable	Accreting	4.7-4.75
29	Hodges	Mangrove Swamp	Limestone	Mang-rove	Stable	Accreting	4.75-4.8
30	Hodges	Mangrove Swamp	Limestone	Mang-rove	Stable	Stable	4.8-4.85
31	Hodges	Mangrove Swamp	Limestone	Sand	Stable	Accreting	5.65-5.7
32	Hodges	Mangrove Swamp	Limestone	Sand	Stable	Accreting	5.7-5.75

a MONA Geoinformatics, 2001- Soil Map Data

b MONA Geoinformatics, 2001- Geology Map Data

c MONA Geoinformatics, 2001- Land Cover Map Data; Google Earth Pro, 2016

d Zelzer, 2015- Historical Erosion Rates 2003-2012

e Recent Erosion Rates, this study; Google Earth Pro, 2016

f Beach Km, see Appendix B

vegetation. At sand beach sites, full topographic surveys were completed. At mangrove sites, the distance from the edge of the forest to the berm was measured and the height of the berm was estimated. Transects were set up with the auto level on the berm at 10 m on the measuring tape. The transects extended 10 m inland from the berm and around 20 m

into the water from the water line. Three transects spaced 20 m apart were surveyed at each sand beach sample site.

Topographical profiles were done in the field using survey equipment. The surveying sheet was loosely based on the protocol developed by Psuty and Skidds (2012). Two teams of four to five people used Topcon AT-B4 auto levels on tripods to determine the elevations along the profile transects using metric stadia rod measurements. An elevation measurement was taken along each transect at every change in slope and at important beach features such as the vegetation line, the berm, and the water line (Boon and Green, 1988). The measurements were noted on the field sheets. GPS points were also taken along each transect with a Trimble and a GPS camera at 0 m on the tape, at the berm (10 m), and the water line. A total of 28 sand beach surveys and 4 mangrove beach surveys were sampled. Beach characteristics were also observed and recorded as either present or not present on the field sheets at each site (Table 2). A photo log of field work can be found in Appendix D.

Beach profiles were graphed using the beach survey measurements for each transect (Appendix E). A complete file with all of the beach profiles and geomorphic assessments can be found on the Ozarks Environmental Water Resources Inststute server. Using these topographic profile, it was possible to determine the berm height and the beach width from the berm to the water line. Berm height was found by determining the vertical elevation of the berm above the water line. Beach width was found by subtracting the horizontal tape distance of the waterline from the horizontal tape distance of the berm. The waterline is used as a reference because the tidal range on the south coast of Jamaica is very low, averaging about a 0.4 m difference between low and high

Table 2: Beach erosion or accretion indicator method of measurement and Relative Percent Difference (RPD) of the triplicate spatial variability.

Beach Characteristic	**Method of Measurement**	**Reference**	**25th Percentile of RPD**	**50th Percentile of RPD**	**75th Percentile of RPD**
Berm Height (m)	Auto Level	Weir et al., 2006	17.8	30.2	36.2
Beach Width (m)	Auto Level	Boon and Green, 1988	30.0	50.8	64.3
Beach Angle (degrees)	Electronic Level	Wang et al., 2006	9.8	25.2	27.7
Active Scarp	Presence or Absence	Short and Hesp, 1982	0	0	200
Toppled Vegetation	Presence or Absence	Williams et al., 1999	0	0	200
Substrate >2 mm	Presence or Absence	Folk et al., 1970	0	0	200
Vegetated Backbeach	Presence or Absence	Hanslow, 2007	0	0	200
Beach Ridge	Presence or Absence	Goy et al., 2003	0	0	0

tide (Renaud et al., 2003). The neap tide range is about 0.2 m and the spring tide range is about 0.6 m. Low berm heights and

narrow beach widths are associated with erosion (Wang et al., 2006). Duplicate site measurements yield relative percent differences (RPD) ranging from 8.4-48.6% for berm height and 1.5-64.7% for beach width. The slope of the beach face was measured at three points for each transect at the midpoint between the berm and the water line using a 2 ft long electronic level. Beach slope increases with larger sediment size and lower wave energy (Wang et al., 2006). Duplicate site measurements yield a RPD from 0-64.7%.

The presence of the following characteristics indicate erosion. Active scarps are nearly vertical slopes located seaward of the berm and indicate higher wave energy than what formed the berm (Short and Hesp, 1982, Silva et al., 2014). Duplicate site measurements yield RPDs of 0-200%. Toppled vegetation indicates the loss of sediment

or soil around roots by erosion (Williams et al., 1999). Duplicate sites yield RPDs ranging from 0-200%. The presence of substrate greater than 2 mm on the foreshore was recorded. The presence of substrate larger than 2 mm is an indication of higher wave energy, which is more effective at eroding beaches and removing finer sediment (Folk et al., 1970). The RPD of substrate larger than 2 mm ranges from 0-200%.

The following characteristics are indicators of accretion, so the lack of these features indicates erosion. A beach ridge, or past berm, is located inland of the current berm, and indicates accretion (Goy et al., 2003). Duplicate site measurements yield RPDs ranging from 0-200%. A vegetated backbeach has ground vegetation and leaf litter that has not been eroded by waves overtopping the berm and uprooting plants or depositing sand on top of vegetation (Hanslow, 2007). Ground vegetation includes grass, forbs, and vines. The presence ground vegetation and leaf litter present indicates that waves have not had high enough energy recently to overtop the berm and affect the backbeach and vegetation (Miot da Silva et al., 2008). The RPD range for vegetated back beach is 0-200%.

Coral protection decreases the energy of the waves before they reach the shore, causing less erosion to occur than if there was no coral protection. In Hodges Bay where there is coral protection, it would be expected that berm heights would be greater, foreshore beach width would be narrower, and beach angle would be higher than in Malcolm Bay where there is no reef protection. Erosion indicators such as active scarps and toppled vegetation would be less prevalent in a coral protected bay, while accretion indicators such as beach ridges and vegetated backbeaches would be more common. The exception to this relationship is the presence of substrate greater than 2 mm. Larger

substrates are often associated with higher wave energy (Folk et al., 1970), but most of the large substrate in this region is composed of broken shells and coral. With Hodges Bay so close to the source of this larger substrate, it would be expected that there would be more of it on the beaches.

In May 2016, duplicates and two new sites were surveyed in a second round of field work. The previous sample sites were found again using the navigation tool on the Trimble GPS units. For duplicates, only the center transect was repeated. Accuracy and error analyses were run on the site triplicates and duplicates (Table 3). The coefficient of variation for the three transects within each sample site represents the spatial variation of the beach characteristics. The relative percent differences for the 11 duplicate sites represent temporal variability. The relative percent difference of the duplicate transects is two to three times higher than the coefficient of variation for the same variables. This shows temporal variability, as there is a five-month gap in time between duplicate surveys. Beaches are very dynamic systems, so this shows just how much the features on a beach can change in a fairly short amount of time.

Statistical Analysis

An Excel database of all of the data collected was created. This database allowed for the average, standard deviation, minimum, and maximum to be calculated. Several statistical analyses were run to determine the relationship between erosion rate and beach characteristics. Simple linear regressions analyze the relationship between a dependent variable and one independent variable. This analysis can be done in Microsoft Excel. Simple linear regressions were generated to try to show how each different beach

Table 3: Coefficient of Variation (CV %) is between the 3 transects within a sample site. Relative Percent Difference is between the same transect done during the January and May 2016 research trips.

	Spatial Variability (CV%) (Site triplicates- 20 m spacing)		Temporal Variability (RPD) (5 month duplicates)	
Beach Characteristic	Malcolm	Hodges	Malcolm	Hodges
Berm Height	15.1 %	15.8 %	31.9 %	22.3 %
Beach Width	15.1%	24.2 %	29.7 %	62.7 %
Beach Angle	10.0 %	15.7 %	19.5 %	29.1 %
Vegetated Backbeach	23.1 %	0 %	40 %	100 %
Active Scarp	5.8 %	39.4 %	80 %	100 %
Toppled Vegetation	34.6 %	47.2 %	80 %	100 %
Beach Ridge	0 %	0 %	80 %	0 %
Substrate >2 mm	17.3%	7.8 %	100 %	50 %

characteristic is related to erosion rate, but these regressions yielded extremely low R^2 values that showed no statistical significance, so other methods had to be pursued.

Multiple linear regression determines the relationship between the dependent variable and multiple independent variables, in this case recent erosion rate and a beach characteristics. Multiple regression is performed in IBM Statistical Package for the Social Sciences (SPSS), a software program that can be used for extensive statistical analyses (Rogerson, 2015). Multiple linear regression was used because no single beach characteristic was significantly related to recent erosion rate. The backwards phase of stepwise regression was used in order to maximize the number of possible erosion indicators for use in the erosion risk classification. Backwards multiple linear regression starts with all of the variables and removes the least significant variables one at time.

After selecting linear regression analysis, the dependent and independent variables are entered and the method is changed from "enter" to "backwards". The option to also generate correlations, descriptive statistics, covariance matrices, and plots can also be selected. The significance for backward multiple linear regression was set to 0.05, meaning it will eliminate the variables that are not significant and will cause the least amount of change in the R^2 value (Rogerson, 2015). The output window shows all of the statistics generated by the program.

Erosion Classification

Once the most statistically significant beach characteristics were determined, a classification system was developed to indicate areas of very high risk to low risk (Table 4). This classification was created in order to represent both erosion rates and erosion indicators in a simple, visual way that can be easily distributed and understood. Erosion rates indicate year to year changes in the beach, while erosion indicators indicate more seasonal and immediate erosion. The erosion indicators were chosen based on their statistical significance. Areas of long term erosion (2003-2016) are also identified. Having a classification system that considers both of these factors is good at identifying areas of risk. A map of erosion risk in Galleon Fish Sanctuary was then created using this classification. This map can be used to make recommendations for shoreline management in the study area so that the marine protected area can be sustained and flourish. An accompanying substrate map will show where there are mangroves, sand beaches, and coral reefs. For the purpose of this study, the shoreline will only be classified as mangrove if there are fringe mangroves or basin mangroves within 10 m of the berm, and

the rest will be classified as sand. Areas with the highest risk of erosion or a new occurrence of erosion indicators can be monitored more closely, especially if mangroves are at risk.

Table 4: The risk levels used for the Erosion Risk Map are based on the recent erosion rates from 2012-2016 and the erosion indicators that were found to be statistically significant in SPSS for each bay.

Risk Level	Description
Very High	Is actively eroding (> -0.34 m/yr) and displays erosion indicators.
High	Is actively eroding (> -0.34 m/yr) but does not display erosion indicators.
Moderate	Is currently stable or accreting (-0.34 to +2.62 m/yr) but displays erosion indicators.
Low	Is currently stable or accreting (-0.34 to +2.62 m/yr) and does not display erosion indicators.

CHAPTER 5- RESULTS AND DISCUSSION

Recent Erosion Rates

The updated erosion rates for the years 2012-2016 showed that most of the beach along the sanctuary is recovering or stable (Figure 14). Within the sanctuary, 24% of the shoreline was eroding (> -0.34 m/yr), 32% of the shoreline was stable (-0.34 m/yr to 0.34 m/yr) and 44% of the shoreline was accreting (> 0.34 m/yr). The range for stability is based on the test point error of the satellite images; anything within the range is insignificant. The average rate of shoreline change was +0.23 m/yr for 2012-2016, ranging from -2.95 m/yr to +2.62 m/yr, with an error of ±0.34 m/yr (Figure 15 and 16). For comparison, the 2003-2012 average rate of shoreline change was -0.21 m/yr and the range was from -2.23 m/yr to +1.42 m/yr (Figure 11) (Zelzer, 2015). Greater rates of accretion from 2012-2016 are likely due to the relative lack of storms compared to 2003-2012. By adding the recent vegetation line change to the historical vegetation line change for each transect, it was determined that only 36% of Malcolm Bay and 53% of Hodges Bay and Dead-Man Hole have recovered to their pre-Hurricane Ivan position (Figure 17). While this indicates that recovery is occurring, the damage done by hurricanes between 2004 and 2012 and the effects of sea level rise overall are still having effects on the shoreline. It is possible that sea level rise could also be playing a role in the area. If sea level rise is outpacing sediment deposition in the area, the beach would erode, and even if sea level rise and sediment deposition occurred at the same rate, the beach would not be able to recover nearly as quickly if at all from storms and other sources of erosion.

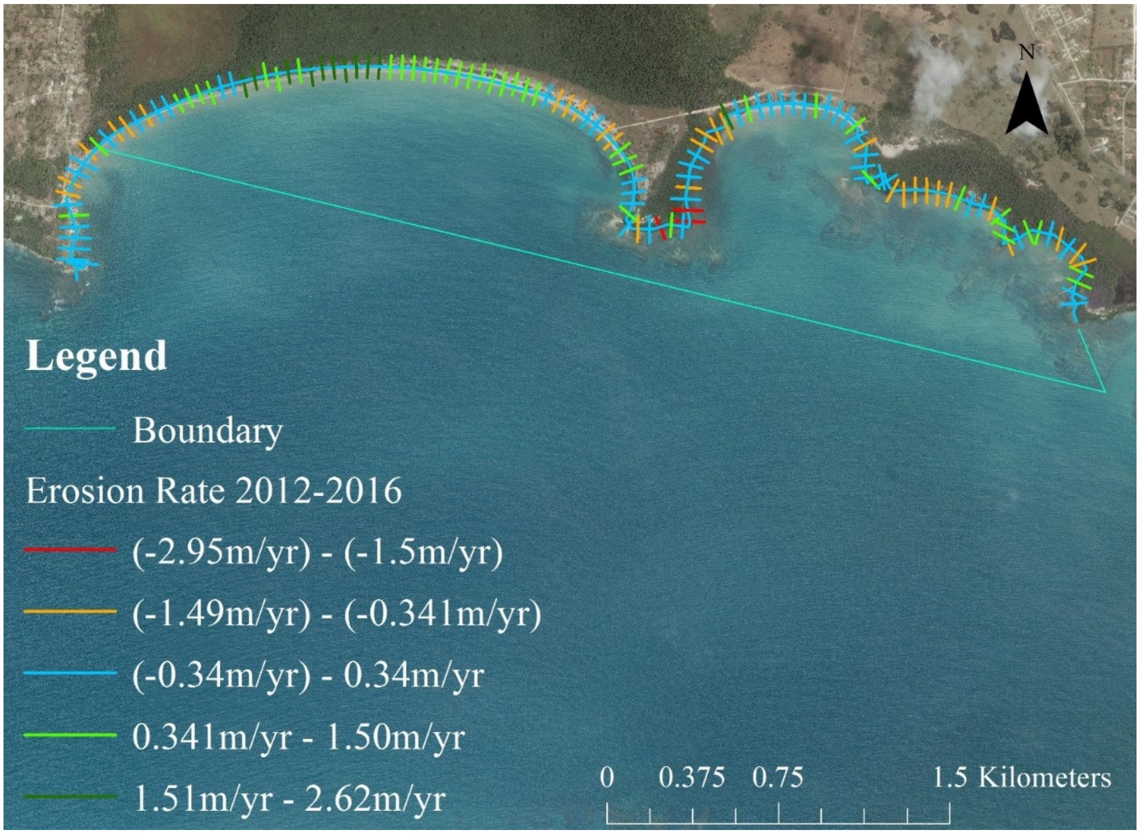

Figure 14: Recent shoreline change rates for 2012-2016 (this study). Satellite imagery is from 2003 and obtained from The Nature Conservancy (2010).

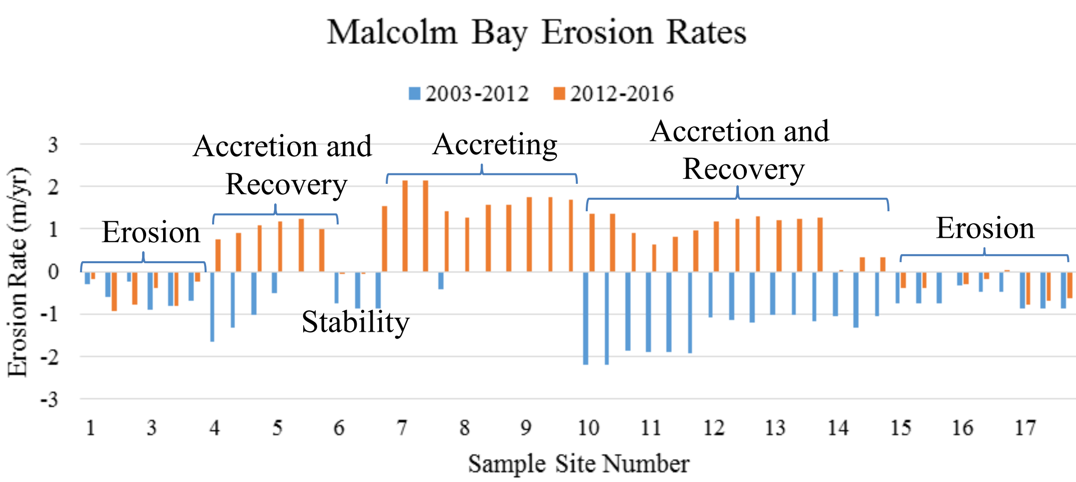

Figure 15: Comparison of beach change rate between the Zelzer (2015) erosion rates and the Geier erosion rates for Malcolm Bay. Positive erosion rates indicate accretion. The error is ±0.34 m/yr.

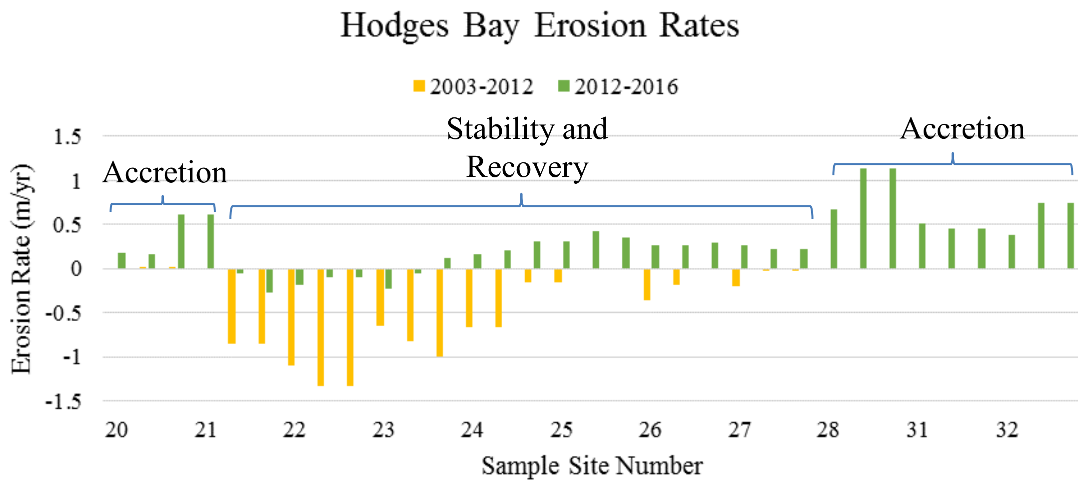

Figure 16: Comparison of beach change rate between the Zelzer (2015) erosion rates and the Geier erosion rates for Hodges Bay. Positive erosion rate indicates accretion. The error is ±0.34 m/yr.

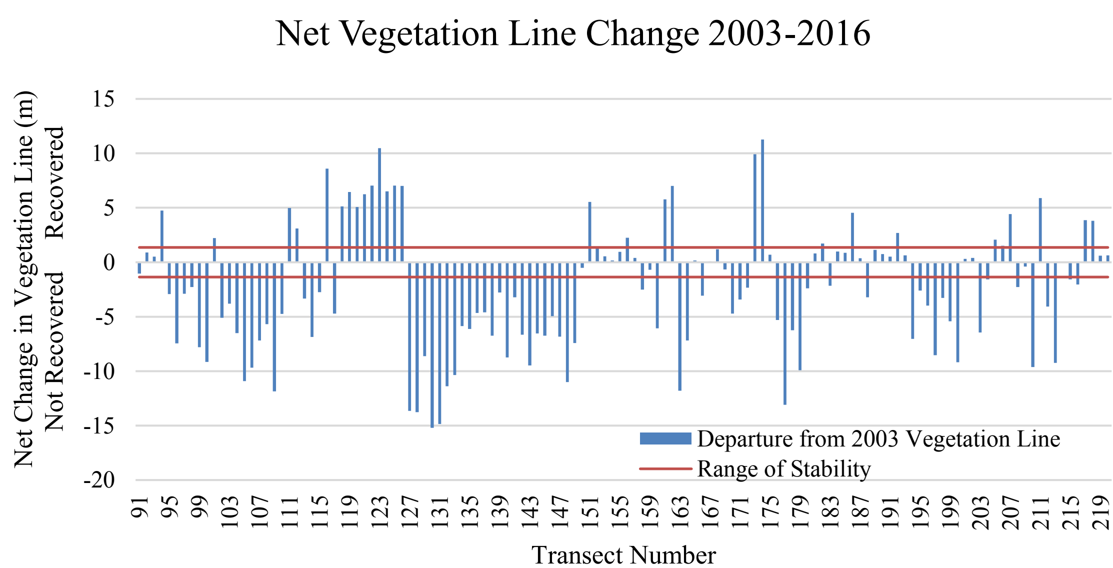

Figure 17: The net vegetation line change from 2003-2016 showing the number of beach transect that have recovered to their 2003 position and those that have not. The error is ±1.36 m.

Beach Morphology

Topographic beach profile data were analyzed to find the averages, standard deviation, and range of values (Table 5). They were also graphed to show general trends and variance (Figures 18 and 19). Berm height and beach width in Galleon Fish Sanctuary are much smaller than those reported in Wang et al. (2006). The average berm height in Galleon Fish Sanctuary was about a meter and the average width was about 8.63 m, compared to the Wang et al. (2006) average berm height of about 2 m and the average beach width of 36 m. The Wang et al. (2006) beach width was measured from the high tide line to the base of the first dune, however, so it would be expected to be wider. The average of the coefficient of variation for each beach characteristic is less than 20%, which shows that repeatability is good within the sample site.

Table 5: Descriptive statistics of the measured beach characteristics of Malcolm Bay and Hodges Bay.

Beach Characteristic	Mean	Standard Deviation	Maximum	Maximum Site	Minimum	Minimum Site
Malcolm Bay						
Berm Height (m)	0.98	0.34	1.81	14a	0.34	15c
Beach Width (m)	8.63	2.92	16	14b	3.6	3a
Beach Angle (degrees)	7.26	1.34	10.2	13c	4.1	4c
Hodges Bay						
Berm Height (m)	0.65	0.20	1.3	32b	0.4	23c
Beach Width (m)	7.05	2.4	15.1	22c	2.6	21b
Beach Angle (degrees)	5.61	1.24	9.13	32a	3.6	31a

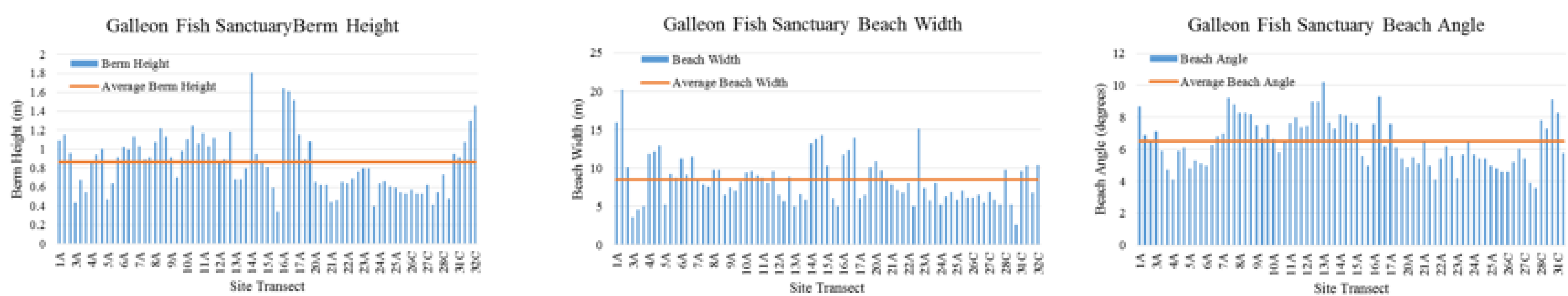

Figure 18: A) Berm height at each field transect with respect to average berm height. B) Beach width at each field transect with respect to average beach width. C) Beach angle at each field transect with respect to average beach angle.

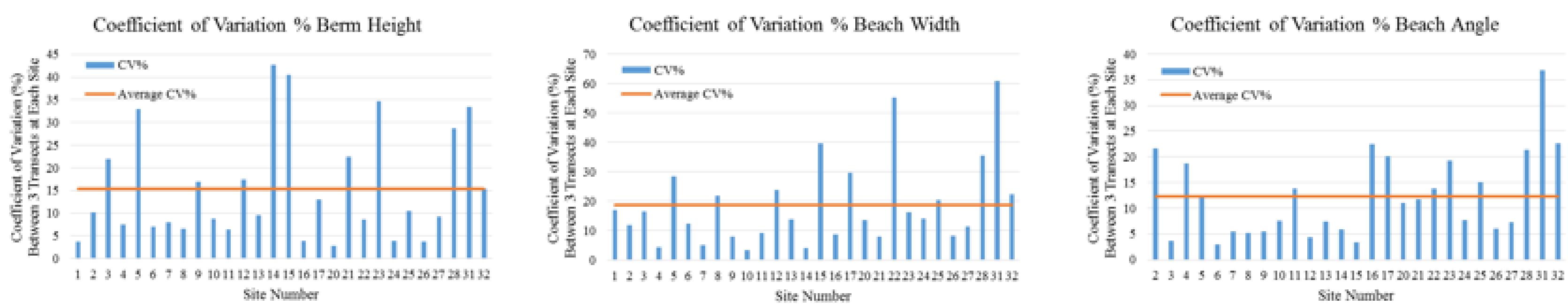

Figure 19: A) Coefficient of Variation for berm height at each sample site with respect to average CV% for berm height. B) Coefficient of Variation for beach width at each sample site with respect to average CV% for beach width. C) Coefficient of Variation for beach angle at each sample site with respect to average CV% for beach angle.

Features visible in the topographic profiles also indicate whether a beach is eroding, stable, or accreting. Erosional beaches are wide, with less distinct berms and low foreshore angles (Wang et al., 2006; Wright and Short, 1984). They may also have beach scarps, which indicate that wave energy is reaching further inland (Short and Hesp, 1982). Stable beaches are narrow, with distinct berms and high foreshore angles (Wright and Short, 1984). Accretionary beaches may have beach ridges, indicating the previous position of the berm before the beach grew out (Goy et al., 2003). The following beach profiles are examples of these three beach states (Figure 20).

Multiple Linear Regression

Multiple linear regression in SPSS was run using recent erosion rate as the dependent variable and the following as the independent variables: berm height, beach width, beach angle, active scarp, toppled vegetation, substrate greater than 2 mm, vegetated backbeach, and beach ridge. The model was run for the whole sanctuary using the recent erosion rates from 2012-2016 and the total erosion rates from 2003-2016. Then, Malcolm Bay and Hodges Bay were run separately because Hodges Bay is protected by extensive coral reef coverage, which influences the energy of waves approaching the shoreline. The models were selected had a combination of a significant F statistic, an R^2 value that indicates that at least half of variation in the erosion rate can be explained by the independent variables, and independent variables that were statistically significant, with a confidence interval of 95% (Appendix F). The SPSS results provide valuable information on how each of the beach characteristics is related to erosion or accretion rate (Table 6).

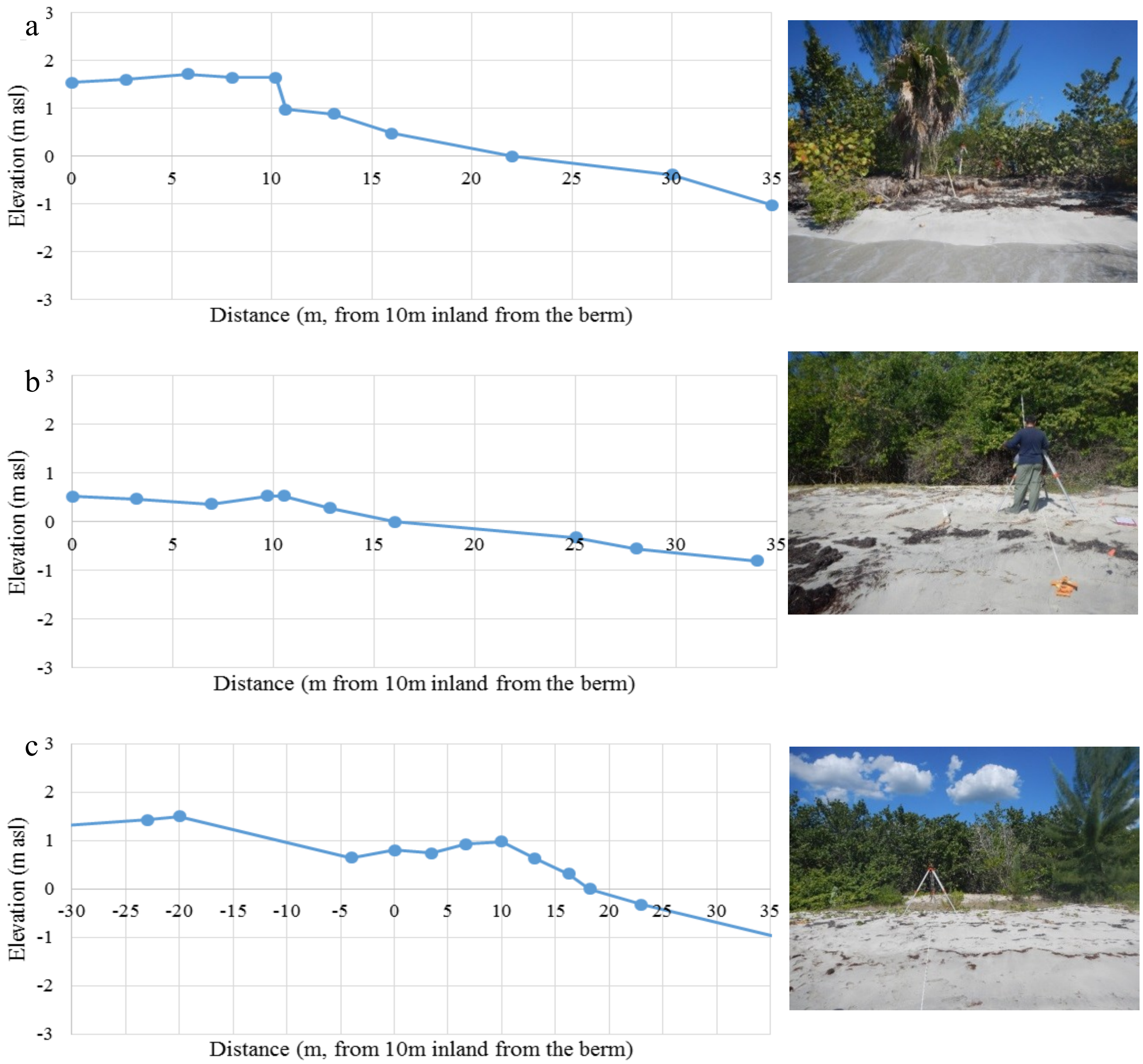

Figure 20: a) Site 16 T-1, an example of an erosional beach with a beach scarp. The erosion rate at this site was -0.38 m/yr. b) Site 27 T-2, an example of a stable beach with a distinct berm and a narrow shoreface. The beach change rate was +0.06 m/yr. c) Site 9 T-3, an example of an accretionary beach with a beach ridge. The accretion rate at this site was +1. 29 m/yr.

For the relationship between the recent erosion rate and the independent variables in the whole sanctuary, the 6th model with 3 of the 8 variables was used. This model had an R^2 value of 0.153 and an F value of 4.5. Toppled vegetation and substrate greater than 2 mm were statistically significant indicators of erosion, as they had negative regression coefficients. A relatively higher berm was associated with accretion, as it had a positive

regression coefficient. For the relationship between the total erosion rate and the independent variables in the whole sanctuary, the 7th model with 2 of the 8 variables was used. Active scarps indicated erosion, while vegetated backbeaches indicated accretion. This model had an R^2 value of 0.075 and an F value of 3.079, making this model statistically insignificant. Temporally, erosion and accretion indicators do not have a strong relationship with long term erosion trends. The model for the recent short term erosion rates indicates a better relationship with erosion and accretion indicators, but it still only explains about 15% of the beach change in the sanctuary. To determine if there is a geographic component to the relationship, the two bays were split. The extensive reef protection in Hodges Bay dissipates wave energy, causing the beaches in Hodges Bay to relatively more stable and accretionary than the dynamic beaches in Malcolm Bay (Maragos et al., 1996).

Table 6: SPSS results for how beach characteristics are related to beach change rate. For Malcolm Bay, positive coefficients represent accretionary characteristics while negative coefficients represent erosional characteristics. For Hodges Bay, positive coefficients represent accretionary characteristics while negative coefficients represent characteristics of stability.

	Malcolm Bay			Hodges Bay	
	Substrate < 2 mm $_a$	Vegetated Backbeach $_b$	Beach Ridge $_c$	Vegetated Backbeach $_d$	Beach Ridge $_e$
Regression Coefficient	-0.498	+0.647	+1.186	-0.591	-0.301
Standard Error	0.219	0.209	0.197	0.150	0.080
Standardized Coefficient	-0.246	+0.363	+0.707	-0.503	-0.444
Significance	0.028	0.003	<0.0005	<0.0005	0.001

For Malcolm Bay, the 6th model that had 3 of the original 8 variables is used. For this model, $R^2 = 0.509$, $F = 14.539$, Significance < 0.0005, and the regression equation was $Y= -0.174 – 0.498x_a + 0.647x_b + 1.186x_c$.. A negative coefficient is associated with erosion and a positive coefficient is associated with accretion. For Malcolm Bay, the presence of substrate greater than 2 mm was the best predictor of beach erosion, while the presence of beach ridges and a vegetated backbeach were the best predictors of accretion. All of these beach characteristics correspond to what would be expected on eroding or accreting beaches.

For Hodges Bay, the 7th model with 2 of the original 8 variables was used. For Hodges Bay, the $R^2= 0.58$, $F= 20.68$, significance < 0.0005, and the regression equation wass $Y= 0.984 – 0.591x_d – 0.301x_e$. The SPSS results can be found in Appendix F. These R^2 values show that more than half of the recent erosion rate values in both bays can be explained by these groups of variables. These R^2 values are much higher than the R^2 value for the whole sanctuary; the independent variables explain 51-58% of the beach change in the sanctuary. In Hodges Bay, the beach is either stable or accreting at all of the sample sites. Therefore, negative coefficients correspond to greater stability and positive coefficients correspond to accretion. The presence of vegetated backbeaches or beach ridges was a significant indicator of stability as opposed to accretion. Vegetated backbeaches are expected on stable beaches. A beach ridge could represent that the beach was previously accreting, but is now stable.

Erosion Risk Classification

The Galleon Fish Sanctuary was first classified based on substrate (Figure 21). The western part of Malcolm Bay, the point separating the two bays, and almost all of Hodges Bay and Dead-Man Hole have mangroves within 10 m of the berm. The part of Malcolm Bay closest to the harbor, and the eastern part of Malcolm Bay are sand beaches with no mangroves within the sample site. The mixed mangrove and sand area in Hodges Bay has sample sites where there are mangroves alternating with sample sites that did not have mangroves. Coral reefs are located in Hodges Bay, Dead-Man Hole, and bordering the headland that separates Malcolm Bay from Hodges Bay. Coral reefs attenuate wave energy, so it would be expected that coral reef protected beaches would experience less erosion than a beach with no coral reef protection (Maragos et al., 1996). This is the case for most of Hodges Bay and Dead-Man Hole, as there is less erosion in Hodges Bay and Dead-Man Hole than in Malcolm Bay. The exception is the headland that separates the bays. This could be caused by the greater energy of the waves that are reflected by the coral reefs and the headland rather (Carter et al., 1990). The coral reef may be too damaged to provide adequate protection, but this would need to be verified.

Using all of the data collected and analyzed, the shoreline of the Galleon Fish Sanctuary was classified and mapped based on erosion risk and the presence of toppled vegetation or substrate greater than 2 mm, the statistically significant erosion indicators found using SPSS (Figure 22, Table 7). The highest threat of erosion is along the east and west portions of Malcolm Bay, displaying both recent erosion and the presence of erosion indicators. The western very high risk area is mangrove forest, while the eastern very high risk area is sand beach. The mangrove forest along the resistant headland between

Figure 21: Map of beach type in the Galleon Fish Sanctuary based on field observations. The substrate is based on what was present 10 m landward from the berm. Mixed substrate had alternating sample sites of sand and mangrove.

the two bays and in the eastern part of Hodges Bay are currently experiencing erosion, and therefore are high risk areas. Galleon Harbor, where there are a few structures and livestock pastures close to the shore, is also a high risk area. Due to the fact that there are shops, houses, and farmland threatened by erosion in this part of the bay, action should be taken in this area. The moderate risk areas have erosion indicators but are currently stable or accreting, so there is less concern in these areas. Low risk areas should be checked intermittently for the appearance of erosion risk indicators. The high and very high risk areas are where waves converge because of the headlands, while low and moderate risk level areas are associated with diverging wave energy within the bays (Pipkin et al., 2011). The long term risk areas are where there is net erosion from 2003-2016, even if it has been depositional or stable in the past four years. These areas are where storm damage would likely be the greatest in the future.

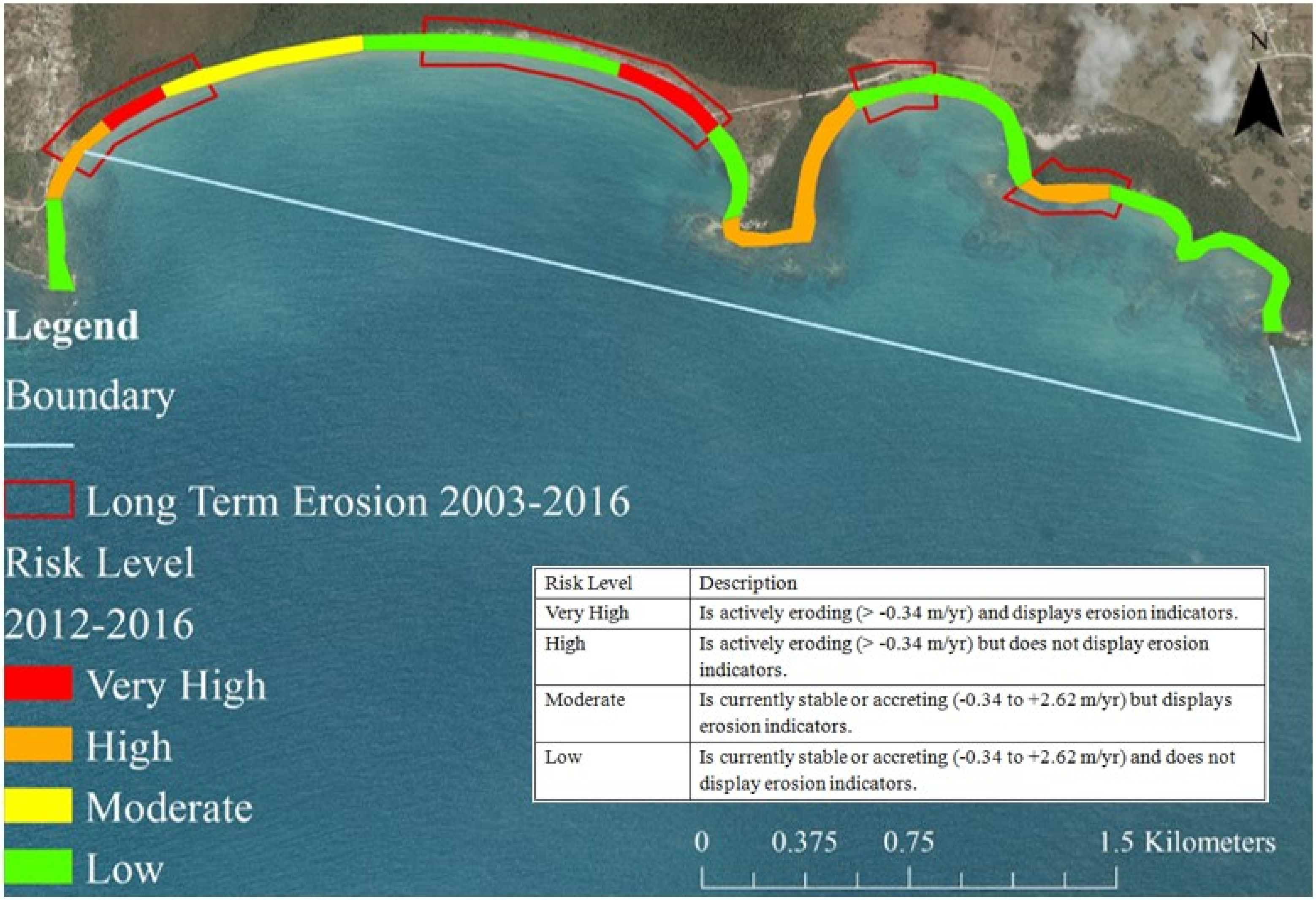

Figure 22: Erosion risk map for Galleon Fish Sanctuary. The areas in the east and west of Malcolm Bay classified as very high risk level should be monitored closely.

Table 7: Percent of each bay and the total sanctuary within each risk level category.

Risk Level	Malcolm Bay (%)	Hodges Bay (%)	Total Sanctuary (%)
Very High	20 %	0 %	11 %
High	12 %	36 %	23 %
Moderate	19 %	11 %	15 %
Low	49 %	53 %	51 %

Mangrove Forest Threats

Mangrove position was analyzed to gain a better understanding of the substrate along the beach. The mangroves on the seaward side of the berm can trap sediment to build the beach back out, anchoring the new sediment in place. The alternative is that they will die and fall over as their roots are loosened by lack of sediment. There is evidence of this happening elsewhere in the form of old root stumps and toppled mangrove vegetation on the beaches in some areas. There are more mangroves within 10 m of the berm in Hodges Bay than Malcolm Bay (Figure 23).

Based on the 2012-2016 erosion rates, a third of the mangrove beaches are eroding, and two thirds of the mangrove beaches are stable or accreting (Figure 24). The eroding mangroves are located in the western portion of Malcolm Bay, closest to the town of Crawford, and on headlands exposed the highest wave energy. The headlands themselves are made of resistant rock, but if the sediment mangroves need to grow is removed from the surface by erosion, mangroves will fall, causing the shoreline to appear to erode in satellite imagery. Conservation of the mangroves is important because they

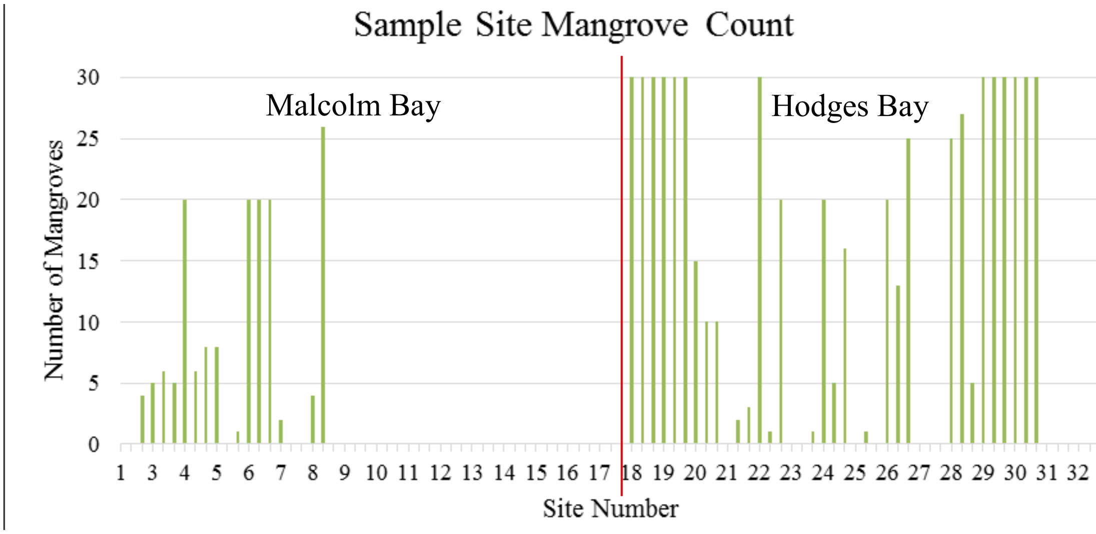

Figure 23: Number of mangroves at each sample site. The red line designates the split between Malcolm Bay and Hodges Bay. There are more mangroves within 10 m of the berm in Hodges Bay than Malcolm Bay.

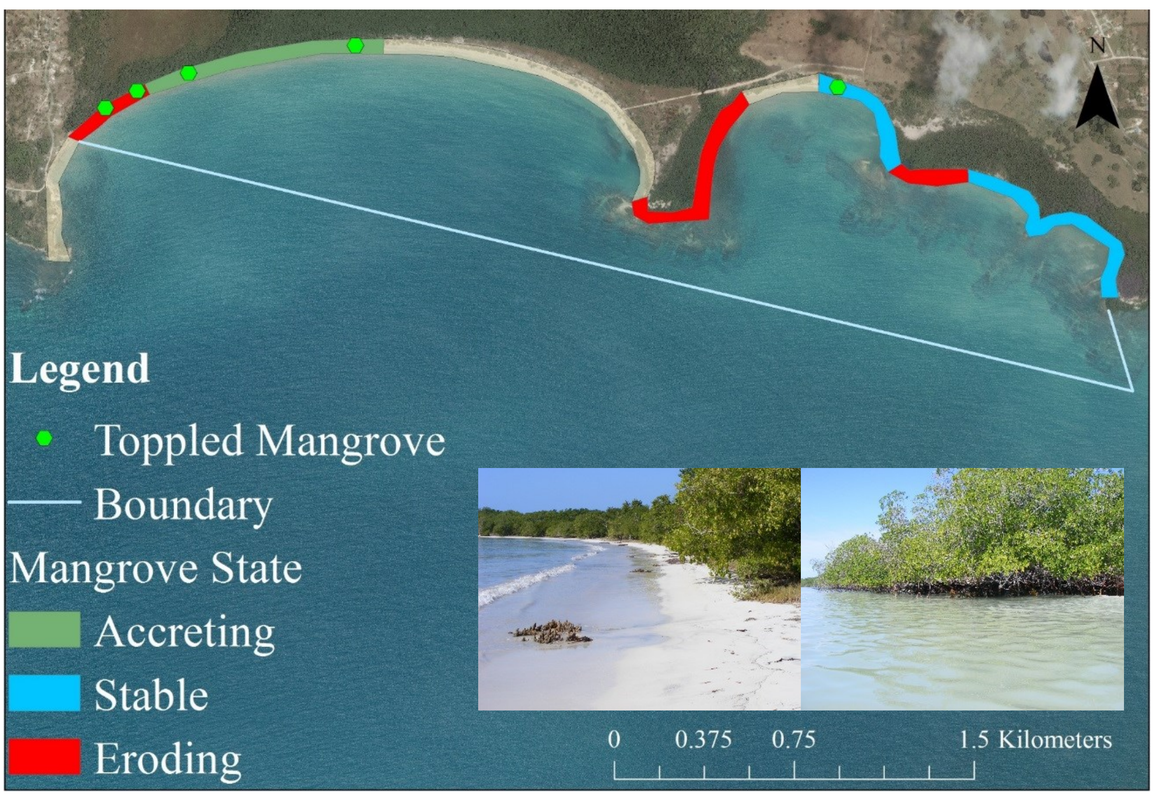

Figure 24: Mangroves in a state of erosion are at risk. Toppled vegetation is an erosion indicator.

filter runoff, serve as an important habitat for young fish, and anchor beaches. Mangrove restoration is already active in the Galleon Fish Sanctuary, but this information on where the mangroves are at the greatest risk of erosion can be used to allocate the resources for restoration more efficiently.

Outlook for Galleon Fish Sanctuary

The mangrove forest in the eastern part of Malcolm Bay and the sand beach on the western part of Malcolm Bay are at the greatest risk for erosion because of their location on the flanks of the headlands where the reflected wave energy is concentrated (Carter et al., 1990). These areas also have no coral protection to dissipate wave energy. With sea level rise and the erosion rates calculated by Zelzer (2015), a total of 4150 m of mangrove is at risk in the next 30 years. The average beach change rate for Galleon Fish Sanctuary is +0.23 m/yr. Robinson et al. (2012) determined that the erosion rate for Negril, Jamaica to be -0.41 m/yr. Therefore, Galleon Fish Sanctuary is doing better than developed tourist areas in Jamaica and areas that are not protected by coral reefs, mangroves, and embayments.

CHAPTER 6- CONCLUSIONS

The risk of erosion threatens beaches around the world. Geomorphic indicators and GIS can be used to determine where erosion risk is the greatest. Little previous research on beach morphology and erosion indicators had been done in Jamaica. The Galleon Fish Sanctuary's importance as a natural resource and its diverse and complex beach types make it an ideal location for the creation of a classification system for erosion risk.

A geomorphic assessment of Galleon Fish Sanctuary included topographic profiles of shorelines, erosion indicators, and vegetation. Shoreline change rates were updated for the years 2012-2016, and the relationship between these erosion and accretion rates and the geomorphic beach characteristics were determined. An erosion risk classification was created based on these relationships. Field research was conducted in January and May of 2016. The following are the key findings of this study:

1) The average erosion rate for the updated recent erosion rates from the years 2012-2016 was found to be +0.23 m/yr with a range of -2.95 m/yr to +2.62 m/yr. Within the sanctuary, 24% of the shoreline was eroding, 32% of the shoreline was stable, 44% of the shoreline was accreting. The Galleon Fish Sanctuary is therefore doing well compared to many of the beaches in the world, but erosion is still a concern.

2) Malcolm Bay does not have the coral reef protection that Hodges Bay does, so it experienced more erosion when Hurricane Ivan hit in 2004. It was determined that 36% of Malcolm Bay and 53% of Hodges Bay and Dead-Man Hole have recovered to their pre-Hurricane Ivan position. No hurricanes have come within 75 nautical miles of Jamaica within the past 4 years, which has given some beaches in the sanctuary a sufficient amount of time to recover from the storms that occurred between 2003 and 2012. However, when the next hurricane does hit the south coast of Jamaica, erosion could be extensive, and continued sea level rise will impede recovery.

3) One third of the mangrove-lined along the shoreline is eroding, especially on the flanks of the resistant headland. This is due to the wave convergence along the headland and possible degradation of the protective reefs. Damage to the mangroves that

provide protective anchoring to the beaches is a concern for beach health. Reforestation of eroding areas should be expanded based on the findings of this study.

4) Multiple linear regression was used to evaluate the relationships between beach morphology and recent erosion rates (2012-2106). For the whole sanctuary, toppled vegetation and substrate greater than 2 mm were the most statistically significant erosion indicator. In Malcolm Bay, erosion is associated with substrate less than 2 mm. In Hodges Bay, none of the sampled sites were eroding. Vegetated backbeaches and beach ridges indicated more stable beaches. These beach characteristics can be used by management to identify eroding beaches. Multiple linear regression using the long term erosion rates (2003-2016) found active scarps to be the best indicator of long term erosion, but it was not statistically significant.

5) Significant erosion indicators and current erosion rates were used to classify the beaches in the Galleon Fish Sanctuary based on risk from very high to low. A map was then created to show erosion risk in the fish sanctuary. This map and classification system will be shared with the managers of the Galleon Fish Sanctuary. In Malcolm Bay, 49% of beaches had a low erosion risk, 19 % had a moderate erosion risk, 12 % had a high erosion risk, and 20% had a very high erosion risk. In Hodges Bay, 53% of beaches had a low erosion risk, 11% had a moderate erosion risk, and 36% had a high erosion risk. Beaches classified as having a very high risk of erosion should be monitored more closely by the sanctuary managers.

In the future, a more extensive study on the mangrove forests could be completed in order to gain a better understanding of the health of the forests and their ability to protect the shoreline. Erosion rates can be updated whenever new satellite imagery becomes available so that the beach can be monitored remotely. Resurveying the beaches could also provide information on whether erosion continued to occur where erosion indicators were present or if the beach has stabilized or accreted. The developed classification system could also be used on other beaches in the Jamaica or the Caribbean threatened by erosion.

The east (beach kilometer 0.25 km- 0.8 km) and west (beach kilometer 2.5 km- 2.85 km) portions of Malcolm Bay located on the flanks of the headlands have high or very high erosion risk classification levels. The eastern part of Malcolm Bay is where Galleon Harbour, the town of Crawford, and the mangrove forest is located. Therefore,

this area should be a priority for managers to monitor, as buildings and structures are in jeopardy. In Hodges Bay, mangrove forests along the headlands (beach kilometer 3.25 km- 4.15 km and 5.05 km- 5.4 km) are classified as high erosion risk. Efforts to replant mangroves should be concentrated in the areas where they are at the greatest risk. The central part of Malcolm Bay and most of Hodges Bay have a low to moderate risk level and therefore there is the least concern in these areas.

Scientifically, classifying beaches by erosion risk is important for communication about beach changes. Sharing methods and results helps expand the extent and efficiency of research. Combining field and remote sensing based methods allows for a comprehensive understanding of beach changes. Recent erosion rates provide up to date information about where erosion is occurring in the sanctuary. The significant erosion indicators found using statistical analyses provide simple, visual signs that managers can use to deduce where erosion is occurring without field equipment and remote sensing programs. The assessment of beach form, beach change, and mangrove interactions in the Galleon Fish Sanctuary provides managers with information they can use to ensure the health and sustainability of the sanctuary.

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APPENDICES

Appendix A: GIS Data

Maps throughout this thesis were created using ArcGIS® software by Esri. ArcGIS® and ArcMap™ are the intellectual property of Esri and are used herein under license. Copyright © Esri. All rights reserved. For more information about Esri® software, please visit www.esri.com.

Appendix A-1**.** Satellite Image Data Sources

Data Source	Data	Year of Map
The Nature Conservancy, MONA GeoInformatics	Multispectral Imagery, Base Map	2003
Digital Globe	GeoEye Multispectral and Panchromatic Imagery	2012
Google Earth Pro, CNES/Astrium	Multispectral Imagery, JPEG	2016

Appendix A-3**.** Trimble GPS point accuracy, differentially corrected using MONA base provider as a reference.

Range	Percentage
0.15 m- 0.30 m	2.8 %
0.30 m- 0.5 m	35.9 %
0.5 m- 1.0 m	34.5 %
1.0m – 2.0 m	25.5 %
2.0 m- 5.0 m	1.3 %

Appendix A-2**.** Test Point Error for 2016 Google Earth Pro Georectified Image. The test point error is found using the distance formula. The average distance for these six test points is 1.36 m.

Year	Point X	Point Y	Distance
2016	191402.4165	1995954.274	1.381168
2012	191403.713	1995954.75	
2016	191773.0192	1996951.385	1.322919
2012	191773.0192	1996950.062	
2016	197154.0067	1995926.146	2.831171
2012	197156.2557	1995924.426	
2016	196782.9278	1996276.72	1.04586
2012	196782.3325	1996275.86	
2016	191240.5362	1997312.257	1.206688
2012	191241.277	1997311.305	
2016	197734.164	1996482.09	0.363073
2012	197733.9008	1996481.84	

Appendix B: Sample Site Locations

Appendix B-1. From Trimble GPS points in the field

Malcolm Bay

Site	Longitude	Latitude
1a	-77.9097	18.0328
1b	-77.9096	18.0329
2a	-77.9084	18.0338
3a	-77.9073	18.0344
3b	-77.9072	18.0345
3c	-77.9070	18.0346
4a	-77.9060	18.0349
4b	-77.9059	18.0349
4c	-77.9057	18.0349
5a	-77.9054	18.0351
5b	-77.9051	18.0352
5c	-77.9050	18.0352
6a	-77.9039	18.0354
6b	-77.9037	18.0356
6c	-77.9036	18.0356
7a	-77.9030	18.0357
7b	-77.9028	18.0358
7c	-77.9026	18.0358
8a	-77.9009	18.0361
8b	-77.9007	18.0361
8c	-77.9005	18.0362
9a	-77.8988	18.0363
9b	-77.8986	18.0363
9c	-77.8984	18.0363
10a	-77.8974	18.0363
10b	-77.8972	18.0363
10c	-77.8970	18.0363
11a	-77.8963	18.0363
11b	-77.8961	18.0363
11c	-77.8960	18.0363
12a	-77.8944	18.0362
12b	-77.8942	18.0361
12c	-77.8940	18.0361
13a	-77.8932	18.0360
13b	-77.8931	18.0360
13c	-77.8929	18.0359
14a	-77.8917	18.0357
14b	-77.8916	18.0357
14c	-77.8913	18.0356
15a	-77.8911	18.0355
15b	-77.8909	18.0354
15c	-77.8907	18.0354
16a	-77.8897	18.0350
16b	-77.8894	18.0348
16c	-77.8893	18.0348
17a	-77.8886	18.0344
17b	-77.8885	18.0342
17c	-77.8884	18.0341

Hodges Bay

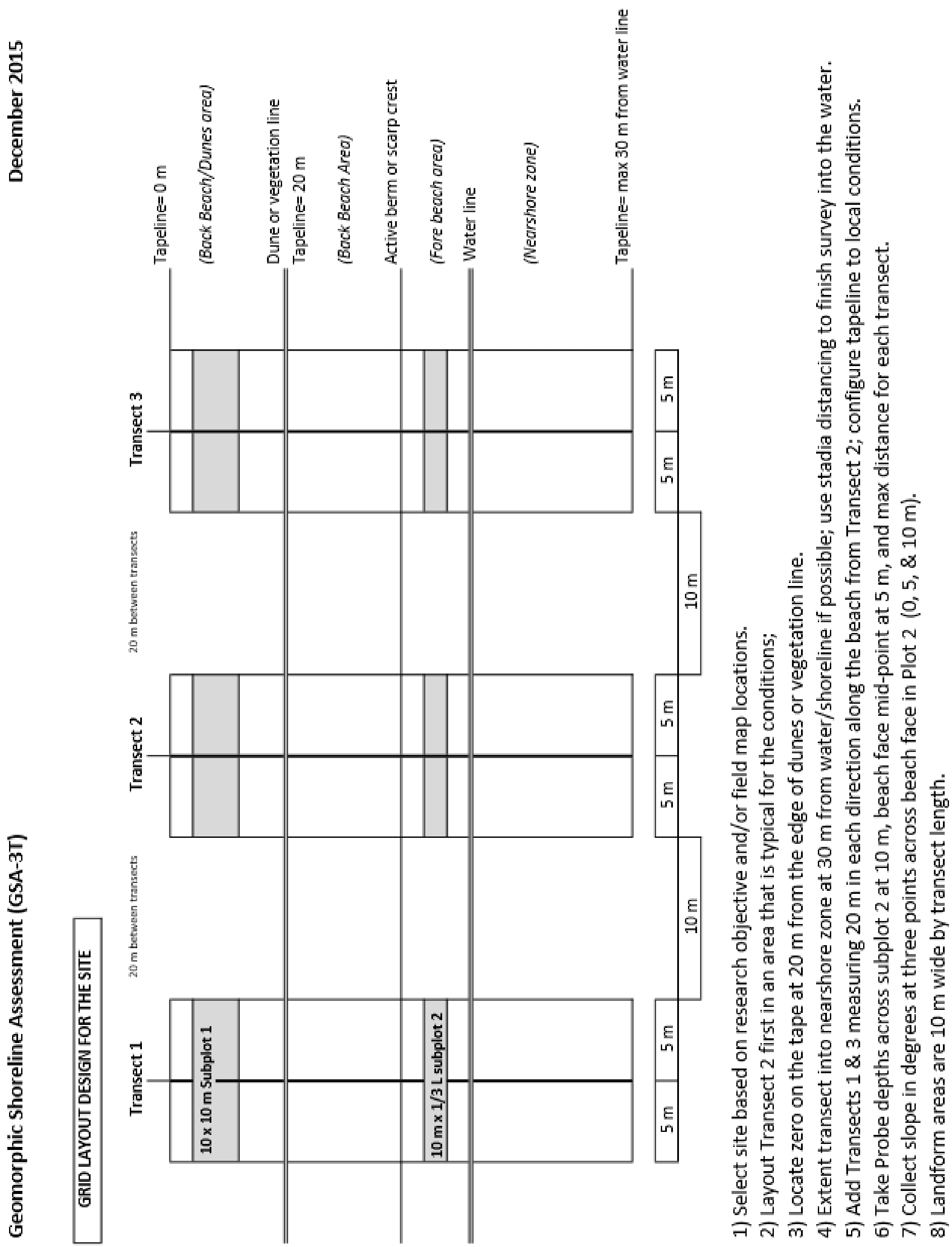
Site	Longitude	Latitude
20a	-77.8832	18.0347
20b	-77.8830	18.0347
20c	-77.8829	18.0348
21a	-77.8829	18.0347
21b	-77.8826	18.0349
21c	-77.8825	18.0349
22a	-77.8824	18.0350
22b	-77.8822	18.0350
22c	-77.8820	18.0351
23a	-77.8816	18.0351
23b	-77.8814	18.0351
23c	-77.8812	18.0352
24a	-77.8808	18.0352
24b	-77.8806	18.0352
24c	-77.8804	18.0351
25a	-77.8803	18.0351
25b	-77.8801	18.0351
25c	-77.8799	18.0351
26a	-77.8798	18.0350
26b	-77.8796	18.0350
26c	-77.8794	18.0350
27a	-77.8791	18.0349
27b	-77.8789	18.0349
27c	-77.8787	18.0348
28a	-77.8786	18.0347
28b	-77.8784	18.0346
28c	-77.8782	18.0345
31a	-77.8724	18.0312
31b	-77.8722	18.0311
31c	-77.8721	18.0310
32a	-77.8720	18.0309
32b	-77.8719	18.0308
32c	-77.8718	18.0306

Appendix B-2. By transect number and beach kilometer

Beach Km	Transect	Site Number	Beach Km	Transect	Site Number	Beach Km	Transect	Site Number
Malcolm Bay			2.15	134	Site 12	4.25	176	Site 22
0	91		2.2	135		4.3	177	
0.05	92		2.25	136	Site 13	4.35	178	Site 23
0.1	93		2.3	137		4.4	179	
0.15	94		2.35	138		4.45	180	Site 24
0.2	95		2.4	139		4.5	181	Site 25
0.25	96		2.45	140	Site 14	4.55	182	Site 26
0.3	97		2.5	141	Site 15	4.6	183	Site 27
0.35	98		2.55	142		4.65	184	
0.4	99		2.6	143		4.7	185	Site 28
0.45	100	Site 1	2.65	144	Site 16	4.75	186	Site 29
0.5	101		2.7	145		4.8	187	Site 30
0.55	102		2.75	146		4.85	188	
0.6	103	Site 2	2.8	147	Site 17	4.9	189	
0.65	104		2.85	148		4.95	190	
0.7	105		2.9	149		5	191	
0.75	106	Site 3	2.95	150		5.05	192	
0.8	107		3	151		5.1	193	
0.85	108		3.05	152		5.15	194	
0.9	109	Site 4	3.1	153		5.2	195	
0.95	110	Site 5	3.15	154		5.25	196	
1	111		3.2	155		5.3	197	
1.05	112		3.25	156		5.35	198	
1.1	113	Site 6	3.3	157		5.4	199	
1.15	114		3.35	158		5.45	200	
1.2	115		3.4	159		5.5	201	
1.25	116	Site 7				5.55	202	
1.3	117		Hodges Bay			5.6	203	
1.35	118		3.45	160		5.65	204	Site 31
1.4	119		3.5	161		5.7	205	Site 32
1.45	120	Site8	3.55	162		5.75	206	
1.5	121		3.6	163		5.8	207	
1.55	122		3.65	164		5.85	208	
1.6	123		3.7	165		5.9	209	
1.65	124		3.75	166		5.95	210	
1.7	125	Site 9	3.8	167		6	211	
1.75	126		3.85	168		6.05	212	
1.8	127		3.9	169		6.1	213	
1.85	128	Site 10	3.95	170		6.15	214	
1.9	129		4	171		6.2	215	
1.95	130	Site 11	4.05	172	Site 18	6.25	216	
2	131		4.1	173	Site 19	6.3	217	
2.05	132		4.15	174	Site 20	6.35	218	
2.1	133		4.2	175	Site 21	6.4	219	

Appendix C: Field Sheets

Appendix C-1. Front page of Geomorphic Shoreline Assessment form for sample site set up.



Appendix C-2. Back Page of Geomorphic Shoreline Assessment form for sample site set up.

GSA-3T Field Codes

FORM TYPES

Nearshore	
Cor	Coral head/patch
Reef	Reef flat/platform
N	Nearshore bed
Bar	Longshore Bar
TR	Longshore Trough
Fore beach	
BF	Beach face
AB	Active berm crest
SC	Scarp crest
Back beach	
B	Backbeach
PB	Past berm crest
Coast	
DU	Dune
ID	Interdune
Mar	Marsh/lagoon
OV	Overwash fan
RT	Reef terrace
OT	Other terrace
PL	Flat plain/field
BL	Bluff/hillslope
Other	
Mon	Monument
X	Structure

SUBSTRATE

X	Hard Artificial
R	Road/trail (dirt)
RR	Reef rock
OR	Other rock
E	Cut earth
6	Cobbles (> golf ball)
5	Pebbles (>2 mm)
4	Coral/shells (>2 mm)
3	Sand
2	mud/fines
1	Soil

Appendix C-3. Front Page of Beach Profiles form for recording survey points.

Jamaica Beach Profiles- Jan 2016

Location=	Team=	Site=	Date=	Time=

Profile A

Aspect Azimuth (°)=

No.	Tape	Stadia (m)		Station			
	Dist. (m)	(+)	(-)	Form	Sub.	Rod Ht.	W/P D
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							
11							
12							
13							
14							
15							
16							
17							
18							
19							
20							

GPS Points (0m, veg & water lines)

Pictures (Veg & water lines, berm to sea)

Reef protection (<200 m) YES NO MAYBE

Profile B

Aspect Azimuth (°)=

No.	Tape	Stadia (m)		Station			
	Dist. (m)	(+)	(-)	Form	Sub.	Rod Ht.	W/P D
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							
11							
12							
13							
14							
15							
16							
17							
18							
19							
20							

GPS Points

Camera Pics

YES NO MAYBE

Profile C

Aspect Azimuth (°)=

No.	Tape	Stadia (m)		Station			
	Dist. (m)	(+)	(-)	Form	Sub.	Rod Ht.	W/P D
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							
11							
12							
13							
14							
15							
16							
17							
18							
19							
20							

GPS Points

Camera Pics

YES NO MAYBE

Appendix C-4. Back Page of Beach Profiles form for recording beach characteristics.

Team=	Site=	Date=	GSA-3T Jan 2016

Erosion Indicator Rating

0- none	3- half affected
1- present	5- all affected

	Fore shore Rating Score By Transect Grid			*Back beach* Rating Score By Transect Grid		
	T-1	T-2	T-3	T-1	T-2	T-3
1) Eroded and bare back beach/dunes						
2) Recent beach scarps						
3) Overwash fan deposits						
4) Reef rock failures						
5) Reef rock debris/deposits						
6) Marsh peat exposed on beach						
7) Narrow beach, no dry areas						
8) Toppled vegetation						
9) Woody debris strandlines (>0.1 m dia)						
10) Artificial structures undermined						

Beach Face Slope

Transect	Slope in degrees			Avg
	i	ii	iii	
T-1				
T-2				
T-3				

Soil Depth

Soil Layer	Depth in cm (10 m SP 1)			Avg
	T-1	T-2	T-3	
Litter				
Duff				
A-hor				

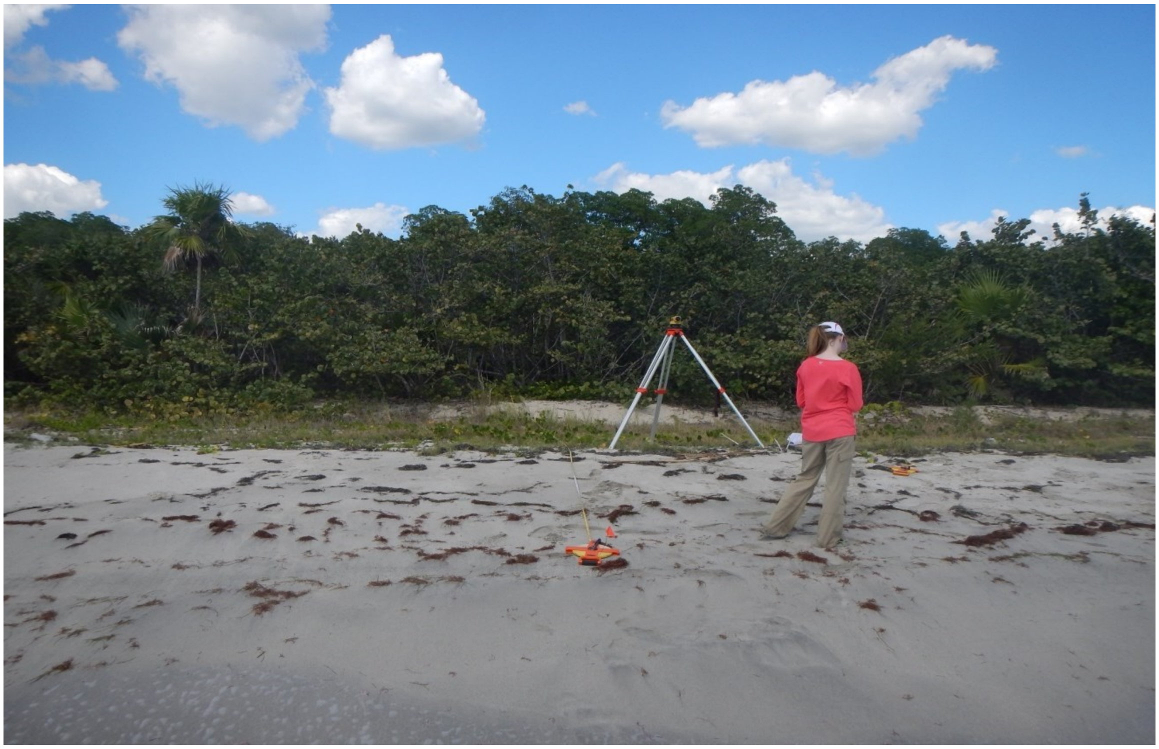
Substrate Types	*Assess subplot 2 area* Substrate % (=100%)		
	T-1	T-2	T-3
Hard Artificial			
Road/trail (dirt)			
Reef rock			
Other rock			
Cut earth			
Cobbles (> golf ball)			
Pebbles (>2 mm)			
Coral/shells (>2 mm)			
Sand			
mud deposit			
Soil			
SUM			

Ground/Canopy Cover <0.5 m ht (%)

	Artificial	Rock	Sand	Soil	Litter	Grass	Vines	Forbs
T-1								
T-2								
T-3								

	Canopy Cover %			Stem Count			Mangrove stems (no.)			Max. DBH (m)	
	0.5-2 m	2-5 m	>5 m	Shrubs	Trees >1"	Trees >5"	Red	Black	White	1	2
T-1											
T-2											
T-3											

Appendix D: Photo Log



Survey set up with auto level on berm crest, tape pinned with 10 m at berm crest.

Example of an accretionary beach with a beach ridge.


Typical sand beach at Galleon Fish Sanctuary with ground vegetation landward of berm.


The berm has migrated into the mangrove forest, but there is still beach in front of it.

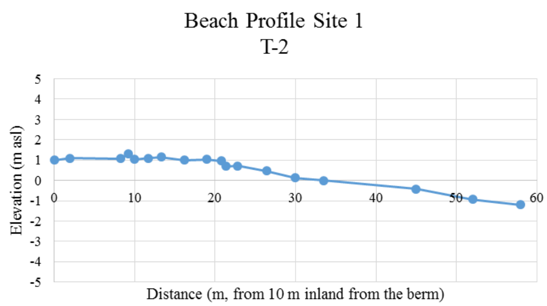

Mangrove forest with very narrow beach.

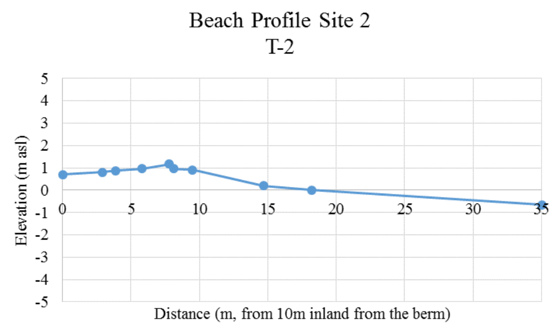

Site 16, Transect 1: An example of an eroding beach with an active scarp.

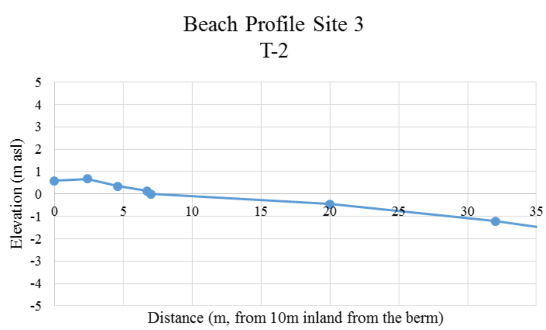
Site 6, Transect 2: Example of a stable beach.

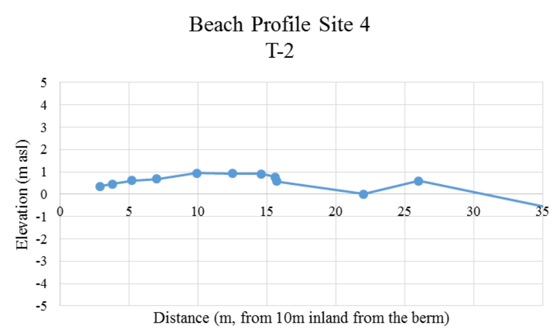
Example of an accretionary beach building out from present berm.

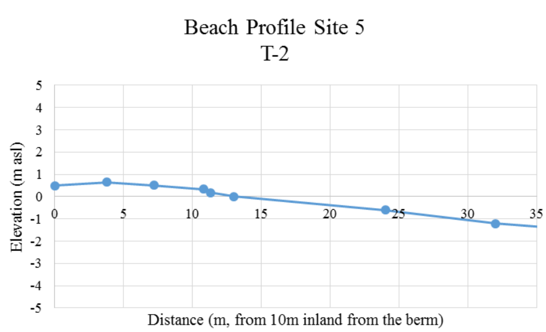
Appendix E: Selection of Beach Profiles

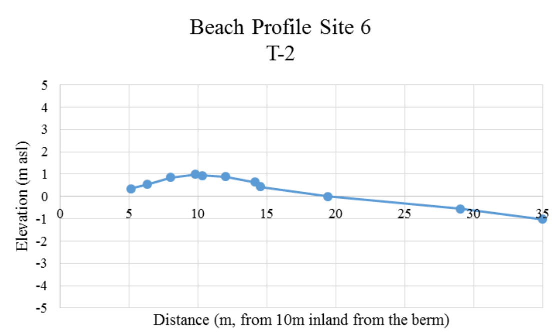


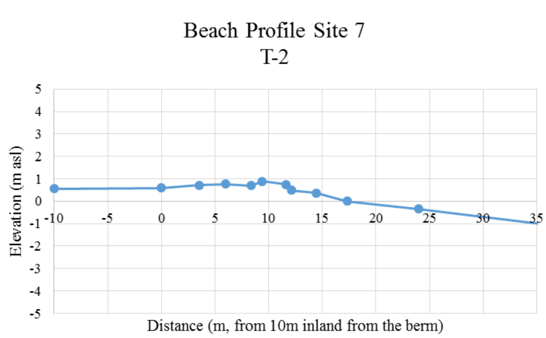


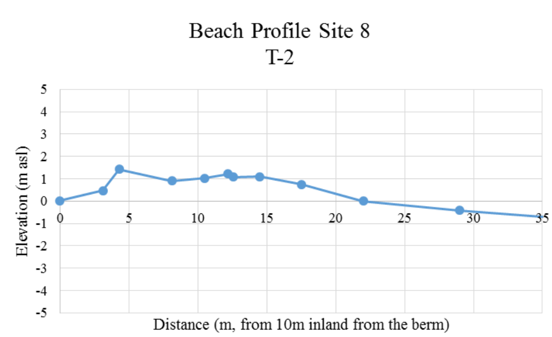


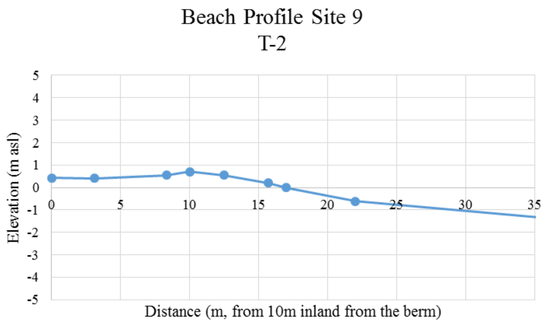


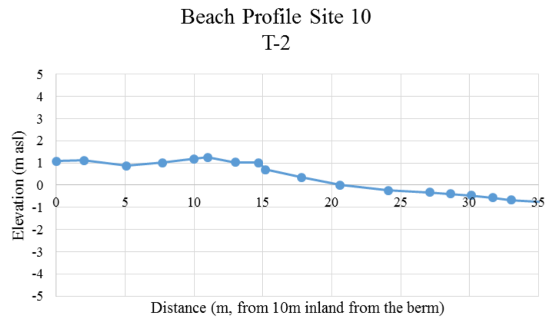


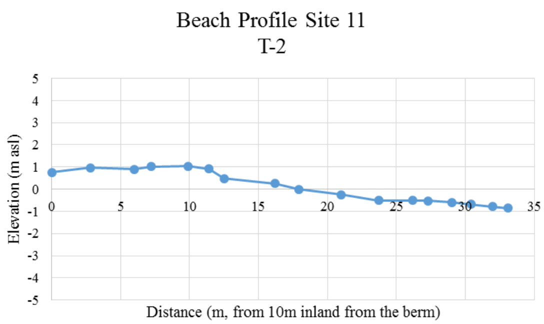


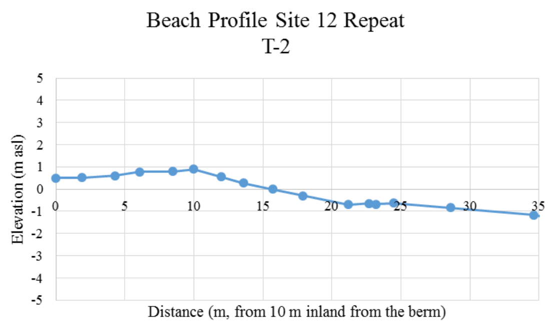


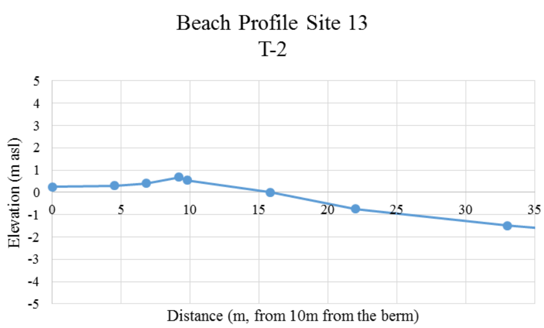


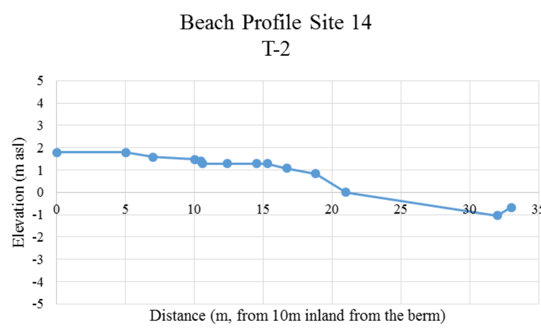

Beach Profile Site 9
T-2
Elevation (m asl)
Distance (m, from 10m inland from the berm)

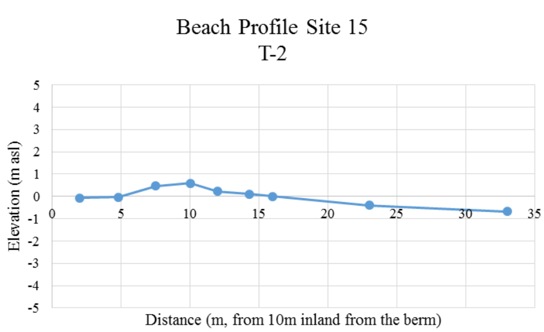

Beach Profile Site 10
T-2
Elevation (m asl)
Distance (m, from 10m inland from the berm)

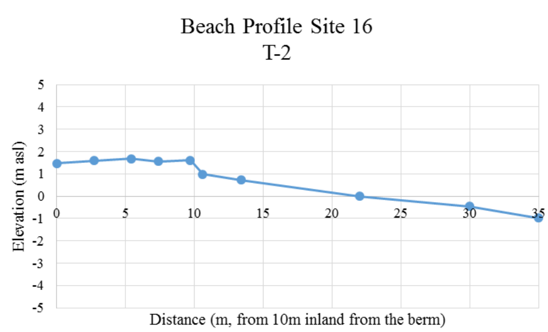

Beach Profile Site 11
T-2
Elevation (m asl)
Distance (m, from 10m inland from the berm)

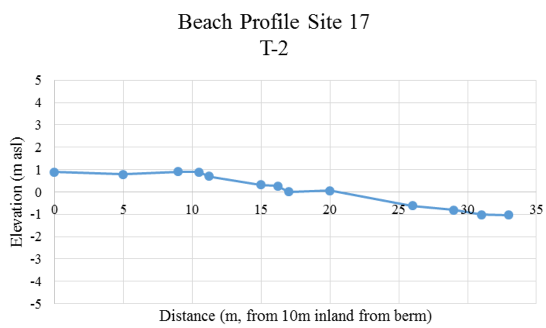

Beach Profile Site 12 Repeat
T-2
Elevation (m asl)
Distance (m, from 10 m inland from the berm)

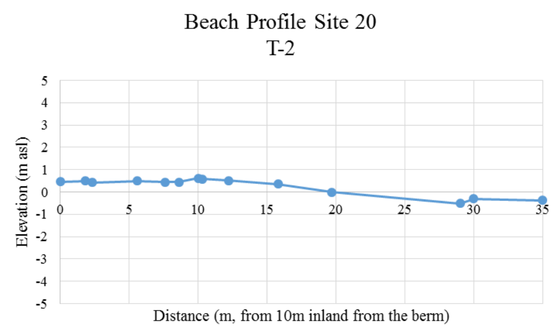

Beach Profile Site 13
T-2
Elevation (m asl)
Distance (m, from 10m from the berm)

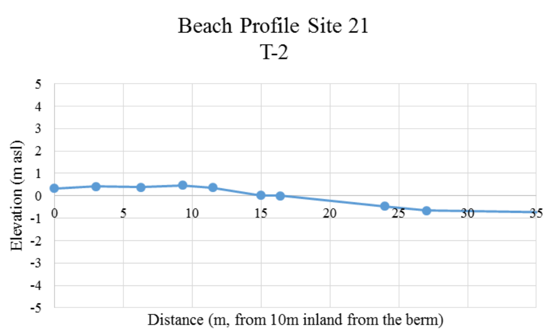

Beach Profile Site 14
T-2
Elevation (m asl)
Distance (m, from 10m inland from the berm)

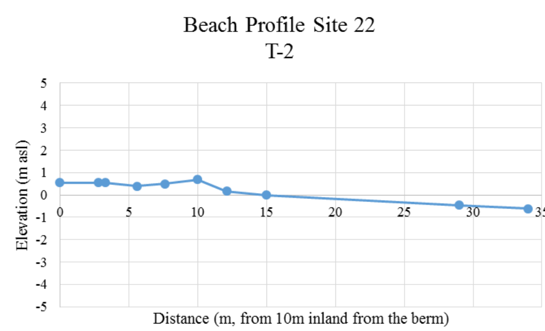

Beach Profile Site 15
T-2
Elevation (m asl)
Distance (m, from 10m inland from the berm)

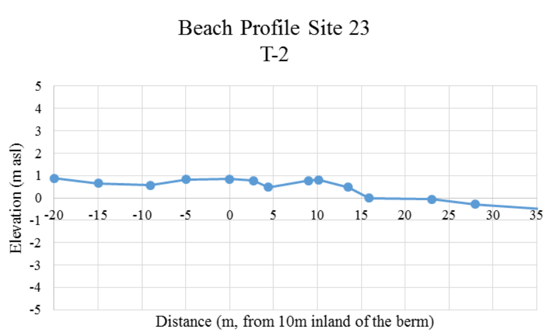

Beach Profile Site 16
T-2
Elevation (m asl)
Distance (m, from 10m inland from the berm)

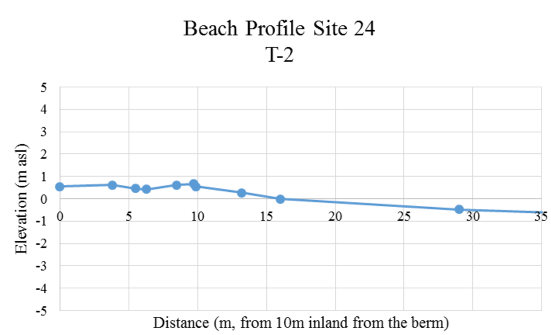

Beach Profile Site 17
T-2
Elevation (m asl)
Distance (m, from 10m inland from berm)

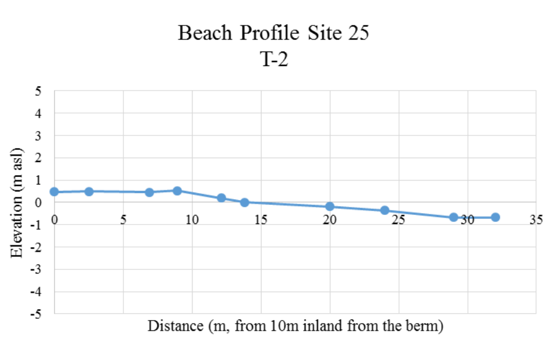

Beach Profile Site 20
T-2
Elevation (m asl)
Distance (m, from 10m inland from the berm)

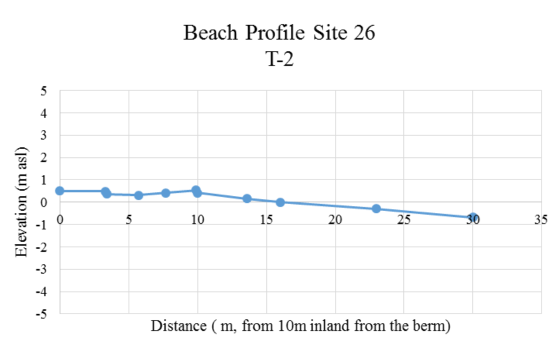

Beach Profile Site 21
T-2
Elevation (m asl)
Distance (m, from 10m inland from the berm)

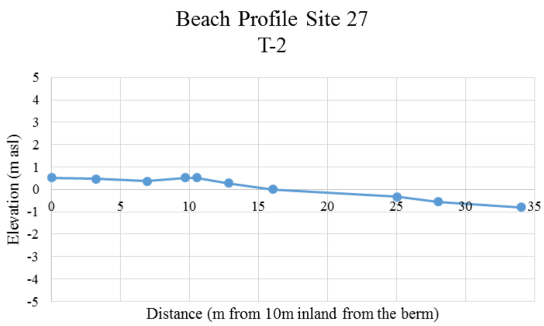

Beach Profile Site 22
T-2
Elevation (m asl)
Distance (m, from 10m inland from the berm)

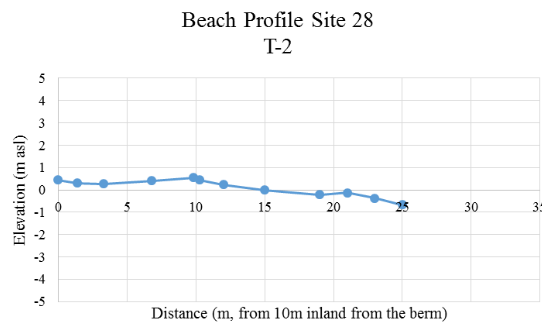

Beach Profile Site 23
T-2
Elevation (m asl)
Distance (m, from 10m inland of the berm)

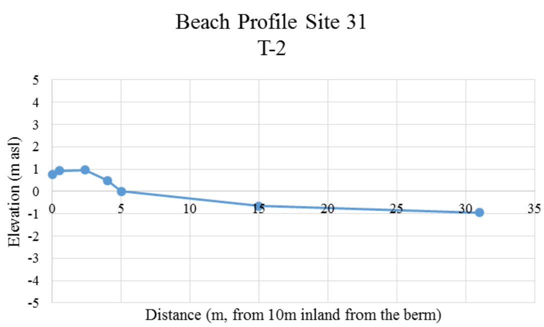

Beach Profile Site 24
T-2
Elevation (m asl)
Distance (m, from 10m inland from the berm)

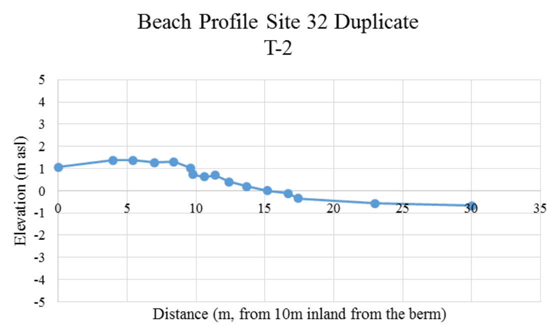

Beach Profile Site 25
T-2
Elevation (m asl)
Distance (m, from 10m inland from the berm)


Beach Profile Site 26
T-2
Elevation (m asl)
Distance (m, from 10m inland from the berm)


Beach Profile Site 27
T-2
Elevation (m asl)
Distance (m from 10m inland from the berm)


Beach Profile Site 28
T-2
Elevation (m asl)
Distance (m, from 10m inland from the berm)


Beach Profile Site 31
T-2
Elevation (m asl)
Distance (m, from 10m inland from the berm)


Beach Profile Site 32 Duplicate
T-2
Elevation (m asl)
Distance (m, from 10m inland from the berm)

Appendix F: SPSS Multiple Linear Regression Results

Appendix F-1. Whole Sanctuary, Recent Erosion Rate

Descriptive Statistics

	Mean	Std. Deviation	N
Recent_Ero	.5341	.70435	79
Berm_Ht	.8445	.31147	79
Beach_W	8.1149	2.72504	79
Beach_A	6.4682	1.50892	79
Veg_BB	.7722	.42212	79
Scarp	.4177	.49634	79
Top_Veg	.3418	.47733	79
Substrate2mm	.2405	.43012	79
Ridge	.4557	.50122	79

Model Summary[g]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.442[a]	.195	.104	.66689	.195	2.126	8	70	.044
2	.442[b]	.195	.116	.66234	.000	.033	1	70	.855
3	.439[c]	.192	.125	.65879	-.003	.230	1	71	.633
4	.435[d]	.190	.134	.65546	-.003	.265	1	72	.609
5	.420[e]	.176	.132	.65630	-.013	1.189	1	73	.279
6	.391[f]	.153	.119	.66101	-.023	2.081	1	74	.153

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	7.564	8	.946	2.126	.044[b]
	Residual	31.132	70	.445		
	Total	38.697	78			
2	Regression	7.550	7	1.079	2.458	.026[c]
	Residual	31.147	71	.439		
	Total	38.697	78			
3	Regression	7.449	6	1.241	2.860	.015[d]
	Residual	31.248	72	.434		
	Total	38.697	78			
4	Regression	7.334	5	1.467	3.414	.008[e]
	Residual	31.363	73	.430		
	Total	38.697	78			
5	Regression	6.823	4	1.706	3.960	.006[f]
	Residual	31.874	74	.431		
	Total	38.697	78			
6	Regression	5.927	3	1.976	4.522	.006[g]
	Residual	32.770	75	.437		
	Total	38.697	78			

Appendix F-1. Continued

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95.0% Confidence Interval for B		Correlations			Collinearity Statistics	
		B	Std. Error	Beta			Lower Bound	Upper Bound	Zero-order	Partial	Part	Tolerance	VIF
1	(Constant)	-.090	.504		-.178	.859	-1.094	.915					
	Berm_Ht	.502	.368	.222	1.364	.177	-.232	1.236	.155	.161	.146	.434	2.304
	Beach_W	-.020	.038	-.077	-.523	.603	-.096	.056	.033	-.062	-.056	.533	1.876
	Beach_A	.066	.056	.141	1.164	.249	-.047	.178	.174	.138	.125	.787	1.270
	Veg_BB	.038	.209	.023	.183	.855	-.379	.456	-.098	.022	.020	.730	1.369
	Scarp	.082	.178	.058	.458	.648	-.274	.438	-.014	.055	.049	.727	1.376
	Top_Veg	-.418	.186	-.284	-2.254	.027	-.788	-.048	-.220	-.260	-.242	.727	1.376
	Substrate2mm	-.348	.196	-.213	-1.777	.080	-.739	.043	-.166	-.208	-.191	.803	1.245
	Ridge	.218	.178	.155	1.225	.225	-.137	.573	.286	.145	.131	.716	1.396
2	(Constant)	-.035	.403		-.087	.931	-.839	.769					
	Berm_Ht	.481	.348	.213	1.383	.171	-.212	1.175	.155	.162	.147	.479	2.088
	Beach_W	-.021	.037	-.082	-.575	.567	-.095	.052	.033	-.068	-.061	.555	1.802
	Beach_A	.066	.056	.141	1.174	.244	-.046	.177	.174	.138	.125	.787	1.270
	Scarp	.085	.177	.060	.479	.633	-.267	.437	-.014	.057	.051	.733	1.365
	Top_Veg	-.414	.183	-.280	-2.266	.027	-.778	-.050	-.220	-.260	-.241	.740	1.351
	Substrate2mm	-.346	.194	-.212	-1.783	.079	-.734	.041	-.166	-.207	-.190	.805	1.242
	Ridge	.217	.177	.155	1.229	.223	-.135	.569	.286	.144	.131	.717	1.395
3	(Constant)	-.028	.401		-.069	.945	-.827	.771					
	Berm_Ht	.528	.332	.234	1.592	.116	-.133	1.190	.155	.184	.169	.521	1.921
	Beach_W	-.019	.036	-.072	-.514	.609	-.091	.054	.033	-.061	-.054	.567	1.765
	Beach_A	.062	.055	.133	1.125	.264	-.048	.172	.174	.131	.119	.802	1.247
	Top_Veg	-.415	.182	-.281	-2.284	.025	-.777	-.053	-.220	-.260	-.242	.741	1.350
	Substrate2mm	-.337	.192	-.206	-1.751	.084	-.720	.047	-.166	-.202	-.185	.814	1.228
	Ridge	.194	.169	.138	1.147	.255	-.143	.531	.286	.134	.121	.776	1.288
4	(Constant)	-.132	.344		-.383	.703	-.818	.554					
	Berm_Ht	.431	.271	.191	1.589	.116	-.110	.972	.155	.183	.167	.771	1.297
	Beach_A	.069	.053	.147	1.289	.202	-.038	.175	.174	.149	.136	.849	1.178
	Top_Veg	-.431	.178	-.292	-2.418	.018	-.785	-.076	-.220	-.272	-.255	.762	1.312
	Substrate2mm	-.327	.190	-.200	-1.717	.090	-.706	.052	-.166	-.197	-.181	.822	1.216
	Ridge	.181	.166	.129	1.090	.279	-.150	.513	.286	.127	.115	.792	1.262
5	(Constant)	-.100	.343		-.291	.772	-.784	.584					
	Berm_Ht	.481	.268	.213	1.796	.077	-.053	1.015	.155	.204	.189	.794	1.260
	Beach_A	.076	.053	.164	1.442	.153	-.029	.182	.174	.165	.152	.864	1.157
	Top_Veg	-.497	.168	-.337	-2.966	.004	-.831	-.163	-.220	-.326	-.313	.863	1.158
	Substrate2mm	-.401	.178	-.245	-2.255	.027	-.756	-.047	-.166	-.254	-.238	.943	1.060
6	(Constant)	.281	.221		1.274	.206	-.158	.721					
	Berm_Ht	.606	.255	.268	2.373	.020	.097	1.114	.155	.264	.252	.886	1.129
	Top_Veg	-.507	.169	-.343	-3.005	.004	-.843	-.171	-.220	-.328	-.319	.865	1.157
	Substrate2mm	-.356	.176	-.217	-2.017	.047	-.707	-.004	-.166	-.227	-.214	.974	1.027

Appendix F-2. Whole Bay, Total Erosion Rate

Descriptive Statistics

	Mean	Std. Deviation	N
Total_Ero	-.2612	.49138	79
Berm_Ht	.8445	.31147	79
Beach_W	8.1149	2.72504	79
Beach_A	6.4682	1.50892	79
Veg_BB	.7722	.42212	79
Scarp	.4177	.49634	79
Top_Veg	.3418	.47733	79
Substrate2mm	.2405	.43012	79
Ridge	.4557	.50122	79

Model Summary

					Change Statistics				
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	R Square Change	F Change	df1	df2	Sig. F Change
1	.364[a]	.132	.033	.48321	.132	1.332	8	70	.242
2	.363[b]	.132	.046	.47984	.000	.012	1	70	.914
3	.361[c]	.130	.058	.47697	-.002	.141	1	71	.708
4	.348[d]	.121	.061	.47615	-.009	.750	1	72	.389
5	.325[e]	.106	.057	.47711	-.016	1.300	1	73	.258
6	.303[f]	.092	.056	.47750	-.014	1.122	1	74	.293
7	.274[g]	.075	.051	.47878	-.017	1.410	1	75	.239

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	2.489	8	.311	1.332	.242[b]
	Residual	16.344	70	.233		
	Total	18.833	78			
2	Regression	2.486	7	.355	1.543	.167[c]
	Residual	16.347	71	.230		
	Total	18.833	78			
3	Regression	2.454	6	.409	1.798	.112[d]
	Residual	16.380	72	.227		
	Total	18.833	78			
4	Regression	2.283	5	.457	2.014	.087[e]
	Residual	16.550	73	.227		
	Total	18.833	78			
5	Regression	1.988	4	.497	2.184	.079[f]
	Residual	16.845	74	.228		
	Total	18.833	78			
6	Regression	1.733	3	.578	2.533	.063[g]
	Residual	17.100	75	.228		
	Total	18.833	78			
7	Regression	1.412	2	.706	3.079	.052[h]
	Residual	17.422	76	.229		
	Total	18.833	78			

Appendix F-2. Continued

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95.0% Confidence Interval for B		Correlations			Collinearity Statistics	
		B	Std. Error	Beta			Lower Bound	Upper Bound	Zero-order	Partial	Part	Tolerance	VIF
1	(Constant)	-.282	.365		-.772	.443	-1.010	.446					
	Berm_Ht	.220	.267	.139	.824	.413	-.312	.751	-.141	.098	.092	.434	2.304
	Beach_W	-.009	.028	-.052	-.343	.732	-.064	.045	-.183	-.041	-.038	.533	1.876
	Beach_A	.004	.041	.014	.108	.914	-.077	.086	-.015	.013	.012	.787	1.270
	Veg_BB	.233	.152	.200	1.535	.129	-.070	.535	.209	.180	.171	.730	1.369
	Scarp	-.212	.129	-.214	-1.636	.106	-.469	.046	-.195	-.192	-.182	.727	1.376
	Top_Veg	-.190	.134	-.185	-1.415	.161	-.458	.078	-.132	-.167	-.158	.727	1.376
	Substrate2mm	-.178	.142	-.156	-1.253	.214	-.461	.105	-.062	-.148	-.140	.803	1.245
	Ridge	-.221	.129	-.225	-1.711	.091	-.478	.037	-.110	-.200	-.191	.716	1.396
2	(Constant)	-.258	.292		-.885	.379	-.840	.324					
	Berm_Ht	.231	.246	.146	.939	.351	-.259	.720	-.141	.111	.104	.505	1.981
	Beach_W	-.010	.027	-.056	-.376	.708	-.063	.043	-.183	-.045	-.042	.556	1.798
	Veg_BB	.233	.151	.200	1.547	.126	-.067	.533	.209	.181	.171	.730	1.369
	Scarp	-.213	.127	-.216	-1.679	.098	-.467	.040	-.195	-.195	-.186	.741	1.350
	Top_Veg	-.190	.133	-.184	-1.422	.159	-.456	.076	-.132	-.166	-.157	.728	1.374
	Substrate2mm	-.175	.138	-.153	-1.264	.210	-.451	.101	-.062	-.148	-.140	.834	1.199
	Ridge	-.219	.127	-.223	-1.722	.089	-.473	.035	-.110	-.200	-.190	.726	1.378
3	(Constant)	-.312	.253		-1.235	.221	-.816	.192					
	Berm_Ht	.197	.227	.125	.866	.389	-.256	.650	-.141	.102	.095	.581	1.720
	Veg_BB	.245	.146	.210	1.670	.099	-.047	.537	.209	.193	.184	.763	1.311
	Scarp	-.223	.124	-.225	-1.793	.077	-.470	.025	-.195	-.207	-.197	.769	1.301
	Top_Veg	-.199	.130	-.193	-1.528	.131	-.459	.061	-.132	-.177	-.168	.754	1.326
	Substrate2mm	-.167	.136	-.147	-1.230	.223	-.439	.104	-.062	-.143	-.135	.852	1.174
	Ridge	-.226	.125	-.231	-1.807	.075	-.475	.023	-.110	-.208	-.199	.742	1.348
4	(Constant)	-.148	.167		-.886	.378	-.482	.185					
	Veg_BB	.189	.131	.162	1.438	.155	-.073	.451	.209	.166	.158	.945	1.059
	Scarp	-.183	.115	-.185	-1.589	.116	-.413	.047	-.195	-.183	-.174	.887	1.127
	Top_Veg	-.159	.121	-.154	-1.307	.195	-.401	.083	-.132	-.151	-.143	.865	1.156
	Substrate2mm	-.154	.135	-.135	-1.140	.258	-.423	.115	-.062	-.132	-.125	.863	1.159
	Ridge	-.200	.121	-.204	-1.649	.104	-.441	.042	-.110	-.189	-.181	.788	1.269
5	(Constant)	-.205	.160		-1.278	.205	-.524	.114					
	Veg_BB	.183	.132	.157	1.391	.168	-.079	.445	.209	.160	.153	.946	1.057
	Scarp	-.196	.115	-.198	-1.708	.092	-.425	.033	-.195	-.195	-.188	.896	1.116
	Top_Veg	-.125	.118	-.121	-1.059	.293	-.360	.110	-.132	-.122	-.116	.920	1.087
	Ridge	-.160	.116	-.163	-1.376	.173	-.392	.072	-.110	-.158	-.151	.859	1.164
6	(Constant)	-.260	.152		-1.715	.091	-.562	.042					
	Veg_BB	.194	.131	.166	1.476	.144	-.068	.455	.209	.168	.162	.952	1.051
	Scarp	-.213	.114	-.215	-1.871	.065	-.440	.014	-.195	-.211	-.206	.914	1.094
	Ridge	-.135	.114	-.138	-1.187	.239	-.363	.092	-.110	-.136	-.131	.895	1.117
7	(Constant)	-.362	.125		-2.883	.005	-.612	-.112					
	Veg_BB	.225	.129	.193	1.745	.085	-.032	.482	.209	.196	.193	.992	1.008
	Scarp	-.175	.110	-.177	-1.599	.114	-.394	.043	-.195	-.180	-.176	.992	1.008

Appendix F-3. Malcolm Bay, Recent Erosion Rate

Descriptive Statistics

	Mean	Std. Deviation	N
Recent_Ero	.6950	.84446	46
Berm_Ht	.9677	.30101	46
Beach_W	8.7843	2.77072	46
Beach_A	7.0948	1.39491	46
Vegetated_BB	.6739	.47396	46
Scarp	.5652	.50121	46
Top_Veg	.4130	.49782	46
Substrate2mm	.2174	.41703	46
Ridge	.4565	.50361	46

Model Summary[g]

					Change Statistics				
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	R Square Change	F Change	df1	df2	Sig. F Change
1	.756[a]	.571	.478	.60989	.571	6.159	8	37	.000
2	.756[b]	.571	.492	.60204	.000	.027	1	37	.869
3	.755[c]	.570	.504	.59465	-.001	.050	1	38	.825
4	.752[d]	.566	.512	.59010	-.004	.390	1	39	.536
5	.735[e]	.540	.495	.60010	-.026	2.401	1	40	.129
6	.714[f]	.509	.474	.61222	-.030	2.714	1	41	.107

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	18.327	8	2.291	6.159	.000[b]
	Residual	13.763	37	.372		
	Total	32.090	45			
2	Regression	18.317	7	2.617	7.220	.000[c]
	Residual	13.773	38	.362		
	Total	32.090	45			
3	Regression	18.299	6	3.050	8.625	.000[d]
	Residual	13.791	39	.354		
	Total	32.090	45			
4	Regression	18.161	5	3.632	10.431	.000[e]
	Residual	13.929	40	.348		
	Total	32.090	45			
5	Regression	17.325	4	4.331	12.027	.000[f]
	Residual	14.765	41	.360		
	Total	32.090	45			
6	Regression	16.348	3	5.449	14.539	.000[g]
	Residual	15.742	42	.375		
	Total	32.090	45			

Appendix F-3. Continued

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95.0% Confidence Interval for B		Correlations			Collinearity Statistics	
		B	Std. Error	Beta			Lower Bound	Upper Bound	Zero-order	Partial	Part	Tolerance	VIF
1	(Constant)	-.539	.986		-.547	.588	-2.536	1.458					
	Berm_Ht	-.074	.448	-.026	-.166	.869	-.982	.834	.001	-.027	-.018	.454	2.202
	Beach_W	.032	.049	.103	.647	.522	-.067	.130	-.053	.106	.070	.453	2.208
	Beach_A	.022	.094	.036	.234	.817	-.169	.213	.053	.038	.025	.479	2.089
	Vegetated_BB	.696	.257	.391	2.704	.010	.175	1.217	.083	.406	.291	.556	1.799
	Scarp	.314	.271	.187	1.160	.253	-.235	.863	-.179	.187	.125	.449	2.230
	Top_Veg	-.376	.223	-.221	-1.688	.100	-.827	.075	-.356	-.267	-.182	.673	1.485
	Substrate2mm	-.687	.262	-.339	-2.624	.013	-1.217	-.156	-.278	-.396	-.282	.694	1.441
	Ridge	1.162	.238	.693	4.889	.000	.680	1.643	.581	.626	.526	.577	1.733
2	(Constant)	-.567	.959		-.592	.558	-2.507	1.373					
	Beach_W	.028	.043	.092	.648	.521	-.059	.115	-.053	.105	.069	.563	1.776
	Beach_A	.021	.093	.034	.223	.825	-.167	.208	.053	.036	.024	.483	2.073
	Vegetated_BB	.707	.245	.397	2.893	.006	.212	1.202	.083	.425	.307	.599	1.668
	Scarp	.308	.265	.183	1.163	.252	-.228	.845	-.179	.185	.124	.457	2.190
	Top_Veg	-.383	.215	-.226	-1.781	.083	-.819	.052	-.356	-.278	-.189	.702	1.424
	Substrate2mm	-.685	.258	-.338	-2.653	.012	-1.207	-.162	-.278	-.395	-.282	.696	1.438
	Ridge	1.152	.228	.687	5.063	.000	.691	1.613	.581	.635	.538	.613	1.631
3	(Constant)	-.385	.497		-.775	.443	-1.391	.620					
	Beach_W	.026	.042	.086	.625	.536	-.059	.111	-.053	.100	.066	.584	1.711
	Vegetated_BB	.700	.239	.393	2.924	.006	.216	1.185	.083	.424	.307	.610	1.640
	Scarp	.272	.206	.161	1.320	.194	-.145	.688	-.179	.207	.139	.738	1.356
	Top_Veg	-.383	.213	-.226	-1.803	.079	-.813	.047	-.356	-.277	-.189	.702	1.424
	Substrate2mm	-.660	.231	-.326	-2.857	.007	-1.128	-.193	-.278	-.416	-.300	.846	1.182
	Ridge	1.154	.225	.688	5.138	.000	.700	1.609	.581	.635	.539	.614	1.629
4	(Constant)	-.147	.315		-.465	.644	-.784	.491					
	Vegetated_BB	.632	.212	.355	2.986	.005	.204	1.060	.083	.427	.311	.768	1.302
	Scarp	.306	.197	.181	1.549	.129	-.093	.704	-.179	.238	.161	.792	1.263
	Top_Veg	-.340	.199	-.200	-1.705	.096	-.743	.063	-.356	-.260	-.178	.785	1.274
	Substrate2mm	-.684	.226	-.338	-3.019	.004	-1.141	-.226	-.278	-.431	-.315	.868	1.152
	Ridge	1.165	.222	.695	5.242	.000	.716	1.614	.581	.638	.546	.618	1.619
5	(Constant)	.106	.275		.385	.702	-.449	.660					
	Vegetated_BB	.565	.211	.317	2.680	.011	.139	.990	.083	.386	.284	.802	1.246
	Top_Veg	-.334	.203	-.197	-1.647	.107	-.744	.075	-.356	-.249	-.175	.785	1.273
	Substrate2mm	-.597	.223	-.295	-2.675	.011	-1.047	-.146	-.278	-.386	-.283	.925	1.081
	Ridge	1.043	.211	.622	4.935	.000	.616	1.470	.581	.610	.523	.706	1.416
6	(Constant)	-.174	.220		-.792	.433	-.618	.270					
	Vegetated_BB	.647	.209	.363	3.100	.003	.226	1.069	.083	.432	.335	.851	1.176
	Substrate2mm	-.498	.219	-.246	-2.273	.028	-.941	-.056	-.278	-.331	-.246	.996	1.004
	Ridge	1.186	.197	.707	6.025	.000	.789	1.583	.581	.681	.651	.848	1.179

Appendix F-4. Hodges Bay, Recent Erosion Rate

Descriptive Statistics

	Mean	Std. Deviation	N
Recent_Ero	.3098	.34263	33
Berm_Ht	.6727	.23833	33
Beach_W	7.1818	2.40058	33
Beach_A	5.5948	1.20939	33
Vegetated_BB	.9091	.29194	33
Scarp	.2121	.41515	33
Top_Veg	.2424	.43519	33
Substrate2mm	.2727	.45227	33
Ridge	.4545	.50565	33

Model Summary[h]

					Change Statistics				
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	R Square Change	F Change	df1	df2	Sig. F Change
1	.789[a]	.623	.497	.24308	.623	4.947	8	24	.001
2	.789[b]	.622	.517	.23818	.000	.003	1	24	.960
3	.789[c]	.622	.535	.23375	-.001	.042	1	25	.840
4	.788[d]	.621	.551	.22970	-.001	.073	1	26	.790
5	.786[e]	.618	.563	.22649	-.003	.224	1	27	.640
6	.783[f]	.614	.574	.22368	-.004	.283	1	28	.599
7	.761[g]	.580	.552	.22945	-.034	2.567	1	29	.120

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	2.339	8	.292	4.947	.001[b]
	Residual	1.418	24	.059		
	Total	3.757	32			
2	Regression	2.338	7	.334	5.889	.000[c]
	Residual	1.418	25	.057		
	Total	3.757	32			
3	Regression	2.336	6	.389	7.126	.000[d]
	Residual	1.421	26	.055		
	Total	3.757	32			
4	Regression	2.332	5	.466	8.840	.000[e]
	Residual	1.425	27	.053		
	Total	3.757	32			
5	Regression	2.320	4	.580	11.308	.000[f]
	Residual	1.436	28	.051		
	Total	3.757	32			
6	Regression	2.306	3	.769	15.362	.000[g]
	Residual	1.451	29	.050		
	Total	3.757	32			
7	Regression	2.177	2	1.089	20.679	.000[h]
	Residual	1.579	30	.053		
	Total	3.757	32			

Appendix F-4. Continued

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients			95.0% Confidence Interval for B		Correlations			Collinearity Statistics	
		B	Std. Error	Beta	t	Sig.	Lower Bound	Upper Bound	Zero-order	Partial	Part	Tolerance	VIF
1	(Constant)	.915	.300		3.045	.006	.295	1.535					
	Berm_Ht	.329	.262	.229	1.258	.220	-.211	.869	.177	.249	.158	.475	2.104
	Beach_W	.001	.021	.007	.051	.960	-.042	.044	-.054	.010	.006	.727	1.376
	Beach_A	-.024	.048	-.085	-.500	.621	-.123	.075	.040	-.102	-.063	.549	1.820
	Vegetated_BB	-.648	.192	-.552	-3.376	.002	-1.044	-.252	-.632	-.567	-.423	.588	1.701
	Scarp	.040	.135	.049	.298	.768	-.238	.318	.094	.061	.037	.592	1.690
	Top_Veg	-.043	.111	-.055	-.386	.703	-.273	.187	-.060	-.078	-.048	.784	1.275
	Substrate2mm	.029	.146	.038	.196	.846	-.273	.331	.177	.040	.025	.422	2.370
	Ridge	-.256	.139	-.378	-1.842	.078	-.543	.031	-.589	-.352	-.231	.374	2.672
2	(Constant)	.922	.258		3.576	.001	.391	1.453					
	Berm_Ht	.333	.244	.232	1.364	.185	-.170	.836	.177	.263	.168	.524	1.910
	Beach_A	-.024	.046	-.086	-.528	.602	-.120	.071	.040	-.105	-.065	.567	1.764
	Vegetated_BB	-.650	.185	-.554	-3.521	.002	-1.030	-.270	-.632	-.576	-.433	.610	1.638
	Scarp	.041	.129	.050	.320	.752	-.225	.308	.094	.064	.039	.615	1.627
	Top_Veg	-.042	.108	-.054	-.390	.700	-.265	.181	-.060	-.078	-.048	.798	1.254
	Substrate2mm	.029	.143	.039	.204	.840	-.265	.324	.177	.041	.025	.424	2.360
	Ridge	-.254	.128	-.374	-1.981	.059	-.517	.010	-.589	-.368	-.243	.423	2.363
3	(Constant)	.905	.239		3.782	.001	.413	1.397					
	Berm_Ht	.341	.237	.237	1.439	.162	-.146	.827	.177	.272	.173	.536	1.865
	Beach_A	-.022	.044	-.077	-.501	.621	-.112	.068	.040	-.098	-.060	.610	1.638
	Vegetated_BB	-.630	.155	-.537	-4.074	.000	-.949	-.312	-.632	-.624	-.491	.837	1.195
	Scarp	.032	.119	.039	.269	.790	-.212	.276	.094	.053	.032	.705	1.418
	Top_Veg	-.049	.102	-.062	-.477	.638	-.258	.161	-.060	-.093	-.057	.868	1.152
	Ridge	-.272	.089	-.401	-3.060	.005	-.455	-.089	-.589	-.515	-.369	.845	1.183
4	(Constant)	.885	.224		3.956	.000	.426	1.344					
	Berm_Ht	.360	.221	.251	1.628	.115	-.094	.814	.177	.299	.193	.593	1.688
	Beach_A	-.020	.043	-.071	-.474	.639	-.107	.067	.040	-.091	-.056	.624	1.603
	Vegetated_BB	-.625	.151	-.532	-4.145	.000	-.934	-.316	-.632	-.624	-.491	.851	1.175
	Top_Veg	-.047	.100	-.060	-.473	.640	-.253	.158	-.060	-.091	-.056	.870	1.150
	Ridge	-.275	.086	-.406	-3.185	.004	-.453	-.098	-.589	-.523	-.377	.863	1.159
5	(Constant)	.905	.217		4.178	.000	.461	1.349					
	Berm_Ht	.343	.215	.239	1.594	.122	-.098	.784	.177	.288	.186	.609	1.642
	Beach_A	-.022	.042	-.078	-.532	.599	-.108	.063	.040	-.100	-.062	.630	1.587
	Vegetated_BB	-.636	.147	-.542	-4.334	.000	-.937	-.335	-.632	-.634	-.506	.873	1.146
	Ridge	-.272	.085	-.401	-3.200	.003	-.446	-.098	-.589	-.518	-.374	.870	1.150
6	(Constant)	.829	.161		5.144	.000	.500	1.159					
	Berm_Ht	.276	.172	.192	1.602	.120	-.076	.628	.177	.285	.185	.928	1.078
	Vegetated_BB	-.640	.145	-.546	-4.422	.000	-.936	-.344	-.632	-.635	-.510	.875	1.143
	Ridge	-.271	.084	-.399	-3.228	.003	-.442	-.099	-.589	-.514	-.373	.870	1.149
7	(Constant)	.984	.132		7.426	.000	.713	1.254					
	Vegetated_BB	-.591	.145	-.503	-4.072	.000	-.887	-.295	-.632	-.597	-.482	.917	1.091
	Ridge	-.301	.084	-.444	-3.590	.001	-.472	-.130	-.589	-.548	-.425	.917	1.091