RECENT SHORLINE EROSION RATES ALONG BLACK RIVER BAY, JAMAICA: EROSION AND RECOVERY AFTER HURRICANE IVAN IN 2004

A Masters Thesis
Presented to
The Graduate College of
Missouri State University

In Partial Fulfillment
Of the Requirements for the Degree
Master of Science, Geospatial Science and Physical Geography

By
Karen Louise Zelzer
May 2015

RECENT SHORELINE EROSION RATES ALONG BLACK RIVER BAY, JAMAICA: EROSION AND RECOVERY AFTER HURRICANE IVAN IN 2004

Geography, Geology, and Planning

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ABSTRACT

Rising sea level is threatening coastal areas, particularly those in the Caribbean which rely heavily on tourism and marine resources to support local economies. The purpose of this study is to analyze shoreline position along the south coast of Jamaica to determine the locations and rates of coastal change. IKONOS satellite imagery sets for 2003, 2007 and 2012 were used to monitor land use and shoreline changes along Black River Bay, including Galleon Beach Fish Sanctuary, in St. Elizabeth, Jamaica. In particular, the effect of Hurricane Ivan in 2004 on shoreline changes was evaluated. Erosion rates were significantly higher during 2003-2007, the period including Hurricane Ivan (-0.90 m/yr), with reduced erosion rates and some recovery by deposition observed during the post-hurricane period (0.21 m/yr). Little to no changes were observed along limestone headlands and mangrove swamps with highest rates on sandy beaches lacking offshore coral reef protection and exposed to storm waves. Overall, shoreline recession averaged -0.31 m/yr during the study period with a peak erosion rate of -1.13 m/yr at Parrottee Point. Within the next 10 to 30 years, an expected 9 km of mangrove swamps and over 100 buildings are at risk due to sea level rise and shoreline erosion.

KEYWORDS: shoreline, erosion, sea-level rise, Jamaica, climate change

This abstract is approved as to form and content

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

Coastal shorelines are dynamic since they represent the interface between marine-driven wave and current forces and terrestrial geological and biological materials of variable resistance (Bush and Young, 2009). In the coastal zone, geomorphic processes involving wind and wave action are most effective in landform development including bedrock headlands, coastal dunes, longshore bars, spits, and pocket beaches (Huggett, 2011). Beaches form on coastal shorelines where sediments from local sources accumulate due to the influence of waves and currents (Bush and Young, 2009). Beaches can form from a range of sedimentary clasts and grain sizes, from cobbles to fine sand. Sandy beaches are the most desired beaches in the Caribbean region and are important for economic, social, and ecological reasons. However, sandy shorelines are particularly prone to changes in size and shape over human timescales due to variations in wave energy including seasonal and annual time frames. Shoreline changes are caused by changes in wind speed and patterns and intensity of storms such as hurricanes (Davidson-Arnott, 2005).

The geomorphic impacts of natural processes and human activities on the ecological balance of the coastal zone, including geomorphic processes and sediment budget, need to be understood in order to plan for sustainable communities (Correa, Alcantara-Carrio, and Gonzalez, 2005). The sediment budget indicates the balance between sediment added or removed by natural or human action (Morton, 2002; Richards, 2008). If sediment supply is relatively high, shorelines can resist erosion and even build seaward by deposition. This is often where depositional landforms such as beaches, spits, and bars form. If the supply of sediment is low, shorelines will erode and disappear (Huggett, 2011).

Island nations in the Caribbean rely heavily on marine resources and coastal tourism to support their economies (Cambers, 2009). Coral reefs, mangrove forests, and sandy beaches are important economic, social, and ecological factors due to their link to tourism as well as fisheries and local culture (Gable, 1997). Economic development on island nations in the Caribbean began along the coast since it provided easy and convenient settlement as well as resources to make a settlement successful (Small and Nicholls, 2003). Accessibility to resources, ships and a food source created the foundation for Caribbean settlement along the coastline. Over the past decades, the main economic support for island nations in the Caribbean is tourism (Cambers, 2009). Tourism in the Caribbean accounts for approximately 15 percent of the regions gross domestic product (GDP) and is dependent on the attractiveness and condition of the beaches, as well as the warm climate, and other marine factors (Bueno *et al*., 2008). Resorts and cruise lines are the most popular forms of tourism for these islands, and they are also located along the coast since it is the ideal location for accepting stop-over tourists as well as the perfect balance of sea, sun and sand (Beekhuis, 1981). Tourism also provides primary and secondary employment opportunities for the local population in the form of accommodation work, retail trade, transport operations, construction, and agriculture (Beekhuis, 1981).

Beaches are also important socially for population growth and for recreational and cultural services (Jin, *et al.*, 2003). Most major cities located on Caribbean islands are located near the coast since these areas are usually the first settled upon arrival (Hanson and Lindh, 1993). The beaches near these populated areas are used by tourist and locals as a location for social activity. Bar and restaurant owners tend to locate their businesses near beaches to increase revenue and appeal to the island's public. This contributes to the overall tropical island culture which identifies with the coastal zone (Gable, 1997).

In addition to beaches, coral reefs and mangroves are important ecologically for habitats, fisheries, and the local culture (Gable, 1997). Coral reefs are structures made from the buildup of calcium carbonate skeletons deposited by coral polyps. Coral reefs create ecosystems suitable for fish and other aquatic organisms; and this provides a primary food source for local populations (Burke and Maidens, 2009). Mangroves are tropical trees that thrive in shallow marine settings. The roots of these trees are typically the habitat for juvenile fish and shellfish species and help keep the overall coastal ecosystem in balance (Lugo and Snedaker, 1974). The root systems are dense and serve as traps for sediment from river input and onshore transport from nearshore sand bars. This sediment trapping process acts as a natural seawall which reduces the rate of erosion from large storm events (Beck, 2014) as well as regulating the amount of sediment being transported offshore. By filtering the coastal sediment, this protects coral reefs, seagrass and other aquatic organisms from being smothered in sediment and sediment-associated pollutants (Rath, 2014).

Increased global temperatures have increased sea water temperature and changed weather patterns worldwide (Cubasch, *et al*., 2013; Peterson, Stott, and Herring, 2012; Seneviratne, *et al*., 2012). Recent trends of worldwide sea-level rise (SLR) threaten beach stability. Sea level has fluctuated over geologic history. It is higher at times of warmer global temperatures when there are fewer ice caps, and it is lower during glacial periods when there is a greater volume of grounded global ice (Figure 1). This is generally a natural process; however, climate scientists agree increased carbon emissions from fossil fuel combustion have raised global atmospheric temperatures resulting in increased ocean temperatures, thermal expansion, and increased rates of SLR. Over the past 130 years, global sea level (GSL) rose by <1 mm/yr until about 1930 after which rates increased to almost 2 mm/yr and are currently around 3.0-3.3 mm/yr (Figure 2) (Cabanes, Cazenzve, and Provost, 2001; Davidson-Arnot, 2005; Gable, 1997; Williams, 2013; Church, *et al*., 2013).

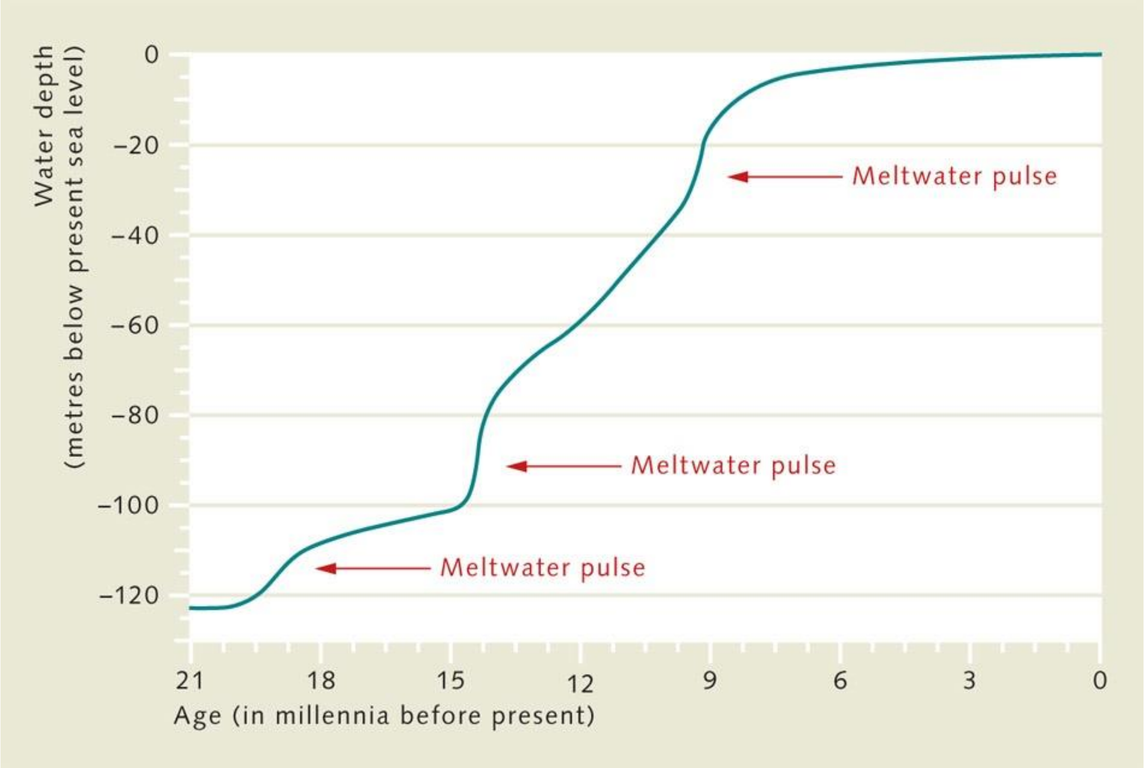

Figure 1. Generalized Global Sea-Level Rise. Global sea-level rise trends showing major times when sea level rose drastically due to changes in the climate. Source: Bollmann, *et al*., 2010.

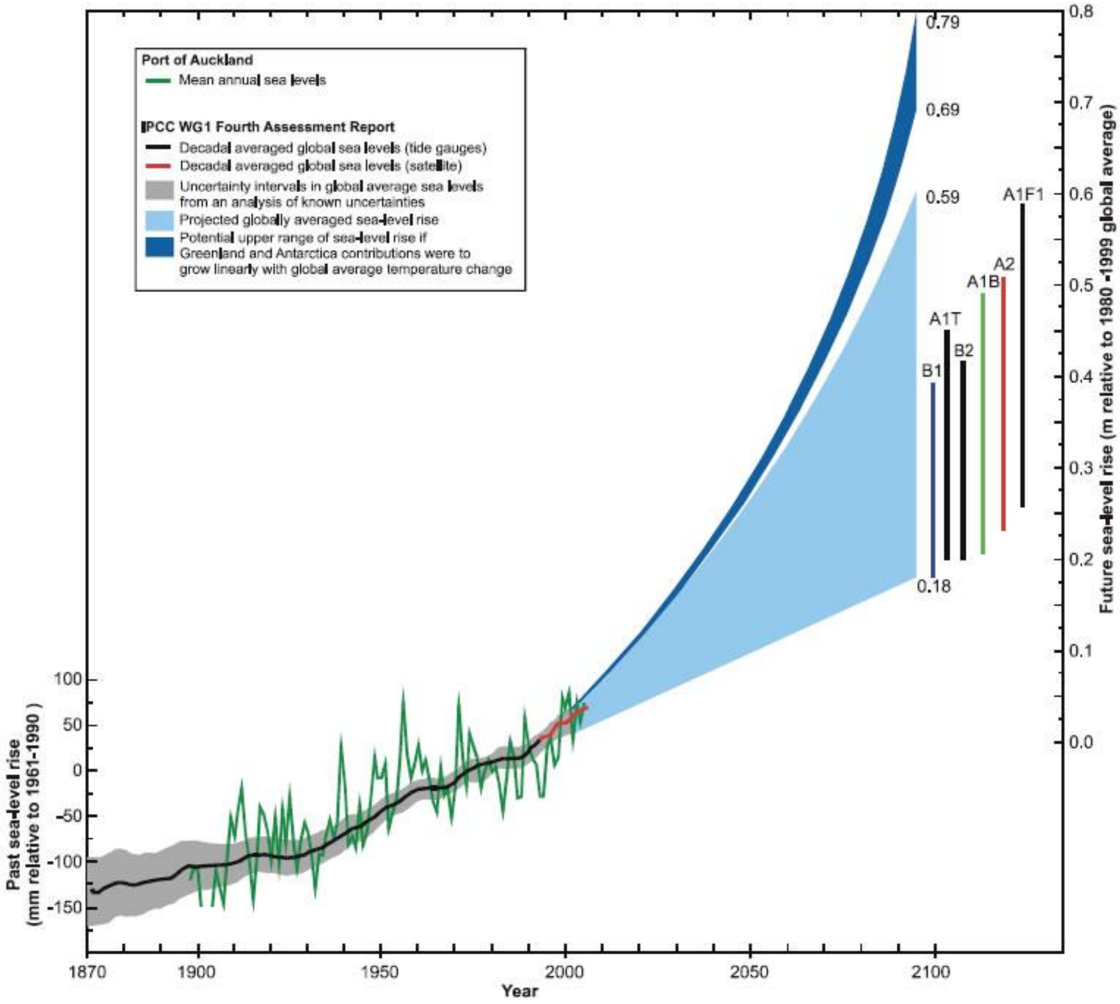

Figure 2. Predicted Sea Level Trends. Current observed GSL rates and predicted sea level rates based on IPCC AR4. Data has been collected from the early 1900s to 2013. The predictions are based on previous trends and are expected to reach between 0.18 m and 0.59 m depending on the rates at which the Greenland and Antarctic ice sheets melt. Various models suggest different rates and are indicated by the vertical bars. Source: Intergovernmental Panel on Climate Change (IPCC) WG1 Fourth Assessment Report, 2013.

In the Caribbean, SLR is a concern and threatens many of the islands. Recent studies by Gable (1997), Robinson, Rowe, and Khan, (2005) and Davidson-Arnott (2005) show an average increase in SLR from 1 to 2 mm/year over the past 100 years. More recent sea-level rates have been calculated from 1955-96 with an average rate of 1.6 mm/yr (Cabanes, *et al*., 2001; Williams, 2013). This estimated rate has since increased to 3.0 to 3.3 mm/yr (Church, *et al*., 2013; Williams, 2013). As sea-level rises, beach erosion rates tend to increase and shorelines tend to recede. The sediment budget for a beach area becomes negative as more sediment is removed from the beach to offshore storage or inland as overwash or inlet deposits (Huggett, 2011).

Rising sea level is causing more frequent and larger wave interaction with the coastal zone, including potentially the impact of more powerful hurricanes (NASA, 2013). Erosion rates vary depending on tectonic setting, elevation, composition of the beaches, and reef protection (Gable, 1997; Zhang, Douglas, Leatherman, 2004). Shorelines with unconsolidated sediment such as sandy beaches are more susceptible to wave action and will erode more rapidly (Dolotov, 1992). A study conducted in 2005 observed erosion rates along various coastal environments in Colombia. This coastline consists of high igneous and limestone cliffs, low beaches, mangrove swamps, and deltas. Erosion over the past 70 years was averaged to be between 0.43 m/yr and 0.71 m/yr depending on location and environment. The study revealed increased erosion rates ranging from 0.5 m/yr along the cliff faces and 4 m/yr along the beaches (Correa, Alcantara-Carrio, Gonzalez, 2005). Another study observed comparable rates along the coast of California, where the shorelines are made up of both rocky and sandy beaches as well as cliffs and wave-cut benches. The cliff erosion rates were higher than the beach rates at 0.3 m/yr and 0.2 m/yr respectively. These are averaged rates and some of the beaches were accreting and the rates varied depending on protection, composition and wave interaction. This led to a lower erosion rate for the beach environments (Hapke Reid, and Richmond, 2009).

Beach Concerns in Jamaica

Jamaica is a country reliant on tourism and beach attractions to support its economy (Richards, 2008). Recently, there have been concerns over the risk of beach degradation and erosion due to SLR (Wong, *et al*., 2014). Northern Jamaica has ample reef protection to resist beach erosion rates, but South Jamaica does not have this protection (Figure 3). Along the south coast, patches of fringing reefs are more common and have a higher percentage of dead coral opposed to living coral. This is likely due to hurricane wave action damaging the reefs in this area (Charpentier, 2005).

Southern Jamaica is made up of small communities supported by small-scale agriculture, fishing, and tourism activities. These communities are self-supporting for the most part but rely on tourism to support their economies. In 2000, 26.7 percent of Jamaica’s gross national product (GNP) was from the tourism industry (Thomas-Hope and Jardine-Comrie, 2007). In contrast to the north coast, there are only a few “all-inclusive” resorts along the south coast of Jamaica. These resorts attract tourists through Jamaica’s tropical climate and sandy beaches – and these tourists then support the local communities through souvenir shops, restaurants, and guided tours around the area (Richards, 2008).

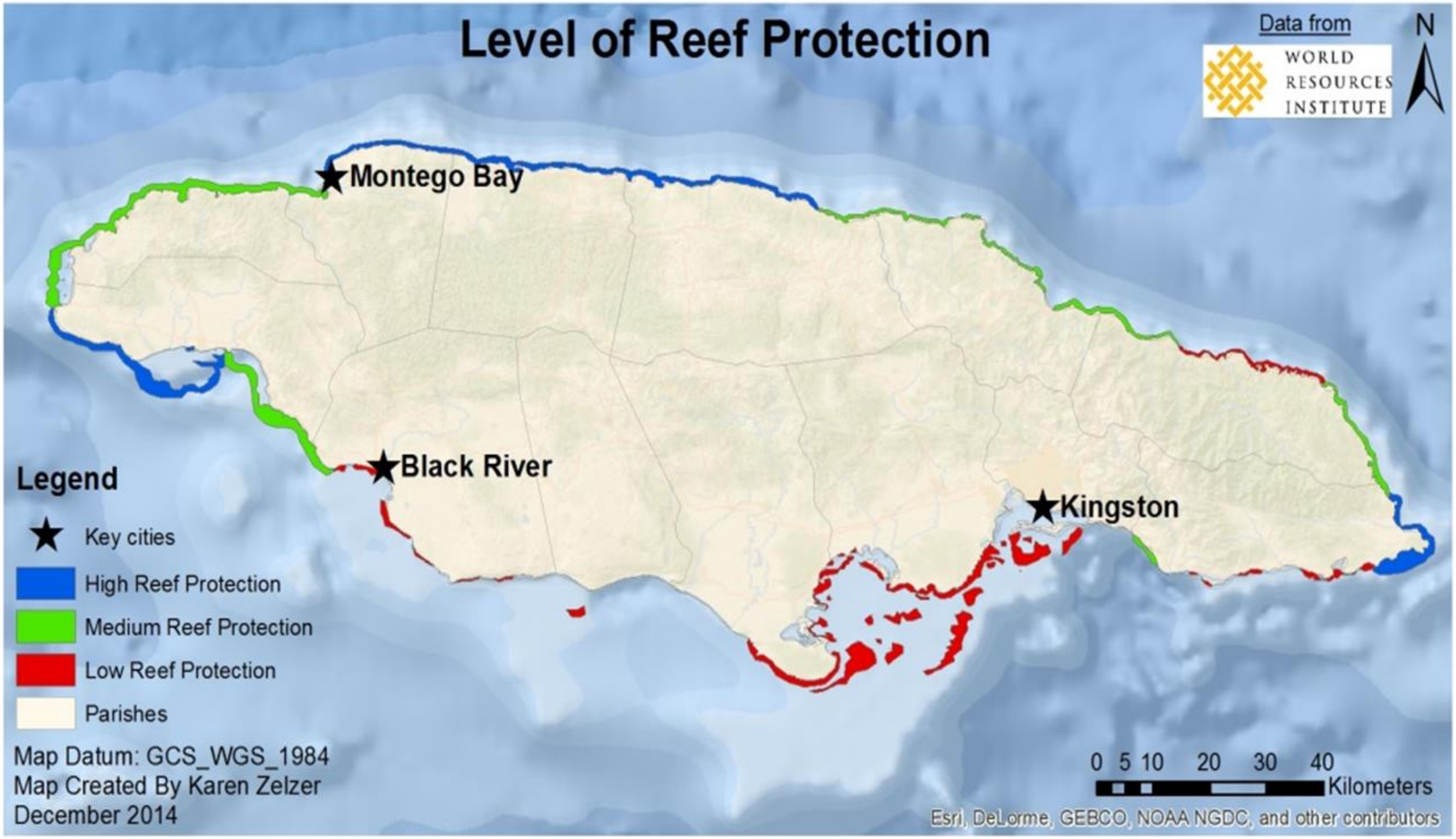

Figure 3. Coral Reef Protection Around Jamaica. Reef protection is based on reef shape, slope, orientation and distance from the shore. Exposed reefs allow waves to break on the reef face and provide the most protection. Source MGI, 2011 and World Resources Institute, 2001.

Richards (2008), reports that rising sea levels are decreasing the amount of sandy beaches along Jamaica’s shoreline and thereby decreasing the amount of tourist visits per year. Roughly 2.5 percent of Jamaica’s shoreline is composed of sandy beaches and seaside parks. The majority of these sandy beaches are located along the north, northwest, west and southwest coasts. The eastern part of the island is mainly composed of bluffs and headlands. The northern beaches are composed of white sand from the erosion of offshore corals and calciferous algae. The southern beaches are composed of darker sand due to the large portion of the sediment supply comes from river sediment (Richards, 2008; Moses, 2008). Sandy beaches are the most vulnerable to changes in sea level and the climate. These beaches are less consolidated than headlands or vegetated shorelines so the geomorphic factors have a greater effect on these beaches. This makes the reduction of energy reaching the sandy shoreline more important (Huggett, 2011).

Coral reefs line most of Jamaica’s shoreline. These reefs are located offshore and are formed from the calcium carbonate skeletons of coral. The presence of these reefs reduces the energy of waves from reaching the shoreline. It is estimated that 60 percent of Jamaica’s shorelines are protected by fringing, patch or barrier reefs (Burke and Maidens, 2004). Most of these reefs are found along the northern and western part of the country leaving the southern coast exposed to the full force of wave energy from storms and rising sea levels. Sandy beach profiles with reef protection tend to be more stable and change at a slower rate since low energy waves are the dominate wave type reaching the shoreline (Munoz-Perez, Tejedor, Medina, 1999).

Purpose and Objectives

Most studies of sea-level effects on Jamaica have focused on either coral reefs or beaches located on the north or west coast (Robinson, *et al*., 2012; Richards, 2008; Robinson, Rowe, and Khan, 2005). Even though average beach erosion rates for Jamaica have been reported to range from 0.23 to 0.30 m/year (Robinson *et al*., 2012), no studies of beach erosion rates along the south coast have been completed. Long Beach in Negril is located along the west coast and is one of the few beaches studied close to the southwestern portion of Jamaica. Discussions with members of the communities in the parishes of Westmoreland and Saint Elizabeth are aware that their beaches are disappearing. However, the understanding as to why this is happening and where beach loss is greatest is lacking. More scientific analysis is needed to increase our understanding of beach erosion rates and their spatial variability along the south coast of Jamaica. The purpose of this study is to determine the effect of recent sea level change and other factors on erosion rates of sandy beaches along southern Jamaica with a focus on the Black River Bay area. Black River Bay is the capital of St. Elizabeth Parish and has an estimated population of over 5,000 residences. The economy of this town relies on coastal resources and tourism which is vulnerable to SLR since the majority of the town is at or below an elevation of 3 meters. Vulnerable areas within the bay that supply resources to the area are the Galleon Fish Sanctuary and the Black River ecosystem.

Hurricanes are intense storm events that produce high-energy waves capable of transporting large amount of sediment and changing the shoreline during a single event. Hurricane Ivan occurred during September 2004 and passed within 32 km from the southern coast of Jamaica. On average, the Caribbean region experiences 6 hurricanes per year (NOAA, 2015), causing property damage, loss of life, homelessness, and disruption of economies. They are the main threat to islands in the region, specifically to Black River Bay due to its low elevation and sandy shoreline.

Remote sensing and satellite imagery is used to determine the shoreline changes of Black River Bay beaches since 2003. The objectives of this thesis are:

(1) Geospatially determine patterns of shoreline erosion and accretion rates for 30 km of shoreline over the past 9 years including the effects of Hurricane Ivan in 2004. Digitized beach widths, vegetation lines, and water lines for each satellite image year were used to determine erosion and deposition trends for the shoreline; (2) Determine the relationships between erosion patterns and geology, vegetation, and reef protection. Shoreline zones were classified according to land form type, reef protection, and seaward orientation to evaluate erosion-deposition relationships. Each factor was assessed using the IKONOS satellite images to determine how they influence erosion patterns of beaches along Black River Bay; and (3) Use beach erosion rates, topography, and land use/vegetation relationships to evaluate erosion risk to natural and cultural resources in the area.

Benefits

This is the first study on the south coast of Jamaica to measure erosion and deposition rates with high resolution satellite imagery. The results of this study will quantify beach erosion rates and patterns, suggest caused factors to explain erosion patterns, and identify locations of higher and lower risk to beach erosion along Black River Bay. This study will help to better understand the erosion patterns of the south coast of Jamaica as well as aid to the overall understanding of how increased SLR and hurricane events like Hurricane Ivan will affect sandy beaches; specifically the south coast of Jamaica. The procedures developed and results will provide a baseline approach on how to measure the rate of erosion or recovery of beaches by satellite imagery and help to set up longer-term monitoring programs.

Information provided by this study will help the communities of southern Jamaica understand erosion and deposition trends and help guide future coastal management. Fish sanctuaries, such as the Galleon Beach Marine Protected Area in Black River Bay, help monitor fish populations, fishing regulations, coral reefs, beach conditions and coastal habitats. These sanctuaries are monitored by non-profit foundations such as BREDS (www.breds.org) and SeaVibe (www.seavibe.org) and work with the community to enforce and manage the fish sanctuary. Fish and coral populations are allowed to increase and counter the effects of overfishing and habitat degradation which aid in preventing increased coastal erosion.

Socially, results of this study can be used to raise awareness about coastal erosion in Jamaica and can help encourage government response to help aid in coastal protection. Fish sanctuaries and marine protected areas and the Beach Control Act have been created by the government in Jamaica to help manage coastal resources for sustainable use. Businesses such as Sandals (www.sandalsfoundation.org) have funded projects for the communities to help decrease the effects felt by human activities. The Sandals Foundation focuses on community, education, and environmental projects that help train skilled workers, support educational facilities, and preserve reefs, marine life, beaches, and the local flora and fauna (Sandals Foundation, 2010). However, most of these projects and government responses are located elsewhere in Jamaica and has a limited presence in Black River Bay. In 2009, the Galleon Fish Sanctuary was declared the first and only marine sanctuary in Black River Bay, located between Malcolm Bay and Hodges Bay. This was created to regulate fish populations and protect marine and coastal resources from natural and anthropogenic threats (BREDS, 2014). For the most part, the town of Black River is located at less than 3 meters above sea level. This increased sea level will threaten the town and its infrastructure and natural resources. Increased government involvement and management for this area is needed to monitor shoreline changes, predict storm effects, and prepare for future risks.

CHAPTER 2. BACKGROUND

The coastal system is influenced by changes in SLR resulting from climate change over timescales of decades to centuries (Bush and Young, 2009). Sandy beaches in particular are some of the most dynamic areas on earth and susceptible to coastal hazards such as storm surges, coastal erosion, and inundation. Factors affecting beach erosion include: wave height and duration, coral reef protection, dune and beach vegetation cover, beach orientation and angle, and composition determine the rate a shoreline will erode and how vulnerable it is to SLR (Huggett, 2011; Bush and Young, 2009). The majority of beaches along the south coast of Jamaica are sandy, low-angled beaches with little reef protection (Richards, 2008). The degree of beach protection, wave action and type of sandy beaches found along Black River Bay will be discussed in this chapter. This chapter will elaborate on the geomorphic characteristics and behavior of beaches in the Jamaica setting.

Beach Morphology

Coastlines are influenced by both natural and human systems. The natural system includes features like headland bluffs, beaches, sand dunes, lagoons, river mouths, wetlands, and coral reefs. The human system includes structures that were built like sea walls, buildings, roads, groins, and breakwaters. Sandy beaches are an equilibrium landform within the coastal system and respond to changes in energy, sediment supply, and resistance. Morphologic changes of beaches rely on factors such as wave, wind and current energy, the sediment budget, and resistance factors such as coral reefs, bedrock, and human barriers (Wong, *et al*., 2014).

A beach is generally a highly dynamic landform formed by wave action along marine, estuarine, and lacustrine shorelines. A beach is commonly referred to as the shoreline area between the lowest tide level and a physiographic feature such as a dune, cliff or permanent vegetation indicates the landward extent of wave-induced sediment transport or erosion (Masselink and Kroon, 2004). Beaches can be primarily composed of silt, sand, or gravel sized grains depending on the energy of the environment. The most vulnerable to erosion are sandy beaches.

Beach Morphology Model. Beach morphology is complex and depends on the temporal and spatial scale. The scale can be extremely short such as seconds to measure grain interactions, days to measure changes due to a single storm event, or the scale can be much larger and cover shoreline evolution over decades or centuries (Tarbuck and Lutgens, 2007). The morphology of a beach can be divided into two parts, the primary profile and secondary morphological features. The overall beach profile is known as the primary beach profile and is used to classify beaches (Masselink and Kroon, 2004). At this scale, years and kilometers are used to measure the temporal and spatial changes of the overall beach shape and movement. The features formed on the primary profile and at smaller scales are known as secondary morphological features. These are features that form on a temporal scale of hours to years and range in size from 10 to 1000 meters (Masselink and Kroon, 2004). Some of the main secondary morphological features include bars, berms, beach cusps, beach steps, and low tide terraces. These features can help classify a beach, identify the erosional factors that are interacting with the beach and can help predict what the beach profile might look like in the future (Masselink and Kroon, 2004; Huggett, 2011).

A wave dominated beach model can be used to describe sandy beaches along the south coast of Jamaica (Figure 4). This model is used for microtidal zones where beaches experience less than a 2 m change in tides; therefore, tide processes are negligible and waves are the main factor for changes in beach morphology (Short, 1996). Wave dominated beaches are composed of three dynamic zones, the nearshore, the foreshore or beach face, and the backshore. The nearshore is where waves approach the shore and become shallower and more unstable until they break, usually at a bar. The surf zone is within the nearshore and the foreshore and is the area after a wave breaks and interacts with the shoreline. A berm crest is formed at the boundary between the foreshore and the backshore. This is where sediment carried from a wave gets deposited and indicates the high waterline. The backshore is the area where only the waves with the highest energy will reach, which usually only occurs during a storm event (Huggett, 2011; Komar, 1976). The vegetation and waterline are focused on in this study to help determine changes in the shoreline morphology.

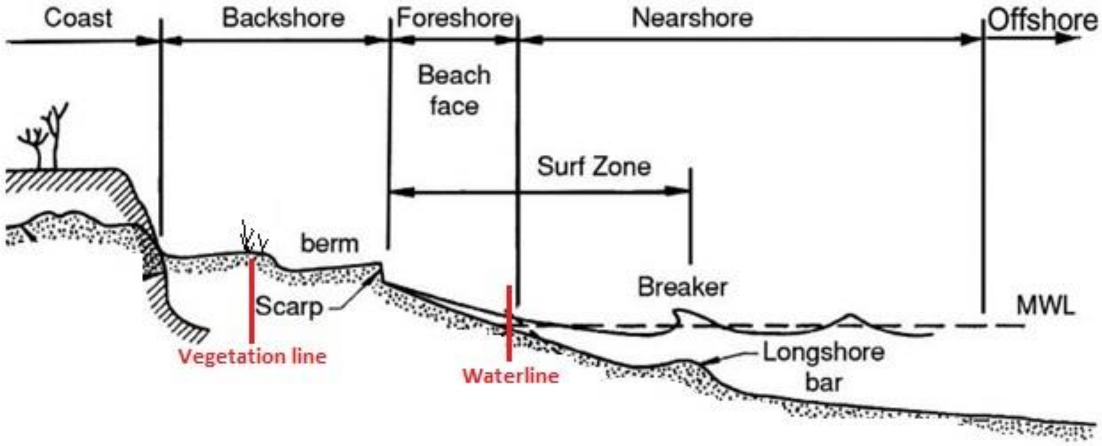

Figure 4. Wave Dominated Beach Model. This model represents the typical beaches along the south coast of Jamaica. Some variations in this model occur due to different resistance factors such as sea walls and groins and due to different levels of reef protection located offshore. The typical location of the vegetation line and waterline are indicated in red. These features are used in this study to determine changes in shoreline morphology. Modified from source: Firoozfer, Neshaei, and Dykes, 2014.

Resistance factors, such as coral reefs, will deflect or reduce the energy reaching the shoreline and change the dynamics of the wave dominated model. The incoming waves will break along the offshore side of the reef, reducing the amount of energy that will eventually reach the shore by an average of 97 percent (Richards, 2008; Sheppard, 2005, Valentine, 2014). Headlands are more resistant to erosion and deflect the energy of the wave away from the more vulnerable sandy beaches (Kohsiek, Hulsbergen, and Terwindt, 1987). Humans try to recreate natural barriers by creating cement seawalls, ripraps, groins, or artificial reefs. These are meant to direct or reduce the energy reaching the shore as well as prevent sediment from being transported offshore (Huggett, 2001).

Wave Processes. Waves and the energy of ocean currents are the main factor for changing the morphology of a beach. This energy is derived from differences in air temperature which creates wind, as well as the rotation of the earth. A greater difference in temperature creates a stronger wind. In the tropics, the air is warmer than at higher latitudes. This warm air rises and is replaced by denser, colder air from either the north or south creating a major wind belt. The wind then flows over the surface of the ocean, creating a drag and forms a wave (Bascom, 1980). The energy of waves varies greatly over the surface of the earth. The Caribbean is located in the Northeast Trade Wind belt located north of the equator. Here, the air is constantly moving, creating waves which strike the coastline at a fairly constant rate. Easterly winds dominate the Caribbean for most of the year and are the dominate wind direction for Jamaica (Figure 5). Storm events such as tropical storms and hurricanes occur multiple times a year in the Caribbean usually from June to November. These storms create changes in wind direction and produce high energy waves and storm swells which are capable of transporting large amounts of sediment from the shoreline in a short amount of time (Bascom, 1980; Richards, 2008; Huggett, 2011).

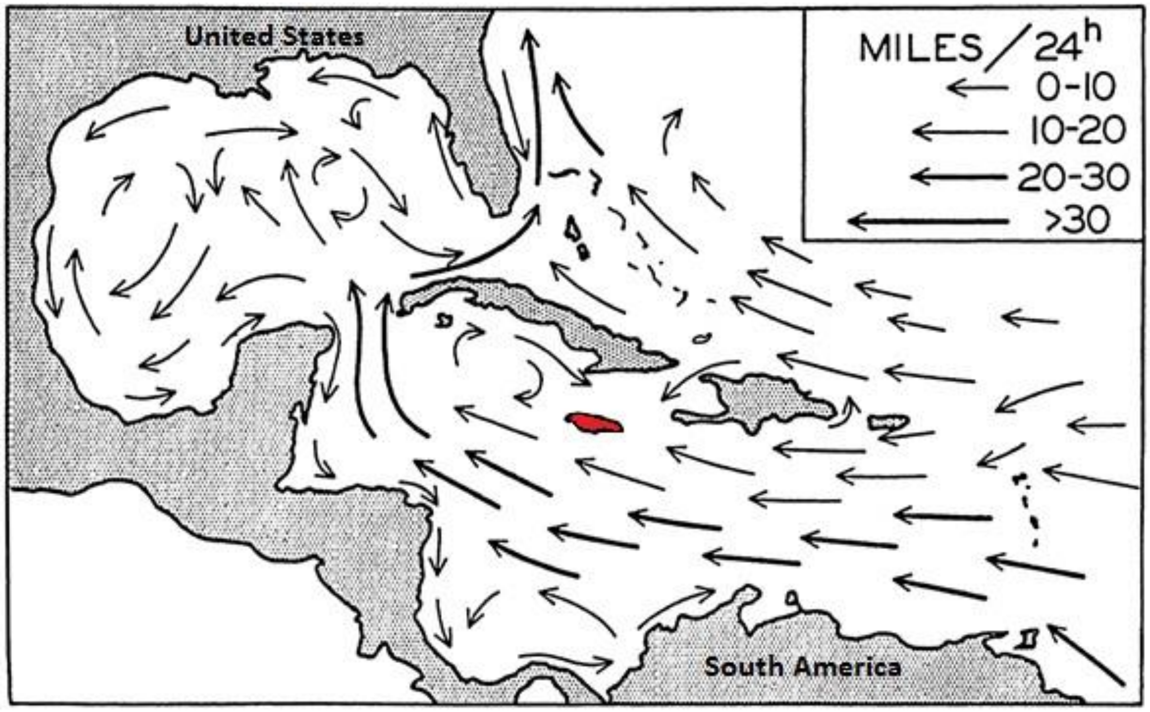

Figure 5. Dominate Wind Direction for the Caribbean. Jamaica is indicated in red and the arrows show a generalized wind velocity for the region. Modified from Sverdrup, Johnson, and Fleming, 1942.

The dominant wave direction will influence the orientation and spatial location of sandy beaches along a shoreline. Overtime, a beach can appear to move along the coast and change its location (Hamblin and Christiansen, 2003). This natural process is called longshore drift. This process indicates the relationship between sediment transport and form changes along the coast. As waves approach the shoreline at a degree other than 90, sediment will be moved in the direction of the dominate current (Figure 6). Overtime, this will cause the beach to move along the shoreline in the direction of the current.

Waves hitting the beach at a 90 degree angle will carry sediment to and from the beach perpendicular to the shoreline. The shoreline will remain in its relative position with variability either inland or offshore (Hamblin and Christiansen, 2003; Tarbuck and Lutgens, 2007).

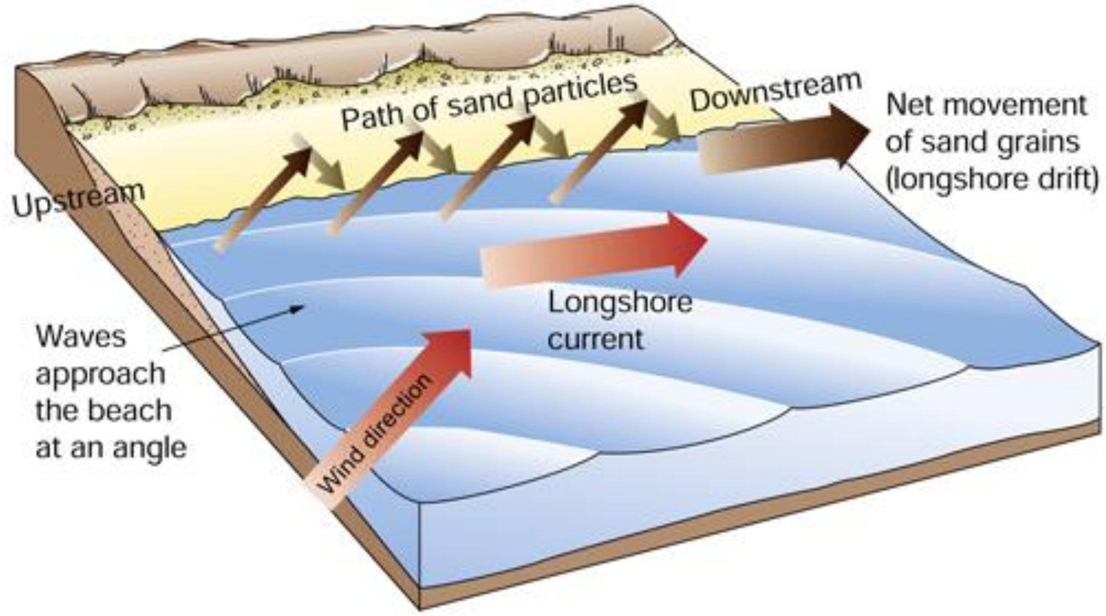

Figure 6. Longshore Drift. Longshorre drift of beach sediment due to longshore currents. Waves hit the beach at an angle and move sediments down shore. Overtime the beach moves in the direction of the current. Source: Pearson Prentice Hall, 2004.

Sediment Budget. The rate at which a coastline will erode or accrete depends on the amount of sediment available. The net amount of sediment available for transport and how sediment is stored in different beach features is described as the sediment budget and it is an important concept for understanding shoreline in equilibrium. Beaches where there is roughly the same amount of sediment transported to and from the beach are classified as being in equilibrium. If more sediment is added than can be transported offshore or along shore, the beach is accreting and will often appear as if the waterline is moving seaward due to accretion (progradation). If more sediment is being transported than deposited, then the beach is considered to be eroding and the waterline will move landward (recession) (Hanson and Lindh, 1993; Short and Wright, 2006; Limber, Patsch, and Griggs, 2008; Prothero and Schwab; 2004).

The beaches in Jamaica receive their sediment supply from the erosion of coral reefs, limestone headlands, and from river discharges. The northern beaches are composed of white, carbonate sands with a large amount originating from the erosion of coral reefs located offshore. The process of eroding and breaking down the reefs' calcareous skeleton into rubble, sand or silt and clay, is called bioerosion and is done by organisms such as pufferfish, parrotfish, hermit crabs, urchins, barnacles and sponges (Glynn, 1997). These organisms help sculpt the reef and produce sediment that eventually ends up depositing on the adjacent shoreline. This creates a healthy sediment supply and helps to keep the reef and beach system in equilibrium. Caribbean reefs are bioeroding at an estimated rate of 0.96 to 3.67 kg $CaCO_3$ /m /yr (Perry, *et al.*, 2014). This sediment is bioeroded by organisms and chemical processes and then transported from the offshore reefs and deposited on the shoreline (Perry, *et al.*, 2014; Holl; 2003). Reefs are less common along the southwest coast of Jamaica, so the majority of sediment for these beaches originate from nearby river systems (Richards, 2008). The reefs in Black River Bay account for only 1.6 percent of Jamaica's coral reefs. Within Black River Bay, 55 percent of the shoreline is protected by fringing reefs. This is less than the northern part of the island where the average percent of shoreline protection is roughly 70 percent (ReefBase, 2015) therefore, bioerosion is greater and more sediment from coral reefs is produced.

Shoreline Types

Caribbean shorelines are varied and range from headlands to sandy beaches. Different shoreline features respond to hurricanes, rising sea levels, and human interactions differently. The shoreline types focused in this study are the main features found along the shorelines of southwestern Jamaica but are also commonly found throughout the Caribbean.

Sandy Beaches. These make up roughly 20 percent of the world's coastline and are more common in microtidal regions (Masselink and Kroon, 2004). Most of the Caribbean is classified as a microtidal environment, so wave dominated beaches are the most common. These beaches experience persistent ocean swells and constant wave interactions (Huggett, 2011). Storm events generally lower beach gradients, widen beaches and increase beach erosion by changing the wave interaction with the beach face (Chambers, 1997). A general understanding of beach formation is that high-energy waves tend to form wide, flat, fine grained beaches whereas more protected lower energy beaches tend to be narrower, steeper and can often form rip currents. A more detailed beach classification system was created by Short and Wright (2006). This system groups beaches into dissipative, intermediate, or reflective beaches (Figure 7). This study will only focus on the beaches most commonly found in Jamaica.

Dissipative Beaches. These are generally high-energy wave environments where waves average 2.5 meters in height and the beaches are composed of fine grained sand. High-energy environments produce large waves that transport sediment offshore creating a wide, low angled surf zone with offshore bars parallel to the shore. Waves tend to break on these bars and can reform multiple times before reaching the shore. These beaches are generally straight and featureless but the presence of headlands or reefs decrease and redirect the wave energy and can cause an overall crescent shape or cusps and berms to form (Short, 1996). A dissipative beach can also form in low-energy environments where very fine sand is present and where there is an abundance of sand (Hesp, 2012). These beaches are heavily affected by storm events such as hurricanes and often show high signs of erosion during these events (Huggett, 2011; Short, 1996).

Intermediate Beach. These types of beaches experience less wave energy and are more dynamic than dissipative beaches. One type of intermediate beach is a low tide terrace or ridge-runnel. This type of beach is composed of fine to medium sand and a relatively steep beach face. Small, shallow rips can form, creating weak currents between the bar and beach face. Cusps can form along the backshore where high swells may reach during storm events (Huggett, 2011; Short,1996).

Reflective Beaches. These beaches are the lowest energy beach type. They are generally steeper with coarser sand (0.4mm) and wave heights between 0 and 1 m and tend to be narrower than the other beach types and often display a berm. These beaches could also be moderate to high-energy beaches with coarse to gravel sized grains (Hesp, 2012). They are usually well protected and located on highly sheltered coasts where embyments are formed and commonly found behind coral reefs (Huggett, 2011; Short, 1996). These beaches display little temporal variability and remain relatively stable unless there is a drastic increase in wave height and energy in which beach erosion will rapidly occur (Short and Wright, 2006).

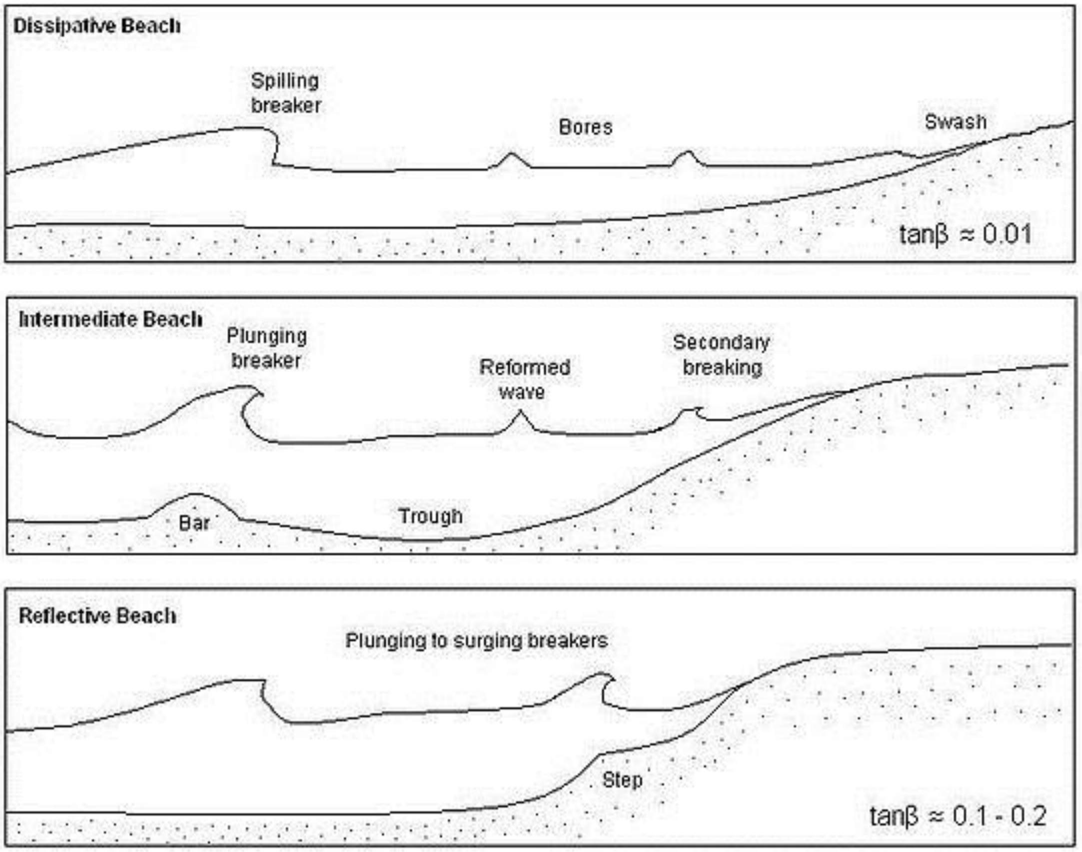

Figure 7. Generalized Beach Classification. The classification system is based on Short and Wright (2006). Beach scales are exaggerated.

Beaches within Black River Bay are predominantly dissipative since the wave energy is high in many areas. The beaches are dominantly fine grained with a low slope angle. The shorelines that have reef protection are generalized as intermediate beaches, specifically low tide terrace beaches. These have a slightly steeper slope and cusps are generally found on the beach face. The areas where intermediate beaches are thought to dominate are along the south portion of the study area, past Parrottee Point. The beach classifications for Black River Bay are based off of observations and profile measurements from satellite imagery.

Headlands and Resistant Shorelines. Coastal headlands are rocky shorelines surrounded by water on three sides and usually adjacent to a bay. These headlands are composed of bedrock and are more resistant to changes made from waves and other coastal processes. More resistant shorelines made of bedrock can be composed of either hard or soft rock. The hard rock is more resistant to wave forces and will change at a slower rate, usually over centuries to millennia. A softer rock will change more rapidly, usually over a few decades. A less resistant soft rock such as a clay or silt rock is usually adjacent to a more resistant hard rock like limestone (Geomorphic Solutions, 2010). Differential erosion from waves and abrasion cause the soft rock to erode at a faster rate than the hard rock, causing a bay to form. The sediment eroded from the rocky shoreline deposits in the bay and forms a crescent beach surrounded by headlands (Huggett, 2014; British Broadcasting Corporation (BBC), 2014).

Headlands are usually high bluffs where waves break and are diffused into the bay. The headland takes the full force of the energy produced by waves and the more sheltered bay receives refracted waves which are lower in energy (Figure 8). Since headlands receive more energy from waves than the adjacent bays, the erosion rate of these landforms are greater than in the bays; however, headlands are more stable than beaches. Beaches are more mobile and easily changed making geomorphic changes more noticeable on human timescales (Huggett, 2011). Shorelines where headlands are absent are where the highest rates of erosion and changes are observed since the beaches and shorelines are exposed to the full force of the energy from waves and movement is not restricted (Tarbuck and Lutgens, 2007).

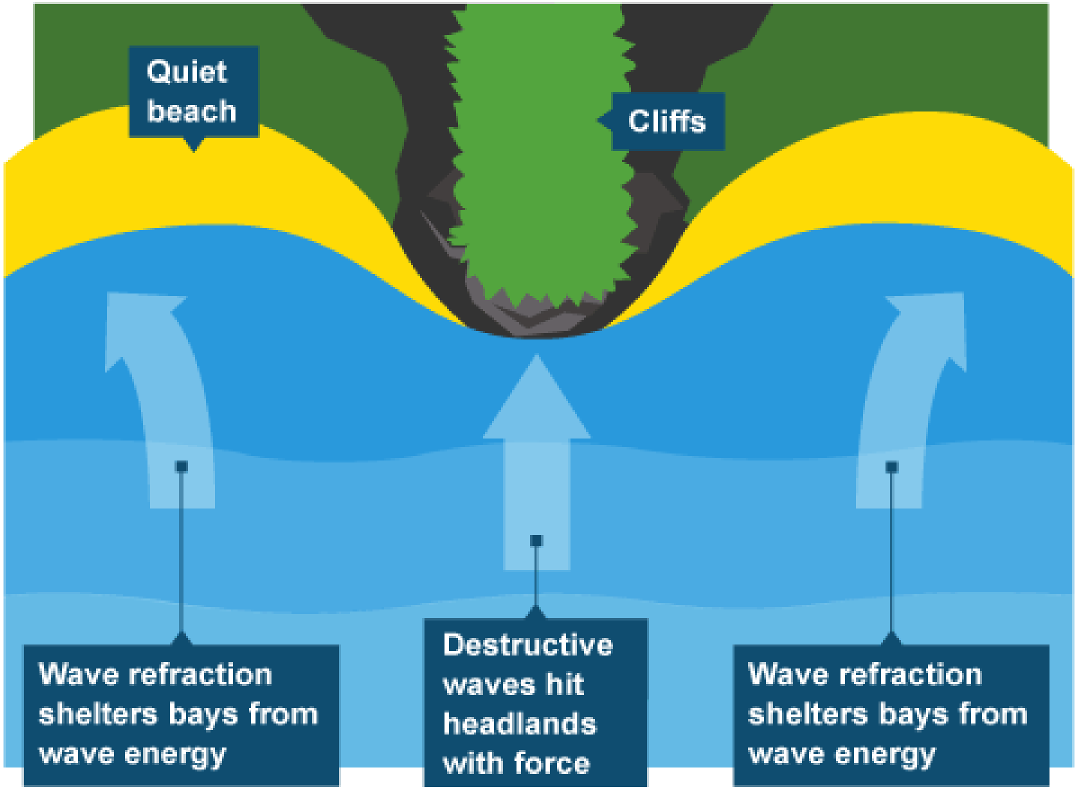

Figure 8. Shoreline Composition. Headlands, such as limestone bluffs, are more resistant to wave processes but receive the full force of wave energy. Waves are refracted into the adjacent bays. Source: British Broadcasting Corporation (BBC), 2014.

Reef Protected Shorelines. Similar to headlands, coral reefs are a resistant feature that provides shoreline protection from wave energy. The type and condition of a coral reef determines the amount of energy absorbed from wave and storm events from reaching the shoreline. Coral reefs can absorb an overall average of 97 percent of the energy from wind produced waves (Valentine, 2014; National Oceanic and Atmospheric Administration, 2013; The Nature Conservancy, 2014). In general, as waves approach a reef, they break on the reef crest, releasing most of the wave's energy. Reefs that are exposed above the surface of the water provide a higher level of protection than submerged reefs (Carey, 2014). There are two types of coral reefs found along the coast of Jamaica and vary in the level of shoreline protection. A fringing reef is the most common and are either connected to the shore or located very close to the shoreline. A barrier reef is located offshore usually within 1,000 m from the shore and separated from the shore by a lagoon. Often these reefs are damaged by storms. Overtime, they can become so damaged only patch reefs remain (Microdocs, 2012). Thus, SLR and increased storm intensity can reduce coral reef protection.

In addition to shoreline protection, coral reefs are a productive ecosystem important to the fishing community, and provide sediment through bioerosion for the adjacent beaches as well as coastal protection from waves and storm events (Beck, 2014). Most coral reefs are located in shallow, tropical regions and are home to 25 percent of all the known species of marine life which include around 4,000 fish species and 800 reef-building corals (Burke, *et al*., 2011). Since 2003, the fishing industry for members of the Caribbean Community (CARICOM) has produced and consumed fish products above the global average of 16.4 kg per capita. CARICOM members such as Barbados, Belize, Grenada, Jamaica, St. Kitts, and St. Lucia, have produced between 14.2 to 52.2 kg per capita in 2003 of fish products making this industry important to the Caribbean economy (CARICOM Secretariat, 2013).

Reefs are at risk and require protection from natural and anthropogenic factors. It is estimated that 30 percent of the world's reefs are seriously damaged and 60 percent could be lost by 2030 (UNEP-WCMC, 2006). Overfishing, pollution, coral mining, sedimentation, tropical storms, and coral bleaching are all serious threats to coral reefs. As these structures are damaged or destroyed, the fishing industry is threatened as well as an important source of income for many coastal communities. Damaged reefs also allow more energy to reach the shoreline, increasing the rate of shoreline erosion. These reef systems should be managed along with other coastal resources to help insure their existence in the future (UNEP-WCMC, 2006).

Artificial Shorelines. Structures built to protect shorelines from the natural process of erosion are being constructed to protect infrastructure built too close to the shoreline. These artificial structures, such as seawalls, groins, and breakwaters are used as a management practice to deflect wave energy and change the natural flow of sediment along the coast. This process is usually called hard stabilization (Tarbuck and Lutgens, 2007) and has a varied degree of success (Pilkey and Wright, 1988).

Hard structures are designed to trap sediment to increase beach widths or to prevent waves from eroding the shoreline to the point where infrastructure will be damaged. Structures such as groins are built perpendicular to the shoreline and trap sediment within updrift cells to slow sediment transport and reduce sediment loss. However, these structures interfere with the natural process of longshore drift and usually too much sediment collects on the windward side of the groin so that the lee side becomes sediment deprived (Tarbuck and Lutgens, 2007). Seawalls and breakwaters are built parallel to the shore to resist wave energy directly and prevent excessive erosion due to waves and storm swells. Seawalls are built on the shore to prevent loss of property and infrastructure whereas breakwaters are built offshore and act similar to reef systems by reducing wave energy. The problem with these structures is that reflected or dissipated waves create a scour at the base of the structure and cause erosion to occur without allowing sediment to be replenished. This disrupts the equilibrium of the beach system and the area on the seaward side of the wall will erode and often cause the structure to collapse (Figure 9). Building these hard structures only helps a few and degrades or destroys natural beaches (Tarbuck and Lutgens, 2007; Twu and Liao, 1999).

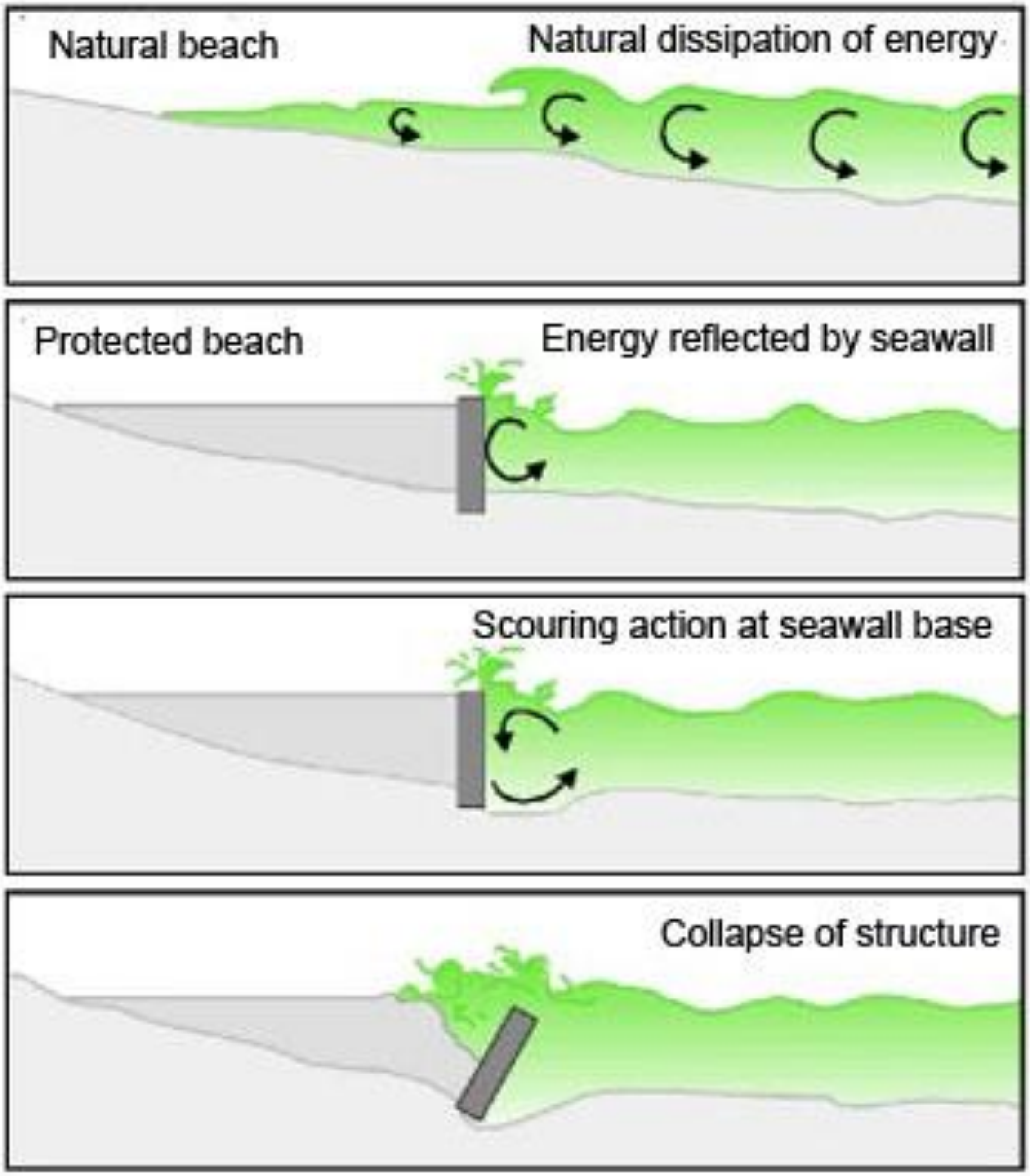

Figure 9. Collapse of Seawalls. Seawalls are built on shorelines to protect a beach or infrastructure. The incoming waves hit the wall and reflect in a downward motion. This causes souring to occur at the base, increasing erosion. Eventually the structure may collapse. Source: Spiegel, 2013.

Beaches as Environmental Indicators

Beaches are dynamic and can be used to understand changes in the environment. Beaches are formed by waves and respond to changes in seasons, storm events, and sediment supply by either eroding, accreting, or relocating down shore. The level of sediment transport between waves and a beach depends on the level of protection by vegetation or landforms and the level of human interaction with the shoreline. Rising sea levels are pressuring coastal regions and beaches are one of the first features to feel the full effect of climate change and increased sea levels.

Depositional Landforms. Wave processes and currents influence the movement of sediment and create erosional and depositional landforms. Depositional landforms such as spits, bars, barriers, forelands, coastal dunes, and beaches are relatively mobile and will change over human timescales or during a single storm event (Huggett, 2011; Tarbuck and Lutgens, 2007). These landforms form when there is an adequate source or supply of fine grained sediment such as the sediment discharged from the Black River. These depositional landforms are found along the south coast of Jamaica and can be used to help determine the direction of longshore currents and dominate wave direction. A spit is an accumulation of sand that projects out into a bay and is only attached to the shore on one side. Spits can either be long and straight with a hook-like shape (hooked spit) or shaped more like a triangle where the length of the spit is less than the width (foreland spit). Areas where spits form are usually places where the shoreline abruptly changes direction and the spit only receives longshore movement on one side (Huggett, 2011). A bar is a straight accumulation of sand that forms parallel to the shore. Bars can become barriers and cut off a bay to form a lagoon. These depositional landforms often form in shelter areas and are usually formed when a spit complexly seals off a body of water. Coastal dunes can form along the shoreline and are formed by wind energy; however the sediment that forms these dunes is important to the sediment supply being removed or added to the coastal zone. Beaches are the most common depositional landform and will form in bays as pocket beaches and along shorelines where sediment can be deposited (Huggett, 2011; Tarbuck and Lutgens, 2007).

Seasonal Changes and Storm Events. Changes in wave energy and direction due to seasons and storm events can be seen in changes in beach morphology. Generally, the changes in energy during the seasons create summer and winter beach profiles. Storms and wave heights generally increase from fall into the winter during hurricane season from late August through November. This creates flatter beaches due to increased wave energy. Beaches with a low angle will show a greater geomorphic change due to storms since wave swells are able to travel further inland and interact with berms, vegetation and stored sediment (Bascom, 1980). During these storm events, berms typically erode and the fine grained beach tends to flatten as sand is pulled offshore and deposited on offshore bars (Figure 10). The beach may appear to be growing and becoming wider; however, the vegetation line and berm line are damaged or eroded which actually cause the shoreline to regress. During late spring to early summer waves are generally calmer and smaller so beaches tend to recover as sand is slowly returned from the offshore bars onto the beach and berm. The rate vegetation recovers is slower than beach recovery and if multiple storm events occur during one season, a beach will have less time to recover and the geomorphic changes due to erosion are greater (Robinson, Rowe, and Khan, 2005).

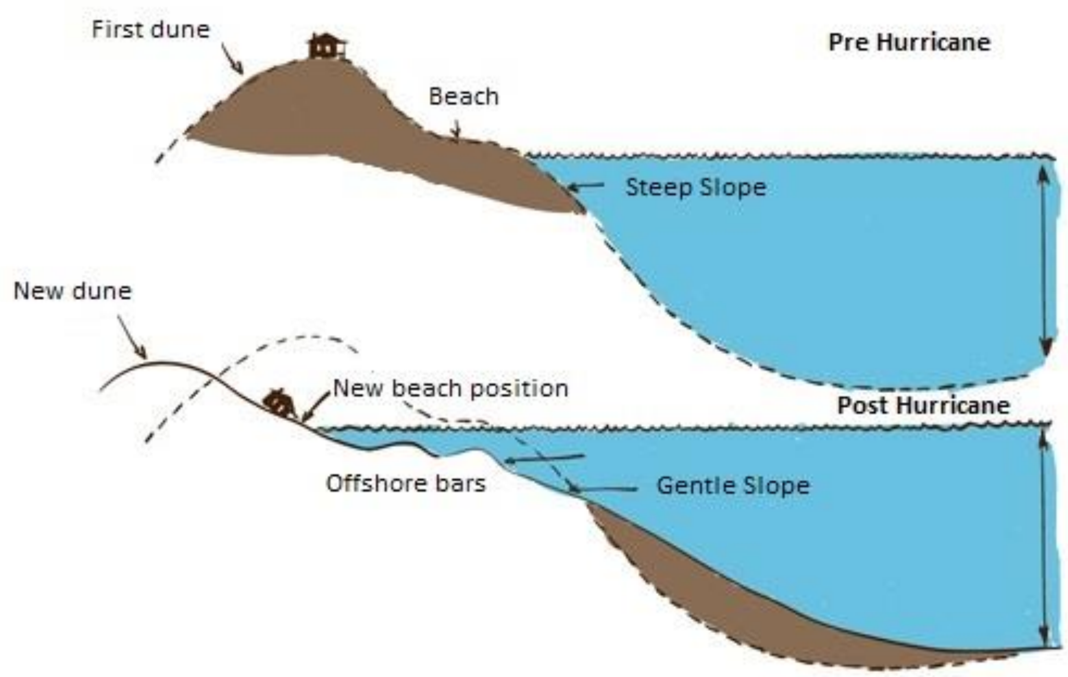

Figure 10. Storm Profiles. General beach profile change before and after a hurricane or strong storm event. Level of profile change is exaggerated. Source: University of South Florida, 2015.

Hurricanes and strong storm events produce large storm swells with average heights doubling normal wave heights. These waves are capable of changing beach profiles over short timeframes of hours or days (Bosser *et al*., 2000; Daniel and Abkowitz, 2005). These beaches will recover during non-storm events. Studies on the level of beach change during storm events have been increasing during the past 30 to 40 years. Cambers (1997) explains the profile changes on Caribbean islands during two major hurricanes; Hugo in 1988 and Luis in 1995. The study documents periods ranging 1 to 10 years on islands in the Lesser Antilles (Anguilla, Antigua-Barbuda, British Virgin Islands, Dominica, Grenada, Montserrat, St. Kitts/Nevis, St. Lucia, St. Vincent, and the Grenadines) (Cambers, 1997). Monitoring stations where placed along the shoreline of these islands and data was collected quarterly and immediately after a large storm event. These measurements were taken using simple surveying techniques by staff members of the COSALC coordinating centers. The profile and width of the beaches are then averaged for each year and the first year was used as the baseline. On average, 70 percent of the beaches were eroding and 30 percent were accreting. This trend changed drastically after a hurricane event in which the profile areas decreased from 6 to 40 percent (Cambers, 1997). Included are Cambers' table (Table 1) and Camber's graph (Figure 11) displaying the results that hurricanes have a large effect on the shape and rate of change on beach profiles.

Table 1. Changes in Beach and Dunes from Hurricanes in 1995. Source: Cambers, 1997.

Island	Distance to Center of Hurricane Luis (km)	Average Change in Profile Area (percent)	Average Change in Beach Width (m)	Average Retreat of Veg/Dune Line (m)
Barbuda	5	-40	-1.1	-17.5
Anguilla	28	-40	-8.7	-8.9
Antigua	40	-23	-4.9	-4.9
St. Kitts	70	-6	-3.2	-4
Nevis	90	-30	-5.7	-5.2
Montserrat	90	-31	-10.9	-3.5
Dominica	180	-24	-6.7	-2.5

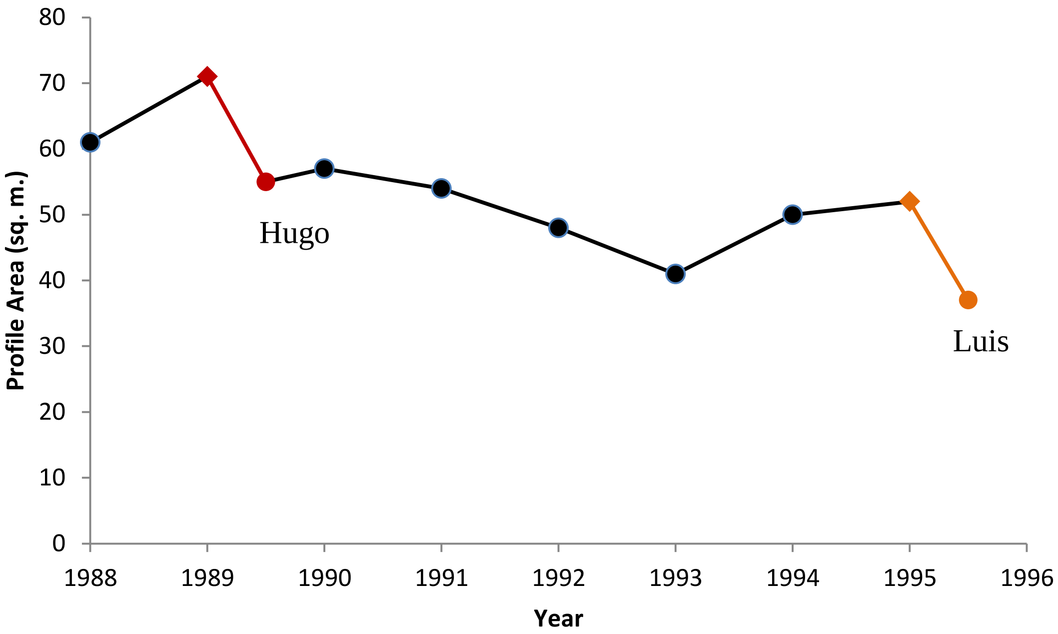

Figure 11. Beach Changes from Cambers' Study in 1997. The diamond indicates the data collected before Hurricane Hugo (red) and Hurricane Luis (orange). The graph shows the drastic change before and after a hurricane and the smaller changes between extreme storm events.

Global warming has been indicated as a possible reason for hurricane intensification as well as accelerating SLR (Mousavi, 2010). As more CO_2 enters the atmosphere, the greenhouse effect causes the surface of the oceans and the air above it to increase. Warmer air is able to hold more moisture, so evaporation occurs in tropical areas. Preexisting climatic disturbances begin to interact with the moisture in the heated atmosphere, causing a spiral to form and eventually a hurricane. The lighter and warmer the air is above the storm, the more time the hurricane has to build up strength. Therefore, rising global temperatures favor stronger storm systems (Mousavi, 2010). The threat of stronger storms and rising sea level increases risks to coastal zones. Higher water levels mean more water displacement onto the land. This increases the rate at which waves interact with the shoreline, ultimately removing more sediment than lower sea levels (Hubbard, 1992).

Sea Level Rise in Jamaica

Studies by Robinson and Hendry (2012), Robinson *et al*., (2012), and Robinson, Rowe, and Khan, (2005) explain the history of sea level changes during the Holocene and the effects on Jamaican shores. At the beginning of the Holocene, global temperatures increased as the climate transitioned from a glacial to an interglacial period. The melting of ice sheets caused sea level to rise gradually by roughly 6 mm/yr. This equals a total displacement of 25 meters within the first 4,000 years (Robinson, Rowe, and Khan, 2005). This was a gradual increase until around 14,000 years ago when sea level rapidly increased to 4.5 cm/yr (Robinson, Rowe, and Khan, 2005). This trend of gradual then rapid SLR continued until 6,000-7,000 years ago. After this initial rise, sea level fluctuated and followed a slowly increasing trend to where sea level is today (Donoghue and White, 1995).

Recently, SLR has accelerated due to thermal expansion of the ocean due to global warming (Bueno *et al*., 2008). While SLR can have natural causes, SLR has been accelerating due to burning of fossil fuels and the release of greenhouse gases (Causes of Climate Change, 2013). The most extensive research conducted in Jamaica on shoreline erosion has been along Long Bay in Negril. This is located along the west coast of Jamaica. Studies by Mondon and Warner, (2012), Robinson and Hendry (2012) and Robinson *et al*. (2012), produce a wide range of erosion rates along this shoreline. Over the past 30 to 60 years, erosion rates have been measured from 0.23 to 0.30 m/yr for the whole of Long Bay. In some areas, erosion rates have been measured to be as high as 0.59 m/yr over a 37 year span (Robinson *et al*, 2012).

Longshore drift has been observed along the beaches in Negril and Vere. Notable coastal recession has been observed in both areas over a 30 to 50 year period. Spits and barrier bars have disappeared and occurred elsewhere along the shoreline (McKenzie, 2012; Robinson, Rowe, and Khan, 2005). Each shoreline is different and the effects of SLR on beaches are site specific. Continued research is needed to understand how specific shorelines around Jamaica will respond to rising sea levels.

Responding to Sea Level Rise. Rising sea levels and associated shoreline changes are pressuring coastal communities in the Caribbean including Jamaica (Gable, 1997). The "Coasts at Risk" index rates which coastlines are most at risk of floods, tsunamis and SLR based on exposure and vulnerability. Jamaica is one of the top 20 countries most at risk (Coasts at Risk, 2014). Most shoreline erosion studies have occurred in other countries or along the north coast of Jamaica. There is major concern about the degree of property loss, reduced tourism, and degradation of coral reefs and fisheries related to SLR throughout Jamaica, specifically along the south coast of Jamaica (Richards, 2008).

To help reduce the pressures of SLR on the beaches in Negril, the local government has made some attempts at beach restoration. A recent article from The Gleaner by Veira (2014) explains the current proposed solutions and the repercussions the plans will have on the local community and its beaches. Proposed solutions in 2007 by a local engineer, Smith Warner were: sand nourishment, nearshore breakwaters, reef extension and a combined solution. Other proposed solutions for beach restoration included restoring mangroves, sea grasses and coral reefs along with improvements in water quality. These latter proposals have largely been ignored by the government and The National Environment and Planning Agency (NEPA). Instead, NEPA started designing rubble mound breakwaters along the ends of the beach (Veira, 2014).

The local stakeholders have expressed their concerns about the project stating it will affect businesses, tourism, daily traffic, and a loss of revenue (Veira, 2014). The environmental and economic factors and repercussions must be considered in any restoration project. This proposed idea will deflect most of the daily wave action from reaching the beach as well as waves produced from storm events. This case study strengthen the need for a better understanding of SLR and erosion rates in Jamaica since its effects are already being felt by the local communities**.**

There are many proposed solutions for dealing with shoreline erosion. Some solutions are more permanent, effective and less expensive than others. In Negril, the nearshore breakwater structures will require nine months for construction, 53,280 cubic meters of armor stone, and cost roughly US$20 million - US$40 million to construct (Veira, 2014). The breakwater structures will reduce the wave heights by 0.1-0.3 m and reduce the wave energy up to 30 percent, therefore, reducing the erosion rate by up to 50 percent (Mondon and Warner, 2012). These breakwater structures act as an artificial barrier reef but are costly to build.

Other possible solutions are to replenish the sand supply by bringing in sediment from inland, adding it to the existing beach. This could double the width of the beach; however is only a temporary fix and has a lifespan of 20-25 years. Reef extension or rebuilding of a dying reef would reduce the wave energy hitting the shoreline and have a similar effect as the breakwater solution (Veira, 2014). Mangrove restoration or the restoration of other coastal vegetation would also be a solution as this would create new habitats for marine and coastal life as well as act as natural seawalls, allowing the natural flow of sediment to occur, unlike the anthropogenic structures (Thampanya *et al.*, 2006). All these solutions and their repercussions need to be taken into account when proposing a coastal plan. Understanding the dynamics of the shoreline will improve the decision-making process.

CHAPTER 3. STUDY AREA

Black River Bay is located on the southwest coast of Jamaica in the parish of St. Elizabeth. It is one of Jamaica’s oldest towns and is the parish capital with an estimated population of 5,717 in 2009 (St. Elizabeth Parish Development Committee, 2013). The town was founded sometime before 1685 as a port city at the mouth of the Black River where the export of logwood allowed the town to expand and prosper until it was declared the parish’s capital in 1773 (Jamaica National Heritage Trust, 2011). The town became an important port for the slave trade and became the main economic and commercial center for the parish. By the early 1900’s, Black River was the second most important town in Jamaica with Kingston being the most important. Black River grew in wealth and in 1893 became the first Jamaican town to be lit by electricity. In 1903, Black River became the first town to have cars and telephones (Fiwi Roots Jamaica, 2007). Today, Black River is a medium-sized town, where the seaport is less important and environmental tourism and fishing are the main industries (Jamaica National Heritage Trust, 2011). The area has also become a destination for tourist looking to experience the historic Jamaican culture along with the typical tropical experience of sun, sand, and sea.

Geography

Jamaica is the third largest island of the Greater Antilles located in the Caribbean Sea; approximately 150 km south of Cuba (Moses, 2008). Jamaica’s has a high interior reaching 2,256 m in the Blue Mountains, surrounded by a coastal plain that is less than 3.2 km wide in most areas along the north and south coast and slightly wider along the east and west coast (Figure 12) (Richards, 2008). The island has an area of 10,911 km^2

and the coastline is roughly 895 km in length and described as irregular, varying from sandy beaches, mangrove swamps, to limestone bluffs. The southern coast of the island has a shallow shelf of less than 36 m and extends 8-32 km from the shore where barrier reefs, sand clays and low reef protection are found (Richards, 2008).

The area of Black River Bay used in this study includes roughly 30 km of shoreline composed of sandy beaches and limestone headlands. The area begins roughly 500 m northwest of the Fonthill Nature Reserve beach and ends 1.5 km east of Parrottee Point. Most of these beaches are dissipative beaches and located 1 to 3 meters above sea level (Figure 13). The main beaches focused on in this study are Fonthill Beach Park, Hunts Bay, Malcolm Bay, and Parrottee Point. Hunts Bay and Malcolm Bay are sandy beaches with limestone headlands on either side of the beach. Parrottee Point is a sand spit located in the southern portion of the study area and has high protection from coastal dunes and fringing reefs along the southeastern part of the shoreline.

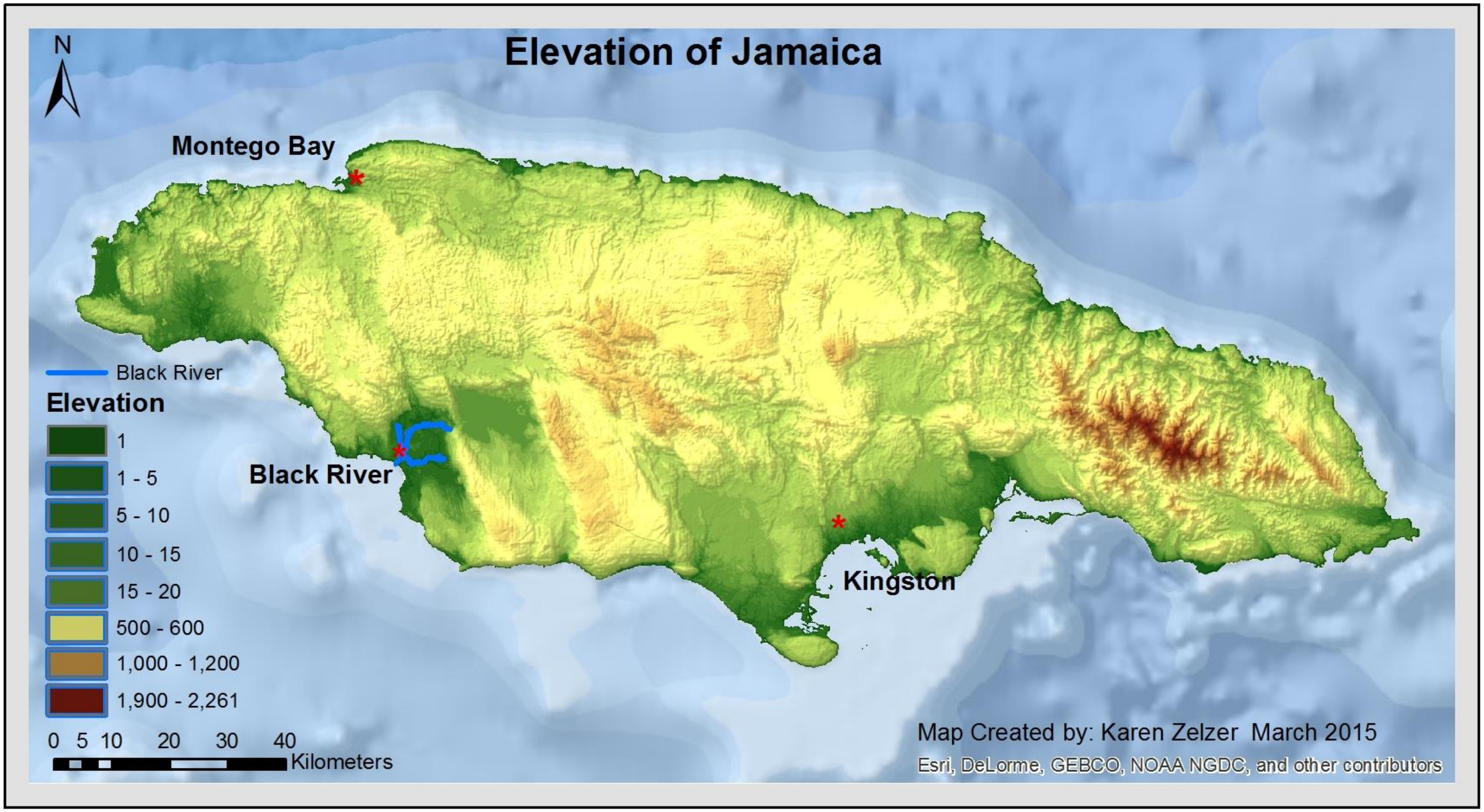

Figure 12. Elevation of Jamaica.

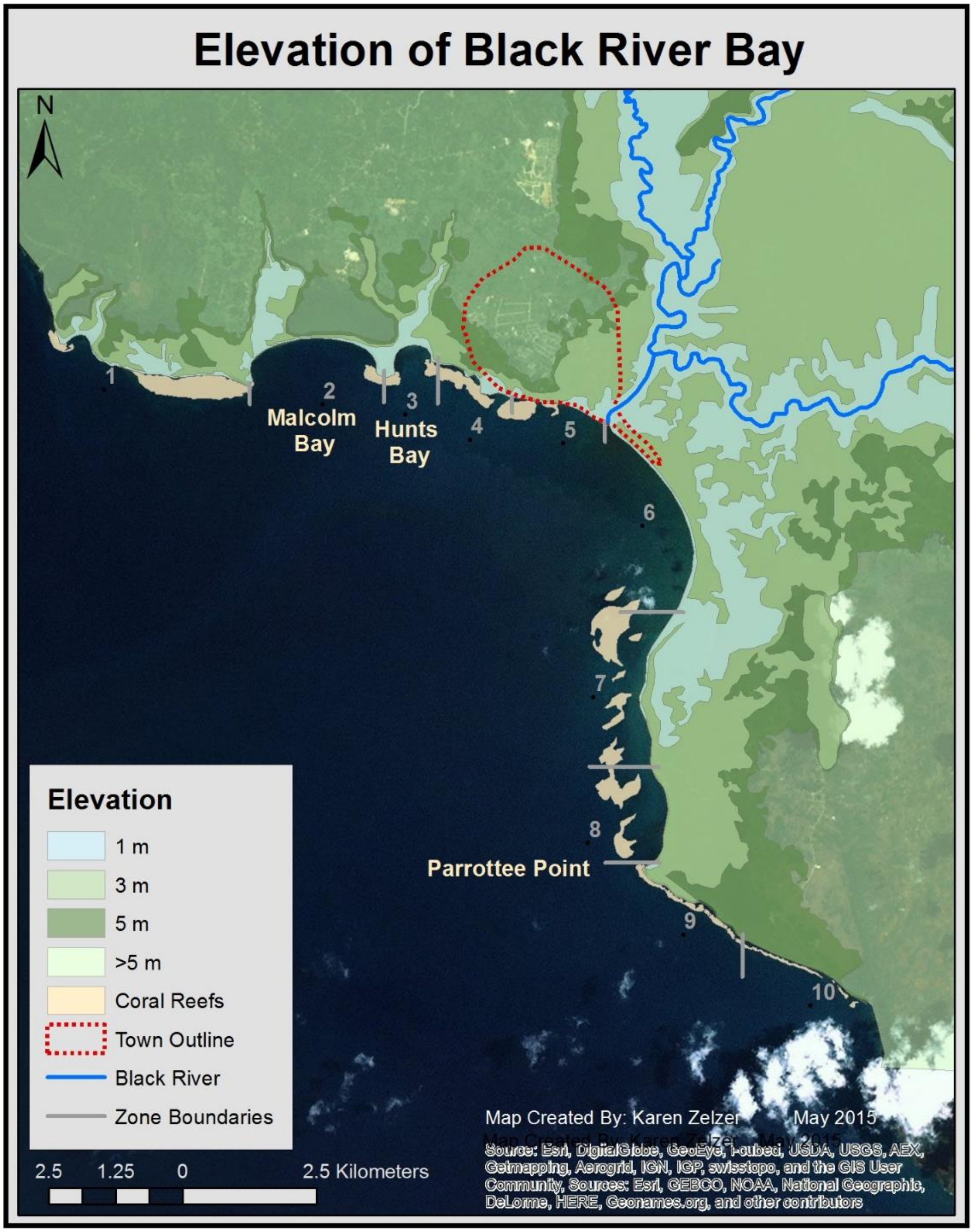

Figure 13. Elevation of Black River Bay. The main beaches of this study are indicated.

Geology

The island of Jamaica is located on the northern edge of the Caribbean plate which is adjacent to the North American Plate. The Cayman Trench runs between Cuba and Jamaica, separating the North American plate from the Caribbean plate (Moses, 2008). During the upper Cretaceous period, subduction of the North American Plate under the Caribbean plate created an uplift of crust that formed the core of Jamaica. A series of marine submergences after the island was formed and caused a limestone mantle to deposit which formed almost two-thirds of the island (Asprey and Robbins, 1953). The western portion of the island is dominated by post-Eocene carbonates overlaying the Cretaceous basement rock.

Stratigraphy. The Black River Bay is mainly composed of alluvium deposited on top of limestone formations. The carbonates in this area are divided into the White and Yellow Limestone groups (Table 2). The White Limestone, specifically the Troy Formation, dominates the outcrops in the study area. The Troy Formation is the lowest unit in the White Limestone Group and consists of dolostones and crystalline limestones. This unit was formed during the Mid-Eocene and is a compact, well-bedded, recrystalliszed limestone with little to no fossils present. The Montpelier Limestone Formation is composed of two lithofacies; the Monteague/Cobre and the Montpelier Beds (Robinson and Mitchell, 1999). These are not distinguishable from each other and have been grouped at the Montpelier Formation. The geology within the Black River Bay (Figure 14) is composed of few limestone outcrops of the White Limestone group. Most of the low-lying area surrounding the Black River is covered with alluvium deposits (Mitchell, 2004).

Table 2. Stratigraphy of Southwest Jamaica. Source: Robinson and Mitchell, 1999.

Group	Formation	Period	Age
White Limestone	**Alluvium***	Pleistocene and Holocene	2.5 million years ago to present
	Montpelier Limestone	Mid- Miocene	23 to 5.3 million years ago
	Bonny Gate	to	
	Troy Limestone	Mid-Eocene	55.8 to 33.9 million years ago
Yellow Limestone**	Masenmure	Paleocene	65.5 to 55.8 million years ago
	Jerusalem-Thickett River Limestone	to	
	Tom Spring	Late Cretaceous	99.6 to 65.5 million years ago
	Birch Hill		

* Not a formation

**Not all units are included for the Yellow Limestone Group

Bolded text represents main layers in Black River Bay

There are a series of faults throughout Jamaica with a dominantly NNW-SSE trend. The major fault in the Black River region is the Montpelier Newmarket Belt (Figure 14). This belt is highly deformed and has caused some NE-SW shortening and NW-SE extension in the area and is believed to be a reverse fault with an upthrown block to the NE (Wiggins-Grandison and Atakan, 2004). The area west of the major fault accreted over a series of transgression events.

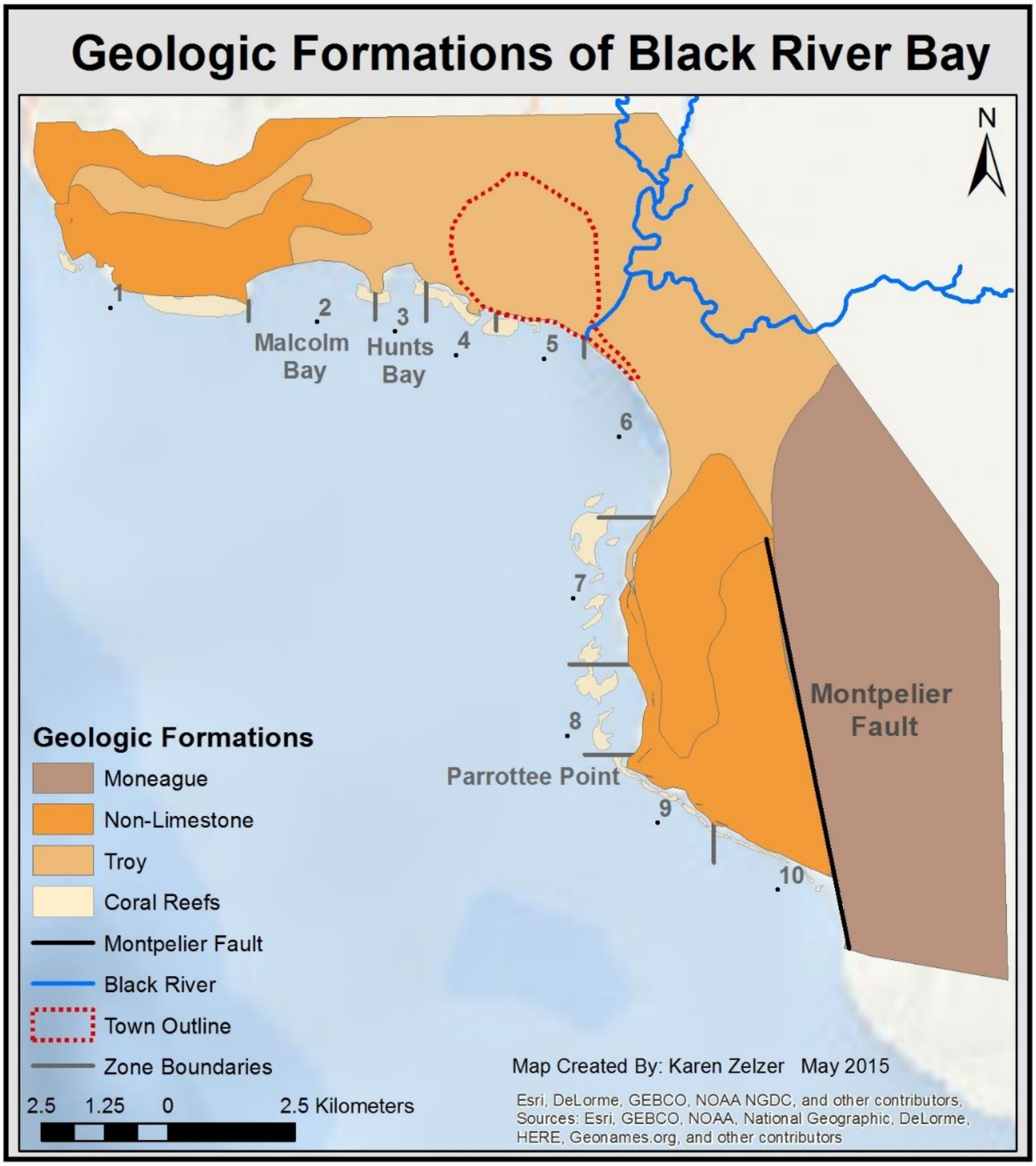

Figure 14. Geologic Formations in Black River Bay. Alluvium deposits are not included in this formations map but alluvium covers most of the area surrounding the Black River. Source: Robinson and Mitchell, 1999.

Soils. Black River Bay is located in the Coastal Plain Region where it is sheltered by rain-bearing monsoon winds and is composed of dry, flat to gently undulating coastal plains. These plains are formed by lacustrine or marine and river sediments (Hennemann and Mantel, 1995). The area is mainly composed of five different soil series: The Crane, Bonny Gate, Carron Hall, Cashew, and Hodges. An unnamed series makes up a large portion of the bay surrounding the Black River, this series will be labeled Coastal Swamps for the purpose of this study. The Cashew and Hodges formations are not found along the coast and are associated with higher elevations of greater than 5 meters. They are mainly composed of clay loam or silica sand (Ministry of Agriculture, 1989). The Bonny Gate series is located in the southern portion of the bay where the elevation is generally higher (> 5 m). This series is a stony loam that consists of large bedrock clasts and residuum (Ministry of Agriculture, 1989) and represents an upland or hillslope area. The majority of Black River contains the Coastal Swamp, Crane, and Carron Hall (Figure 15) which are located at lower elevations (between 1 m and 5 m) with gentle to nearly level slopes. The Coastal Swamps are composed of gravely clay loam and are likely fluvial or lacustrine deposits. The Crane series is a coarse loam and are likely dune or sand barriers. This series is located along the shoreline as well as the area around and behind Parrottee Pound. This could indicate the location of a previous shoreline before sea level fell during the Wisconsin glaciation (late Pleistocene) and fluvial sediments were deposited. The sea level then rose during the interglacial period, creating the current shoreline (Ministry of Agriculture, 1989; Mickelson and Colgan, 2003). The Carron Hall series is clay and likely old weathered colluvium that overlies bedrock or residuum (Ministry of Agriculture, 1989).

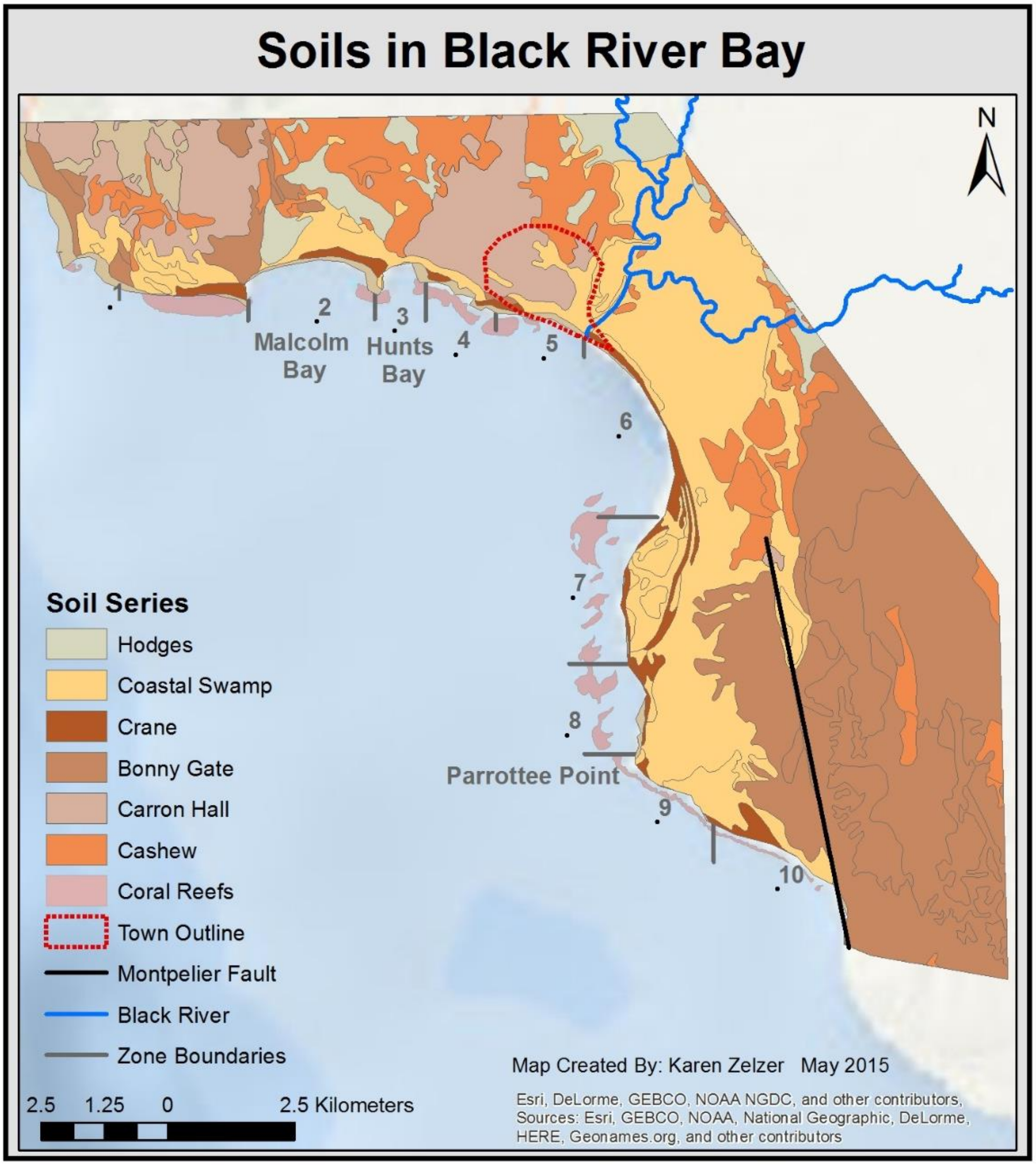

Figure 15. Soils in Black River Bay.

Climate

Jamaica's climate is tropical and similar to the other Greater Antilles with an average temperate ranging between 72°F and 88°F, year round along the coast. It is located in the Northern Trades belt which creates small seasonal temperature ranges. June through August is the country's warmest months and the stormiest months run from June through November. This is when the risk for a hurricane is heightened (Richards, 2008). The annual precipitation rate averages 1,980 mm, with higher rates along the east coast. The Blue Mountains receive around 7,620 mm a year (World Travel Guide, 2014) and the south coast receives the least amount of rainfall at roughly 813 mm a year (Meteorological Service, 2002).

Wave, Wind, and Storm Patterns

The Caribbean Sea is composed of different water masses that originate from the North or South Atlantic. The dominate surface current is a westward direction starting from the Lesser Antillies Islands until the area south of Jamaica before taking a more northwestern direction (Centurioni & Niiler, 2003). This current is known as the Caribbean Current and is caused by the northeast trade winds and the southeast trade winds converging in the Intertropical Convergence Zone (ITCZ). Hurricanes tend to form in the ITCZ and travel westward (Figure 16). Tropical cyclones such as tropical storms and hurricanes form in this region of the Atlantic Ocean. Often, these storms start as tropical depressions which are strong storm systems that develop a cyclonic (counter-clockwise) rotation due to pressure changes (U.S. Geological Survey, 2012).

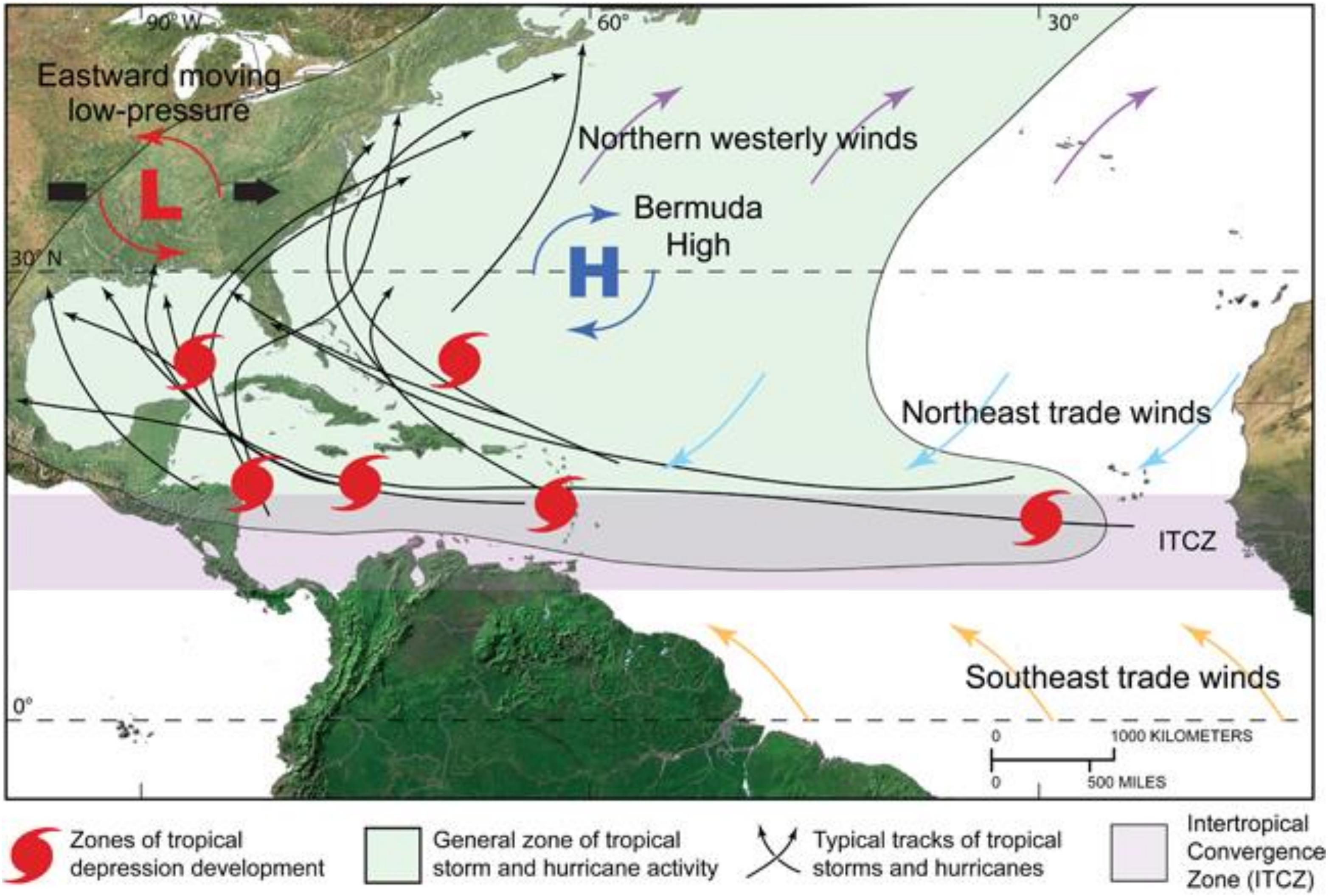

Figure 16. General Storm Patterns in the Caribbean Region. The ITCZ is located south of Jamaica. This creates strong winds that dominate from the Southeast Source: Barnhardt, 2009.

The recent major storm that hit Jamaica was Hurricane Ivan. This was a category 5 storm that occurred in September 2004. This hurricane followed an unusual path (Figure 17 and 18) that started off the West coast of Africa, traveled between 32 to 40 km of the southern coast of Jamaica before heading northwest and making landfall in Alabama, United States (ECLAC, 2004). Sustainable winds reached speeds of 180 km/hr accompanied by rainfall several times the normal average for the southern coast. This resulted in flooding, mass wasting and 595 million US dollars' worth of damage. Seventeen people were killed and over 369,000 people were directly affected, making Ivan one of the worst hurricanes to hit Jamaica since Hurricane Gilbert in 1988 (ECLAC, 2004). Ivan was the second hurricane to affect the southern coast of Jamaica in 2004 with Hurricane Charley occurring first on August 10. Charley was only a category 1 hurricane but brought strong wind and rain, mainly affecting the parishes of St. Elizabeth and Manchester (ECLAC, 2004).

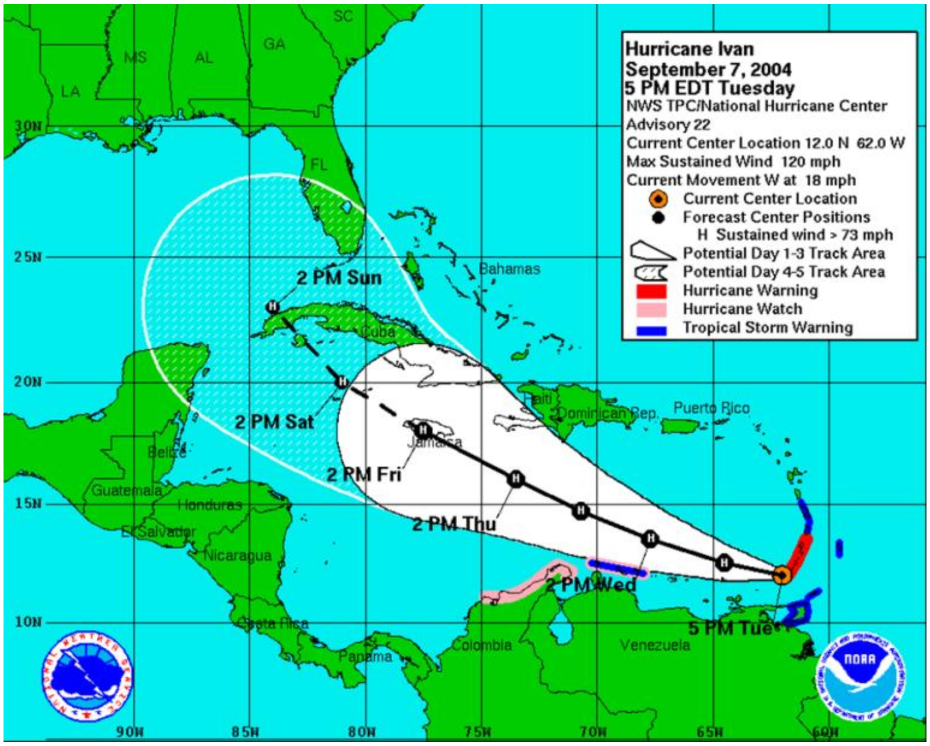

Figure 17. Path of Hurricane Ivan Throughout the Caribbean. Source: NOAA, 2015.

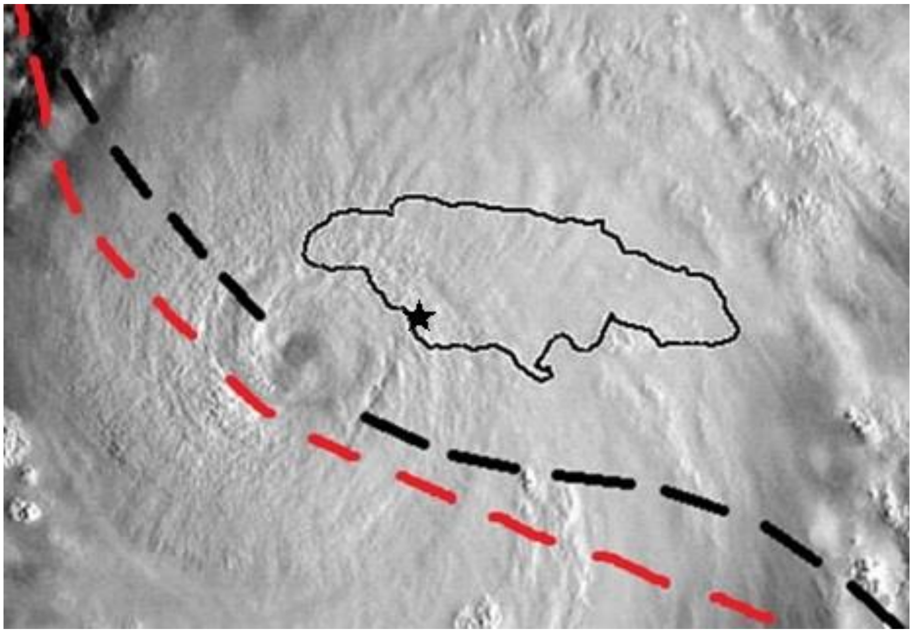

Figure 18. Hurricane Paths. General path of Hurricane Ivan (black) and Hurricane Charley (red) off the coast of Jamaica in 2004. Source NOAA, 2015.

Waves approach the south coast of Jamaica mainly from the east and become almost parallel as the waves enter the bay. Waves generally follow the topography of the sea floor causing the waves to approach a bay roughly parallel to the shore until they interact with headlands or reefs. As the waves near the shore, drag pulls them closer to the headlands where they will break and reflect into the bays. The presence of fringing and barrier reefs will cause the waves to break and decrease in energy before reaching the shore. The waves will refract slightly off of the reefs and then continue on towards the shore (Bascom, 1973).

Land Use

The highest density of urban infrastructure in Black River Bay is located around and downshore from the mouth of the Black River. Most residential buildings are located along the southern portion of the bay between the mouth of the Black River and before Parrottee Bay. The area around the Black River is fertile and an important habitat for fish and wildlife (Jamaica National Heritage Trust, 2011). This made the area around the river an ideal location for early settlement.

The Black River is one of Jamaica’s longest rivers measuring 53.4 km in length and is supported by many tributaries. The river originates as an underground stream in the mountains of Manchester and flows westward, disappearing again for a distance until it reemerges in St. Elizabeth. The river flows into the Upper Morass (Jamaica’s largest swampland) before it flows into the sea. The water of the Black River is clear but the river receives its name for the dark black sediment that lines the riverbed (Jamaica National Heritage Trust, 2011).

Most of the land surrounding the Black River is at or below 3 m making it vulnerable to inundation from storm events and SLR. A large portion of infrastructure is located within 100 m from the coast and below 3 m (Figure 19). Other than the area around the Black River, most of the land use along the bay is fields, mangroves, or herbaceous wetlands.

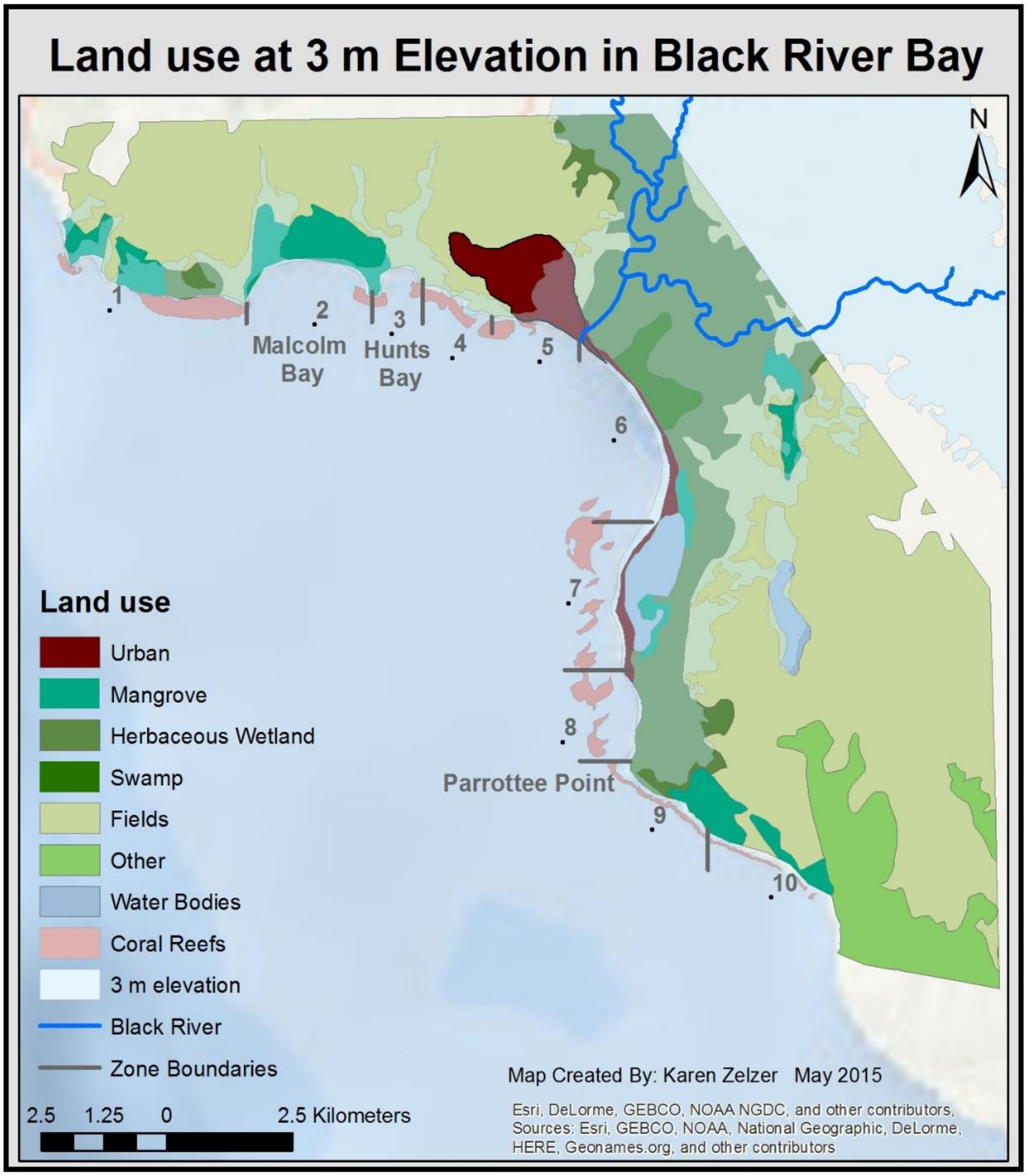

Figure 19. Land Use at 3 m Elevation Within Black River Bay.

Description of Zones

Black River Bay was split into ten zones based on geographic features. These zones act as boundaries to help explain where erosion or accretion is occurring and where the shorelines are stable. The zones include geologic formations, land use, and elevation ranging from 1 to 5 m (Table 3). Each zone includes a main geomorphic feature such as a bay, river, or point and uses the local names for these features.

Table 3. Zone Descriptions. Description of zone boundaries and the percent of geologic formations, land use, and elevation that is found in each zone. Percent of total shoreline is in parentheses.

Zone Name	Boundary Description	Length (m)	Geology	Landuse	Elevation*
1. Fonthill	Headland point to start to headland point	4350	Non-limestone (100)	Herbaceous wetland (71) Fields (29)	1 m (100)
2. Malcolm Bay	Malcolm Bay: Headland to Headland	3550	Non-limestone (42) Troy (58)	Herbaceous wetland (80) Field (20)	1 m (100)
3. Hunt Bay	Hunts Bay: Headland to Headland	17501	Troy (100)	Herbaceous wetland Field (54)	1 m (100)
4. Hodges Bay	Hodges Bay to start of Urban area	1950	Troy (100)	Field (100)	1 m (100)
5. Black River Bay West	Start of Urban area to mouth of Black River	1900	Troy (100)	Field (76) Urban (23)	1 m (100)
6. Black River Bay East	Mouth of Black River to start of Parrottee Pond	4450	Troy (100)	Urban (100)	1 m (100)
7. Parrottee Pond	Parrottee Pond	3150	Troy (46) Non-limestone (54)	Urban (100)	1 m (71) 3 m (29)
8. Parrottee Bay	Parrottee Bay: from edge of pond to headland	19010	Non-limestone (100)	Urban (100) Herbaceous wetland (84)	3 m (100)
9. Parrottee Point	Parrottee Point: Headland to start of straight shoreline	2700	Non-limestone (100)	Herbaceous wetland (61) Mangrove (38)	3 m (55) 5 m (44)
10. Starve Gut Bay	Start of straight shoreline to end of study area	3850	Non-limestone (67) Montpelier (32)	Mangrove (50) Field (21) Short Open Dry (29)	5 m (68) > 5 m (32)

*Elevation within 100 m of the shoreline

Level of Beach Protection

The beach is the boundary between land and sea and is where waves interact with the land. Waves drive the development and movement of beaches, but the interaction with coastal features also influences the orientation and spatial movement of beaches. Coastal features in Black River Bay that influence beach morphology are coastal vegetation, reef protection, headlands and land use.

Coastal vegetation acts as a natural buffer for the shoreline against wave agitation and rising sea levels. The roots of coastal plants hold sediment and prevent waves from carrying the sediment offshore (Figure 20). This creates a more stable and increased energy is needed to change the morphology of the beach (Gedan, *et al*., 2010; Mimura and Nunn, 1998; Dahdouh-Guebas, *et al*., 2005).

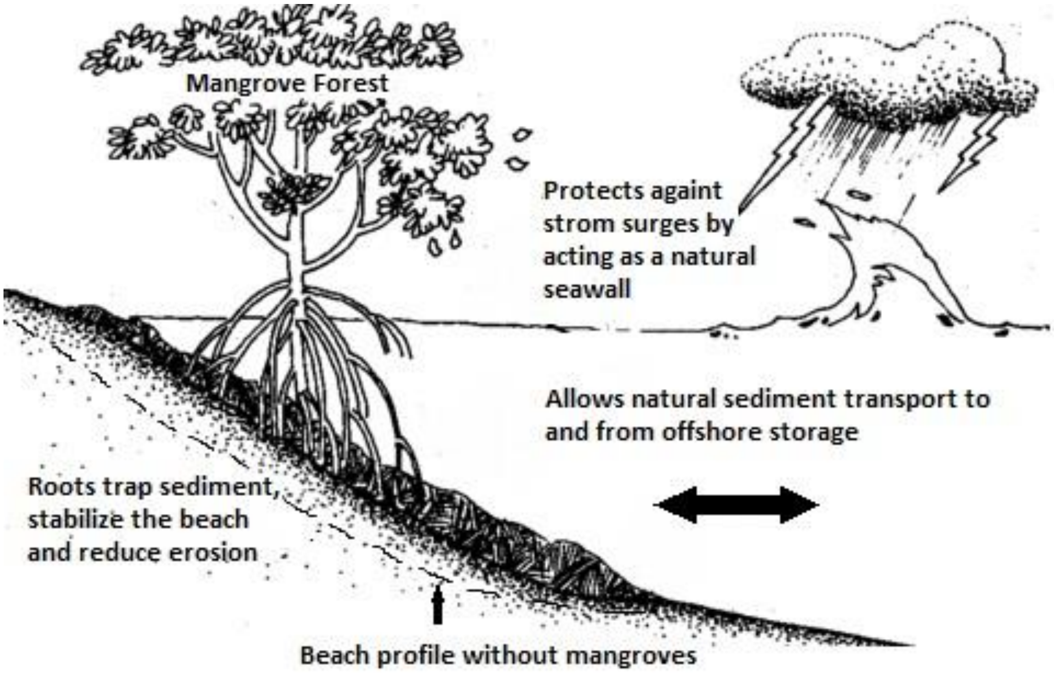

Figure 20. Beach Protection by Vegetation. Mangroves and coastal vegetation traps sediment and stabilizes the beach, preventing excessive beach erosion. Vegetation also protects the shoreline from large storm surge by acting as a natural seawall. Modified from CoastvsErosoin, 2015.

The type of coastal vegetation and level of coverage determines how stable the beach is and the level of protection. The type of substrate is less important than vegetation type for coastal erosion so the focus will be on the latter (Coups *et al*., 1996). Along Black River Bay, there are mangroves, beach grass, and grassy coastal plains (Asprey and Robbins, 1953). The level of coverage can be broken down in to high, medium, and low coverage. High coverage plants have large, deep root systems and are permanent plants such as mangroves and coastal trees. Medium coverage will be plants with shallower root systems and are less permanent such as coastal grass and smaller trees. Low coverage will be plants with shallow root systems, sparsely dense and less permanent such as dune grass and beach grass. These low vegetation areas are also areas that have been disturbed and cleared due to urban development.

Along Black River Bay, mangrove forests and herbaceous wetlands make up 9.96percent and 33.8percent of the shoreline respectively, providing a high level of shoreline protection for these areas. Mangroves are stable, woody plants that grow in forests in saline coastal habitats and have a dense root system. Herbaceous wetlands are non-woody, leafy plants that attract wildlife and provide some protection from coastal processes since they are usually densely populated (Silberhorn, 1994). The presence of mangroves along shorelines have decreased erosion rates and in some cases promoted progradation. Areas of mangrove deforestation generally show increased erosion rates since the sediment is not restrained and free to move. This indicates that mangroves are important to coastal protection from ersoin, storm events and rising sea levels (Thampanya, *et al*., 2006).

Vegetation found along Black River Bay are pioneer plants, low creeping plants, para grass, scrub and various large wooded trees (Asprey and Robbins, 1953). Pioneer plants are a group of species that are usually the first to grow in disturped ecosystmes such as coastal zones after a large storm event. The root systems are generally shallow and they are easliy removed when the coastal zone is disturbed. These plants provide low protection and often form in patches along the backshore or coastal dunes (Allaby, 2004). Low creeping plants are usually found on coastal dunes or further from the beach face and have shallow roots. They provide a bit more protection than pioneer plants but are still catagorized as low protection. Para grass a group of grazing or pasture vegetation. The root system is usually shallow but the land coverage is greater than the previously mentioned vegetaion types . This type of vegetation provides a medium level of protection against coastal erosion. Scub is a common term for a mixture of shrubs and para grass that forms further inland and had and increase in protection level since the roots are deeper and the plants are generally more stable than grasses or pioneer plants (Allaby, 2004). Lastly, there are a variety of large stable trees, other than mangroves that can occur along the shoreline. These trees can vary in density but are often found sparingly along the shoreine. The densely populated areas are concidered to have a high protection level since the roots are deep and the plants are stable (Asprey and Robins, 1953).

Landforms also influence how beaches erode and change over time. The coastal landforms found along Black River Bay are depositonal landforms, reefs, and limestone headlands. The level of landform protection can be grouped into high or low protection based on if a landform is prescent in the area or not. Beaches with a high level of protection from landforms will be areas where fringing reefs are located offshore or headland bluffs are located adjacent to the beach. Low protection level will be areas where these landforms are absent and the beach recieves the majority of the wave's force (Huggett, 2011; Tarbuck & Lutgens, 2007).

Beaches are the boundary between land and the ocean and have a high level of land use and developemnt within 100 m from the coast. Storm swells can reach to heights of 4 to 8 meters above normal wave heights (Morton, 2003; Stewart, 2004) making areas near the shore at low elevations highly vulneravle to inundation and erosion. Most of Black River Bay is less than 5 m above sea level making this area highlly vulnerable in rising sea levels.

As sea-level rises, the shoreline along Black River Bay will expect to erode, become inundated, and change geomorphologically. Normal wave and storm swells interaction with the backshore will increase and cause the vegetation along the coast tobecome damaged and receed. This will cause the shoreline to become more unstable as the level of vegetation protection is decreased. As the shoreline's protection is decreased, waves will have a greater effect on sediment transport and beaches will tend to move inland or elsewhere causing an expected loss of the overall shoreline (Sorensen , Weisman, and Lennon, 1984). Sediment transported from the shore and deposited offshore will effect reef systems and hinder their productiviy and possible cause them to become damaged or die (Rogers, 1990). This will further decrease the level of shoreline protection causing more wave energy to reach the shore and increase erosion rates. The infalstructure along the coast will likely become damaged or lost (Huggett, 2011; Cambers, 1997). This will effect the tourism economy, local busnesses, and the community of Black River since the coast supports a large part of their economy and food source.

CHAPTER 4. METHODS

Images used in this study were taken by the Quickbird and GeoEye satellites. The Quickbird satellite was launched October 18, 2001 and orbits at an altitude of 450 km at a speed of 7.1 km/second. The orbit time is 93.5 minutes and produces the largest swath width of any available commercial satellite. This produces images with resolutions as detailed as 0.6 m/pixel. Standard images like the ones used in this study are radiometricallly corrected, sensor corrected, geometrically corrected and mapped to a cartographic projection and have uniform pixel spacing throughout the whole image (DigitalGlobe, 2006).

The GeoEye-1 satellite was launched September 6, 2008 and orbits at an altitude of 770 km at a speed of 7.5 km/second. It has an orbit time of 98 minutes and capable of producing images with 0.46-0.5m/pixel resolution. All Standard images from DigitalGlobe have been rectified and have a Root Mean Square Error of 2.3 m. This error will be added to the error found during the georeferncing stage (Satellite Imaging Corporation, 2004).

IKONOS satellite images were used to identify beach features, such as berms, dunes, vegetation, coral reefs, and anthropogenic structures. Field surveys and Global Positioning System (GPS) cameras were used to evaluate current placement and conditions of beaches in the study area. IKONOS satellite images were purchased from Digital globe for the study area. The images acquired were from the Quickbird satellite for April 2003 and December 2007 and from the GeoEye satellite for March 2012. All sets of images included both panchromatic and multispectral images (Table 4). The panchromatic images were the primary source for this study.

Table 4. Imagery Database from Digital Globe.

Image Source	Image Band	Acquisition Date	Spatial Resolution	Radiometric Resolution	RMS Error
QuickBird	Multispectral	April 2003	2.4 m	16 bit	0.297 pixels
QuickBird	Panchromatic	April 2003	0.6 m	16 bit	
QuickBird	Multispectral	December 2007	2.4 m	16 bit	0.452 pixels
QuickBird	Panchromatic	December 2007	0.6 m	16 bit	
GeoEye	Multispectral	March 2012	2 m	11 bit	0.325 pixels
GeoEye	Panchromatic	March 2012	0.5 m	11 bit	

Data Preparation and Processing

The first step to monitoring a shoreline is to assemble any preexisting information about the study area such as historic land use or previous field surveys of beaches in the study area. Geographic Information System (GIS) layers of land use, geology and soil for the Black River Bay area was obtained from Mona-Geoinformatics Institute (MGI) and used in conjunction with satellite images to interpret the conditions and behaviors of sandy beaches along the shoreline. GIS data layers including elevation and coral reef locations were acquired from various sites including World Resources Institute and GeoCommunity. A full list of data sources can be found in Appendix A.

After the preexisting information is gathered, the next step is to prepare the data and to determine the uncertainties associated with the data source and the measurement method (Thieler, *et al.*, 2013). The IKONOS images were examined for spatial resolution and bit size. They were then mosaicked using the georeference image method and then each image was georectified to an ESRI basemap. The accuracy of each georectified image is examined through ground control points (GCP) and the root mean square (RMS) error which is found by using the equation:

$$\text{RMS error} = [(x_b - x_i)^2 + (y_b - y_i)^2]^{\frac{1}{2}} \qquad (1)$$

where x_b and y_b are the coordinates for the basemap and x_i and y_i are the coordinates for the image being georectified (Linder, 2009; Hughes, McDowell, and Marcus, 2006). The RSM error determines how accurate the images are georectified to the basemap by using GCPs. GCPs link the satellite images to the corresponding location on the earth's surface by creating a regression equation (Equation 1) that indicates how far in the x and y direction each pixel should be moved to rectify the image. A first order polynomial regression is created for each image using the GCPs. The distance the GCPs are from the regression line is measured by the RMS error which is automatically generated in ArcMap (Linder, 2009). This RMS error indicates the number of pixels the GCPs need to move in order to become perfectly rectified. Any RMS values under 1.0 are acceptable and values close to zero are desired since this indicates accuracy between the images (Schmitz *et al*., 2008). A manual check to compare measurements between photos was performed and compared to the maximum RMS error. GCP from 10 well defined locations where measured to the shoreline and rates were calculated. An error of 0.22 m was determined for the three photos.

For this study, a minimum of four, evenly distributed GCPs were used; mainly building corners, intersections between roads and other well-defined objects to georectify each of the images. The RMS error for each GCP calculated during the georectification process can be found in Appendix B. Since the RMS for the 2003, 2007, and 2012 images were 0.297, 0.452, and 0.325 pixels respectively, the georectification was successful and the images were warped to the map projection, Universal Transverse Mercator (UTM) WGS 84, zone 18N using a first order polynomial transform algorithm (El-Asmar and Hereher, 2010; Chen, Hsu, and Lee, 2004). The equation:

$$\text{Georectification error} = (\text{RMS error}) * (\text{Image Pixel Length}) \qquad (2)$$

where the RMS error and the image pixel length is was used to find a the georectification error for each image (Linder; 2009). The maximum error of 0.27 m from the photos was used to determine the maximum georectification error for the study.

The coastal zone is defined as the boundary between water and land. Therefore, the high water line (HWL) and the vegetation line are used in this study to determine the placement of the shore and are identified by the vegetation line and the beach swash zone (Leon and Tavares Correa, 2004). The vegetation line is a hard line easily identified by satellite images and is used to indicate the back or end of the beach area (Robinson *et al*. 2012). For this study, the vegetation line will be used as the main indicator for overall shoreline change since it represents a more permanent loss over the nine year period. Coastal grass can be removed easily due to coastal development and other disturbances. This was taken into consideration during the digitization process; therefore, the use of the vegetation line is the most accurate depiction of shoreline change for this study. Changes in the waterline are varied and depend on tides and seasons; therefore, the use of the waterline for determining shoreline change is less accurate for the method used in this study and would be more appropriate for studies where beach profiles and water heights are monitored monthly. Changes in beach widths are beneficial to observe but for this study it is not a good indicator for changes in shoreline position or for determining the rate of beach erosion or recovery. A beach width can increase due to increased wave energy by decreasing the beach slope. Sediment is transported offshore and erosion has technically occurred; however, from a spatial observation, the beach appears to have increased in size. Without the beach slope and observations in beach profiles, the changes in beach widths are a less accurate depiction of shoreline changes and therefore, will not be used to determine the rate of shoreline change for Black River Bay.

After georectifing the images to insure accuracy, the images were digitized by hand for each year at a 1:1250 scale. A baseline was created 100 m offshore to measure the spatial movement of the shoreline. A transect was created with 50 meter spacing and a measurement for beach width, change in vegetation line and change in waterline were then taken at each of the 593 transects (Appendix C) . The study area was then split into 10 zones based on physical features such as bays, headlands or urban areas. The measurements were then graphed by zone for the full area and trends were identified. Box plots show variation in rates by zones. The circles in the box plot graphs represent outliers 1.5 times the box length and the asterisk represents outliers 3 times the box length.

Fieldwork was conducted during January 2014. A team of 9 members split into 3 groups to conduct beach surveys along two beaches within the study area to identify geomorphic features and to become familiar with the study area. A photo log (Appendix D) was created to document beach conditions along Hunts Bay and Parrottee Point. Locations of the waterline (beach toe), berm line and vegetation line were noted for locations along Parrottee Point and Hunts Bay. Field observations were used as a field check to compare and understand features seen in the satellite photos. The field observations determined Parrottee Point had a sandy dune system located along the southeastern stretch and no protection on the western portion. Hunts Bay was observed as a sandy shoreline with mangrove forests protecting each side of the beach. Fringing reefs were identified offshore of the dune systems along Parrottee Point and Starve Gut Bay and also located around Hunts Bay and Hodges Bay.

A manual measurement error (MME) was determined by duplicating the digitation process for a 2 km section along the southern portion of the study area. A new line was digitized along the 2 km sample area and measurements of the waterline and vegetation line for each year were taken at transects 500 to 540. The new measurements were then compared to the original measurements and a percent change equation was used to determine the accuracy between the datasets by calculating a percent difference between the measurements (Hapke and Reid, 2007; Bolstad and Smith, 1992). The manual error was calculated to be between 0.33 m and 0.39 m for the waterline and vegetation line respectively (Bolstad and Smith, 1992).

The error for georectification and the manual measurement error were then added to the maximum error from the satellites to determine the overall uncertainty and detection limit used for this study:

$$\text{Measurement Uncertainties (m)} = [(\text{Georectification error})^2 + (\text{MME})^2 + (\text{Satellite RMS error})^2]^{1/2} \qquad (3)$$

Therefore; the measurement uncertainty is $[(0.27\text{ m})^2\ (0.39\text{ m})^2 + (2.3\text{ m})^2]^{1/2} = 2.4\text{ m}$ indicating that the detection limit is ±2.4 m and all measurements between -2.4 m and +2.4 m are considered to have no change (Hapke and Reid, 2007). The annualized retreat rate uncertainty (m/yr) based on the image errors is calculated by taking the value calculated from Equation 3 and dividing the value by the studied time period of nine years. This comes out to an annual rate uncertainty of ±0.3 m/yr (Hapke and Reid, 2007). A summary of the errors (Table 5) were used to determine the maximum errors used in the study.

Table 5. Uncertainty and Error Values

Uncertainties or Errors	Values
Satellite Image RMS error	2.30 m
2003 RMS error	0.30 pixels
2007 RMS error*	0.46 pixels
2012 RMS error	0.32 pixels
2003 Georectification error	0.18 m
2007 Georectification error*	0.27 m
2012 Georectification error	0.16 m
Manual Measurement error	0.39 m
Measurement Uncertainty	± 2.40 m

*Used as Maximum error

Predicting Shoreline Change

SLR is currently rising at a 0.003 m/yr rate and is predicted to increase to 0.18 to 0.59 m/yr by 2100 (Church *et al*., 2013). This will cause increased coastal inundation and increased wave interaction with the shoreline. Coastal erosion will likely increase putting coastal resources and infrastructure at risk. There are different models used to predict the level of inundation SLR will have a coastal area (FitzGerald *et al*., 2008). Predicted shoreline erosion calculated from the shoreline changes and SLR over the nine year study was used to predict erosion rates. In many studies the Bruun rule is used to predict the displacement along a shoreline due to SLR; however, the beach slopes are unknown for the study area so this method would be better used with field studies associated with beach profile measurements (Schwartz, 1967; Dubois, 1975). Since the beaches are all assumed to be low angled, the generalized assumption used by the IPCC of 1:100 movement will be used for this study. This states that 1 unit of SLR will result in 100 units of inland movement. (Wong *et al*., 2014; Church *et al*., 2013; FitGerald *et al*., 2008). Therefore, SLR of 0.003 m/yr results in a 0.3 m inland movement. The equation based on Robinson *et al*., (2012):

$$\text{Shoreline Change}_{\text{Years}} = (\text{Movement due to SLR})^{*}\ \text{Years} + (\text{Erosion Rate of Black River Bay})^{*}\text{Years} \qquad (4)$$

will be applied to the overall shoreline as well as for each zone for 10, 20 and 30 years to predict the estimated shoreline change along Black River Bay.

Classification of Shoreline Protection

The shoreline was grouped into classifications of vulnerability based on reef protection, the presences of sandy beaches, vegetation, and resistant shorelines. Coral reefs were classified as a low, medium, or high level or protection based on if they are present along the shoreline and the distance they are located from the shoreline. Shorelines that lack a reef are classified as low reef protection. Shorelines where a reef is located roughly 700 m from the shore are considered offshore reefs and provide a medium level of protection. Areas along the shore where reefs are located within 300 m are considered nearshore reefs and classified as providing a high level of reef protection.

Areas along the shoreline were identified as either a sandy beach a non-sandy beach. The locations where sandy beaches were identified were used to understand the relationship between erosion rates and reef protection. Vegetation located within 100 m from the shoreline was identified as mangrove swamps, wetlands, or other. Resistant shorelines such as headlands, bluffs, or seawalls were identified and classified as either natural or artificial**.**

CHAPTER 5. RESULTS AND DISCUSSION

The results of this study indicate that most of the sandy beaches along Black River Bay have changed since 2003 either by erosion or accretion. The most change occurred during the storm period from 2003 to 2007 when Hurricane Ivan passed in 2004. According to the vegetation line, 50 percent of the measured transects experienced and only 3 percent experienced accretion and 47 percent experienced no measureable change during the storm period (Appendix E). During the post-storm period from 2007 to 2012, only 10% of the transects experienced erosion while 25 percent experienced accretion and 65 percent experienced no measurable change. Of the transects measured during this time, 47 percent experienced no change during the storm period and 66 percent during the post-storm period. This pattern suggests that a relatively long segment of the shoreline in Black River Bay is stable with most change occurring in ‘hot spot’ erosion areas or ‘cold spot’ accretion areas which are mainly unprotected beaches along the coast where sand sediment can be easily transported onshore, offshore, or alongshore by wave currents.

Rates of Shoreline Change

Overall Trends. Erosion and deposition trends vary among different landforms and among the different geographic zones (Figure 21 to 23). More variability is seen in the southern zones where most of the sandy shorelines are located.

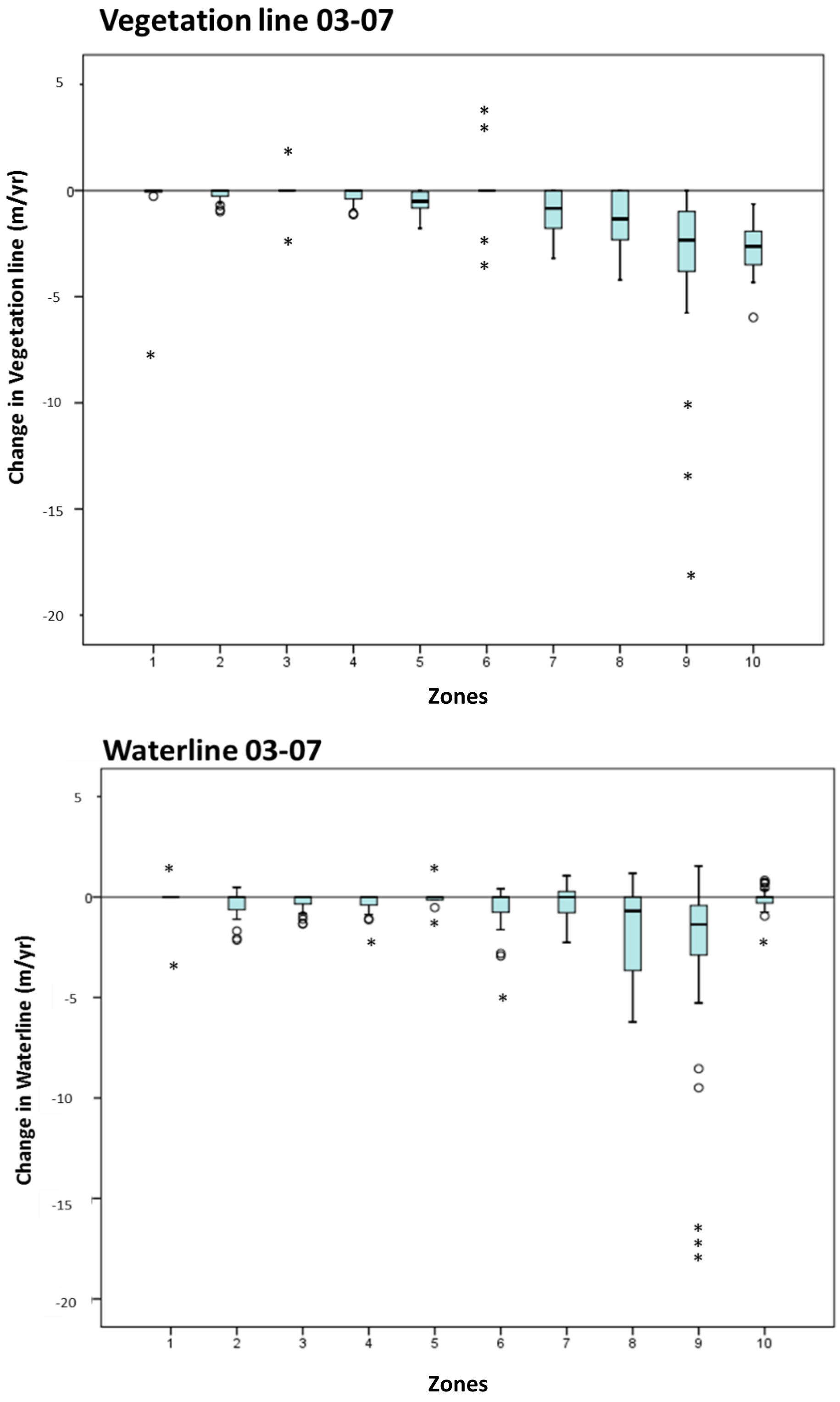

Figure 21. Shoreline Changes from 2003 to 2007 by Zone. Top graph shows vegetation line differences and the bottom graph shows waterline differences. Zones descriptions are in Table 3.

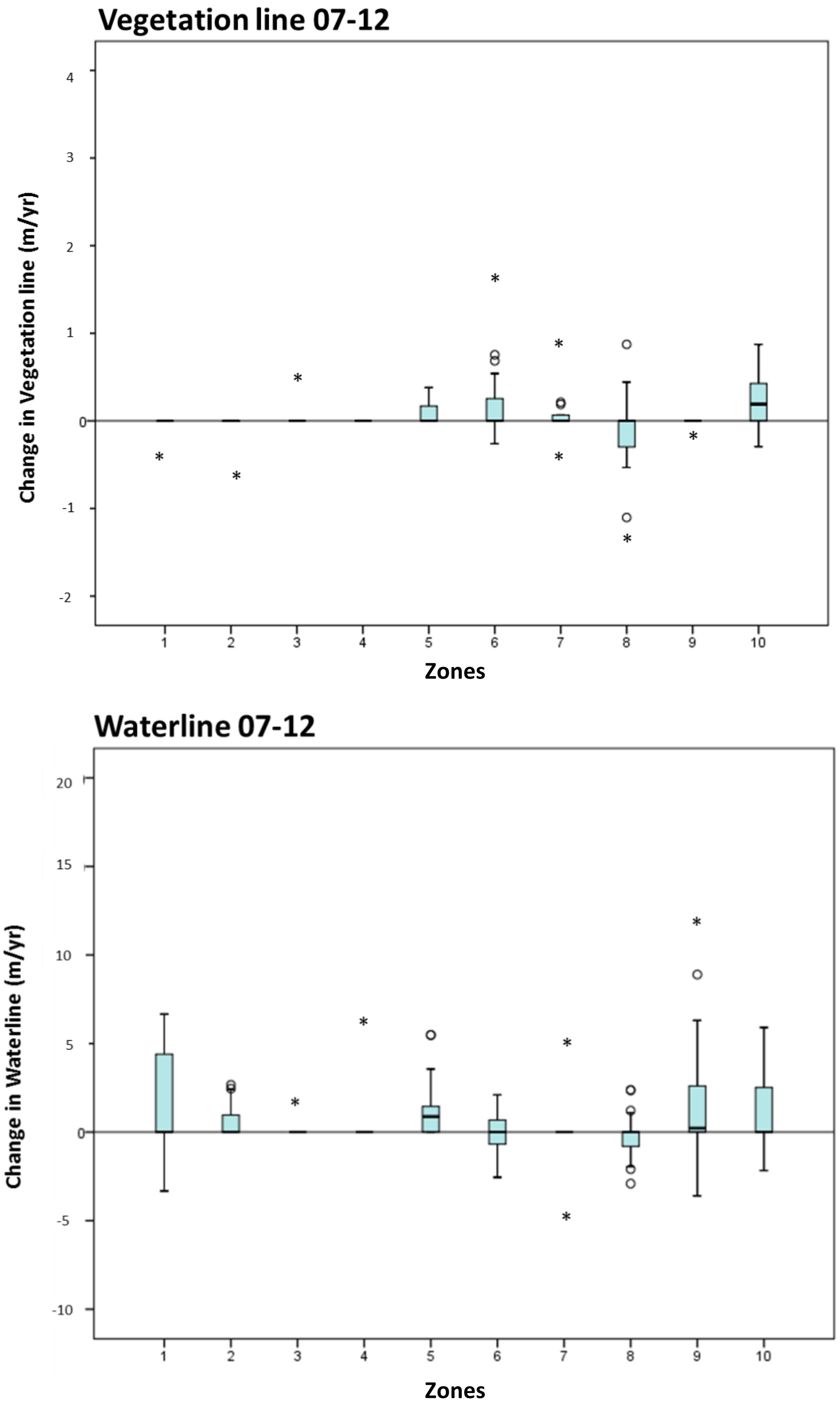

Figure 22. Shoreline Changes from 2007 to 2012 by Zone. Top graph shows vegetation line differences and the bottom graph shows waterline differences. Zones descriptions are in Table 3.

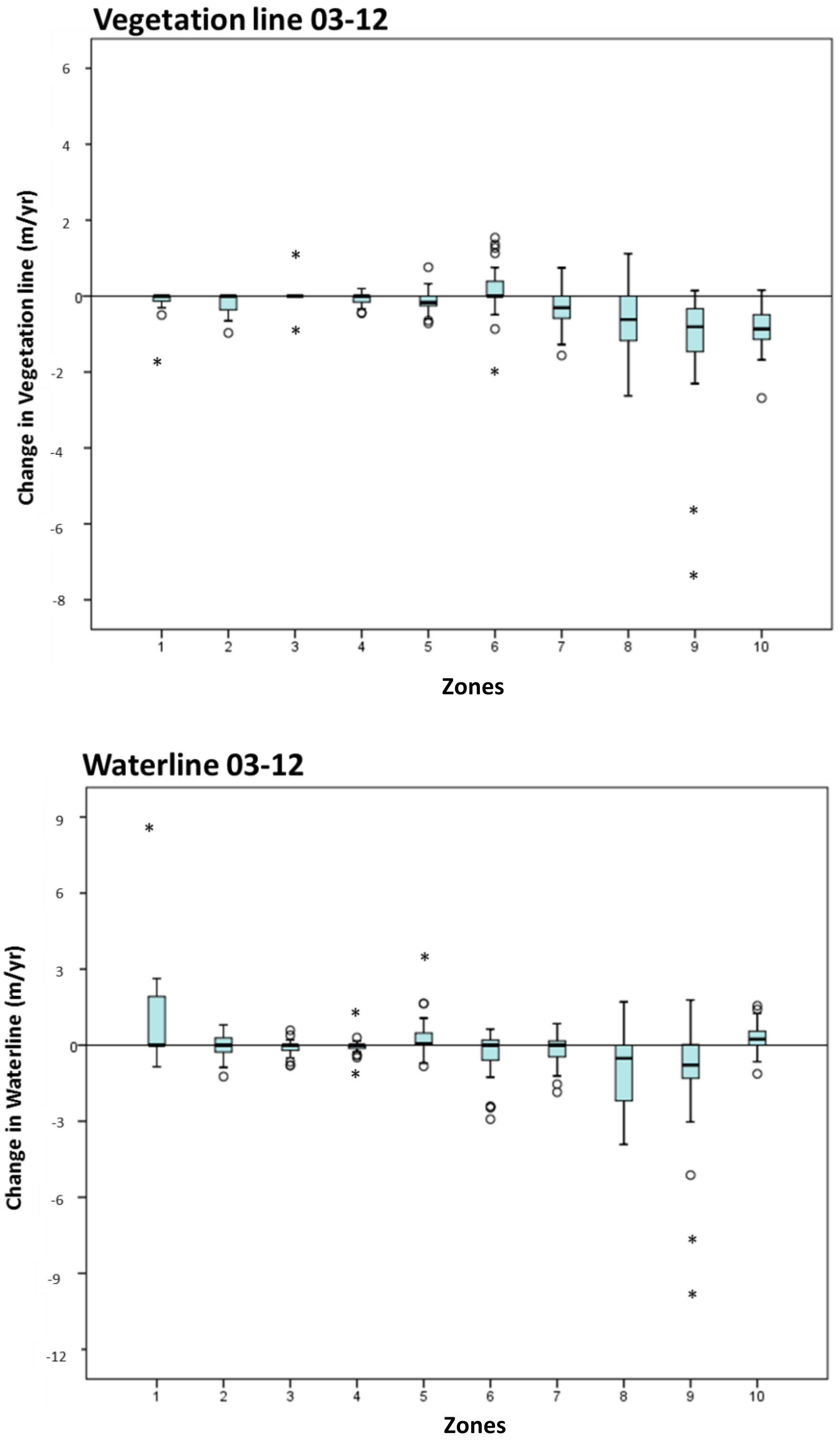

Figure 23. Shoreline Changes from 2003 to 20012 by Zone. Top graph shows vegetation line differences and the bottom graph shows waterline differences. Zones descriptions are in Table 3.

Within Black River Bay, shorelines located near the seaward side of the bay are expected to experience greater changes and vary more due to higher wave energies and current velocities. During the storm period from 2003 to 2007, zones 1 through 5 showed little to no change in both the vegetation and waterline. The greatest change occurs in the southeastern part of Black River Bay from zones 6 through 9 where erosion dominates with the largest change occurring at zones 8 and 9. These zones are Parrottee Bay and Parrottee Point and almost all of the shoreline in these zones is composed of sandy beaches which are the most vulnerable to changes due to storms. This area is also located outside of the large bay and is exposed to more frequent waves, higher energy waves, and higher current velocities. High variability in both vegetation and waterline is seen in zone 8 where waves appear to lack a dominate direction. There is also a break in reef protection in the middle of the zone which could be possible reasons behind large variability in the zone. Zone 9 has the largest outliers which are due to the disappearance of a foreland spit along Parrottee Point.

After an intense storm event, wave energy will decrease and return to natural, daily currents. Sediment will be transported back to shore and the shoreline will start to recover. In some cases, depositional landforms will appear due to an access of sediment being delivered back to the shore. During the post-storm period from 2007 to 2012, zones 1 through 4 experienced no change in the vegetation line but a seaward movement of the waterline in zones 1 and 2. This is due to the formation of a hooked spit in zone 1 at Fonthill Park where access sand was being deposited. Since the vegetation line does not recover during the post-storm period for this zone, an overall erosion trend was observed. The southern portion of Black River Bay generally experienced recovery of the vegetation line and waterline in all zones except in zone 8 where a mix of erosion and recovery occurred. The greatest amount of recovery during this time appears to have occurred in zone 10. This area has a high level of reef protection as well as coastal dunes on the back shore. This could possibility be due to the storm's energy being reduced from fringing reef protection and was only able to transport a small amount of sand from the shoreline. The sand that was removed was then easily replaced during the post-storm period due to the large sediment supply from the dunes and sediment bars located just offshore.

Overall, the net change in the shoreline from 2003 to 2012 was erosional with areas of varying degrees of recovery and stability (Table 6 and Figure 24). The averaged shoreline changes and estimated rates for each zone are summarized in Appendix F. The vegetation line was used to calculate the annual rate of -0.31 m/yr for the entire study area. The greatest rate of erosion occurred in zone 9 at -7.90 m/yr over the 4.25 year period. Most of this erosion likely occurred during Hurricane Ivan in 2004 and has since recovered at a rate of roughly 3.32 m/yr. If this rate continues, it will theoretically take an estimated 21 years to recover the sediment lost during Ivan. The greatest recovery during the post-storm period occurred in zone 6 with a maximum rate of 3.20 m/yr. Accretion is expected here since it is a back bay where waves are calmer and located south of the Black River where river sediments are likely deposited.

Table 6. Vegetation Line Changes and Rates from 2003 to 2012.

Geographic Zone	Transects (n)	2003-07 Rates (m/yr)			2007-12 Rates (m/yr)			2003-12 Rates (m/yr)			Mean Recovery Rates
		Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	
1. Fonthill	87	-0.72	-2.94	0.30	-0.16	-2.70	0.00	-0.42	-2.90	0.29	0.56
2. Malcolm Bay	72	-0.66	-1.90	0.01	-0.12	-0.70	0.50	-0.37	-1.90	0.01	0.54
3. Hunt Bay	33	-0.10	-1.00	1.13	0.03	0.00	0.40	-0.03	-1.04	1.13	0.13
4. Hodgens Bay	40	-0.55	-1.50	0.00	0.08	-0.25	0.80	-0.22	-1.30	0.22	0.63
5. Black River Bay West	39	-0.44	-0.79	0.00	0.29	0.00	1.75	-0.05	-0.80	1.75	0.73
6. Black River Bay East	88	-0.20	-1.70	1.23	1.06	-0.30	3.20	0.47	-1.70	3.15	0.80
7. Parrottee Pond	170	-0.75	-1.50	0.56	0.20	-0.60	1.00	-0.25	-1.70	0.97	0.95
8. Parrottee Bay	38	-1.31	-1.90	0.00	-0.10	-1.40	1.20	-0.67	-2.92	1.24	1.21
9. Parrottee Point	54	-2.88	-7.90	1.20	0.44	-1.20	2.40	-1.13	-8.09	2.03	3.32
10. Starve Gut Bay	78	-1.38	-2.70	0.00	0.40	-0.30	1.04	-0.44	-2.98	0.28	1.78
Annual Rate (m/yr)		-0.90			0.21			-0.31			1.07

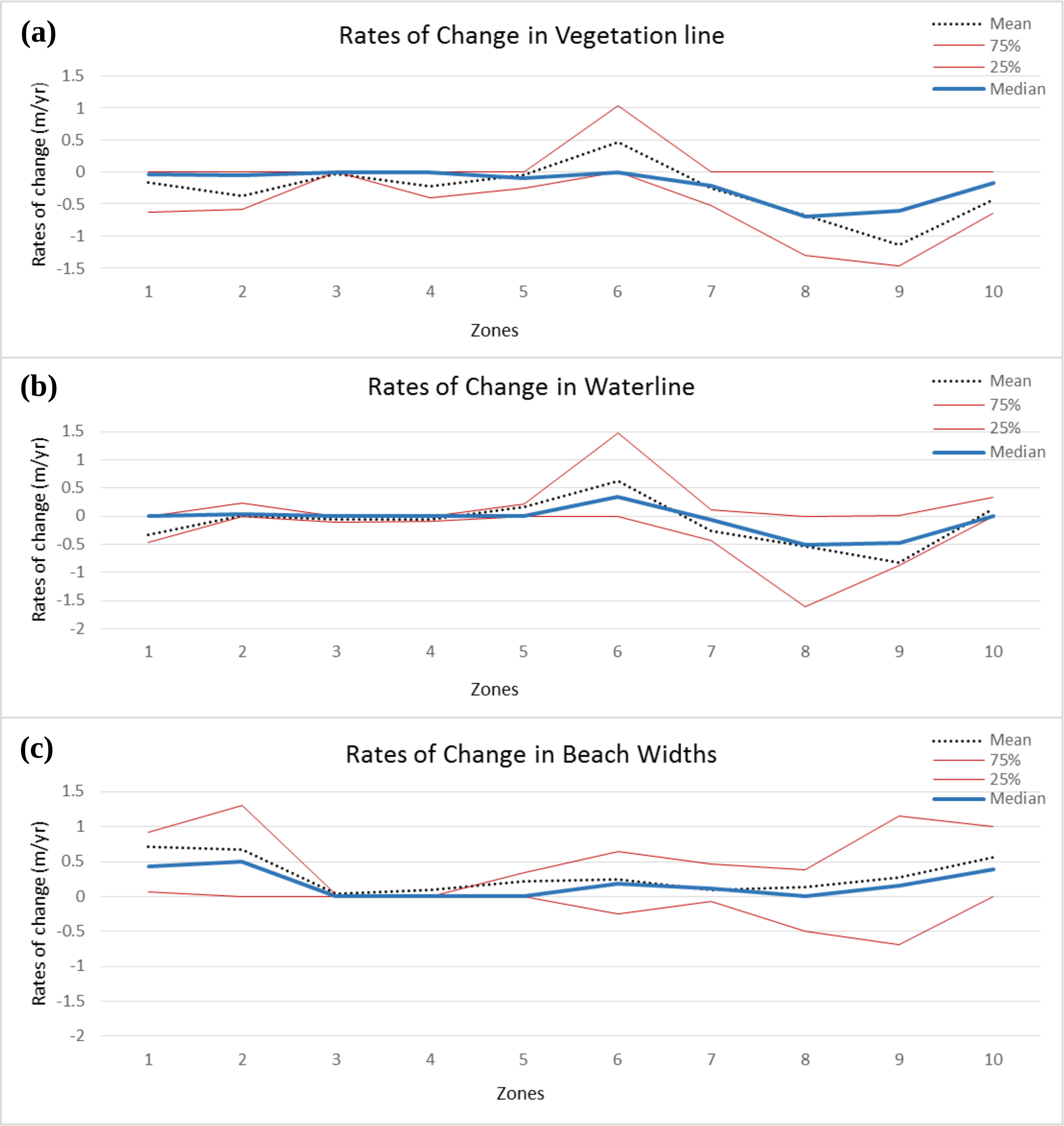

Figure 24. Rates of Change by Zones. Variability is greatest where sandy shorelines are located. The southern portion of Black River Bay is predominately sandy shoreline. (a) Rates of change in vegetation line from 2003-2012, (b) rates of change in waterline from 2003-2012, (c) rates of change in beach widths from 2003-2012.

Spatial Changes. Changes in location of a shoreline are due to the greater frequency or rate of erosion or accretion at a site. Increased rates in erosion or accretion will cause the waterline and vegetation line to respond by either moving landward or seaward. Along Black River Bay, the shoreline occurred changes along the southern portion of the bay, in zones 7 through 9, during the storm period (Figure 25). The shoreline moved landward as it eroded the back shore trying to replace the sediment removed during this period. There is greater spatial variability in the waterline than the vegetation line since the waterline moves and responds to changes in the sediment budget faster than the vegetation line. Sediment lost during a storm event can recover and accrete along a shoreline, increasing the beach width and moving the waterline seaward, faster than vegetation can recover. This often causes a lag in the relationship between waterline and vegetation line.

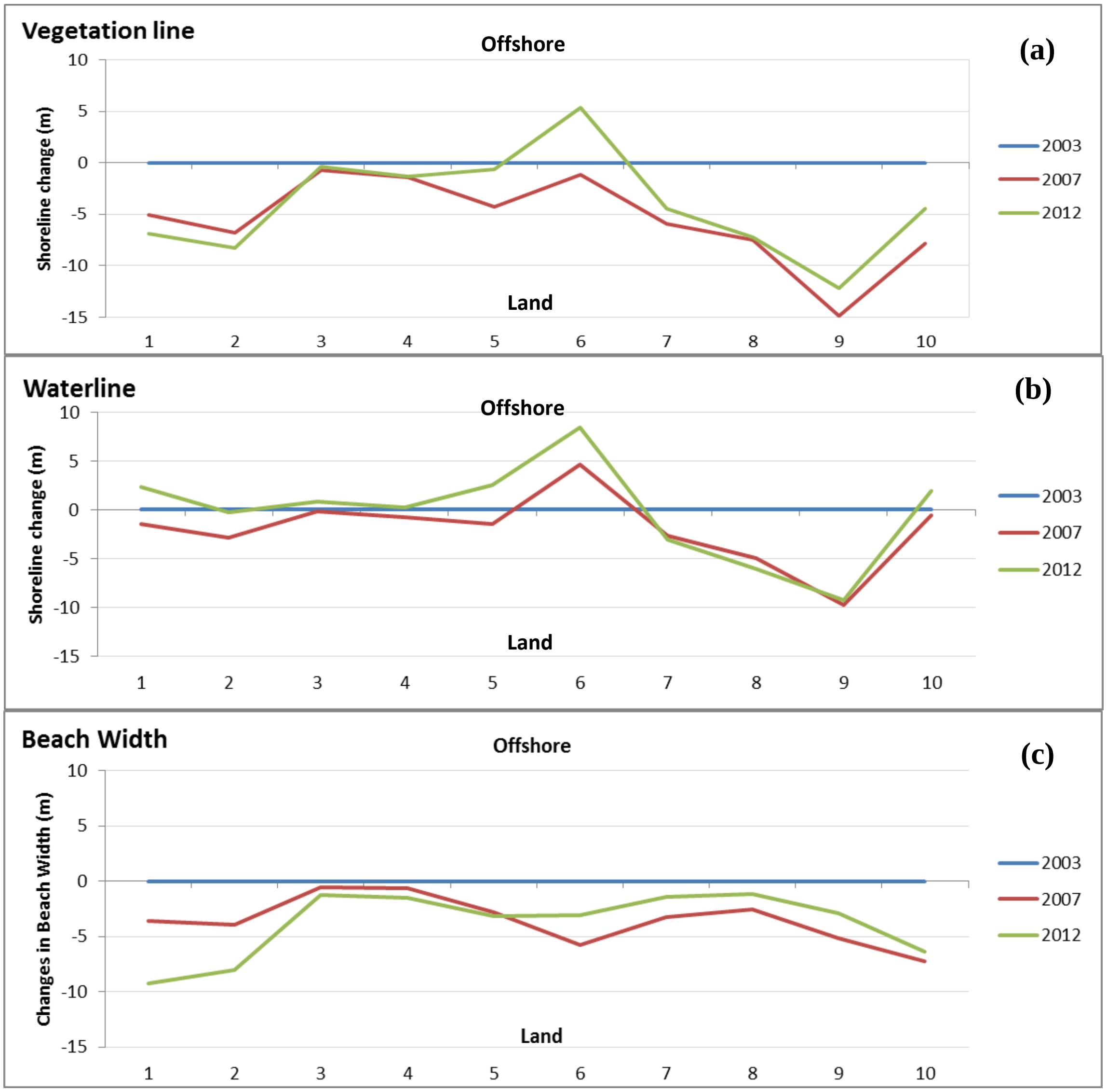

Figure 25. Spatial Shoreline Change from 2003 to 2012. The change in the vegetation line (a), waterline (b) and beach width (c) along the shoreline of Black River Bay. The 2003 shoreline was used as the baseline. During the 9 year study period, the vegetation line and waterline experienced the greatest change in zones 7 through 9 with the greatest recovery in zone 6. The beach widths follow the trends of both the vegetation and waterline.

Hot and Cold Spots. Trends in vegetation line change for each period and help determine hot spots and cold spots for each zone. Each hot spot and cold spot experience different average shoreline change and rate of change for the nine year period (Table 7) and are seen as a group of spikes in the data (Figure 26). Graphs for the waterline and beach widths can be found in Appendix G. The shaded bar is used to represent the areas below the detection limit and can be considered to experience no change over the time period. Transects with a positive value indicate accretion/progradation of the shoreline and negative values indicate erosion/recession of the shoreline. Four main hot spot areas are seen along the bay in zones 1, 2, 8 and 9 while the main cold spot areas are in zones 3, 5, 6 and the last half of zone 10.

Table 7. Locations and Averaged Change and Rate for Hot Spots and Cold Spots.

Label	Zone(s)	Transects (n)	Average Shoreline Change (m)	Rate of Change (m/yr)
HS 1	1	35-61	-12.7	-1.4
HS 2	3	127-150	-10	-1.1
HS 3	8	436-454	-15.2	-1.7
HS 4	9	465-474	-42.3	-4.7
CS 1	3-4	~151-221	0	0
CS 2	6	319-338	15.8	1.8
CS 3	10	571-593	0	0

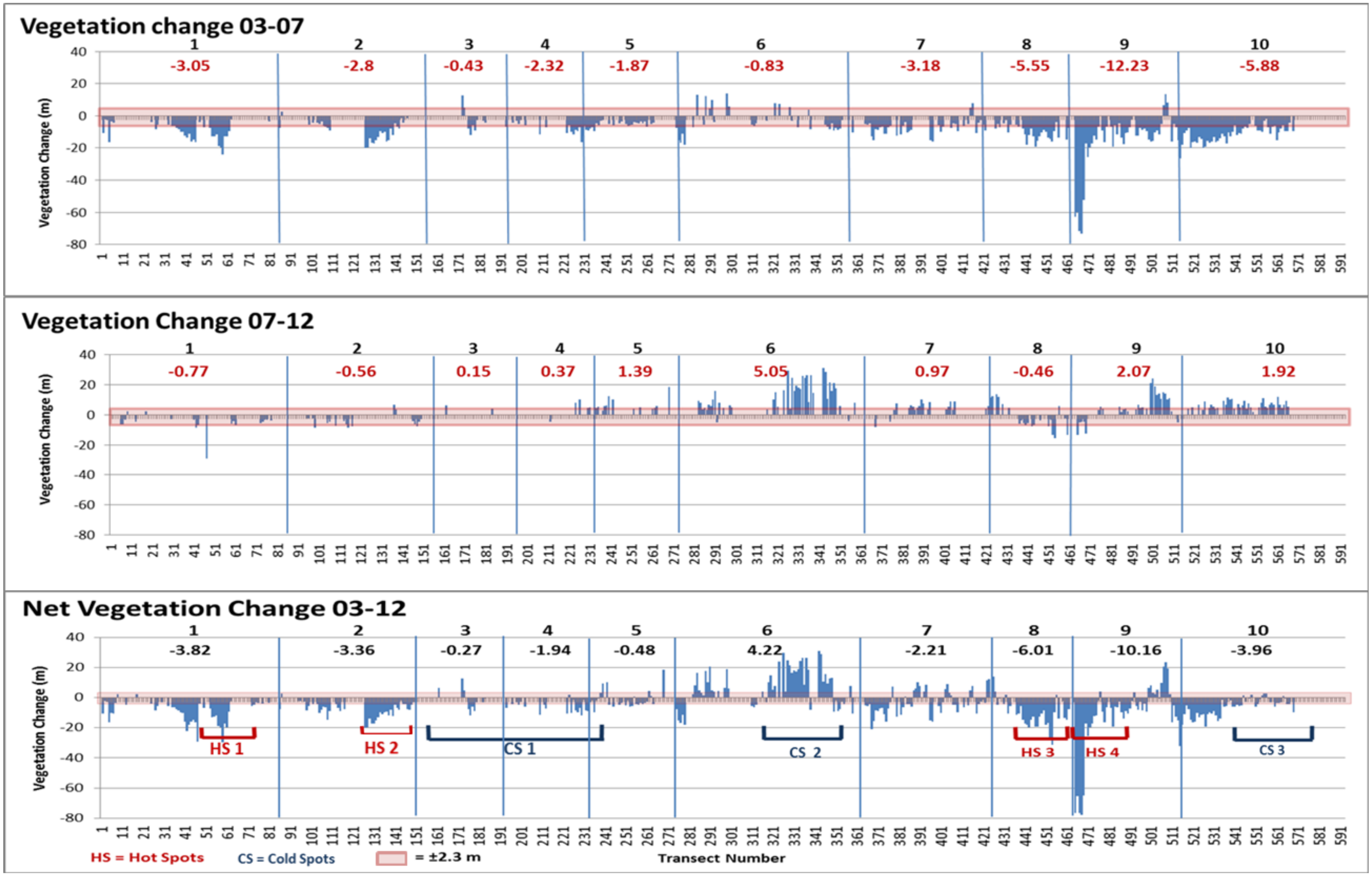

Figure 26. Changes in Vegetation Line by Zone. The average change for each zone is displayed below the zone number and all have an uncertainty of ±2.4 m. Negative values indicate erosion.

Hot Spots. Hot spots are areas along the shore where erosional factors dominate and there are high rates of erosion (Appendix H). These areas are generally found in high energy environments where there is low protection from reefs or vegetation. The hot spot located in zone 1 (HS 1) is mainly due to a sand bar and the area directly upshore and downshore from the bar from transects 35 to 61. The bar closes off a lagoon and has little permanent vegetation making it vulnerable to changes from storm events. The average erosion loss for this bar is -12.7 m and an estimated -1.4 m/yr erosion rate.

The hot spot in zone 3 (HS 2) is due to the erosion along the eastern portion of Malcolm Bay with some erosion along the western section of the bay (transects 127 through 150) where the waves mainly hit. As waves approach Malcolm Bay, they hit at the western portion of the bay and deflect carrying sediment downshore and depositing the sediment in this area. This is where the main part of the sandy beach is located and experienced an average loss of -10 m and an average rate of -1.1 m/yr. There is a high amount of cloud coverage on the 2003 QuickBird image so shoreline position for this year could not be determined and is not included in the hot spot's averaged loss and erosion rate.

Parrottee Pond in zone 8 is where HS 3 it located. This area has some reef protection located roughly 650 to 750 meters offshore. There is a break in reef protection between transects 436 and 454 which is mainly where the highest shoreline loss in the zone occurred. This area experienced an average loss of -15.2 m at an average rate of -1.7 m/yr. Most of this loss occurred during 2003 to 2007 and is likely due to Hurricane Ivan and other strong storms.

The largest hot spot (HS 4) located along the bay occurs in zone 9 at Parrottee Point. This area is a sand spit and experienced an average loss of -42.3 m between transects 465 and 475 with a maximum loss of -78 m at the tip of the point. An average erosion rate of -4.7 m/yr occurred in this location with some accretion located roughly 1,250 m downshore. It is likely that the sediment removed during the storm period from the point was deposited along this downshore location during the post-storm period.

Cold Spots. Shoreline locations where accretion or no change was experienced are termed cold spots. These areas are the least likely to experience property loss since the land has prograded or remained stable over the measured time period and are expected to continue this trend. The most stable locations (CS 1) are in zones 3 and 4 where there are two pocket beaches protected by vegetated headlands and fringing reefs. Some erosion occurs in areas where there is a break in reef protection but the overall trend for the area is stability and little to no change during the nine years.

The area where the largest accretion experienced was in zone 6 (CS 2) between transects 319 and 338. This area is located roughly 2,100 m downshore from the mouth of the Black River. Sediment discharged from the river is the likely origin for the accretion during the post-storm period. The shoreline is also located in a back bay where calmer waves reach the shore and deposition is allowed to occur. This area experienced an average gain of +15.8 m and an average accretion rate of +1.8 m/yr. The southeastern section of zone 10 (CS 3) between transects 571 to 593 is the most stable area within the study area with no change experienced during the 9 year period. This area is composed of limestone bluffs with an elevation of >5 m. Therefore, this area is the most resistant to changes in the shoreline.

Influence of Shoreline Geology and Reef Protection

The areas that are predominantly sandy beaches showed the largest change in shoreline and are the most affected by intense storm events. In Black River Bay, sandy beaches make up 74 percent of the shoreline while a mix of headlands, mangroves and rocky shores make up the remaining 26 percent (Table 8). Coral reefs protect 55 percent of the shoreline and are expected to reduce the rate at which sandy shorelines erode. Resistant shorelines, both natural (headlands and bluffs) and artificial (seawalls) can influence how waves interact with the shoreline. These areas remained relatively stable over the nine year period with the exception of the shoreline in front the seawall. Shoreline vegetation such as mangrove forests and wetland swamps make up 70 percent of the shoreline and the coastal area within 100 m from the shore. Mangroves provide some shoreline protection in zones 1 and 2 where they are present at headlands and directly along the shore.

Table 8. Percent of Shoreline Type Along Black River Bay.

			Reef Protection		Sandy Shoreline		Vegetation			Resistant Shoreline		
Geographic Zone	Zone Length (m)	Total % of Shoreline	Present	Not Present	Sandy Shore	Non-Sandy	Mangrove	Wetlands	Other	Natural	Artifical	Urban
1	4,350	15%	9%	8%	14%	1%	7%	3%	4%	1%	0%	1%
2	3,600	12%	1%	13%	9%	5%	11%	0%	0%	3%	0%	1%
3	1,650	6%	1%	6%	2%	5%	3%	0%	3%	4%	0%	0%
4	2,000	7%	6%	2%	2%	6%	0%	0%	6%	5%	0%	5%
5	1,950	7%	7%	5%	6%	0%	0%	0%	5%	1%	1%	6%
6	4,400	15%	0%	0%	15%	0%	13%	1%	0%	0%	0%	8%
7	3,200	11%	10%	2%	10%	0%	6%	0%	5%	0%	0%	2%
8	1,900	6%	6%	2%	5%	3%	0%	10%	1%	2%	0%	0%
9	2,700	9%	9%	0%	9%	0%	4%	5%	0%	0%	0%	0%
10	3,900	13%	7%	7%	3%	5%	7%	0%	6%	3%	0%	0%
Shoreline Totals	29,650	100%	55%	45%	74%	26%	51%	19%	30%	18%	1%	24%

Reef protection is expected to reduce the rate of shoreline erosion; however, in Black River Bay, this is not always the case. A clear relationship cannot be determined between the rates of shoreline change and reef protection along the bay (Table 9). Some segments of the shoreline show reduced rates in locations where reefs are present such as zone 8. This zone has a medium level of reef protection from offshore reefs. The rate of erosion from 2003 to 2012 was observed to be lower at -0.34 m/yr where reefs are present opposed to -1.17 m/yr in areas without reef protection. Other zones, such as zone 10, experienced higher erosion rates in areas where reef protection was high. Along the shoreline in zone 10, shorelines with reef protection experienced a rate of -0.67 m/yr opposed to -0.19 m/yr where reef protection is absent. Some of these areas were limestone bluffs and narrow beaches. This indicates that other factors such as wave energy and substrate likely have a larger influence on beach morphology and erosion rates than the presence of coral reefs. Coral reefs are still an important factor to a healthy marine ecosystem but their importance to shoreline protection along Black River Bay is unclear.

Table 9. Rates of Sandy Shores Sue to Reef Protection from 2003 to 2012 (m/yr).

Geographic Zone	Transects (n)	Sandy	Transects (n)	Low Reef	Transects (n)	Med Reef	Transects (n)	High Reef	Reduced Shoreline Erosion
1	87	-0.37	35	0.5	0		50	-0.72	No
2	72	-0.42	67	-0.47	0		5	0	Yes
3	33	-0.12	27	-0.12	0		6	0	Yes
4	40	-0.65	7	-0.81	0		33	-0.43	Yes
5	39	-0.03	21	-0.02	0		18	-0.03	Neither
6	88	0.54	88	0.54	0		0		No
7	64	-0.25	10	-0.02	54	-0.28	0		No
8	38	-0.49	6	-1.17	33	-0.34	0		Yes
9	54	-1.13	5	-2.75	49	-0.93	0		Yes
10	78	-0.6	33	-0.19	50	-0.67	0		No

Predicted Shoreline Change

Using the general understanding of 1:100 m displacement for SLR (0.003 m/yr SLR = 0.3 m shoreline loss) along the calculated annual erosion rate for Black River Bay of -0.31 m/yr the predicted shoreline change will be determined for Black River Bay by using Equation 4. This predicts a 6 to 18 m loss over the whole bay from 2022 to 2040 with increased rates in hot spot locations and decreased rates in cold spot locations (Table 10).

Table 10. Predicted Shoreline Change for the Next 10 to 30 Years.

Geographic Zone	Estimated Annual Rate (m/yr)	Change in 10 years	Buildings at Risk 10 years	Buildings at Risk 30 years	Vegetation at Risk Mangroves (m)	Vegetation at Risk Wetlands (m)
Whole Bay	-0.31	-6	50	95	15,100	6,000
1	-0.42	-8	1	3	1,950	1,100
2	-0.37	-7	4	5	3,400	0
3	-0.03	-3	0	0	750	0
4	-0.22	-5	0	0	0	0
5	-0.05	-4	1	17	0	0
6	0.47	8	12	12	4,000	400
7	-0.25	-6	15	42	1,900	0
8	-0.67	-10	13	16	0	2,950
9	-1.13	-14	4	0	1,050	1,550
10	-0.44	-7	0	0	2,050	0
HS 1	-1.4	-17	0	0	600	0
HS 2	-1.1	-14	0	0	1,150	0
HS 3	-1.7	-20	8	17	0	890
HS 4	-4.7	-50	0	0	0	450
CS 1	0	-3				
CS 2	1.8	21				
CS 3	0	-3				

The estimated erosion rates of -0.31 m/yr will cause an estimated loss of 18 meters in the next 30 years. This will affect sandy beaches, coastal vegetation and coastal buildings. Hot spot areas will experience a greater loss in the shoreline (Appendix I) such as an estimated 60 m at HS 3 and up to 150 m at HS 4. These predictions are the maximum expected loss and are based off of extreme erosion events. The area downshore of the Black River (CS 2) is hard to predict since little to no change was observed during the storm period and a large rate of recovery was observed during the post-storm period. This is likely due to the discharge from the Black River as well as the calm waters since the shoreline is located in a back bay, furthest away from seaward currents. Changes in SLR, storm events, and protection measures will influence how the shoreline changes. Since the effects these factors will have on future shoreline position is hard to predict, the estimated shoreline changes and the predictions for this study can change in response to these factors.

Sea level rise is expected to increase so the rates calculated along Black River Bay will increase in relation to the rate SLR is changing. The number and intensity of storm events that will occur in this area will also cause a change in erosion rates. Storm events are likely to increase in intensity in relation to changes in SLR and global temperatures. More intense storms will transport more sediment and cause greater changes along the shoreline. The presences of artificial structures such as the seawall at transects 258 to 260 will likely protect the shoreline behind it to some degree. The beach in front of the wall will most likely disappear within the next 10 to 20 years and the wall might even fail within the next 20 to 30 yrs. This will then allow the shoreline behind the wall to erode and become vulnerable to SLR and coastal erosion.

Property damage is already occurring along segments in Black River Bay. One example is a series of buildings located at transect 398 (Figure 27 and 28) where SLR and shoreline erosion has damaged the building and it is not located at the waterline. In the next 10 years, the most seaward building will likely be lost and in 30 years the second building could also be permanently damaged. This threat of shoreline loss is predicted along the shoreline in zones 5, 7 and 8 where increased erosion rates were observed. Predictions indicate that roughly 50 urban structures are at risk within the next 10 years and 95 within the next 30 years. The predictions also indicate that roughly 9 km of mangrove forests and 4 km of coastal wetlands located within 100 m of the shoreline will be at risk to SLR, inundation and shoreline erosion in the next 10 to 30 years.

Figure 27. Property Damage Due to SLR and Shoreline Erosion. Picture taken in January, 2014.

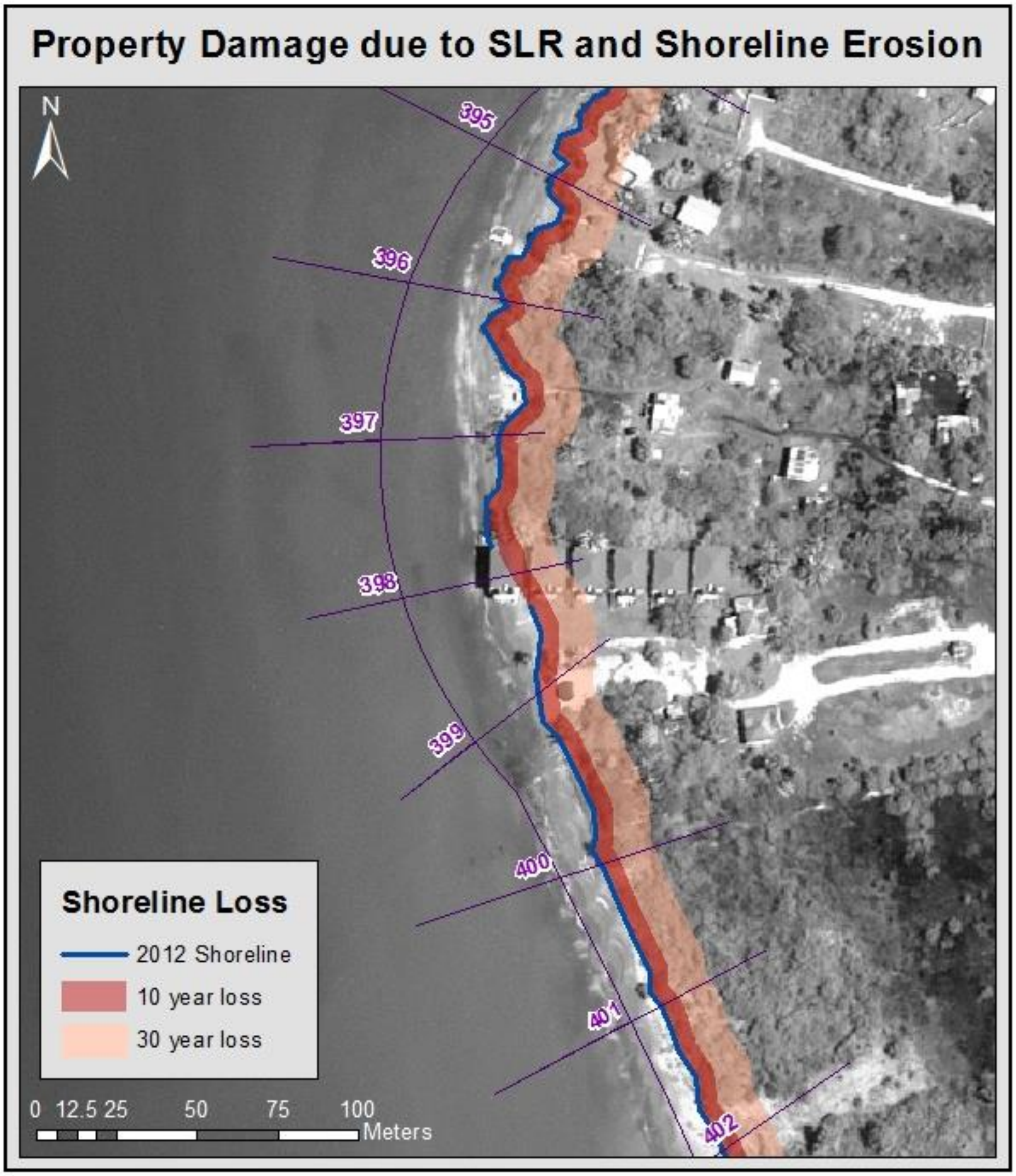

Figure 28. Property Damage Along Black River Bay. A loss of -6 meters is expected in 10 years and -18 meters in the next 30 years. This loss of shoreline will damage properties such as the condos seen above.

Threats and Responses to Coastal Resources

The increased removal of sediment due to increased erosion rates and SLR will harm the fringing reefs located in the bay. The deposition on the reefs will decrease the amount of light availed for photosynthesis and make filter feeding difficult for corals. This will cause the corals to become stressed and expel the algae zooxanthellae. This leads to coral bleaching and potentially the death of the reef ecosystem (James, 1982). As these reef systems deteriorate, the shoreline protection the reefs provide will decrease and the marine ecosystem will deteriorate. This could lead to increased rates of erosion along the shoreline where reef protection is observed to reduce rates. The deterioration of reefs will also affect fish population and the fishing industry. The creation of marine statuaries such as Galleon Bay Fish Sanctuary will help limit the effects felt by human forces in hopes to preserve the fish and coral populations.

Coastal ecosystems located in wetlands and mangroves will also become damaged and deteriorate as SLR increases and the shorelines erode. Limiting deforestation and replanting deforested areas will help decrease the rate of erosion along Black River Bay. Allowing the natural flow of sediment while protecting the back shore from increased wave interactions are the main benefit of maintaining coastal vegetation as well as providing a healthy habitat for coastal wildlife.

Artificial structures such as seawalls can be a temporary solution for land protection. These structures limit the flow of sediment and can become costly to maintain. They will reduce the rate of erosion along the back shore and the area behind the structure which can be beneficial in some cases. The seawall located in Black River Bay was built to protect a road from shoreline erosion. In 2003, there was roughly 8 m of shoreline on the seaward side of the seawall, this decreased to roughly 4 to 5 meters in 2007. By the end of the study period in 2012, the shoreline increased to about 5 to 6 meters. This means, on average, the shoreline in front of the seawall eroded by -0.46 m/yr and had an average loss of -4.5 m. The recover for this segment is minimal and, as expected, has not fully recovered from the storm period. These structures should be used only with a coastal management plan to insure the shoreline in front of the wall is not being depleted at an alarming rate. Often, seawalls with evenly spaced holes along the base allow some sediment to be returned to the beach and can yield more effective results than a completely solid structure.

Summary

The prediction of shoreline erosion is an estimation since many factors besides SLR are needed in order to determine the spatial pattern of erosion and recovery. All factors must be considered when determining the vulnerability of a shoreline, including coral reef protection, vegetation coverage, wave energy, and shoreline geology. Sandy beaches will spatially change faster than headlands or highly vegetated areas which will remain more stable over time. Areas less than 3 m will flood easily during storm events and areas between 3-5 meters will flood often during extreme storm events. Sandy beaches will erode at a faster rate than more resistant areas such as headlands, mangroves, and sea walls. If the estimated loss in shoreline occurs, over 65 buildings will be lost or at risk and all 1300 buildings are at risk of inundation.

Pocket beaches such as Fonthill Beach, Malcolm Bay, and Hunts Bay will spatially change faster than other parts of the bay. Parrottee Point is a sand spit and highly vulnerable to spatial changes in shoreline position. The area downshore of the Black River is an area that experienced accretion and could continue to accrete in the next 10 to 30 years. The areas with the least risk of erosion are the headlands adjacent to Malcolm and Hunts Bay in zones 3 and 4 and the bluffs located at the southern portion of the study area. These areas will see little to no spatial change over the next 30 years.

CHAPTER 6. CONCLUSIONS

The island of Jamaica relies on its shorelines for coastal resources and economic support through tourism and the fishing industry. Sea-level rise is stressing coastal communities through the risk of inundation and increased rates of erosion due to increased wave interactions and large swells produced during storm events such as Hurricane Ivan in 2004. Black River Bay, located along the southwest coast, is a vulnerable area to SLR and erosion since the majority of the area is located at or below 3 m elevation and the amount of reef protection is low compared to the northern portion of the island.

The use of satellite images helped to geospatially determine the changes along Black River Bay from 2003 to 2012 in response to normal wave interactions and changes due to Hurricane Ivan. Relationships between the digitized vegetation line and waterline were used to determine changes in beach widths and spatial changes along the shoreline. These changes, along with a shoreline classification, were used to determine the most vulnerable areas within the study area and to determine overall shoreline erosion and recovery rates along the shoreline and used to predict shoreline changes for the next 10 to 30 years.

An overall erosion rate for Black River Bay from 2003 to 2012 was found to be -0.31 m/yr. The average rate during the storm period between 2003 and 2007 was higher, at a rate of -0.90 m/yr while recovery of the shoreline was observed during the post-storm period from 2007 to 2012. A rate of +0.21 m/yr was observed during this period which allowed most of the sediment to be returned to the shore and some coastal vegetation to recover, but not completely.

Black River Bay has fringing reefs as well as open shorelines which influence where erosion is higher and where shorelines are more stable. The presence of coastal vegetation such as mangroves also influences the rate of erosion along the shoreline. Hot spots were located in the areas with little to no protection with the exception of Parrottee Point which experienced the highest rate of erosion due to the disappearance of a foreland spit. Cold spots were located in some areas where fringing reefs were located within 300 m from the shore and mangrove headlands were present. An exception to this observation was the shoreline located downshore from the mouth of the Black River. This area has little to no reef protection and has the most coastal development while experiencing a large accretion rate.

Predicted loss of land was calculated using the current SLR rate of 0.003 m/yr as well as the calculated rate of change for the bay. An average loss of 6 to 18 meters is expected within the next 10 to 30 years respectively. Predicted loss is higher in hot spots and lower in cold spots as expected. Coastal management plans should be created to help combat and limit the effects felt by shoreline erosion. The protection and preservation of coral reefs and coastal vegetation is important. Artificial structures should be used only with coastal management to insure the effects will be beneficial to the coastal communities and the surrounding environment.

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APPENDICES

Appendix A: Database sources.

Data Source	Data Type	Data
Digital Globe	IKONOS satellite image	QuickBird Multispectral and Panchromatic Imagery
	IKONOS satellite image	GeoEye Multispectral and Panchromatic Imagery
MONA GeoInformatics (MGI)	GIS Data Layer	Geology Formations Landuse Soils
World Resources Institute (WRI)	GIS Data Layer	Coral Reef Locations
GeoCommunity	GIS DEM	Elevation DEM
ESRI	Base Maps	Various Global Base Maps

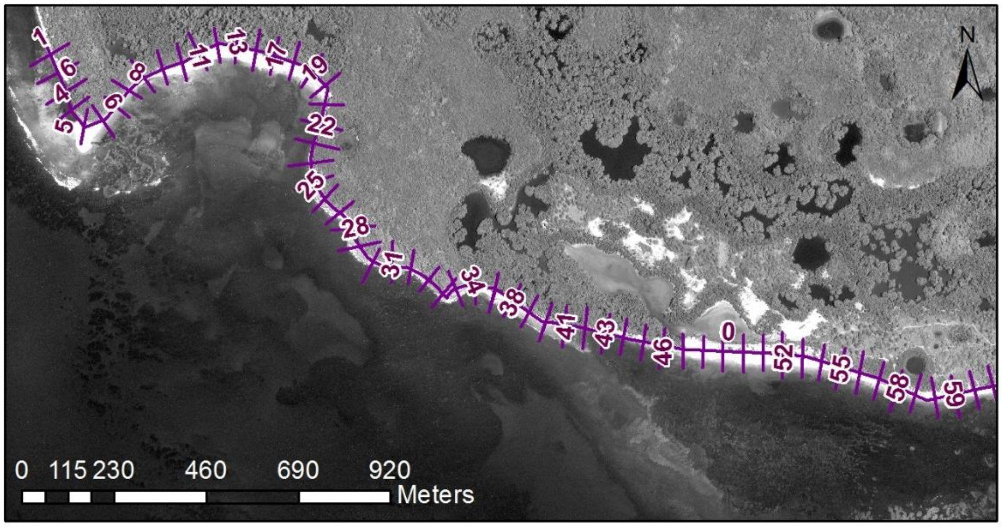
Appendix B: Georeferencing Coordinates and Corresponding RMS Error.

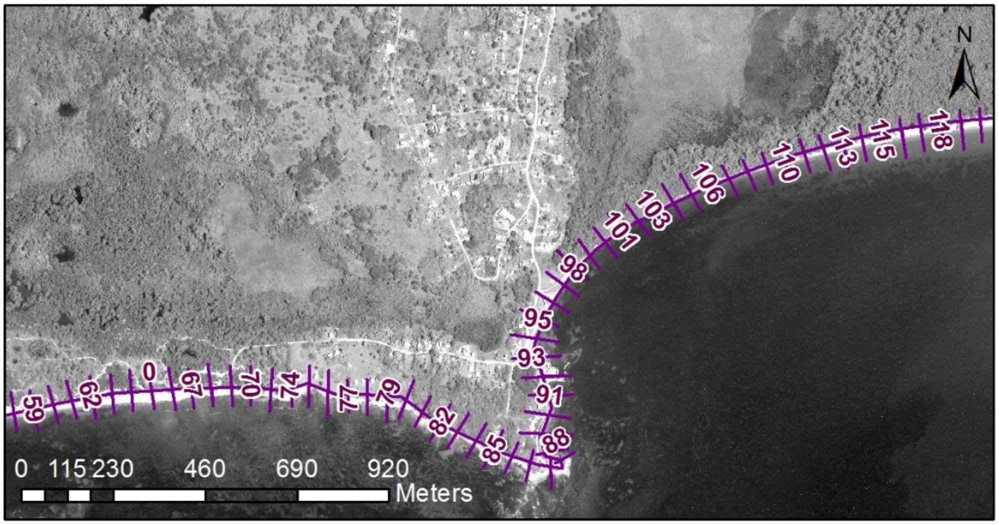
X BaseMap	Y BaseMap	X April 03	Y April 03	Residual X	Residual Y	RMS	RMSE
194256.6796	199594.0909	194262.7154	1995943.771	-0.0494941	-0.0534475	0.0728444	**0.297353 pixels**
199334.2033	1994280.147	199337.6219	19942763.96	0.264151	0.28525	0.388772	
20021.29116	1992697.925	200215.9767	1992692.64	-0.291733	-0.315036	0.429367	
199401.0436	1989358.015	19905.48645	1989352.954	0.0770762	0.0832334	0.11344	

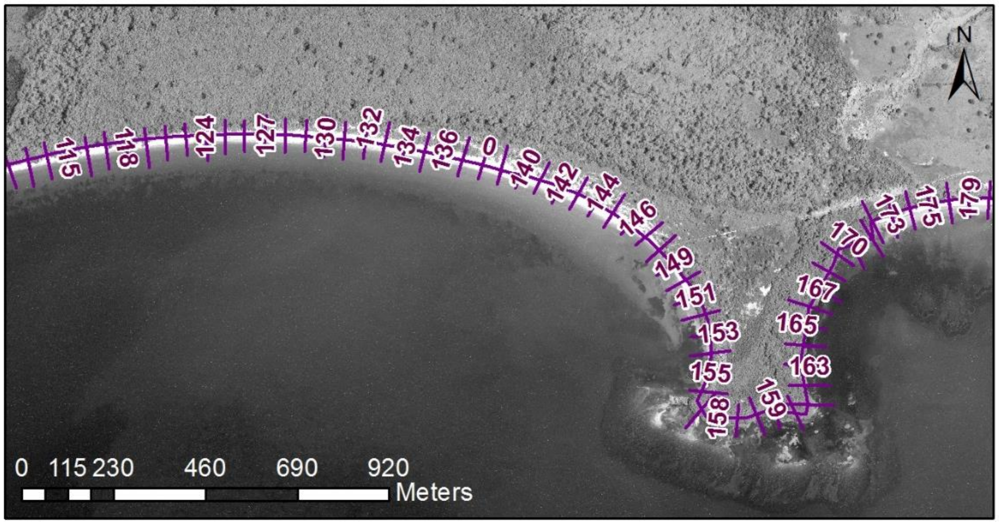
X BaseMap	Y BaseMap	X Dec 07	Y Dec 07	Residual X	Residual Y	RMS	RMSE
203383.834	1984144.268	203389.5596	1984133.772	0.105828	0.00	0.105828	**0.451823 pixels**
191765.8776	1995994.398	191773.0966	1995990.546	0.0360891	0.00	0.0360891	
200221.0567	1992701.144	200224.8413	1992696.491	0.558631	0.02125	0.559061	
200263.2686	991578.1539	200266.3595	1991572.614	-0.700548	-0.0244948	0.701087	

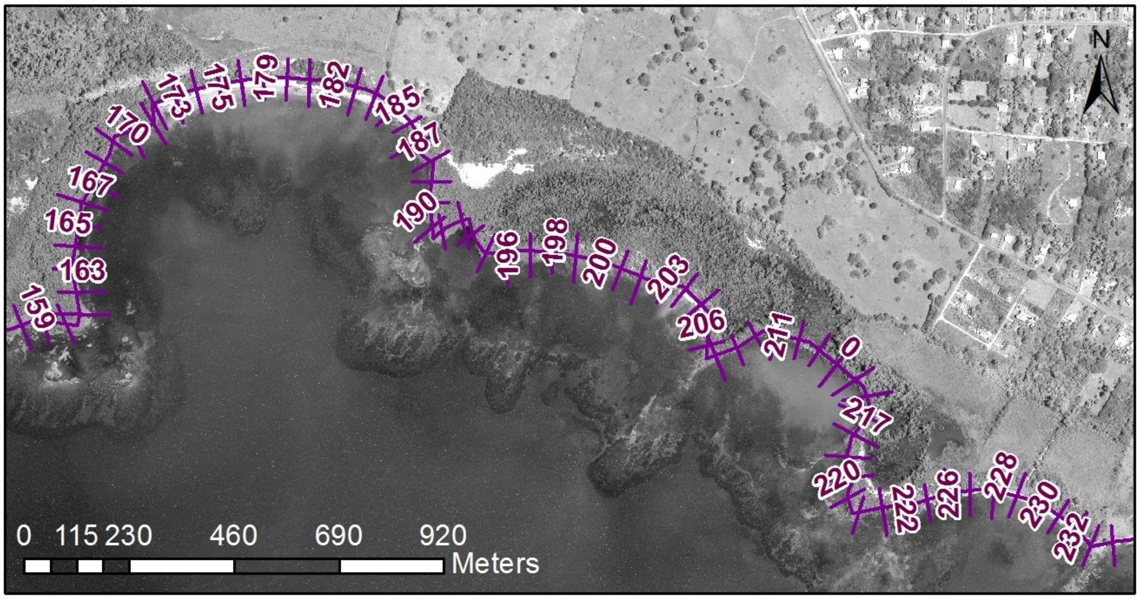
X BaseMap	Y BaseMap	X March 07	Y March 07	Residual X	Residual Y	RMS	RMSE
202427.722	1987435.506	202425.6305	1987427.783	-0.46722	0.13516	0.485901	**0.324946 pixels**
191371.0987	1995959.27	191386.997	1995952.166	-0.100097	0.0289885	0.10421	
196726.0825	1995924.361	196731.5282	1995918.702	0.259058	-0.0750247	0.269703	
203630.9994	1983062.295	203626.4284	1983052.67	0.307761	-0.0891303	0.320408	

Appendix C: Black River Bay Map with Transects.





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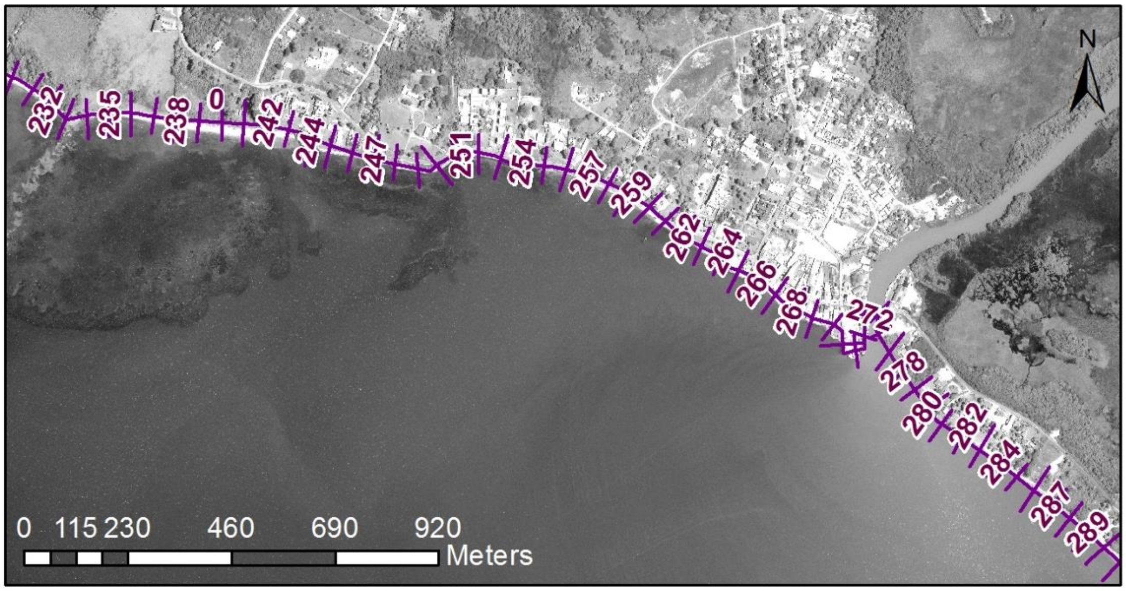
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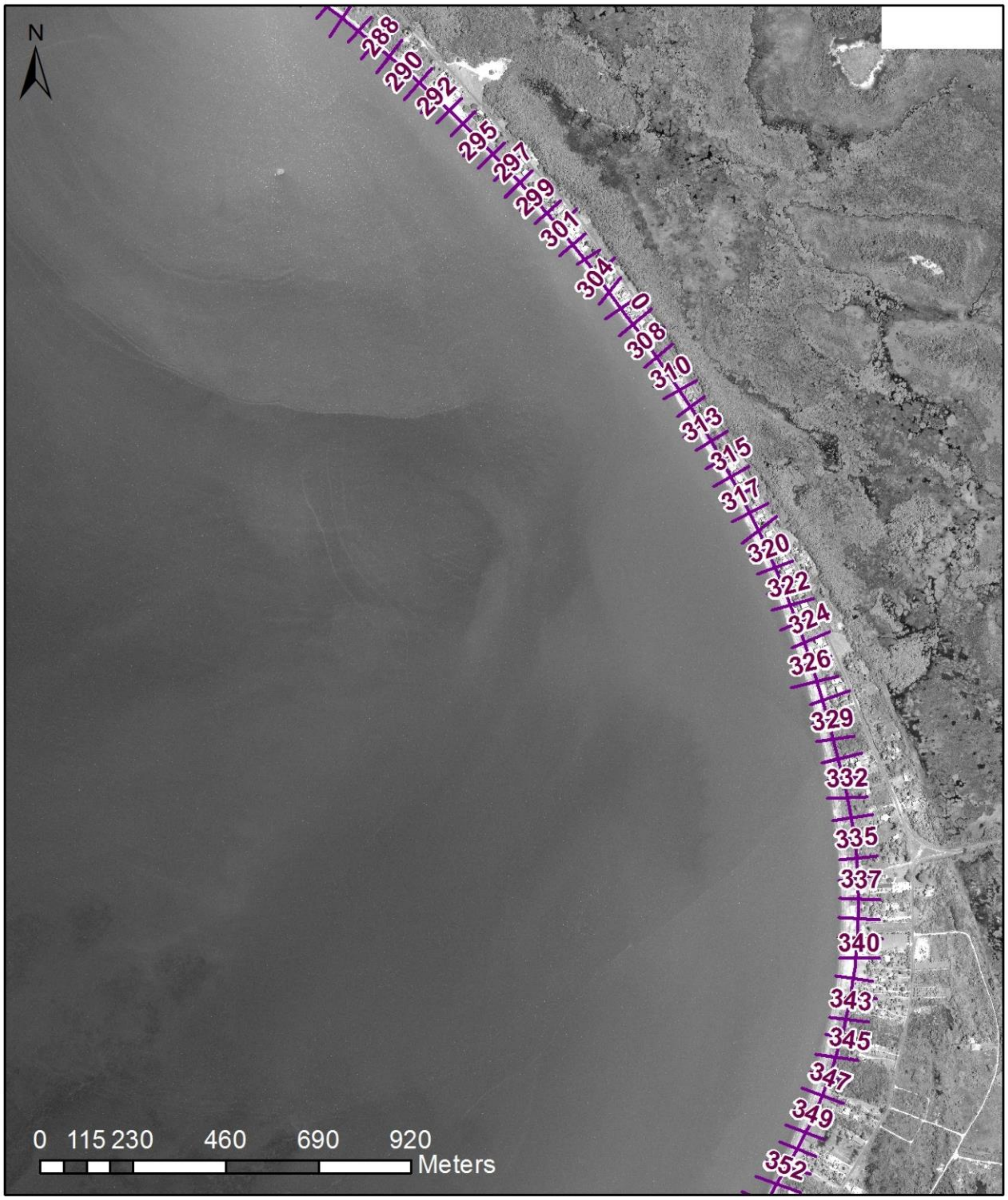
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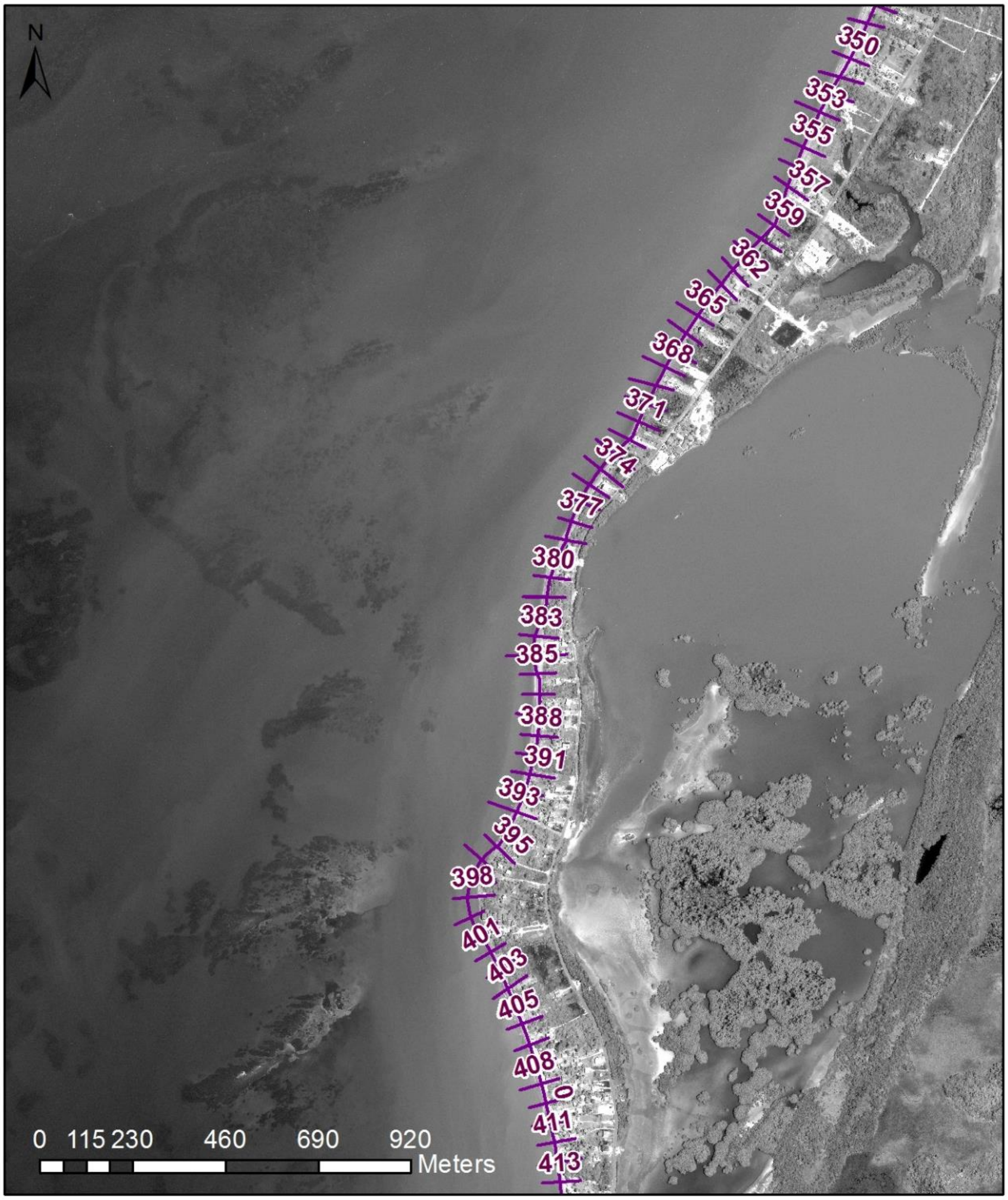
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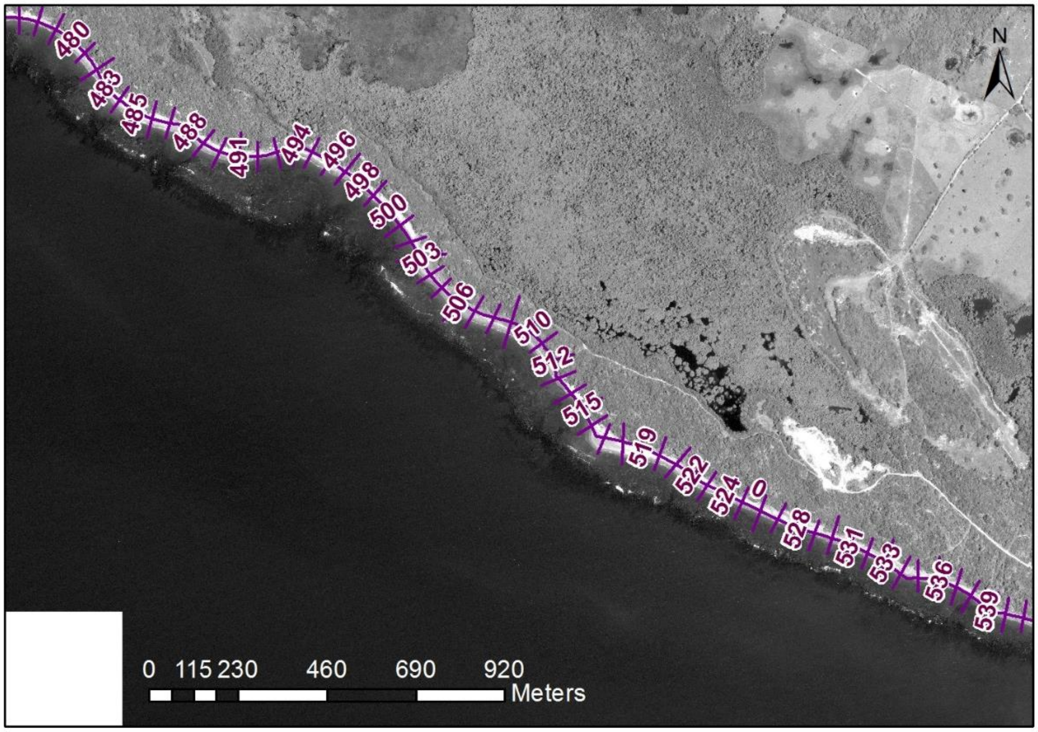
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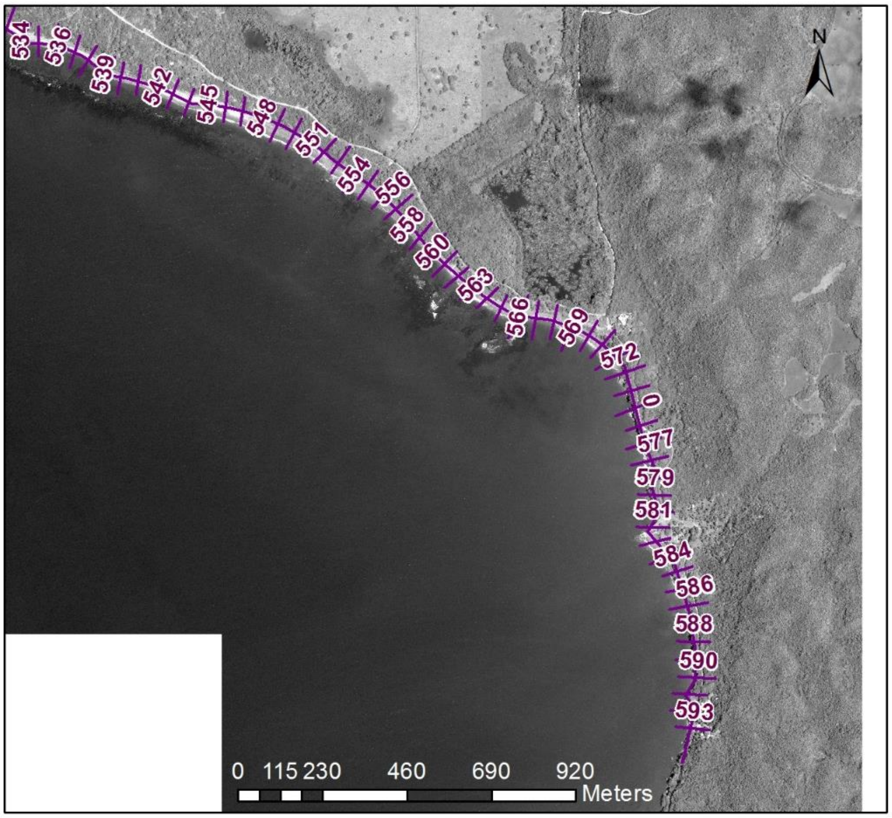
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Appendix D: Photo Log.

Mangroves along Hunts Bay (transect 169).

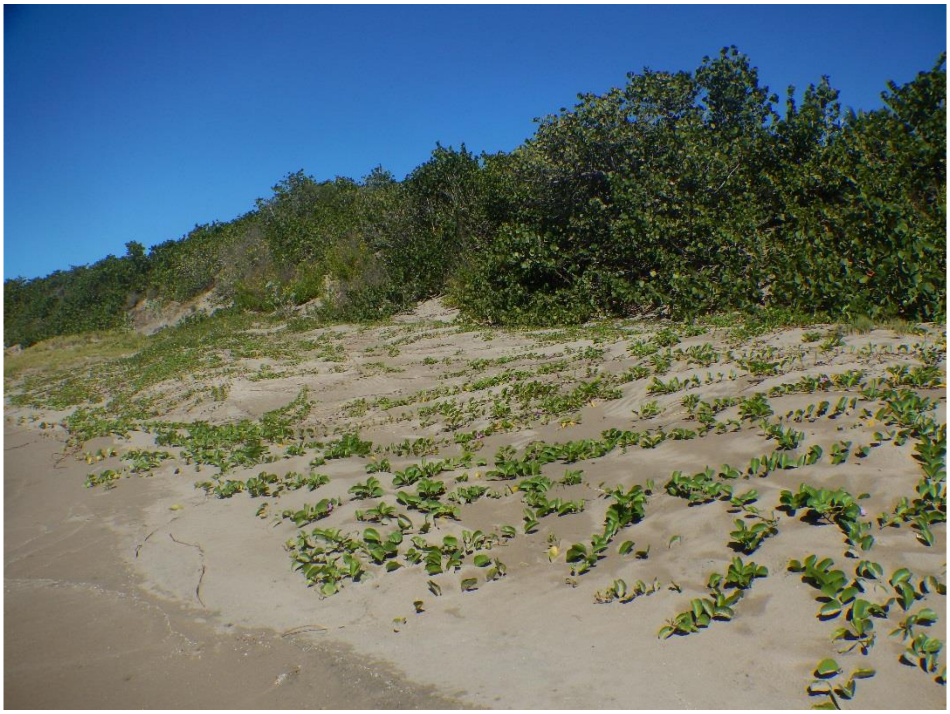
Damaged infrastructure (transect 440).

Mangroves protection (transect 443).

Shoreline along Parrottee Bay (transect 461).

Shoreline along Parrottee Bay (transect 464).

Dunes along Parrottee Point and Starve Gut Bay (transect 478).



Dunes and coastal vegetation (transect 487).

Shoreline along Starve Gut Bay.

Buildings along Black River Bay.

Appendix E: Percent of Shoreline Experiencing Change

Change in Vegetation line	2003 to 2007	2007 to 2012	2003 to 2012
Erosion	50%	10%	46%
No Change	47%	66%	40%
Accretion	3%	25%	14%

Change in Waterline	2003 to 2007	2007 to 2012	2003 to 2012
Erosion	34%	13%	3%
No Change	46%	47%	35%
Accretion	20%	40%	35%

Change in Beach Widths	2003 to 2007	2007 to 2012	2003 to 2012
Erosion	69%	25%	15%
No Change	39%	42%	31%
Accretion	42%	33%	54%

Appendix F: Changes and Rates by Zones.

Vegetation line

Zone	Location	Transect Numbers	Length (m)	2003-2007 (m)	2007-2012 m	2003-2012 m	2003-2007 Rates (m/yr)	2007-2012 Rates (m/yr)	Annual Rates (m/yr)
1	Fonthill	1-87,	4350	-3.05	-0.77	-3.82	-0.72	-0.16	-0.42
2	Malcolm Bay	87-159	3600	-2.8	-0.56	-3.36	-0.66	-0.12	-0.37
3	Hunt Bay	159-192	1650	-0.43	0.15	-0.27	-0.10	0.03	-0.03
4	Hodgens Bay	192-232	2000	-2.32	0.37	-1.94	-0.55	0.08	-0.22
5	Black River Bay West	232-271	2000	-1.87	1.39	-0.48	-0.44	0.29	-0.05
6	Black River Bay East	271-359	440	-0.83	5.05	4.22	-0.20	1.06	0.47
7	Parrottee Pond	359-423	3200	-3.18	0.97	-2.21	-0.75	0.20	-0.25
8	Parrottee Bay	423-461	1900	-5.55	-0.46	-6.01	-1.31	-0.10	-0.67
9	Parrottee Point	461-515	2700	-12.23	2.07	-10.16	-2.88	0.44	-1.13
10	Starve Gut Bay	515-593	3900	-5.88	1.92	-3.96	-1.38	0.40	-0.44
			Average Change (m)	**-3.81**	**1.01**	**-2.80**			
					Annual Rate (m/yr)		**-0.90**	**0.21**	**-0.31 m/yr**

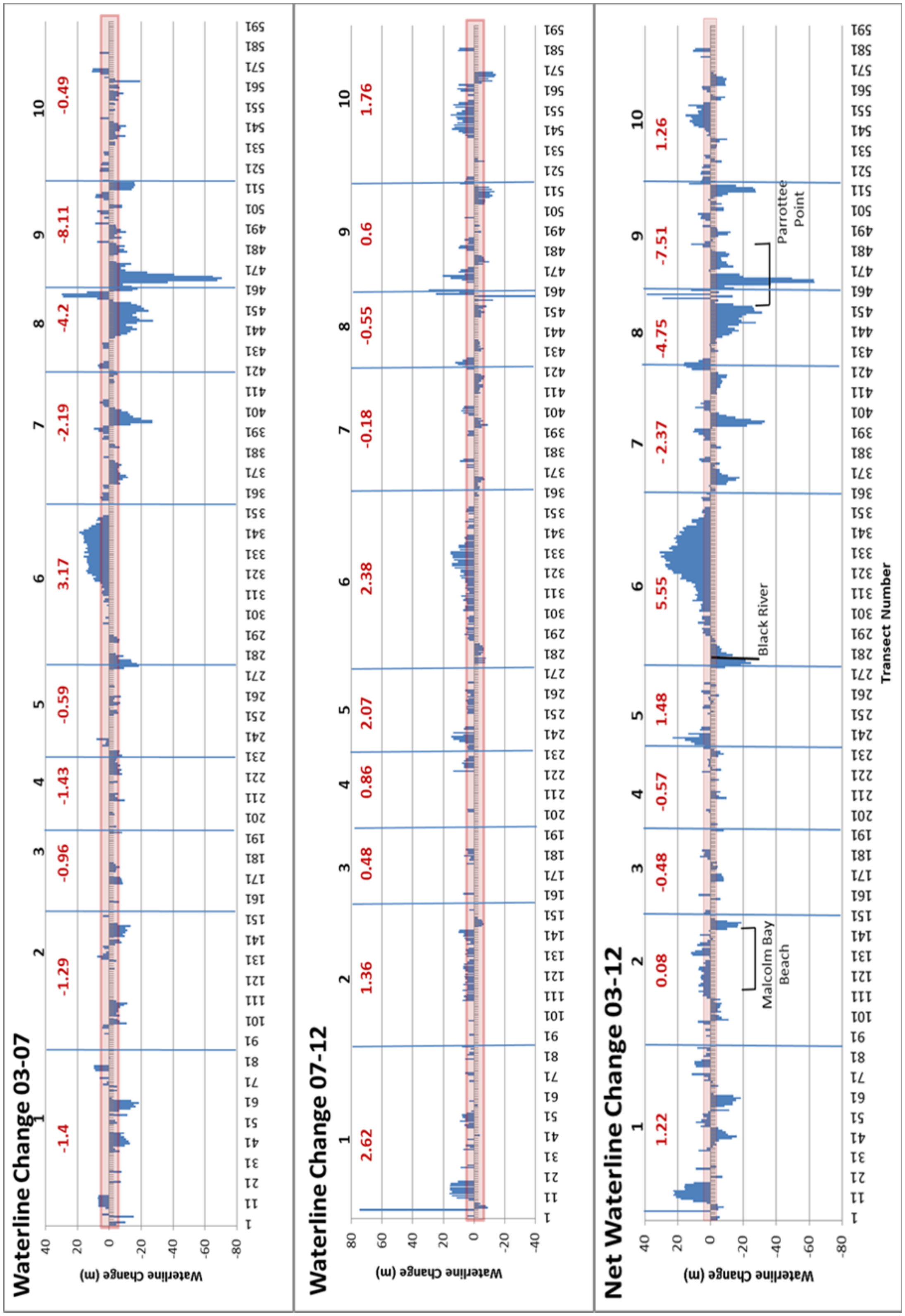
Waterline

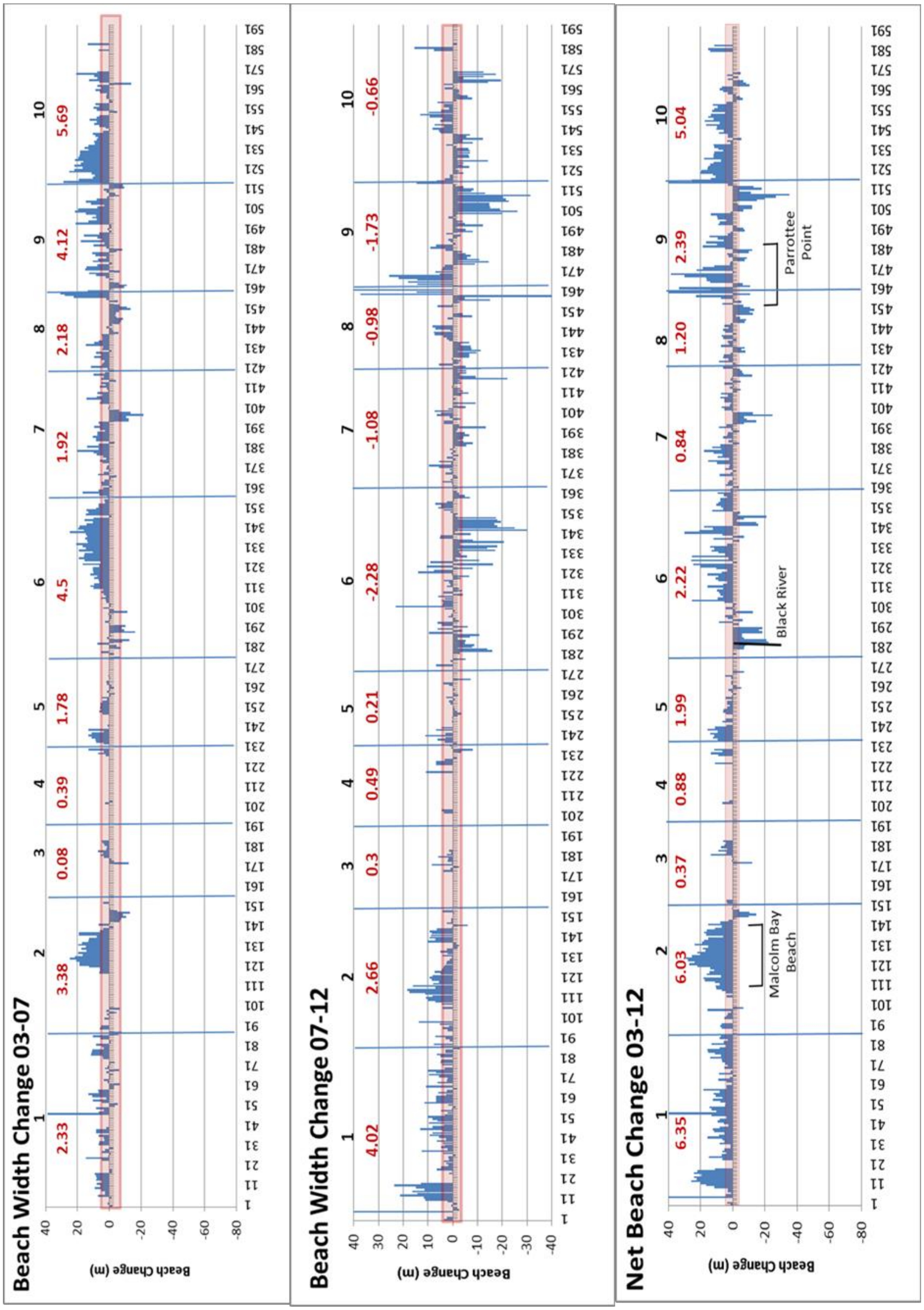
Zone	Location	Transect Numbers	Length (m)	2003-2007 (m)	2007-2012 (m)	2003-2012 (m)	2003-2007 Rates (m/yr)	2007-2012 Rates (m/yr)	Annual Rates (m/yr)
1	Fonthill	1-87,	4350	-1.4	2.62	1.22	-0.33	0.55	0.14
2	Malcolm Bay	87-159	3600	-1.29	1.36	0.08	-0.30	0.29	0.01
3	Hunt Bay	159-192	1650	-0.96	0.48	-0.48	-0.23	0.10	-0.05
5	Black River Bay West	232-271	2000	-0.59	2.07	1.48	-0.14	0.44	0.16
6	Black River Bay East	271-359	440	3.17	2.38	5.55	0.75	0.50	0.62
7	Parrottee Pond	359-423	3200	-2.19	-0.18	-2.37	-0.52	-0.04	-0.26
8	Parrottee Bay	423-461	1900	-4.2	-0.55	-4.75	-0.99	-0.12	-0.53
9	Parrottee Point	461-515	2700	-8.11	0.6	-7.51	-1.91	0.13	-0.83
10	Starve Gut Bay	515-593	3900	-0.49	1.76	1.26	-0.12	0.37	0.14
			Average Change (m)	**-1.75**	**1.14**	**-0.61**			
					Annual Rate (m/yr)		**-0.41**	**0.24**	**-0.068m/yr**

Beach Width Change

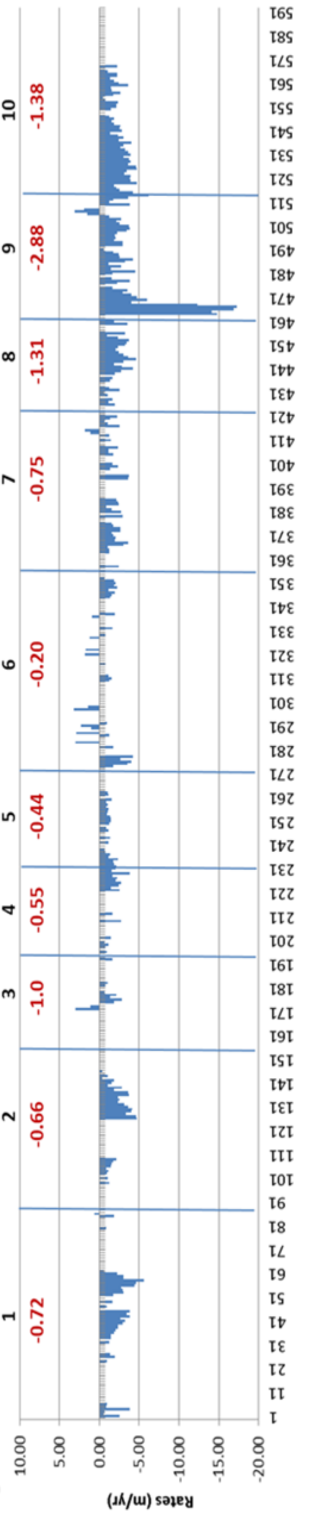
Zone	Location	Transect Numbers	Length (m)	2003-2007(m)	2007-2012 (m)	2003-2012 (m)	2003-2007 Rates (m/yr)	2007-2012 Rates (m/yr)	Annual Rates (m/yr)
1	Fonthill	1-87,	4350	2.33	4.02	6.35	0.55	0.85	-0.71
2	Malcolm Bay	87-159	3600	3.38	2.66	6.03	0.80	0.56	0.67
3	Hunt Bay	159-192	1650	0.08	0.3	0.37	0.02	0.06	0.04
4	Hodgens Bay	192-232	2000	0.39	0.49	0.88	0.09	0.10	0.1
5	Black River Bay West	232-271	2000	1.78	0.21	1.99	0.42	0.04	0.22
6	Black River Bay East	271-359	440	4.5	-2.28	2.22	1.06	-0.48	0.25
7	Parrottee Pond	359-423	3200	1.92	-1.08	0.84	0.45	-0.23	0.09
8	Parrottee Bay	423-461	1900	2.18	-0.98	1.2	0.51	-0.21	0.13
9	Parrottee Point	461-515	2700	4.12	-1.73	2.39	0.97	-0.36	0.27
10	Starve Gut Bay	515-593	3900	5.69	-0.66	5.04	1.34	-0.14	0.56
			Average Change (m)	**2.64**	**0.10**	**2.73**			
					Annual rates (m/yr)		**0.62**	**0.02**	**0.30 m/yr**

Appendix G: Trends in Shoreline Change.

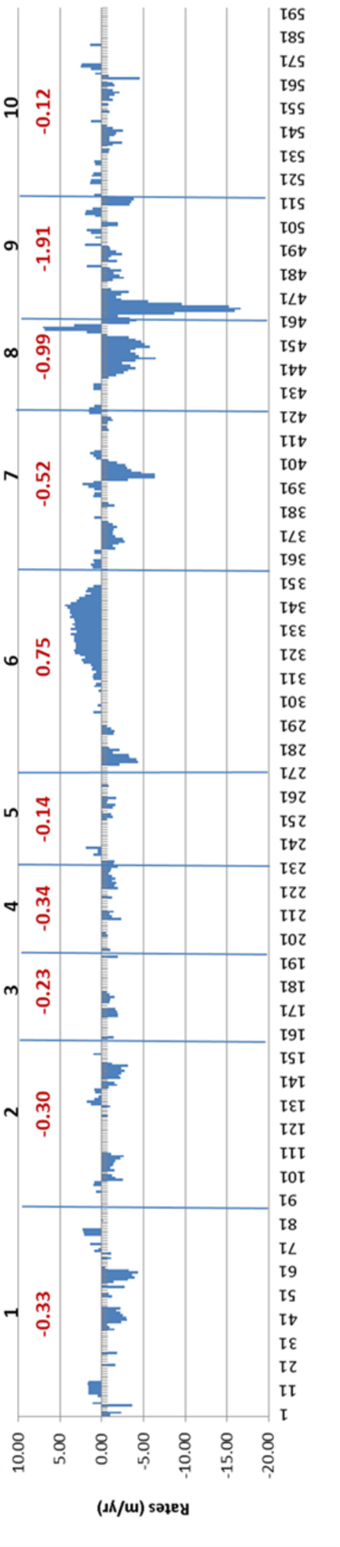



Beach Width Change 03-07
Beach Change (m)
40
20
0
-20
-40
-60
-80
1
2
3
4
5
6
7
8
9
10
2.33
3.38
0.08
0.39
1.78
4.5
1.92
2.18
4.12
5.69
Beach Width Change 07-12
Beach Change (m)
40
30
20
10
0
-10
-20
-30
-40
4.02
2.66
0.3
0.49
0.21
-2.28
-1.08
-0.98
-1.73
-0.66
Net Beach Change 03-12
Beach Change (m)
40
20
0
-20
-40
-60
-80
6.35
6.03
0.37
0.88
1.99
2.22
0.84
1.20
2.39
5.04
Malcolm Bay Beach
Black River
Parrottee Point
1 11 21 31 41 51 61 71 81 91 101 111 121 131 141 151 161 171 181 191 201 211 221 231 241 251 261 271 281 291 301 311 321 331 341 351 361 371 381 391 401 411 421 431 441 451 461 471 481 491 501 511 521 531 541 551 561 571 581 591

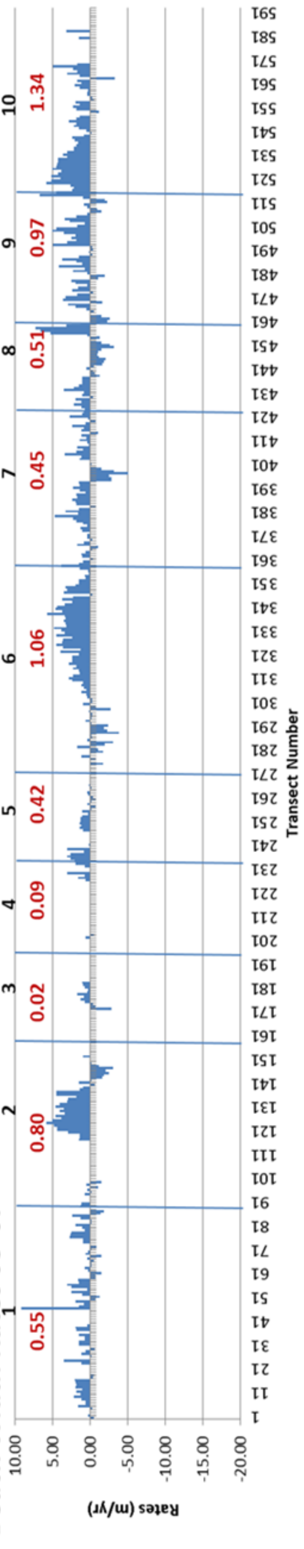
Vegetation line Rates 03-07

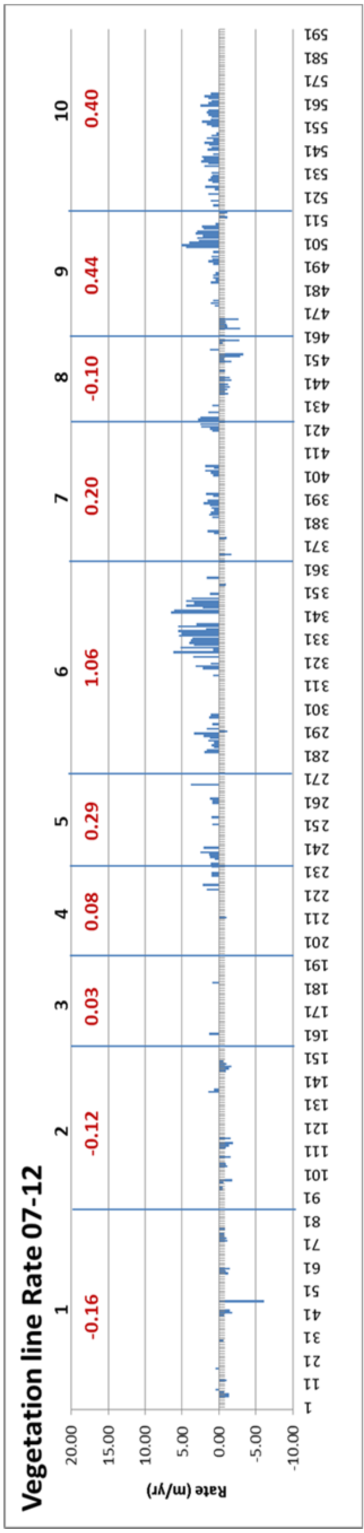


Waterline Rates 03-07

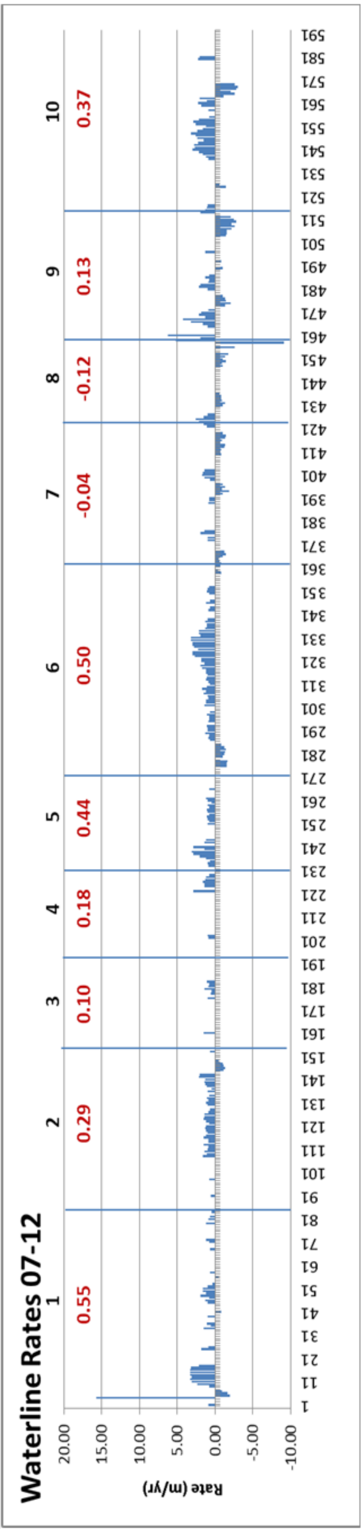


Beach Width Rates 03-07

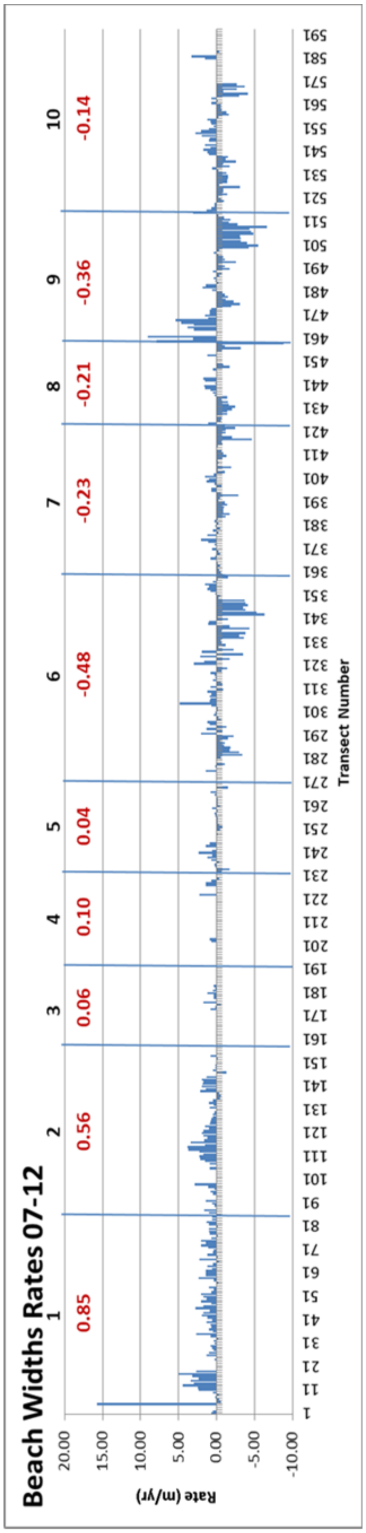




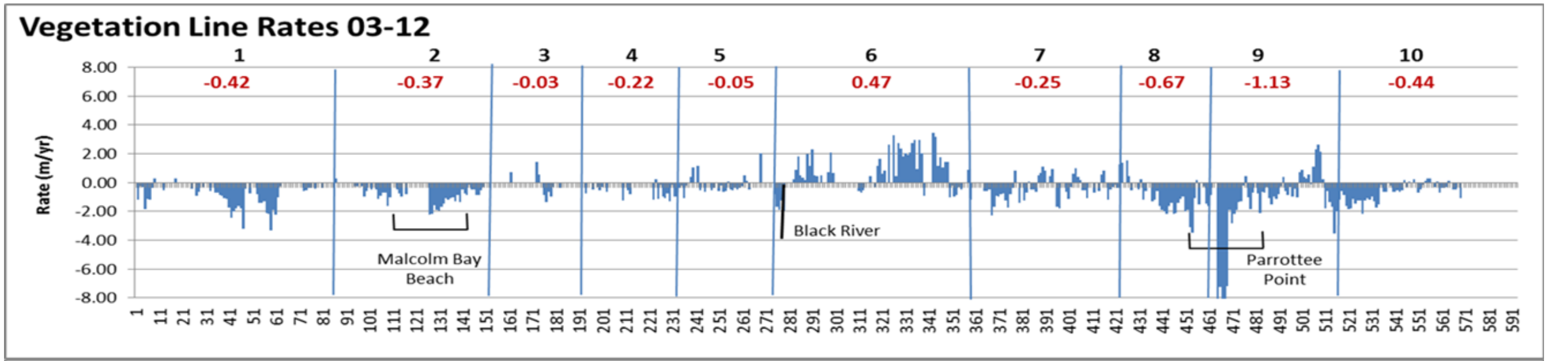
Vegetation line Rate 07-12

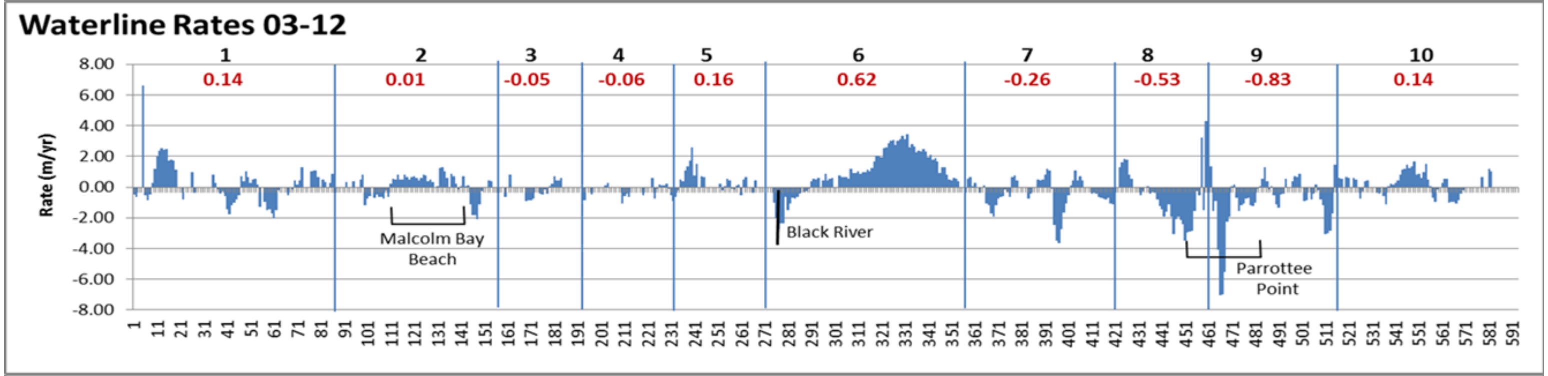


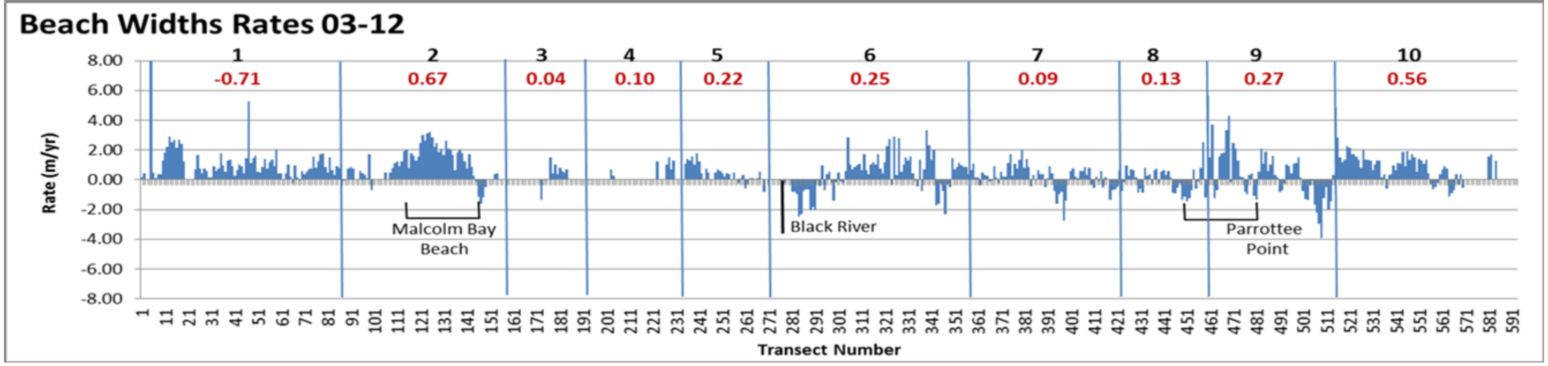
Waterline Rates 07-12



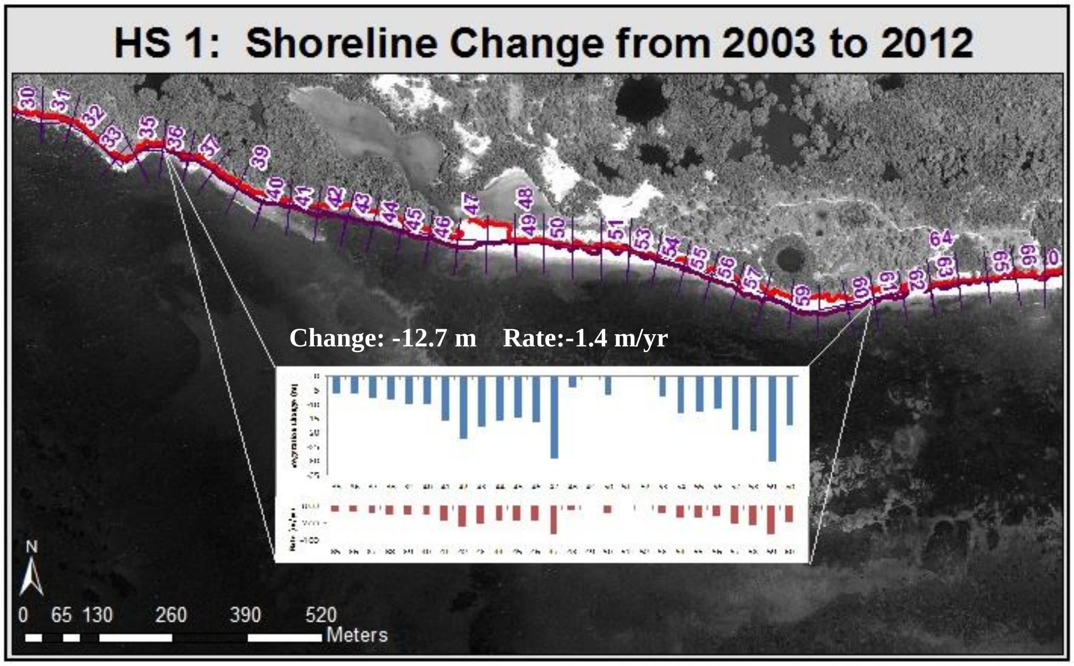
Beach Widths Rates 07-12


Vegetation Line Rates 03-12

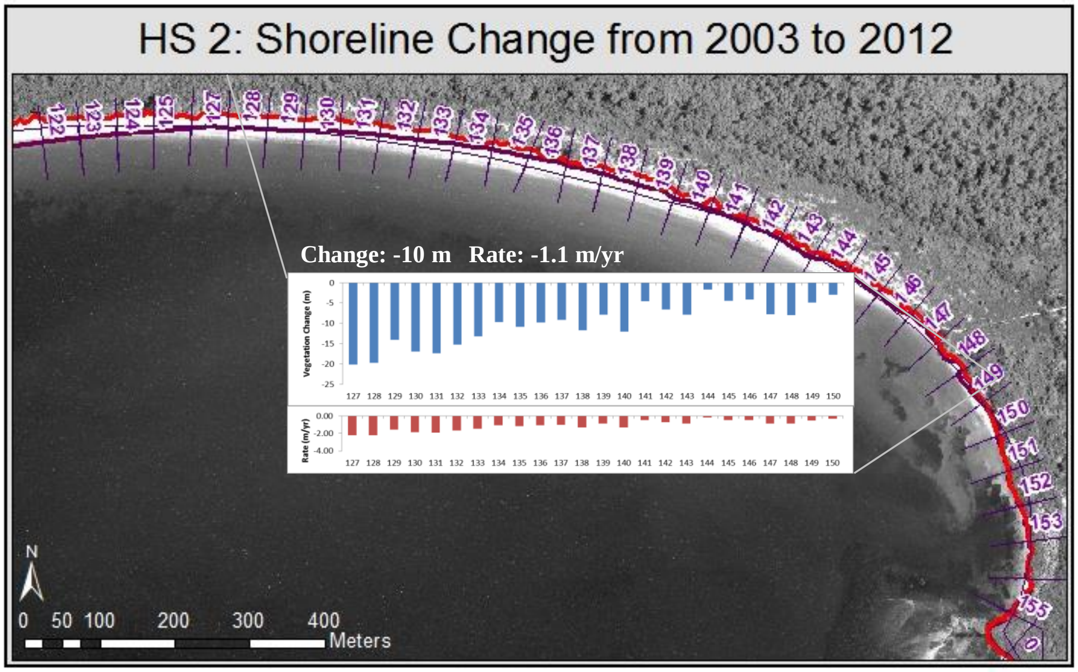

Waterline Rates 03-12


Beach Widths Rates 03-12

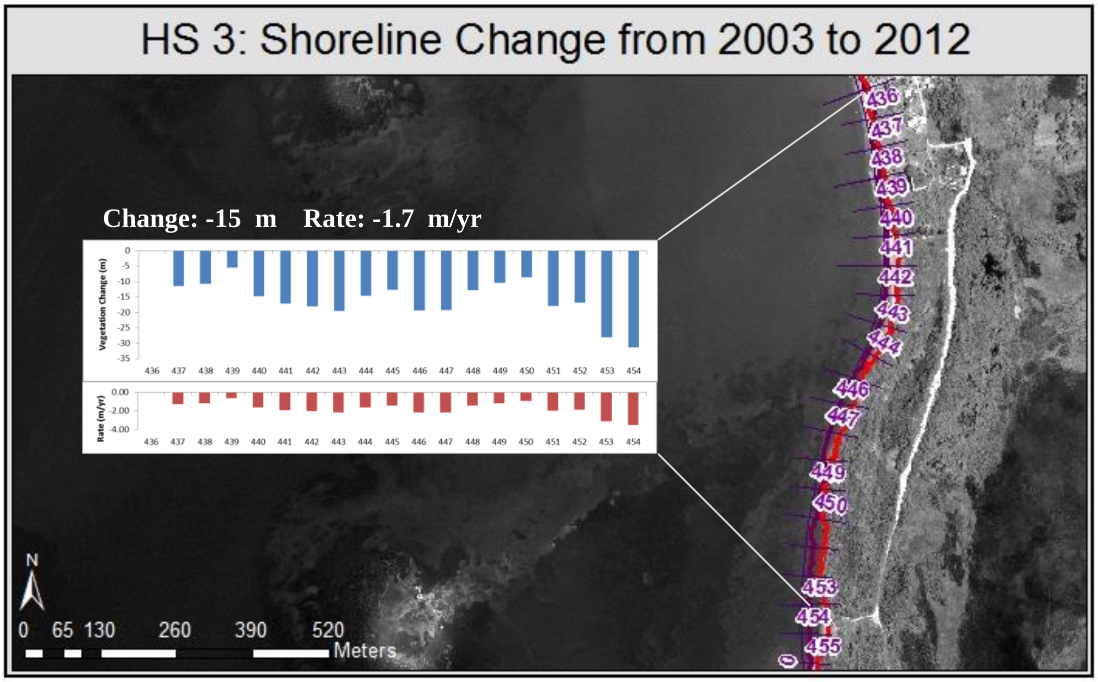
Appendix H: Hot and Cold Spots.



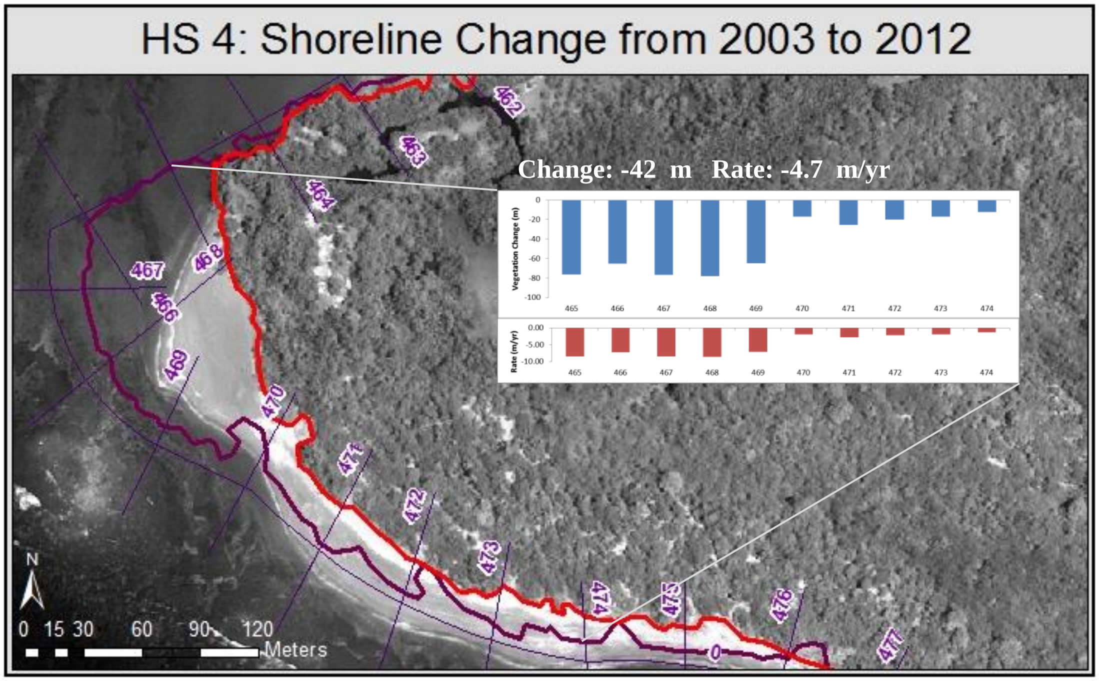
Observed shoreline change at hot spot 1 (transects 36 to 60).



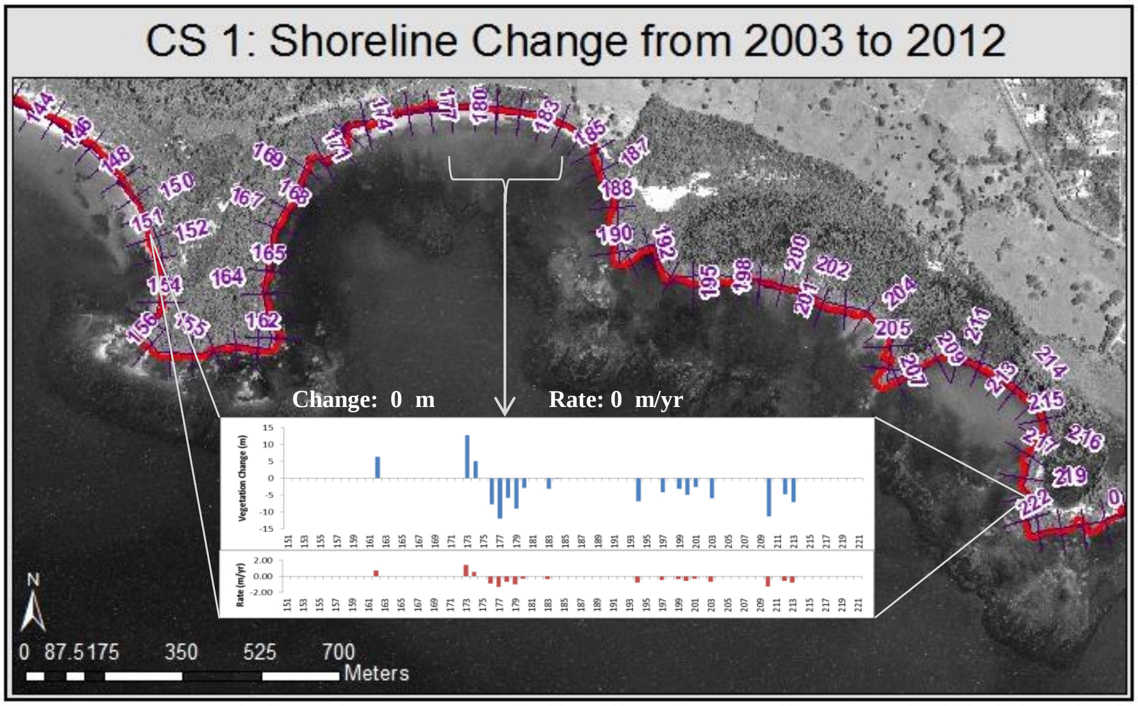
Observed shoreline change at hot spot 2 (Transects 128 to149).



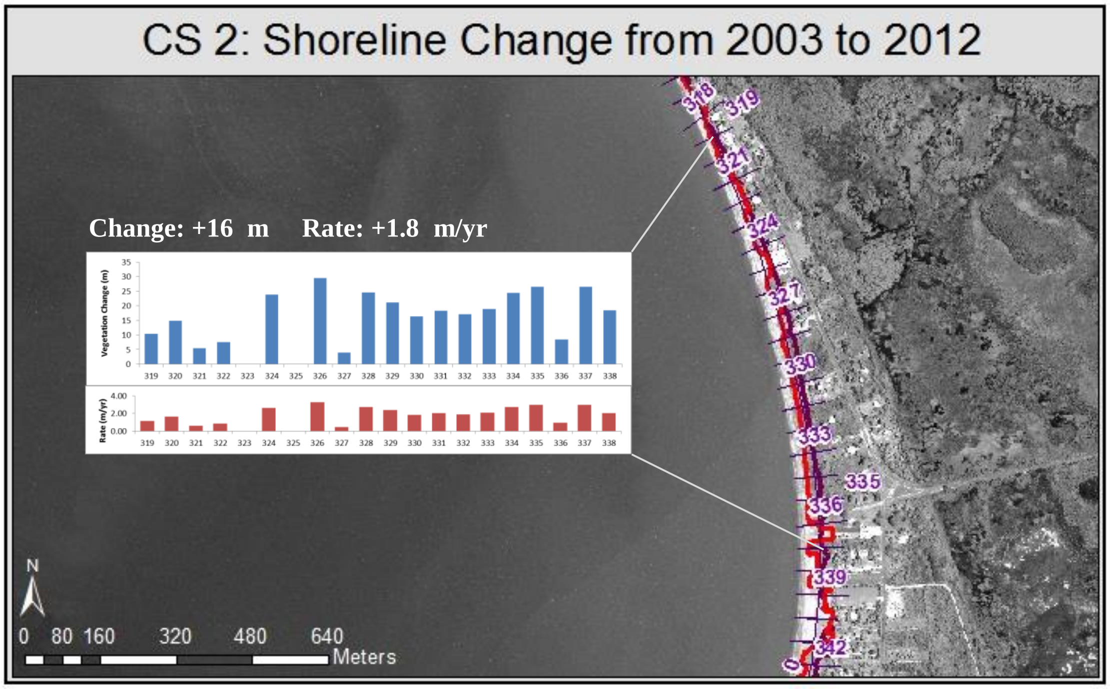
Observed shoreline change at hot spot 3 (transects 436 to 454).



Observed shoreline change at hot spot 4 (transects 466 to 474).

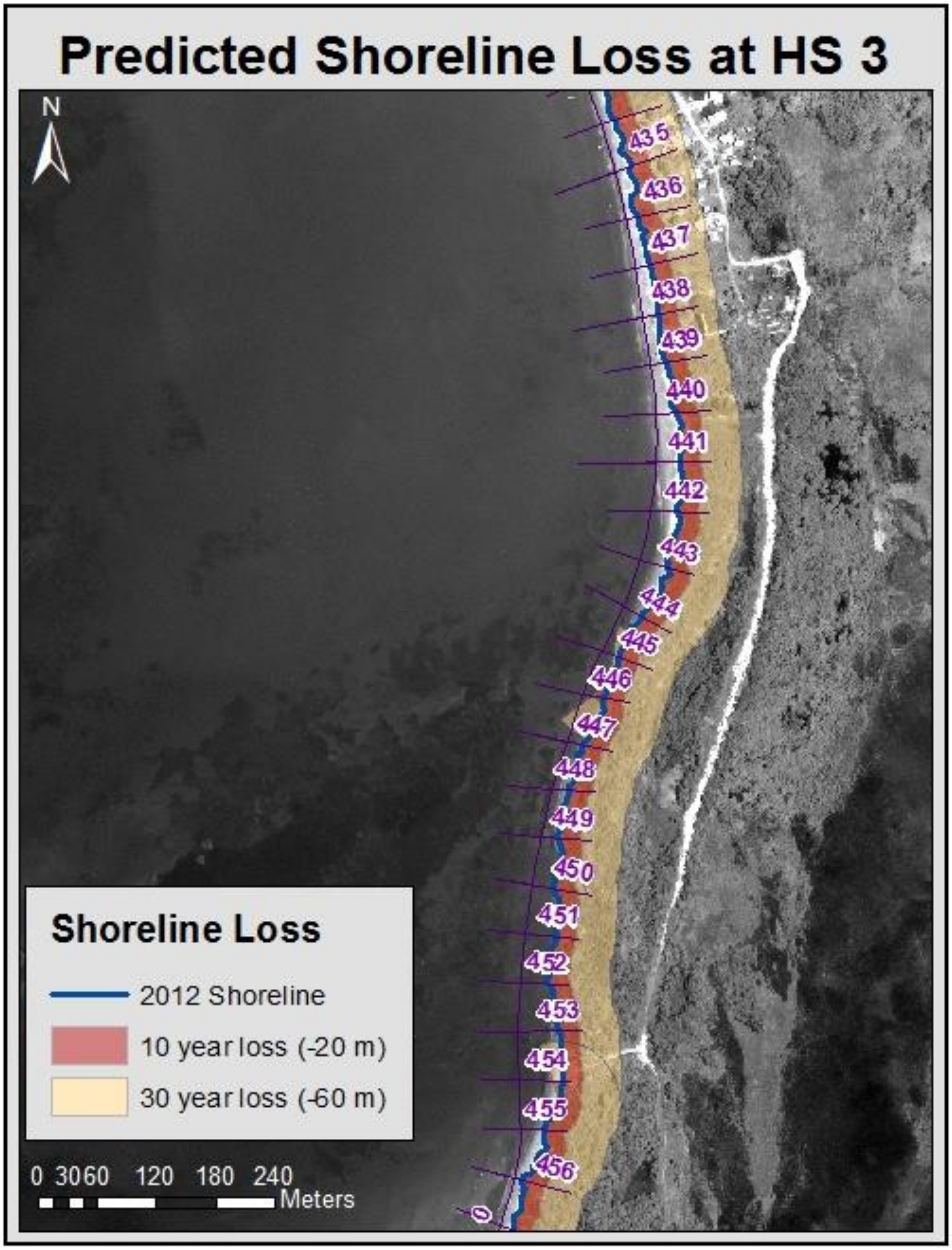


Observed shoreline change at cold spot 1 (transects 152 to 222).

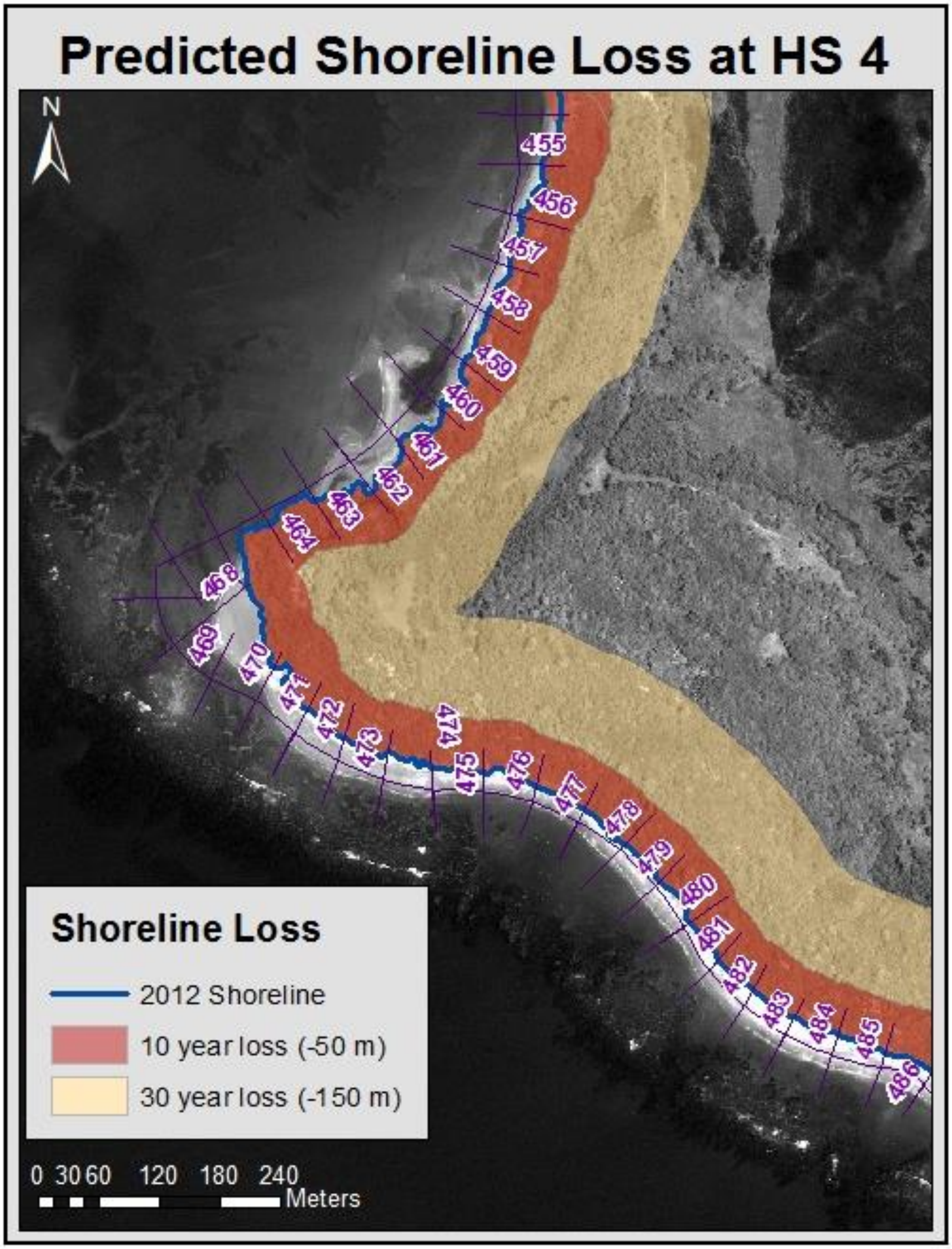


Observed shoreline change at cold spot 2 (transects 319 to 338).

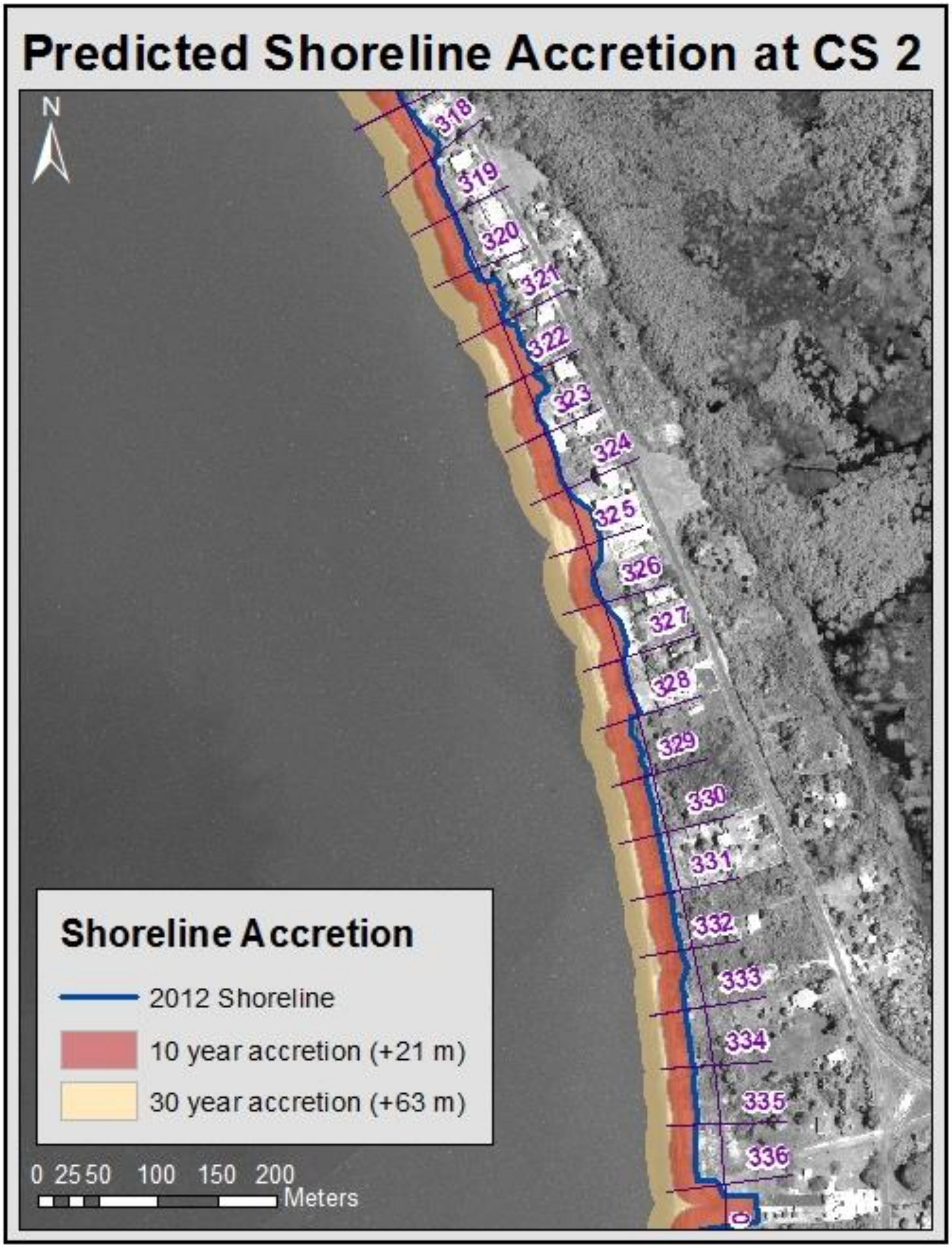
Appendix I: Predicted Shoreline Changes.



Predicted shoreline loss at hotspot 1 for the next 10 to 30 years.



Predicted shoreline loss at hotspot 4 (Parrottee Point) for the next 10 to 30 years.



Predicted shoreline accretion at cold spot 2 for the next 10 to 30 years.