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Beach Erosion and Recovery Since Hurricane Ivan in 2004 Along a Headland-Bay Coast in Treasure Beach, Jamaica

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BEACH EROSION AND RECOVERY SINCE HURRICANE IVAN IN 2004 ALONG A HEADLAND-BAY COAST IN TREASURE BEACH, JAMAICA

A Master's Thesis

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Master of Science, Geography

By

Elandé Engelbrecht

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ABSTRACT

Anthropogenic climate change is causing sea-level rise and shoreline changes that threaten the environment and economy of coastal communities in Caribbean Island nations. To assess this risk, this study quantifies shoreline changes at Treasure Beach in St. Elizabeth Parish on the south coast of Jamaica from 2001 to 2023. The effects of storm events on erosion were also assessed. Over 10 km of shoreline are assessed with about half being sandy pocket beaches ranging from 300 to 900 m in length, separated by rocky headlands and beach rock outcrops. Sand beach erosion trends since 2001 are assessed for seven sandy beaches including Great Bay, Old Wharf, Calabash Bay, Frenchman's Bay, Billy's Bay, Mahoe Bay and Black Bay. Seven years of satellite imagery as well as field surveys are used to evaluate beach erosion rates at annual scales. Average shoreline erosion rates ranged from 0.1 to 1.3 m/yr from 2001 to 2023. Beach widths ranged from 0 to 77 m from 2001 to 2023. Local shoreline changes from 2001 to 2023 ranged from 38 m seawards (deposition) and 51 m landward (erosion). Both sand deposition and erosion occurred during storm events. Overall, Treasure Beach lost about 38% of its beach area due to the passage of Hurricane Ivan in 2004 which was one of the most damaging storms in the Caribbean over the past century. Beach recovery has occurred locally, and the sandy beach area increased with 6% from 2005 to 2021. However, Treasure Beach lost a total of 29% of its sandy beach area from 2001 to 2023.

KEYWORDS: sea-level rise, beach erosion rates, storm events, rock headlands, sandy pocket beaches, satellite imagery

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CHAPTER 1. INTRODUCTION

Coastal erosion is an escalating environmental threat around the world affecting more than just beaches, but also human settlements, coastal recreation areas, and animals like sea turtles, which rely on beaches as nesting habitats (Roy, et al., 2021; Bouwer, 2011; Hanson & Lindh, 1993; Hendry, 1993). Sandy beaches are of major concern since they are prone to rapid erosion and deposition and can adjust form rapidly (Jackson & Nordstrom, 2020). Beach systems are composed of landforms that naturally tend to adjust by geomorphic processes to moderate changes in sand supply, storm wave attack, and sea level fluctuations (Hapke, et al., 2013; Armaroli, et al., 2013) (Figure 1). Hydrodynamic and geologic processes affecting coastline evolution and form can vary in action over multiple-scales including: 1) sea level rise, 2) tides and currents, 3) storm magnitude and frequency, direction, and duration, 4) climatic cycles like El Niño, 5) sand supply from reefs and rivers and 6) tectonic processes causing uplift or subsidence of coasts (Vitousek, et al., 2017). However, climatic changes and storm events that impact coastal areas over periods of 10-100 years have become more frequent, intense, and destructive over the last century (Cambers, 2009). Thus, anthropogenic climate-forcing of rising sea level and active storm events during the past 50-100 years are the main causes of accelerated beach erosion rates that exceed the natural deposition or recovery rates to return to pre-storm conditions (Athanasiou, et al., 2020; Phillips, et al., 2015; Leatherman, et al., 2000).

When considering beach changes, natural processes like storm events, wind direction and speed, rain, longshore drift/littoral drift, sea currents and tectonic uplift are important, but shoreline morphology, tidal range, and coastal submergence due to sea level change are the most important determinants of erosion at different spatial scales (Miret-Villaseñor, et al., 2019; Phillips, 1986). Storm-generated waves can cause several meters of beach erosion along several kilometers of shoreline in a matter of minutes to a day, whereas eustatic and isostatic (geological) sea-level rise, long term sediment supply, and plate tectonics can result in significant changes over thousands to millions of years along coastlines thousands of kilometers in length (Chelton, 2001).

Recent global warming trends have accelerated sea level rise by increasing ocean volume through thermal expansion and melting of ice sheets in polar regions (DeConto & Pollard, 2016). Global sea level rise for the 20th century was approximately 0.001-0.002 m/year according to the Third Assessment Report of the Intergovernmental Panel on Climate Change (2001). Davidson-Arnott (2005) argued that predictions of global sea level rise have been too conservative, but an estimate of 0.003-0.006 m/y in sea level rise can be expected over the next century. Between 1901 and 2018, global mean sea level increased by 0.2 (0.15 to 0.24) m according to the Assessment Report of the Intergovernmental Panel on Climate Change (2023). A broad range of 0.15-0.23 m in global mean sea level rise under low greenhouse gas emissions and 0.20-0.29 m under high greenhouse gas emissions has been predicted by 2050 (Intergovernmental panel on climate change, 2023). Titus (2004) predicted that over the next 50 to 60 years, most of the world's sandy beaches will erode up to 15 to 30 meters, depending on the slope of the beach face (Figure 1). Nevertheless, in many regions sea level rise has already increased beach erosion rates beyond the ability to recover leading to narrower beaches and loss of dune-vegetation sea-habitats, often due to the lack of accommodation space since inland beach migration can be limited by coastal infrastructure or bluffs (Athanasiou, et al., 2020; Vitousek, et al., 2017; Bulleri & Chapman, 2010; Feagin, et al., 2005; Leatherman, et al., 2000).

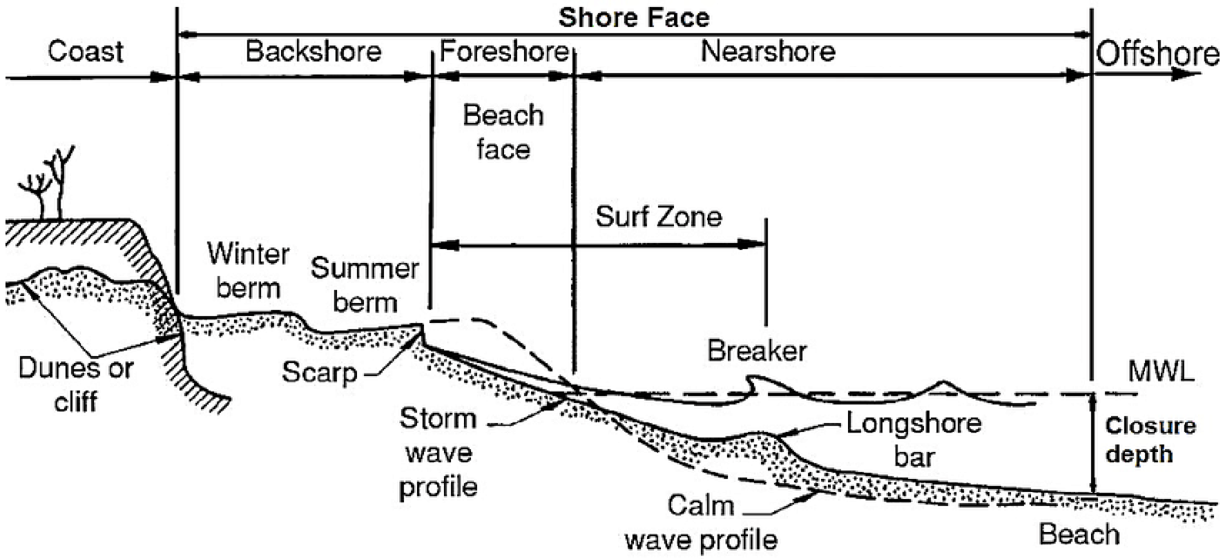

Figure 1. A typical beach cross-section with beach terminology. Source: (Ataei, Adjami, and Neshaei, 2018).

This thesis will assess sandy beach erosion and deposition trends during the past two decades along the south coast of Jamaica. Little research has focused on the recent status of beach erosion rates on island nations in the Caribbean. This thesis will address this gap by examining the spatial variability of beach response due to Hurricane Ivan in 2004 and recovery trends until present along Treasure Beach in Saint Elizabeth Parish. The factors that typically influence beach morphology and erosion rates are described below.

Seasonal and Storm Changes. There are often significant variations in beach form and sand distribution due to seasonal cycles in storm frequency, wind strength and direction, and wave attack (Gallop, et al., 2020). A summer beach profile formed during periods of fair weather and calm conditions will form depositional landforms like berms with steep beach faces and high dune crests. However, a winter beach profile may be more erosional as stronger winds and larger breaking waves cause beach face retreat, offshore bar formation, and dune erosion (Island Beach State Park, 2017) (Figure 1). Large storms can have major impacts on beach erosion rates but with periods of fair weather and lower energy wave conditions, beaches can recover to their pre-storm form within a few months to a year, depending on the severity of the storm and the amount of beach erosion (Dodet, et al., 2019; Phillips, et al., 2015).

Anthropogenic climate change can increase tropical storm frequency and intensity so it may be helpful to consider the magnitude, frequency, timing, duration, and sequence of tropical storm events to better understand beach responses (Vitousek, et al., 2017). Tropical storm events such as hurricanes lead to sand loss as well as sand accretion on beaches. Not only do the wind and waves of a storm cause beach changes, but also the storm surge associated with the storm that raises the local sea surface and allows larger waves to impact the beach. Some storm surge floods can travel up to 25 miles inland, depending on the coastal topography and storm movement and pressure (Federal Emergency Management Agency, n.d.). During storm events, sediment eroded from the beach is transported seaward and deposited on the nearshore bottom (Park & Edge, 2011). This temporarily stored sediment can be remobilized and either be gradually redeposited on the beach by waves and current of moderate strength or lost to deeper offshore areas out of reach of future wave or current transport (Bruun, 1962).

A stable beach profile is typically assumed to fluctuate about a mean condition, being relatively unaltered by waves and tides and without any long-term erosion or deposition (Klein, et al., 2003). However, while relatively rapid changes in sandy beach form can occur in association with an intense storm or series of moderate storms, recovery periods can take several years or more or never even obtain the pre-storm condition (Hoyle & King, 1957; Fontoura Klein, et al., 2003). For example, coastal storm Johanna hit the French Atlantic Coast in 2008 causing dune retreat of up to 6 m. While some dune recovery was observed in the month following the storm event, the dune system has not fully reformed to its pre-storm location and size yet in 2012 (Suanez, et al., 2012). Thus, as is often the case in coastal systems, the response to high-energy events is dramatic and rapid while recovery is slow and periodic (Castelle, et al., 2017).

Sediment Budget and Transport. The sediment budget refers to the net mass of sediment remining after summation of individual components of sediment lost or gained by the beach (Komar, 1998; Figure 2). A sediment budget is negative if beach erosion or sand loss occurs and positive if it is accumulating or gaining sand. The sediment or sand budget of a beach is regulated by the balance between the amount of sediment delivered to the beach and the energy provided by waves or currents to remove it (Inman & Jenkins, 2003). Further, beaches can recover more rapidly to their pre-storm extent where higher supply rates occur (Montreuil, et al., 2020). Conversely, human or natural processes that reduce sediment supply can limit the ability of the beach to recover to pre-storm conditions.

Regionally, the long-term sediment supply to a shoreline segment can be linked to geology and tectonic activity, sea level changes, river sediment inputs, currents and storm wave influence that influence longshore transport (French and Burningham, 2011). Longshore transport moves sediment along the coast in association with nearshore tidal and wind-driven currents. Longshore drift refers to higher concentrations of sand moving along and parallel to the beach, often causing deposition on the updrift side of groins while erosion occurs on the downdrift side (Vitousek, et al., 2017). Sediment gained on the beach can be due to longshore or shoreward transport of sand onto the beach by waves and currents.

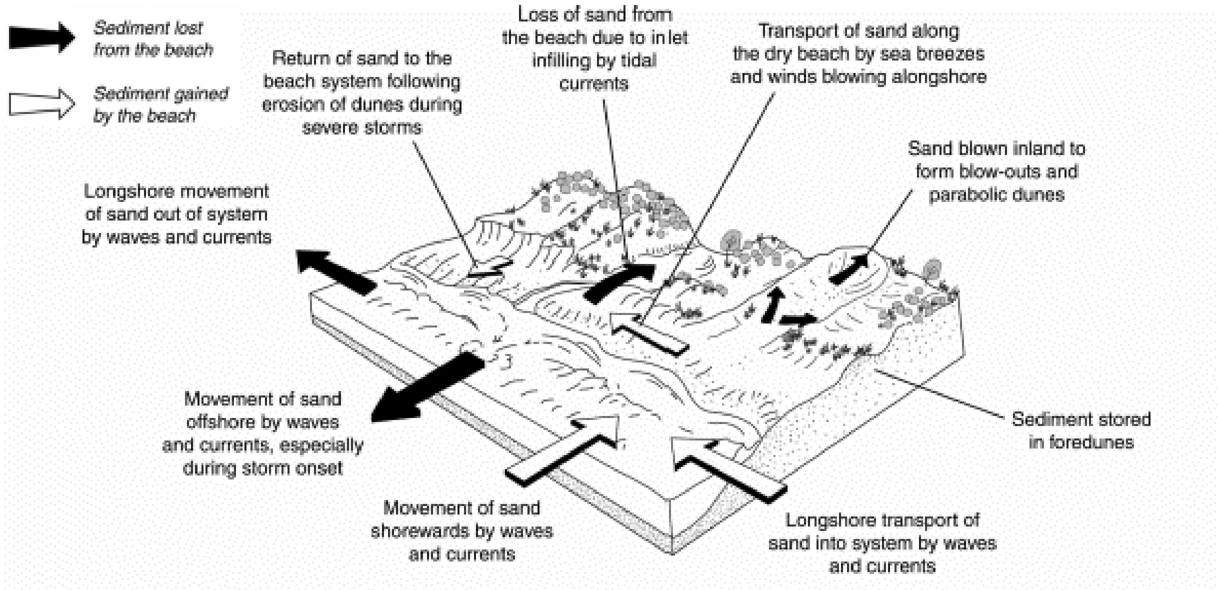

Figure 2. The components of a coastal sediment budget. Source: Komar (1998).

As sediment moves on to beaches by wind, waves, currents, and fluctuating sea levels, the shoreline adjusts its form and sediment storage locations (Kana, 2011). Some beach types naturally prevent the loss of sediment, due to their shape and sediment transport characteristics. For example, sediment tends to accumulate in small bays between rocky headlands to form pocket beaches with the degree of sand deposition and beach stability increasing with the offshore extent of headland protection (Bruun, 1995). Wave energy is directed at the headlands and away from the bay areas due to wave diffraction that bends wave fronts toward deeper areas along the rocky bluff, allowing sand to accumulate in the lower energy zones in the pocket bays (Trenhaile, 2016). Further, the nearshore component of longshore transport or littoral drift can increase deposition on the updrift side of obstructions like groins, jetties, and rocky headlands with erosion on the downdrift side (Bruun, 1995).

Sediment entering the beach systems may become stored for short or long periods in back beach or offshore areas (French & Burningham, 2011). Sediment may be temporarily stored within foredunes or the primary dune system to be remobilized later and transported to the beach by winds or erosion by waves during storm events. Sand can be transported further inland and effectively lost to beach systems by progressive inlet deposition and formation of wash-over fans during storms (Toimil, et al., 2020; Goff, et al., 2010). Sand can also be lost to offshore storges at depths greater than 20 to 30 m which is considered the limit of seaward bidirectional sediment exchange (Hilton & Hesp, 1996). Major storm wave events are key drivers of transporting sand to the depth of closure and beyond headland effects (Valiente, et al., 2019).

Beach Protection. Coastal features that enhance sand deposition to help maintain longer-term stability provide beach protection functions. While beach protection is often associated with structural approaches to beach maintenance such as the construction of groin fields and sea walls, natural conditions can also exist to provide for enhanced sand storage and lower erosion rates for nearby beaches including rocky headlands, coral reefs, and eolian sand supplies (Trenhaile, 2016; Maxam, et al., 2011). As introduced above, physical characteristics of the coastline can act to enhance sediment deposition and increase sand storage periods for beaches found along a headland-pocket bay coastline (Bruun, 1995). In addition, coral reefs reduce coastal erosion by attenuating wave energy during normal and storm conditions but are less effective in reducing the effect big waves and storm surges have on coasts during storm events (Maxam, et al., 2011). Nevertheless, damage to coral reefs can make beaches more vulnerable to erosion by storm current and wave attack (Kushner, et al., 2011). A hurricane caused high rates of beach erosion, shoreline recession, and complete beach loss in some areas along a beach lacking reef protection in Cancun, Mexico (Silva et al., 2006). However, less than 30 km away, the same storm produced sand deposition and beach accretion on a reef-protected beach in Puerto Morelos (Silva, et al., 2006). In general, the effectiveness of coral reefs to reduce beach erosion increases with potential to absorb energy from the most erosive breaking waves by being located closer to shore, reaching shallow depths, and containing more complex and live coral structures (Reguero, et al., 2018; Maxam, et al., 2011). Berms and dunes, which are natural or artificial ridges or mounds of sand, landward of the beach, also can serve as protection for beach erosion (Heinz, 2000). When these structures are not present on beaches, erosion rates tend to increase (Park & Edge, 2011).

Sea Level Rise. Climate driven sea-level rise is causing the acceleration of beach erosion along coastlines worldwide (Holgate & Woodworth, 2004). Sea level rise, together with the sediment budget is responsible for erosion and deposition on a beach (Figure 3). If sediment supply and landward migration rate is slower than rising sea level, beach erosion will exceed deposition rates and the beach erode, lose sediment, and become narrower (Martins & Pereira, 2014). As sea level transgresses or rises, beach systems will generally retrograde and migrate landward on the coastal plain (Figure 3). However, if the sediment supply is high and sediment budget positive, then beach systems can aggrade vertically or prograde seaward even when the sea level is rising (Posametier and Allen, 1999). Nevertheless, most shorelines have been migrating landward during this recent period of rapid sea level rise with little time for increased sediment supply and landform accommodation space to offset beach erosion (Pontee, 2013). Bruun (1962) developed a model to predict the horizontal recession of shorelines with the increase in sea level rise by considering: (1) height of the berm or other sand forming the eroding beach area, (2) depth of the closure, marking the transition from nearshore to offshore sediments as well as the cross-shore distance to depth. The “Bruun Rule” predicted that coastal recession would be as much at 10 to 50 times sea level rise, depending on the slope of the beach (Bruun, 1962). However, subsequent research has updated these coastal recession estimates to be 100

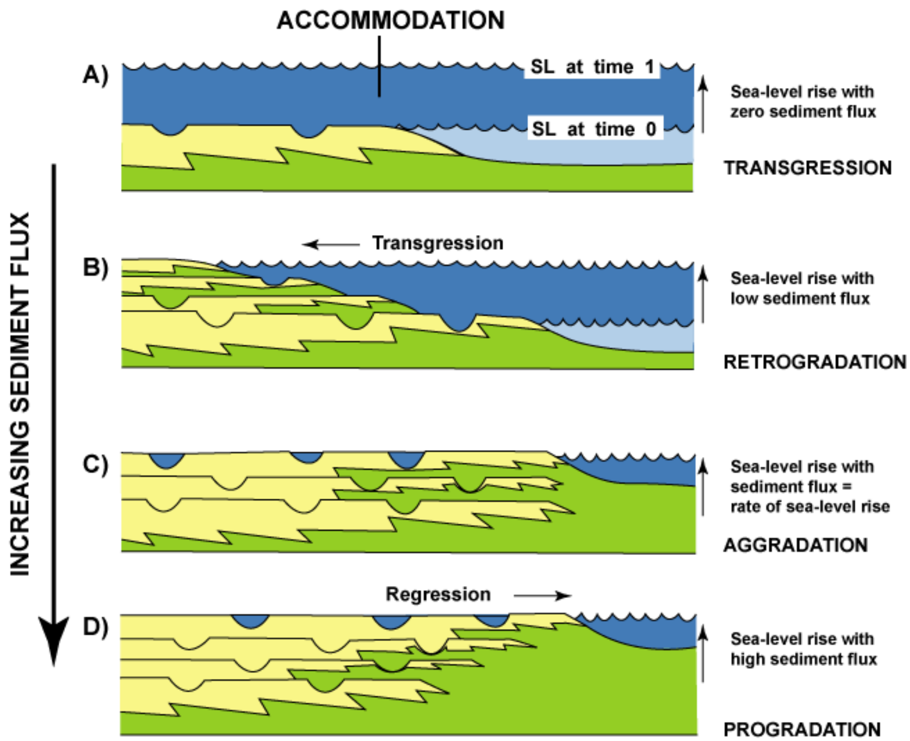

Figure 3. Changing coastal trajectories responding to sediment budget and sea level rise. Source: Posametier and Allen (1999).

times the rate of sea level rise on flat beaches (NASA Earth Observatory, 2015). Coastal topography can influence the inland extent of sea level rise effects considerably with effects more variable and widespread along low, gently sloping coastal plains. However, while beach erosion and loss can occur locally, inland effects will be more infrequent along high relief coasts (Kana, 2011).

Sea Level Rise and Coastal Erosion Concerns in the Caribbean and Jamaica

Storm surges, tropical storms and hurricanes in the Caribbean have caused extensive beach erosion (Schwartz, 2005). Beach erosion has been reported in most countries in the Caribbean and Gulf of Mexico where sandy beaches are found including Anguilla, Antigua-Barbuda, the British Virgin Islands, Dominica, Grenada, Montserrat, St Kitts/Nevis, St. Lucia, and St. Vincent (Chambers, 1997) (Table 1). Increased incidence of tropical storms and hurricanes were believed to be responsible for high erosion rates in the Northeastern coast of

Cuba where beach erosion occurred at 86% of beaches surveyed with 44% of beaches eroding at at rates >1.2 m/yr due to increases in storm wave heights over the past three decades due to both rapid climate change and El Niño-Southern Oscillation circulation events (Paneque & Finkl, 2020; Juanes, 1996). As sea level continues to rise, it is projected that 14 % of beaches on the northeastern coast of Cuba could be lost and 27% of the remaining beaches could have a significant width decrease by the end of the twenty-first century (Paneque & Finkl, 2020).

Based on a survey of reported erosion rates (Table 1), the average beach erosion rate for Jamaica is 0.26 m/year with a maximum erosion rate is 0.76 m/year. The degradation of Jamaica's coral reefs due to overfishing, pollution, coastal development, coral bleaching and diseases, as well as the added effect of hurricanes, may be a large contributor to the beach erosion with the loss of reef integrity leading to decreased wave energy attenuation and an increase in wave heights (Kushner, et al., 2011). At Negril, Jamaica, modeled water level elevations along shorelines at current and degraded reef conditions predicted an increase wave height of 0.5 m for the 1-year storm or the largest storm that occurs during a typical year at Negril and a 0.4 m increase for a 25-year storm event (Maxam, et al., 2011). Predicted sea level rise for Jamaica ranged from 1.2 – 1.3 m by 2030 to 2.8 – 3.6 m by 2100 suggesting that beach migration effects could extent inland up to 400 m by the next century (State of the Jamaican Climate report, 2015). Further, beach migration rates are only one impact of sea level rise given that the increased frequency of storms with larger waves and higher storm surge elevations can affect coastal areas even further inland. Thus, projected sea level rise in Jamaica may affect coastal areas with elevations up to 10 m and increase the area of coastal flood zone exposure and vulnerability considerably compared to beach migration erosion rates alone (Pacific Disaster

Centre, 2016; Figure 4). Therefore, a substantial retreat of shoreline and land use can be expected with just a small increase in sea level (Davidson-Arnott, 2005).

Table 1. Beach Change Rates in the Caribbean. Note: erosion (+) and accretion (-)

Beach	Average Rate (m/year)	Maximum Annual Rate (m/year)	Sources
Quinam	-10.0	-9.0	Singh, et al. (2003)
Guayaguare	-2.5	-7.0	Singh, et al. (2003)
Icacos (Coral Point)	-2.0	-12.0	Singh, et al. (2003)
South Cocos	-1.7	-9.0	Singh, et al. (2003)
Los Iros	-1.6	-10.0	Singh, et al. (2003)
Dominica	-1.1	Unavailable	Chambers (1997)
Blanchicheuse	-1.0	-5.0	Singh, et al. (2003)
Saline	-1.0	-4.0	Singh, et al. (2003)
Antigua	-0.85	Unavailable	Chambers (1997)
Nevis	-0.85	Unavailable	Chambers (1997)
Negril, Jamaica	-0.76	Unavailable	Williams-Raynor (2015)
Old Harbour Bay, Jamaica	-0.74	Unavailable	Williams-Raynor (2015)
British V.I.	-0.36	Unavailable	Chambers (1997)
Long Bay, Jamaica	-0.36	Unavailable	Mondon, et al. (2012)
Grenada	-0.31	Unavailable	Chambers (1997)

Table 1- Continued. Beach Change Rates in the Caribbean. Note: erosion (+) and accretion (-)

Beach	Average Rate (m/year)	Maximum Annual Rate (m/year)	Sources
Black River Bay, Jamaica	-0.31	-1.13	(Zelzer, 2015)
Montego Bay, Jamaica	0.30	Unavailable	(Kushner, et al., 2011)
Ocho Rios, Jamaica	0.30	Unavailable	(Kushner, et al., 2011)
St. Kitts	-0.27	Unavailable	Chambers (1997)
Galleon, Jamaica	+0.23	-3.0 to 2.6	(Geier, 2017)
Montserrat	+1.07	Unavailable	Chambers (1997)

Figure 4. Jamaica's Coastal Flood Zone Vulnerability, with Treasure Beach indicated with the red box. Source: Pacific Disaster Centre (2016).

Purpose and Objectives

Few studies have assessed beach erosion rates in Jamaica, with none focused on Treasure Beach in St. Elizabeth Parish. To address this gap, this study will assess beach changes with the use of satellite images to determine main and sub-classifications for beaches in Treasure Beach, Jamaica, to quantify beach erosion rates at annual and post-storm event scales over a 20-year period from 2001 to 2023. Most studies of beach erosion overall tend to focus on large barrier or spit type sandy beaches. However, this study will focus on a 12 km long headland-pocket beach system where several sandy pocket beaches are formed within discrete bays typically less than 1 km in length. Further, significant beach erosion for the region was reported by Hurricane Ivan in 2004 and most residents attribute this storm as a turning point in the beginning of erosional beach conditions along the south coast of Jamaica. However, no studies have yet evaluated the changes in beach width and erosion at Treasure Beach due to Hurricane Ivan and whether significant recovery to pre-Ivan conditions has occurred.

The objectives of this study are to: (1) determine the spatial and temporal variations in beach erosion and deposition rates in Treasure Beach, on the South coast of Jamaica from immediately before Hurricane Ivan to present; (2) assess if beach changes reflect the influence of storm/hurricane passage and protection by headlands, coral reefs, and nearshore rock outcrops and (3) determine if waterlines and sandy beach areas have recovered to their previous pre-Ivan location or state over the past 20 years.

This study will evaluate four hypotheses about Treasure Beach erosion rates:

(1) Beach erosion rates will indicate a net loss of sand during the study period as based on recent sea level rise and storm frequency records. Sea level rise, storm frequency and beach erosion are shown to have an important relationship and is linked to long-term shoreline retreat (Athanasiou, et al., 2020; Vousdoukas, et al., 2020; Leatherman, et al., 2000);

(2) Beaches with headland rock, beach rock, or reef protection and relatively high local sand supplies (i.e., thicker beach and back beach dune deposits) will yield lower erosion rates.

Local beach factors, such as dunes and shore protection structures are likely to dominate the response of the shoreline (Cooper, et al., 2020);

(3) Assuming current erosion trends and sea level rise rates, total beach loss may occur along some beach communities along Treasure Beach within 50 years (Athanasiou, et al., 2020; Titus, 2004);

(4) Most bays have sandy beaches with reduced sand supplies and therefore progress toward recovery to pre-Hurricane Ivan conditions will be minimal and erosion rates will be more sensitive to disturbances (Manakul, 2022; Anfuso, et al., 2021; Spiske, et al., 2021).

Significance of the Study

The scientific contribution of the research is the understanding of erosion and deposition patterns and expected future conditions in sandy, pocket beaches with rocky headlands, with similar characteristics as Treasure Beach at different spatial and temporal scales. An insight into beach recovery after major storm events in Treasure Beach can therefore be used to predict future beach characteristics after storm events. The underlying relationship between shoreline characteristics and erosion risk will be evident, as well as the use of erosion estimation to evaluate beach loss risk. Few studies have been conducted on erosion rates and sea level rise on sandy pocket beaches and rocky headlands in Jamaica, and how storm events influence beach erosion and recovery post-storm events. This is the first study at Treasure Beach to measure erosion and deposition rates as well as beach recovery after storm events with high resolution satellite imagery. Most island nations in the Caribbean rely on their attractive beaches for tourism as main source of revenue for economic activity (Nicholls, 1998). The loss of beaches in the Caribbean threatens revenue loss and potential loss of buildings along the coastline. Beaches in the Caribbean, like Treasure Beach are essential nesting habitats for endangered species, such as sea turtles (Hendry, 1993). This study will provide information on beach erosion risk which can be used by community planners and business owners to consider planning for economic development.

CHAPTER 2. STUDY AREA

Jamaica is located west of Haiti and south of Cuba and is the third largest island in the Caribbean. Treasure Beach is located along the South coast of Jamaica in St. Elizabeth Parish (Environmental Solutions, 2018). The 11.5 km coastline consists of sandy pocket beaches with rocky headlands. Black Bay (0.6 km), Mahoe Bay (0.5 km), Billy's Bay (0.9 km), Frenchman's Bay (0.8 km), Calabash Bay (0.6 km), Old Wharf (0.9 km) and Great Bay (1.5 km) is located along Treasure Beach, the South coast of Jamaica in St. Elizabeth's Parish (Figure 5). Treasure Beach emphasizes community tourism and relies on their beaches to support their economy. The community depends mostly on fishing, farming, and tourism as their main economic activities (Environmental Solutions, 2018).

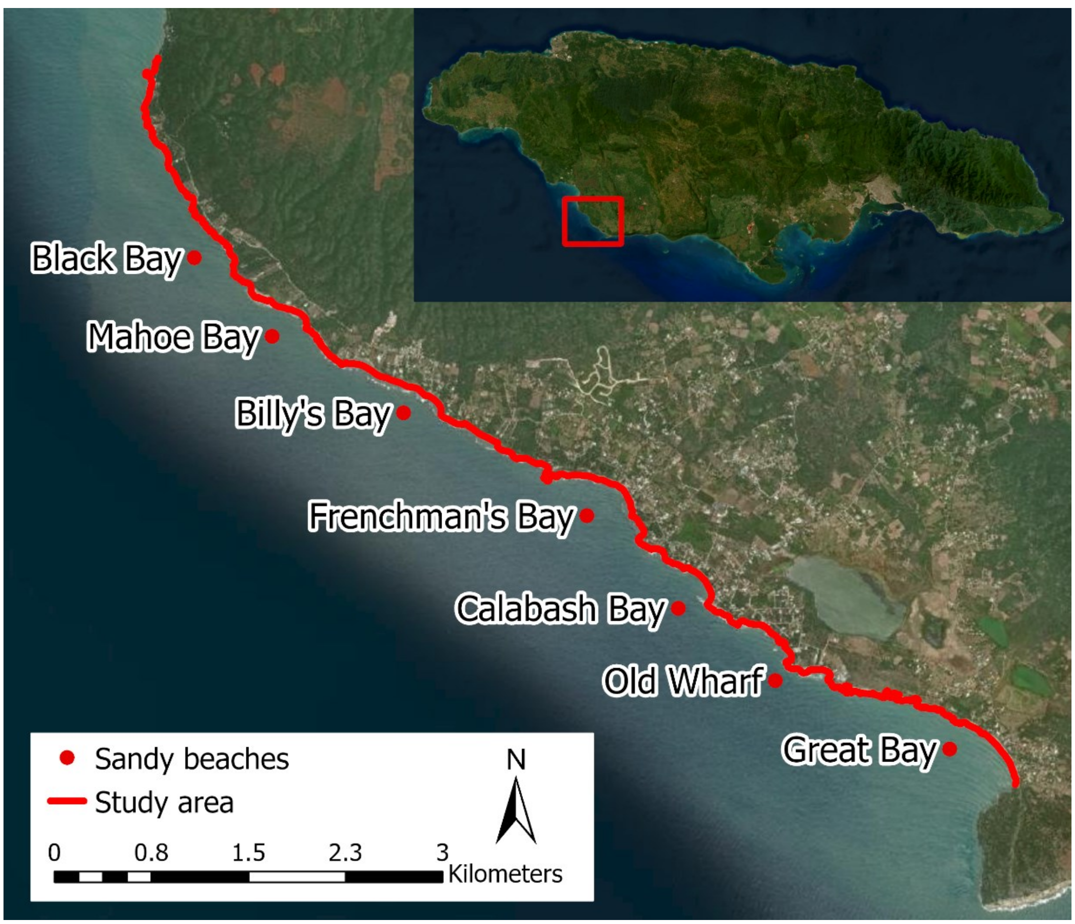

Figure 5. Study area with the seven main sand pocket beaches.

Geology

The coastal geology of Treasure Beach consists of shallow and deep-water limestones often overlain by aeolian or alluvial deposits and the Coastal group often outcropping as beach bluffs from Calabash Bay to Black Bay, as well as a small amount fringing Pedro Bluff (Kenning, 2018; Benford et al., 2012; Brown & Mitchell, 2010) (Figure 6). The deep-water limestones (carbonates) were formed from pelagic algae, planktonic foraminifera, and eroded coral debris from the carbonate platforms and the shallow water limestone formed from skeletal plants and animals (Mitchell, 2016). The sand at Treasure Beach is mainly re-worked from coastal or aeolian sandstones which are not well cemented and therefore very susceptible to erosion during storm events (Environmental Solutions, 2018). Jamaica was uplifted during the last 10-12 million years and still experiences earthquakes annually (Mitchell, et al., 2020). There are at least two faults located at Treasure Beach (Koehler & Brown, 2009). Treasure Beach has fringing reefs which are located < 1 km from the shore (Maxam, et al., 2011).

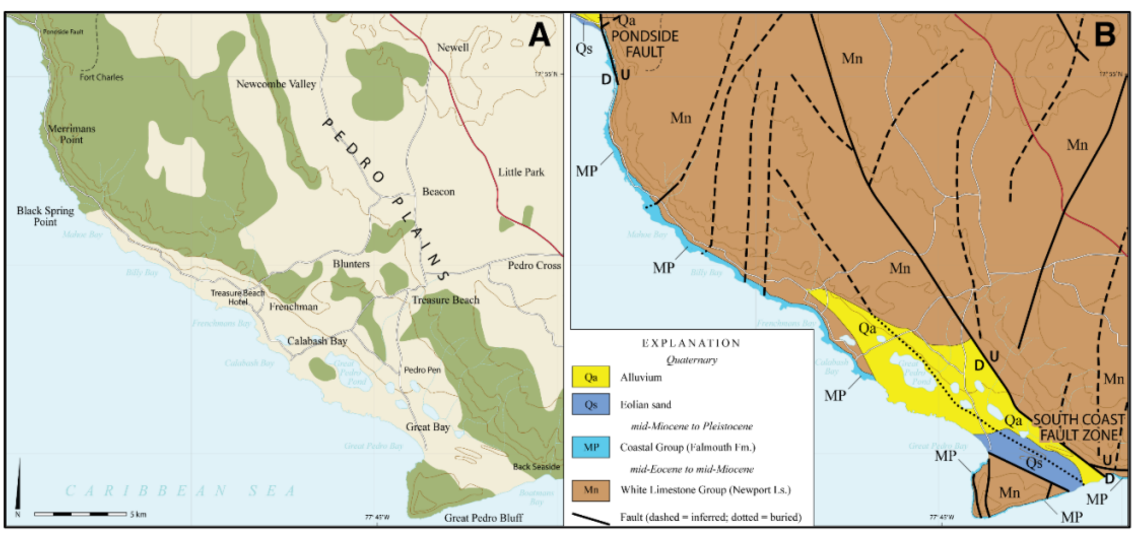

Figure 6. Geographic and geologic map of Treasure Beach, St. Elizabeth Parish. Source: Modified from Benford et al. (2012).

Climate

Jamaica has a tropical climate, therefore Treasure Beach experiences prevailing hot temperatures with an average of 82.5 °F (28.1 °C) per year, and a relatively cool season from December to March (World Climate Guide, n.d.). The rainy season is from late April to October with about 800 mm (31.5 in) rainfall per year, but Treasure Beach experiences two peak precipitation periods in May and October (World Climate Guide, n.d.). January is the windiest month, with an average windspeed of 8.5 mph, followed by March and December. The maximum sustained winds are the highest in January and December, with an average sustained speed of >12 mph for a minimum of 5 days (NOAA, 2023).

Wave and Storm Patterns

Treasure Beach is micro-tidal, with a tidal range from 0.2 to 0.3 m. Winds are typically generated by the northeastern and southeastern trade winds which are locally directed on-shore by rising air over warmer land areas during the day (Centurioni & Niiler, 2003). Hurricanes typically form in the Intertropical Convergence Zone in the eastern, mid-Atlantic Ocean, build power in the Easterlies over warmer seas, bend to the northwest into the Caribbean Sea, and often make landfall on the southeastern and eastern coasts of the United States (Barnhardt, 2009). Storms usually occur annually from June to November or every few years, with storms occurring in different stages and wind speeds when they reach the south coast of Jamaica (World Climate Guide, n.d.) (Table 2). Hurricane Ivan in 2004, Emily in 2005 and Dean in 2007 had Category 4 hurricane status when passing by the south coast. Even though Hurricane Emily had a slightly higher windspeed than Ivan, less coastal destruction was caused by Emily due to the distance of the Hurricane track from Treasure Beach (Figure 7). Storms with tracks further away from the coast are still important to note since the storm surge and waves generated can still cause damage and changes on the coastline.

Table 2. Storm History from central to southern Jamaica from 2001 to 2021. Source: National Oceanic and Atmospheric Administration (2021).

Date	Name	Strom stage closest to Treasure Beach	Location affected in Jamaica	Wind speed closest to Treasure Beach (kt)
2001, Oct 7	Iris	Cat. 1 Hurricane	South coast	75
2002, Sep 18	Isidore	Tropical storm	Southwestern coast	40
2004, Sep 11	Ivan	Cat. 4 Hurricane	South Coast	130
2005, Jul 16	Emily	Cat. 4 Hurricane	South Coast	135
2005, Oct 15	Wilma	Tropical Depression	Southwestern Coast	25
2007, Aug 20	Dean	Cat. 4 Hurricane	South Coast	125
2008, Aug 29	Gustav	Tropical Storm	South Coast	55
2012, Oct 24	Sandy	Cat. 1 Hurricane	South-eastern	75
2020, Sep 1	Nana	Tropical storm	Southern coast	50
2021, Aug 17	Grace	Tropical storm	Central	50

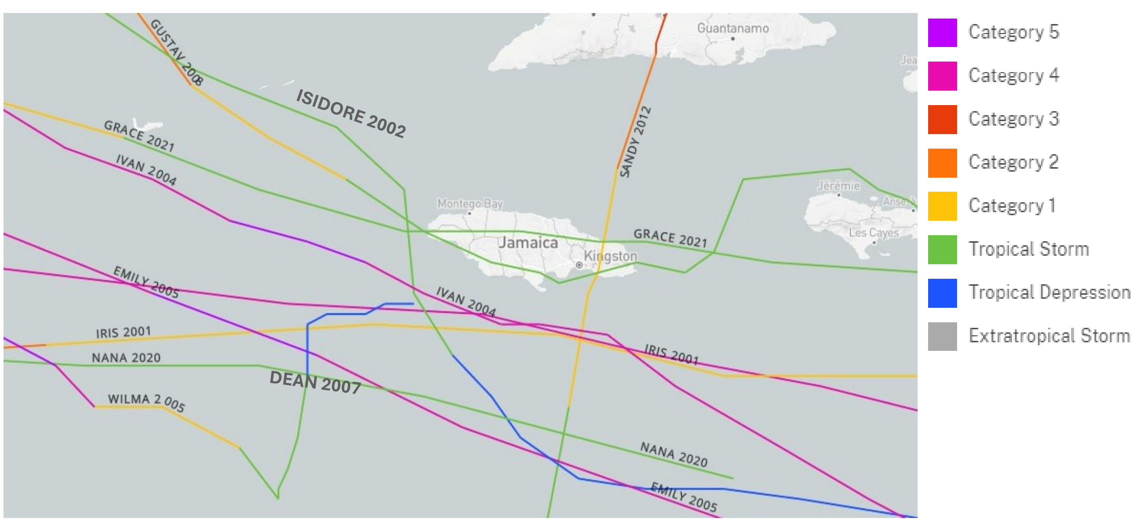

Figure 7. Historical hurricane tracks from 2001 to 2021 in a 100-mile radius from Treasure Beach, Jamaica. Source: National Oceanic and Atmospheric Administration (2021).

Beach Morphology

The sandy pocket beaches (bays) along Treasure Beach in between resistant rock headlands have mostly sandy shores, with the occasional limestone rock outcrop, paleo-coral reef and beach rock exposures, and sand stored on raised shoreline platforms or wave-cut platforms (Climate Studies Group, 2020; Environmental Solutions, 2018). Approximately half of the world's coastlines are headland-bay beaches, with examples of similar beach forms to Treasure Beach in the literature at the South China coast and Santa Catarina, Brazil among others; where several bays are located between rock headlands along a stretch of coastline (Manakul, et al., 2022; Yu & Chen, 2011; Klein, et al., 2003). The transition zone between the backshore and uplands at Treasure Beach is either steep or gradual consisting of (i) limestone or Coastal Group escarpments (vertical walled bluffs); (ii) sandy and vegetated bluffs often composed of medium to high paleo sand dunes; or (iii) infrastructure of coastal properties such as brick or stone walls, wire or wooden fences, and building walls. The local relief of Treasure Beach ranges between a maximum of 2 to 15 m in elevation approximately 100 m inland (Floodmap, 2017). Treasure Beach reaches a depth of 10 meters at an approximate distance of 7 kilometers offshore (Figure 8). Treasure Beach is classified as having low reef protection based on assessments of reef type, reef shape, the distance of the reef from the shore, reef orientation, and percentage of reef in the 0 – 15 m bathymetric zone (MGI, 2011) (Figure 9).

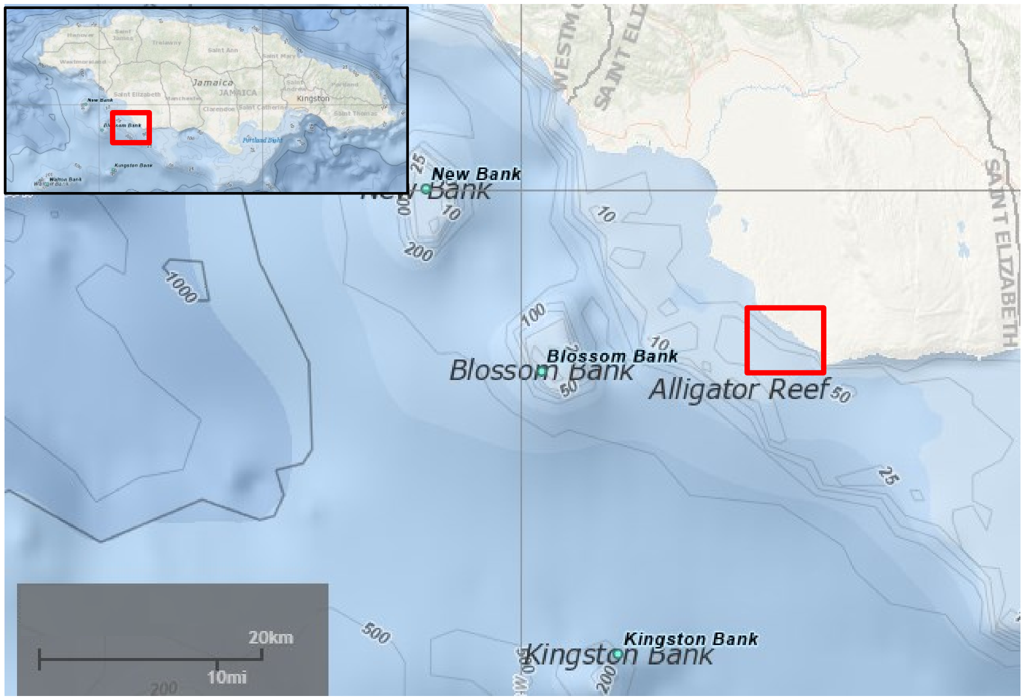

Figure 8. Offshore bathymetry for the southwestern coast of Jamaica, with Treasure Beach indicated with the red box. The isobars connect areas on the seafloor with the same depth in meters. (Modified from the International Hydrographic Organization, 2023)

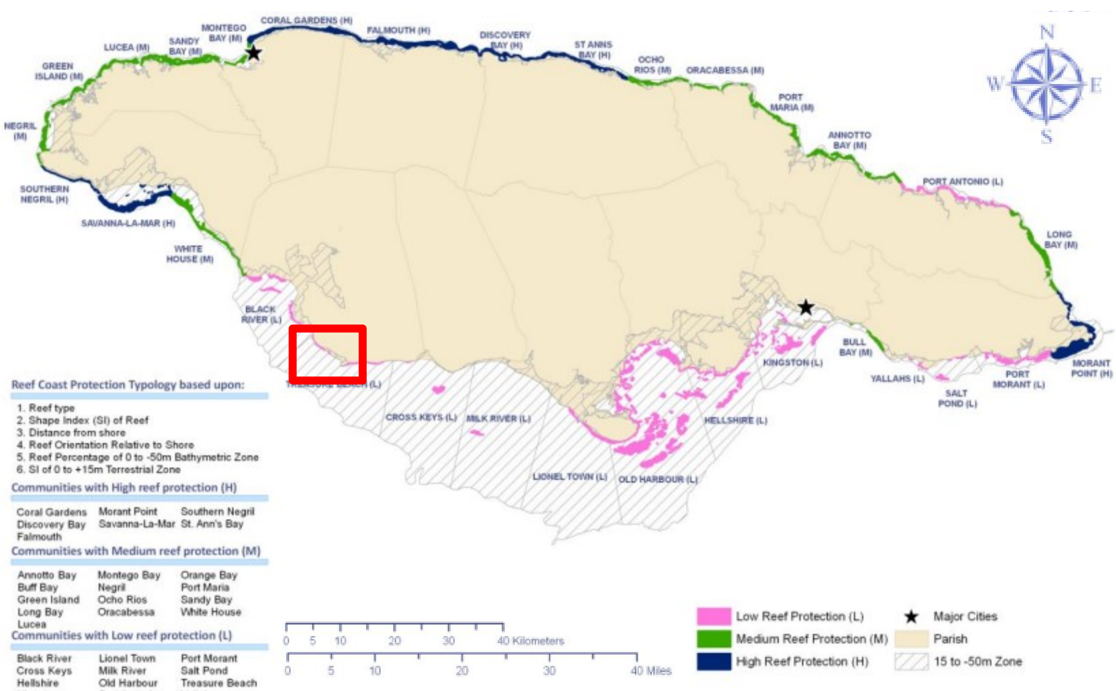

Figure 9. Jamaica shoreline reef protection level based on coral reef type, slope and orientation, distance from shore, and the complexity of the reef shape. Treasure beach is indicated with the red box. Source: MGI (2011).

CHAPTER 3. METHODS

Field and geospatial methods were used to assess beach characteristics and changes in Treasure Beach. The methods were set up to best represent these features and to enable comparison between field and geospatial analysis. Data collected were analyzed using Geographical Information System tools and Microsoft Excel calculations.

Field Methods

Fieldwork including field observations, beach surveys and informal interviews with residents was conducted along Treasure Beach during January 7-13, 2022 and March 9-11, 2023 (Figure 10). All transects were visually assessed for sand deposition and rock area. In addition, beach surveys were completed at transects classified as being sandy (see classification results in next chapter) including the berm height from the water surface to the crest using a hand level and beach face angle using a digital level (Figure 11) and berm height (Figure 12). The back beach line was field checked with GPS points and beach width measurements were taken from the waterline to the back beach line along each transect. A visual classification of the back beach was done at each transect and the presence of anthropogenic structures like seawalls, fences, buildings, clearing of vegetation on dunes and the back beach were recorded, as well as where fishing beaches and boat moorings were located. A visual beach classification was done per transect by distinguishing between sand and rock beaches, as well as where there was both sand and rock present and sand on rock. Where both sand and rock were present the percentage of each occurring at a transect was noted. The presence of berms, dunes and aeolian sand sheets were noted too, as well as the vegetation present on the back beach including grass/forbs, woody shrubs, and trees.

Figure 10. Example of beach lines used in beach change analysis.

Figure 11. Measuring beach slope angles on the foreshore.

Figure 12. Measuring berm heights with an auto-level.

Satellite Imagery

Seven different years of satellite images were used to digitize the location of water lines and back beach border to measure beach widths and erosion/deposition rates (Table 3 and Appendix A). The satellite images were previously rectified/georeferenced by the data supplier.

The IKONOS satellite was launched September 24, 1999 and collected its last images on December 20, 2014. IKONOS had an orbit altitude of 681 km at a speed of 7.5 km/second. The IKONOS satellite has a resolution of 0.8 m/pixel and was the first high resolution satellite launched in 1999. Quickbird satellite was launched October 18, 2001, collected its last images on December 17, 2014 and had orbit altitude of 482 km until mid-2011, with a gradual descent to 450 km onwards. At a speed of 7.1 km/second, Quickbird had a resolution of 0.60 m/pixel. The WorldView-2 satellite was launched on October 8, 2009. The orbit time is 100.2 minutes at an altitude of 770 m. This produces images with a resolution as detailed as 0.4 km/pixel (Apollo Mapping, n.d.). The GeoEye-1 satellite was launched September 6, 2008. At an altitude of 681 km and speed of 7.5 km/s, it produces high resolution imagery of 0.4 km/pixel. Pleiades-1 satellite was launched December 17, 2011. Pleiades-1 has an orbit altitude of 695 km and a resolution of 0.5 m/pixel. Detecting coastline changes is just one of its applications, due to its high resolution, high temporal resolution and multiple acquisitions (GISGeography, 2022). In addition to imagery (Table 3), 2023 beach lines were collected using a portable Bad Elf/I-PAD system.

Table 3. Imagery Database. Source: Satellite Imaging Corporation (2022).

Image Source	Image Band	Acquisition Date	Spatial Resolution	Radiometric Resolution	AOI Size (Km^2)	Point-to-point Error (m)
IKONOS	Panchromatic	02/18/2001	0.8 m	11-bits	25	1.06
QuickBird	Panchromatic	04/19/2003	0.6 m	16-bits	49	1.04
QuickBird	Panchromatic	06/22/2005	0.6 m	16-bits	25	0.81
WorldView-2	Panchromatic	04/20/2010	0.5 m	11-bits	49	0.98
WorldView-2	Multispectral	06/13/2014	2.0 m	11-bits	49	1.51
GeoEye-1	Panchromatic	08/14/2019	0.5 m	11-bits	25	2.41
Pleiades-1	Panchromatic	03/30/2021	0.5 m	12-bits	49	Reference map

Geospatial Analysis and Geomorphic Classification

To determine beach changes and rates of change between time periods on satellite images, it is necessary to have a baseline which stays constant between the images, an accurately identified boundary between the beach and water level, as well as between the beach and the back beach vegetation. Two stages are important when identifying a shoreline. Firstly, it is the selection and definition of a shoreline indicator feature, and secondly, it is the detection of the chosen shoreline feature within the available data source (Boak & Turner, 2005). Shoreline indicators are an important and useful tool when analyzing beaches all around the world. Boak and Turner (2005) mention many shoreline indicators and features used to identify where the water meets the coast. These indicators can help identify where the shoreline is when using manual techniques, supervised digital image analysis and digital image analysis. The indicators that were used in this study to discriminate between sand and water include a bank line/crest of a slope, the seaward edge of dune vegetation, and dune line, a beach crest, instantaneous high waterline, shoreline, wet/dry line, wet line, waterline and beach toe. These indictors helped to discriminate between tides and where the vegetation and dunes meet the shoreline. The wet and dry line was the indicator used the most, since differentiation between where the waterline is, regardless of wave action, was possible.

ArcGIS was used to analyze satellite images and to digitize waterlines, a fixed back beach line and offshore beach protection structures. Nearshore landforms such as reefs were identified to determine areas where beaches are protected against erosion during storm events. Changes in waterlines and beach widths were measured on satellite images at transects spaced perpendicular to the shoreline of 2021 at 50 m intervals against a fixed back beach line along sandy beaches in Treasure Beach (Martinez, et al., 2021) (Appendix B). The layout of transects was done before fieldwork was conducted and was used in the field to locate each transect with GPS for the beach surveys. The waterline is the indication of where the ocean meets the sand. Beach widths were therefore measured between the waterline and back beach line. Net Shoreline Movement (NSM) were measured for three periods: 2001 to 2005 (Hurricane Ivan), 2005 to 2015 (post Ivan period), and 2015 to 2021 or 2023 (recovery period) to show the spatial-temporal distribution of shoreline changes at Treasure Beach (Biondo, et al., 2020). A negative

NSM indicates erosion (shoreline retreat/retrogradation) and positive NSM values indicate areas of deposition (accretion/progradation).

Beach Widths and Rates of Change. The 2022 back beach locations were used as the baseline reference for all the beach lines digitized from imagery and collected by GPS. To check beach width measurements along transects by digitizing or GPS, beach widths were measured in the field along each transect from the waterline to the back beach line in 2022. However, as expected, good agreement was found between the two methods, so all beach widths were assessed using geospatial techniques.

To better understand longshore drift and offshore protection influence on individual bay beach form, each of the seven pocket beaches were divided into three sections: the updrift, middle and downdrift section (Figure 13). By doing this, sections of each pocket beach can be identified where erosion or deposition is dominant. A study by Silva, et al. (2024) characterized different sections of an embayment beach by using a model of magnitude and direction of wave incidence along an embayment. The model does not account for spatio-temporal variability and bathymetric irregularities, therefore more research was needed to enhance the classification.

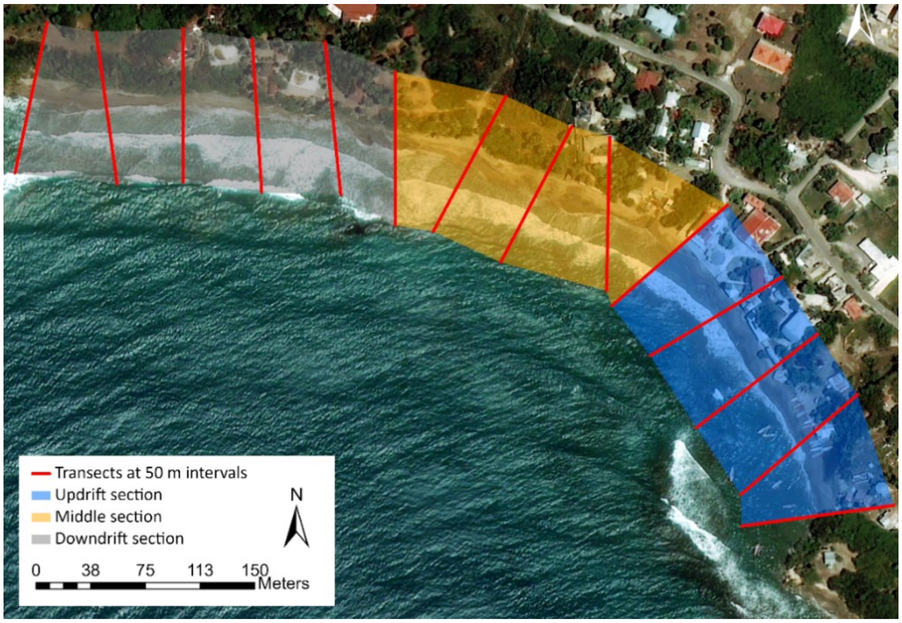

Figure 13. Example of the updrift, middle and downdrift section of each pocket beach.

These methods are beyond the scope of this study, therefore drift sections on each pocket beach were systematically divided into a third of the length of the sand beach (Silva, et al., 2024). The average beach widths were calculated by dividing the area of the sand beach, for each pocket beach, by the length of the beach for each year with a satellite image. The average beach width change between satellite images was then calculated per bay to determine beach width changes over a few years.

Area of Change. The area of sandy beach lost or gained were calculated by creating polygons that cover the sandy areas of the pocket beaches. The polygon boundaries were created with the connected fixed back beach line and waterline per year. These polygons were compared between consecutive years as well as before and after Hurricane Ivan to the yield net sandy beach area loss or gain, and to determine total sandy beach area for all of the years with available satellite images. The waterline location for 2023 was collected with GPS points in the field and used to create the sandy beach area polygons for 2023.

Beach Characteristics. The bay length, in contrast to beach length, was measured by drawing a line between primary headlands for each pocket beach, and the maximum bay width was measured perpendicular to the bay length line and to the back beach line of each pocket beach. Nearshore protection structures were digitized by comparing satellite images on wind-still days to see the outline of the coral reef or rock outcrops, as well as on windy days, where wave splashes against the coral reefs or rocky outcrops were considered as the approximal boundary of where these structures are located. To determine the number of houses per beach and how many new beach developments there were over the 20-year period, a 50-m buffer was created from the back beach line to the coastal residential areas and the number of houses present per beach was identified for both 2001 and 2021.

Error Calculation. An approximate point-to-point error was determined for the pre-rectified satellite images by using distance differences between ten control points, as well as approximate tidal ranges for the southern coast of Jamaica (Appendix A). The 2021 satellite image was used as the base image against which the point-to-point error was calculated for the rest of the years of satellite images. Based on equation 1, the range of point-to-point errors between the seven satellite images is 0.81 to 2.41 m, with an average of 1.30 m (Table 3).

$$\text{Point-to-point error} = [(xb-xi)^2+(yb-yi)^2]^{1/2} \quad (1)$$

Daily fluctuations in waterline elevations assuming a maximum tidal range of 0.2-0.3 m ranged from 1.7-2.7 m in horizontal distance based on beach slope measurements. Both photograph errors and maximum tide line errors were similar indicating that beach width errors were typically 1-2 m and usually <3 m.

CHAPTER 4. RESULTS AND DISCUSSION

This study shows that sandy beaches along Treasure Beach have been subjected to periods of both net erosion and accretion since 2001. The highest erosion rates occurred during the period from 2003 to 2005 when Hurricane Ivan passed just south of Jamaica as a category 4 hurricane in September 2004. Overall, between 2001 and 2021, 91% of sandy beach transects indicated net erosion, 3% showed no change, and only 6% of the transects indicated accretion. Besides storm event erosion, there has been a systematic loss of beach area along Treasure Beach. The results of the study are presented in six sections: (i) beach classification and characteristics of Treasure Beach, (ii) human influences, (iii) beach area changes over time especially with the effect of Hurricane Ivan, (iv) average beach widths for each pocket beach over time, (v) rates of change and (vi) implications for Treasure Beach.

Beach Characteristics

Treasure Beach is a faulted coastline with sandy pocket beaches formed between headlands consisting mainly of the White Limestone Group (mid-Eocene to mid-Miocene) and Coastal Group consisting of calcareous sandstones and coral deposits (late Pleistocene) (Kenning, 2018). In general, Jamaica has been tectonically active since it was uplifted above sea level from 10 to 12 million years ago (Mitchell, et al., 2020). The study area is located between two large fault systems running along the coast with the Pondside fault to the west and the South Coast Fault Zone to the east. There are potentially active faults located at Treasure Beach including two major faults at Great Bay, one at Old Wharf, and several secondary faults running obliquely to the shoreline from Old Wharf to the west (Koehler & Brown, 2009). Raised wave-cut platforms occur frequently along the shoreline indicating tectonic uplift in the past (Kenning, 2018). Moreover, about three-fifths of the total shoreline length is structurally composed of Coastal group or raised reef rocks with no significant sandy beach deposits.

Beach classification indicated that the shoreline along Treasure Beach is composed of both sand and rock components. Out of the 225 total transects located within the Treasure Beach study area, 32% were sandy beaches, 8% were composed of mixed sand and rock, 53% were only rock, 4% were locations where sand deposits overlay rock, and 3% were located at the base of rock bluffs (Figures 14 to 18). The seven bays vary in length between a larger bay such as Great Bay (1,430 m) and a smaller bay such as Black Bay (472 m) (Table 4). Small sandy coves are present along western Great Bay (2) and Old Wharf (1), which individually do not exceed 50 m in length and were included in this study. This study focuses on the analysis of the shoreline transects classified as "sand" or "mixed sand and rock" beaches representing 40% of all the transects evaluated by this study.

The average beach angle for the sandy beaches were 7.7º with Black Bay having the steepest beach faces at 10.1º and Calabash Bay and Great Bay the lowest with 6.1º and 6.7º, respectively (Table 4). Calabash Bay had the highest average berm height above the base of the swash zone of 0.81 m and Old Wharf had the lowest average berm height of 0.40 m (Table 4).

Rock protection for Treasure Beach is classified as nearshore protection, since the rock outcrops and coral reefs are all located between the landward limit of storm-wave influence and the seaward depths where shoaling begins (Inman, 2002). The presence of visible nearshore beach protection per transect per beach varies throughout Treasure Beach (Table 4). Out of the 225 transects, only 76 transects (34%) had visible nearshore beach protection and 149 transects (66%) did not have any. For Great Bay, only 2% of the transects had visible nearshore beach protection, Old Wharf had 54%, Calabash Bay had 53%, Frenchman's Bay had 29%, Billy's Bay had 47%, Mahoe Bay had 86% and Black Bay had 13%. However, Great Bay is protected at larger scale by Great Pedro Bluff which blocks the direct approach of Easterly driven waves.

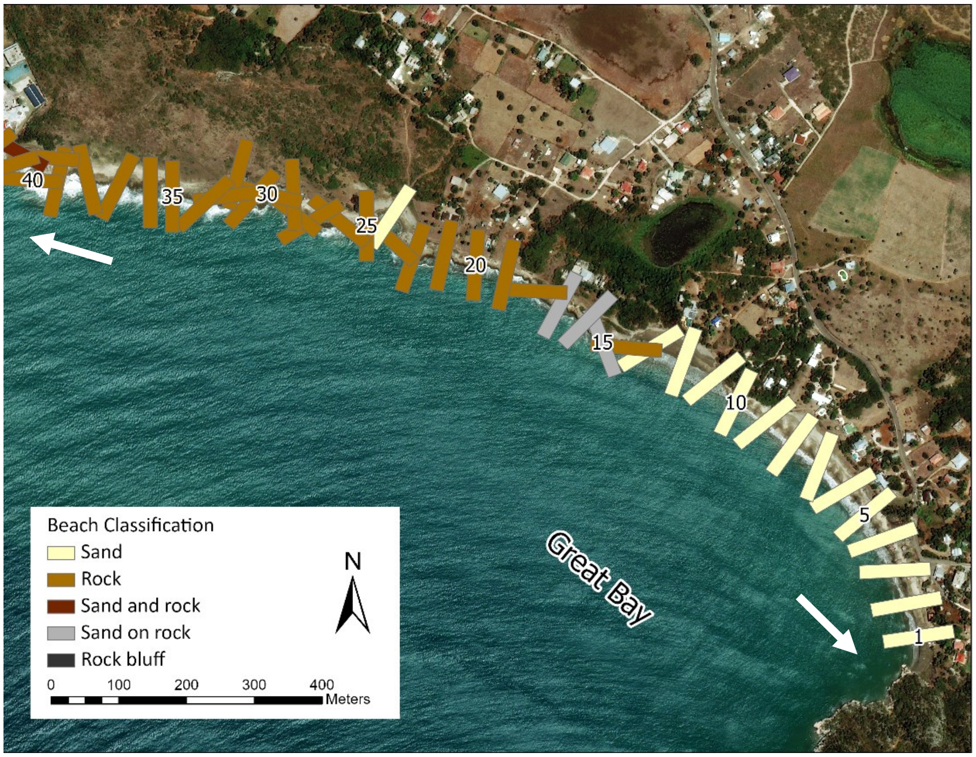

Figure 14. Beach classification at Great Bay, with Old Wharf to the northwest.

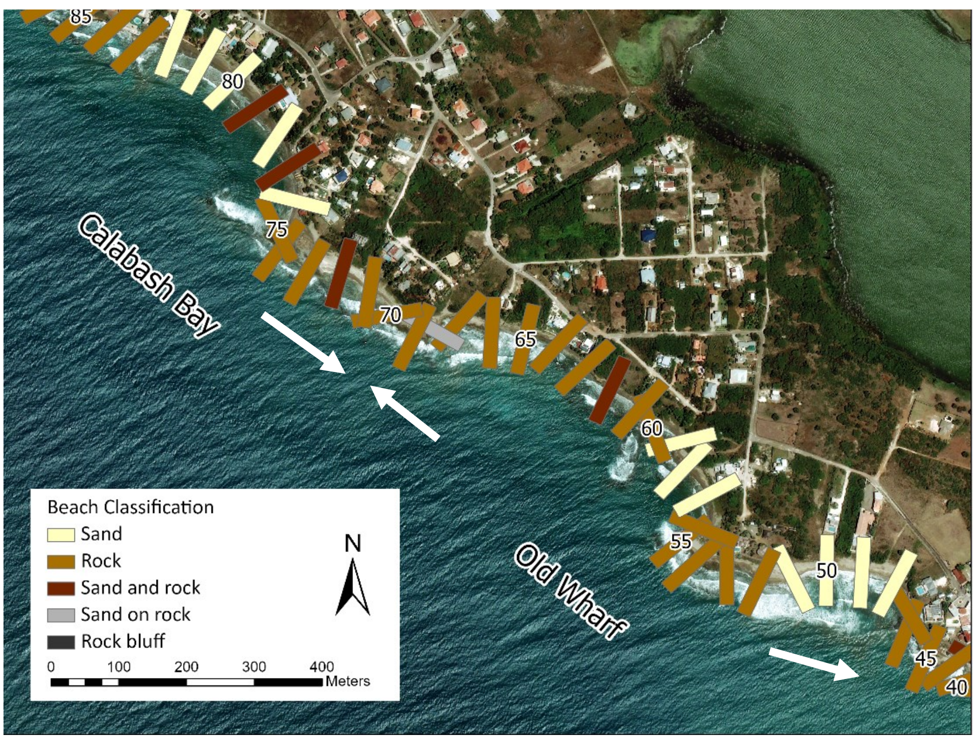

Figure 15. Beach Classification of Old Wharf and Calabash Bay, with Great Bay to the southeast and Frenchman's Bay to the northwest.

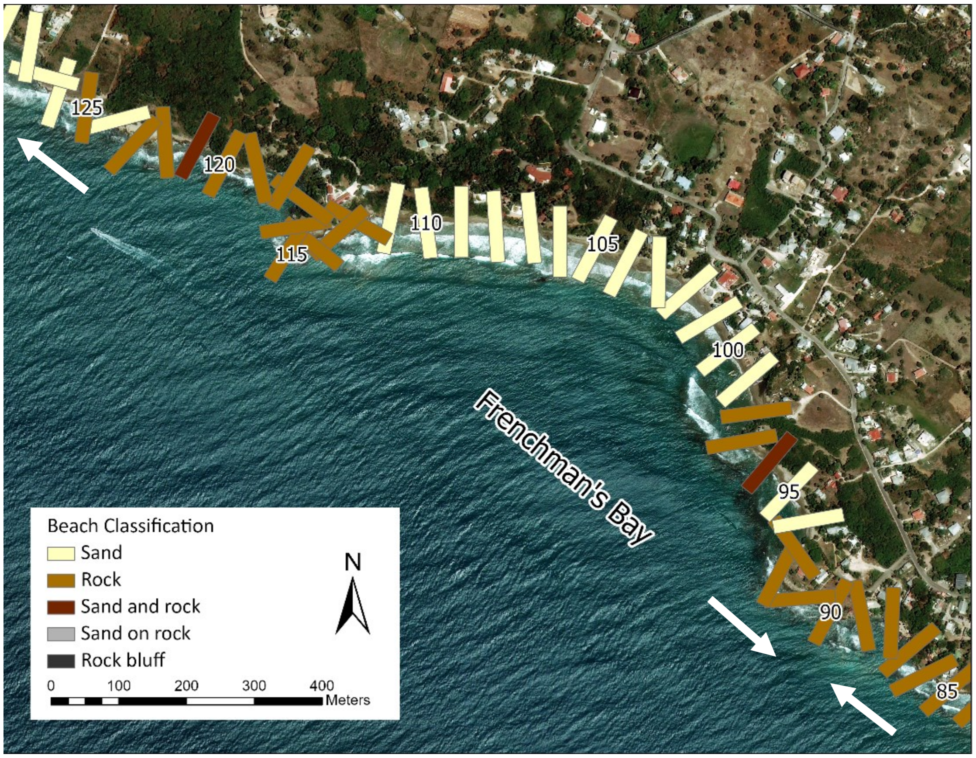

Figure 16. Beach Classification of Frenchman's Bay, with Calabash Bay to the southeast and Billy’s Bay to the northwest.

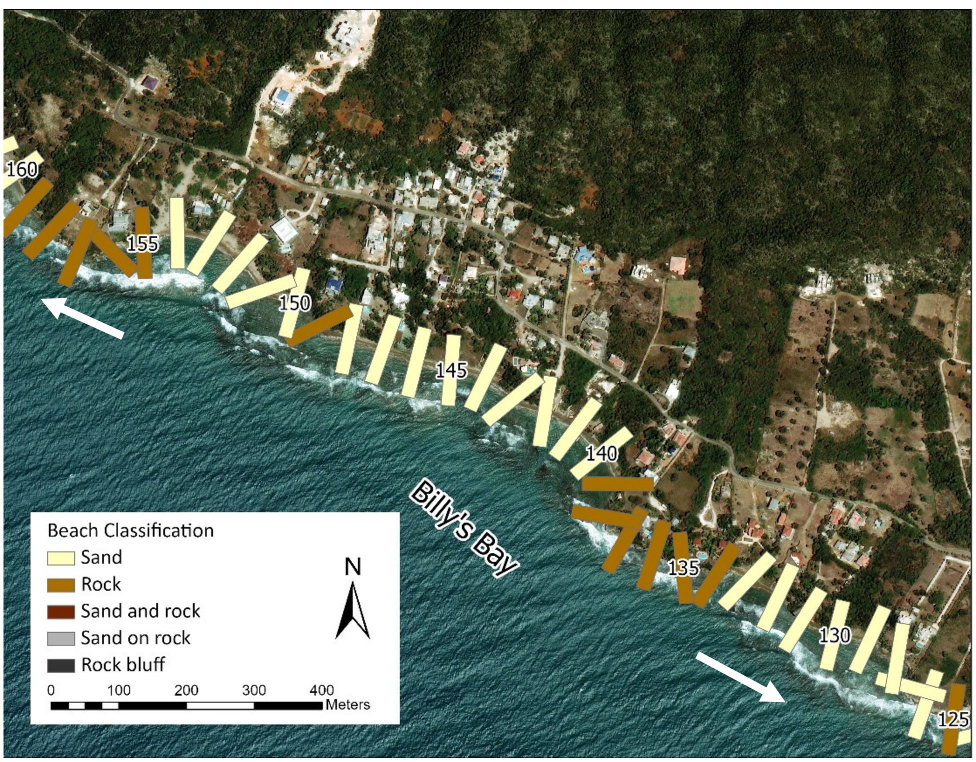

Figure 17. Beach Classification of Billy's Bay, with Frenchman's Bay to the southeast and Mahoe Bay to the northwest.

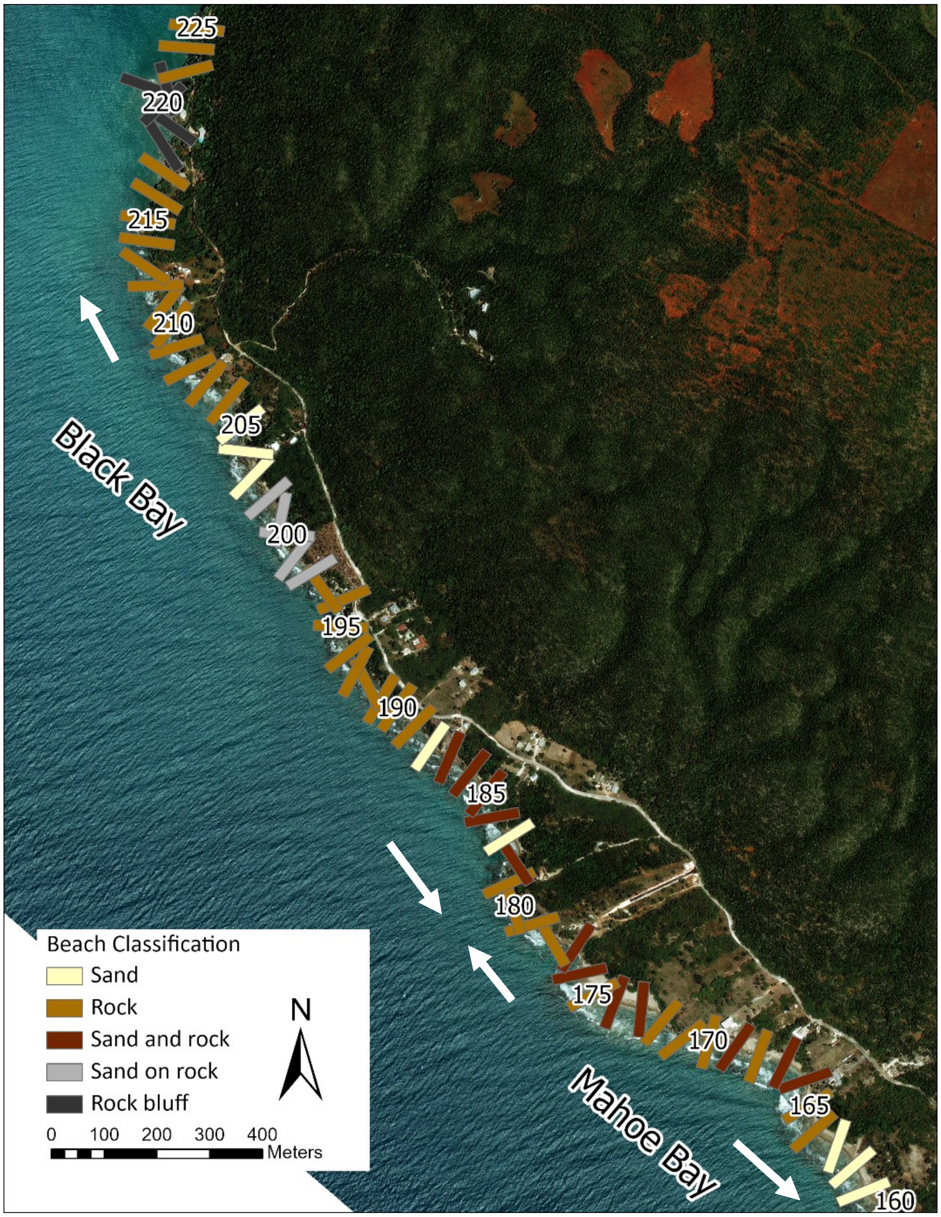

Figure 18. Beach classification of Black Bay and Mahoe Bay, with Billy's Bay to the southeast.

Table 4. Beach morphology for each of the sandy beaches based on 2021 satellite images and 2021 field data.

	Black Bay	Mahoe Bay	Billy's Bay	French-man's Bay	Calabash Bay	Old Wharf	Great Bay
Total bay length (m)	1,600	1,050	1,450	1,850	900	1,150	2,350
Bay length (m)	472	599	1,325	805	597	867	1,430
Max bay width (m)	61	101	119	271	125	128	454
Secondary headlands	2	1	1	2	2	1	2
Beach aspect (°) (Direction)	243 (WSW)	229 (SW)	204 (SSW)	218 (SW)	226 (SW)	222 (SW)	218 (SW)
Sandy beach length (m)	300	900	900	850	500	500	650
Sandy beach length out of total bay length (%)	19	86	62	46	56	43	28
Average beach width (m)[1] (CV%)	8.3 (91.2%)	19.2 (58.6%)	10.5 (66.1%)	11.6 (42.9%)	19.0 (82.5)	16.1 (61.0%)	27.3 (48.2%)
Average berm height (m) (CV%)	1.0 (27.6%)	0.8 (27.0%)	1.0 (9.1%)	1.0 (21.7%)	0.9 (18.3%)	1.00 (16.3%)	1.00 (13.6%)
Beachface angles (°) (CV%)	10.1 (13.7%)	7.9 (35.5%)	7.5 (14.2%)	7.9 (32.2%)	6.1 (43.3%)	7.8 (20.4%)	6.7 (31.3%)
Dunes on sand/sand and rock beaches (%)	30	55	37	10	0	50	7
Rock/reef protection (Nearshore) (%)	13	86	47	29	53	54	2

[1] Sandy beach area/sandy beach length

Human Influences

Human impacts on the sandy beaches in Treasure Beach range from properties built on the beach, to vegetation removal, and even erosion prevention structures (Table 5). There are many fences and walls built along the back beaches of the pocket beaches. In Great Bay, 36% of the transects had a low wall, fence, sea wall, or building along the back beach boundary. At Old Warf, 38% of the transects intersected a man-made structure, Calabash Bay had 42%, Frenchman's Bay had 32%, Billy's Bay had 33%, Mahoe Bay had 27% and Black Bay had 7% (Appendix C and D). These structures may prevent the beach from migrating landward with a rising sea level and also increase the erosional effects and property damage by storm events (Bacopoulus & Clark, 2021; Silva, et al., 2020). Rock groins along the berm and swash zone at Mahoe Bay and rip-rap along the back beach at Billy's Bay are two examples of erosional mitigation efforts implemented by the community (Appendix C-4). There was a large section of vegetation removed from the back beach at Billy's Bay which might lead to more erosion in the future since vegetation can anchor sand deposits and help stabilize dunes (Sigren, et al., 2014; Olafson, 1997). In addition, artificial runoff channels that direct erosive storm water from neighborhoods onto the beach at Billy's Bay may increase local beach erosion rates or provide a source of water or sediment pollution.

Table 5. Human interactions and influence on the sandy areas of each beach.

	Black Bay	Mahoe Bay	Billy's Bay	French-man's Bay	Cala-bash Bay	Old Wharf	Great Bay
Buildings 50 m from backbeach line (2021)	1	4	18	16	15	7	24
Buildings 50 m from backbeach line (2001)	0	0	7	14	12	0	11

Table 5- Continued. Human interactions and influence on the sandy areas of each beach.

	Black Bay	Mahoe Bay	Billy’s Bay	French-man’s Bay	Cala-bash Bay	Old Wharf	Great Bay
Fish beach or harbor (% of length)	0.0	0.0	0.0	12.5	6.3	0.0	12.5
Wood fences (% of transects)	0.0	0.0	7.1	6.3	18.2	10.0	12.5
Concrete or stone wall (% of transects)	0.0	8.3	7.1	18.8	36.4	0.0	25.0

Beach Area Change (Area Polygon Analysis)

The total sandy beach area within the entire Treasure Beach study area was reduced by about one-third by Hurricane Ivan in 2004 (Figure 19). Some bays lost more than half of their beach area during the period from 2003 to 2005 with beach loss decreasing in the following order: Black Bay, 58%; Old Wharf, 49%; Billy’s Bay, 47%; Frenchman’s Bay, 43%; Mahoe Bay, 39%; Calabash Bay, 33%; and Great Bay, 10% (Figure 19; Appendix E). Beach area changes appear to have been relatively stable since then with fluctuations +/- 20% from 2005 to 2023 (Figure 19 and 20). During the post-Ivan period from 2005 to 2023, five of the bays maintained their beach areas and were relatively stable with beach area generally fluctuating by +/- 20% from year to year until 2023 (Figure 20). However, two bays showed different trends. Billy’s Bay lost 41% more beach area from 2005 to 2014 (68% loss compared to 2003) and then appeared to stabilize from 2014 to 2023 (Figure 20). Conversely, while losing only 10% of its beach area during Ivan, Great Bay gained 68% more beach area from 2005 to 2014 (an increase of 51% compared to the pre-Ivan period or 2003) (Figure 20). However, between 2014 and 2019, Great Bay lost 29% of its beach area and then stabilized yielding a net gain of 10% from 2003 to 2023 (Figure 20). The beach area for Calabash Bay included some rock areas since it occurred between two larger sandy beaches. The rock area was about 37% of the total beach area in 2003, but since rock areas were excluded during average beach width calculations, the average sandy beach withs at Calabash Bay were not affected by the rock areas.

Beach area changes did not occur similarly for a given year of observation at all bays. However, as noted above, similar trends over time were noted overall for the response in beach area to Hurricane Ivan and during the recovery period for five or possibly six of the bays (Figure 19). The specific processes and mechanisms responsible for beach area differences among beaches is beyond the scope of this study. However, longshore sediment transport and budget factors and variations in storm wave approach and energy dissipation can influence beach erosion in the Caribbean (Inman & Jenkins, 2003; Jena, et al., 2001). Great Bay is the only beach with a higher sandy beach area in 2023 than 2001. For example, direct wave approach into Great Bay is limited greatly by Great Pedro Bluff. Further, Billy's Bay is located furthest from Great Pedro Bluff and just updrift from more rocky beaches influenced by apparent higher rates of longshore transport.

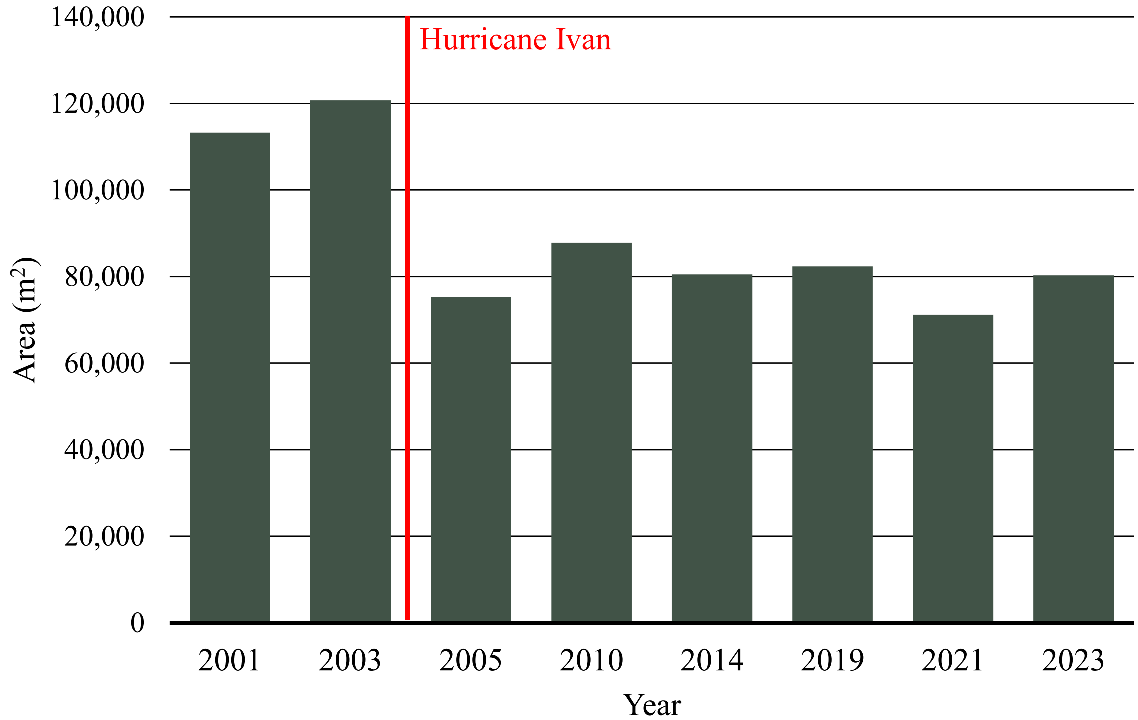

Figure 19. Total sandy beach area for all sandy pocket beaches from 2001 to 2023.

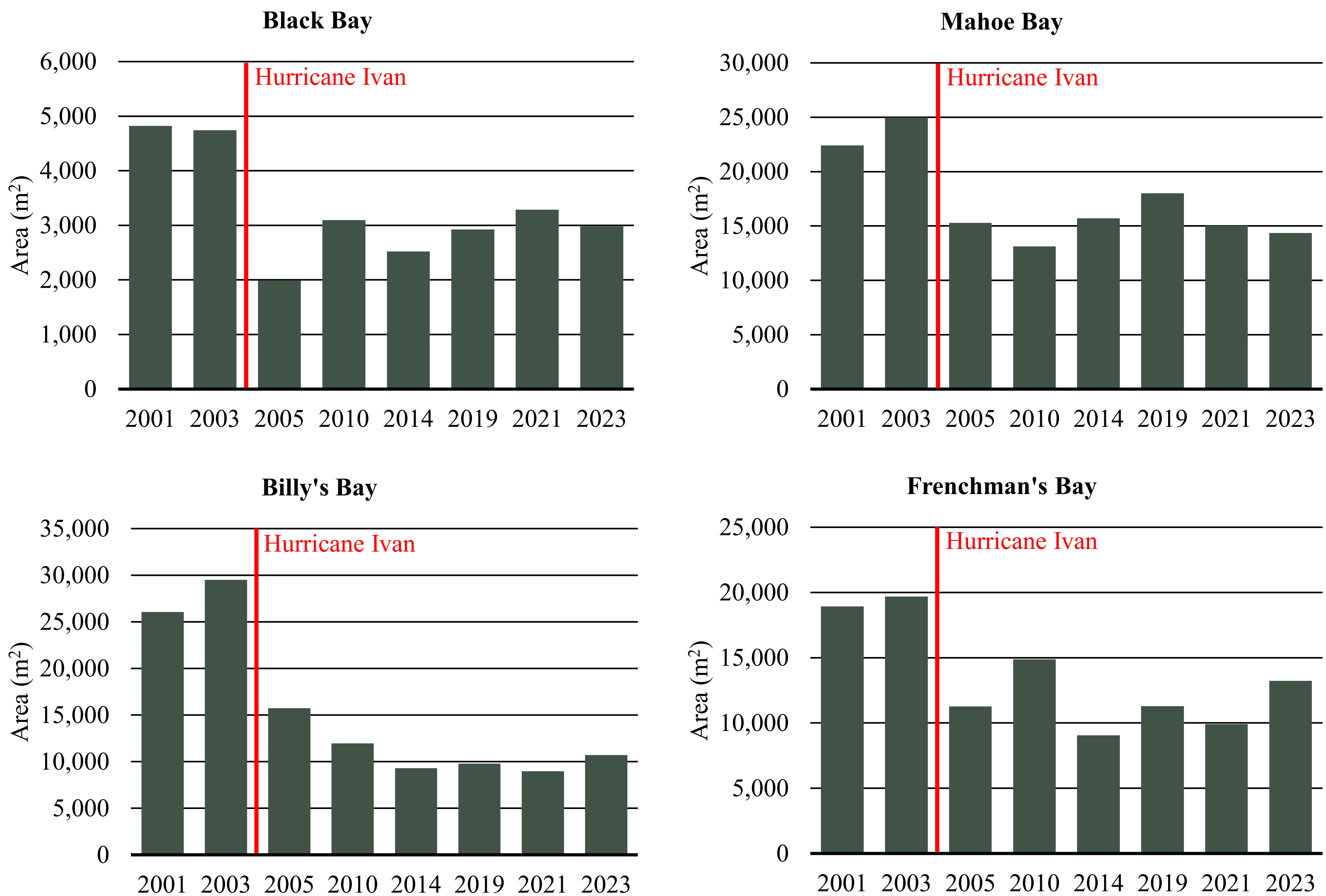

Figure 20. Total sandy beach area for all sandy pocket beaches from 2001 to 2023.

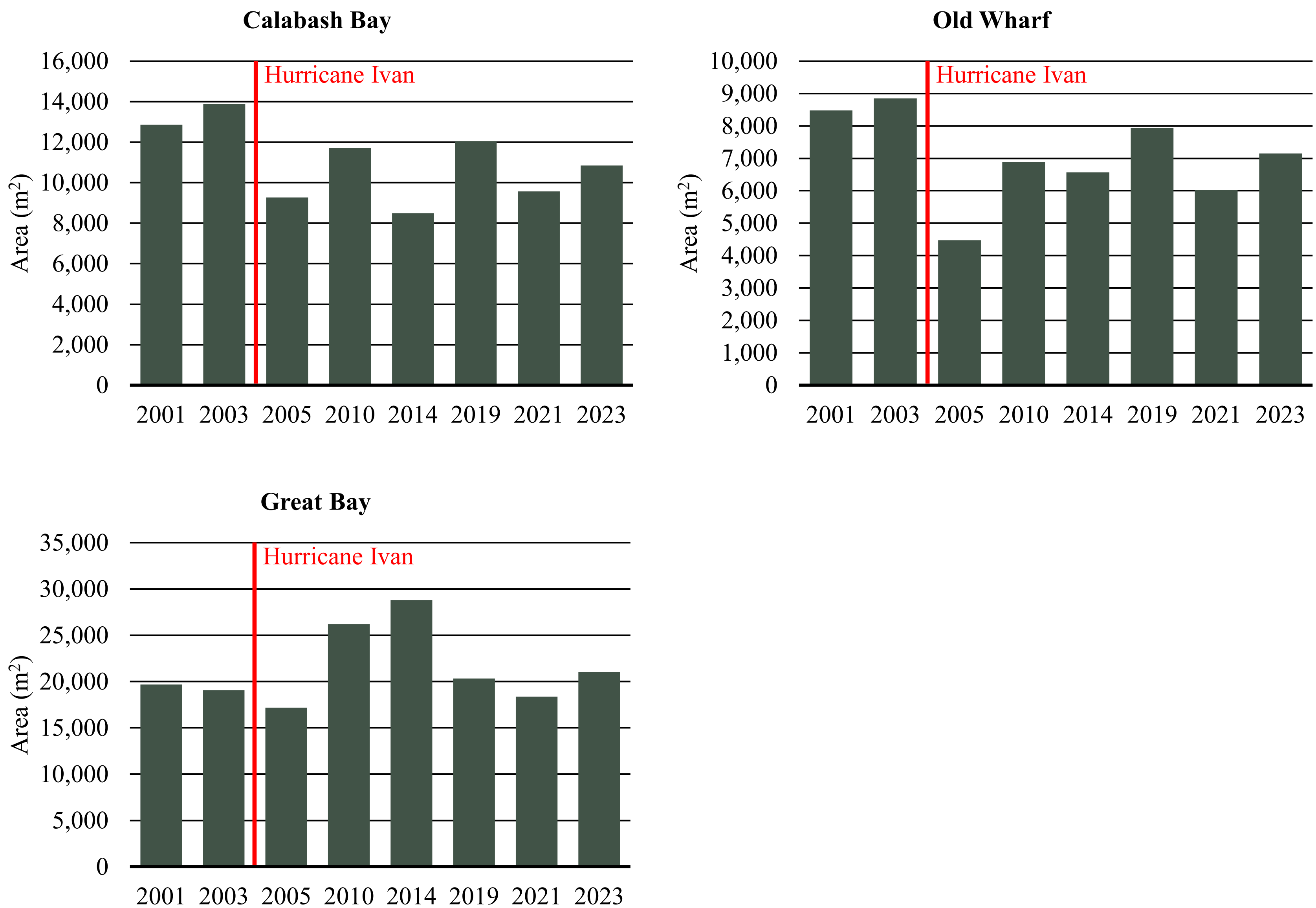

Figure 20. Continued.

Changes in Beach Width

Beach width is more easily observed by residents compared to area and better reflects the magnitude of beach changes since beach length is removed from consideration. While the trends in beach width are generally like those for beach area as described previously, beach width changes tend to magnify the relative trends in beach area. From east to west following the primary longshore drift direction, average beach widths for each bay prior to Hurricane Ivan and the minimum width after Ivan were as follows: Great Bay, 15 m & 14 m; Old Wharf, 10 m & 5 m; Calabash Bay, 13 m & 9 m; Frenchman's Bay, 10 m & 3 m; Billy's Bay, 16 m & 2 m; Mahoe Bay, 15 m to 6 m; and Black Bay, 9 m & 2 m (Figure 21). More than two-thirds of average beach width was lost at Frenchman's Bay, Billys Bay, and Black Bay. In contrast, less than one-third of the average beach width was lost at Great Bay and Calabash Bay during Ivan. Average beach width in 2023 as a percentage of the pre-Ivan Average beach width varies among bays as follows: Great Bay, 140%; Old Wharf, 80%; Calabash Bay, 85%; Frenchman's Bay, 70%; Billy's Bay, 31%; Mahoe Bay, 67%; and Black Bay, 67% (Figure 21; Appendix F).

As an example, the comparison of satellite images of Billy's Bay for 2001, 2005 and 2021 shows major sandy beach area loss after Hurricane Ivan and no recovery of the sandy beach area or waterline location to pre-Ivan conditions (Figure 22). The sandy beach area polygons represent the transgression between the water line of 2001 and the water line of 2005 after Hurricane Ivan, and an area of 10,314 m^2 sandy beach loss. In 2001, vegetation and sand are present in the mapped beach area, but in 2005 the area was completely eroded away in 2005. There has been almost no recovery to pre-Ivan conditions by 2021 with beach properties intersecting the watering in some places. The comparison of the satellite images before hurricane Ivan (2001), after hurricane Ivan (2005), and in 2021 shows that the most damage (erosion) to the beach occurred behind a gap in nearshore rock protection where the beach is open to direct wave attack, leaving the sandy beach vulnerable to approaching waves (Mulcahy, et al., 2016). In general, the highest erosion rates and most variable sand areas occurred along unprotected sandy beaches at Billy's Bay.

High rates of beach erosion due to Hurricane Ivan were also observed at Long Bay Beach at Negril in Jamaica, the Coastline of Bonaire in the Netherlands Antilles, the Northwestern Florida Barrier-Island Coast, and the Gulf Shores from Alabama to Pensacola Beach, Florida (Browder, 2012; McKenzie, 2012; Scheffers & Scheffers, 2006; Wang, et al., 2006). Further, field observations indicated evidence of beach erosion by waves, swash, or over-wash. Exposed foundations of back beach walls at Calabash Bay (Figure 23) and an old well with exposed walls at Billy's Bay (Figure 24) are just two examples of sand loss on the sandy, pocket beaches at Treasure Beach. Assuming a future rate of beach width loss like the past 20 years, the average erosion rates reported by this study would suggest that critical beach loss to the point of average zero width would range from less than two decades for Billys Bay, 40 to 80 years for Old Wharf, Frenchman's Bay, Mahoe Bay, and Black Bay, and greater than a century for Great Bay and Calabash Bay. While these are only estimates based on general assumptions, the rates of sea level rise and frequency of storms are projected to increase in the region over the next several decades thus increasing the risk for higher beach erosion rates (Losada, et al., 2013).

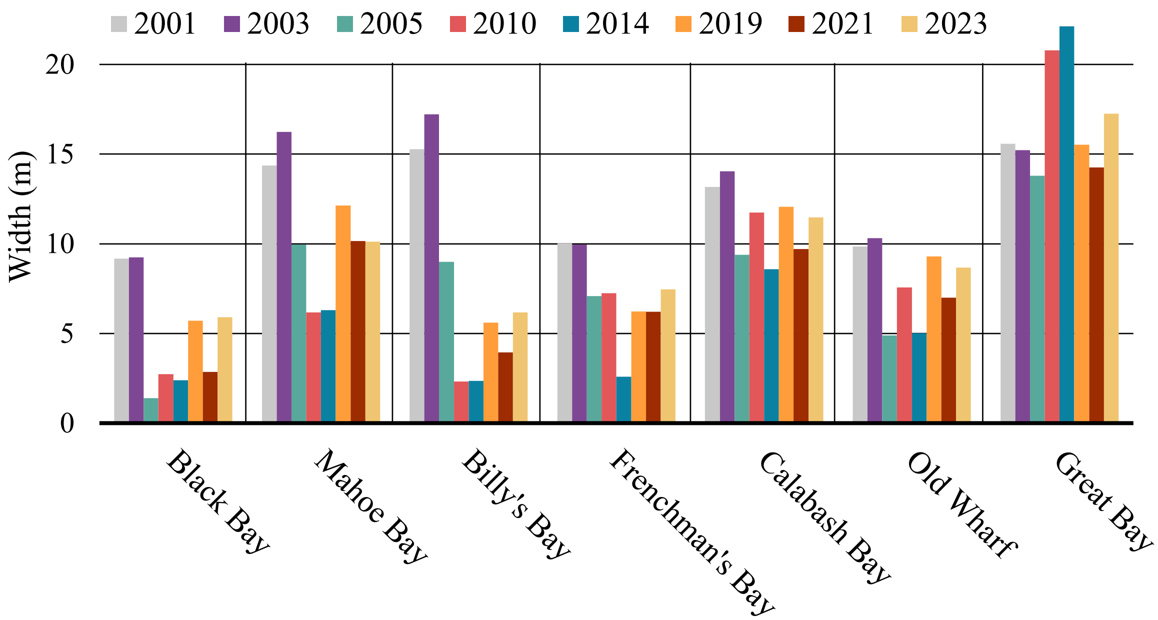

Figure 21. Average beach width per sandy pocket beach per satellite image from 2001 to 2021 and 2023 with field data points.

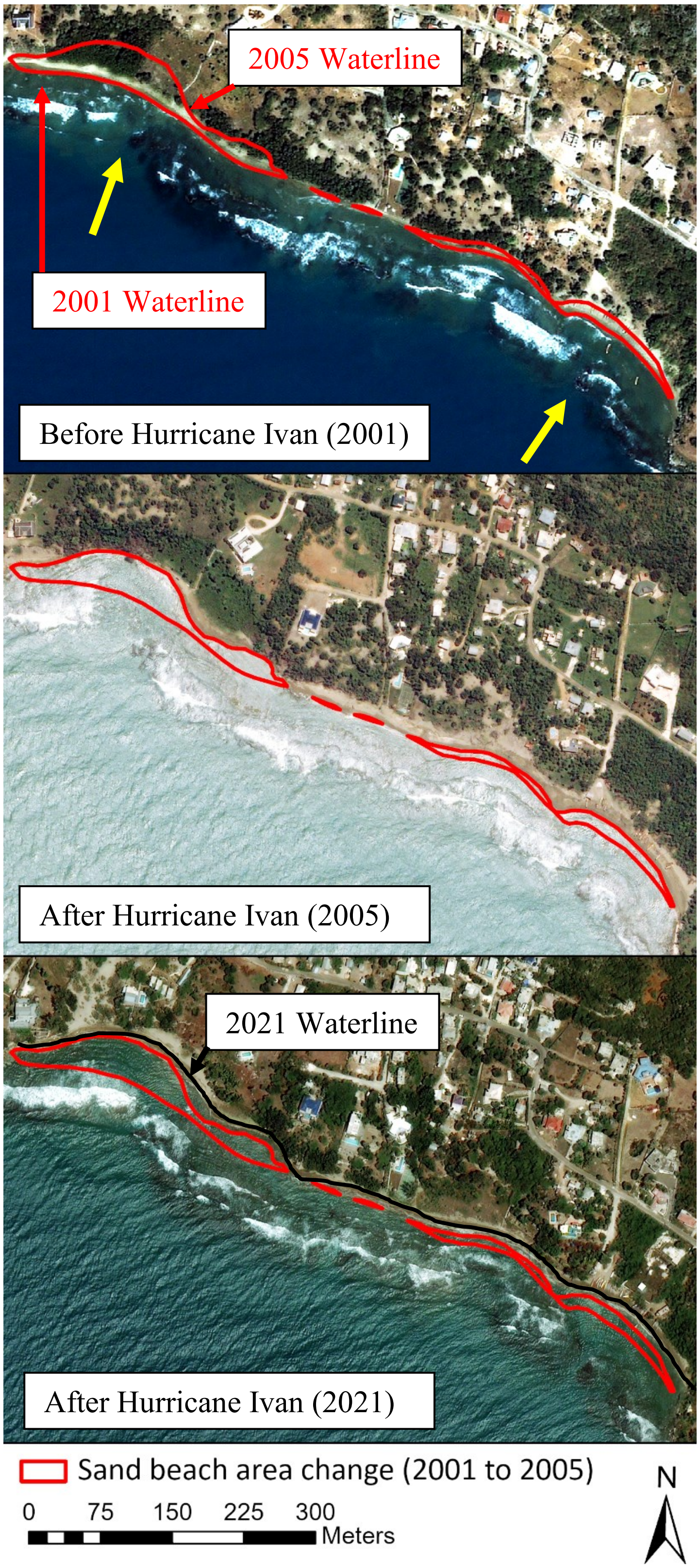

Figure 22. An example of beach changes at Billy's Bay from 2001, before Hurricane Ivan, to after Hurricane Ivan in 2005 and 2021. The yellow arrows point out openings in the nearshore protection where maximum erosion took place.

Figure 23. An example of an eroding beach in front of a stone wall at Calabash Bay (03/18/2021).

Figure 24. Example of an eroding beach, exposing a well house and pit wall at Billy's Bay (01/12/2021).

Within Beach Variability (Transect Analysis)

Previous results focused on assessing the changes of the total beach area in each bay. The results in this section will focus on evaluating smaller-scale variations in beach erosion or deposition within each bay through historical analysis of beach changes at multiple transects with 50 m spacing. The transect perspective gives insight into the variability of beach changes within a sandy bay and the spatial distribution of erosion in relation to longshore drift direction and influence of nearshore rock protection. Approximately 30% or more of the length of each bay was analyzed and all beaches except for Black Bay and Mahoe Bay had overall higher percentages of sand beaches compared to mixed sand and rock beaches (Table 6).

Table 6. Transect analysis of all sandy pocket beaches.

Sandy Pocket Beaches	Number of Total Transects that are Sandy	Percentage of Total Transects that are Sandy (%)	Percentage of Sandy Transects that are “sand” (%)	Percentage of Sandy Transects that are “mixed sand and rock” (%)
Black Bay	9	27.3	44.4	55.6
Mahoe Bay	11	50	36.4	63.6
Billy's Bay	19	63.3	100	0
Frenchman's Bay	21	55.3	90.5	9.5
Calabash Bay	8	42.1	62.5	37.5
Old Wharf	8	33.3	87.5	12.5
Great Bay	15	31.9	93.3	6.7

The overall average transect erosion rate for all 91 sandy beach transects in Treasure Beach was -1.3 m/yr 2001 to 2023. Average erosion rates for each bay during the period of Hurricane Ivan (2003-2005) indicated erosion as expected: Great Bay, -1.5 m/yr; Old Wharf, -

1.2 m/yr; Calabash Bay, -2.2 m/yr; Frenchman's Bay, -1.0 m/yr; Billy's Bay, -1.1 m/yr; Mahoe Bay, -0.01 m/yr; and Black Bay, -3.5 m/yr (Appendix F). While all bays were erosional during the Hurricane Ivan period, >25% of the transects at each bay indicated net deposition suggesting that sand readily moved on- and off-shore probably between local storage sites within nearshore and beach areas (Figure 9; Appendix G). However, average beach change rates for each bay during the post-Ivan period from 2005 to 2021 tended to be mixed with erosion rates of -0.2-0.3 m/yr along the western segment of Treasure Beach and deposition rates of +0.05 to 0.2 m/yr along the eastern segment (Appendix F and H). The average beach change rates for the post-Ivan period for each bay were: Great Bay, 0.2 m/yr; Old Wharf, 0.05 m/yr; Calabash Bay, -0.2 m/yr; Frenchman's Bay, -0.2 m/yr Billy's Bay, -0.3 m/yr; Mahoe Bay, 0.1 m/yr; and Black Bay, 0.4 m/yr (Appendix F and H). Overall, the range of erosion and deposition rates during the post-Ivan periods was much narrower compared to the influence of Ivan (Figure 25).

Interestingly, Black Bay produced the highest deposition rate of all at 0.4 m/yr during the post-Ivan period, but this bay had a relatively narrow beach to start with and a high frequency of rock outcrops along the shoreline. Further, the beach lost a lot of sand during Ivan suggesting that recovery rates there may have reflected the redeposition of locally stored sediment (Table 7 A and B). Moreover, Great Bay was affected by high rates of deposition several years after Hurricane Ivan possibly as the result lower wave energy and longshore drift delivery due to protection from wave attack by Great Pedro Bluff (Figures 20 and 26). A beach erosion study completed for the shoreline near Black River, Jamaica observed similar rates of change, with the higher erosion rates during the period of 2003 to 2007 after Hurricane Ivan of -0.9 m/yr, and an average rate of change from 2003 to 2012 of -0.3 m/yr. Beach monitoring data for eight Caribbean islands from 1985 to 2000 yielded an average beach erosion rate of -0.5 m/yr with the highest rates on those beaches affected by a larger number of hurricanes (Cambers, 2009). Hurricanes typically have major impacts on sandy beaches resulting in high erosion rates and shoreline retreat (Dietz, et al., 2018). After a period of erosion, the beach responds with a period of accretion to recover to pre-storm conditions which explains the fluctuation between erosion and deposition for different years and bays on the sandy beaches of Treasure Beach (Houser & Hamilton, 2009).

Table 7. Frequency distribution of sandy beach change rates in meters per year. Negative values represent erosion and positive values represent deposition.

A) 2003 to 2005	Min	10%	25%	50%	75%	90%	Max
Black Bay	-6.7	-6.1	-5.1	-3.0	-1.7	-1.6	-1.5
Mahoe Bay	-11.8	-7.1	-4.6	0.0	2.7	6.7	16.0
Billy's Bay	-11.4	-6.9	-5.3	-2.2	4.3	6.2	9.0
Frenchman's Bay	-9.8	-6.6	-4.0	0.3	1.8	4.3	6.8
Calabash Bay	-7.7	-6.5	-5.9	-1.9	0.4	2.2	5.5
Old Wharf	-7.1	-6.3	-3.0	-0.8	1.7	2.8	2.9
Great Bay	-5.8	-4.2	-3.5	-0.9	0.2	1.1	2.4

B) 2005 to 2023	Min	10%	25%	50%	75%	90%	Max
Black Bay	-1.8	-1.1	-0.2	0.2	0.9	1.9	6.8
Mahoe Bay	-9.1	-2.0	-1.2	0.1	0.9	2.8	8.9
Billy's Bay	-5.8	-2.2	-1.1	-0.3	0.6	1.7	7.0
Frenchman's Bay	-7.5	-2.9	-1.2	0.5	2.0	3.5	9.0
Calabash Bay	-10.9	-3.0	-1.4	0.0	2.1	3.8	10.4
Old Wharf	-5.6	-3.0	-1.4	0.4	1.6	3.2	5.0
Great Bay	-16.5	-5.4	-2.9	1.8	5.1	9.0	17.1

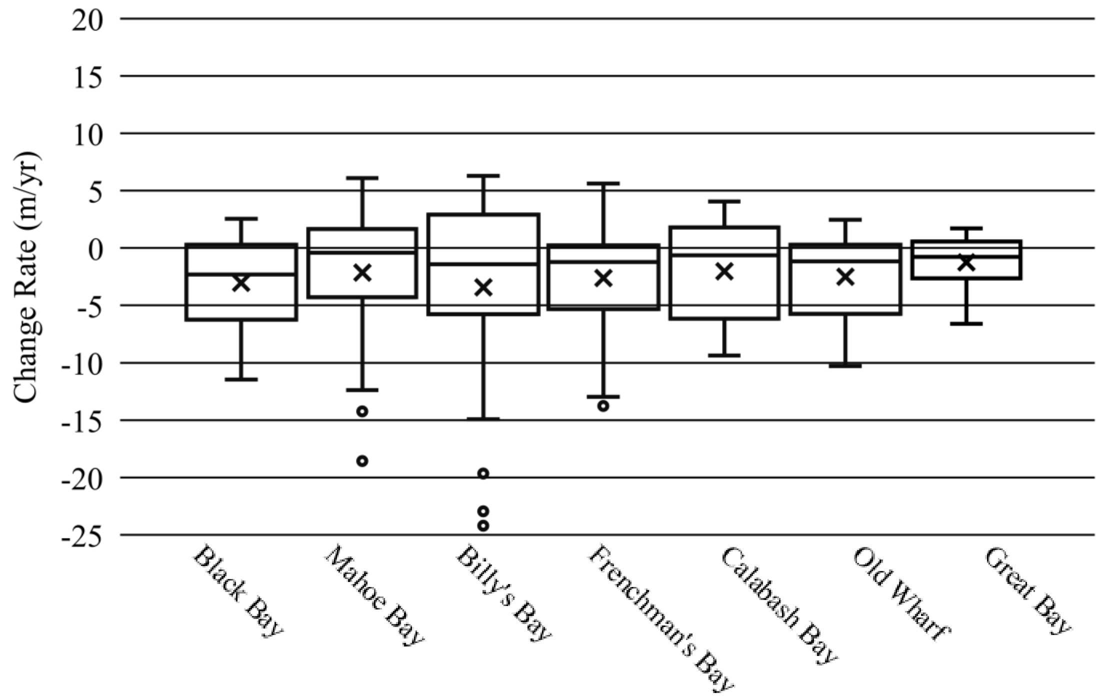

Figure 25. Change rate ranges for each sandy pocket beach from 2001 to 2005.

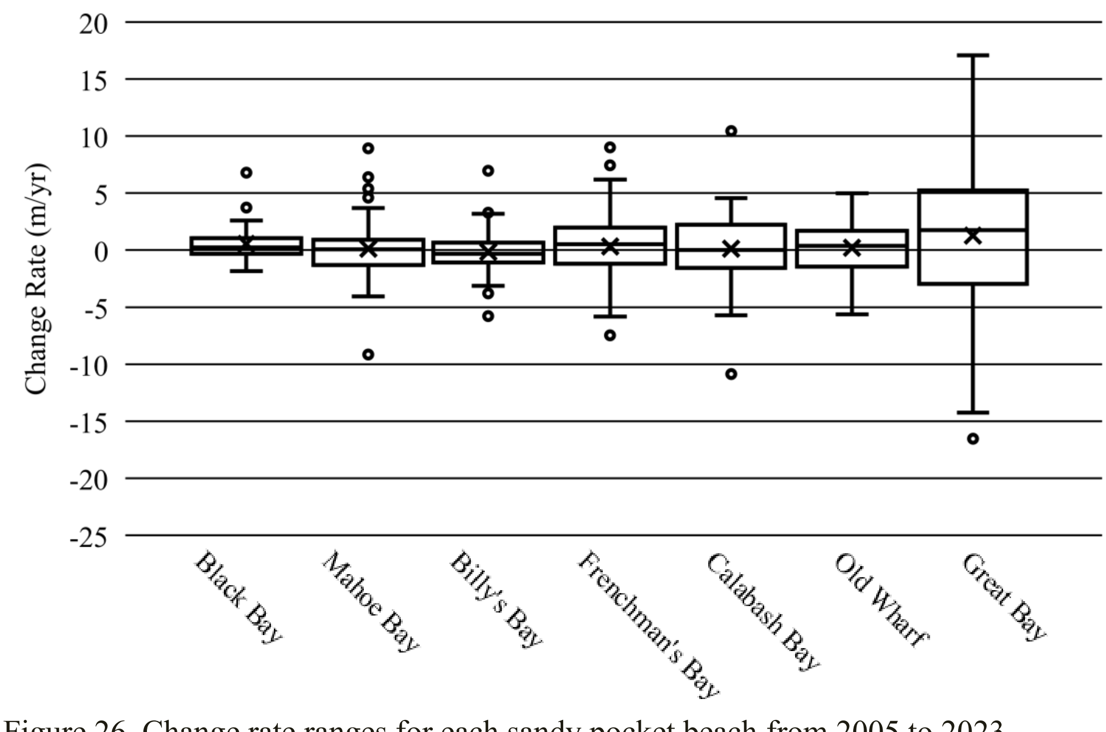

Figure 26. Change rate ranges for each sandy pocket beach from 2005 to 2023.

An assessment of beach changes in relation to the drift location of the transect yielded mixed results given the scale and scope of this study. Recall that drift segments were delineated based on a simple division of one third of beach length each for upper, middle, and down drift segments. There were no consistent trends between beach morphology and drift locations for average values of beach width berm height, beach angle (Table 8). During the Hurricane Ivan period, drift trends for Treasure Beach indicated that the highest erosion rates occurred on the downdrift segment averaging about -3 m/yr while the middle and updrift segments had average erosion rates less than 0.5 m/yr generally having no net change. However, in both groups, maximum erosion rates of the 25%-tile values were similar at about -5 m/yr (Figure 27). Beach changes rates were more variable and erosional during the Ivan Period compared to the post-Ivan recovery periods (Figures 27 and 28; Appendix I). The quartile range during Ivan was 6-7 m/yr while during the post-Ivan period it was only about 3 m/yr (Figure 28). Further, while beach changes for the downdrift segments were more variable compared to the other drift segments during the post Ivan period, average change rates were similar and ranged from 0 to +0.5 m/yr (Figure 28).

Table 8. Summary of sandy beach characteristics per drift section for 2003 to 2021.

Beach	Drift Section	n	Ave Width (m)	Ave Berm Hight (m)	Ave Beach Slope (°)	Nearshore Protection (# transects)	Ave Change Rate (m/yr)
Black Bay	Down	2	6.8	1.0	10.7	2	-0.3
	Middle	2	7.9	0.9	10.5	2	0.2
	Up	2	10.2	1.1	9.1	2	0.0
Mahoe Bay	Down	6	27.4	0.7	6.3	6	0.1
	Middle	6	13.5	0.9	9.9	6	0.1
	Up	6	16.8	0.7	8.4	6	0.2
Billy's Bay	Down	6	14.4	1.0	8.8	5	-0.5
	Middle	6	8.1	0.9	6.9	6	-0.1
	Up	6	9.1	1.0	7.2	5	-0.6
Frenchman's Bay	Down	7	10.4	0.9	9.0	2	-0.5
	Middle	5	14.3	0.9	6.6	1	-0.2
	Up	5	10.5	1.1	7.3	5	-0.1
Calabash Bay	Down	4	12.2	0.9	6.9	3	-0.3
	Middle	3	10.8	0.9	4.4	3	-0.8
	Up	3	36.4	1.1	8.3	3	-0.2
Old Wharf	Down	4	15.2	0.9	6.7	3	0.0
	Middle	3	17.0	0.9	7.5	3	-0.2
	Up	3	16.5	1.2	9.8	3	-0.1
Great Bay	Down	5	25.9	1.1	6.8	0	0.3
	Middle	4	38.1	1.0	5.0	0	0.4
	Up	4	18.5	0.9	7.0	0	-0.6

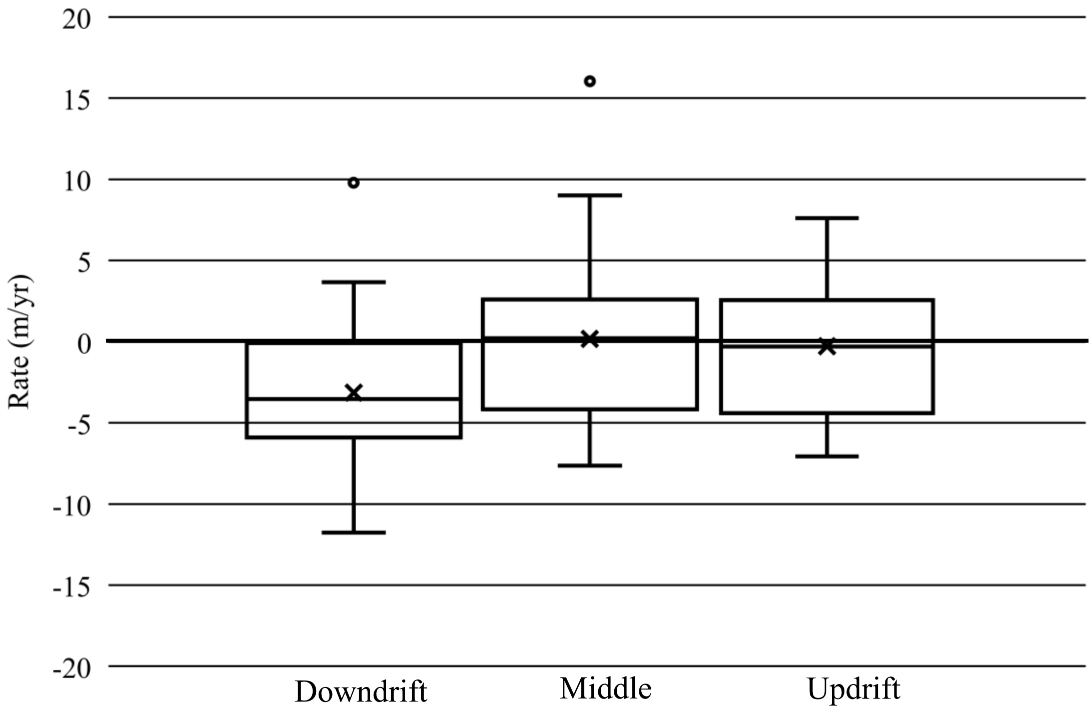

Figure 27. Erosion and accretion variability according to drift sections for all the sandy beaches from 2003 to 2005. There are 34 downdrift transects, 29 middle transects, and 29 updrift transects.

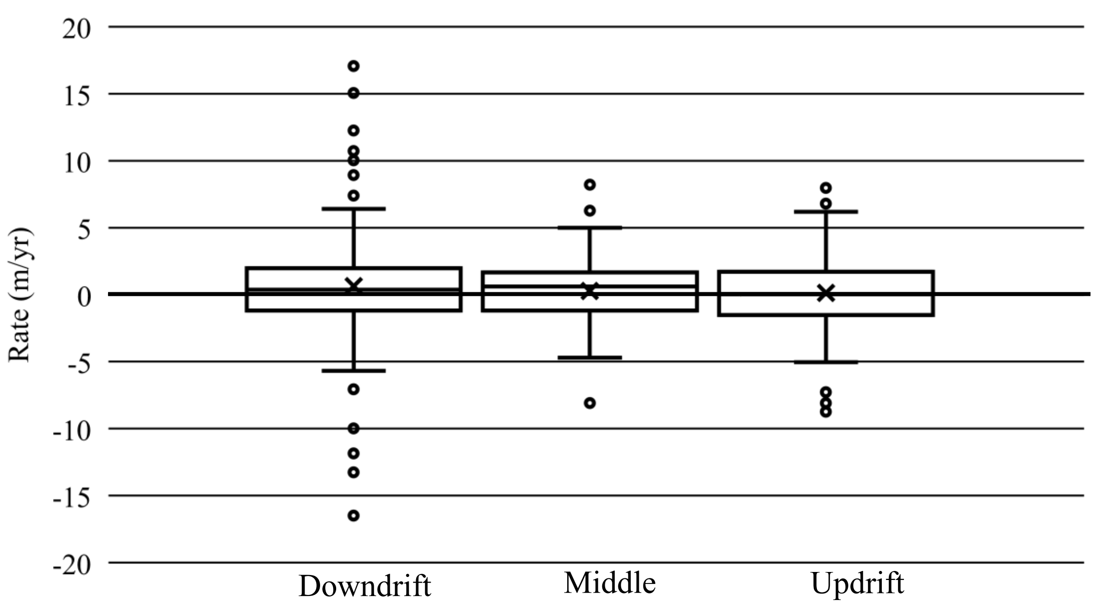

Figure 28. Erosion and accretion variability according to drift sections for all the sandy beaches from 2005 to 2023. There are 165 downdrift, 142 middle, and 140 updrift transects.

To further investigate the influence of bay morphology on beach change trends, the influence of rock and reef protection on beach processes was evaluated by contrasting erosion trends between those transects protected by nearshore rock or reef obstacles and those not protected (Figures 13 and 14). During the period from 2003 to 2021 including both Hurricane Ivan and Post-Ivan periods, transects classified as having no rock protection to reduce wave energy yielded wide range of beach changes for down and middle drift transects from -0.6 m/yr to +0.6 m/yr with an average change close to zero (Figure 29). Interestingly, all transects had erosion rates >0.4 m/yr for the updrift segments suggesting that higher wave energy or reduced sand supply may affect unprotected updrift locations more directly compared to downdrift locations (Figure 29). However, the sample size for the transects without protection was relatively low with only five updrift transects being evaluated. To a degree, transects with rock and reef protection tended to be more erosional than those without protection averaging about -0.3 m/yr for downdrift, -0.2 m/yr middle, and 0.05 m/yr for updrift segments (Figure 30). Further, the updrift transects with protection tended to be only slightly erosional and with change rates ranging from -0.5 to +0.3 m/yr (Figure 30).

Russell (1959) was the first to observe that nearshore protection from wave attack and the presence of beach rocks in some Caribbean beaches resulted in different than expected beach morpho-dynamics and seasonal morphological trends (Komar, 1998; Aubrey & Ross, 1985). Rock protected beaches were found to erode during periods of fair-weather waves and accrete during periods of larger waves during the winter storm season (Rey, et al., 2004, Russel & McIntire, 1965, Russel, 1959). In other studies, nearshore rocks in the swash zone served as protection for the beach and prevented shoreline retreat (Williams, et al., 2018; Prasetya, 2007; Dickinson, 1999). At Treasure Beach downdrift transects tended to erode more than updrift transects at protected locations during Hurricane Ivan (Figure 31). Further, during the post-Ivan period from 2005 to 2023, the three drift segments tended to respond similarly with almost no average change with downdrift transects but having a wider range of beach changes from -10 to +10 m/yr while the updrift locations only ranged from -5 to +5 m/yr (Figure 32). This study focused attention on the updrift and downdrift bay segments as possibly being affected by the variable influence of headland obstruction, storm wave attack, and attachment or deflection of sediment in longshore drift. Nearshore protection can be barrier to wave attack and provide conditions for sediment deposition (Russell, 1959; Aubrey & Ross, 1985; Komar, 1998). However, in Treasure Beach shore protection may be an indicator of beach segments that are more sensitive to erosion that can create conditions for either beach erosion or deposition within a bay (Appendix J and K). More research is needed to classify drift sections of each pocket beach according to wave energy, while keeping beach changes and bathymetric irregularities in mind.

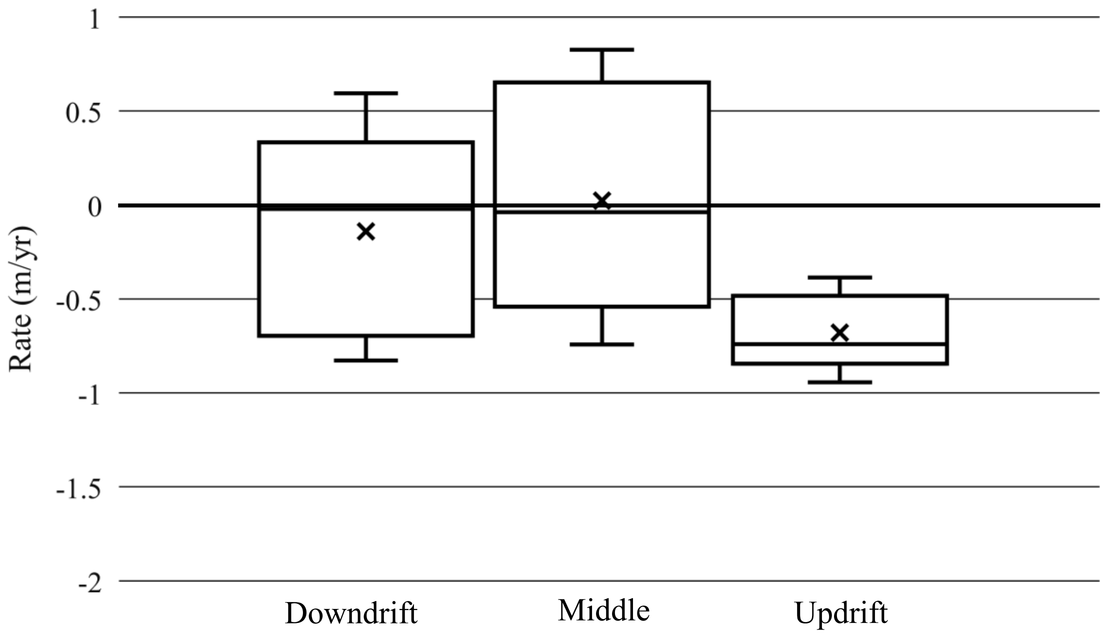

Figure 29. Erosion and accretion variability according to drift sections for all the sandy beaches without nearshore rock or coral reef protection from 2003 to 2021. There are 13 downdrift transects, 8 middle transects, and 5 updrift transects.

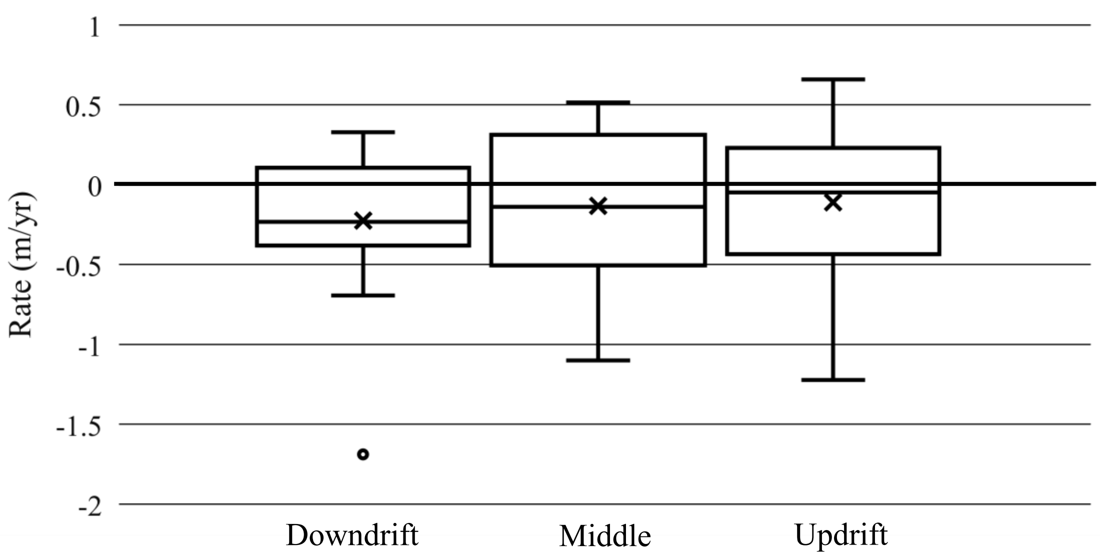

Figure 30. Erosion and accretion variability according to drift sections for all the sandy beaches with nearshore rock or coral reef protection from 2003 to 2021. There are 21 downdrift transects, 21 middle drift segments, and 24 updrift segments.

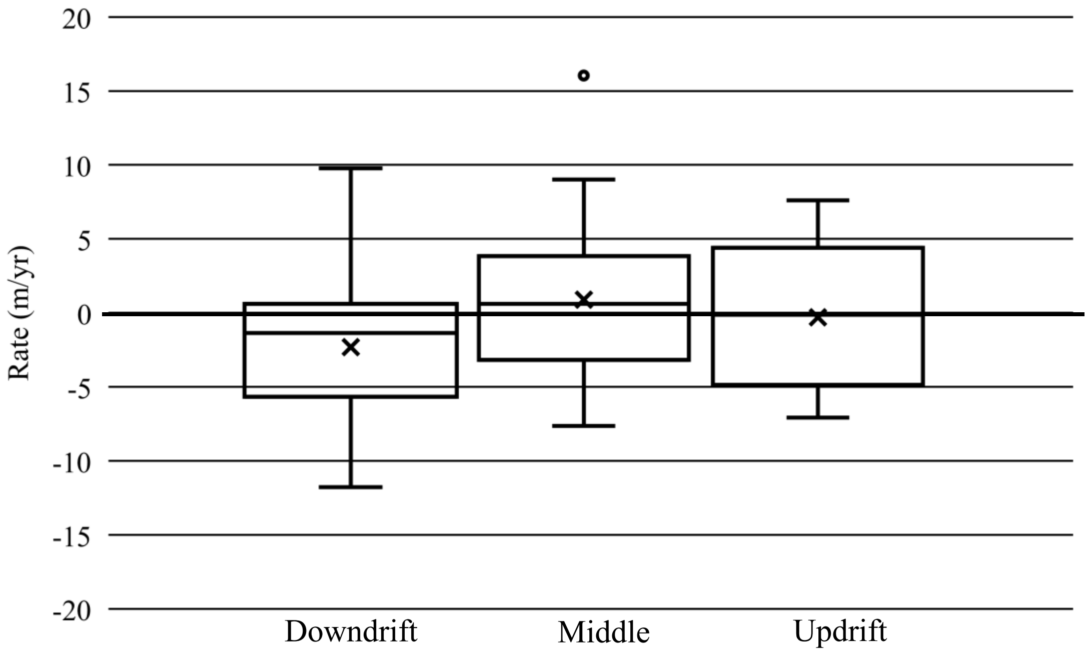

Figure 31. Erosion and accretion variability according to drift sections for all the sandy beaches with nearshore rock or coral reef protection from 2003 to 2005. There are 21 downdrift, 21 middle, and 24 updrift segments.

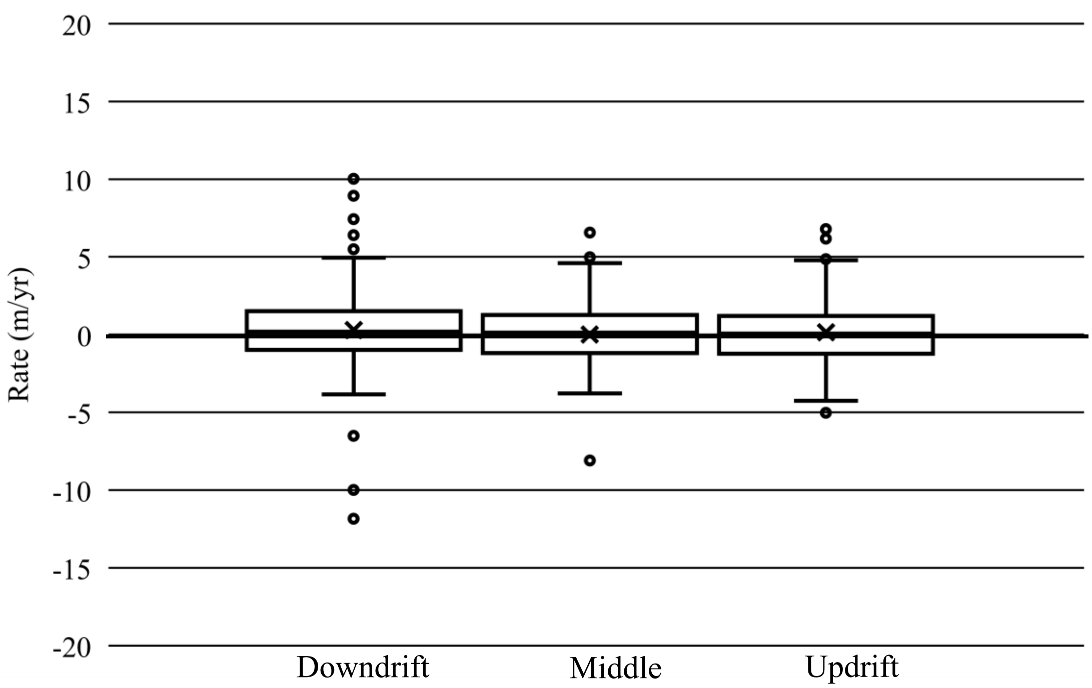

Figure 32. Erosion and accretion variability according to drift sections for all the sandy beaches with nearshore rock or coral reef protection from 2005 to 2023. There are 100 downdrift, 102 middle, and 115 updrift transects.

CHAPTER 5. CONCLUSION

Accelerated beach erosion is a global problem which affects the economy and ecology of local communities. Rising sea levels and storm intensity due to anthropogenic climate change is the main driver along with coastal subsidence in some regions. Island nations in the Caribbean Sea are particularly susceptible to sea level rise and hurricanes. However, beach erosion assessments have only been completed in a few countries and only locally in others. This study assessed beach erosion trends with several bays located along the south coast of Jamaica in Treasure Beach where the economy is supported mainly by tourism, fishing, and agriculture. There have only been a few beach erosion studies completed in Jamaica. Hurricane Ivan in 2004 caused high rates of beach erosion in Treasure Beach and data was available to monitor the locations and rates of recovery until present. This scenario makes it an ideal location for addressing a gap in knowledge by assessing storm erosion-recovery response on a headland-bay coast in the Caribbean.

A geomorphic assessment of Treasure Beach included a planimetric assessment of sandy beach changes in beach areas, erosion and deposition rates, and post-storm recovery along a mixed sand and rock pocket beach coastline. Beach changes were assessed during the period from 2001 to 2023 which included Hurricane Ivan in 2004. Areas of higher erosion rates compared to the rest of the shoreline were identified, as well as areas where the beach responded differently than most of the pocket beaches. Field research was conducted in January 2022 and March 2023. The following are the key findings of this study:

1) The average sandy beach area for each bay from 2001 to 2023 was: Great Bay, 21,334.1 m^2; Old Wharf, 7,046.9 m^2; Calabash Bay, 11,088.9 m^2; Frenchman's Bay, 13,530.4 m^2; Billy's Bay, 15,251.7 m^2; Mahoe Bay, 17,362.4 m^2; and Black Bay, 3,295.8 m^2. The average sand beach widths for each bay from 2001 to 2023 was: Great Bay, 16.8 m; Old Wharf, 7.8 m; Calabash Bay, 11.3 m; Frenchman's Bay, 7.1 m; Billy's Bay, 7.7 m; Mahoe Bay, 10.7 m; and Black Bay, 4.9 m.

2) Sandy beach area decreased significantly by 38% after the passage of Hurricane Ivan in 2004. Sandy areas increased thereafter and fluctuated in size, but all pocket beaches, except for Great Bay, have not reached their pre-Ivan sandy beach area.

3) The average net erosion rate including all seven bays during the study period 2001-2023 was 1.3 m/yr. The maximum erosion rate for a single transect from 2001 to 2023 was 24.2 m/yr (Billy's Bay) and the maximum deposition rate was 17.1 m/yr (Great Bay). Within the study area, 91% of the sand transects have been eroding, 3% did not change and 6% accreted from 2001 to 2023. As expected, the highest erosion rates occurred during the period including Hurricane Ivan in 2004. Erosion rates measured in Treasure Beach due to Ivan were higher than other rates reported for Jamaica.

4) The three longshore transport drift segments of each of the pocket beaches show variability in patterns between erosion and deposition rates per year. The updrift segments of all the beaches had a total of 41% erosion, the middle segment had 39% and the downdrift segment had 47%, with the rest of the remaining areas showing accretion. During the period from 2003 to 2021, transects classified as having no nearshore protection had a wide range of beach changes for down and middle drift transects from -0.6 m/yr to +0.6 m/yr with an average change close to zero. All transects had erosion rates >0.4 m/yr for the updrift segment. Transects nearshore protection tended to be more erosional than those without, averaging about -0.3 m/yr for downdrift, -0.2 m/yr middle, and 0.05 m/yr for updrift segments. The erosion trend on beaches with nearshore protection might be a result of the location of rock or coral outcrops and wave energy reflecting to adjacent sand beach areas, resulting in areas of high erosion, as well as areas of accretion.

5) Beach widths fluctuated between 2001 and 2023, with the maximum overall loss in beach width at all beaches during 2003 to 2005 after Hurricane Ivan. Beach widths increased since then but did not reach their per-Ivan widths in 2023. Beach width changes ranged between a maximum of 51 m erosion (landward movement) and 37 m accretion (seawards) from 2001 to 2023.

6) Coral reef and nearshore protection does not seem to reduce erosion rates at all locations, and high rates of change were observed in areas where the nearshore rock protection is present. More research is needed to determine whether the percentage of offshore beach protection is correlated with the percentage of the shoreline of the pocket beaches that experience erosion, as well as whether protection does have an influence on where on the beach the most erosion occur.

7) Beach recovery is slow after a major storm event. Some beaches in Treasure Beach are not able to deposit enough sediment to return to their pre-storm conditions. After Hurricane Ivan in 2004, only Great Bay had enough sand accretion to reach the total pre-storm sandy beach area, possible due to a limited sand budget for Treasure Beach. A combination of sufficient sediment supply, the protection of Great Pedro Bluff,

longshore drift, wave energy and a possible drop-down block due to fault lines might have been the contributing factors for Great Bay responding differently than the other pocket beaches in Treasure Beach.

8) Some beaches showed signs of accretion in the form of dunes, sand sheets and sand terraces at the transects with overall accretion from the year 2001 to 2023. Mahoe Bay and Old Wharf had sand dunes, sand sheets or some sort of sand accretion on the beach at approximately half of the transects on the beach, Black Bay and Billy's Bay had about a third, Frenchman's Bay and Great Bay had about a tenth and Calabash Bay did not have any. The dunes or sand sheets may buffer erosion to some degree and should be protected or enhanced to increase sand storage in back beach areas.

9) Erosion is a concern since the community relies on sandy beaches for tourism and shoreline development. Over the past two decades, sandy beaches have been narrowing in most places and in some places, beachfront properties are being eroded with infrastructure located near or within the beach zone. Wood fences were present on Black Bay (12.5%), Calabash Bay (6.3%) and Great Bay (12.5%). Concrete or stone walls were present on Mahoe Bay (8.3%), Billy's Bay (7.1%), Frenchman's Bay (18.8%), Calabash Bay (36.4%) and Great Bay (23.0%). These structures may be damaged by future storms or ongoing beach erosion. Moreover, they may increase erosion rates locally by amplifying over-wash turbulence and interfering with the sediment budget thus raising the potential for damage to the property for which the structures were intended to protect.

10) The reality of projected beach erosion and land use being in the way is not favorable for a community that does not have the resources to implement beach nourishment projects that will maintain beach widths for coastal tourism (Phillips & Jones, 2006). With rising sea levels and the increased frequency of storm events, waterlines, and beach widths have not recovered since Hurricane Ivan and are projected to narrow due to decreasing sand supply and beach front structures or rock outcrops not allowing beaches to migrate landward (French & Burningham, 2011).

Erosion rates were highest in Frenchman' Bay, Billy's Bay and Mahoe Bay and these areas should be a priority for authorities to monitor and implement mitigation strategies to mitigate future erosion rates as much as possible. Great Bay has been more accretional than the other beaches and remains the widest beach in Treasure Beach. Efforts to keep vegetation succession as successful as possible could help with dune accretion on the back-beach. Appropriate sand fences could also aid in dune formation on the back-beach to keep the sand budget positive with aeolian accretion. "Hard" prevention techniques like breakwaters, revetment, seawalls, and bulkheads could be implemented on beach areas where maximum erosion rates occur. Structures such as groins and artificial coral reefs could also be a potential solution. Engineering options may be too costly for this area; hence the community could help to build protective structures with available natural vegetation and other resources.

This study adds to our understanding how sandy beach erosion due to sea level rise and increased storm frequency is affecting pocket beaches in general and Treasure Beach in Jamaica specifically. Erosion trends on headland-bay beaches are highly variable due to their small size, variable influence of coastal geology, and complex interaction of longshore drift and nearshore and onshore reef/rock protection. Nevertheless, based on the beach erosion trends measured by this study, total sand loss along Treasure Beach could occur within a few decades to a century or more depending on individual bay characteristics, storm intensity, and rate of sea level rise.

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APPENDICES

Appendix A: GIS Data

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

Appendix A-1. Satellite Image Data Sources.

Data Source	Data Type	Data	Acquisition Date
Satellite Imaging Corporation	IKONOS satellite image	IKONOS Panchromatic Imagery	02/18/2001
	QuickBird satellite image	QuickBird Panchromatic Imagery	04/19/2003, 06/22/2005
	Worldview-2 satellite image	Worldview-2 Panchromatic and Multispectral Imagery	04/20/2010 06/13/2014
	GeoEye-1 satellite image	GeoEye-1 Panchromatic Imagery	08/14/2019
	Pleiades-1 satellite image	Pleiades-1 Panchromatic Imagery	03/30/2021

Appendix A-2. Test Point Error for 2001, 2003, 2005, 2010, 2014, and 2019 Satellite Images with the 2021 Satellite Image as the base map. The test point error is found using the distance formula. The average distance for the ten test points is 1.06 m, 1.04 m, 0.81 m, 0.98 m, 1.51 m, 2.41 m respectively.

Year	Point X	Point Y	Distance (m)
2021	208037.6563	1978468.875	1.564452
2001	208036.3594	1978468	
2021	209664.0781	1977506.375	2.666524
2001	209663.6094	1977503.75	
2021	209111.1719	1977884.375	1.017426
2001	209110.9844	1977883.375	
2021	207550.4531	1978694.25	0.412512
2001	207550.2813	1978693.875	
2021	207330.1719	1978924	1.300541
2001	207329.1094	1978923.25	
2021	206938.2969	1979487.625	0.528716
2001	206938.125	1979487.125	
2021	206927.4531	1979512.75	0.376300
2001	206927.7344	1979512.5	
2021	206548.4531	1979823	0.883883
2001	206548.3281	1979822.125	
2021	203483.3594	1982647.25	0.910148
2001	203483.875	1982646.5	
2021	205662.9688	1980207.875	0.958234
2001	205662.5781	1980207	

Appendix A-2- Continued. Test Point Error for 2001, 2003, 2005, 2010, 2014, and 2019 Satellite Images with the 2021 Satellite Image as the base map. The test point error is found using the distance formula. The average distance for the ten test points is 1.06 m, 1.04 m, 0.81 m, 0.98 m, 1.51 m, 2.41 m respectively.

Year	Point X	Point Y	Distance (m)
2021	208048.4063	1978468.25	2.320299
2003	208050.5	1978469.25	
2021	209609.375	1977611.125	1.682937
2003	209611.0156	1977610.75	
2021	208485.4844	1978085.125	0.945797
2003	208486.4219	1978085.25	
2021	207609.2344	1978762.375	0.679104
2003	207609.5	1978763	
2021	207268.7969	1979286.375	0.566177
2003	207269.0625	1979286.875	
2021	205115.375	1980530.625	0.390625
2003	205114.9844	1980530.625	
2021	203860.9063	1981734.5	0.919090
2003	203861.1875	1981735.375	
2021	203547.9375	1982176.625	1.104412
2003	203548.4063	1982177.625	
2021	203483.4531	1982647.25	0.484375
2003	203483.9375	1982647.25	
2021	203384.4063	1984129.75	1.352082
2003	203385.5313	1984130.5	

Appendix A-2- Continued. Test Point Error for 2001, 2003, 2005, 2010, 2014, and 2019 Satellite Images with the 2021 Satellite Image as the base map. The test point error is found using the distance formula. The average distance for the ten test points is 1.06 m, 1.04 m, 0.81 m, 0.98 m, 1.51 m, 2.41 m respectively.

Year	Point X	Point Y	Distance (m)
2021	203384.375	1984129.625	1.884352
2005	203384.5625	1984131.5	
2021	203483.2813	1982647.25	0.790569
2005	203484.0313	1982647.5	
2021	203860.8281	1981734.125	0.894864
2005	203861.0156	1981735	
2021	204258.2188	1981386	0.755837
2005	204258.3125	1981386.75	
2021	205521.4219	1980462.875	1.057433
2005	205521.0781	1980461.875	
2021	205822.375	1980006	0.737030
2005	205821.9844	1980005.375	
2021	206939.9063	1979630.125	0.485130
2005	206940.375	1979630.25	
2021	207090.1094	1979636.875	0.519399
2005	207090.25	1979637.375	
2021	207399.6094	1979381.5	0.498288
2005	207399.9375	1979381.875	
2021	209905.4063	1977229.625	0.470050
2005	209905.8594	1977229.5	

Appendix A-2- Continued. Test Point Error for 2001, 2003, 2005, 2010, 2014, and 2019 Satellite Images with the 2021 Satellite Image as the base map. The test point error is found using the distance formula. The average distance for the ten test points is 1.06 m, 1.04 m, 0.81 m, 0.98 m, 1.51 m, 2.41 m respectively.

Year	Point X	Point Y	Distance (m)
2021	209771.8594	1977278.75	1.576500
2010	209773.3906	1977278.375	
2021	209715.375	1977425.875	0.328125
2010	209715.7031	1977425.875	
2021	209289.3906	1977743.25	2.721622
2010	209291.9219	1977742.25	
2021	209106.8906	1977828	1.097316
2010	209107.9219	1977827.625	
2021	207538.5781	1978799.125	1.030776
2010	207539.5781	1978799.375	
2021	206927.2188	1979512.875	0.421875
2010	206927.6406	1979512.875	
2021	205096.2031	1980516.5	0.775762
2010	205096.9688	1980516.375	
2021	203861.1875	1981734.375	0.718750
2010	203861.9063	1981734.375	
2021	203483.3281	1982647.125	0.927551
2010	203484.1094	1982646.625	
2021	205822.2969	1980006	0.218750
2010	205822.0781	1980006	

Appendix A-2- Continued. Test Point Error for 2001, 2003, 2005, 2010, 2014, and 2019 Satellite Images with the 2021 Satellite Image as the base map. The test point error is found using the distance formula. The average distance for the ten test points is 1.06 m, 1.04 m, 0.81 m, 0.98 m, 1.51 m, 2.41 m respectively.

Year	Point X	Point Y	Distance (m)
2021	209916.0469	1977220.125	1.097316
2014	209915.0156	1977219.75	
2021	209106.9219	1977828	1.244127
2014	209105.7031	1977828.25	
2021	207455.7656	1978864.25	0.640625
2014	207455.9063	1978864.875	
2021	206938.3906	1979473	0.312500
2014	206938.5781	1979473.25	
2021	205852.8125	1979962	0.644235
2014	205852.2188	1979962.25	
2021	205462.1563	1980293.375	2.363097
2014	205460.0781	1980294.5	
2021	205114.3906	1980492.875	1.652487
2014	205112.7813	1980493.25	
2021	204629.0313	1980845.5	3.409295
2014	204625.8594	1980846.75	
2021	203843.1094	1981717.25	1.261761
2014	203843.2813	1981718.5	
2021	203548.0781	1982176.75	2.445949
2014	203546.25	1982178.375	

Appendix A-2- Continued. Test Point Error for 2001, 2003, 2005, 2010, 2014, and 2019 Satellite Images with the 2021 Satellite Image as the base map. The test point error is found using the distance formula. The average distance for the ten test points is 1.06 m, 1.04 m, 0.81 m, 0.98 m, 1.51 m, 2.41 m respectively.

Year	Point X	Point Y	Distance (m)
2021	209753.8281	1977303.25	2.730801
2019	209755.6875	1977305.25	
2021	209524.1406	1977592	3.077292
2019	209526.6719	1977593.75	
2021	208294.9063	1978137.125	3.377314
2019	208297.0313	1978139.75	
2021	207550.25	1978694.125	1.635782
2019	207551.4375	1978695.25	
2021	207164.4063	1979015.375	2.128673
2019	207165.7813	1979017	
2021	206943.625	1979437.5	1.152443
2019	206944.375	1979438.375	
2021	205600.5156	1980077.875	3.207809
2019	205602.3594	1980080.5	
2021	205219.7969	1980394.375	1.075291
2019	205220.4219	1980395.25	
2021	203789.5	1981776.5	2.419858
2019	203790.3906	1981778.75	
2021	203548.0156	1982176.75	3.328712
2019	203550.0625	1982179.375	

Appendix B: Transect Locations

Appendix B-1. Transect number and beach kilometer.

Transect Number	Beach Kilometer
Great Bay	
1	0.05
2	0.1
3	0.15
4	0.2
5	0.25
6	0.3
7	0.35
8	0.4
9	0.45
10	0.5
11	0.55
12	0.6
13	0.65
14	0.7
15	0.75
16	0.8
17	0.85
18	0.9
19	0.95

Transect Number	Beach Kilometer
20	1
21	1.05
22	1.1
23	1.15
24	1.2
25	1.25
26	1.3
27	1.35
28	1.4
29	1.45
30	1.5
31	1.55
32	1.6
33	1.65
34	1.7
35	1.75
36	1.8
37	1.85
38	1.9
39	1.95

Appendix B-1- Continued. Transect number and beach kilometer.

Transect Number	Beach Kilometer	Transect Number	Beach Kilometer
40	2	61	3.05
41	2.05	62	3.1
42	2.1	63	3.15
43	2.15	64	3.2
44	2.2	65	3.25
45	2.25	66	3.3
46	2.3	67	3.35
47	2.35	68	3.4
Old Wharf		69	3.45
48	2.4	70	3.5
49	2.45	71	3.55
50	2.5	Calabash Bay	
51	2.55	72	3.6
52	2.6	73	3.65
53	2.65	74	3.7
54	2.7	75	3.75
55	2.75	76	3.8
56	2.8	77	3.85
57	2.85	78	3.9
58	2.9	79	3.95
59	2.95	80	4
60	3	81	4.05

Appendix B-1- Continued. Transect number and beach kilometer.

Transect Number	Beach Kilometer
82	4.1
83	4.15
84	4.2
85	4.25
86	4.3
87	4.35
88	4.4
89	4.45
90	4.5
Frenshman's Bay	
91	4.55
92	4.6
93	4.65
94	4.7
95	4.75
96	4.8
97	4.85
98	4.9
99	4.95
100	5
101	5.05
102	5.1

Transect Number	Beach Kilometer
103	5.15
104	5.2
105	5.25
106	5.3
107	5.35
108	5.4
109	5.45
110	5.5
111	5.55
112	5.6
113	5.65
114	5.7
115	5.75
116	5.8
117	5.85
118	5.9
119	5.95
120	6
121	6.05
122	6.1
123	6.15
124	6.2

Appendix B-1- Continued. Transect number and beach kilometer.

Transect Number	Beach Kilometer
125	6.25
126	6.3
127	6.35
128	6.4
Billy's Bay	
129	6.45
130	6.5
131	6.55
132	6.6
133	6.65
134	6.7
135	6.75
136	6.8
137	6.85
138	6.9
139	6.95
140	7
141	7.05
142	7.1
143	7.15
144	7.2
145	7.25

Transect Number	Beach Kilometer
146	7.3
147	7.35
148	7.4
149	7.45
150	7.5
151	7.55
152	7.6
153	7.65
154	7.7
155	7.75
156	7.8
157	7.85
158	7.9
Mahoe Bay	
159	7.95
160	8
161	8.05
162	8.1
163	8.15
164	8.2
165	8.25
166	8.3

Appendix B-1- Continued. Transect number and beach kilometer.

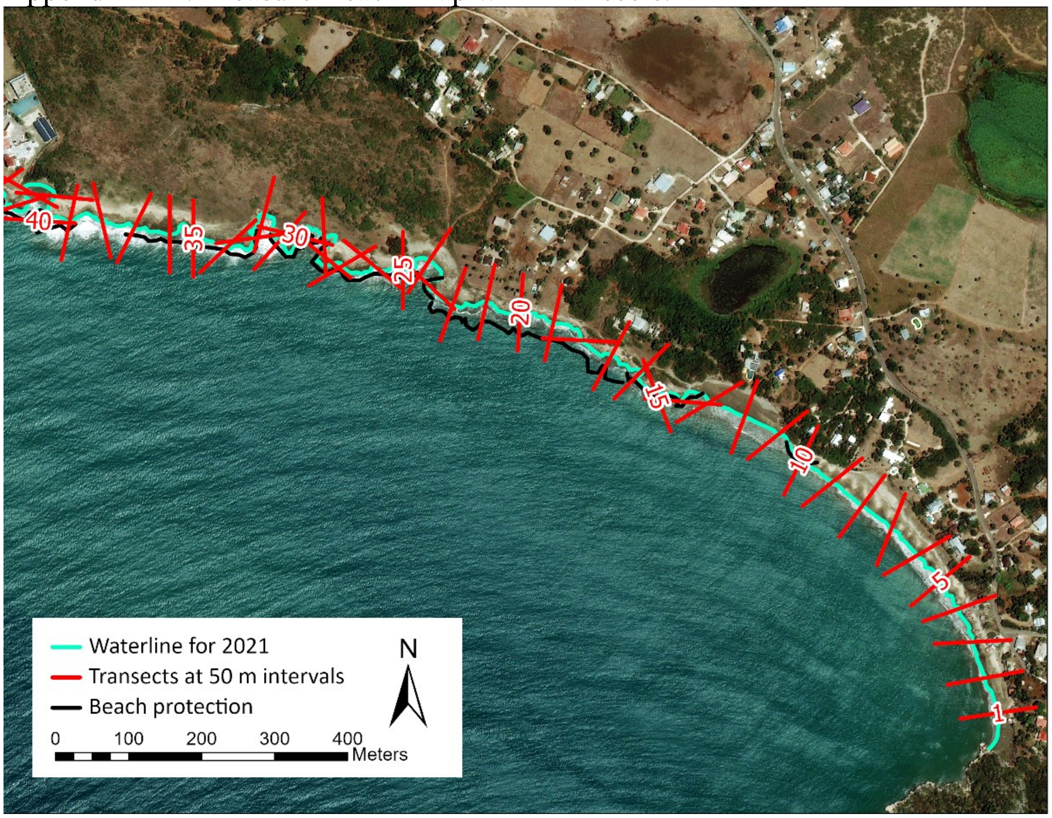
Transect Number	Beach Kilometer
167	8.35
168	8.4
169	8.45
170	8.5
171	8.55
172	8.6
173	8.65
174	8.7
175	8.75
176	8.8
177	8.85
178	8.9
179	8.95
180	9
Black Bay	
181	9.05
182	9.1
183	9.15
184	9.2
185	9.25
186	9.3
187	9.35

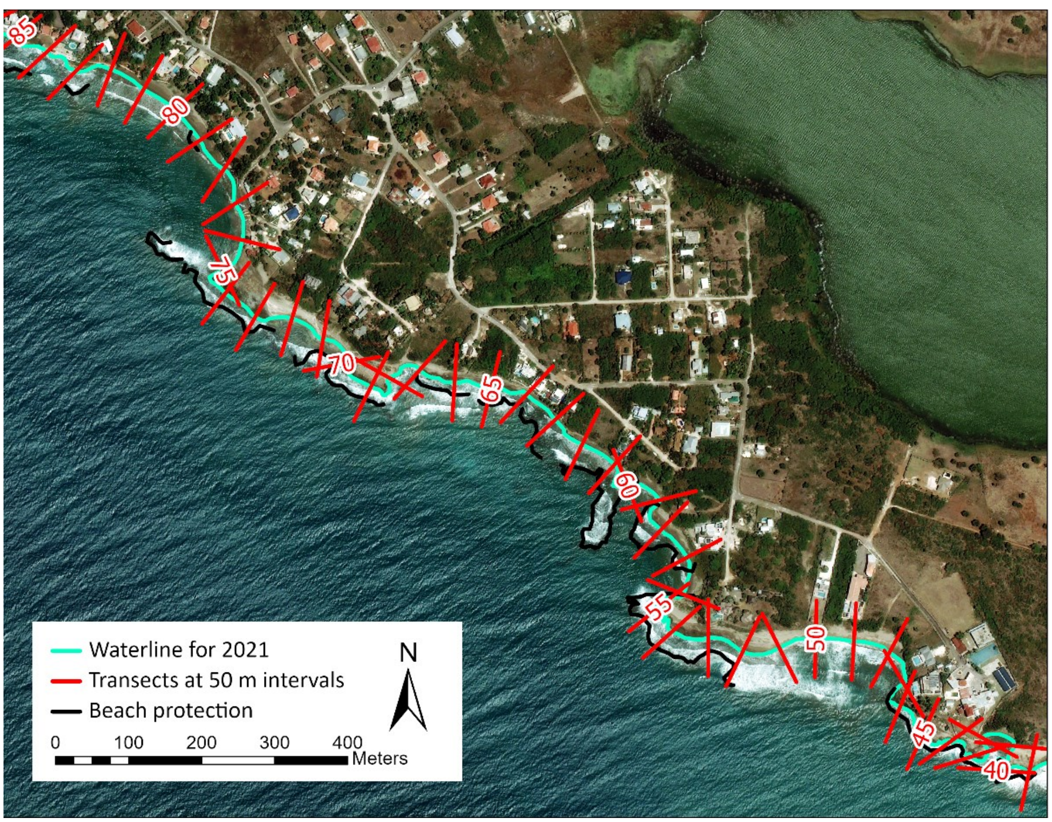
Transect Number	Beach Kilometer
188	9.4
189	9.45
190	9.5
191	9.55
192	9.6
193	9.65
194	9.7
195	9.75
196	9.8
197	9.85
198	9.9
199	9.95
200	10
201	10.05
202	10.1
203	10.15
204	10.2
205	10.25
206	10.3
207	10.35
208	10.4
209	10.45

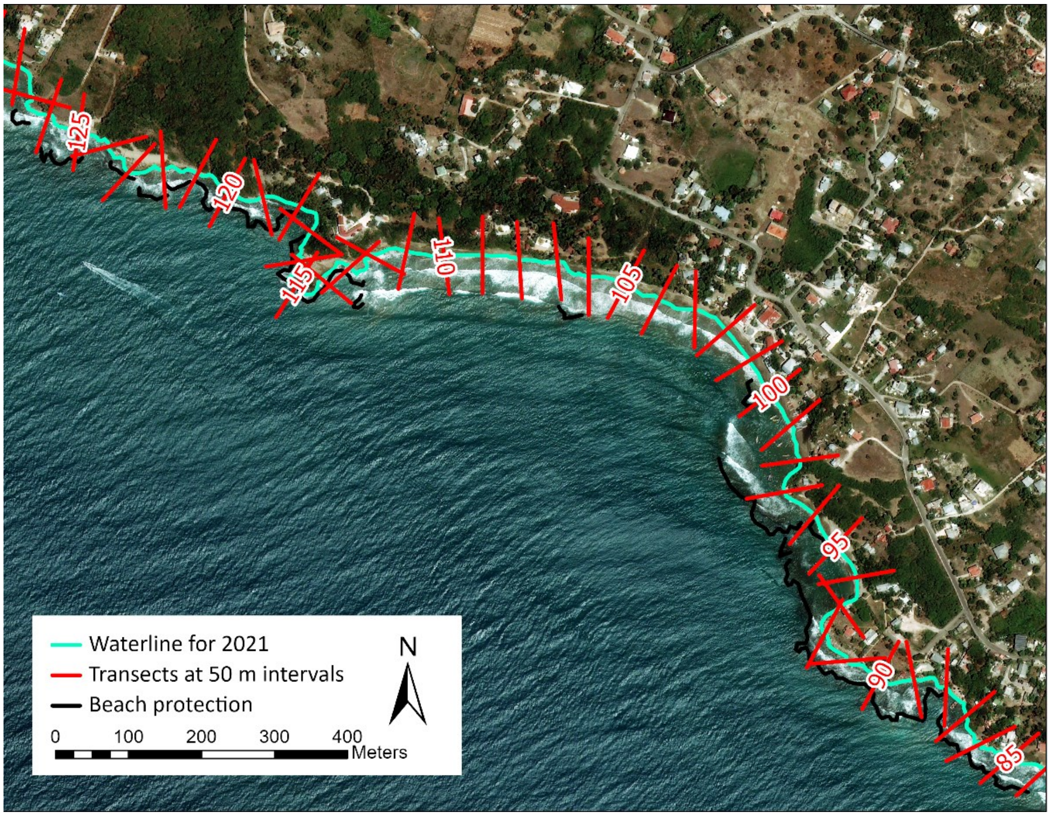
Appendix B-1- Continued. Transect number and beach kilometer.

Transect Number	Beach Kilometer
210	10.5
211	10.55
212	10.6
213	10.65
Starvegut Bay	
214	10.7
215	10.75
216	10.8
217	10.85
218	10.9
219	10.95
220	11
221	11.05
222	11.1
223	11.15
224	11.2
225	11.25

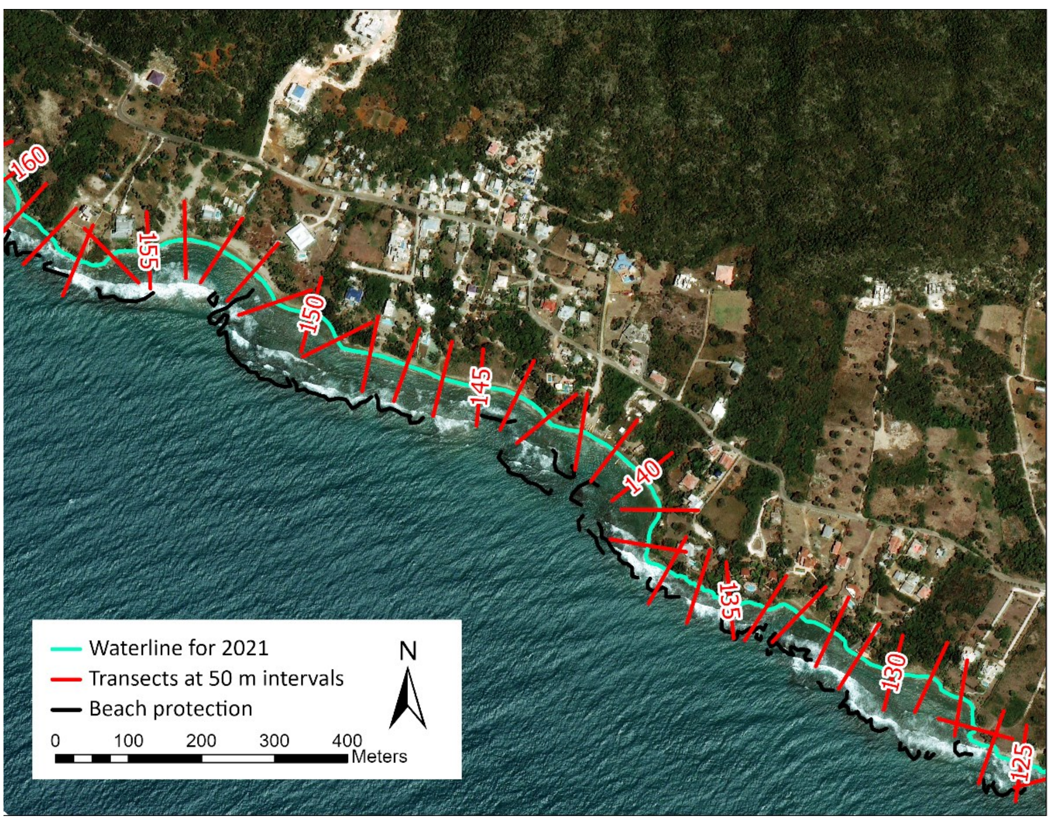
Appendix B-2. Treasure Beach Map with Transects.



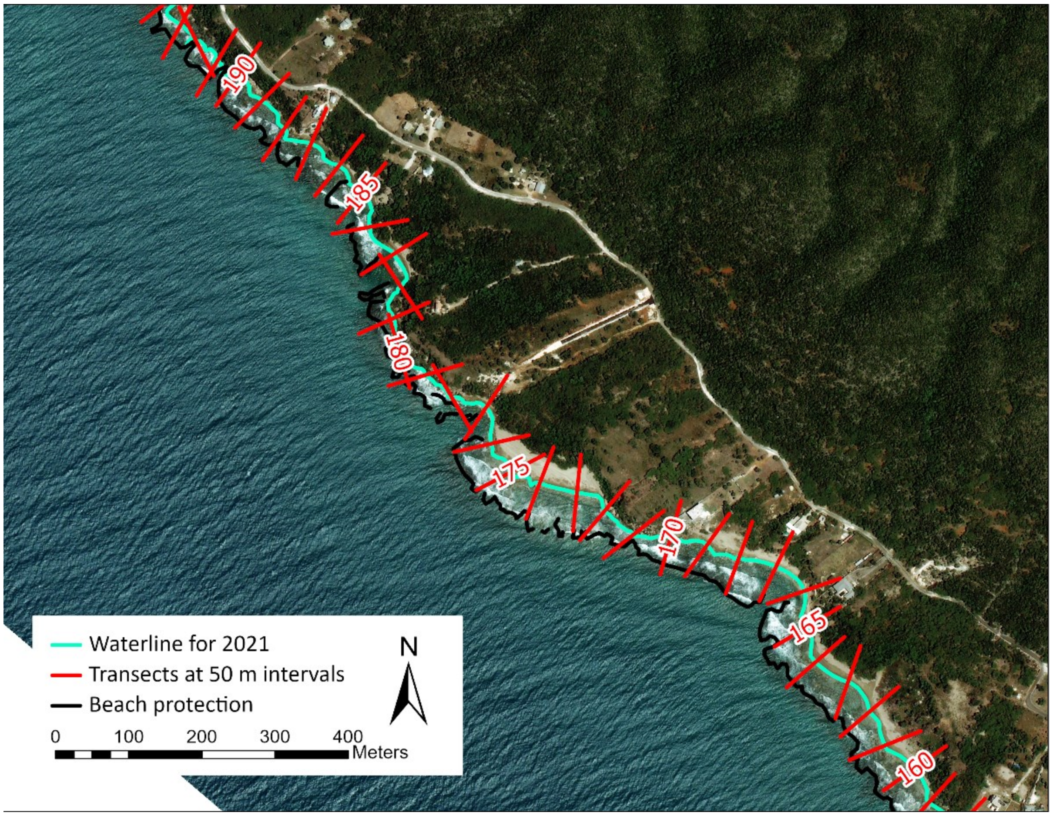


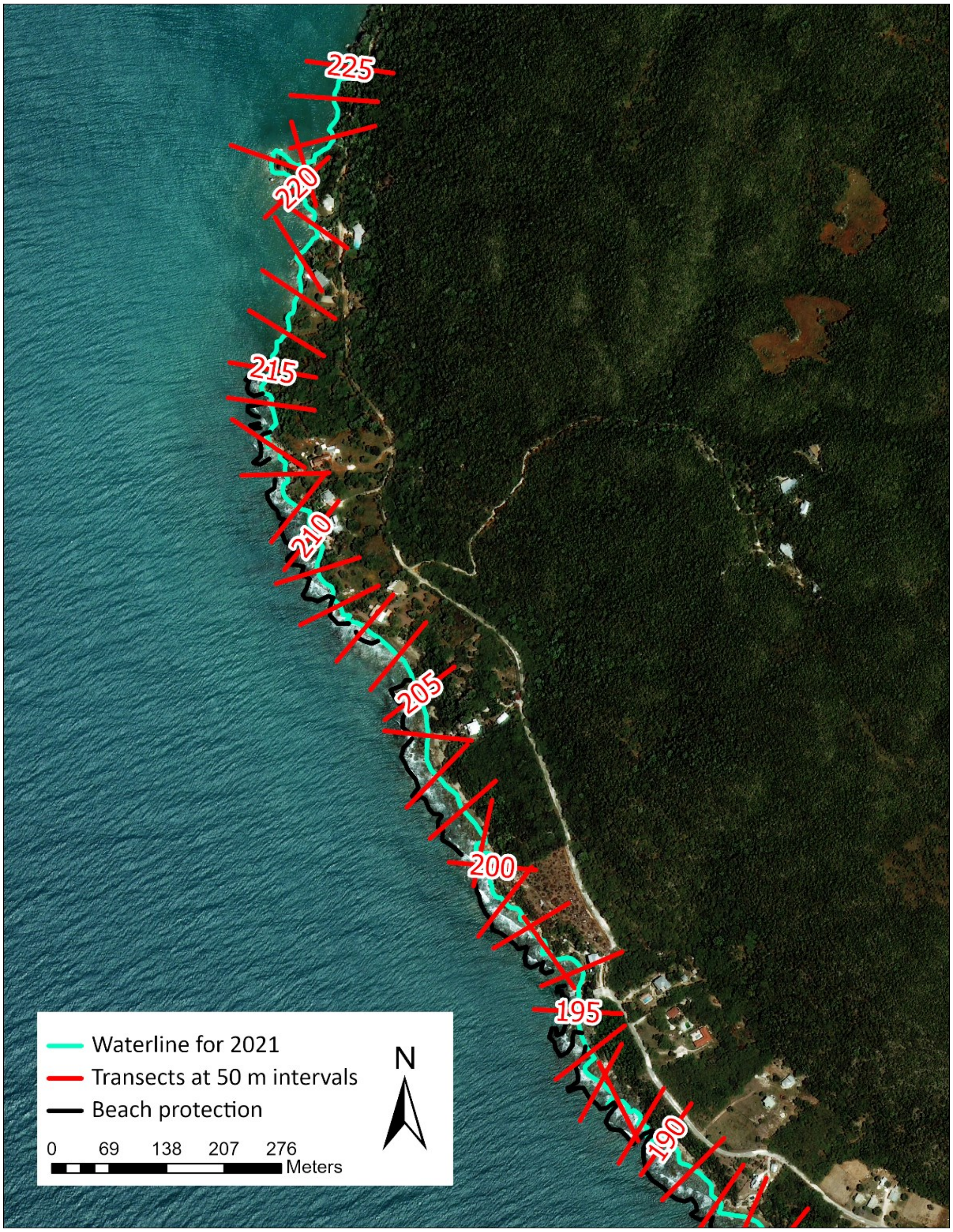


125
120
115
110
105
100
95
90
85
Waterline for 2021
Transects at 50 m intervals
Beach protection
0
100
200
300
400
Meters
N



160
155
150
145
140
135
130
125
Waterline for 2021
Transects at 50 m intervals
Beach protection
0
100
200
300
400
Meters
N


190
185
180
175
170
165
160
Waterline for 2021
Transects at 50 m intervals
Beach protection
N
0
100
200
300
400
Meters


225
220
215
210
205
200
195
190
Waterline for 2021
Transects at 50 m intervals
Beach protection
N
0 69 138 207 276
Meters

Appendix C: Photo Log

Appendix C-1. Beach types at Treasure Beach.

Embayed sandy pocket beach at Frenchman's Bay.

Small, embayed sandy pocket beach at Old Wharf.

Rock headlands of small, embayed pocket beach at Old Wharf, and Great Pedro Bluff in the back.

Wave cut platform and intertidal rock pool at Old Wharf.

Appendix C-2. Different beach classifications at Treasure Beach.

Wide sandy pocket beach at Great Bay (sand classification).

Sandy beach on rock pavement with intertidal rock outcrops at Calabash Bay (sand on rock classification).

Sandy beach on rock pavement and fossil coral formation outcrops at Calabash Bay (sand on rock classification).

Sand on beach rock platform, with wave cut platform, Old Warf (sand on rock classification).


Sandy beach behind rock and old coral reef outcrops at Billy's Bay (sand and rock classification).


Rock bluff with no beach at Starvegut Bay (rock bluff classification).

Appendix C-3. Beach protection.

Vegetation encouraging sand dune formation, with shrubs on the backbeach at Old Wharf.

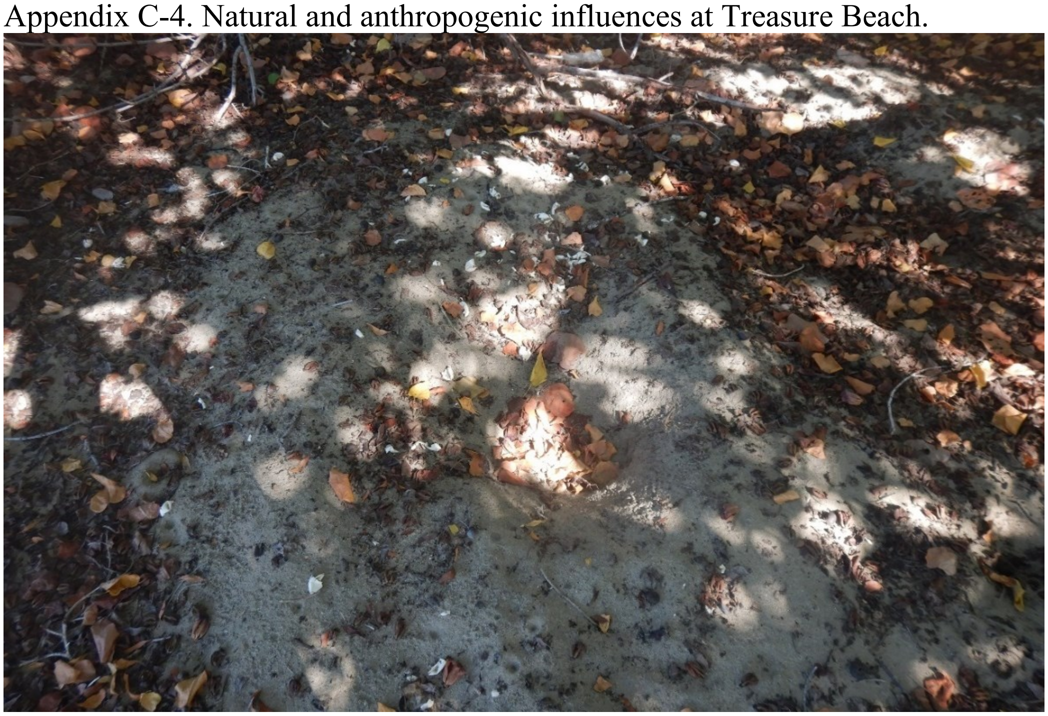
Sand dunes covered with creeping vegetation on the beach, with a stone wall on the backbeach at Old Wharf.

A very narrow beach covered with trees at Billy's Bay.

Aeolian rock on the back beach encouraging dune formation at Old Wharf.


Example of a beach with low wave energy and berm formation on the foreshore at Great Bay.

Appendix C-4. Natural and anthropogenic influences at Treasure Beach.


A turtle nest on the beach at Black Bay.


Wire and wood fence on the beach at Frenchman's Bay.

Fisherman's beach and houses built on the backbeach at Calabash Bay.

Example of vegetation cleared in front of a beachfront property at Old Wharf.

Cement wall built on the back beach at Old Wharf.


Narrow beach with cement and stone wall on the backbeach at Great Bay.


Two groins built with rocks at Mahoe Bay.

Vegetation clearing at Billy's Bay.

Cement and wood wall preventing beach propagation at Calabash Bay.

A narrow beach with a concrete wall on the backbeach, preventing beach propagation at Calabash Bay.

Cement and wood wall at Calabash Bay.


Wood fence with vegetation cleared in front of a beach front property at Old Wharf.


Stone wall encouraging dune formation on the backbeach at Old Wharf.

Boats on the sand at a fishermans beach at Great Bay.


Rip-rap on the backbeach at a beach house at Billy's Bay.


Lagoon draining in the sea at Old Wharf.


Water draining from a neighborhood on the beach at Billy’s Bay.

Drainage system draining on the beach at Billy's Bay.

Waterway draining on the backbeach at Billy's Bay.

Appendix D: Field Sheets

Appendix D-1: Geomorphic Shoreline Assessment for transect sites beach survey.

Code	Description
Beach Name	
BB	Billy's Bay
BLB	Black Bay
BS	Black Spring
BSB	Bob Sims Bay
CB	Calabash Bay
FB	Frenchman's Bay
FC	Fort Charles
GB	Great Bay
HB	Harvey Bay
JR	John Rocks
MB	Mahoe Bay
OW	Old Wharf
PB	Pedro Bay
SB	Shelly Bay
SGB	Starvegut Bay
TB	Treasure Beach
TTB	Turtle Beach
Field Note	
F	Fault

Code	Description
UL	Uplifted
WCP	Wave cut paltform
WB	Welded berms
RW	Rough waves
SS	Sand storage
T	Trees
EC	Exposed coral
FBh	Fisherman's Beach
BtB	Boat Beach
SC	Sea caves
Beach Classification	
R	Rock
S	Sand
SaR	Sand and Rock
SoR	Sand on Rock
RB	Rock Bluff
Offshore Protection	
1	Present
0	Not present

Appendix D-1- Continued. Geomorphic Shoreline Assessment for transect sites beach survey.

Code	Description	Code	Description
Beach Protection Classification and Vegetation		R	Rock
AD	Aeolian dune	RB	Rock bluff
AS	Aeolian sheet	Rbo	Rock bolder
ASbR	Aeolian sheet behind rock	RoS	Rock on sand
BD	Back dune	RR	Rip rap
DT	Dune terrace	SB	Sand bluff
G	Grass	SbR	Sand between rock
GoD	Grass on dune	SD	Sand dune/s
GoSS	Grass on sand sheet	SDbLV	Sand dune behind low vegetation
HSB	High sand bluff	Sh	Shrubs
HSD	High sand dune/s	ShT	Shoreline terrace
HSlB	High soil bluff	Sl	Soil
LASD	Low aeolian sand dune	SoR	Sand on Rock
LBT	Low beach terrace	T	Trees
LS	Low sand	TcS	Trees cover sand
LSB	Low sand bluff	U	Uplands
LSD	Low sand dune/s	V	Vegetation
LSh	Low shrubs	VoD	Vegetation on dune
LSht	Low sheet	VoS	Vegetation on sand
LST	Low sand terrace		
LV	Low vegetation		
OSD	Old Sand Dune		

Appendix D-1- Continued. Geomorphic Shoreline Assessment for transect sites beach survey.

Code	Description
Anthropogenic Feature	
BW	Brick wall
Bl	Building
WF	Wire fence
WH	Wood house
F	Fence
SW	Stone wall
WdF	Wood fence
LF	Low fence
SW	Stone wall
LSW	Low stone wall
RW	Rock wall
SW	Sea Wall
BRW	Big rock wall
CaWW	Cement and wood wall
CW	Cement wall
Bt	Boat
ZF	Zinc fence
LW	Low wall
WoR	Wall on rock
WD	Wetland drain
W	Wall

Code	Description
BF	Brick foundation
RR	Rip rap
AbP	Altered by people
RW	Rock wall
Landuse/ Landcover	
N	Natural
BUA	Built-up area

Appendix D-2: Field data based on the 2021 and 2023 beach surveys.

Tran -sect	Beach Name	Other Name	Notes	Berm Height (m)	Beach Angle	Vegetated Sand (m)	Beach Width (m)	Landuse/ Landcover
1	GB	PB	N/A	1.28	7.3	0	18	BUA, N
2	GB	PB	N/A	1.08	8	2	32	BUA, N
3	GB	PB	N/A	0.78	7	0	25	BUA, N
4	GB	PB	N/A	0.68	5.8	0	31	BUA, N
5	GB	PB	N/A	0.88	6	0	49	BUA, N
6	GB	PB	N/A	0.38	2.3	9	45	BUA, N
7	GB	PB	N/A	0.38	5.2	10	50	BUA, N
8	GB	PB	F	0.18	6.6	18	58	BUA, N
9	GB	PB	N/A	0.58	7.6	0	30	BUA, N
10	GB	PB	N/A	-0.12	5	2	43	BUA, N
11	GB	PB	N/A	0.58	5.2	4	38	BUA, N
12	GB	PB	N/A	0.08	8.7	7	70	BUA, N
13	GB	PB	N/A	-0.42	7.7	0	55	N
14	GB	PB	N/A	0.18	5.1	2	28	N
15	GB	PB	N/A	N/A	N/A	N/A	N/A	N
16	GB	PB	N/A	N/A	N/A	N/A	N/A	BUA, N
17	GB	PB	N/A	N/A	N/A	N/A	N/A	BUA, N
18	GB	PB	N/A	N/A	N/A	N/A	N/A	N
19	GB	PB	N/A	N/A	N/A	N/A	N/A	N
20	GB	PB	UL	N/A	N/A	N/A	N/A	BUA, N
21	GB	PB	N/A	N/A	N/A	N/A	N/A	BUA, N
22	GB	PB	N/A	N/A	N/A	N/A	N/A	BUA, N

Appendix D-2- Continued. Field data based on the 2021 and 2023 beach surveys.

Tran -sect	Beach Name	Other Name	Notes	Berm Height (m)	Beach Angle	Vegetated Sand (m)	Beach Width (m)	Landuse/ Landcover
23	GB	PB	N/A	N/A	N/A	N/A	N/A	N
24	GB	PB	N/A	0.58	11.8	10	29	N
25	GB	PB	N/A	N/A	N/A	N/A	N/A	N
26	GB	PB	N/A	N/A	N/A	N/A	N/A	N
27	GB	PB	N/A	N/A	N/A	N/A	N/A	N
28	GB	PB	N/A	N/A	N/A	N/A	N/A	N
29	GB	PB	N/A	N/A	N/A	N/A	N/A	N
30	GB	PB	N/A	N/A	N/A	N/A	N/A	N
31	GB	PB	N/A	N/A	N/A	N/A	N/A	N
32	GB	PB	N/A	N/A	N/A	N/A	N/A	N
33	GB	PB	N/A	N/A	N/A	N/A	N/A	N
34	GB	PB	N/A	N/A	N/A	N/A	N/A	N
35	GB	PB	N/A	N/A	N/A	N/A	N/A	N
36	GB	PB	N/A	N/A	N/A	N/A	N/A	N
37	GB	PB	N/A	N/A	N/A	N/A	N/A	N
38	GB	PB	N/A	N/A	N/A	N/A	N/A	N
39	GB	PB	N/A	N/A	N/A	N/A	N/A	N
40	GB	PB	N/A	N/A	N/A	N/A	N/A	N
41	GB	PB	N/A	N/A	N/A	N/A	N/A	N
42	GB	PB	N/A	0.08	7.8	4	18	BUA, N
43	GB	PB	N/A	N/A	N/A	N/A	N/A	BUA, N

Appendix D-2- Continued. Field data based on the 2021 and 2023 beach surveys.

Tran-sect	Beach Name	Other Name	Notes	Berm Height (m)	Beach Angle	Vegetated Sand (m)	Beach Width (m)	Landuse/ Landcover
44	GB	PB	UL, F, WCP	N/A	N/A	N/A	N/A	BUA, N
45	GB	PB	WCP	N/A	N/A	N/A	N/A	BUA, N
46	GB	PB	N/A	N/A	N/A	N/A	N/A	BUA, N
47	GB	PB	N/A	N/A	N/A	N/A	N/A	BUA, N
48	OW	N/A	N/A	-0.42	10.6	0	27	N
49	OW	N/A	WB, RW	0.58	N/A	10	27	BUA, N
50	OW	N/A	N/A	-0.52	9	4	22	BUA, N
51	OW	N/A	RW	0.78	7.8	8	33	BUA, N
52	OW	N/A	N/A	N/A	N/A	N/A	N/A	BUA, N
53	OW	N/A	N/A	N/A	N/A	N/A	N/A	BUA, N
54	OW	N/A	N/A	N/A	N/A	N/A	N/A	BUA, N
55	OW	N/A	F	N/A	N/A	3	14	BUA, N
56	OW	N/A	N/A	N/A	N/A	N/A	N/A	BUA, N
57	OW	N/A	N/A	0.88	7	10	18	BUA, N
58	OW	N/A	N/A	0.58	7.6	4	19	BUA, N
59	OW	N/A	N/A	0.78	7.6	8	18	N
60	OW	N/A	N/A	N/A	N/A	N/A	N/A	BUA, N
61	OW	N/A	N/A	0.88	5.1	0	18	BUA, N
62	OW	N/A	N/A	0.38	7.3	8	25	N
63	OW	N/A	N/A	N/A	N/A	N/A	N/A	BUA, N
64	OW	N/A	N/A	N/A	N/A	N/A	N/A	BUA, N

Appendix D-2- Continued. Field data based on the 2021 and 2023 beach surveys.

Tran -sect	Beach Name	Other Name	Notes	Berm Height (m)	Beach Angle	Vegetated Sand (m)	Beach Width (m)	Landuse/ Landcover
65	OW	N/A	N/A	N/A	N/A	N/A	N/A	N
66	OW	N/A	N/A	N/A	N/A	N/A	N/A	BUA, N
67	OW	N/A	N/A	N/A	N/A	N/A	N/A	N
68	OW	N/A	N/A	N/A	N/A	N/A	N/A	BUA, N
69	OW	N/A	N/A	N/A	N/A	N/A	N/A	BUA, N
70	OW	N/A	N/A	N/A	N/A	N/A	N/A	BUA, N
71	OW	N/A	N/A	N/A	N/A	N/A	N/A	BUA, N
72	CB	N/A	N/A	0.08	8.3	7	28	BUA, N
73	CB	N/A	N/A	N/A	N/A	N/A	45	BUA, N
74	CB	N/A	N/A	N/A	N/A	N/A	40	BUA, N
75	CB	N/A	N/A	N/A	N/A	40	80	BUA, N
76	CB	N/A	N/A	0.68	6.5	0	17	BUA, N
77	CB	N/A	N/A	1.48	4.2	4	24	BUA, N
78	CB	N/A	N/A	0.58	2.6	4	23	BUA, N
79	CB	N/A	N/A	1.58	3	0	23	BUA, N
80	CB	N/A	N/A	0.68	6.7	6	30	BUA, N
81	CB	N/A	N/A	1.08	10.1	2	25	BUA, N
82	CB	N/A	N/A	0.28	7.7	0	22	BUA, N
83	CB	N/A	N/A	N/A	N/A	N/A	N/A	BUA, N
84	CB	N/A	N/A	N/A	N/A	N/A	N/A	BUA, N
85	CB	N/A	N/A	N/A	N/A	N/A	N/A	BUA, N

Appendix D-2- Continued. Field data based on the 2021 and 2023 beach surveys.

Tran-sect	Beach Name	Other Name	Notes	Berm Height (m)	Beach Angle	Vegetated Sand (m)	Beach Width (m)	Landuse/ Landcover
86	CB	N/A	N/A	N/A	N/A	N/A	N/A	BUA, N
87	CB	N/A	N/A	N/A	N/A	N/A	N/A	BUA, N
88	CB	N/A	N/A	N/A	N/A	N/A	N/A	BUA, N
89	CB	N/A	N/A	N/A	N/A	N/A	N/A	BUA, N
90	CB	N/A	N/A	N/A	N/A	N/A	N/A	BUA, N
91	FB	N/A	N/A	N/A	N/A	N/A	N/A	BUA, N
92	FB	N/A	N/A	N/A	N/A	N/A	N/A	BUA, N
93	FB	N/A	N/A	N/A	N/A	N/A	N/A	BUA, N
94	FB	N/A	N/A	1.28	6.5	0	15	N
95	FB	N/A	N/A	0.28	8.7	3	17	BUA, N
96	FB	N/A	SS	N/A	N/A	0	7	N
97	FB	N/A	T, EC	N/A	N/A	0	N/A	BUA, N
98	FB	N/A	SS, T, FBh, BtB	N/A	N/A	0	N/A	BUA, N
99	FB	N/A	FBh, BtB	0.58	6.7	0	22	BUA, N
100	FB	N/A	FBh, BtB	0.78	4.7	0	17	BUA, N
101	FB	N/A	N/A	0.38	6.9	3	14	BUA, N
102	FB	N/A	N/A	0.78	6.1	4	16	BUA, N
103	FB	N/A	N/A	0.98	5.9	0	15	BUA, N
104	FB	N/A	N/A	0.58	9.6	0	20	N
105	FB	N/A	N/A	0.58	9.4	0	22	N
106	FB	N/A	N/A	1.38	6.2	2	24	N

Appendix D-2- Continued. Field data based on the 2021 and 2023 beach surveys.

Tran-sect	Beach Name	Other Name	Notes	Berm Height (m)	Beach Angle	Vegetated Sand (m)	Beach Width (m)	Landuse/ Landcover
107	FB	N/A	N/A	0.38	5.6	2	21	BUA, N
108	FB	N/A	N/A	0.28	8.2	0	N/A	BUA, N
109	FB	N/A	N/A	0.68	9.3	0	N/A	BUA, N
110	FB	N/A	N/A	0.68	15	0	N/A	N
111	FB	N/A	N/A	1.68	9.3	0	N/A	N
112	FB	N/A	N/A	N/A	N/A	N/A	N/A	N
113	FB	JR	N/A	N/A	N/A	N/A	N/A	BUA, N
114	FB	JR	N/A	N/A	N/A	N/A	N/A	BUA, N
115	FB	JR	N/A	N/A	N/A	N/A	N/A	BUA, N
116	FB	JR	N/A	N/A	N/A	N/A	N/A	BUA, N
117	FB	JR	N/A	N/A	N/A	N/A	N/A	BUA, N
118	FB	JR	N/A	N/A	N/A	N/A	N/A	N
119	FB	JR	N/A	N/A	N/A	N/A	N/A	N
120	FB	JR	N/A	N/A	N/A	N/A	N/A	N
121	FB	JR	N/A	N/A	N/A	N/A	N/A	N
122	FB	JR	N/A	N/A	N/A	N/A	N/A	N
123	FB	SB	N/A	N/A	N/A	N/A	N/A	N
124	FB	SB	N/A	N/A	N/A	N/A	N/A	N
125	FB	SB	N/A	N/A	N/A	N/A	N/A	N
126	FB	BSB	N/A	N/A	N/A	N/A	N/A	N
127	FB	BSB	N/A	N/A	N/A	N/A	N/A	N

Appendix D-2- Continued. Field data based on the 2021 and 2023 beach surveys.

Tran -sect	Beach Name	Other Name	Notes	Berm Height (m)	Beach Angle	Vegetated Sand (m)	Beach Width (m)	Landuse/ Landcover
128	FB	BSB	N/A	N/A	N/A	N/A	N/A	BUA, N
129	BB	BSB/ TB	N/A	N/A	N/A	N/A	N/A	N
130	BB	BSB/ TB	N/A	N/A	N/A	N/A	N/A	N
131	BB	BSB/ TB	N/A	N/A	N/A	N/A	N/A	BUA, N
132	BB	BSB/ TB	N/A	N/A	N/A	N/A	N/A	BUA, N
133	BB	BSB/ TB	N/A	N/A	N/A	N/A	N/A	BUA, N
134	BB	TB	N/A	N/A	N/A	N/A	N/A	BUA, N
135	BB	TB	N/A	N/A	N/A	N/A	N/A	BUA, N
136	BB	TB	N/A	N/A	N/A	N/A	N/A	BUA, N
137	BB	TB	N/A	N/A	N/A	N/A	N/A	BUA, N
138	BB	N/A	N/A	N/A	N/A	N/A	N/A	BUA, N
139	BB	N/A	N/A	N/A	N/A	N/A	N/A	BUA, N
140	BB	N/A	N/A	0.18	8	0	11	N
141	BB	N/A	N/A	0.58	6.9	0	20	BUA, N
142	BB	N/A	N/A	0.78	7.9	0	15	BUA, N
143	BB	N/A	N/A	0.38	6	3	15	BUA, N
144	BB	N/A	N/A	0.28	7.2	7	17	BUA, N
145	BB	N/A	N/A	0.88	5.9	5	14	N
146	BB	N/A	N/A	0.48	6.9	1	12	N

Appendix D-2- Continued. Field data based on the 2021 and 2023 beach surveys.

Tran -sect	Beach Name	Other Name	Notes	Berm Height (m)	Beach Angle	Vegetated Sand (m)	Beach Width (m)	Landuse/ Landcover
147	BB	N/A	N/A	0.38	7.4	0	17	BUA, N
148	BB	N/A	N/A	0.58	7	3	21	BUA, N
149	BB	N/A	N/A	N/A	N/A	3	7	BUA, N
150	BB	N/A	Well	1.28	7.4	0	11	N
151	BB	N/A	N/A	0.38	N/A	7	27	N
152	BB	N/A	N/A	0.48	8.1	0	25	BUA, N
153	BB	N/A	N/A	0.28	8.5	2	25	BUA, N
154	BB	N/A	N/A	0.68	9.9	0	11	N
155	BB	N/A	N/A	N/A	N/A	N/A	9	N
156	BB	N/A	N/A	N/A	N/A	N/A	7	BUA, N
157	BB	N/A	N/A	N/A	N/A	N/A	N/A	BUA, N
158	BB	N/A	N/A	N/A	N/A	N/A	N/A	BUA, N
159	MB	BS	N/A	N/A	N/A	N/A	7	N
160	MB	BS	N/A	1.28	8.3	7	13	N
161	MB	BS	N/A	2.18	8.9	9	27	N
162	MB	BS	N/A	1.28	6.7	0	17	N
163	MB	BS	N/A	1.08	9.5	3	20	N
164	MB	N/A	N/A	N/A	N/A	12	28	N
165	MB	N/A	N/A	N/A	N/A	2	24	BUA, N
166	MB	N/A	N/A	1.08	7.8	3	16	BUA, N
167	MB	N/A	N/A	-3.62	11.2	0	30	BUA, N

Appendix D-2- Continued. Field data based on the 2021 and 2023 beach surveys.

Tran-sect	Beach Name	Other Name	Notes	Berm Height (m)	Beach Angle	Vegetated Sand (m)	Beach Width (m)	Landuse/ Landcover
168	MB	N/A	N/A	N/A	N/A	5	16	N
169	MB	N/A	N/A	0.68	10.6	0	18	N
170	MB	N/A	N/A	N/A	N/A	N/A	N/A	BUA, N
171	MB	N/A	N/A	N/A	N/A	N/A	N/A	N
172	MB	N/A	N/A	N/A	N/A	N/A	N/A	N
173	MB	N/A	N/A	0.68	6.3	0	35	N
174	MB	N/A	N/A	0.18	10.9	0	50	N
175	MB	N/A	N/A	N/A	1.3	0	49	N
176	MB	N/A	N/A	1.78	5.2	0	40	N
177	MB	N/A	N/A	1.28	7.6	0	18	N
178	MB	N/A	N/A	N/A	N/A	N/A	N/A	N
179	MB	N/A	N/A	N/A	N/A	N/A	N/A	N
180	MB	N/A	N/A	N/A	N/A	N/A	N/A	N
181	BLB	HB/ TTB	N/A	N/A	N/A	N/A	N/A	N
182	BLB	HB/ TTB	N/A	0.88	7.3	5	13	N
183	BLB	HB/ TTB	N/A	-0.72	10.8	10	35	N
184	BLB	HB/ TTB	N/A	1.88	10.8	7	32	N
185	BLB	HB/ TTB	N/A	-0.22	10.1	1	14	N

Appendix D-2- Continued. Field data based on the 2021 and 2023 beach surveys.

Tran-sect	Beach Name	Other Name	Notes	Berm Height (m)	Beach Angle	Vegetated Sand (m)	Beach Width (m)	Landuse/ Landcover
186	BLB	HB/ TTB	N/A	0.38	10.8	9	23	N
187	BLB	HB/ TTB	N/A	0.58	10.6	6	15	BUA, N
188	BLB	HB/ TTB	N/A	N/A	N/A	N/A	N/A	BUA, N
189	BLB	HB/ TTB	N/A	N/A	N/A	N/A	N/A	BUA, N
190	BLB	HB/ TTB	N/A	N/A	N/A	N/A	N/A	BUA, N
191	BLB	HB/ TTB	N/A	N/A	N/A	N/A	N/A	BUA, N
192	BLB	HB/ TTB	N/A	N/A	N/A	N/A	N/A	BUA, N
193	BLB	HB/ TTB	N/A	N/A	N/A	N/A	N/A	BUA, N
194	BLB	FC/ TTB	N/A	N/A	N/A	N/A	N/A	BUA, N
195	BLB	FC/ TTB	N/A	N/A	N/A	N/A	N/A	BUA, N
196	BLB	FC/ TTB	N/A	N/A	N/A	N/A	N/A	BUA, N
197	BLB	FC/ TTB	N/A	N/A	N/A	N/A	N/A	N
198	BLB	FC/ TTB	N/A	N/A	N/A	N/A	N/A	N
199	BLB	FC/ TTB	N/A	N/A	N/A	N/A	N/A	N

Appendix D-2- Continued. Field data based on the 2021 and 2023 beach surveys.

Tran -sect	Beach Name	Other Name	Notes	Berm Height (m)	Beach Angle	Vegetated Sand (m)	Beach Width (m)	Landuse/ Landcover
200	BLB	FC/ TTB	N/A	N/A	N/A	N/A	N/A	N
201	BLB	FC/ TTB	N/A	N/A	N/A	N/A	N/A	N
202	BLB	FC/ TTB	N/A	N/A	N/A	N/A	N/A	N
203	BLB	FC/ TTB	N/A	N/A	N/A	N/A	N/A	N
204	BLB	FC/ TTB	N/A	N/A	N/A	N/A	N/A	BUA, N
205	BLB	FC/ TTB	N/A	N/A	N/A	N/A	N/A	N
206	BLB	FC/ TTB	N/A	N/A	N/A	N/A	N/A	N
207	BLB	FC/ TTB	SC	N/A	N/A	N/A	N/A	BUA, N
208	BLB	FC/ TTB	N/A	N/A	N/A	N/A	N/A	N
209	BLB	FC/ TTB	N/A	N/A	N/A	N/A	N/A	N
210	BLB	FC/ TTB	N/A	N/A	N/A	N/A	N/A	BUA, N
211	BLB	FC/ TTB	N/A	N/A	N/A	N/A	N/A	BUA, N
212	BLB	FC/ TTB	N/A	N/A	N/A	N/A	N/A	BUA, N
213	BLB	FC/ TTB	N/A	N/A	N/A	N/A	N/A	BUA, N

Appendix D-2- Continued. Field data based on the 2021 and 2023 beach surveys.

Tran -sect	Beach Name	Other Name	Notes	Berm Height (m)	Beach Angle	Vegetated Sand (m)	Beach Width (m)	Landuse/ Landcover
214	SGB	FC	N/A	N/A	N/A	N/A	N/A	N
215	SGB	FC	N/A	N/A	N/A	N/A	N/A	N
216	SGB	FC	N/A	N/A	N/A	N/A	N/A	N
217	SGB	FC	N/A	N/A	N/A	N/A	N/A	N
218	SGB	FC	N/A	N/A	N/A	N/A	N/A	BUA, N
219	SGB	FC	N/A	N/A	N/A	N/A	N/A	BUA, N
220	SGB	FC	N/A	N/A	N/A	N/A	N/A	BUA, N
221	SGB	FC	N/A	N/A	N/A	N/A	N/A	BUA, N
222	SGB	FC	N/A	N/A	N/A	N/A	N/A	BUA, N
223	SGB	FC	N/A	N/A	N/A	N/A	N/A	N
224	SGB	FC	N/A	N/A	N/A	N/A	N/A	N
225	SGB	FC	N/A	N/A	N/A	N/A	N/A	N

Appendix D-3: Beach classification field data based on the 2021 and 2023 beach surveys.

Tran-sect	Beach Clas-sifica-tion	Sand (%)	Rock (%)	Near-shore Pro-tection	Beach Pro-tection Length (m)	Beach Protection Classi-fication	Vege-tation	Anthro-pogenic Feature	Feature Height (m)
1	S	100	0	0	0	R	N/A	N/A	2.7
2	S	100	0	0	2	N/A	T	BW	2.5
3	S	100	0	0	0	GoSS	N/A	N/A	2.2
4	S	100	0	0	0	N/A	N/A	B	2.1
5	S	100	0	0	0	N/A	N/A	WF, WH	2.3
6	S	100	0	0	9	GoSS	N/A	F	1.8
7	S	100	0	0	10	G, AS	N/A	SW	1.8
8	S	100	0	0	8	AS	G	F	1.6
9	S	100	0	0	0	R	N/A	N/A	2
10	S	100	0	0	2	G, SD, R	G, Sh, T	N/A	1.3
11	S	100	0	0	4	R	Sh, T	N/A	2
12	S	100	0	0	7	AS	N/A	WdF	1.5
13	S	100	0	0	0	Sh, SB	N/A	N/A	1
14	R	0	100	0	2	G, SD	Sh, T	N/A	1.6
15	SoR	0	100	0	N/A	N/A	G, Sh, T	N/A	N/A
16	SoR	0	100	0	N/A	N/A	G, Sh, T	N/A	N/A
17	SoR	0	100	0	N/A	N/A	G, Sh, T	N/A	N/A
18	R	0	100	0	N/A	N/A	G, Sh	N/A	N/A
19	R	0	100	0	N/A	N/A	G	WF	N/A
20	R	0	100	0	N/A	N/A	G	WF	N/A
21	R	0	100	0	N/A	N/A	G, LV, LSD	N/A	N/A

Appendix D-3: Beach classification field data based on the 2021 and 2023 beach surveys.

Tran -sect	Beach Clas-sifica-tion	Sand (%)	Rock (%)	Near-shore Pro-tection	Beach Pro-tection Length (m)	Beach Protection Classi-fication	Vege-tation	Anthro-pogenic Feature	Feature Height (m)
22	R	0	100	0	N/A	N/A	LV, LSD	N/A	N/A
23	R	0	100	0	N/A	SoR	Sh	BW	N/A
24	S	100	0	0	10	LS	G, Sh, T	N/A	2
25	R	0	100	0	N/A	N/A	G, Sh, T	N/A	N/A
26	R	0	100	0	N/A	SoR	G, Sh, T	N/A	N/A
27	R	0	100	0	N/A	SoR	G, Sh, T, U	N/A	N/A
28	R	0	100	0	N/A	SoR, SbR	G, Sh, T	N/A	N/A
29	R	0	100	0	N/A	N/A	G, U	N/A	N/A
30	R	0	100	0	N/A	N/A	G, U	N/A	N/A
31	R	0	100	0	N/A	N/A	G, U	N/A	N/A
32	R	0	100	0	N/A	N/A	G, U	N/A	N/A
33	R	0	100	0	N/A	N/A	G	LF	N/A
34	R	0	100	0	N/A	LSD	G	N/A	N/A
35	R	0	100	0	N/A	LSD	G	N/A	N/A
36	R	0	100	0	N/A	LSD, R	G, Sh	N/A	N/A
37	R	0	100	0	N/A	LSD, R	G	N/A	N/A
38	R	0	100	0	N/A	SD	G	N/A	N/A
39	R	0	100	0	N/A	SD	G	N/A	N/A
40	R	0	100	0	N/A	SD, R	Sh	N/A	N/A
41	R	0	100	0	N/A	N/A	T	N/A	N/A

Appendix D-3: Beach classification field data based on the 2021 and 2023 beach surveys.

Tran -sect	Beach Clas-sifica-tion	Sand (%)	Rock (%)	Near-shore Pro-tection	Beach Pro-tection Length (m)	Beach Protection Classi-fication	Vege-tation	Anthro-pogenic Feature	Feature Height (m)
42	SaR	90	10	1	4	LV, Sh	N/A	SW	1.5
43	R	0	100	0	N/A	N/A	N/A	LSW, WF	N/A
44	R	0	100	0	N/A	N/A	N/A	LSW, WF	N/A
45	R	0	100	0	N/A	N/A	V	RW	N/A
46	R	0	100	0	N/A	N/A	N/A	RW	N/A
47	R	0	100	0	N/A	N/A	N/A	SW	N/A
48	S	100	0	1	0	LSht	G, Sh, T	N/A	1
49	S	100	0	1	10	V, T	Sh, T	N/A	2
50	S	100	0	1	4	LV, SD	HSD, LV	N/A	0.9
51	S	100	0	1	8	LV, SD	SDbLV	N/A	2.2
52	R	0	100	1	N/A	ASbR	G, SD	WdF	N/A
53	R	0	100	1	N/A	ASbR	N/A	BRW	N/A
54	R	0	100	1	N/A	SD	LV, Sh	N/A	N/A
55	R	0	100	1	3	SD	Sh	N/A	N/A
56	R	0	100	0	N/A	SD	G, Sh	N/A	N/A
57	S	100	0	1	10	LV, LS	N/A	N/A	2.3
58	S	100	0	1	4	G, AD	T	N/A	2
59	S	100	0	1	8	LV, LSht	N/A	N/A	2.2
60	R	0	100	0	N/A	V, LSD	N/A	N/A	N/A

Appendix D-3: Beach classification field data based on the 2021 and 2023 beach surveys.

Tran-sect	Beach Clas-sifica-tion	Sand (%)	Rock (%)	Near-shore Pro-tection	Beach Pro-tection Length (m)	Beach Protection Classi-fication	Vege-tation	Anthro-pogenic Feature	Feature Height (m)
61	R	0	100	1	0	N/A	N/A	CaWW	2.3
62	SaR	90	10	1	8	V, LSD	N/A	N/A	1.8
63	R	0	100	0	N/A	N/A	N/A	RW	N/A
64	R	0	100	0	N/A	N/A	N/A	CW	N/A
65	R	0	100	0	N/A	LSD	G, Sh	N/A	N/A
66	R	0	100	0	N/A	N/A	N/A	CW	N/A
67	R	0	100	0	N/A	OSD	G, Sh	N/A	N/A
68	SoR	0	100	0	N/A	OSD	G, LV	N/A	N/A
69	R	0	100	0	N/A	LS	G	WdF	N/A
70	R	0	100	0	N/A	LS	G, LSh	BW	N/A
71	R	0	100	0	N/A	N/A	G, LSh	N/A	N/A
72	SaR	0	0	1	7	V, AS	LSh	N/A	1.5
73	R	0	100	1	20	R, LSB, BD	G, V	N/A	N/A
74	R	0	100	1	17	R, LSh	N/A	N/A	N/A
75	R	0	100	1	40	SoR	V, Sh	N/A	N/A
76	S	100	0	1	0	N/A	N/A	Bl	2.1
77	SaR	60	40	1	4	RoS	N/A	Bl	2.9
78	S	100	0	1	4	N/A	N/A	B, ZF, Bl	2
79	SaR	20	80	1	0	N/A	N/A	WdF	3
80	S	100	0	1	6	LS	G, T	LW	2.1

Appendix D-3: Beach classification field data based on the 2021 and 2023 beach surveys.

Tran -sect	Beach Clas- sifica- tion	Sand (%)	Rock (%)	Near- shore Pro- tection	Beach Pro- tection Length (m)	Beach Protection Classi- fication	Vege- tation	Anthro- pogenic Feature	Feature Height (m)
81	S	100	0	0	2	AS, R	N/A	WdF	2.5
82	S	100	0	1	8	AS	N/A	WoR	1.7
83	R	0	100	0	N/A	N/A	N/A	N/A	N/A
84	R	0	100	0	N/A	N/A	N/A	N/A	N/A
85	R	0	100	0	N/A	N/A	N/A	N/A	N/A
86	R	0	100	0	N/A	N/A	N/A	N/A	N/A
87	R	0	100	0	N/A	N/A	N/A	N/A	N/A
88	R	0	100	0	N/A	N/A	N/A	N/A	N/A
89	R	0	100	0	N/A	N/A	N/A	N/A	N/A
90	R	0	100	0	N/A	N/A	N/A	N/A	N/A
91	R	0	100	0	N/A	N/A	N/A	N/A	N/A
92	R	0	100	0	N/A	N/A	N/A	N/A	N/A
93	R	0	100	1	N/A	N/A	N/A	N/A	N/A
94	S	100	0	1	0	LS	T	F	2.7
95	S	100	0	1	3	LS, G	T	F	1.7
96	SaR	40	60	1	0	LS, G, R	N/A	F	N/A
97	R	0	100	1	0	G	N/A	N/A	N/A
98	R	0	100	1	0	N/A	N/A	N/A	N/A
99	S	100	0	1	0	LS	T	WD	2
100	S	95	0	1	0	LS, G	N/A	W	2.2

Appendix D-3: Beach classification field data based on the 2021 and 2023 beach surveys.

Tran-sect	Beach Classification	Sand (%)	Rock (%)	Near-shore Protection	Beach Protection Length (m)	Beach Protection Classification	Vegetation	Anthropogenic Feature	Feature Height (m)
101	S	100	0	0	3	GoD	N/A	CW	1.8
102	S	100	0	0	4	VoD	N/A	CW	2.2
103	S	100	0	0	0	N/A	N/A	BF, WdF	2.4
104	S	100	0	0	0	SD	T	N/A	2
105	S	100	0	0	0	V	T	RR	2
106	S	100	0	1	2	AS	V	RR	2.8
107	S	100	0	1	7	VoS	V	RR	1.8
108	S	100	0	0	2	VoS	V	RR	1.7
109	S	100	0	0	3	VoD, SB	G, T	N/A	2.1
110	S	100	0	0	4.5	D, SB	G, T	N/A	2.1
111	S	100	0	0	9	AS, SB	G, Sh	N/A	3.1
112	R	0	0	1	N/A	R, SB	Sh	N/A	N/A
113	R	0	0	0	N/A	N/A	V, Sh, T	N/A	N/A
114	R	0	0	0	N/A	N/A	N/A	N/A	N/A
115	R	0	0	0	N/A	N/A	N/A	N/A	N/A
116	R	0	0	0	N/A	N/A	N/A	N/A	N/A
117	R	0	0	0	N/A	N/A	N/A	N/A	N/A
118	R	0	0	0	N/A	N/A	N/A	N/A	N/A
119	R	0	0	0	N/A	N/A	N/A	N/A	N/A
120	R	0	0	0	N/A	N/A	N/A	N/A	N/A

Appendix D-3: Beach classification field data based on the 2021 and 2023 beach surveys.

Tran-sect	Beach Clas-sifica-tion	Sand (%)	Rock (%)	Near-shore Pro-tection	Beach Pro-tection Length (m)	Beach Protection Classi-fication	Vege-tation	Anthro-pogenic Feature	Feature Height (m)
121	SaR	0	0	0	N/A	N/A	N/A	N/A	N/A
122	R	0	0	0	N/A	N/A	N/A	N/A	N/A
123	R	0	0	0	N/A	N/A	N/A	N/A	N/A
124	S	0	0	0	N/A	N/A	G	N/A	N/A
125	R	0	0	0	N/A	N/A	N/A	N/A	N/A
126	S	0	0	0	N/A	N/A	G	N/A	N/A
127	S	0	0	0	N/A	N/A	G	N/A	N/A
128	S	0	0	0	N/A	N/A	N/A	N/A	N/A
129	S	0	0	0	N/A	R	N/A	N/A	N/A
130	S	0	0	0	N/A	R	V, Sh	N/A	N/A
131	S	0	0	0	N/A	R	V, Sh	N/A	N/A
132	S	0	0	0	N/A	R	V, Sh	N/A	N/A
133	S	0	0	0	N/A	R	N/A	N/A	N/A
134	R	0	0	0	N/A	R	N/A	N/A	N/A
135	R	0	0	0	N/A	R	N/A	N/A	N/A
136	R	0	0	0	N/A	R	N/A	N/A	N/A
137	R	0	0	0	N/A	R	N/A	N/A	N/A
138	R	0	0	0	N/A	N/A	Sh, T	N/A	N/A
139	R	0	0	0	N/A	N/A	V, Sh, T	N/A	N/A
140	S	100	0	1	N/A	LST	V, Sh, T	N/A	1.6

Appendix D-3: Beach classification field data based on the 2021 and 2023 beach surveys.

Tran -sect	Beach Clas- sifica- tion	Sand (%)	Rock (%)	Near- shore Pro- tection	Beach Pro- tection Length (m)	Beach Protection Classi- fication	Vege- tation	Anthro- pogenic Feature	Feature Height (m)
141	S	100	0	1	N/A	N/A	G, V, T	CW	2
142	S	100	0	1	N/A	SD	V, Sh, T	AbP	2.2
143	S	100	0	1	3	V, LST	G, V, Sh, T	WF	1.8
144	S	100	0	1	7	V, LSD	G, V, Sh, T	WF	1.7
145	S	100	0	1	2	G, LSD	G, V, Sh, T	N/A	2.3
146	S	100	0	1	1	V, LSD	V, Sh, T	N/A	1.9
147	S	100	0	1	5	V, LSD	G, V, T	WdF	1.8
148	S	100	0	1	5	LASD	G, V, T	WF	2
149	R	0	100	1	N/A	SbR	T	N/A	N/A
150	S	100	0	1	N/A	HSB, Sl	G, V, Sh, T	N/A	2.7
151	S	100	0	1	N/A	V, LSD, LBT, R	V, T	N/A	1.8
152	S	100	0	1	0	R	G, V, T	WF	1.9
153	S	100	0	1	10	V, SB, R	G, V, T	N/A	1.7
154	S	100	0	0	N/A	V, SB, R	G, V, T	N/A	2.1
155	R	0	100	1	N/A	R	G, V, T	CW	N/A
156	R	0	100	1	N/A	SbR, RR, R	G, V, T	N/A	N/A
157	R	0	100	0	N/A	R	T	N/A	N/A

Appendix D-3: Beach classification field data based on the 2021 and 2023 beach surveys.

Tran-sect	Beach Clas-sifica-tion	Sand (%)	Rock (%)	Near-shore Pro-tection	Beach Pro-tection Length (m)	Beach Protection Classi-fication	Vege-tation	Anthro-pogenic Feature	Feature Height (m)
158	R	0	100	0	N/A	RB	N/A	WF	N/A
159	R	0	100	1	N/A	SbR, R	Sh, T	N/A	N/A
160	S	100	0	1	7	LBT	V, Sh, T	N/A	2.7
161	S	100	0	1	9	LSD	V, Sh, T	N/A	3.6
162	S	100	0	1	6	DT	V, Sh, T	AbP	2.7
163	S	100	0	1	3	ShT	V, Sh, T	N/A	2.5
164	R	0	100	1	12	LSD, SB, R	G, T	N/A	N/A
165	R	0	100	1	N/A	SbR	G, T	W	N/A
166	SaR	90	10	1	N/A	N/A	G, T	CW	2.5
167	SaR	90	10	1	N/A	N/A	G, V, T	WF	-2.2
168	R	0	100	1	5	V, LSD	G, T	N/A	N/A
169	SaR	5	95	1	5	LSD	G, T	N/A	2.1
170	R	0	100	1	N/A	R	T	N/A	N/A
171	R	0	100	1	N/A	R	T	N/A	N/A
172	R	0	100	1	N/A	R	T	RW	N/A
173	SaR	90	10	1	10	V, SD	Sh, T	N/A	2.1
174	SaR	50	50	1	20	SD	Sh, T	N/A	1.6
175	R	0	100	1	17	HSD	Sh, T	N/A	4
176	SaR	10	90	1	15	LSD	G, T	N/A	3.2
177	SaR	90	10	1	N/A	RR, R	HSlB, T	N/A	2.7

Appendix D-3: Beach classification field data based on the 2021 and 2023 beach surveys.

Tran -sect	Beach Clas-sifica-tion	Sand (%)	Rock (%)	Near-shore Pro-tection	Beach Pro-tection Length (m)	Beach Protection Classi-fication	Vege-tation	Anthro-pogenic Feature	Feature Height (m)
178	R	0	100	0	N/A	R	RB	N/A	N/A
179	R	0	100	0	N/A	R	RB, T	N/A	N/A
180	R	0	100	0	N/A	R	RB, T	N/A	N/A
181	R	0	100	0	N/A	Rbo	T	N/A	N/A
182	SaR	80	20	1	N/A	R	T	WD	2.3
183	S	100	0	1	N/A	LSD, R	T	N/A	0.7
184	SaR	50	50	1	7	TcS	T	N/A	3.3
185	SaR	90	10	1	1	LSD	T	N/A	1.2
186	SaR	90	10	1	N/A	SD, R	T	N/A	1.8
187	SaR	90	10	1	0	RR, R	G, T	F	2
188	S	100	0	0	N/A	N/A	T	N/A	N/A
189	R	0	100	0	N/A	N/A	Sh, T	N/A	N/A
190	R	0	100	0	N/A	N/A	Sh, T	N/A	N/A
191	R	0	100	0	N/A	N/A	T	N/A	N/A
192	R	0	100	0	N/A	N/A	T	N/A	N/A
193	R	0	100	0	N/A	N/A	T	N/A	N/A
194	R	0	100	0	N/A	N/A	T	N/A	N/A
195	R	0	100	0	N/A	N/A	T	N/A	N/A
196	R	0	100	0	N/A	N/A	T	N/A	N/A
197	R	0	100	0	N/A	N/A	T	N/A	N/A

Appendix D-3: Beach classification field data based on the 2021 and 2023 beach surveys.

Tran -sect	Beach Clas-sifica-tion	Sand (%)	Rock (%)	Near-shore Pro-tection	Beach Pro-tection Length (m)	Beach Protection Classi-fication	Vege-tation	Anthro-pogenic Feature	Feature Height (m)
198	SoR	0	0	0	N/A	N/A	Sh, T	N/A	N/A
199	SoR	0	0	0	N/A	N/A	Sh, T	N/A	N/A
200	SoR	0	0	0	N/A	N/A	Sh, T	N/A	N/A
201	SoR	0	0	0	N/A	N/A	Sh, T	N/A	N/A
202	SoR	0	0	0	N/A	N/A	Sh, T	N/A	N/A
203	S	0	0	0	N/A	N/A	G, Sh, T	N/A	N/A
204	S	0	0	0	N/A	N/A	G, Sh, T	N/A	N/A
205	S	0	0	0	N/A	N/A	G, Sh, T	N/A	N/A
206	R	0	0	0	N/A	N/A	Sh, T	N/A	N/A
207	R	0	0	0	N/A	N/A	Sh, T	N/A	N/A
208	R	0	0	0	N/A	N/A	Sh, T	N/A	N/A
209	R	0	0	0	N/A	N/A	Sh, T	F	N/A
210	R	0	0	0	N/A	N/A	Sh, T	N/A	N/A
211	R	0	0	0	N/A	N/A	Sh, T	N/A	N/A
212	R	0	0	0	N/A	N/A	Sh, T	N/A	N/A
213	R	0	0	0	N/A	N/A	Sh, T	N/A	N/A
214	R	0	0	0	N/A	RB	T	N/A	N/A
215	R	0	0	0	N/A	RB	T	N/A	N/A
216	R	0	0	0	N/A	RB	Sh, T	N/A	N/A
217	R	0	0	0	N/A	N/A	Sh, T	N/A	N/A

Appendix D-3: Beach classification field data based on the 2021 and 2023 beach surveys.

Tran-sect	Beach Clas-sifica-tion	Sand (%)	Rock (%)	Near-shore Pro-tection	Beach Pro-tection Length (m)	Beach Protection Classi-fication	Vege-tation	Anthro-pogenic Feature	Feature Height (m)
218	RB	0	0	0	N/A	N/A	Sh, T	N/A	N/A
219	RB	0	0	0	N/A	N/A	Sh, T	N/A	N/A
220	RB	0	0	0	N/A	N/A	Sh, T	N/A	N/A
221	RB	0	0	0	N/A	N/A	Sh, T	N/A	N/A
222	RB	0	0	0	N/A	N/A	T	N/A	N/A
223	R	0	0	0	N/A	N/A	T	N/A	N/A
224	R	0	0	0	N/A	N/A	T	N/A	N/A
225	R	0	0	0	N/A	N/A	Sh, T	N/A	N/A

Appendix E: Percent of Sandy Beaches Experiencing Change

Change in Beach Widths	2001 to 2003	2003 to 2005	2005 to 2010	2010 to 2014	2014 to 2019	2019 to 2021	2001 to 2021
Erosion	37%	91%	32%	67%	49%	64%	91%
No Change	1%	0%	1%	0%	1%	1%	3%
Accretion	62%	9%	67%	33%	50%	35%	6%

Appendix F: Beach Width Change per Sandy Pocket Beach

Beach Section	Average Beach Width (m)	2001	2003	2005	2010	2014	2019	2021	2023
1	Great Bay	15.6	15.2	13.8	20.8	22.1	15.5	14.3	17.3
2	Old Wharf	9.9	10.3	4.9	7.6	5.0	9.3	7.0	8.7
3	Calabash Bay	13.2	14.0	9.4	11.7	8.6	12.1	9.7	11.5
4	Frenchman's Bay	10.0	10.0	7.1	7.2	2.6	6.2	6.2	7.5
5	Billy's Bay	15.3	17.2	9.0	2.3	2.4	5.6	3.9	6.2
6	Mahoe Bay	14.4	16.2	10.0	6.2	6.3	12.1	10.2	10.1
7	Black Bay	9.2	9.2	1.4	2.7	2.4	5.7	2.9	5.9

Appendix F- Continued. Beach Width Change per Sandy Pocket Beach.

	Average Beach Width Change (m)	2001 to 2003	2003 to 2005	2005 to 2010	2010 to 2014	2014 to 2019	2019 to 2021	2021 to 2023
1	Great Bay	-0.3	-1.4	7.0	1.3	-6.6	-1.3	3.0
2	Old Wharf	0.5	-5.4	2.7	-2.5	4.3	-2.3	1.7
3	Calabash Bay	0.9	-4.6	2.4	-3.2	3.5	-2.3	1.8
4	Frenchman's Bay	-0.1	-2.9	0.1	-4.6	3.6	0.0	1.3
5	Billy's Bay	1.9	-8.2	-6.7	0.0	3.2	-1.7	2.2
6	Mahoe Bay	1.9	-6.3	-3.8	0.1	5.8	-2.0	0.0
7	Black Bay	0.1	-7.8	1.3	-0.3	3.3	-2.9	3.1

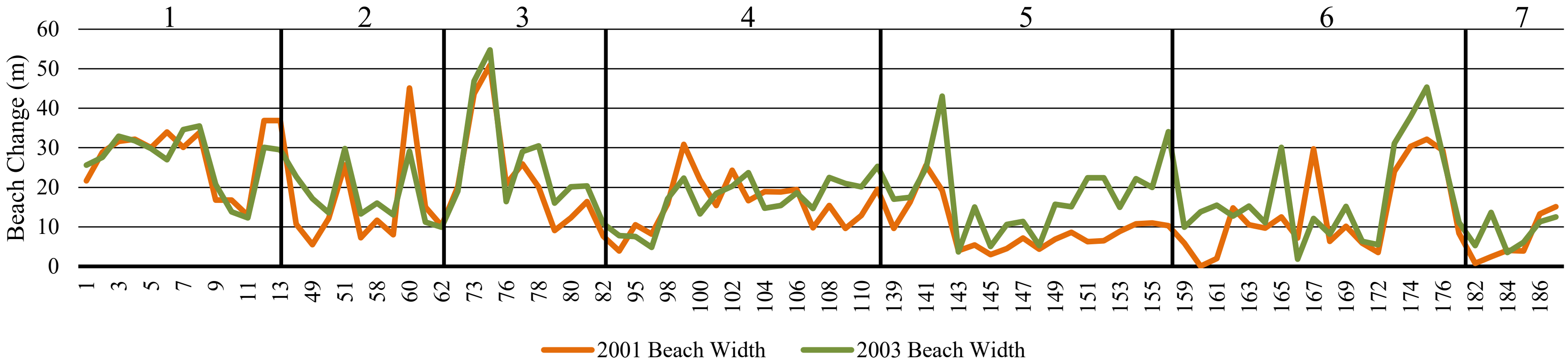
Appendix G: Berm Heights and Angles

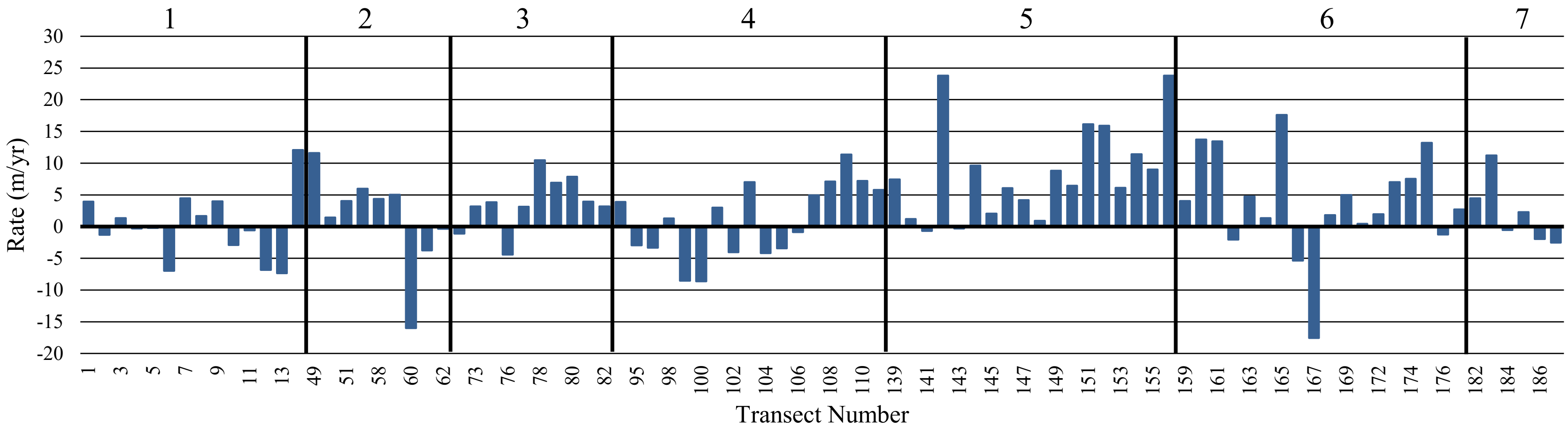
Berm Height (m)	Average	Minimum	Maximum	Range
Great Bay	0.45	-0.42	1.28	1.70
Old Wharf	0.44	-0.52	0.88	1.40
Calabash Bay	0.81	0.08	1.58	1.50
Frenchman's Bay	0.75	0.28	1.68	1.40
Billy's Bay	0.54	0.18	1.28	1.10
Mahoe Bay	0.72	-3.62	2.18	5.80
Black Bay	0.46	-0.72	1.88	2.60

Measured Beach Angles	Average	Minimum	Maximum	Range
Great Bay	6.69	2.30	11.80	9.50
Old Wharf	7.75	5.10	10.60	5.50
Calabash Bay	6.14	2.60	10.10	7.50
Frenchman's Bay	7.87	4.70	15.00	10.30
Billy's Bay	7.47	5.90	9.90	4.00
Mahoe Bay	7.86	1.30	11.20	9.90
Black Bay	10.07	7.30	10.80	3.50

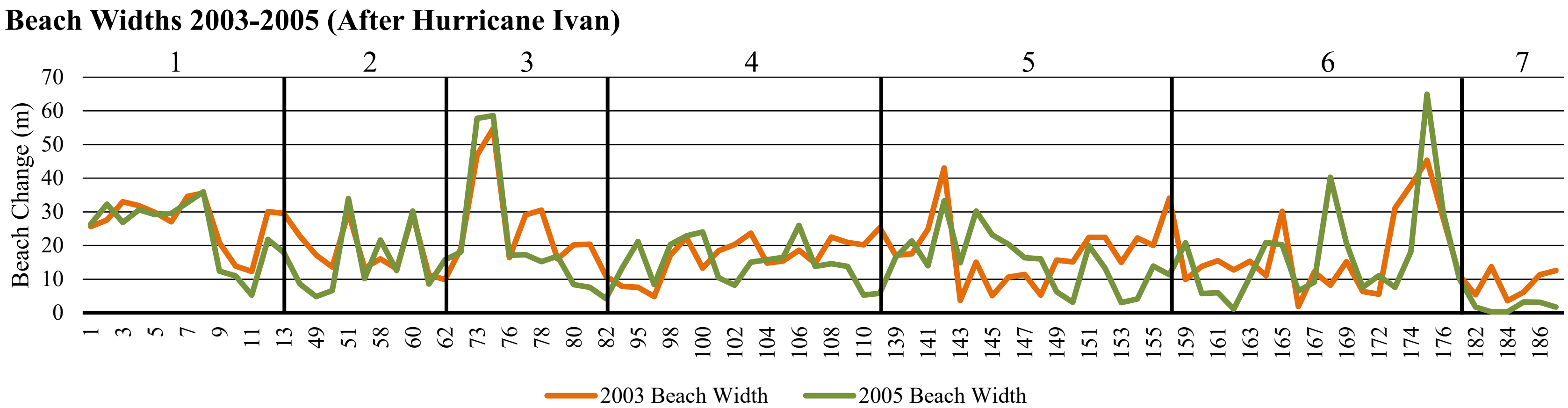
Appendix H: Beach Widths and Rates of Change

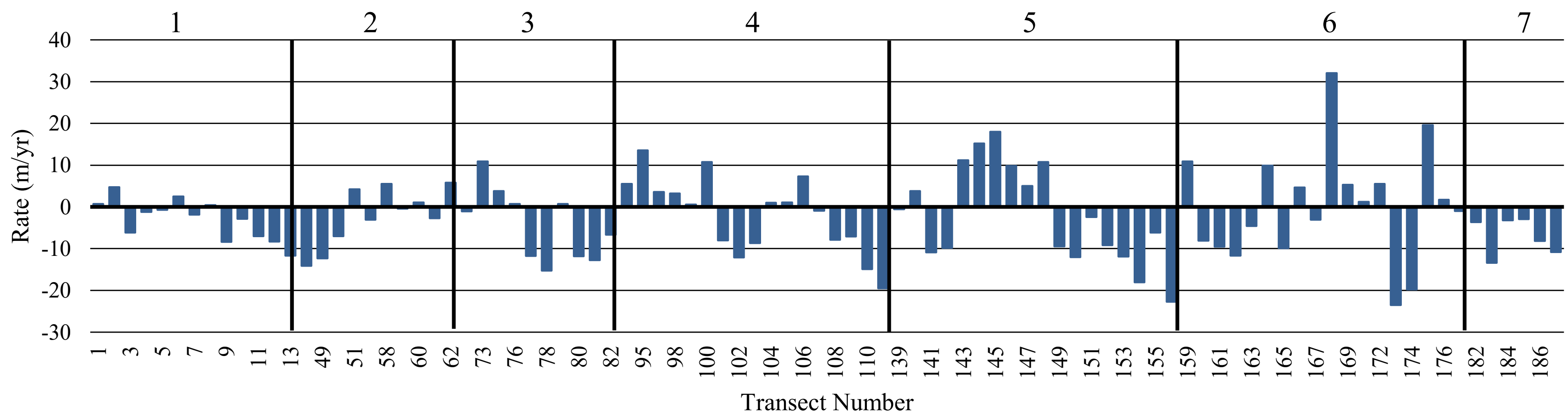
Beach Widths 2001-2003 (Before Hurricane Ivan)





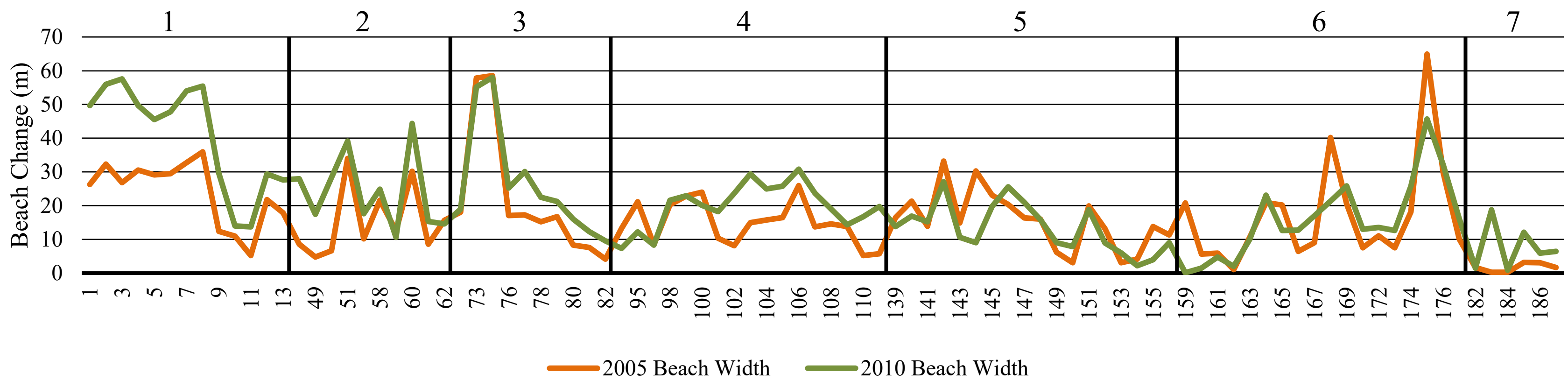
Appendix H- Continued. Beach Widths and Rates of Change.

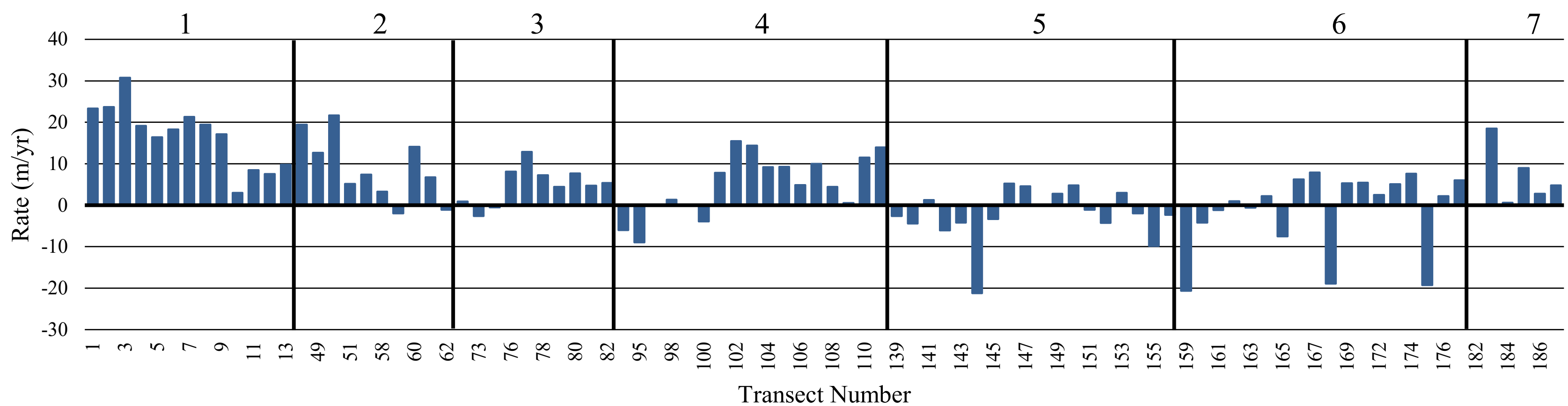




Appendix H- Continued. Beach Widths and Rates of Change.

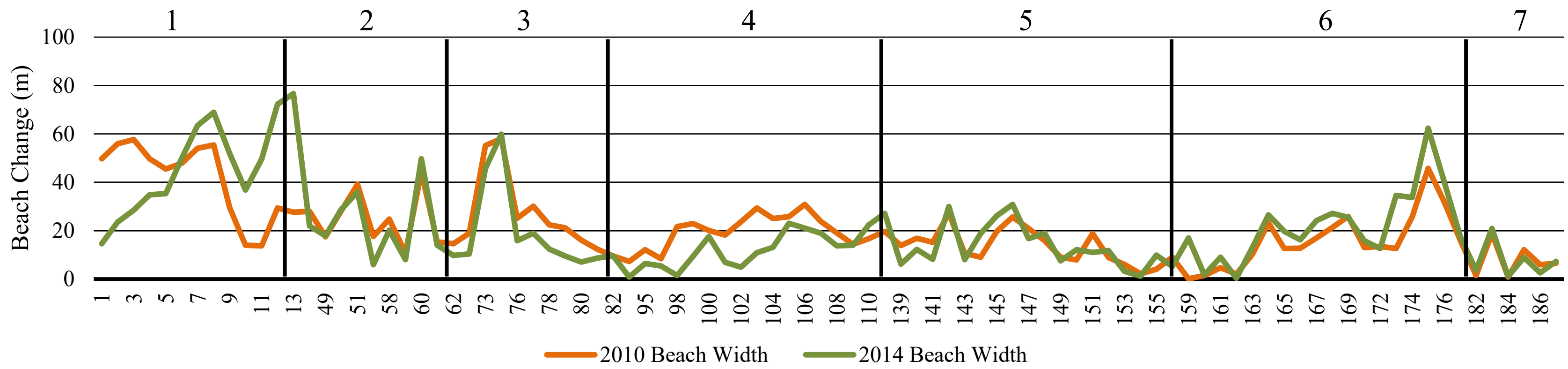
Beach Widths 2005-2010

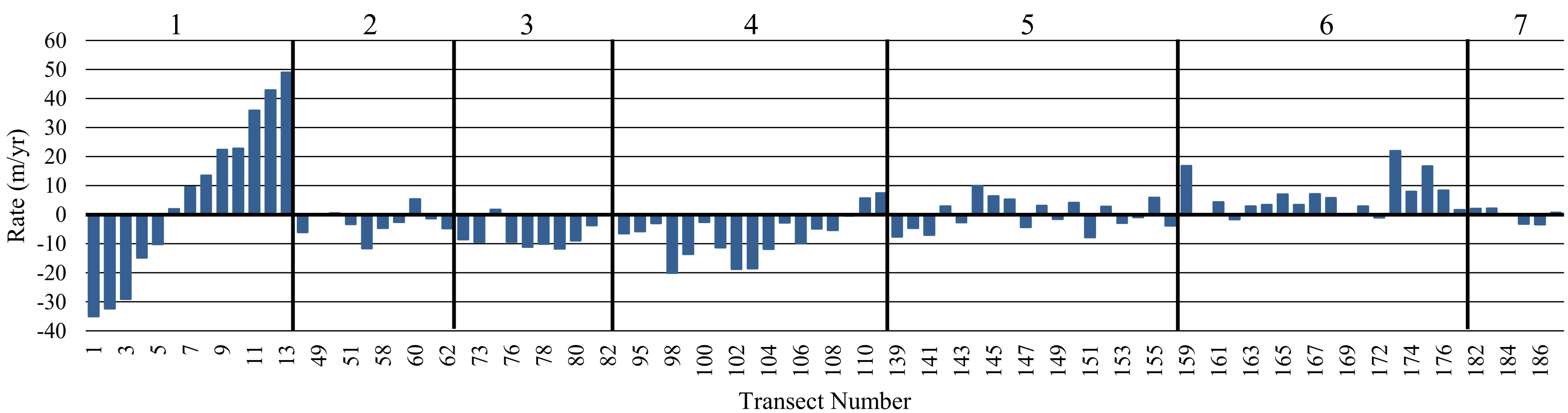




Appendix H- Continued. Beach Widths and Rates of Change.

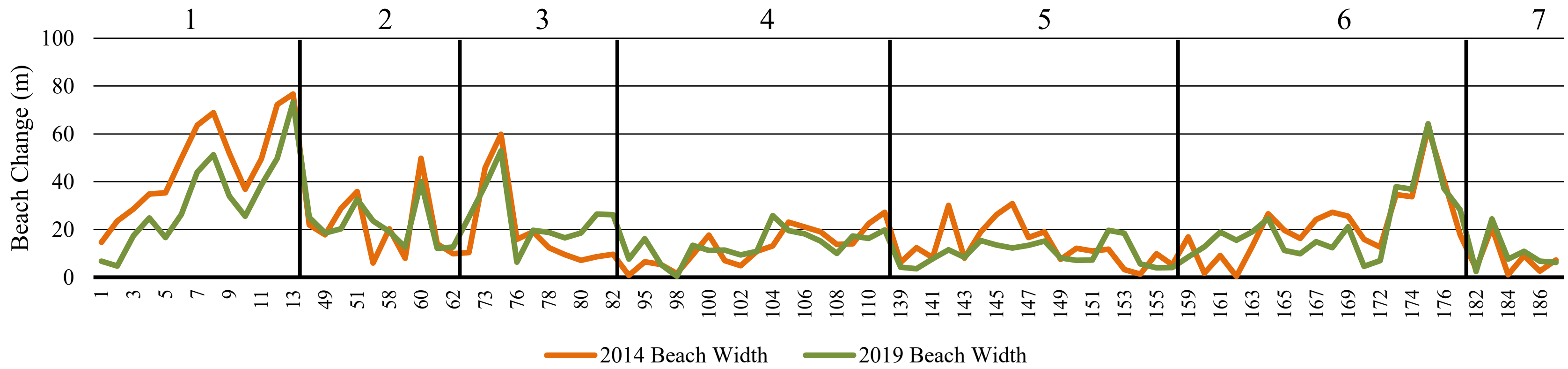
Beach Widths 2010-2014

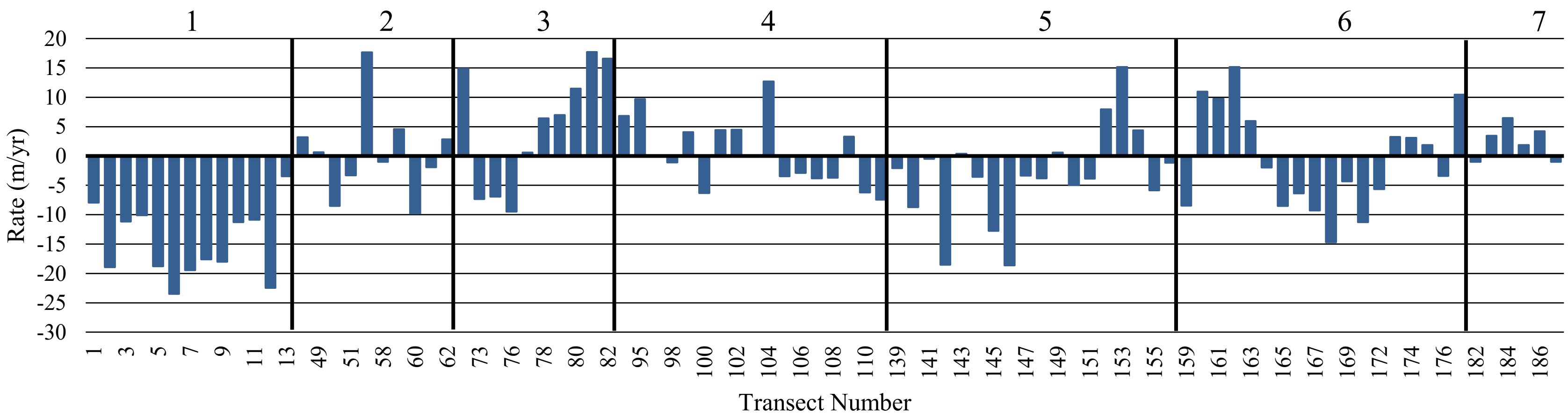




Appendix H- Continued. Beach Widths and Rates of Change.

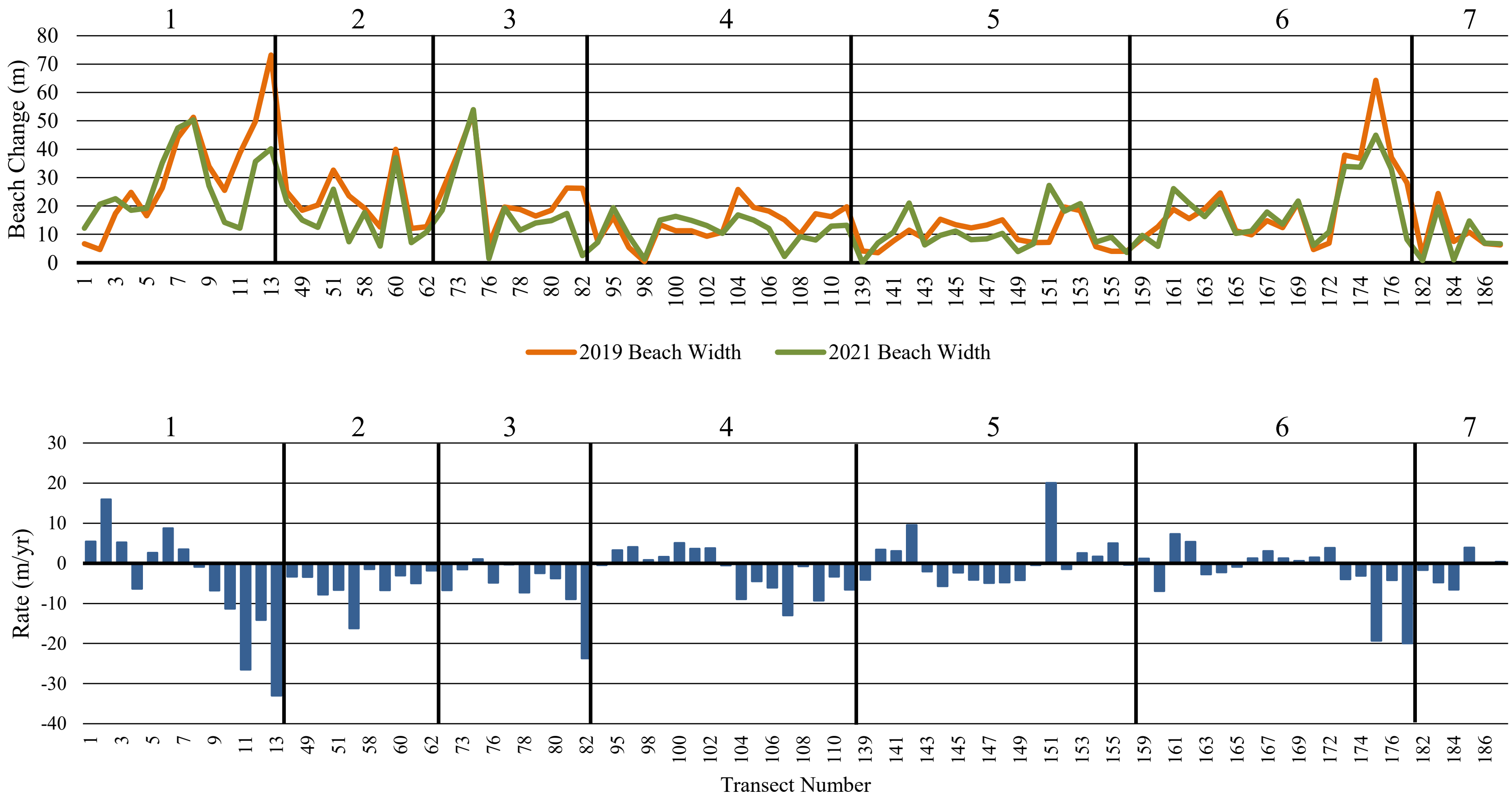
Beach Widths 2014-2019





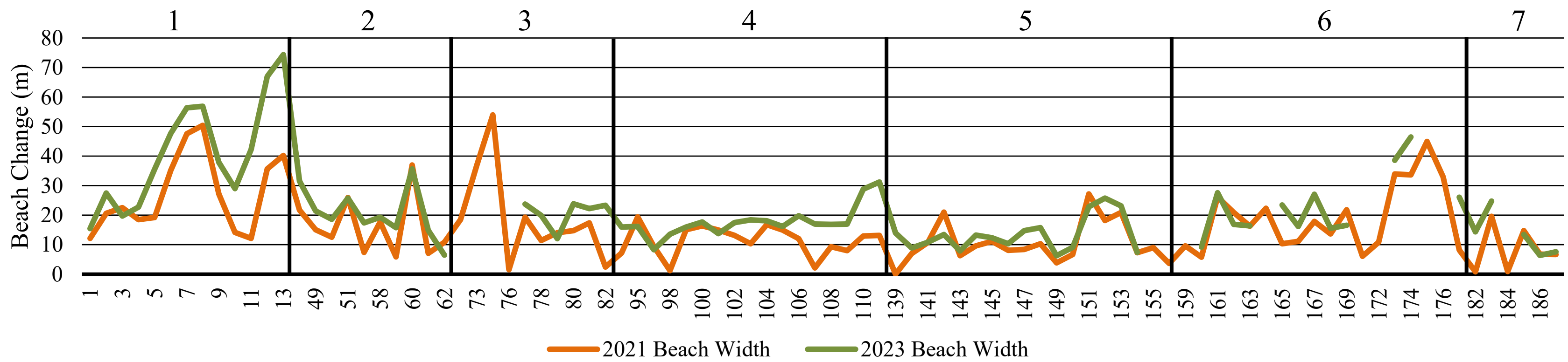
Appendix H- Continued. Beach Widths and Rates of Change.

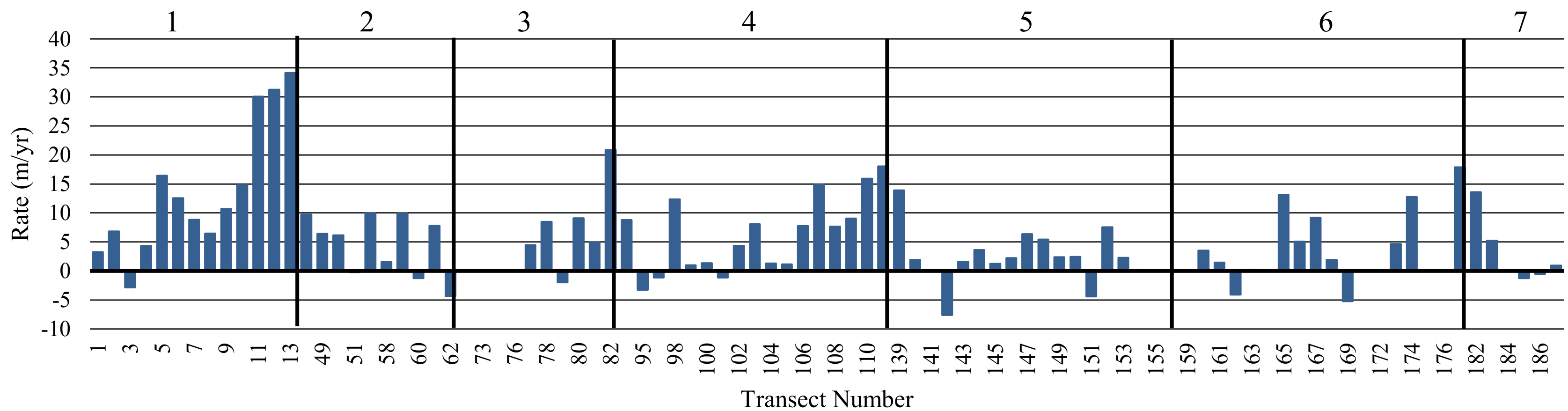
Beach Widths 2019-2021



Appendix H- Continued. Beach Widths and Rates of Change.

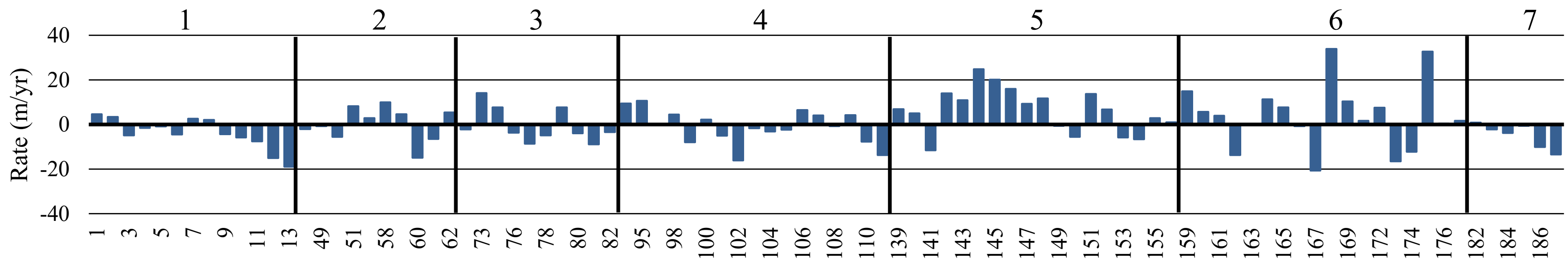
Beach Widths 2021-2023



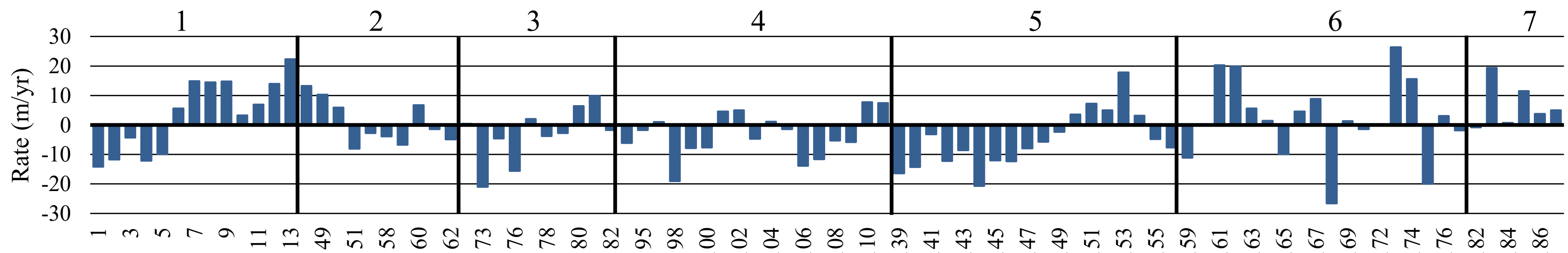


Appendix I: Beach Recovery after Hurricane Ivan

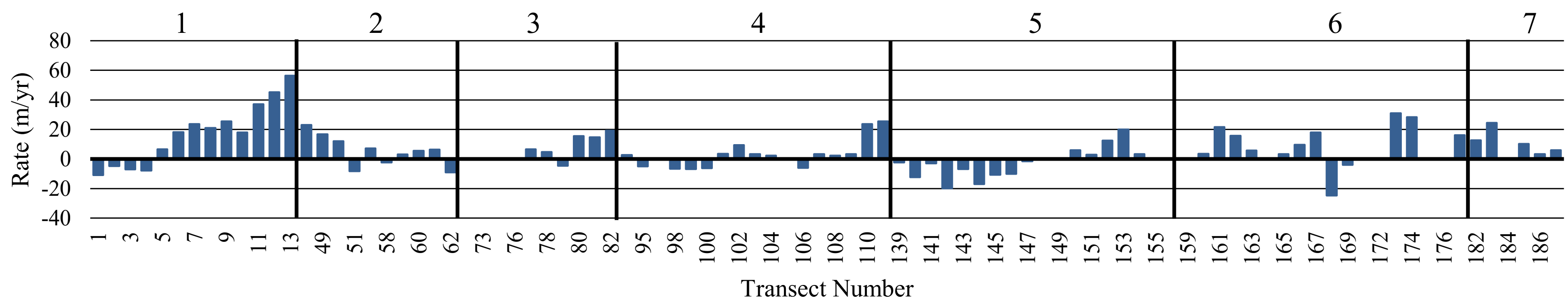
Beach Recovery 2001-2005 (1 Year after Hurricane Ivan)



Beach Recovery 2005-2021 (17 Years after Hurricane Ivan)



Beach Recovery 2005-2023 (19 Years after Hurricane Ivan)



Appendix J: Area of Sandy Beach Change per Sandy Pocket Beach

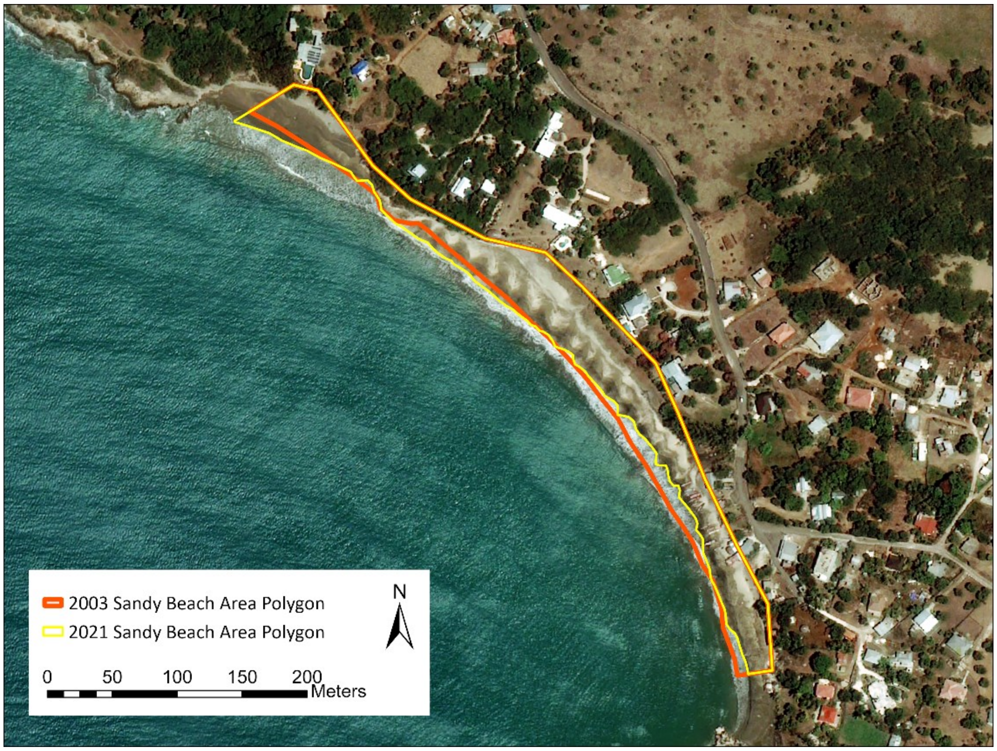
Beach Area (m^2)	2001	2003	2005	2010	2014	2019	2021	2023
Great Bay	19,681.8	19,050.5	17,186.1	26,188.7	28,820.7	20,323.4	18,386.5	21,035.2
Old Wharf	8,481.9	8,855.5	4,474.6	6,879.4	6,569.5	7,946.3	6,015.7	7,152.2
Calabash Bay	12,858.4	13,892.9	9,275.5	11,718.0	8,492.3	12,057.9	9,570.5	10,845.5
Frenchman's Bay	18,937.7	19,681.4	11,266.5	14,881.3	9,054.6	11,282.0	9,918.5	13,221.3
Billy's Bay	26,056.7	29,512.9	15,743.2	11,965.5	9,303.0	9,773.6	8,958.0	10,700.8
Mahoe Bay	22,402.3	24,974.3	15,295.0	13,123.2	15,713.4	18,006.3	15,034.7	14,349.9
Black Bay	4,820.9	4,743.8	1,988.7	3,096.3	2,520.7	2,926.5	3,287.2	2,982.1

Beach Area Change (m^2)	2001-2003	2003-2005	2005-2010	2010-2014	2014-2019	2019-2021	2021-2023	2001-2005	2005-2023
Great Bay	-631.3	-1,864.5	9,002.7	2,632.0	-8,497.3	-1,936.9	2,648.7	-2,495.7	3,849.2
Old Wharf	373.6	-4,380.8	2,404.8	-309.9	1,376.7	-1,930.6	1,136.5	-4,007.3	2,677.6
Calabash Bay	1,034.5	-4,617.4	2,442.4	-3,225.7	3,565.6	-2,487.3	1,274.9	-3,582.8	1,569.9
Frenchman's Bay	743.7	-8,414.9	3,614.8	-5,826.7	2,227.4	-1,363.5	3,302.8	-7,671.2	1,954.8
Billy's Bay	3,456.3	-13,769.8	-3,777.7	-2,662.5	470.7	-815.6	1,742.8	-10,313.5	-5,042.4
Mahoe Bay	2,572.0	-9,679.3	-2,171.8	2,590.2	2,292.9	-2,971.6	-684.8	-7,107.3	-945.1

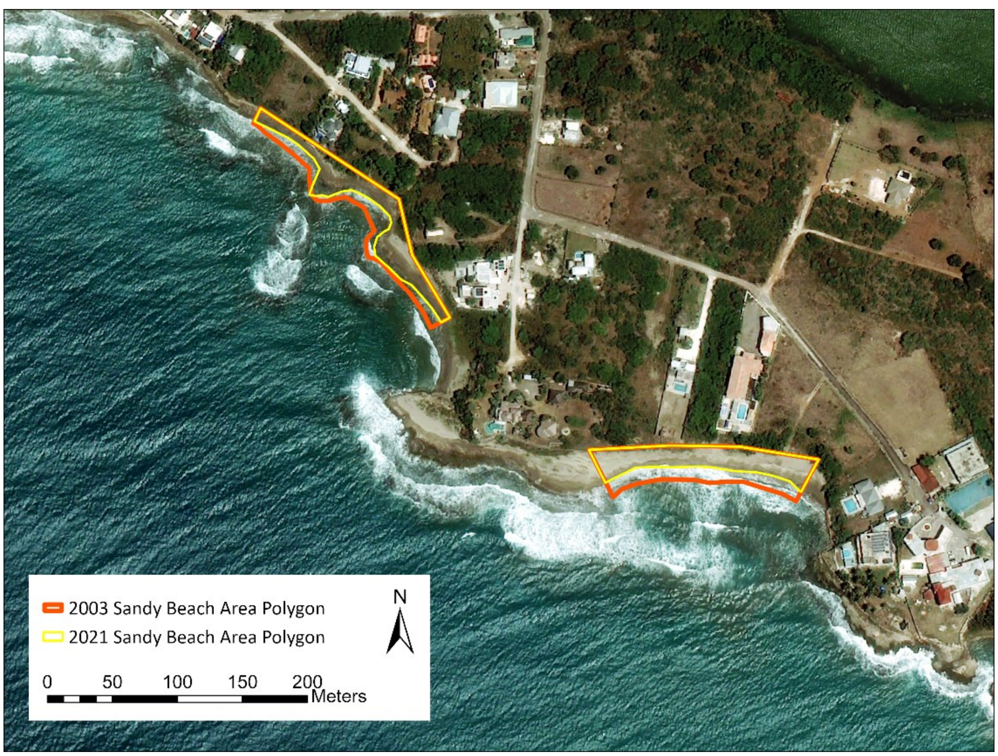
Appendix J- Continued. Area of Sandy Beach Change per Sandy Pocket Beach.

Beach Area Change (m^2)	2001-2003	2003-2005	2005-2010	2010-2014	2014-2019	2019-2021	2021-2023	2001-2005	2005-2023
Black Bay	-77.1	-2,755.1	1,107.7	-575.6	405.8	360.7	-305.1	-2,832.2	993.5

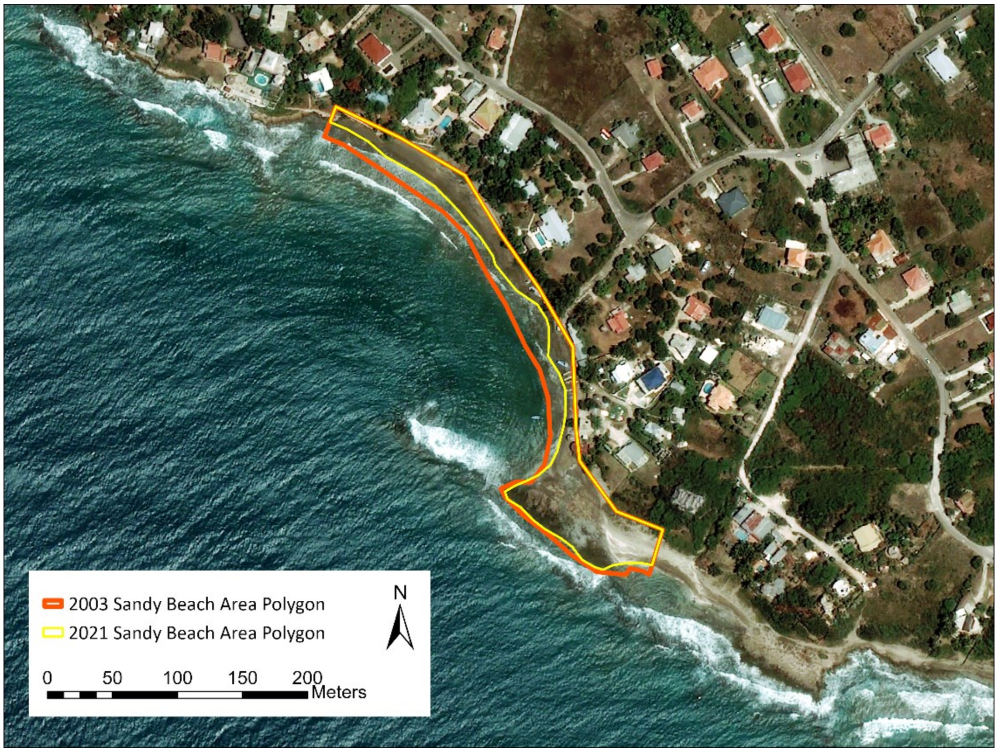
Appendix K: Sandy Beach Area per Sandy Pocket Beach for 2003 and 2021



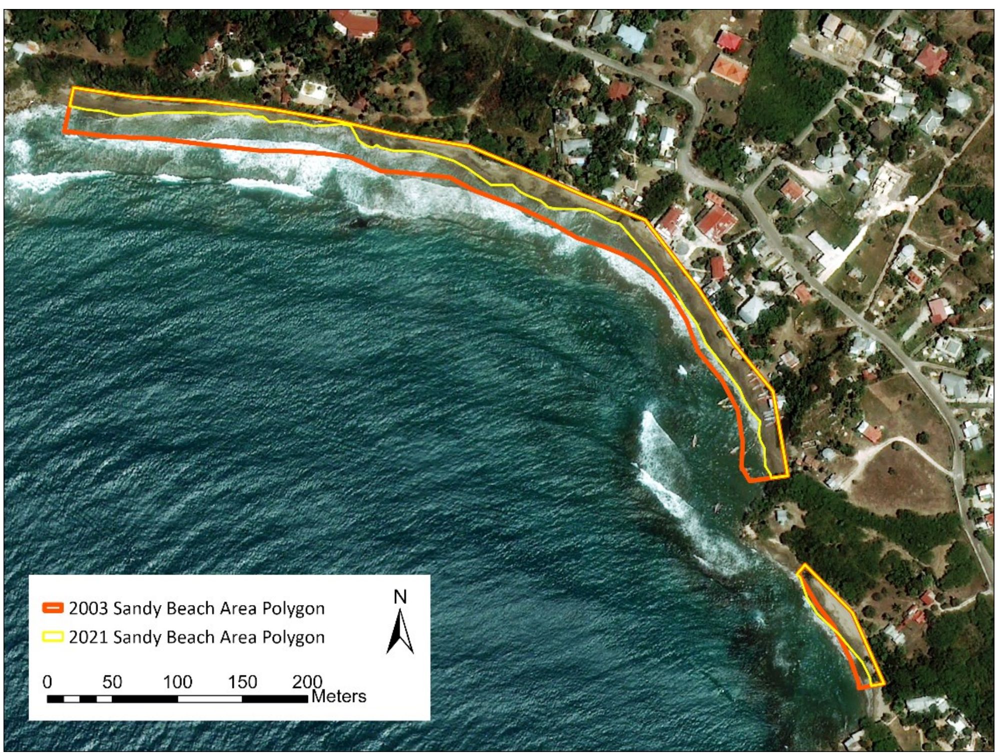
Sandy beach area for Great Bay for 2003 and 2021.



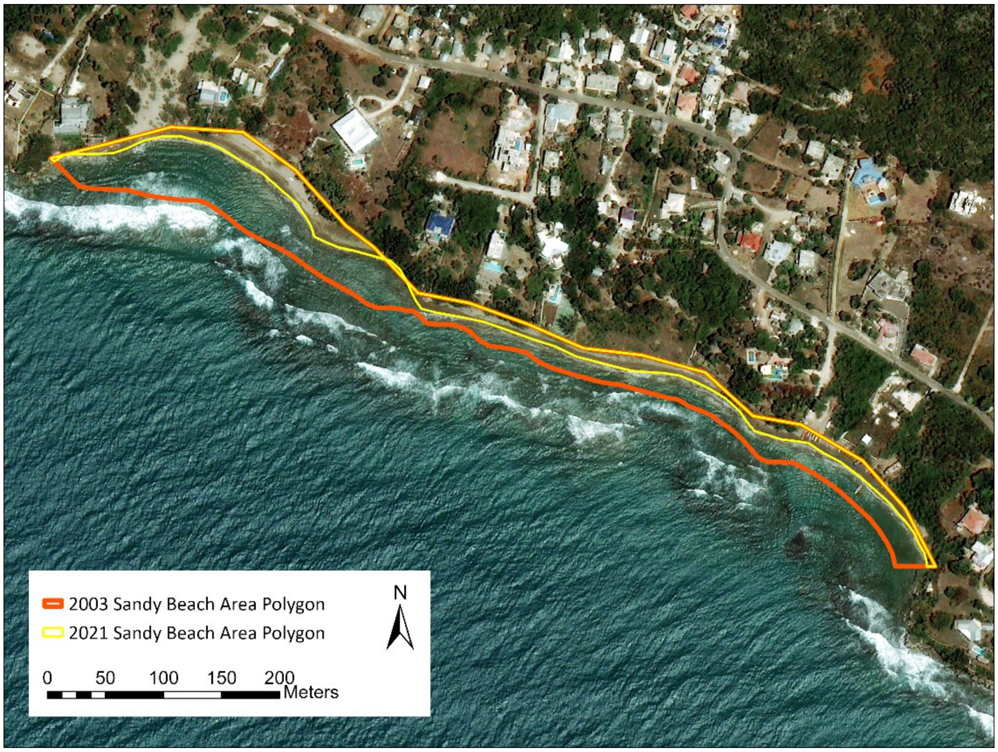
Sandy beach area for Old Wharf for 2003 and 2021.



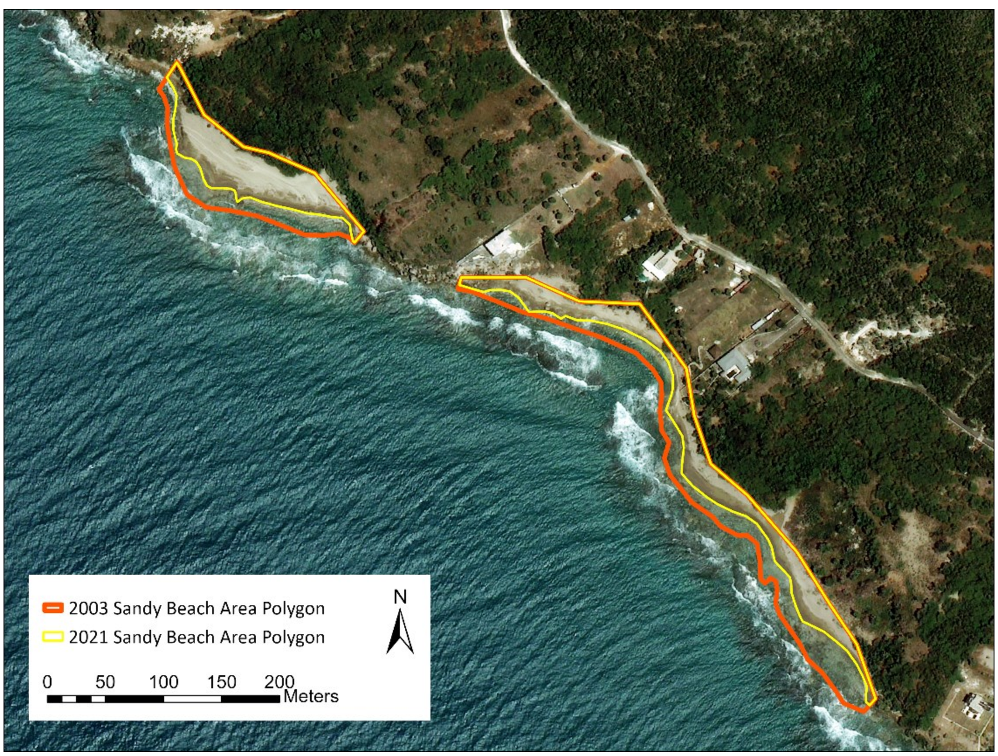
Sandy beach area for Calabash Bay for 2003 and 2021.



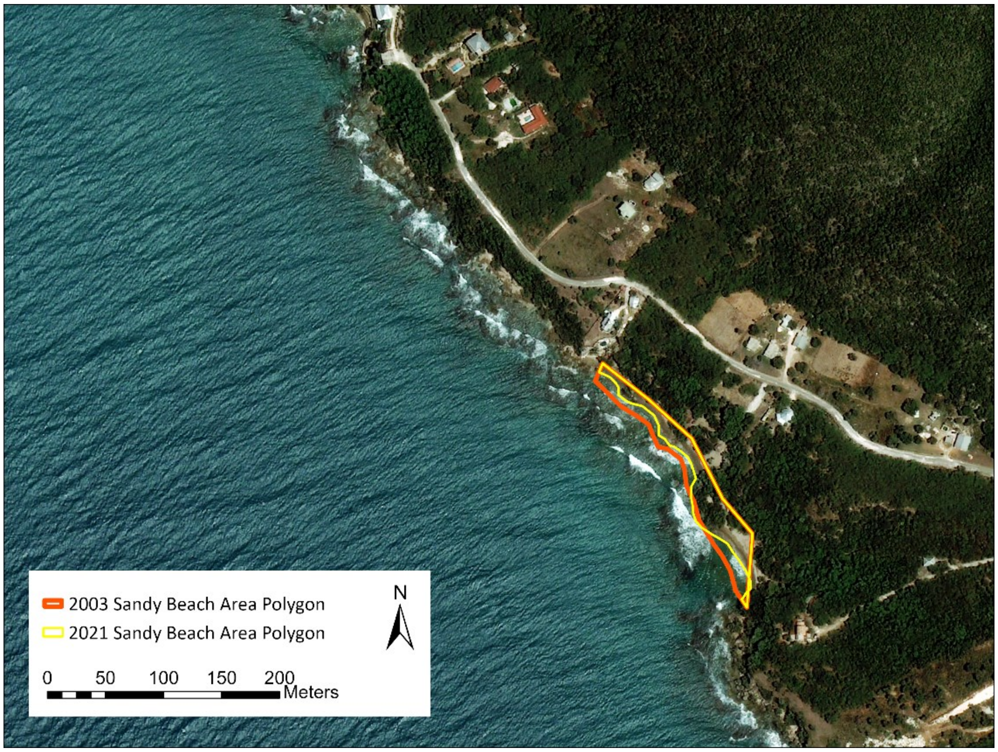
Sandy beach area for Frenchman's Bay for 2003 and 2021.



Sandy beach area for Billy's Bay for 2003 and 2021.



Sandy beach area for Mahoe Bay for 2003 and 2021.



Sandy beach area for Black Bay for 2003 and 2021.