ASSESSING COASTAL VULNERABILITY TO SEA LEVEL RISE IN ST. LUCIA AND THE RESILIENCY OF BEACHES

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Abstract

Saint Lucia, like many other Caribbean islands have not had consistent coastal monitoring programs. This research looks into coastal risk and vulnerability associated with sea level rise and anthropogenic climate change on previously assessed beaches in Saint Lucia. Coastal resources such as mangrove forests, coral reefs and beaches in particular, are critical aspects of the tourism industry, and in turn, Saint Lucia's economy. Using the Emery method, a field assessment of six beaches previously monitored in 2002 was conducted. Factors such as coastal erosion, sediment type and various other backshore and foreshore characteristics were identified for each beach. Beaches were assessed before the hurricane season, two weeks after a storm and one month after the previous assessment to compare variations in shoreline erosion, and profile structure. Profile results displayed anthropogenic backshore infrastructure such as gabion baskets did not recover after a disturbance, unlike that of dune or vegetated backshores. Using the data collected, varying beach stabilization methods ranging from hybridized solutions, beach nourishment and enhanced development legislation creates a basis for proactive mitigation responses for beaches assessed on the island.

Acknowledgements

This project would not have been possible without the guidance of my supervisor, Dr. Danika van Proosdij. Thank you for taking the time to meet with me and teach me, keeping me motivated with kind words and checking in amidst the challenges of the virtual world. I wish I could send you a bucket of warmth and sunshine.

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Chapter 1: Introduction

1.1 Climate change and Saint Lucia

Anthropogenic climate change is the increased concentration of greenhouse gases in the atmosphere leading to massive changes in global climate patterns. This phenomenon has also been linked to an increase in global atmospheric and ocean temperatures, sea level rise, and frequency of extreme climate events such as storms and drought (Scott *et al*., 2012). When discussing small island developing states (SIDS), such as Saint Lucia, climate change and sea level rise (SLR) must be discussed in synergy in regard to the climate crisis. All countries of the Lesser Antilles are highly dependant on the tourism industry (46.3% of Saint Lucia's GDP) along with the agricultural industries- which are highly vulnerable to climate change (Leatherman *et al*,1997; Bevacque et al., 2018, Hutchinson, 2016). Therefore, the loss of these sectors will dramatically affect income generation and in turn, the potential of gaining funding to adapt (Williams at al., 2017; Day *et al*., 2014).

The threat of coastal development has always been evident. However, demands from the tourism industry and coastal development has increased the risk related to sea level rise and storm surges (Cambers, 1997). Coastal squeeze refers to the negative feedback loop created by active erosion and coastal development causing a steepening of the intertidal profile (Scott et al., 2012; Sutton-Grieretal, 2015; Masselink et al., 2020). This essentially reduces the beach width and in essence a beach's aesthetic value (Scott *et al*., 2012).

Scott et al., (2012; page 883) has also estimated a "loss of 29% of resort properties partially or fully submerged, 49% - 60% of properties at risk of beach erosion" with a 1m rise in sea level. A 1.5-degree Celsius increase in temperature would result in 0.26 to 0.77m sea level rise by 2100 (IPCC, 2018). This leaves less than 90 years for SIDS to conduct more precise vulnerability assessments and thus increase their ability to adapt, even in a worst case scenario.

With projected rising sea levels, these challenges can increase socioeconomic consequences already experienced within this sector (ECLAC, 2011). Loss of the tourism and alterations to the agricultural sectors will dramatically affect income and in turn, the necessary funding to adapt to the inevitable impacts from anthropogenic climate change.

The combination of the major climate led challenges faced by SIDS is the greatest driver to develop innovative solutions to the issues mentioned previously. In order to develop a more comprehensive understanding of the risk to coastal zones, the dynamics of coastal processes, shoreline characteristics and resilience must first be understood. A decision tree, that is detailed record of coastal features presented in a standardized hierarchy, was developed for each beach assessed (appendix 2 and 3). This approach has also been used by Day et al., (2014) in the neighbouring island of Grenada when assessing the potential to develop coastal ecosystem-based adaptation. The foreshore, being the most dynamic portion of the beach, rapidly changes during storm surges, but take years to restore to its original state (Davidson-Arnott *et al.*, 2019). Therefore, when creating coastal management plans determining resilience is important to know (Bevacque *et al.*, 2018). A combination of regular assessments and applied scientific research and knowledge will allow St. Lucia to better formulate a mitigation plan- particularly in this case, beach stabilization methods (Cambers, 1997).

1.2 Coastal Processes

In order to grasp the full idea of coastal geomorphology, some basic concepts surrounding the formation of a beach and other coastal features need to be addressed. Coastal processes refer to all natural ocean wave and tide driven processes that influence how a beach is built up or eroded (Environment Foundation, 2015).

The coast or beach is divided into different zones based on where the waves break and where erosion and accretion occur. This allows us to identify the various locations of the foreshore, backshore and nearshore used for surveying (*Figure 1.1*).

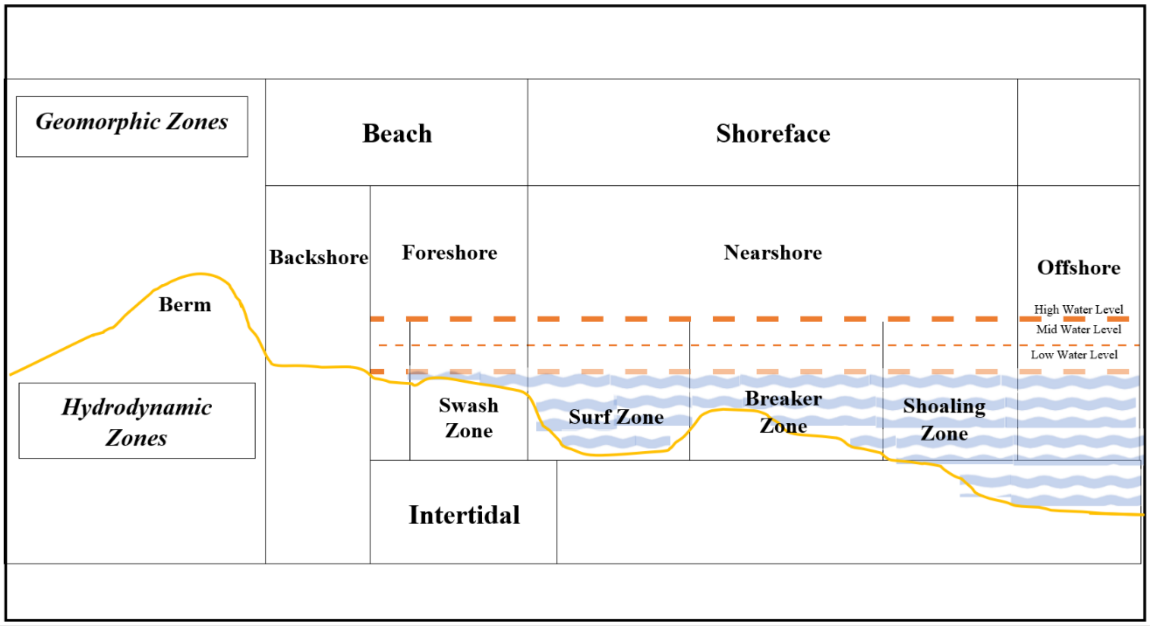


Figure 1.1 Cross sectional profile of coastal zones modified from Davidson-Arnott et al., (2019)

The surf zone or breaker zone is the general area where waves break along the shoreline (Short and Jackson, 2013). It is indicated by a sudden dip in the sand, as shown in *Figure 1.1*. The swash zone generally occurs within the foreshore and is characterized by the excess water from the wave breaking washing onto the shore (Short and Jackson, 2013).

This zone is therefore responsible for the accretionary or deposition and erosion or removal coastal processes (Davidson-Arnott *et al.,* 2019).

Waves, tides and currents are the greatest forces influencing how the shape and structure of the coast changes (Masselink *et al.,* 2020). Tides determine the range, i.e. how far into the backshore/foreshore coastal processes act (Stephenson et al, 2013) and in turn, where coastal processes differ at various times throughout the day. Therefore, beaches vary based on how often waves break, and the height of the tide. A wave dominated beach or a microtidal beach- present in Saint Lucia- is characterised by a tidal range being less than three times the wave height (Short and Jackson, 2003). Waves can be either constructive (accrete), or destructive (erode). The term, destructive waves are used to describe waves which hit the coast at a higher frequency (ten to fourteen waves per minute) causing rapid erosion and steeper slopes along the coast. Constructive waves, therefore, describe waves characteristic of accretionary processes and gently sloping coastlines, generally associated with spilling breakers (Folley, 2017).

Coastal erosion refers to the natural removal of material from the shoreline (Rangel-Buitrago *et al*, 2018). Erosion can occur in two phases- either rapid onset i.e. from storms or flash floods or slow onset erosion over several years. As it relates to climate change, rapid onset erosion increases in risk due to storm surges and sea level rise (Masselink *et al.,* 2020). Sea level rise can cause adverse loss of deposition material therefore causing accelerated erosion (Masselink *et al.*, 2020).

Longshore or littoral drift refers to the direction of sediment transport and wave attenuation, which allows for sediment to be deposited on a beach (Seymour, 2005). Waves which approach the beach at an oblique angle deposit or accrete sediment (swash), then waves retreat and erodes sediment (backwash), perpendicular to the shoreline. This process continues throughout the length of the beach depositing material and building up some parts of the beach while eroding others (Seymour, 2005). The net result of the swash and backwash movement is therefore the acting process in beach formation. Fetch refers to the distance over which wind passes over a surface of a waterbody and determines how large and in what direction waves form (US Department of Commerce, 2013; Davidson-Arnott *et al.*, 2019). Wind speed, water depth and fetch all influence how waves break.

1.2.1 Foreshore, Nearshore and Backshore Characteristics

Davidson-Arnott *et al.* (2019), has described the 'beach' as the section of the shoreline influenced by both high and low tide wave action. The backshore refers to the highest point of the dry beach where waves generally only reach during storm surges or extremely high tides (Davidson-Arnott *et al*, 2019; Inman, 2002). The foreshore refers to the part of the beach impacted by waves during high tide and characterized by a permanent wet or 'swash' zone and steep slope characteristic of active erosion (Davidson-Arnott *et al*, 2019; Inman, 2002). Factors such as grainsize and wave conditions affect the steepness and characteristics of the foreshore (Davidson-Arnott *et al.*, 2019).

The nearshore portion contains the active berm under the water, which is a good indication of a winter beach or summer beach where tidal and erosion variations can be assessed. It is therefore described as the dynamic portion of the beach (Day et al., 2014; Ostrowiki and Pruszak, 2011). Boulder/cobble beaches often have a steep nearshore-foreshore, where waves break a short distance offshore (Davidson-Arnott *et al.*, 2019). Cobble beaches also have a steep foreshore and extensive surf zone due to the distance at which waves break (Davidson-Arnott *et al.*, 2019).

Beaches which have material of a smaller grainsize are moderately sloping, whereas the finest material are gently sloping beaches where breaking occurs at a distance (Davidson-Arnott *et al.,* 2019). Differing from rocky shores, finer sand beaches have thinner surf zones (Davidson-Arnott *et al.,* 2019). Beach stability is therefore defined by a beach's morphodynamics - the result of accretionary and erosion processes (Dora *et al*., 2014).

1.3 Coastal Vulnerability and Resilience

Coastal vulnerability refers to the risk and level at which the coastal environment can be harmed as a result of a storm surge or other extreme weather events (Jimenez, *et al.,* 2008). Williams *et al*., (2017) suggest climate change driven sea level rise should not be top priority for dealing with coastal erosion there are more immediate threats. For example, the article highlights other anthropogenic factors such as the development of harbors, which can influence erosion rates quicker. The effects of erosion and storm surges are exemplified as a result of sea level rise and can destabilize naturally accreting coasts (Scott *at al*., 2012; Mycoo, 2012; Davidson-Arnott et al., 2019; Masslink *et al.,* 2020).

Resilience, broadly speaking, refers to the ability of a system to recover from change caused by a disturbance (Bevacque *et al*, 2018; Day *et al*., 2014). Resiliency is attributed based on the exposure of the beach to external forces such as waves, tides and swash processes, as well as the type of coastal structures present (Day *et al*., 2014). In the climate and coastal sense specifically, it is used to describe the capacity for the coastal environment to cope and withstand the changes caused by dramatic climate events such as storm surges (Masselink & Lauzarus, 2019; Day *et al*., 2014). When coastal development and other anthropogenic stressors are considered, resilience is compromised and may be aided through various engineered approaches, more specifically hard or soft engineered approaches (Bevacque *et al*, 2018).

Hard engineering structures, described as ‘engineering resilience’ by Masselink and Lauzarus (2019) are designed to meet specific, defined standards of a particular threat. Therefore, engineering resilience focuses on a predictable, efficient and consistent steady state equilibrium which refers closely to hard structures created to suit predictable outcomes. On the other hand, soft engineered approaches or ‘ecological resilience models’ account for the various dynamic factors acting on a system before it experiences a dramatic change in “controls and structural organization” (Masselink and Lauzarus, 2019). For example, sandy beaches are more likely to be impacted by sea level rise and climate change than rocky coasts making them less resistant to change. However, sandy beaches are more resilient as they are able to restore themselves relatively rapidly after a disturbance, in comparison to a cobble beach which may not be able to do so (Environment Foundation, 2015). Using this method, vulnerabilities can be reduced through investment and technical expertise in the research and execution phases (GFDRR, n.d.). However, solutions need to made specific for each island and surrounding ecosystems. Therefore, extensive research on the most suitable technique needs to be conducted prior to any project implementation site.

1.3.1 Conducting a resiliency assessment and current state of resiliency testing in St. Lucia and the Lesser Anilities

Resiliency is attributed to the links between the physical or natural world and socio-economic aspects surrounding sustainability of current system and practices and their adaptive capacity (Masselink and Lauzarus, 2019). All aspects of coastal environments are connected. Therefore, disruptions in the coral or seagrass bed systems may show evidence on the beach, for example as broken coral pieces, or changes in deposition patterns (Day *et al*., 2014).

Comparative report between 1990 and 2002 beach assessment conducted by the Government of St. Lucia's Ministry of Planning under the COSALC Programme will be used as reference point for beaches assessed (GOSL, 2001). The COSALC Programme - Coast and Beach Stability in the Lesser Antilles- was implemented in late 1990s and was aimed at providing countries within the region a guide to coastal monitoring (Cambers, 1997). The heightened vulnerability of the region was acknowledged after multiple years of natural disasters such as hurricanes creating immense pressure on the economy in accordance with coastal loss and infrastructural damage. This project highlighted the importance of tide monitoring and initiated conversations surrounding the implementation of the tide gauges in the region.

Tide variations and beach profiles are an integral part in understanding beach morphodynamics (Dora et al., 2014). Measurements for this study were taken during the dry season and during the wet season after a hurricane or tropical storm (a system with heavy winds), to assess coastal variations with recovery overtime (Cambers, 1997).

Tide gauges are instruments used for recording sea level. They are especially important for measuring the change in patterns of sea level rise at a local point (Hails, 1982). Saint Lucia, and several other islands of the Lesser Antilles, are not equipped with tide gauges, thus, calculating sea level rise and global tidal adjustments and its effects on erosion should be approached with caution on a local level (Cambers, 1997). These can be quite useful in determining how vulnerable a country is to sea level rise and has become a suggestion for

SIDS to invest in (IPCC, 2018). In order to combat the lack of tide gauges the NOAA website below was used a reference point for tide adjustments.

In many Caribbean islands, it is common to find hard infrastructure such as gabion baskets and seawalls being used to reduce the impact of coastal erosion. This is an example of attempted beach stabilization used to combat natural forces such as ocean waves, which would otherwise cause significant damage to anthropogenic structures near the coast.

1.4 Beach Stabilization

1.4.1 What is stabilization

Beach stabilization often refers to the use of hard engineering such as impermeable materials such as rocks or concrete, in the form of a groyne, or seawall, which alters the rate and pattern of accretion and/or deposition on a beach (WIDECAST, 2020). However, both hard and soft engineering can be used to combat the effects of sea level rise.

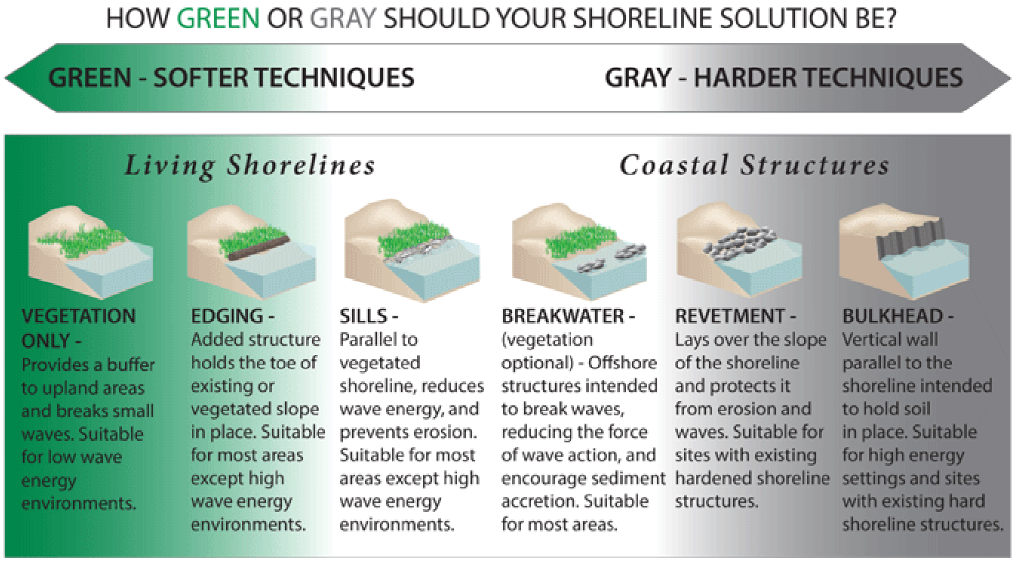


Figure 1.2 Variations in sea level rise adaption taken from https://www.habitatblueprint.noaa.gov/wp-content/uploads/2018/01/NOAA-Guidance-for-Considering-the-Use-of-Living-Shorelines_2015.pdf

1.4.2 Methods of beach stabilization – Hard Engineering

Several methods of hard engineering, described as ‘sea defense’ by Banton *et al.* (2015) or grey infrastructure by (Powell et al., 2018) are present on the coast of most Caribbean islands, including St. Lucia. This can be present in the form of offshore breakwaters, gabion baskets or revetments and seawalls (Williams et al., 2017). Implementation of these methods is often called ‘holding the line’ as referred to by Banton *et al.,* (2015) as they are used to prevent further erosion of the beach. With many techniques, there are both negative and positive aspects to it.

Methods such as the use of groynes alters the natural process or pattern of longshore drift. It therefore allows for accumulation of sand on the updrift side of the groyne, while starving the beach down shore/ after the groyne due to slower rates of deposition (Williams *et al*., 2017; Davidson-Arnott *et al.,* 2019). Seawalls and gabion baskets are used in areas where high tides cause extensive flooding and erosion to vulnerable parts of the coast (Williams et al., 2017; Powell *et al*., 2019). These structures may also cause harm to surrounding communities, as seawalls disperse wave energy and degrade parts of the coastline available for public use. Hard infrastructures in general can also create an imbalance between coastal ecosystems surrounding the structure (Rangel-Buitrago *et al*., 2017). Offshore breakwaters are also commonly used for beach buildup by attenuating waves and encouraging deposition. This method, like many previous techniques mentioned, is quite costly, and is only suitable to shallower, calm environments (Williams et al., 2017).

Hard engineering approaches generally provide quick results and therefore are most common in Caribbean islands, especially in areas of rapid coastal development. This is particularly true for tourist driven locations, where a rapid decrease of coastal erosion, allows for continued tourism development and thus, grey infrastructure is often chosen in favor of ecosystem based approaches, or 'soft engineering' structures (Scott et al, 2012; Rangel-Buitrago *et al*., 2017; Mycoo, 2012).

1.4.3 Soft Engineering

As a result of the large cost and expansive effect on the surrounding environment, more ecosystem-based approaches to adaptation are being explored. In Saint Lucia, soft engineering is specifically based around the conservation or restoration of mangroves, coral reefs, sea grass beds or dune systems (Day *et al*., 2014).

One common stabilization method often proposed for the Caribbean region is implementing artificial reef structures such as reef balls. These could be placed in shallow waters or attached to a breakwater which provides ecologic and environmental services, while also reducing any socio-environmental conflicts which may arise from previous methods of beach stabilization (MacIntosh *et al*., 2018).

Coral reefs, mangroves and seagrass beds and beaches are four critical biodiverse habitats which protect the coast through wave attenuation, increasing sediment deposition and in turn, beach stability (Powell *et al*., 2019; Davidson-Arnott *et al.* 2019). However, these ecosystems are also under critical threat due to increasing storm events and warming ocean temperatures. Coral reefs in the Caribbean have already experienced risks from bleaching and damage caused by extreme events; this also places the tourism sector at risk of losing a valuable, major attraction (Mycoo and Chadwick, 2012). Coral reef transplants and restoration are becoming more popular especially with more climate resilient species (Day *et al*., 2014; Mycoo and Chadwick, 2012).

Mangroves have exhibited characteristics of excellent resilience as well as having a large adaptive capacity to sea level rise driven climate change due to similar increasing accretion rates (Masselink and Lauzarus, 2019). Despite this, mangrove forests are threatened by deforestation reducing their ability to adapt and be resilient (Powell *et al*., 2019; Mycoo and Chadwick, 2012). Similar to coral reefs, restoration and conservation of existing mangrove forests is the best method for coastal protection and shoreline stabilization (Day *et al*., 2014; Mycoo and Chadwick, 2012).

Beach nourishment refers to the addition of sand to the beach to rapidly build and increase stabilization seaward (Peterson and Bishop, 2005). However, even this technique is quite costly and requires ongoing maintenance (Williams et al., 2017). Even a solution such as beach nourishment can have negative impacts based on grainsize and biological processes occurring on the coast as it can smoother existing habitats on dunes and may create additional issues in locations where the sand is being mined (Peterson and Bishop, 2005).

1.4.4 Hybrid Methods

Precautionary measures such as migration and various methods of coastal protection are going to become increasingly difficult as coastal flooding and sea level rise risks also increase (Lawrence et al., 2019). Managed retreat and sacrificial areas are becoming more popular as the inevitable challenges associated with sea level rise and storm surges makes adaptation more difficult (Williams et al., 2017). However, this is not always the most plausible cases for coastal dependant countries such as St. Lucia. Hybrid approaches help to provide ecosystem services through the use of their ‘soft’ infrastructure, as well as other coastal and flood protection services from the combination of hard and soft methods. Built infrastructure aids for high impact storms whereas natural infrastructures are generally sufficient for small or medium threat storms (Sutton-Grier, 2015). As a result of the combination of the soft and hard infrastructure services these hybrid methods provide a greater return on investment in the long run (Sutton-Grier, 2015).

Coral transplants or enhancement of breakwaters, for example through the use of reef balls have also been gaining traction (Williams et al., 2017). Hard and soft coral fragments are attached to plates on the breakwater and allowed to grow in varying conditions of depth and wave intensity (MacIntosh *et al*., 2018). However, coral reefs are only able to reduce the impacts of small storm waves. This technique therefore is more useful as a method of increasing ecological diversity in addition to coastal protection from hardened infrastructure (Arnot *et al.* 2019). Hybrid methods although quite new are used existentially and either as temporary or permanent structures designed specifically for a country's challenge such as what is suggested for SIDS (Cambers *et al.*, 1997).

1.5 Rational and Project Purpose

Masselink *et al.*, (2020) noted regional or local predictions of coastal risk as a result of sea level rise can be made with medium to high level of accuracy, whereas overly generalized predictions provide almost negligible assistance. Therefore, this research will assist in identifying ways to prepare for the future as well as adapt to these rapidly changing systems. (Williams *et al*., 2017). The annual occurrence of the wet or hurricane season, in conjunction with all the uncontrollable challenges associated with climate makes the tourism industry quite fickle. Growing global concerns related to the loss of resources driven by anthropogenic climate change and SLR in particular, calls for the country to design adaption plans which will provide a more comprehensive understanding of coastal resource resilience. Low cost monitoring programs- such as assessments using the Emery method can be reintroduced in order to better assess changes caused by the inevitable sea level rise.

The proposed research questions addressed by this project were suggested by Saint Lucia's National Climate Change Research Strategy 2019-2030, drafted by the Ministry of Education, Innovation, Gender Relations and Sustainable Development. The topics chosen were highlighted under section 5.1.3- Coastal, Marine and Ocean Environments.

"*Broad Topic/Research Question*

- *Which communities and areas will be most affected by sea level rise and coastal erosion?*

Suggested Research Outputs

- *Comparative analyses of the effectiveness of beach stabilisation methods*"

The objectives of this thesis are therefore as follows:

1. Conduct a field assessment of the six previously monitored beaches- Vigie Beach, Reduit Beach, Pigeon Island Causeway, Anse Chastanet Beach, and Malgretoute Beach- for slope, accretion or erosion rates and composition (vegetation and grain size).

2. Examine and determine the resilience of beaches and their capacity to respond to different stabilization methods.

3. Examine the change in shorelines over time using historical and aerial photographs of the beaches to estimate possible outcomes for future changes within the coastal system.

4. Formulate a basis for proactive mitigation response strategy development and assess viable beach stabilization methods for various climate and anthropogenic driven sea level rise projections.

Chapter 2: Site Description and Field Methods

2.1 Site Description

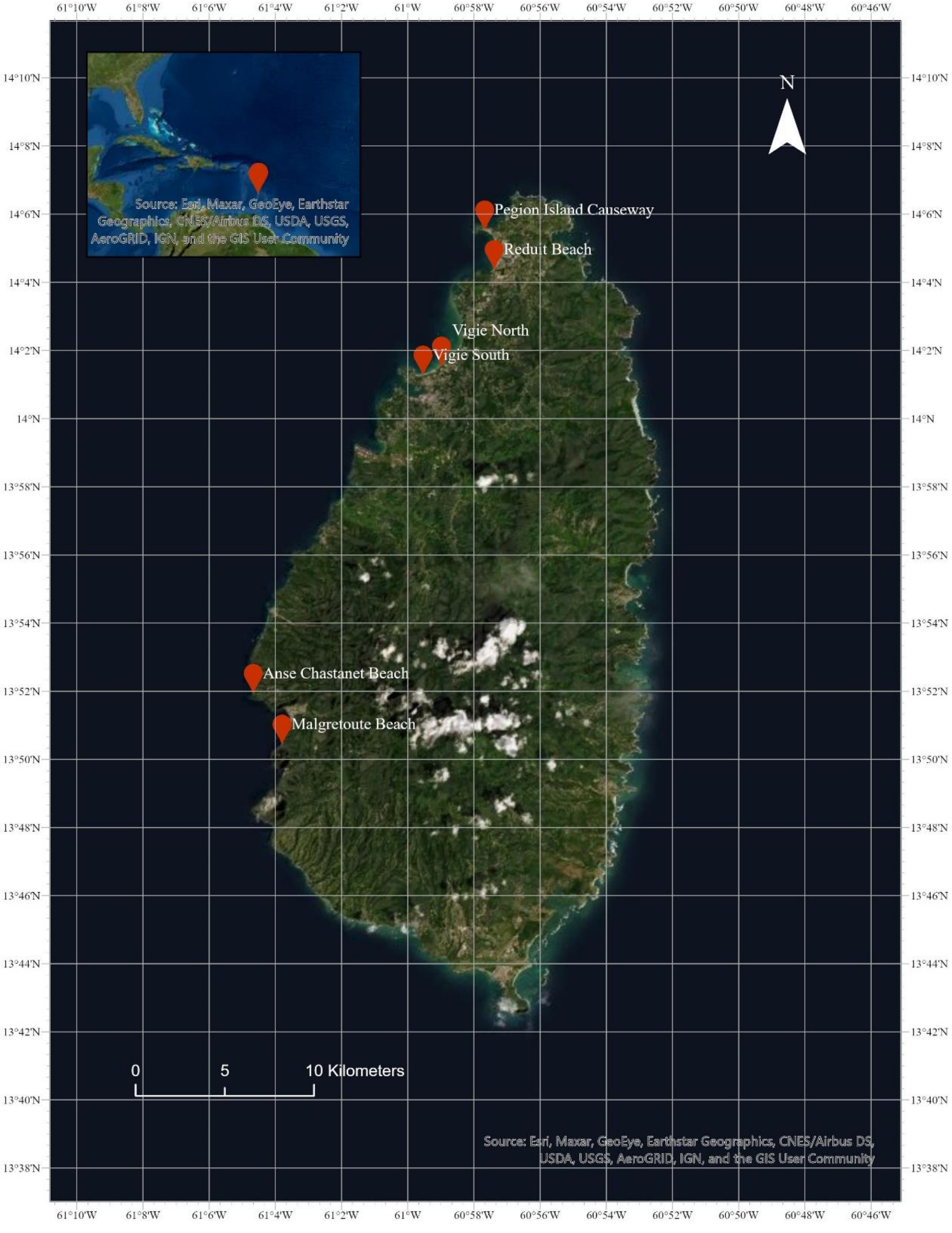
2.1.1 Island Geography and Demographics

Saint Lucia is a 617 km^2 island, located ~14°N and 61°W, within Caribbean Sea to the west, and Mid-Atlantic Ocean to the east. The majority of St. Lucians, live on or near coastal villages as they rely on the various resources it provides (Government of St. Lucia, 2001, Banton *et al*, 2015). This includes recreational activities, fishing and most importantly employment from the tourism and hospitality sector. Important infrastructure such as air and seaports are also located within vulnerable coastal areas or reclaimed land (UNCTAD, 2017).

St. Lucia like many other Caribbean islands, often has a limited resource market due to their geographic remoteness, size and vulnerability to external environmental pressures. Based on these characteristics, St. Lucia falls into the category of a small island developing state (SIDS)- a group of 38 UN member states, and 20 non-member states which experience similar socio-economic and environmental challenges (United Nations, n.d.). The main source of income generation relies on tourism, of which 21.5% of Saint Lucians are directly employed and 46.3% are indirectly employed (Hutchinson, 2017). This sector is heavily driven by the common 'sand, sea and sun' brand satisfied by several Caribbean islands, and therefore needs to be preserved (Scott *et al*., 2012; UNCTAD, 2017,).

For this survey, five beaches on the west side of the island bordered by the Caribbean Sea were assessed based on a previous monitoring project conducted by the Government of St. Lucia's Ministry of Planning under the COSALC Programme (GOSL, 2001). However, the

GOSL project was stopped in the early 2000s due to the extensive labour and time demand. This research therefore serves as a compliment to the previous monitoring project using the most accessed beaches in order to address the question, “Which communities and areas will be most affected by sea level rise and coastal erosion?”



Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 2.1 Map of Saint Lucia (W.I) and Accessed Survey Sites

2.1.2 Location and Description of Individual Beaches

Anse Chastanet Beach

Anse Chastanet Beach is a ~165m long pocket beach located on the West coast of the island. The backshore of this beach is commonly utilized by tourists as two hotels- Anse Chastanet and Jade Mountain Resorts utilize this beach for dining and various recreational activities. This beach is bordered by vast expanses of coral, which is part of the Soufriere Marine Management Area (SMMA). Reefs in this area have been recognized for vast fish diversity and 10-40% of healthy coral cover (Kramer *et al*., 2016). Coral reefs within this area therefore play a vital role in dive tourism and have become an essential part of these resort attractions (*Figure 2.2*). Healthy reefs are also better at attenuating waves than

Figure 2.2 Map of Anse Chastanet Beach

Malgretoute Beach

Malgretoute Beach is a ~187m long beach with a combination of rocky and sandy shore located on the West coast of the island (*Figure 2.3*). The beach is bordered by coral reefs similar to Anse Chastanet Beach with a 20-39% coral cover as when assessed in 2015. It is commonly utilized for recreational activities such as yachting and other watersports (Kramer *et al*., 2016).

Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 2.3 Map of Malgretoute Beach

Vigie Beach

Vigie Beach, located in the North West of the island, has been divided into 2 separate beaches identified as Vigie South (~711m) and Vigie North (~1411m). The surrounding waters of Vigie South has estimated to have a coral cover of 10-20% as of 2015 (Kramer *et al*., 2016). The surrounding backshore is composed of anthropogenic infrastructure including buildings, roadbeds and a cemetery which has been utilized since the First World War (Commonwealth War Graves Commission, 2020) as visible in *Figure 2.4*.

Figure 2.4 Map of Vigie Beach South

Vigie North was identified as the section of the beach beyond the man-made detached breakwater and groyne. This section of the beach consists of raised bedrock in the foreshore and natural dense vegetation in the backshore (*Figure 2.5*).

Figure 2.5 Map of Vigie Beach North

Reduit Beach

Reduit Beach is 960m in length where 80% of the backshore of the beach consists of anthropogenic structures i.e. buildings or roadbeds. This coastal area is also near a marina in the Northern fishing community of Gros Islet. This beach is commonly used for recreational activities and watersports such as yachting jet skiing (*Figure 2.6*).

Figure 2.6 Map of Reduit Beach

Pigeon Island Causeway

Pigeon Island Causeway is the Northern most beach 1262m beach, similar in length to Vigie Beach. This beach is separated into 2 sections by a jetty accessible through the Landings Resort. This beach is part of the reclaimed land joining Pigeon Islet in 1972 and is now utilized by 2 major resorts Sandals Grande (constructed in 2017) and the Landings (constructed in 2007). Areas which are not occupied by the resorts have been left with a vegetated backshore (*Figure 2.7*).

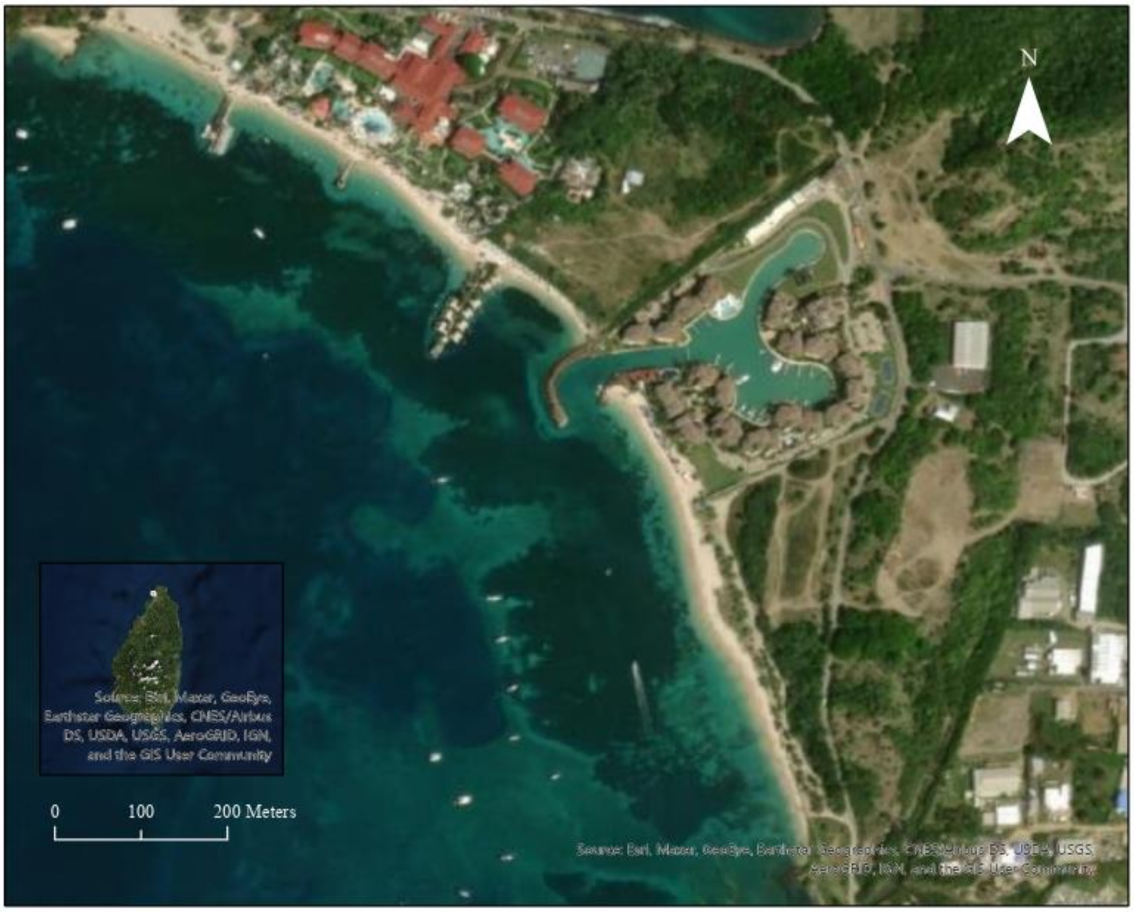


Figure 2.7 Map of Pigeon Island Causeway

2.2 Field Data Collection

2.2.1 Characterizing the Coast

For this study, the Emery method was used in place of the Abney method used in the original profile assessment such as in COSALC, as it allows for a similar accurate coastal assessment with cheaper and simpler instruments (Mossa, 1998; Larasati and Wacano, 2013; Day *et al*., 2014). The emery method is accurate to 4cm as variations in sediment and the lack of suggested rubber pads would decrease accuracy of measurements (Krause, 2009). Measurements for the study were taken during the dry season and during the wet season after a hurricane or tropical storm (a system with strong winds), to study monitoring coastal recovery overtime (Cambers, 1997).

Given the limited data publicly available of vertical markers and starting points used for the previous survey, new vertical markers were established based on the length of each beach. The length of each beach was measured digitally using the path tool on Google Earth Pro, and then split the path into 3 to 5 profile points based on the length of the beach. Three shore perpendicular profiles were established for beaches under 300m, 4 profiles for beaches under 1000m and 5 profiles for beaches over 1000m. This method allowed room for interpretation during the first phase of data collection, where stations could be chosen on the ground based on the presence of new permanent vertical markers, essential for future assessments. A start and end point of the beach was determined comparing the points deduced from the digital map to the actual beach. The coordinates of this location were then noted using a GPS enabled camera, (Nikon Coolplix AW130) which is accurate to +/- 2-5m. A photograph of the vertical marker and starting point for the profile fencing pole or mature tree was then taken. A photograph of each of these changes was then taken from a west and east view of the feature, as well as a backshore and foreshore view from the feature (Appendix A).

The decision tree was made up of multiple queries designed as feature classes in ArcGIS Pro, stemming from ‘FormTyp’. This is a broad category for the feature being assessed such as anthropogenic structure or beach. This was then refined further to define more specifically the type of anthropogenic/ beach feature, and characteristics of vegetation, material type and tidal level within the area. The data were then inputted into the geodatabase and presented on the map where the coastal features were identifiable. Using this method allowed the development of a “comparative analyses of the effectiveness of beach stabilisation methods”, based on backshore and foreshore characteristics. The decision trees used for this characterisation are visible in Appendix B.

2.2.2 Mapping and Characterizing Beaches

A map was created using ArcGIS Pro inputting geotagged photos using the geotagged tool. An OMS file from Open Street Maps was used to outline the coastline 3 times, labelling each individual line as foreshore, backshore and nearshore. The lines were then offset to reflect their relation on the actual ground (Day *et al*., 2014.). Using the geotagged photos and notes from data collection as a guide, the backshore line was then split using the split tool, to characterize attributes of the shoreline in detail. This step was then repeated for the nearshore and foreshore coastlines. The attribute of the backshore and nearshore coasts were then represented under form type (FormTyp), and the features of the foreshore coast under defining features (Features). Shoreline features were characterized based on their stability as in *Figure 2.8* below. Using the ArcGIS Pro Summary Statistics geoprocessing tool, the percentage of each attribute was calculated.

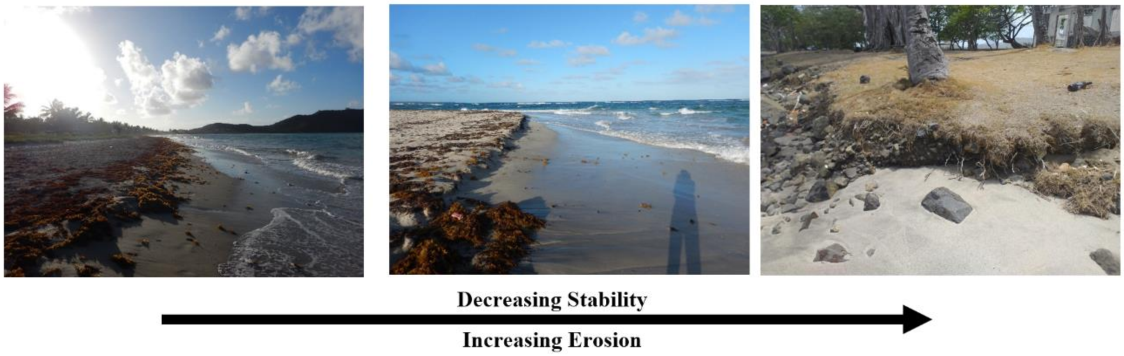


Figure 2.8 Shoreline stability and erosion guide

2.2.3 Beach Profiles- Emery Method

The full length of two straight poles, each 1.5m tall were marked and labelled at equal intervals using a measuring tape. A piece of wool string was used to connect each pole, with a 2m distance in between the poles. The profiles for each beach was initiated as far away from the waterline as possible either at the end of the roadbed or building in an anthropogenic backshore, or at the edge of the vegetated area in a natural cliff or slopped backshore. A detailed description of the vertical marker was made in the notes section of the record sheet (appendix B).

One individual faced the backshore (landward) and other faced the foreshore (seaward), each holding one pole. The individual facing landward stepped back until the string between the two poles was taut. The other individual- facing seaward then positioned themselves such that the top of the opposite pole was in line with the horizon as illustrated in *Figure 2.9*. The individual facing seaward then recorded the value on their pole, which intersects with the landward pole. The individual facing seaward then moved forward into the position previously occupied by the landward pole. This process was then repeated, moving 2m into the foreshore until the low water mark was reached. If the distance to the low water mark is less than 2m measure the distance between the poles with a measuring tape. The beach profile was continued until the intertidal berm (*Figure 2.9*) was reached, and the distance between those poles was measured once again. All the measurements taken were recorded in table 1 (appendix B).

2.2.4 Calculating Profile Slopes and Elevation

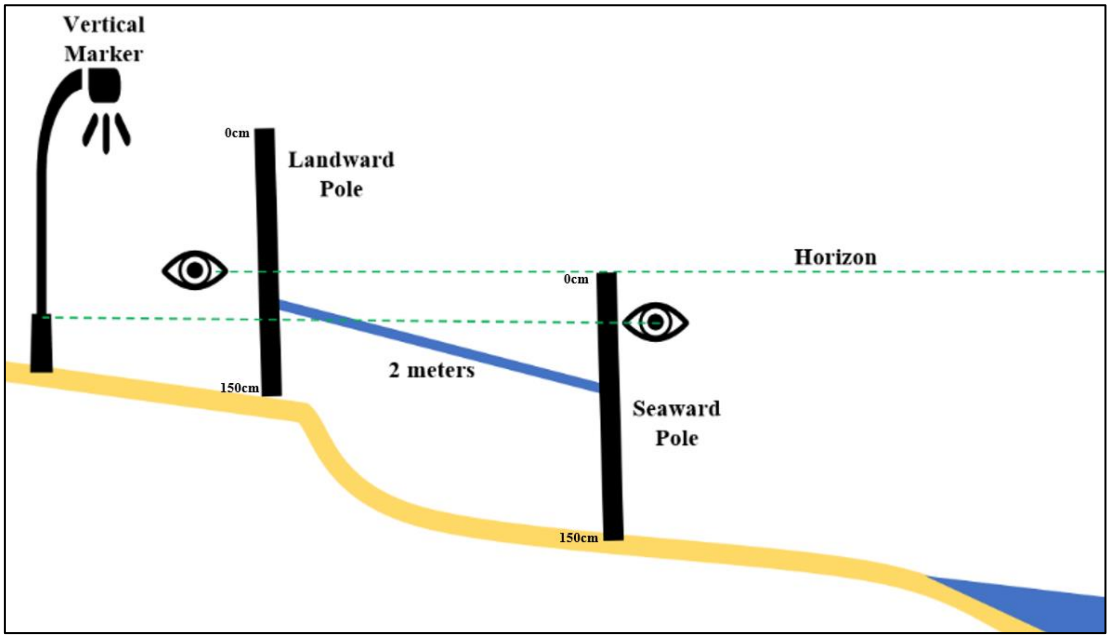


Figure 2.9 Emery Method explanatory diagram adapted from: Larasati and Wacano (2013)

After all the data was collected in the field, vertical values from the raw data sheet were inputted into an excel spreadsheet. These vertical values were then converted from centimetres to metres, as to have consistent units throughout the calculations. The horizontal values from the raw data sheet were then inputted into an excel spreadsheet.

Values for '**cumulative distance- CD'** i.e. the total distance of the profile measures were then calculated, using equation 1:

$$CD = CD_0 + H_1 \qquad (1)$$

The **elevation-E** values of each point of the profile were then calculated using equation 2:

$$\text{When } V=0,\ E = E_0 - V_0 \qquad (2)$$

$$\text{When } V=1,\ E = E_1 - V_1$$

The '**adjusted cumulative distance- ADC'** was then calculated where the adjusted cumulative distance at water line $ACD_W = 0$. The adjusted cumulative distance for points above the low water mark was calculated using equation 3:

$$\text{If } ACD > 0,\ CD_w - CD_{w+1} + ACD_w \qquad (3)$$

$$\text{If } ACD > 1,\ CD_{w+1} - CD_{w+2} + ACD_w$$

The adjusted cumulative distance for points below the low water mark was calculated using equation 4:

$$\text{If } ACD < 0,\ CD_w - CD_{w-1} + ACD_w \qquad (4)$$

$$\text{If } ACD < -1,\ CD_{w-1} - CD_{w-2} + ACD_w$$

Where the low waterline is recorded on the raw data sheet, this value was marked as '0' for the adjusted cumulative distance and adjusted elevation.

The adjusted elevation was then calculated similar to adjusted CD, where the adjusted elevation (AE) at water line $AE_W = 0$. The adjusted elevation above the low water mark will then be calculated using equation 5:

$$\text{If } AE > 0,\ E_w - E_{w-1} + AE_w \qquad (5)$$

$$\text{If } AE > 1,\ E_{w-1} - E_{w-2} + AE_w$$

The adjusted elevation below the low water mark will then be calculated using equation 6:

$$\text{If } AE < 0,\ -(E_{w-1} - E_w) + AE_w \qquad (6)$$

$$\text{If } AE < -1,\ -(E_{w-2} - E_{w-1}) + AE_{w-1}$$

Using NOAA Tide and Currents Predictions below, the height of the tide at the time the profile surveyed was estimated. '**Tide adjusted elevation**' was then calculated using equation 7: This allowed all records to be adjusted to mean water level, as all profiles could be compared to the same water line, without being conducted at the same time.

$$\text{Tide Adjusted Elevation} = \text{Adjusted Elevation} - \text{Tide Adjustment} \qquad (7)$$

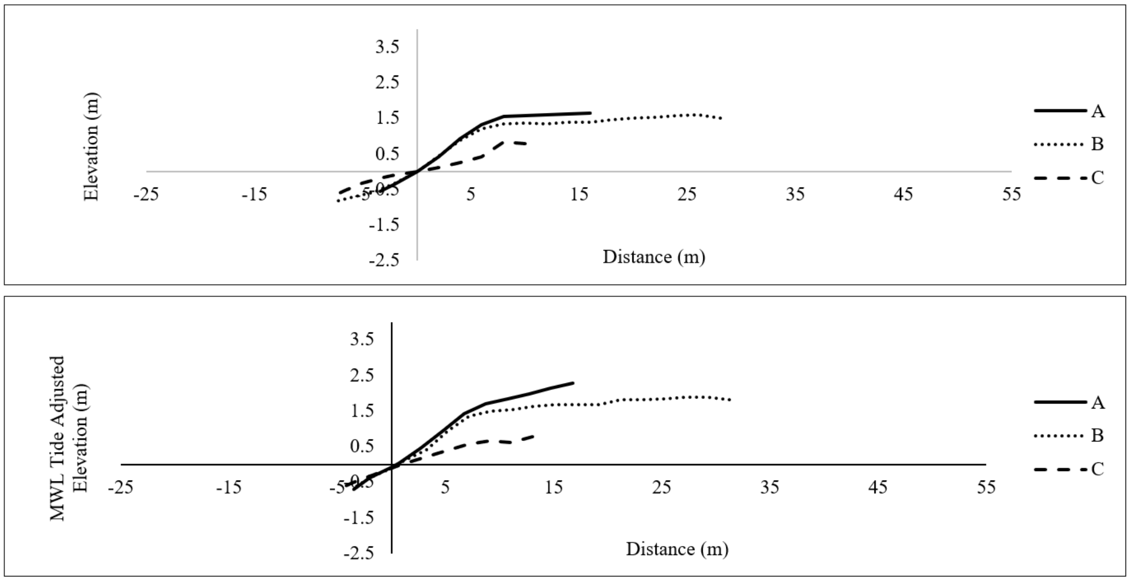


Figure 2.10 Sample beach profile graph before and after mid waterline (MWL) adjustment (Vertical Exaggeration x10.7)

2.2.5 Graphing Beach Profiles

A scatter plot was then created using values of adjusted cumulative distance on the x axis and tide adjusted elevation on the y axis. The slope of the graph was then calculated for the swash zone in the foreshore and the berm in the backshore, and breaker zone in the nearshore where applicable using equation 9:

$$\text{Slope} = AD \div CD * 100 \qquad (9)$$

The steps above were repeated for each beach surveyed.

2.2.6 Post Storm Survey

Utilizing the detailed description of the vertical marker recorded for the initial surveys, each of these steps were repeated a second time at the end of the hurricane season (June to November), and 2-4 weeks after the second survey to assess recovery (see appendix C). The goal of the study was to assess the recovery of the beach after a storm. However, no storms in the offshore zone of the island were formed during this survey. In place of a storm, the effect of Gale force winds were used and highlighted as a 'disturbance'. Geotagged photos of changes in the backshore, and foreshore were taken and changes in characteristics such as erosion levels and damage to backshore structures were noted on the data sheet. The photographs, graphs and maps were collated for the pre and post disturbance then assessed using comparative analysis. A detailed analysis of changes to each beach was then statistically analysed as presented in the results section of this paper.

Table 2.1 Beach Survey Dates

Activity	**End Date**
Data Collection and Entry- First Assessment North Coast Beaches	June 10th and 16th 2020.
Data Collection and Entry – First Assessment West Coast Beaches	September 12th, 2020.
Data Collection and Entry – Second Assessment North Coast Beaches	November 4th, 2020
Data Collection and Entry – Third Assessment North Coast Beaches	December 5th, 2020

Chapter 3: Results

This study analysed the backshore, foreshore and nearshore characterization of all six beaches assessed and presented them in a map as shown in Figure 3.3 to Figure 3.19 below. Specific details regarding material type and exact proportions of the backshore and foreshore were presented in pie charts below for clearer representation. Profiles of all beaches were graphed, where the slope of the backshore and foreshore were assessed in section 3.2. These slopes were particularly important to differentiate the variation in the shoreline before versus after the storm. Photographs taken in the field were also indicative of changes which occurred during this time which may not have been as clear from profile-slope comparisons in section 3.3.

3.1 Coastal Classification

Anse Chastanet

The backshore of Anse Chastanet Beach is made up of 31% anthropogenic structures which includes resort buildings- both wooden and concrete- 63% clastic slopes and 6% brackish waterbody. This beach is a smaller pocket beach and thus, has very few anthropogenic

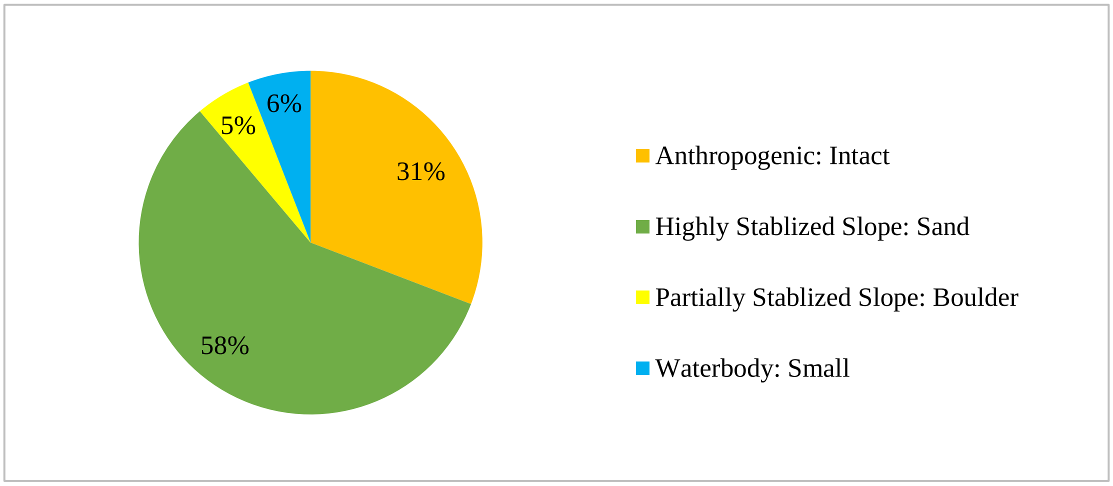


Figure 3.1 Backshore coastal characterization for Anse Chastanet Beach

features in the backshore, in comparison to others assessed further on in the study (*Figure 3.1*.

The foreshore of this beach is generally a sandy beach, however, also contains a 22m groyne feature upon which part of the resort structure lies. The foreshore and nearshore also contain a wharf. Between these 2 anthropogenic foreshore/nearshore features- accounting for 13% of the foreshore, a smaller, partially stabilized sandy beach has been created in the foreshore and nearshore with boulders in the backshore (*Figure 3.3* photo A).

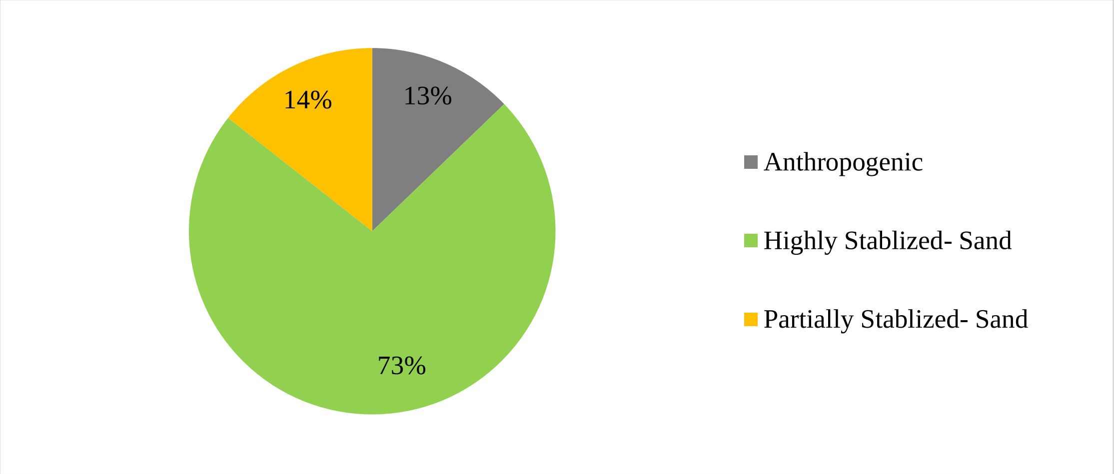


Figure 3.2 Foreshore coastal characterization for Anse Chastanet Beach

As mentioned previously, and through historic satellite imagery on Google Earth Pro, there is minimal development on Anse Chastanet Beach to date. The only visible development on the foreshore is the increased number of wooden umbrellas after 2008.

Figure 3.3 Anse Chastanet coastal characterization map and significant profile points

Malgretoute Beach

Malgretoute Beach is the only beach assessed with a complete cobble beach in both the foreshore, backshore and nearshore. For this reason, a berm could not be determined at 2 of 3 profiles (profile B and profile C). The backshore of the beach is composed of 29% anthropogenic structure, 24% of which is a new intact concrete structure which appears to be part of resort villa, with wooden fencing surrounding the nearby property *Figure 3.6* photo A. The 5% damaged concrete structures appear to be older recreational facilities such as dining areas (*Figure 3.6* photo C). The remaining 71% of the backshore is composed of clastic slope: highly stabilized sandy slope (6%), highly stabilized cobble (56%), partially stabilized cobble- (3% gravel, 6% boulder) as displayed in *Figure 3.4*.

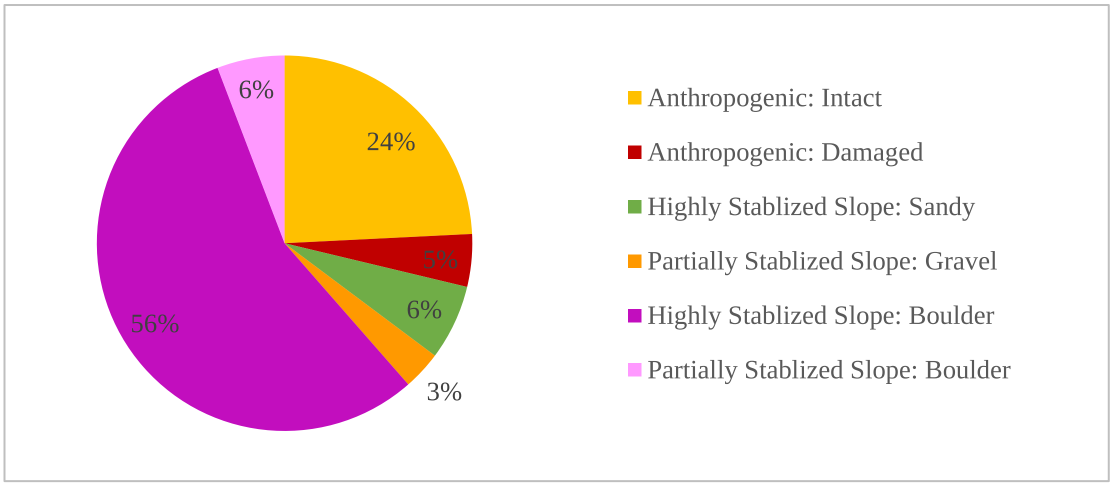


Figure 3.4 Backshore coastal characterization for Malgretoute Beach

The foreshore reflects that of backshore material composition ranging from highly stabilized sandy slope (6%), highly stabilized cobble slope (31%) and partially stabilized cobble beach (63%) as shown in *Figure 3.5*.

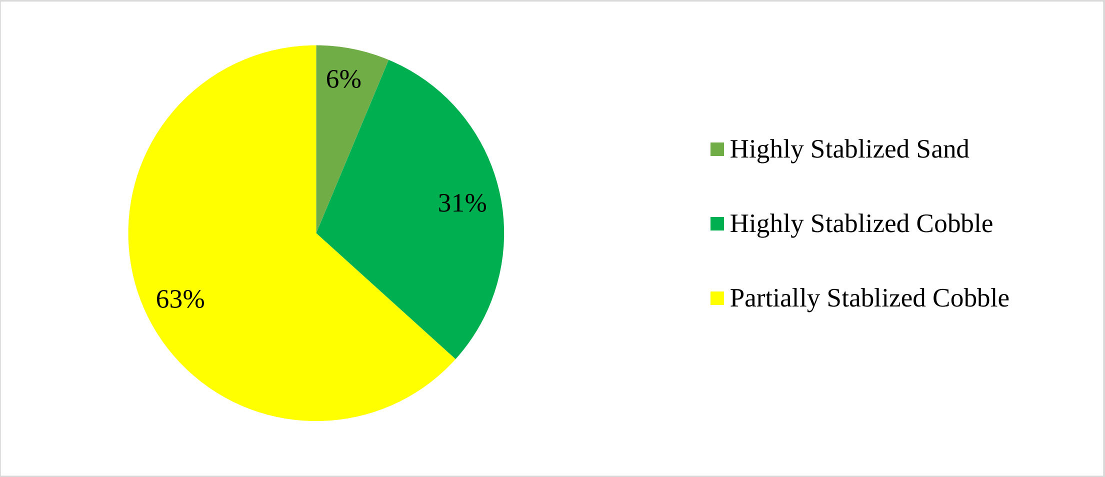


Figure 3.5 Foreshore coastal characterization of Malgretoute Beach

Malgretoute Beach generally has more of an undeveloped foreshore and backshore. Comparing historic satellite imagery on Google Earth Pro, there is a clear decrease in the length of the sandy shore from ~530m in 2007 to 381m in 2020. Images also suggest a general decrease in anthropogenic structures in the backshore. It should be noted however, the location of these structures were not part of this assessment.

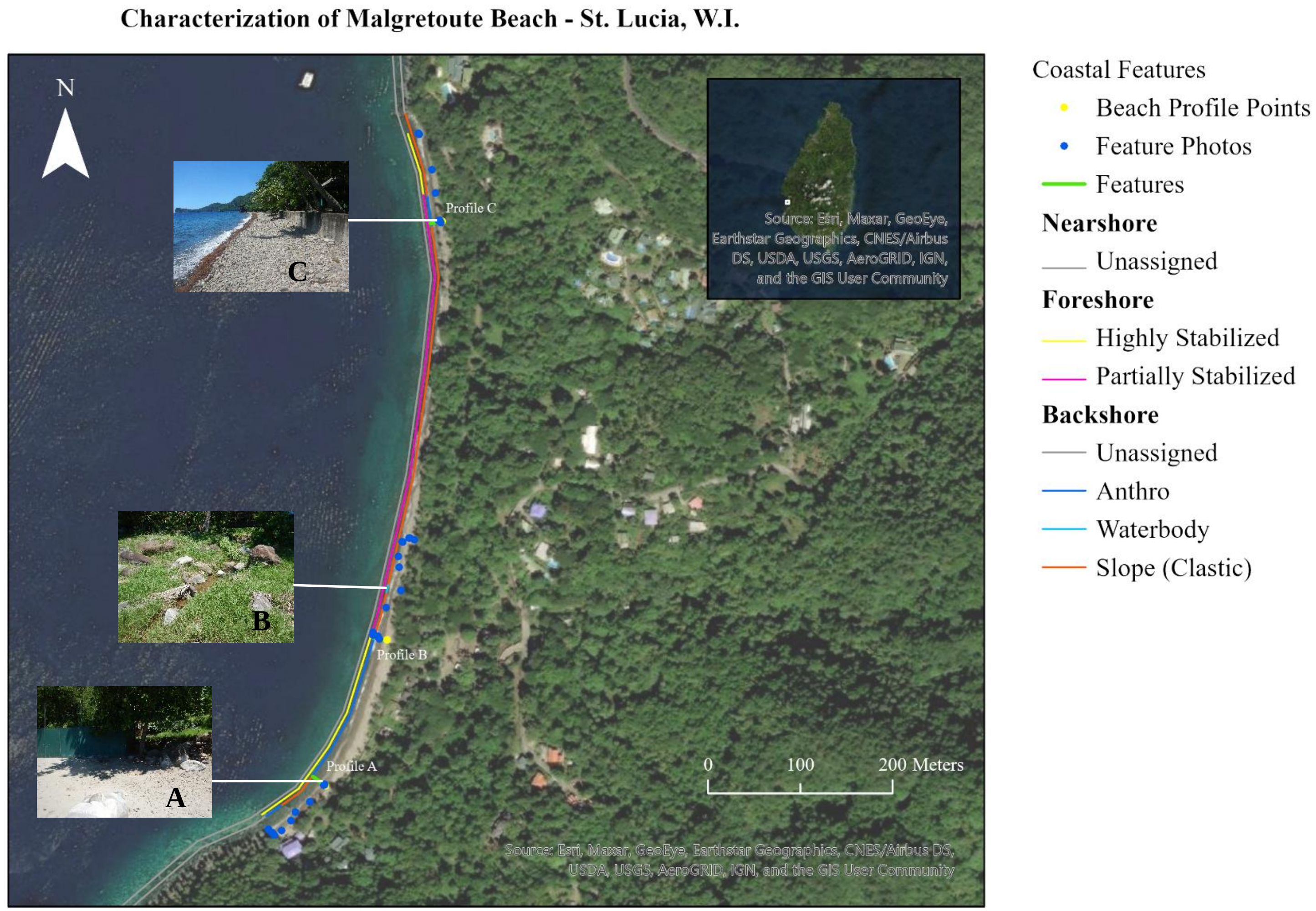


Figure 3.6 Malgretoute Beach coastal characterization map and significant profile points

Vigie South

The backshore composition of Vigie Beach South is the most diverse of all those assessed. Sixty five percent (65%) of Vigie South has been characterized by having an anthropogenic backshore. This comprises of a roadbed, gabion baskets, both concrete and wooden buildings, as well as remanences (masonry) of pre-existing buildings. Of these anthropogenic structures, 43% is intact, 15% of these are damaged, and 7% is failing. The remaining 45% of the beach is characterized by clastic slopes of which 12% is considered highly stabilized, 20% partially stabilized and 3% unconsolidated material- which appears to have been relocated to this portion of the beach (Figure 3.9 photo B)

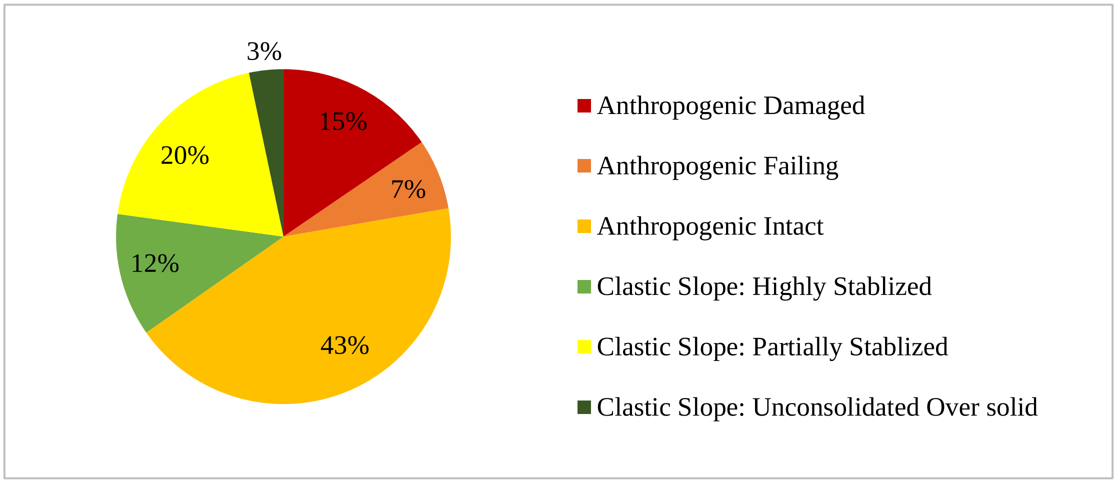


Figure 3.7 Backshore coastal characterization of Vigie South

The Vigie South foreshore is composed of a clastic slope (90%), with one anthropogenic feature- an intact groyne, which encompasses 10% of the foreshore. Sixty two percent (62%) of the coastline was considered highly stabilized, with 1% of this characterized as a cobble slope as opposed to a sandy slope. Similar to the Pigeon Island Causeway, this section of the beach was present at the end of a cliff head. The non stabilized (6%) and partially stabilized (22%) portion of the foreshore was located at the same point of the profile as the cemetery, and exposed gabion baskets, as well as the cobble backshore. There are distinct natural features within the nearshore. However, there is a groyne in the intertidal zone separating Vigie North and South as well as a detached breakwater part of the Vigie South nearshore zone (Figure 3.9 photo D).

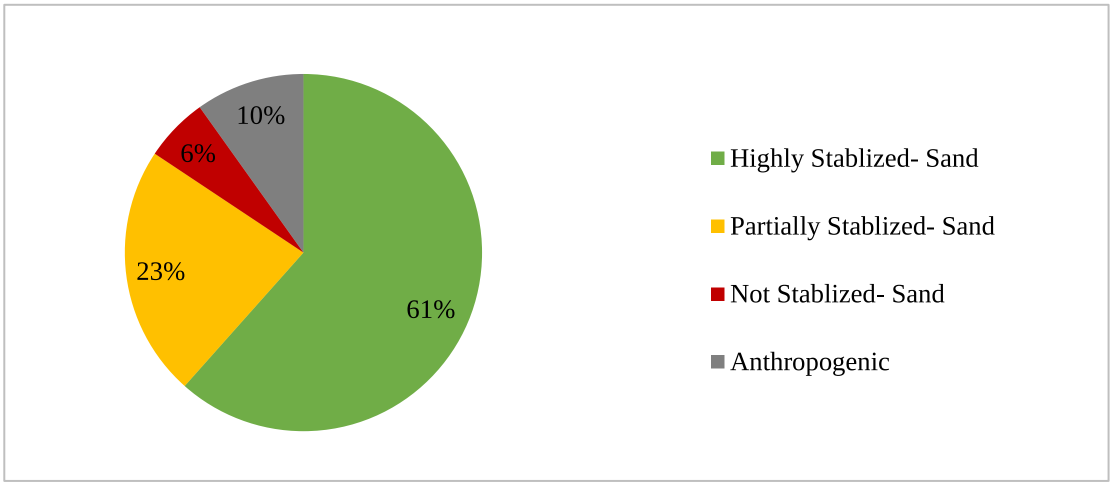


Figure 3.8 Foreshore coastal characterization of Vigie South

Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 3.9 Vigie Beach- South coastal characterization map and significant profile points

Vigie Beach- North

Vigie Beach- North, is the only beach assessed with wetland/mangrove species in the backshore. A mature, stressed mangrove forest makes up only 5% of the backshore. Based on the appearance of the anthropogenic backshore, some of the mangrove system may have been deforested to accommodate the resort (*Figure 3.12*). The forest has been characterized as stressed due to the low buffer zone between the nearest anthropogenic structure and the inundated portion of the forest. Anthropogenic features make up 34% of the backshore. Twenty-five percent (25%) of this section are intact features made of either wood or concrete and are part of the resort's property. The other 6% and of 5% features are remnant or damaged components of older structures respectively, most located midway along the beach profile (*Figure 3.13* photo A). The remaining 66% of the backshore is sandy slope- 45% highly stabilized and 14% partially stabilized.

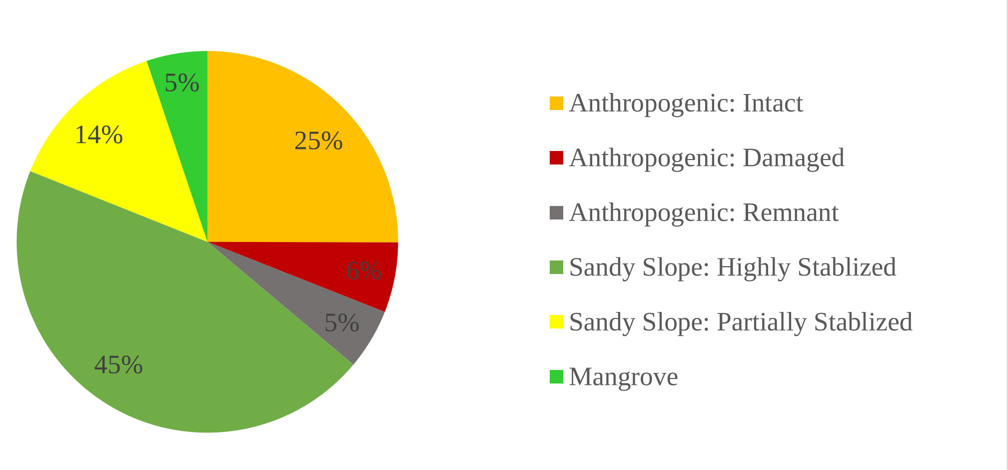


Figure 3.10 Backshore coastal characterization for Vigie Beach- North

The least stabilized foreshore has been highlighted in front of waterbodies. More specifically, in front of the mangrove system (*Figure 3.12*), as well as in front of the smaller water body closer to the Northern end of the beach (*Figure 3.13* photo B). The partially stabilized portion of the beach makes up 45% of the foreshore with varying material types- gravel (32%), and sand (29%). It should be noted that the cobble portion of the beach also consisted of sand with anthropogenic features (masonary) in the backshore (*Figure 3.13* photo A). The gravel portion of the beach similar to the southern most end of Vigie South, was located at the Northern most end of Vigie North, near a cliff head (*Figure 3.13* photo D).

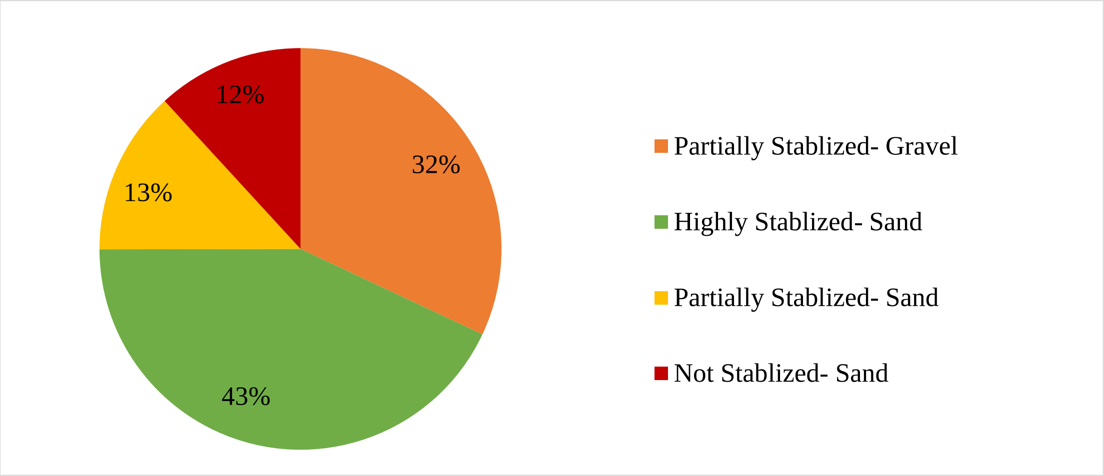


Figure 3.11 Foreshore coastal characterization of Vigie Beach- North

Vigie beach- North, was the only beach assessed with varying natural features within the nearshore. A parallel bedrock platform was observed at 3 points within the nearshore (*Figure 3.13* photo C). Remnant anthropogenic features were also present at varying points in the nearshore, where tides were higher (*Figure 3.13* photo A).

The oldest satellite image of Vigie beach (north and south) was in 2006. Between 2006 and 2020, where the only new anthropogenic structures in the backshore visible from satellite images are the expansion of existing structures such as the cemetery, wooden vending structures and new concrete resort structures. Beyond this, the development of a detached breakwater at the northern end of the beach occurred in 2017. This led to a visible increase in beach width of ~10m in front of the breakwater and 20m width in front of the pre-existing groyne. Images also displayed a clear decrease in backshore vegetation as a result of this new development. There was also a clear decrease in beach width where tides were generally already high.

In the case of Vigie North specifically, there was no dramatic change within the foreshore or nearshore visible from satellite imagery. However, there is evidence of increased vegetation within the backshore.

Figure 3.12 Mangrove bordering resort on Vigie Beach- North

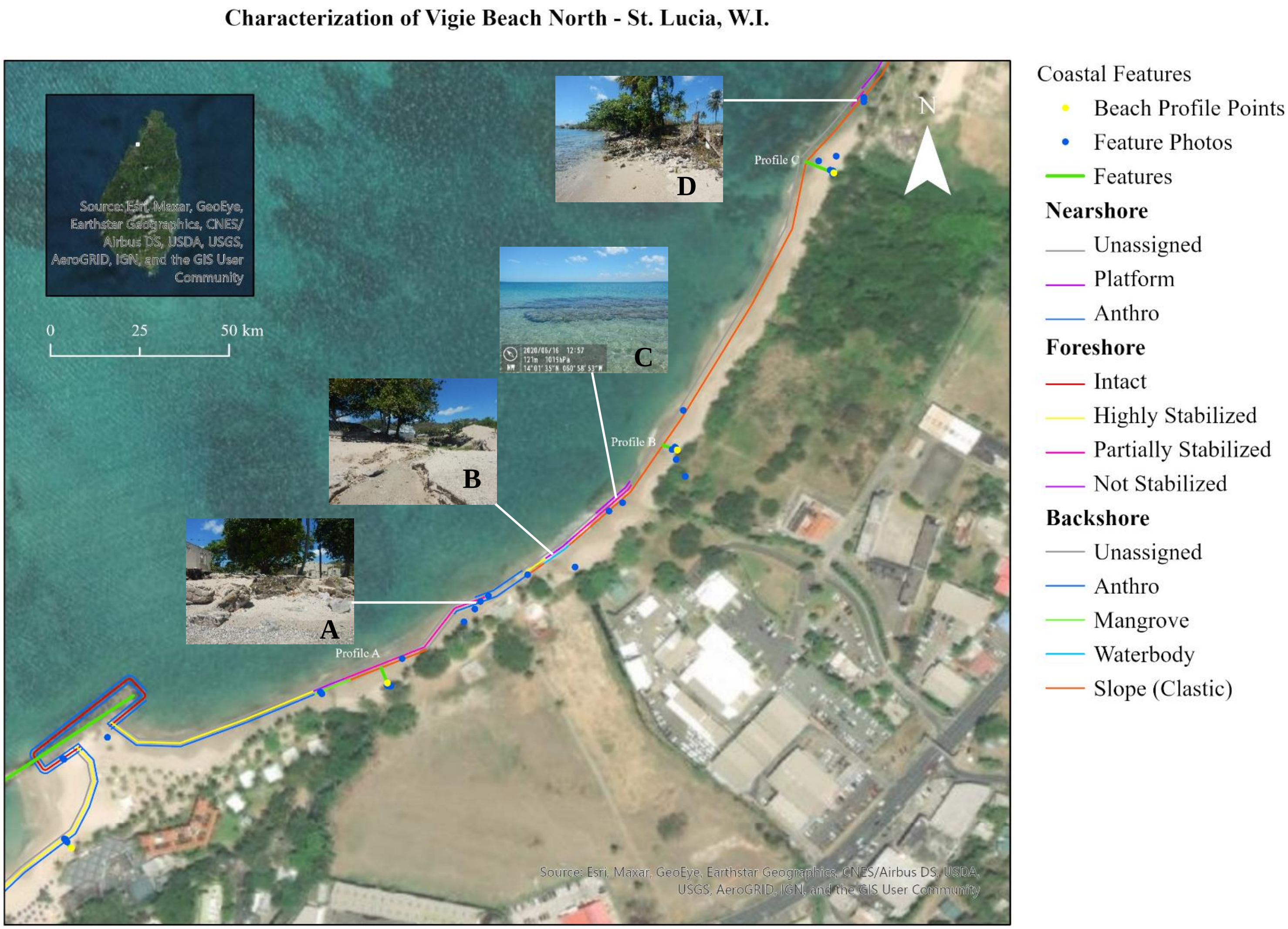


Figure 3.13 Vigie Beach- North coastal characterization map and significant profile points

Reduit Beach

Reduit beach is primarily composed of an anthropogenic backshore, with a shorter portion of the beach (~90m) being a partially stabilized clastic, sandy slope. 87% of the backshore is composed of intact wooden or concrete anthropogenic structures, most of which are resort properties. One section in the backshore, approximately midway into the beach, although presented on the map as being anthropogenic in nature due to the presence of a chain linked fence, is undeveloped (*Figure 3.16* see photo C). The remaining 13% is undeveloped, partially stabilized sandy slope in the east of the beach. This can be observed clearly in *Figure 3.16*.

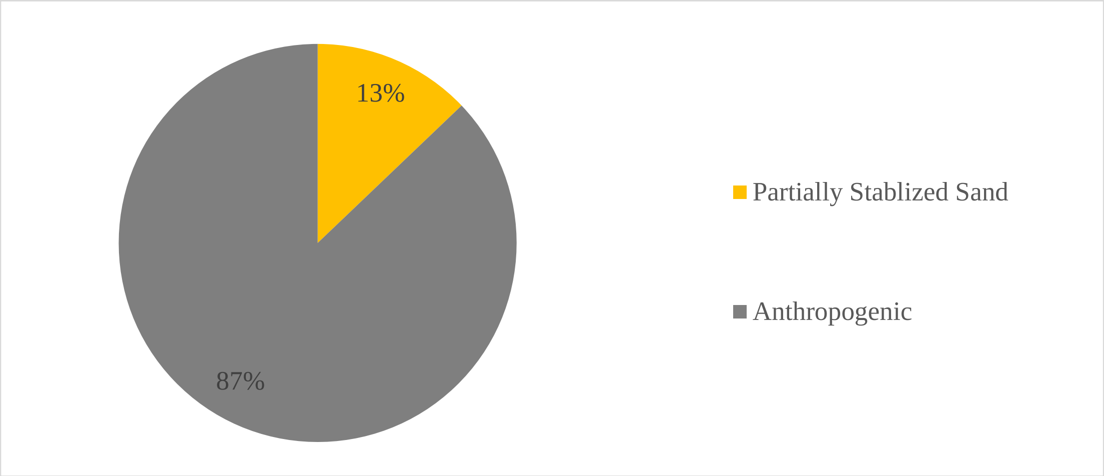


Figure 3.14 Backshore coastal characterization for Reduit Beach

The foreshore of the beach is more complex in comparison to that of the backshore. Thirty one percent (31%) of the foreshore can be identified as being a highly stabilized sandy beach as there was little evidence of active erosion and beach cusps. 5% of this beach was classified as being partially stabilized and 2% not stabilized due to the presence of cobble on a predominantly sandy beach, as well as uneven beach cusps. Thirty-nine percent (39%) of the foreshore was characterized by an active berm, indicative of a relatively medium to steep slope with coarse sand. Twenty- three percent (23%) of the beach was characterized by an impeded berm (*Figure 3.15*).

There is one anthropogenic feature in the nearshore for this beach, i.e. a groyne, part of the Rodney Bay Marina. The remainder of this beach is mainly unassigned, and thus is characteristic of a common dynamic sand bar.

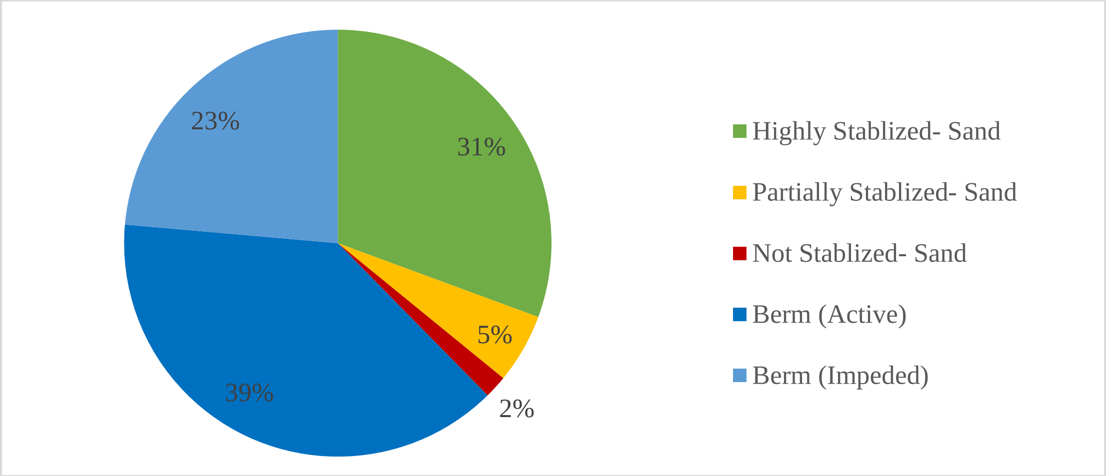


Figure 3.15 Foreshore coastal characterization for Reduit Beach

Utilizing historic satellite imagery from Google Earth Pro, visible alterations in coastal area were identified. For Reduit beach specifically, the oldest visible image was recorded in 2001. Between 2001 and 2020, there is a clear increase in coastal development on Reduit Beach. In the first aerial photograph, taken from 2001, it appears that there are two large resorts, and a third smaller resort along this coast. There were no anthropogenic structures on the western side of this beach until 2006. As of 2020 however, most of the backshore- more specifically all but the eastern most side of the beach is completely developed with anthropogenic concrete or wooden structures. There is therefore a general decrease in vegetation but increase in beach width.

Characterization of Reduit Beach - St. Lucia, W.I.

Figure 3.16 Reduit Beach coastal characterization and significant profile points

Pigeon Island Causeway Beach

The backshore of Pigeon Island Causeway is composed of 50% anthropogenic structures. Similar to Reduit Beach, the anthropogenic backshore is mainly composed of concrete seawalls, acting as resort buildings as well as a roadbed. The remaining 50% is clastic slope with varying degrees of stabilization and material types. Nineteen percent (19%) of the backshore is composed of highly stabilized sandy slope, 15% partially stabilized sandy slope, and 16% partially stabilized cobble slope (*Figure 3.17*).

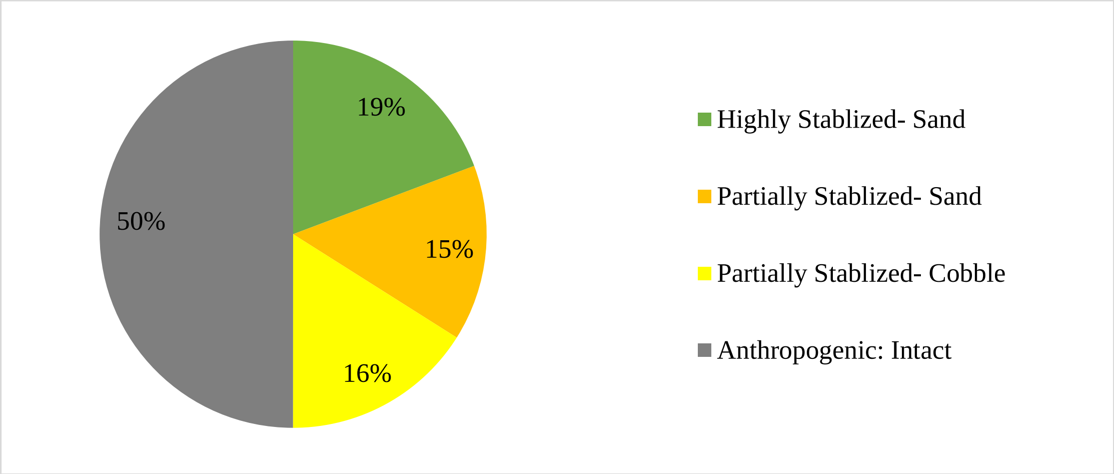


Figure 3.17 Backshore coastal characterization for Pigeon Island Causeway

Eighty-five percent (85%) of the foreshore has been categorized as 'highly stabilized' as there was little evidence of active erosion and beach cusps in both the cobble beach (2%) and sandy slope (83%). The remaining 15% is composed of partially stabilized cobble slopes (10%) and sandy slopes (2%), as well as anthropogenic structures (3%). It should be noted that lengths of cobble, pebble beaches were present at either ends of the beach, near a groyne as well as the end of the profile where a natural cliff was present (*Figure 3.19* photo D). Four points within the nearshore of this beach consists of anthropogenic features, more specifically, a marina and (not accounted for in the foreshore assessment) three groynes.

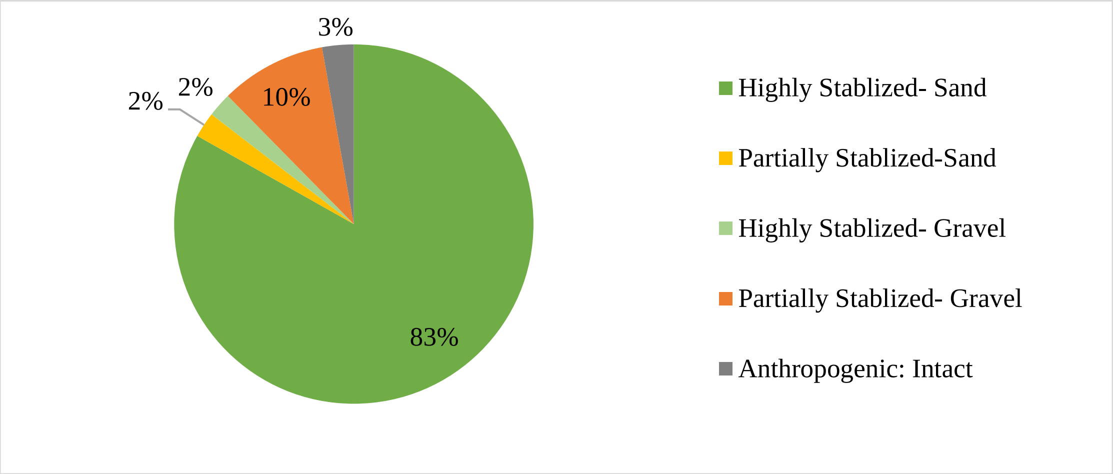
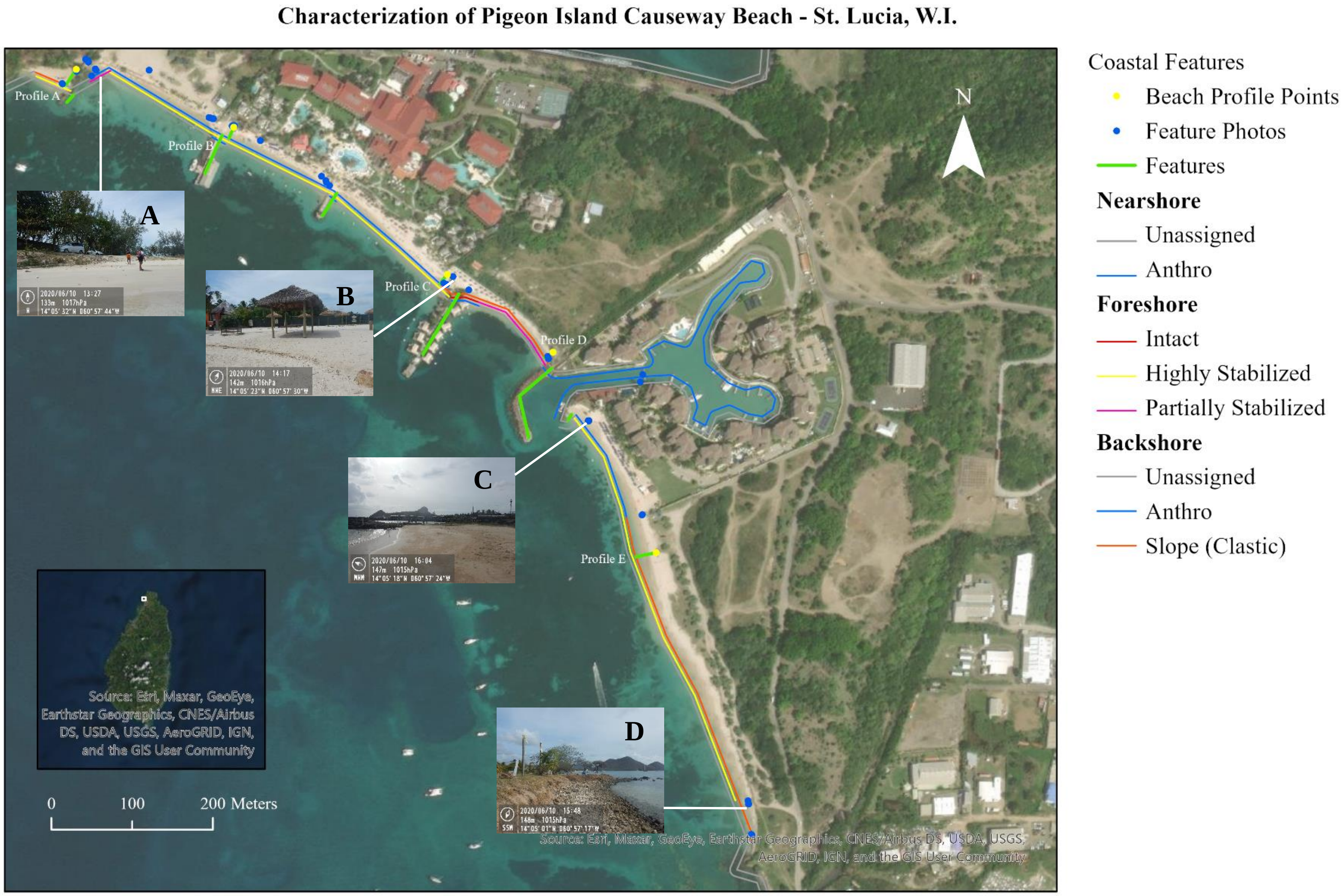


Figure 3.18 Foreshore coastal characterization for Pigeon Island Causeway

Based on satellite imagery, prior to 2001, Sandals Grande was the only major resort on the Pigeon Island Causeway. Before this time, there were 4 groynes constructed along the shore, within minimal construction on each. There was a complete golf course to the East of the resort. As of 2006, there was an appearance of the development of a marina and decrease in vegetation to the east of the existing resort. As of 2020, there is construction on two of the four existing groynes, as well as the expansion of the east most prevalent groyne, to accommodate the new marina and resort. There has been a general decrease in backshore vegetation after construction, with a naturalized portion of the beach where the golf course resided. Satellite images also display a clear decrease in beach width between the last two groynes on the east coast of the beach- in front of the previous golf course. Although difficult to determine, it appears there may have also been a decrease in beach width on the western most side of the beach.



Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 3.19 Pigeon Island Causeway Beach coastal characterization and significant profile points

3.2 Slope Comparisons for Beaches

Anse Chastanet Beach

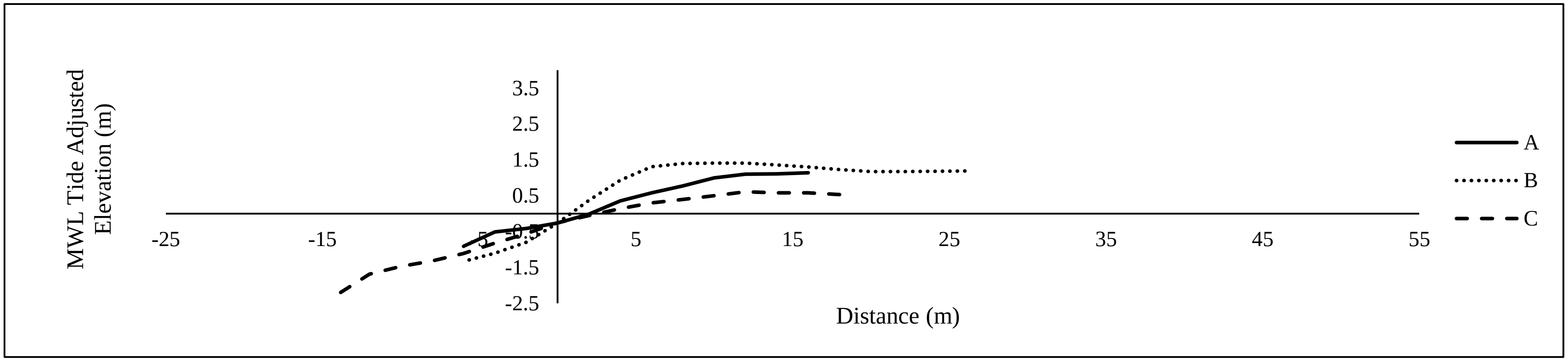


Figure 3.20 Beach profiles and slopes for Anse Chastanet Beach adjusted to the mid water level (Vertical Exaggeration x10.7)

Profile A was the first profile assessed. Profile assessments began from either the northern (or southern) most point selected on the predetermined map, nearest the entrance of the beach, moving north or south along the beach from the first established profile. Profile A recorded a slope of 10%. The backshore of profile A as visible in Figure 3.3 is an anthropogenic source, the restaurant, where the foreshore is bordered by a groyne on the south of side of the map photo B. The backshore of Profile B is a clastic slope of 7%, from which the start point was an almond tree as shown in appendix C below. This profile was the longest assessed measuring 24m from the backshore to the intertidal zone. Profile C (slope: 9%) was measured from another anthropogenic structure- a concrete step as observable in appendix C below. Profile C had an intertidal zone approximately twice that of the other 2 profiles. It is important to note that profile C is bordered by a small brackish waterbody and groyne like feature to the east *Figure 3.3* photo D.

Malgretoute Beach

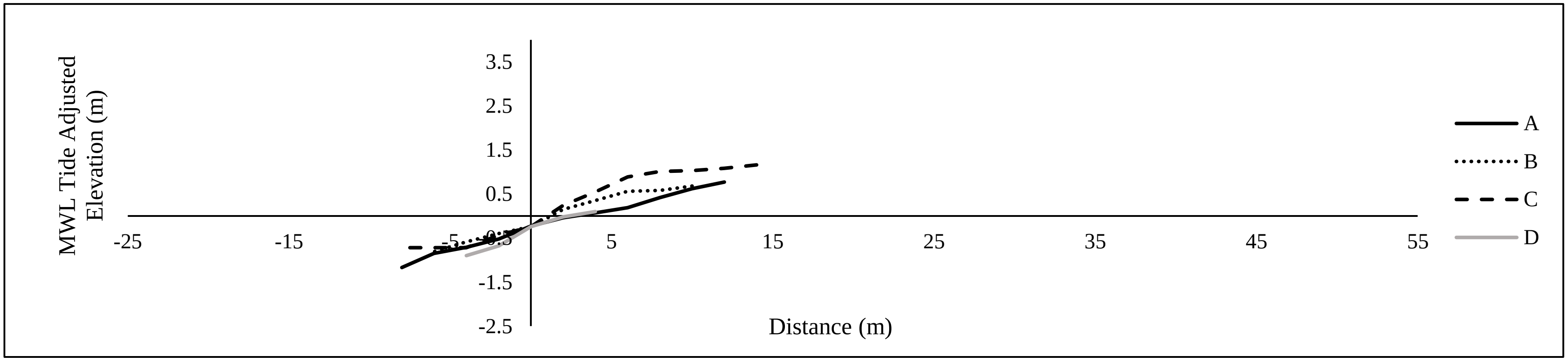


Figure 3.21 Beach profiles and slopes for Malgretoute Beach adjusted to the mid water level (Vertical Exaggeration x10.7)

All 4 profiles of this beach measured approximately the same length. It is important to note however, that the surf zone/intertidal bar for profiles C and D, taken on the predominately cobble section of the beach could not be identified. Profile A, a predominantly sandy region, was identified as having a slope of 9 %. Profile B, was a mixture of cobble, pebble, and sandy beach, measuring a similar slope of 10%. Profile C, a cobble beach measured from clastic sloping backshore, was identified as having a slope of 11%. Similarly, profile D measured from an anthropogenic source in the backshore, recorded a slope profile D 13%.

Vigie Beach- North

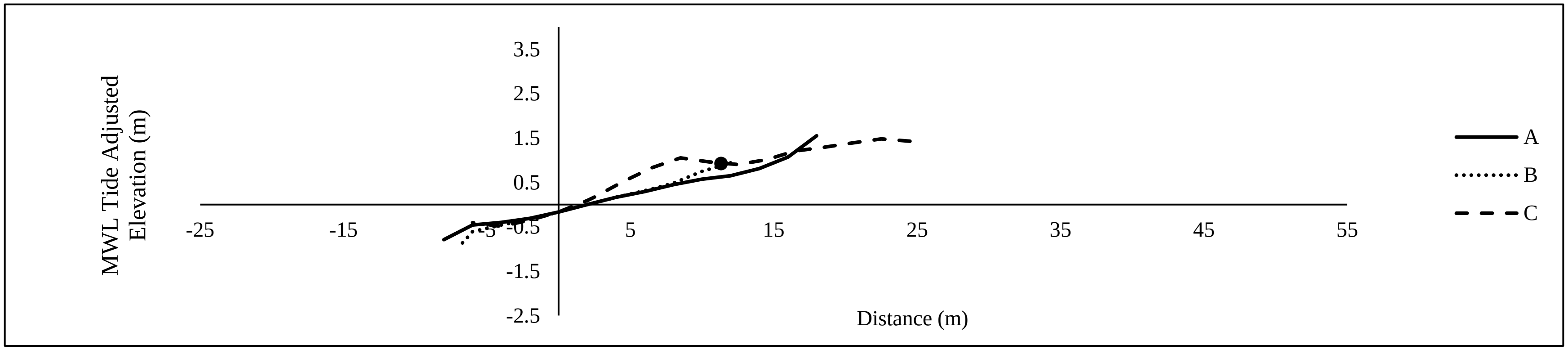


Figure 3.22 Beach profiles and slopes for Vigie Beach- North adjusted to the mid water level (Vertical Exaggeration x10.7)

The profiles of Vigie North were measured solely from clastic slopes in the backshore. Although there were parallel bedrock structures within the nearshore as displayed in *Figure 3.13* photo C, no profiles were influenced by this. Profile A and B were both measured from major exposed tree roots on the slope as observable in appendix C below, registered slopes of 8% and 9% respectively. Profile C on the other hand began with a vegetated surface and registered a slope of 4% within the vegetated portion assessed, and a foreshore slope of 10%.

Pigeon Island Causeway Beach

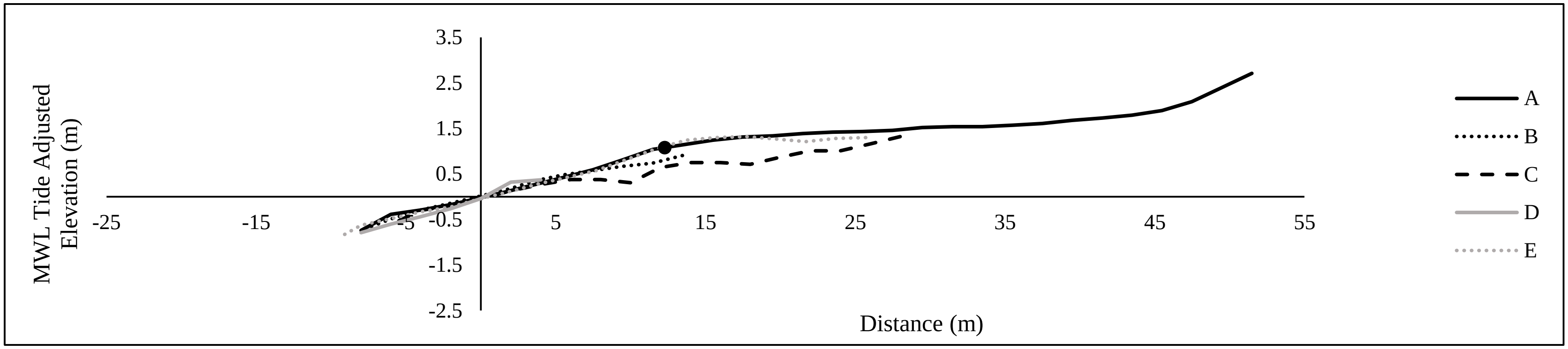


Figure 3.23 Beach profiles and slopes for Pigeon Island Causeway Beach adjusted to the mid water level (Vertical Exaggeration x10.7)

Profile A is the only profile located within an enclosed area bounded within an anthropogenic concrete structure and a groyne to the east of the profile. The backshore of this profile was assessed from a tree further than most profiles, and thus is ~20m longer than the other 4 profiles. This profile, with a slope of 5% began from a gravel, vegetated backshore and ended in a fine sand intertidal zone. Profile B (slope 7%) was located in front of the Sandals Grande Resort property, after the first major groyne as observable in appendix C below. This profile was started from an anthropogenic source, an intact wooden structure on predominantly fine sand beach. Profile C was also located in front of the resort property and was also commenced from an anthropogenic source, a wooden sign erected by the resort. This profile recorded backshore slope of 4% and a foreshore slope of 6%. Profile D was the shortest recorded profile measuring ~22m in length. This profile registered a slope of 10% and was the only predominately cobble profile assessed. Profile E was located after The Landings Resort and marina. Profile E, although assessed within a clastic, vegetated backshore, utilized a permanently erected volleyball net on the beach as vertical marker for this profile. This profile registered a slope of 7%. Due to restrictions, a profile was not established on the beach directly in front of the resort creating a somewhat uneven profile distribution for this beach.

3.3 Beach Recovery Assessment

Reduit Beach

Table 3.1 Reduit Beach profile slopes

Reduit Beach	A	B	C
Pre Disturbance	16%	7%	9%
2 Weeks Post Disturbance	13%	7%	9%
4 Weeks Post Disturbance- Recovery	14%	7%	10%

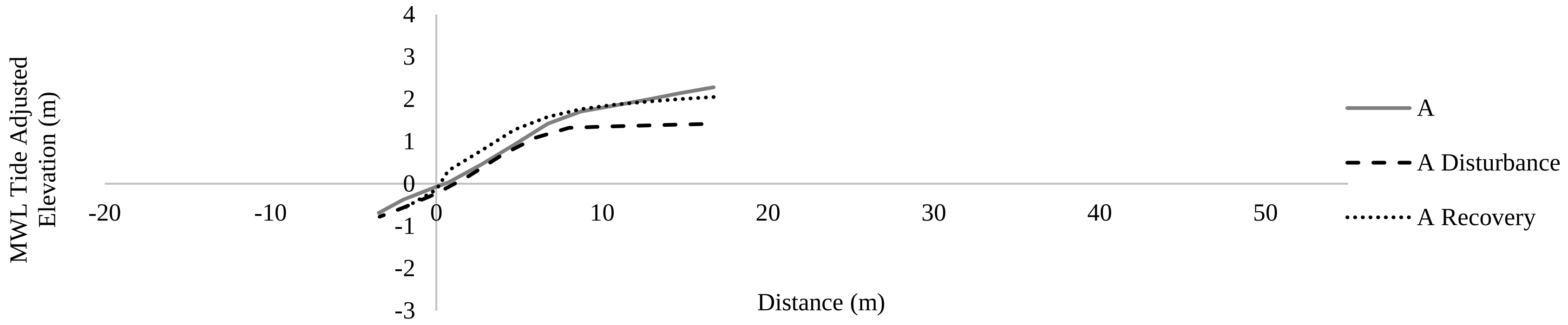


Figure 3.24 Reduit Beach profile A before the disturbance (A), 2 weeks after the disturbance (Disturbance) and 4 weeks after the disturbance (Recovery)

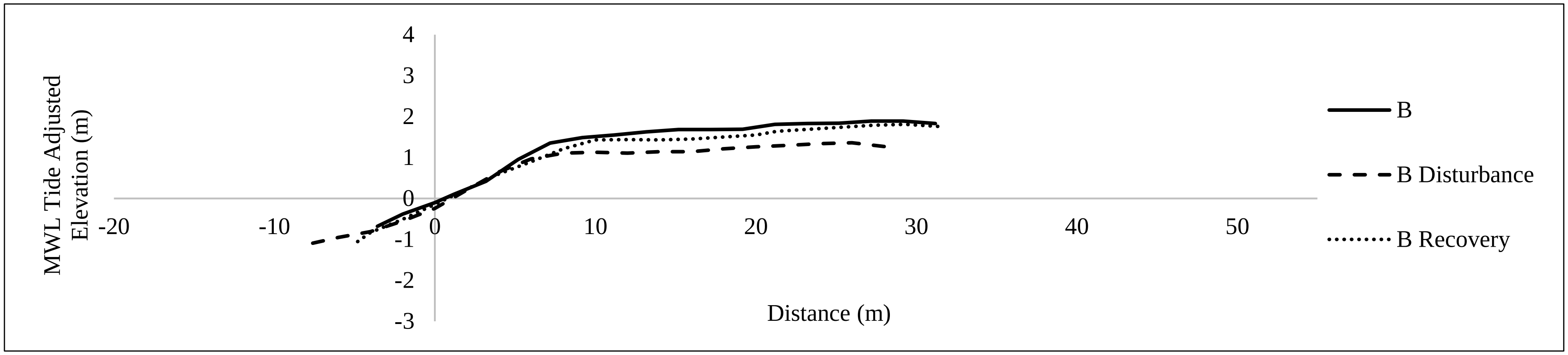


Figure 3.25 Reduit Beach profile B before the disturbance (B), 2 weeks after the disturbance (Disturbance) and 4 weeks after the disturbance (Recovery)

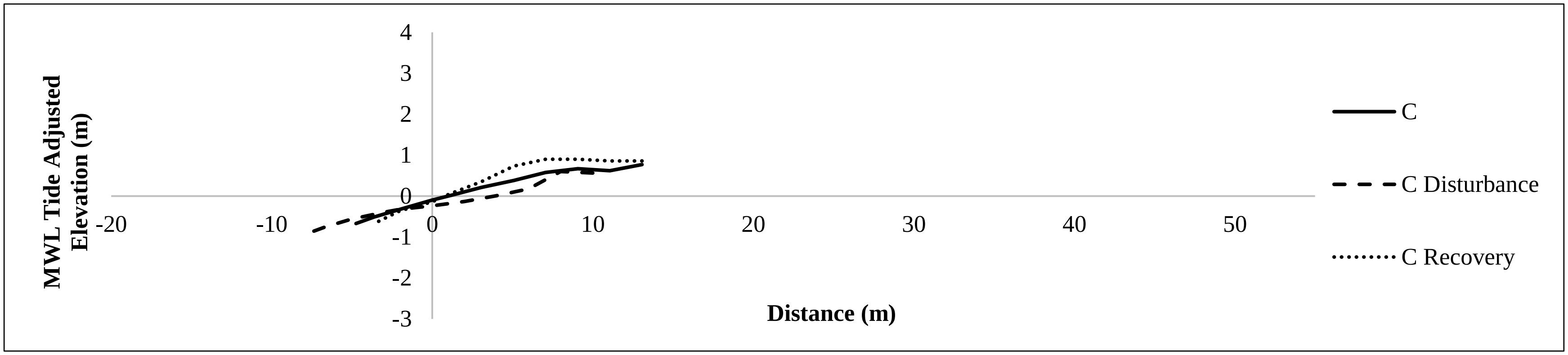


Figure 3.26 Reduit Beach profile B before the disturbance (B), 2 weeks after the disturbance (Disturbance) and 4 weeks after the disturbance (Recovery)

Reduit Beach Profile A displayed a decrease in slope after the disturbance from 16% to 12%. Four weeks after the disturbance (recovery assessment) the slope increased to 14%. However, there was a slight decrease in the length of the profile by ~0.5m. This section of the beach also displayed a higher level of erosion as shown in Figure 3.27.

Profile B displayed no change in slope over the disturbance maintaining a slope of ~7%. However, the length of the profile was decreased by ~0.5m after the disturbance similar to profile A. There was no appearance of distinct erosion as in Figure 3.27.

Profile C displayed no change 2 weeks after the disturbance, however showed an increase in slope of 2% four weeks after the disturbance, as well as experienced a decrease profile length of 0.3m. Profile C also exhibited a material change from solely fine grained sand to a combination of sand and gravel Figure 3.27 two weeks after the disturbance. During the recovery survey however, sand was once again the predominant sediment type.

Figure 3.27 Appearance of Profile A (top left), profile B (top right) and profile C (bottom) waterline 2 weeks post disturbance

The appearance of the beach displayed a more comprehensive representation of the previous disturbance than small changes in the profiles. *Table 3.2* provides a comprehensive review of extreme changes observed on Reduit Beach before the disturbance (pre-disturbance) and 2 weeks after the disturbance (post disturbance).

Table 3.2 Review of visible differences in Reduit beach before and 2 weeks after the disturbance

Pre-Disturbance	Post Disturbance
	
	
	

 Profile C	 Profile C
 	
 	

Vigie Beach- South

Table 3.3 Vigie Beach- South profile slopes

Profile	**A_b**	**A_f**	**B_b**	**B_f**	**C**	**D_b**	**D_f**
Pre-Disturbance	5%	6%	5%	6%	11%	2%	13 %
2 Weeks Post Disturbance	3%	7%	7%	5%	8 %	0%	11%
4 Weeks Post Disturbance-Recovery	2%	9%	3%	6%	8%	5%	12%

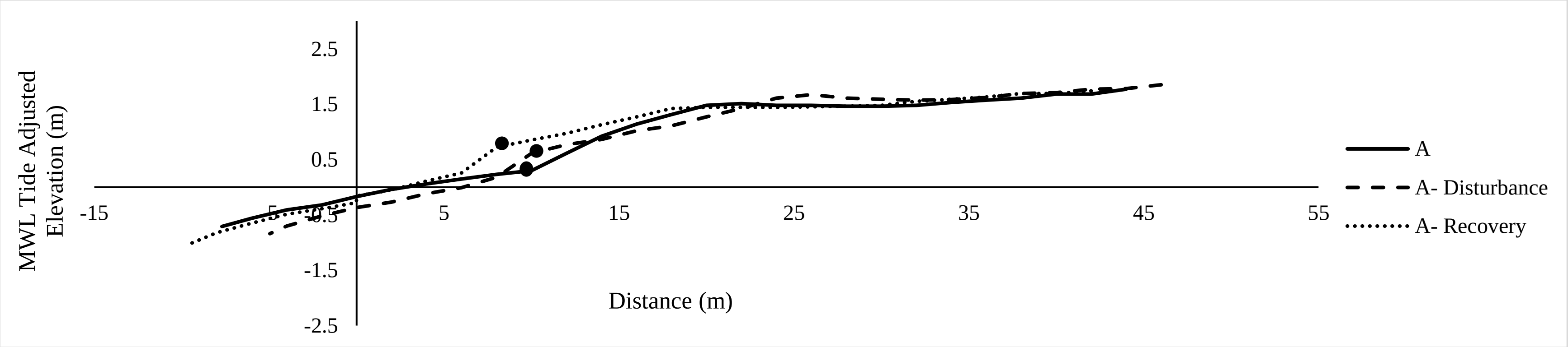


Figure 3.28 Vigie Beach-South profile A before the disturbance (A), 2 weeks after the disturbance (Disturbance) and 4 weeks after the disturbance (Recovery). The black point represents the location on the profile line from which the slope was measured- the left side of the point indicates the section of the foreshore slope, the right side of the point indicates the section of the backshore slope.

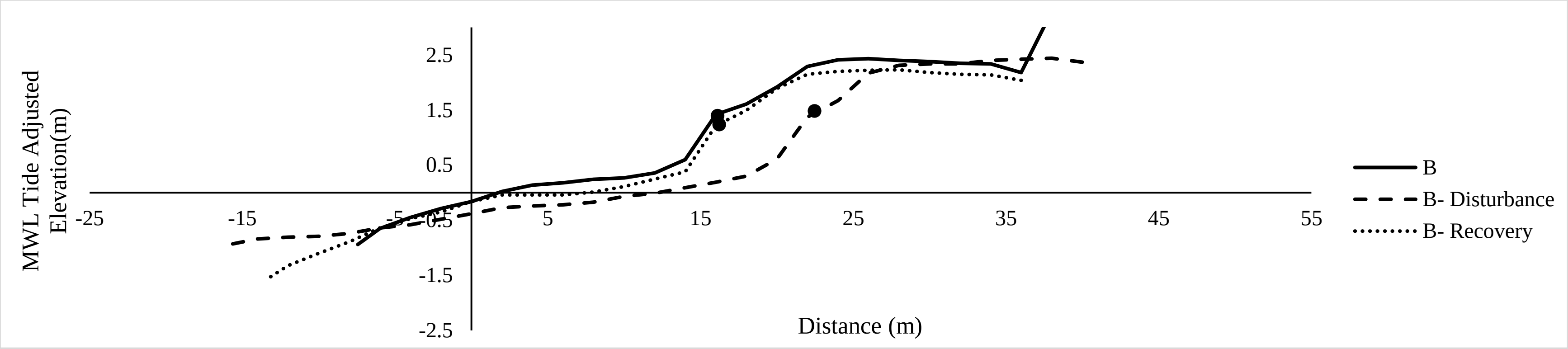


Figure 3.29 Vigie Beach-South profile B before the disturbance (B), 2 weeks after the disturbance (Disturbance) and 4 weeks after the disturbance (Recovery). The black point represents the location on the profile line from which the slope was measured- the left side of the point indicates the section of the foreshore slope, the right side of the point indicates the section of the backshore slope.

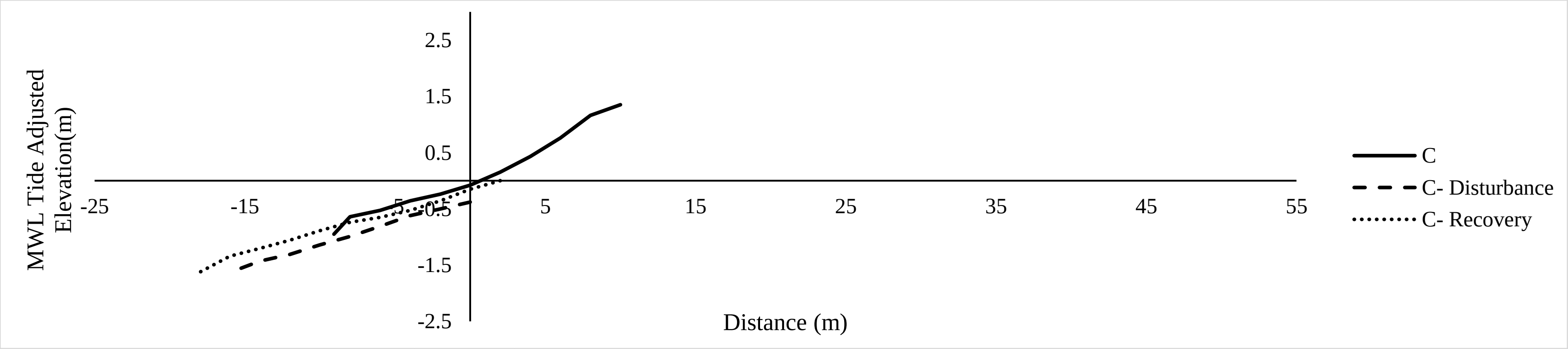


Figure 3.30 Vigie Beach-South profile C before the disturbance (C), 2 weeks after the disturbance (C- Disturbance) and 4 weeks after the disturbance (C- Recovery)

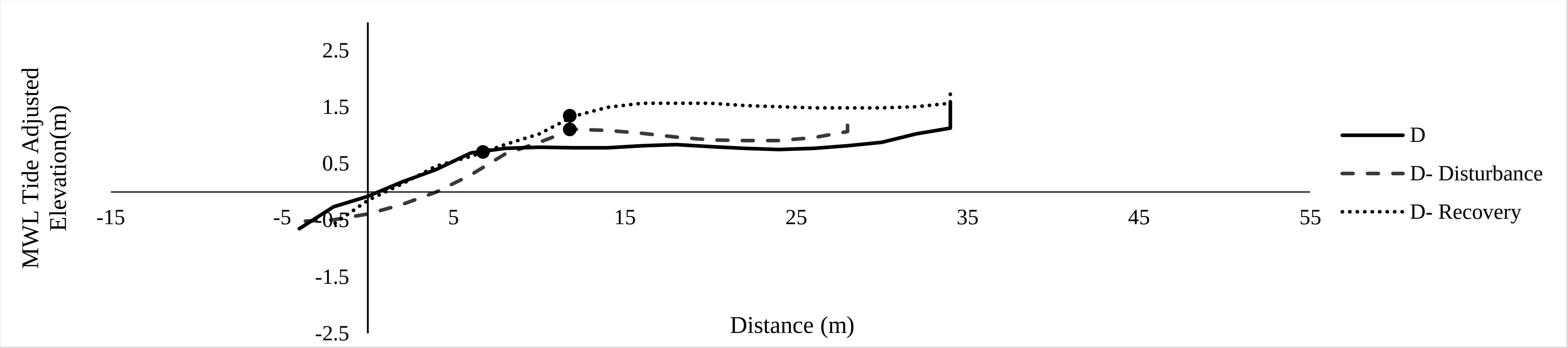


Figure 3.31 Vigie Beach-South profile D before the disturbance (D), 2 weeks after the disturbance (Disturbance) and 4 weeks after the disturbance (Recovery). The black point represents the location on the profile line from which the slope was measured- the left side of the point indicates the section of the foreshore slope, the right side of the point indicates the section of the backshore slope.

The backshore of profile A displays a continuous decrease in slope at all stages of the assessment. The foreshore on the other hand illustrates the opposite with a continuous increase in the slope before, and after the disturbance. The steeper slope in the transition of the foreshore and backshore may be attributed to beach cusp as evident in *Figure 3.32* below. Taking a more visual approach to the profile assessment, the backshore of profile A remains fairly consistent. On the other hand, the swash zone, where beach cusps are present display greater variations in profile appearance such that, the recovery profile has a greater elevation than the pre-disturbance profile. The overlapping section between the intertidial swash zone reflects a more common trend where the disturbance profile has a lower elevation than the recovery profile.

Profile B recorded a 2% decrease in the foreshore slope two weeks after the disturbance, with a complete recovery four weeks after. This change coincided with a 2% increase in the backshore of that profile (B_b) post disturbance and 4% decrease during the recovery. This is in part could be attributed to an error that was made during the survey as well as loss of sediment in the foreshore due to higher than average tides. A visual analysis of the profiles show a dramatic plunge in the profile during the disturbance. This dip is indicative of the naturally hardened backshore of profile B made up of coral fragments, as opposed to more mobile sand.

Profile C began from a gabion basket and thus, the entire profile was recorded below the water line during the two-week post disturbance survey. There was a 3% decrease in the slope two weeks after the disturbance with a 0% decrease during the post disturbance assessment. It should be noted that the final vertical measurement could not be identified due to increased tide levels.

The backshore of profile D showed a decrease in slope before and after the disturbance, and an increase in slope by 5% during the recovery assessment. It should be noted that a nearshore berm could not be observed during the two-week disturbance survey and thus is reflected in a shorter profile length. The foreshore of profile D displayed a decreased slope of 2% before and after the disturbance, with a near complete recovery thereafter.

Figure 3.32 Vigie South 2 weeks post disturbance- Profile A (top left), Profile B (top right), Profile C (bottom)

Table 3.4 Review of visible differences in Vigie Beach- South before and 2 weeks after the disturbance

Pre-Disturbance	Post Disturbance
	
	
	


2020/06/16 11:16
115m 1019hPa
14°01′16″N 060°59′29″W
S


2020/06/16 10:53
121m 1019hPa
14°01′15″N 060°59′39″W
SSW

Chapter 4: Discussion

4.1 Key Insights

To reiterate, the goal of this study was to conduct a vulnerability assessment for the selected beaches, and further examine the resilience of these beaches choosing suitable stabilization methods for each. As highlighted previously, resiliency describes the capacity for the coastal environment to cope with the changes caused by a natural disturbance (Masselink & Lauzarus, 2019; Day et al., 2014). By comparing the beach stability summarized in the pie charts above, as well as visual changes before and after the disturbance, characteristics of the backshore and foreshore of the beach and how they varied between the recovery of different profiles supported this analysis. Through field assessments conducted previously, the basis for a proactive mitigation response strategy was developed and viable beach stabilization methods for sea level rise and increased storm frequency assessed. Using the Emery method and detailed coastal characterization using a decision tree, we were able to assess the unstable sections of various beaches and the associated features.

Several vulnerability assessments for islands of the Lesser Antilles were established in the late 1990s, under the COSALC Programme (Cambers, 1997). Many of these projects however, did not continue beyond the early 2000s, including that of Saint Lucia (GOSL, 2001). More recently, individual islands have been implementing vulnerability assessments such as Barbados (ECLAC, 2011) and Grenada (Day et al., 2014). As previously highlighted by Scott *et al.*, (2012), coastal property development is high risk, especially to that of SLR and storm surges. Hardened methods of coastal protection such as the use of revetments, are the most common methods of coastal protection in mountainous regions

(Day et al., 2014; Banton et al., 2015). This trend is also visible in Saint Lucia as observed on all beaches assessed in the North of the island. With more recent coastal vulnerability assessments however, countries are diverting to sole engineered solutions and are now exploring ecosystem-based adaptation methods (Day *et al*., 2014; ECLAC, 2011).

Through pre and post disturbance assessments of Vigie South and Reduit beach, we were able to identify similarities or overlaps in the recovery process of these beaches. There is no clear distinction between the foreshore stability of a beach based on its backshore characteristics. Despite Pigeon Island Causeway having significant development in the backshore, the presence of multiple groynes and the dissipative nature of the beach itself has allowed it to be one of the more stable coastlines assessed. However, areas such as Vigie North (*Figure 3.13*), natural nearshore features such as bedrock platforms increased the stability of the foreshore (Gallop *et al.,* 2020). Masonary or gabion baskets in the foreshore on the other hand, although maintain the stability of the backshore to an extent, decreased that of the foreshore as it took longer for the beach to recover. This relationship is discussed in more detail in the next few sections.

Most resilience models assess beach recovery on a decadal or annual scale sometimes assessing resilience from multiple disturbances or storms- with a recovery rates of 0.2m per annum. In the case of this study, comparisons of recovery within the foreshore/backshore environment (subaerial) were conducted one month after the disturbance. Therefore, results can only be loosely compared to existing studies (Vousdoukas et al., 2011; Biausque & Senechal, 2018; Philips, 2018).

Slopes for each beach were assessed from the backshore to the nearshore. For profiles with distinct foreshore dunes or berms, the slope was calculated from the backshore to that point in the foreshore, and then from the foreshore to the nearshore. Phillips, (2018) highlighted shoreline and berm recovery as the quickest response to foreshore recovery. This is supported in graphical representations for all profile graphs above. The intertidal zone of the profile lowered during the disturbance assessment, returned closer to the pre-disturbance position after the recovery assessment.

Philips (2018) noted recovery of the berm and coastline in most microtidal beaches (<2m variability between low and high tide) within the first four months to one year after the disturbance. Phillips, (2018 pp. 22) highlighted rapid recovery in a microtidal system as “0.5 and 1.8 m3 /m/day”. In our study, recovery on a daily time scale was not assessed, but a similar recovery rate can be assumed. Using graphical comparisons however, variations in our findings can be compared to those of other studies. For example, the intertidal zone of profile C of Vigie South, measured against an anthropogenic backshore, did not recover within the first month unlike the other profiles. Biausque, & Senechal (2018) highlighted a decreased sediment exchange between backshore dune and beach where hard infrastructure is present as an explanation for this.

Biausque, & Senechal (2018) also identified changes in the slope of beaches based on erosion within the intertidal zone. Profile C of Reduit beach recorded a steeper slope in the ‘recovery’ assessment, than the ‘pre-disturbance’ assessment. This finding may be attributed to the source of material contributing to the berm as described by Biausque, & Senechal (2018). The sediment source for the backshore slope is the intertidal zone. Increased deposition onto the berm from the intertidal zone increases the steepness and thus alters the appearance of the profile. A hardened backshore i.e. where anthropogenic infrastructure such as seawall are present, increases wave reflection, mimicking that of a reflective beach, steeping the foreshore and increasing sediment loss (Vousdoukas et al., 2011; Davidson-Arnott et al., 2019; Pillet et al., 2019).

The analysis made above was a combination of literature and field assessments. As a result, there were some limitations to the study surrounding time constraints of the study as well as methodology.

4.2 Limitations

Time constraints allowed for only two of the six sites to be surveyed for disturbance responses. As a result, cobble beaches such as Malgretoute beach, and Vigie North with a natural platform barrier, could not be compared to that of the sandy sediment beaches, or those without natural protective infrastructure. The extent of the disturbance assessed was also limited to near gale force winds (40km/h) versus storm force winds (96km/h) as described by the US Department of Commerce (2019).

As noted previously, the Emery method is best suited for low tide conditions. As a result, post disturbance surveys conducted during the commencement of high tide- profiles C and D for Vigie South for example, were more difficult to conduct. Identifying the intertidal berm for example was not always possible where water level was above 1m. This limitation may also be attributed to flattening and migration of nearshore bars offshore during high energy or disturbance events (Masselink et al, 2006). Challenges were experienced in stabilizing vertical pole during nearshore surveys may have increased the error margin of horizontal measurements. Despite these limitations, recommendations and an assessment of the stability of each beach was made using the data collated and literature reviewed.

4.3 Recommendations for Increasing Beach Stability

Masselink et al., (2019) highlighted beaches are more resilient than dunes as they are able to recover quicker. This article also noted the challenges associated with developing a resilience model for a dynamic coastal system. In essence, hard engineering approaches, such as those visible along the Pigeon Island Causeway, although stabilizes the beach also inhibits 'natural change'. This suggests regular alterations in the coastal system will continue despite attempted adaptation, leading to increased maintenance and repair costs. Understanding this allows us to segue into identifying greater stabilization methods. Based on the current state of beaches, as well as general risks associated with climate change and SLR for the region, a few suggestions for stabilization methods guided by those of Day *et al.*, (2014) and the Government of Jamaica (2017) were made.

Although the foreshore of several beaches are already occupied by permanent anthropogenic structures, best practice recommendations can be made for future coastal development. Pillet *et al.*, (2019), noted a 50m coastal buffer zone from the high-water level mark will allow sufficient dispersion of wave energy as well as encourage naturalization within this area, further increasing stability. This also alludes to alterations in legislation for repair and reconstruction of existing properties which may be destroyed or degraded in the near future.

Reduit beach for instance, has a heavily anthropogenized backshore as displayed in *Figure 2.6*. Coastal squeeze is particularly evident in the area near profile C. For continued use of these coastal resources, beach nourishment may be the best choice for this beach. The gryone to the north of the beach and the headland to the south, will ensure added sediment will remain. Observable sediment variation (from fine grained sand to mixed gravel sand) during the disturbance assessment, indicates special attention needs to be paid when deciding the size of the sediment for recharge (Day *et al*., 2014; Government of Jamaica, 2017). Other stabilization methods for this beach would need to be implemented on an institutional level to encourage more sustainable development. For example, in the event of a wall being damaged, deliberation with government officials as to whether the wall should be rebuilt, or revegetation to increase the buffer zone as a more sustainable solution should be discussed (Vousdoukas et al., 2011; Government of Jamaica, 2017; Pillet et al., 2019).

Vigie South being one of the more vulnerable sites to beach erosion presented several challenges. It is therefore imperative that future coastal development is restricted- particularly as it is unable to follow the 50m guidelines as suggested by Pillet *et al.,* (2019). This beach is also a critical nesting habitat for sea turtles and thus, hard engineered solutions within the foreshore should be avoided. Government of Jamaica (2017) highlighted the potential for vegetation within gabion baskets using composite rocks which provides a growth medium and protection for seedling establishment. This approach can be applied to existing gabion baskets, as visible in profile C (*Figure 3.9*). Beach nourishment during off nesting seasons may also be beneficial, as it increases the potential for vegetation establishment as well as nesting sites (Government of Jamaica, 2017). Exploration into the use of submerged breakwaters made of may also be an alternative to encourage sediment deposition (Kubowicz-Grajewska, 2015). A hybridized approach to submerged breakwaters such as through the use of artificial reefs such as reef balls may also be a viable option (Day *et al*. 2014; Government of Jamaica, 2017). This provides both shoreline protection and added ecological services. Careful consideration through a detailed study needs to be conducted before this could be implemented as Barnette (2017) highlighted- although artificial reefs provide prime feeding habitat for mature sea turtles, it also increases the risk of predation on juveniles.

Vigie North presented a narrow, stressed mangrove system. Mangroves are ecologically important and effective at wave attenuation and sediment control in addition to coastal protection particularly in the case of tsunamis (Marois and Mitsch, 2015). Further detailed studies will be required in order to identify the most suitable technique of restoration (Government of Jamaica, 2017). Malgretoute and Anse Chastanet beach are relatively stable and thus may not require implementation of engineered structures to restore the beach, but rather, legislation to prevent anthropogenic degradation. Establishing artificial reefs may also be an option for partially stabilized areas of the foreshore at Anse Chastanet beach. Artificial reefs are able to attenuate waves as well as increase valuable coral reef habitat with the Soufriere basin (Harborne *et al.*, 2006).

Chapter 5: Conclusion

Beaches are dynamic, variable ecologically significant habitat and recreational space especially for coastal island communities. The risks on the coast associated with sea level rise and natural hazards such as storms and hurricanes therefore need to be addressed for each beach specifically. Heavily anthropogenized backshores decrease the potential of beach recovery as limited vegetated and dune buffer zones increase sediment loss exacerbates shoreline narrowing. Nearshore engineered structures such as breakwaters and groynes increase the stability of the beach but are quite costly and inhibit natural changes of the coast. More naturalized or hybridized options for beach stabilization such as beach nourishment and revegetation within gabion baskets are common solutions for the beaches assessed. In all situations however, implementation and enforcement of new legislation discouraging deforestation of littoral forests and coastal development beyond 50m from the high-water mark, can reduce most risks associated with these disasters. Future research needs to be conducted in order to select suitable solutions for coastal protection and increased resilience.

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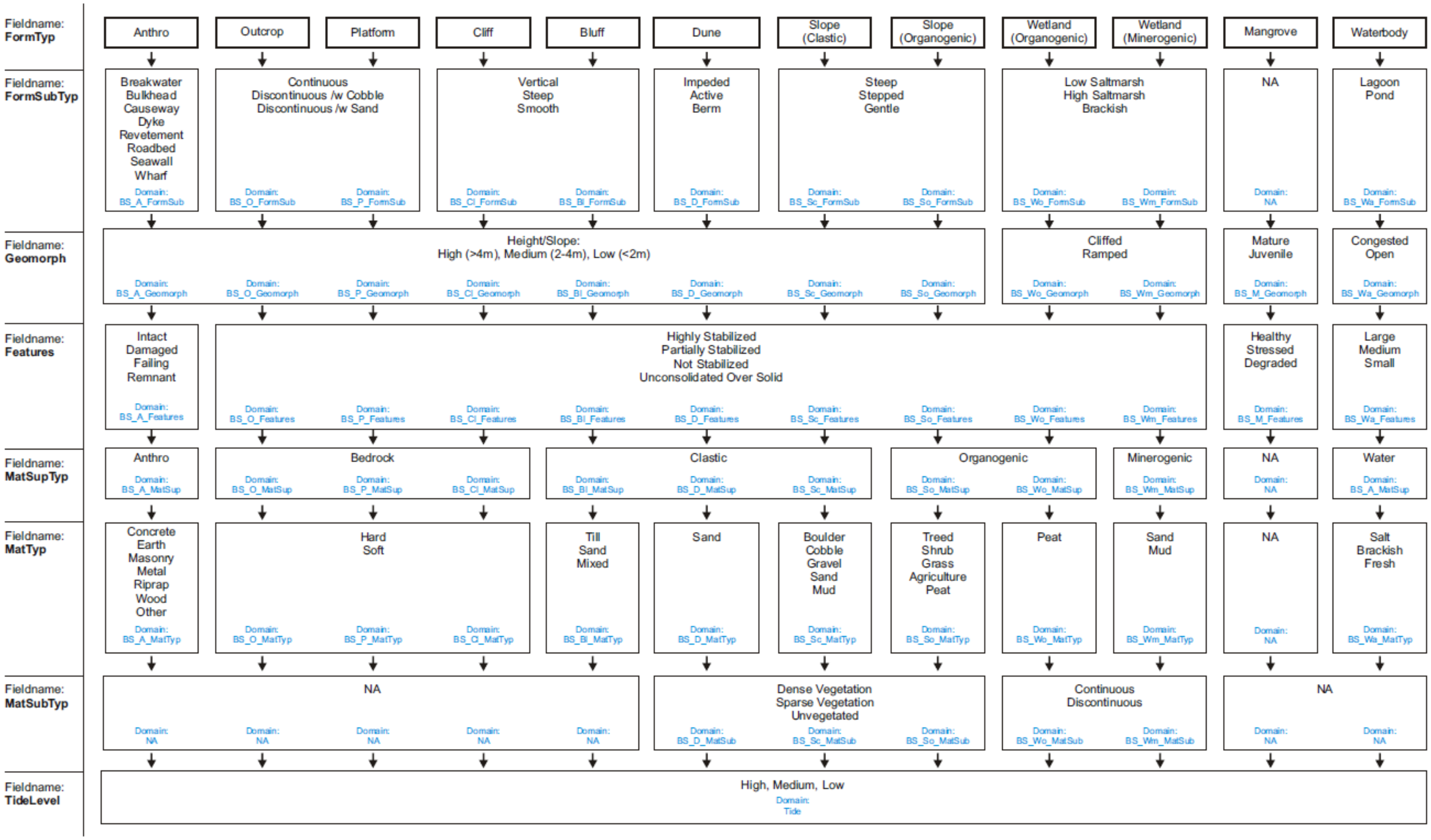
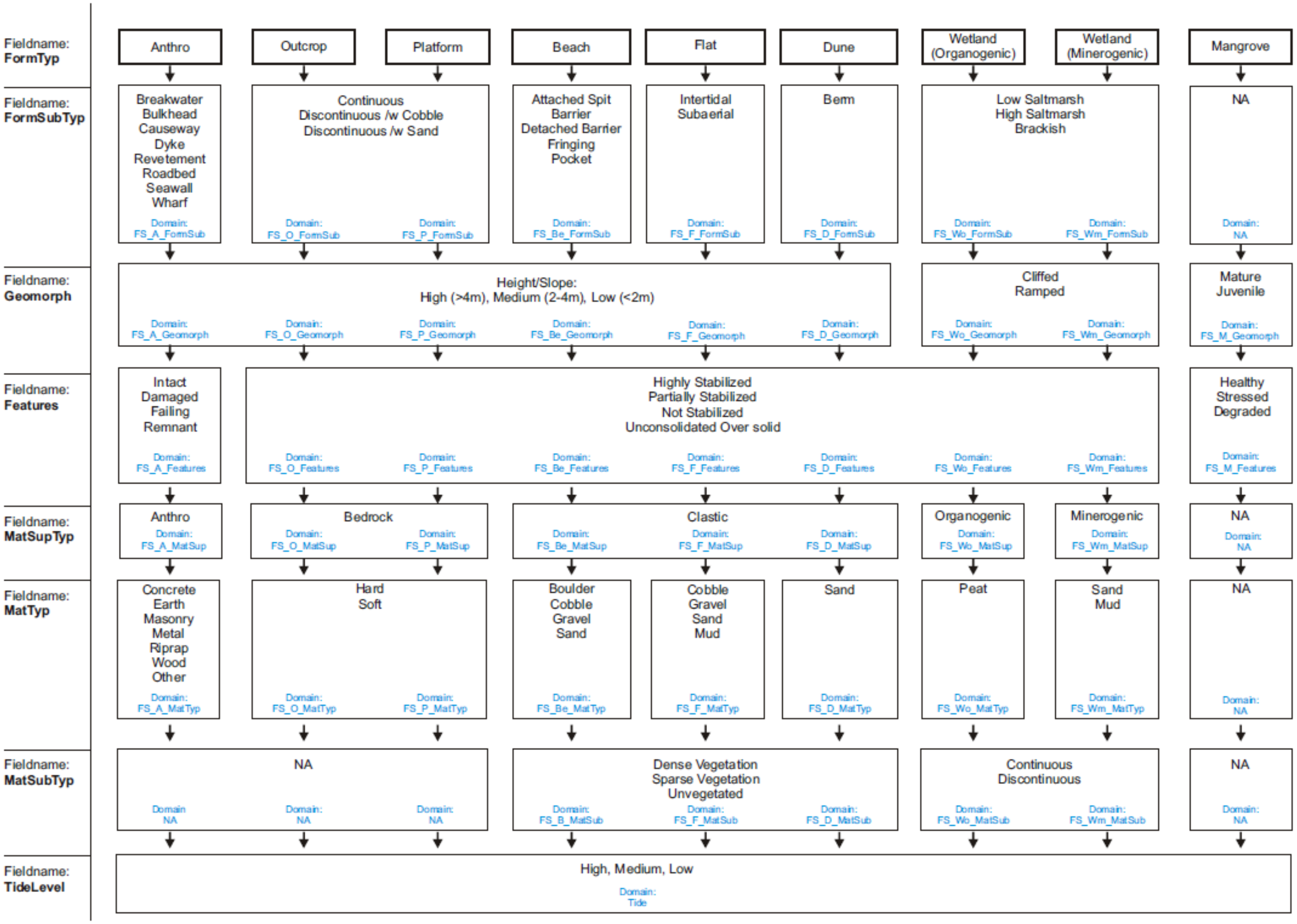
Appendix

A

Decision Tree- Backshore Characterization



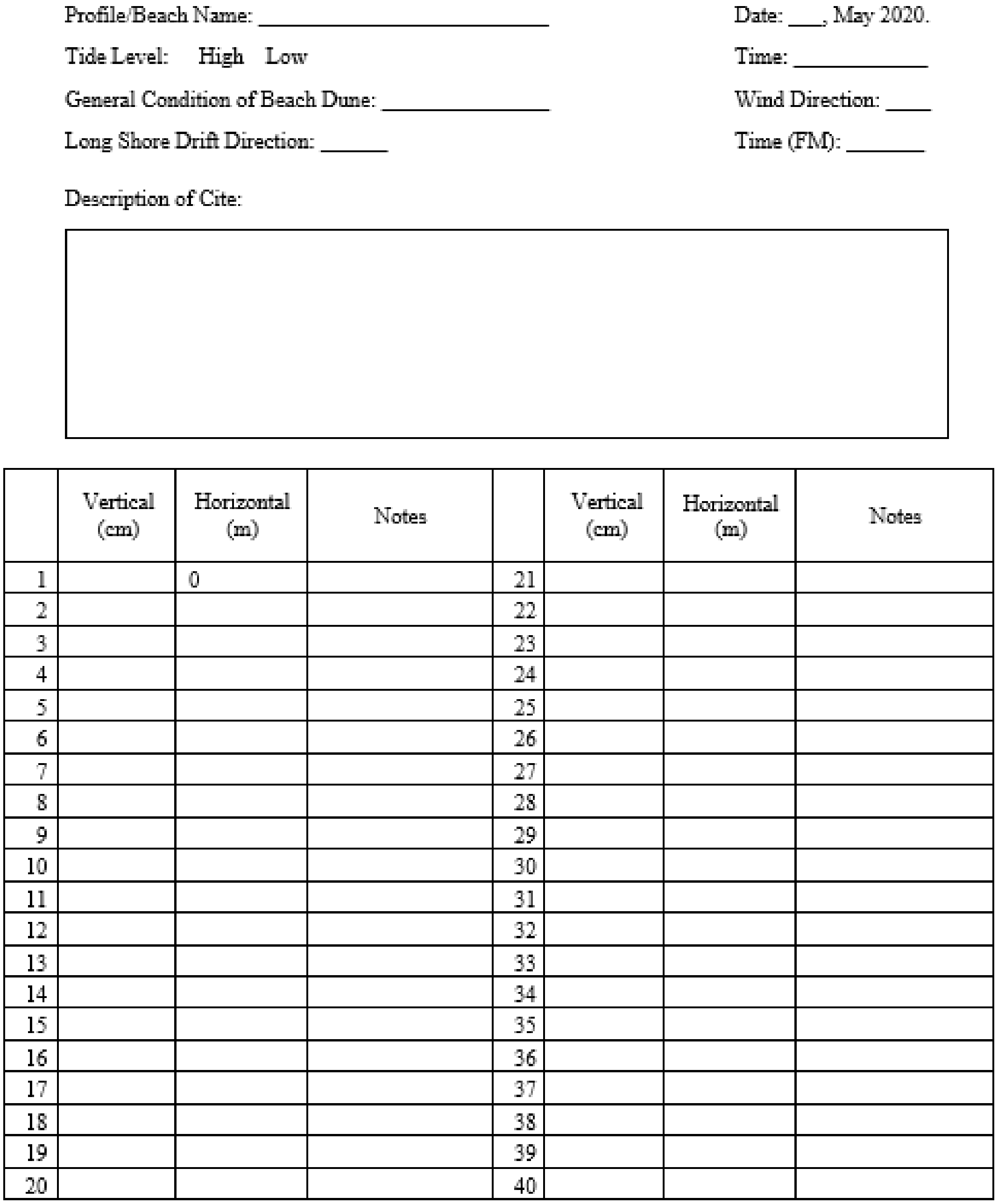
Decision Tree- Foreshore Characterization



Appendix

B

Emery Method Measurement Record Sheet



Profile/Beach Name: ___________________________

Date: ___, May 2020.

Tide Level: High Low

Time: ____________

General Condition of Beach Dune: _______________

Wind Direction: ____

Long Shore Drift Direction: ______

Time (FM): _______

Description of Cite:

	Vertical (cm)	Horizontal (m)	Notes		Vertical (cm)	Horizontal (m)	Notes
1		0		21			
2				22			
3				23			
4				24			
5				25			
6				26			
7				27			
8				28			
9				29			
10				30			
11				31			
12				32			
13				33			
14				34			
15				35			
16				36			
17				37			
18				38			
19				39			
20				40			

Appendix

C

Anse Chastanet Beach Profile Vertical Markers

Figure 5.1 Anse Chastanet Beach profile vertical markers A (top left), B (top right), C (bottom)

Malgretoute Beach Vertical Markers

Figure 5.2 Malgretoute Beach profile vertical markers A (top left), B (top right), C (bottom)

Vigie Beach- South Vertical Markers

Figure 5.3 Vigie Beach-South profile vertical markers A (top left), B (top right), C (bottom left), D (bottom right)

Vigie Beach- North Vertical Markers

Figure 5.4 Vigie Beach-North profile vertical markers A (top left), B (top right), C (bottom)

Reduit Beach Vertical Markers

Figure 5.5 Reduit Beach profile vertical markers A (top left), B (top right), C (bottom)

Pigeon Island Causeway Vertical Markers

Figure 5.6 Pigeon Island Causeway profile vertical markers A (top left), B (top middle), C (top right) D (bottom left), E (bottom right)