Baseline Conditions Report

Bermuda and Climate Change: Impacts from Sea Level Rise and Changing Storm Activity

Prepared for:

Ministry of Home Affairs
Department of Planning
Dame Lois Brown-Evans Building, 5th Floor
Court Street
Hamilton, HM12
Bermuda

Submitted by:

Smith Warner International Limited
Unit 13, Seymour Park, 2 Seymour Avenue
Kingston 10, JAMAICA

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List of Abbreviations

ADCP	Acoustic Doppler Current Profiler
ASTM	American Society for Testing and Materials
AWAC	Acoustic Wave and Current Profiler
BELCO	Bermuda Electric Light Company
BIOS	Bermuda Institute of Ocean Sciences
BOPP	Bermuda Ocean Prosperity Programme
BWS	Bermuda Weather Service
CC	Climate Change
CREF	Caribbean Renewable Energy Forum
ECMWF	European Centre for Medium-range Weather Forecast
ERA5	ECMWF re-analysis (Fifth Generation)
GIS	Geographic Information System
GPS	Global Positioning System
LIDAR	Light Detection and Ranging
MSL	Mean Sea Level
NAO	North Atlantic Ocean
NHC	National Hurricane Centre
NOAA	National Oceanic and Atmospheric Administration
SLR	Sea Level Rise
SIDS	Small Island Developing States
SWI	Smith Warner International
SWRO	Sea Water Reverse Osmosis
TBSWRO	Tyne's Bay Sea Water Reverse Osmosis
TBWTE	Tynes Bay Waste to Energy
TDS	Total Dissolved Solids
UKHO	UK Hydrographic Office
WSS	Water and Sewage Section
WTE	Waste to Energy

1 Introduction

Bermuda is a British Overseas Territory in the North Atlantic Ocean, with the nearest landmass approximately 1,035km to the west-northwest (Figure 1.1). Because of its isolation, it is vulnerable to severe storms – including both tropical and extratropical storms – from almost any direction. With the general consensus of climate change pointing towards more frequent and higher intensity storm activity, Bermuda is a target because of its position.

As the ice caps melt and the fetch (area of ocean surface over which the wind blows in an essentially constant direction) increases, the North Atlantic will experience larger waves. This means that, as hurricanes become stronger, the daily wave conditions on Bermuda's shores will be influenced by climate change. Bermuda also faces unique climate change challenges because it's an island: with more than 70% of the people in Small Island Developing States (SIDS) living on the coast, sea level rise (SLR) is an almost existential threat. Ultimately, innovative planning must be implemented to balance the need for continued development in the face of climate change. Herein lies the challenge for Bermuda's Department of Planning and the reason for this project.

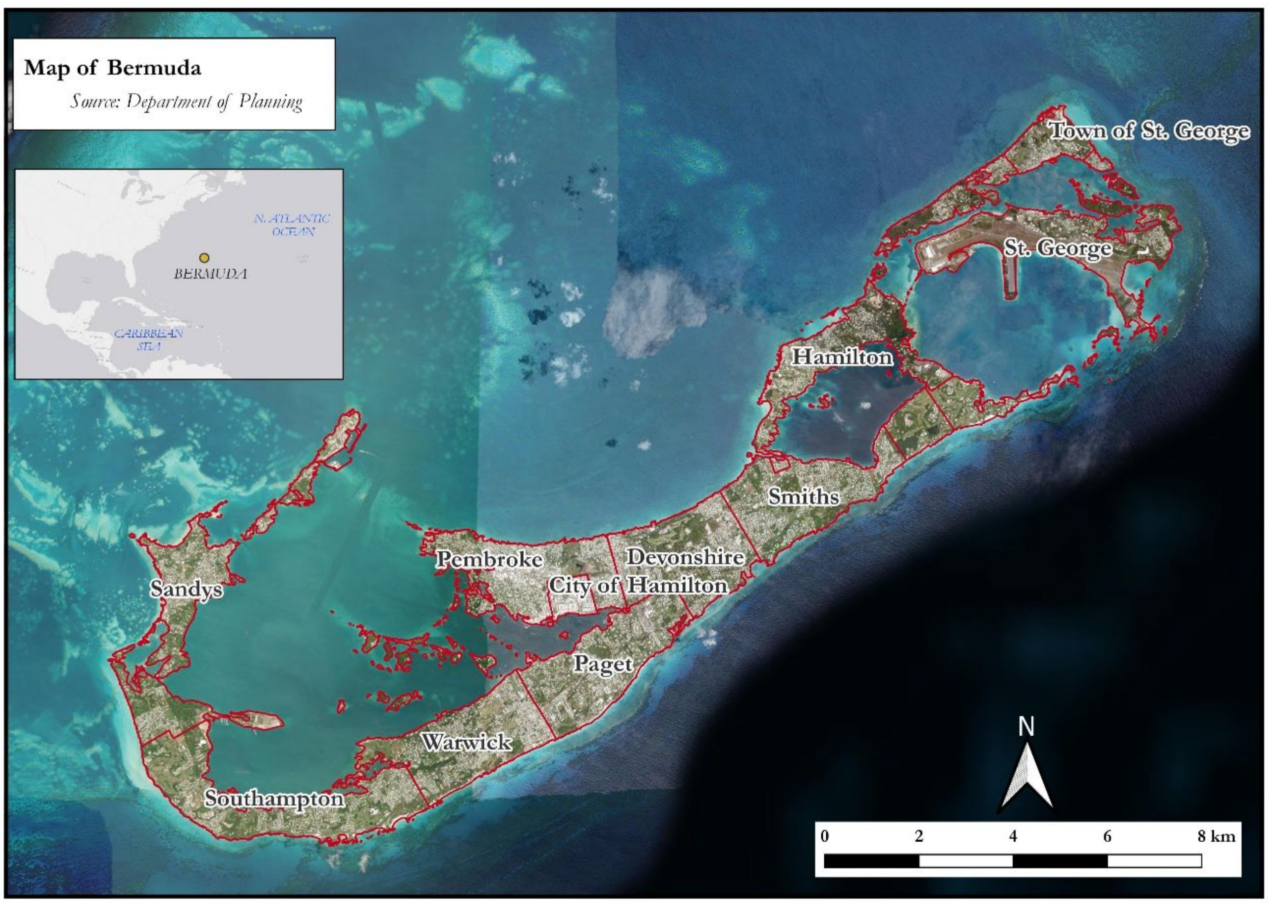
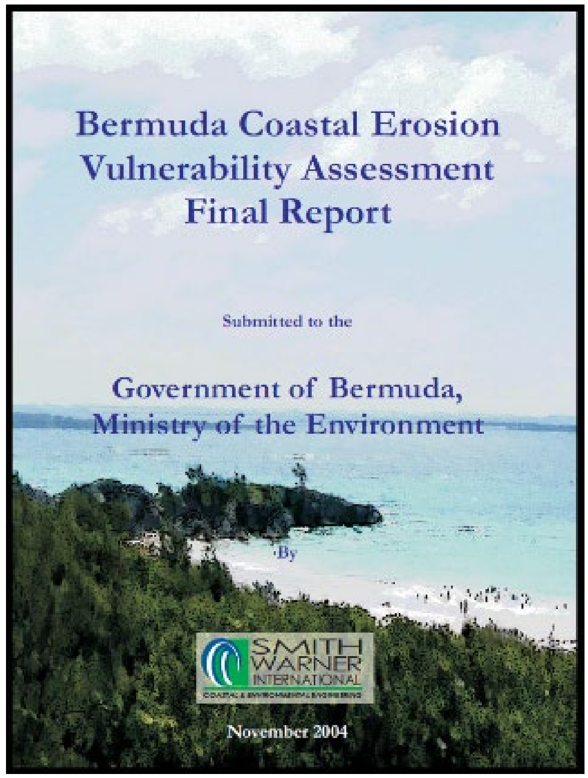


Figure 1.1 Location of Bermuda

This project encompasses the entire island of Bermuda. With a land mass of only 54km^2 and a population of 63,917[1] Bermuda is one of the most densely populated countries on the planet. It also has one of the highest per capita incomes in the world, thanks to an economy based on offshore financial services and tourism. Unfortunately, Bermuda's financial success combined with its limited land space has resulted in significant development pressure, especially along its 291km of shoreline.

1.1 Background and Objectives



In 2004, the Government of Bermuda (GoB) hired Smith Warner International (SWI) to assess Bermuda's vulnerability to coastal erosion. The 2004 study identified specific shorelines that were most vulnerable to erosion and storm inundation due to potential wave run-up. Around Bermuda, two types of shorelines were observed: (i) sandy shores/beaches, and (ii) rocky shores, which can be further split into three sub-types: flat rocky, low cliffs, and high cliffs.

The most significant erosion along the Bermuda coastline is caused by physical forces, particularly wave action. The effects of biological erosion were also visible, with Casuarina tree roots serving as the primary source and boring marine invertebrates serving as another form of biological erosion.

1.2 Scope of Current Services

This study is intended to update the 2004 study considering recent projections of sea level rise and other anticipated climate change impacts, and includes the following:

- Current predictions of global warming in the context of sea level rise, combined with expected more severe weather events. The predictions specifically for Bermuda will contain a projection timeline for best- and worst-case climate change scenarios over short-, medium- and long-term time frames.
- Effects of coastal erosion and sea level rise on the mean sea level (MSL) benchmark.
- Identification of Government and critical infrastructure and facilities located at or close to the shoreline that are at risk from erosion or inundation. Undertaking of a vulnerability assessment for major infrastructure i.e., airport, ports, public highways, power plant, subterranean utility cabling, waste (i.e., Tyne's Bay incinerator, sewage management systems, etc.).

[1] 2016 Population and Housing Census Report, Government of Bermuda, Department of Statistics

- Identification of what effect sea level rise will have on waterways, inshore ponds, marshes, from an ecological perspective.
- Identification of saltwater inundation of agriculture areas (soil salinization), within the context of food security and continued ability to cultivate fields.
- Update coastal erosion and flood inundation projections for the offshore islands, bays, beaches, and dunes, especially during storms and hurricanes.
- Identification of coastal areas prone to hydraulic erosion and / or destabilization of cliff faces or the island's shoreline areas.
- Mapping of projections for inundation island wide, identifying:
  a) low-lying coastal areas that will be periodically or permanently inundated by seawater, and
  b) low-lying freshwater resources that could be impacted, i.e., saltwater intrusion into freshwater lens.
- Recommendations for products / construction methods that are effective in controlling or reducing the effects of erosion. e.g., cliffs, beach dunes, including "green" or hybrid approaches.
- Identification of 'no go' areas for future development based on predicted flood zones and areas identified as being susceptible to high erosion.
- Identification of critical infrastructure components that will be at risk over the near-, medium- and long-term time frames.

1.3 Approach and Methodology

The project can be divided into three stages.

- **Stage 1**: Project Inception and Baseline Studies,
- **Stage 2**: Numerical Modelling
- **Stage 3**: Vulnerability Assessment to Climate Change.

Stage 1 describes the current or baseline conditions through site visits, meetings with stakeholders, and an extensive literature review. In Stage 2, specific numerical modelling will be done to understand how climate change will affect the baseline conditions. Finally (Stage 3), this data will be used to assess the impacts of climate change on the island's vulnerability. This report describes the findings of Stage 1. Our proposed methodology for completing the current scope of works is shown in Figure 1.2.

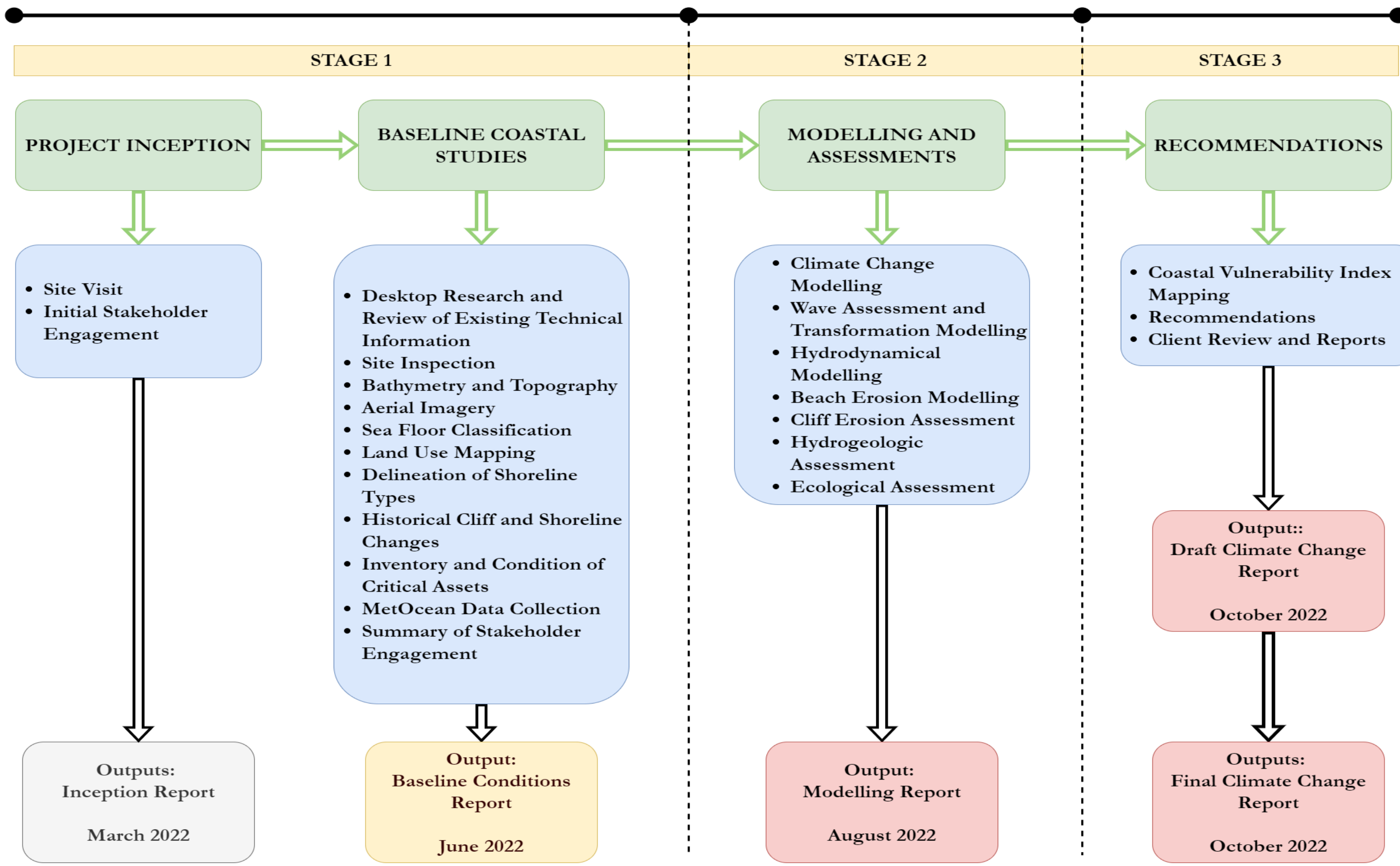


Figure 1.2 Bermuda Climate Change Study flow chart

2 Desktop Research & Review of Existing Technical Information

2.1 Climate

Despite its temperate latitude, Bermuda has a subtropical climate with mild winters and warm summers. Bermuda's climate is affected by an atmospheric pressure gradient over the western North Atlantic (Gulf Stream), which flows west of the island, and the currents in the Sargasso Sea. May to mid-October is the hottest time of the year (23-29°C) and from July to mid-October, humidity levels are at their peak, often exceeding 85%.

Sea surface temperatures closely track air temperatures. Mean annual rainfall is about 1,410mm and the driest months are April, May, and November. The wettest month, on average, is October. The island is exposed to tropical storms and hurricanes between June and November each year, with peak frequency occurring in September and October.

Bermuda has no rivers, and to date the Consultants have not received any published flood measurements or local watershed analyses. According to the City of Hamilton Plan (2015) "Approximately two thirds of the City of Hamilton falls within the Pembroke Marsh Canal Watershed storm water system (north of Victoria Street). The other one third of the City drains towards Hamilton Harbour (see Figure 2). Much of the Pembroke Canal Watershed has a high water table and the Pembroke Marsh Canal has been subject to flooding in the past. All lands that are at or below 4 meters above sea level are affected by this high water table."[2]

[2] City of Hamilton Plan 2015 – Government of Bermuda Department of Planning

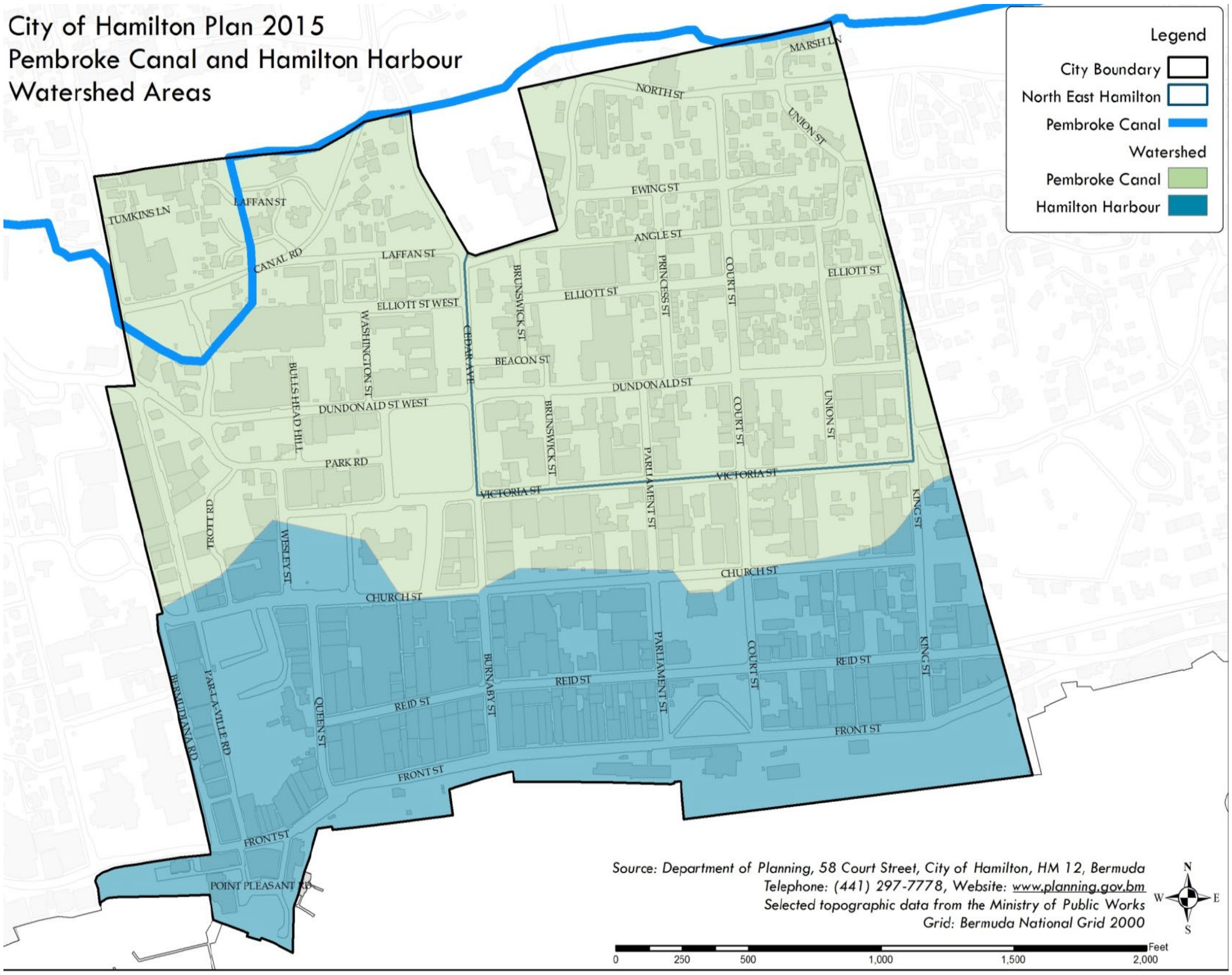


Figure 2.1 Pembroke Canal Watershed and Hamilton Harbour Watershed *(Source: The City of Hamilton Plan 2015, Government of Bermuda Department of Planning)*

Rainfall data, obtained from the Bermuda Weather Service (BWS), shows mean monthly rainfall at the LF Wade Airport between 76mm and 178mm (3-7 inches) over the 71 years from 1949 to 2021 (Figure 2.2).

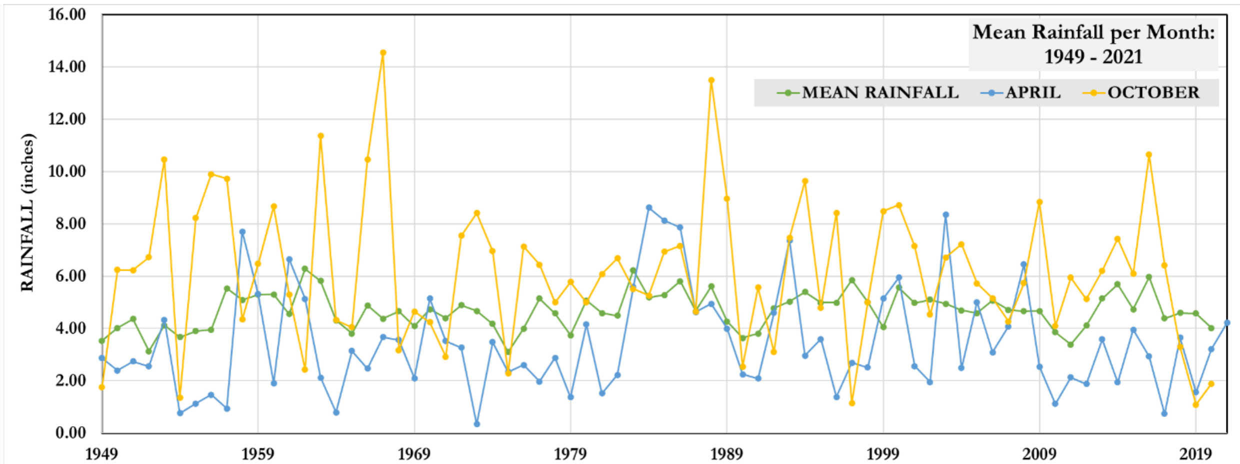


Figure 2.2 Mean monthly rainfall

2.2 Geology

The approximately 139 islands of Bermuda sit atop a long-extinct, mid-ocean volcanic seamount about 1,000km east of the Carolinas in the North Atlantic Ocean. The oceanic crust is estimated to have formed about 124 million years ago from sea floor spreading at the Mid-Atlantic Ridge. The history of the Bermuda Rise and the Bermuda Pedestal is known from seismic-reflection studies and deep drilling of the Bermuda Rise (Tucholke B. V., 1979) (Tucholke & Mountain, 1986). The occurrence on the western Bermuda Rise of an abrupt change from deposition of turbidites from the continental margin to deposition of pelagic sediments dates the initial uplift of the rise as middle to late-middle Eocene (45-50 Ma). The occurrence of volcaniclastic turbidites 140 km southeast of Bermuda indicates that the Bermuda volcanoes built up to sea level and were being actively eroded during the late-middle Eocene to early Oligocene (43-35 Ma). The end of deposition of the volcaniclastics and, by inference, the end of subaerial erosion and the time that the Bermuda volcanic rocks subsided below sea level, was in the late Oligocene (25 Ma).

Rising from the ocean bottom are four northeast-to-southwest trending volcanic peaks, including the Bermuda Pedestal (the only emergent peak), and the submerged Challenger, Argus, and Bowditch seamounts. Ocean waves eroded the exposed Bermuda Pedestal so that by 20-25 million years ago the former volcano was a relatively flat surface, the Bermuda Platform (Figure 2.2). The product of this erosion would have been beaches and seabed sediments made up of black volcanic sand. The platform, with its surrounding reefs, became a sheltered refuge in the middle of the Atlantic for shallow-water marine life including corals, molluscs, foraminifera, and algae. Over time, their skeletons broke down and accumulated, burying the whole platform in carbonate sand.

Ocean waves eroded the exposed Bermuda Pedestal so that by 20-25 million years ago the former volcano was a relatively flat surface, the Bermuda Platform (Figure 2.3). The product of this erosion would have been beaches and seabed sediments made up of black volcanic sand. The platform, with its surrounding reefs, became a sheltered refuge in the middle of the Atlantic for shallow-water marine life including corals, molluscs, foraminifera, and algae. Over time, their skeletons broke down and accumulated, burying the whole platform in carbonate sand (Vacher & Rowe, 1997).

During the Pleistocene Epoch (2.58 million to 12,000 years B.P.) sea levels fluctuated by more than 100m during periods of glacial advance and retreat. These rising and falling sea levels were key in the generation and distribution of carbonate sediments on the Bermuda Platform. Over the last million years (approximately) the cycles increased in amplitude, and it's believed that the limestone islands of Bermuda formed during this period. Proof of seven of such cycles exists in five limestone formations and at least six well-developed fossil soils (paleosols) throughout the islands. These are thin (0.3-1.0 m thick), undulating layers of regosols interbedded with the limestones, separating the geological formations in some cases. These paleosols reflect relatively brief interruptions and inactive areas in the accumulation of carbonate sand (Ruhe, Cady, & Gomez, 1961).

Waves and currents on the Platform moved the sand around and created shoals and eventually low-lying islands. Where wind-blown sand became trapped among vegetation above the high tide level, dunes formed and grew. Despite occasional storm damage, the islands continued to grow, assisted by the ongoing breakdown of the skeletons of shallow water marine creatures, which continued to create carbonate sand. During the Pleistocene, the Bermuda Islands repeatedly underwent partial inundation and re-emergence. The land areas were continuously attacked and reduced by rain and ground water but repeatedly renewed, during times of submergence, by deposition of marine limestone and by contemporaneous additions of shore-born and wind-transported carbonate sand, now eolianite. Paleosols formed under subaerial conditions and were buried beneath later deposits and constitute important stratigraphic markers. The igneous rock appears to have been exposed during some low marine stands, and the former shorelines seem to be recorded by submerged terraces. The major karst features are largely below sea level, and they date from times of continental glaciations (Bretz, 1960) (Vacher & Rowe, 1997).

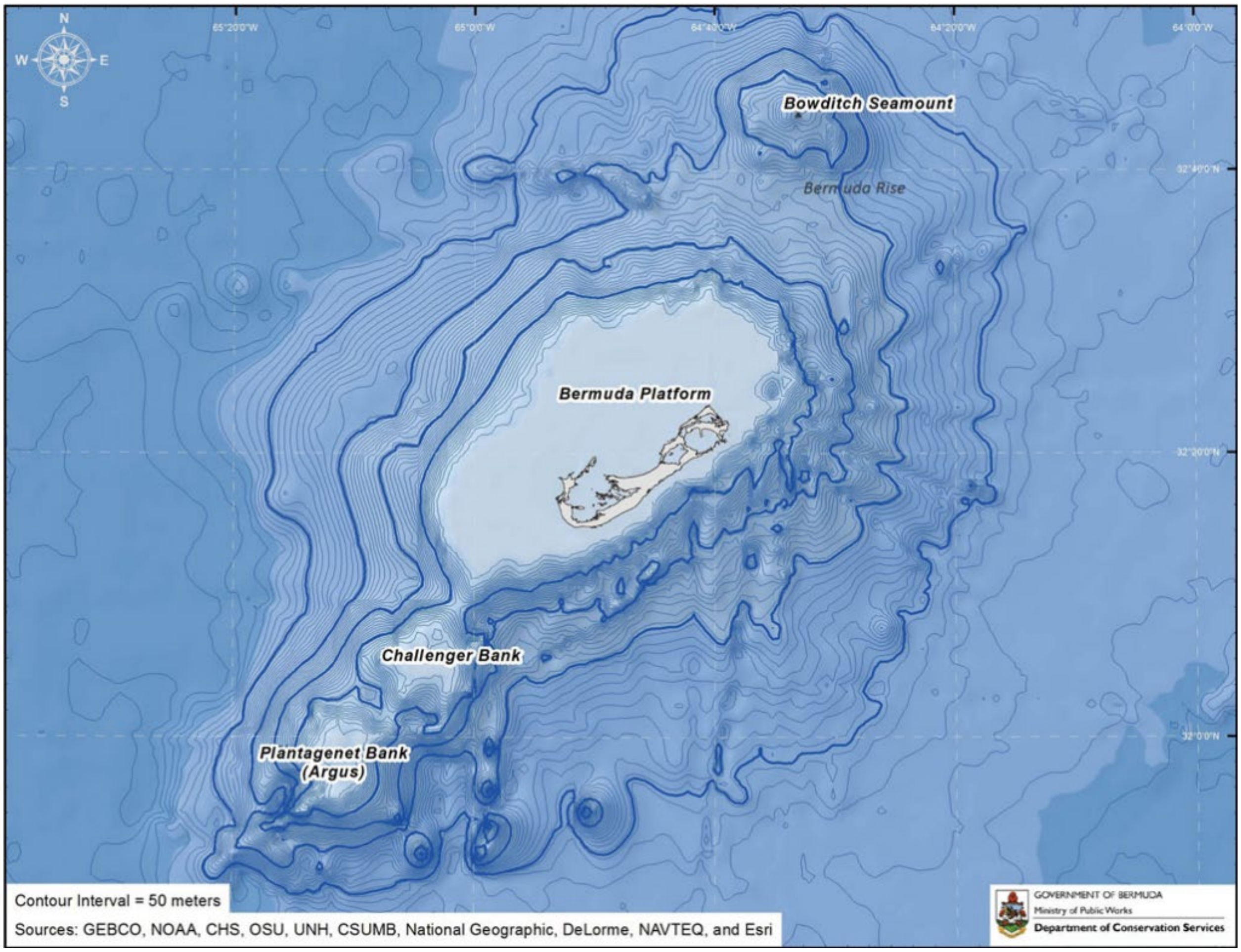


Figure 2.3 Bermuda Pedestal and nearby seamounts; Plantagenet and Challenger to the southwest have relatively shallow platforms, about 50m deep, which support photosynthetic organisms

The present-day Bermuda Platform consists of four geomorphological-ecological provinces: a reef-front terrace at 20m depth; a main reef composed of 4m deep coral algal reefs; a 16m deep lagoon in the north and the islands themselves forming a northeast trending chain along the southern edge of the platform (Vacher L. , 1973).

The limestones of Bermuda consist mostly of cemented dunes, or eolianites, and have been divided into five geological formations. These are separated by paleosols representing significant time gaps. The five limestone formations in order of decreasing age are: the Walsingham, the Town Hill (lower and upper members), the Belmont, the Rocky Bay and the Southampton. They represent successive major episodes of dune building on Bermuda. Variations in the physical character, or lithology, of these formations are primarily age-related. There is a gradation of physical and chemical alteration, (diagenesis), increasing from the youngest to the oldest limestones.

The principal agent of diagenetic change that has acted on Bermuda's limestones is rainwater. As it penetrates, or percolates, through the surface-soil this water becomes weakly acidic. Carbonate sand grains comprising the skeletal remains of marine organisms composed of unstable high-magnesium calcite and aragonite are altered or dissolved. The calcium carbonate is then re-deposited, or precipitated, in the pores of the limestone as stable low-magnesium calcite cement.

In Bermuda, the youngest and therefore least altered and least cemented limestones belong to the Southampton Formation. Older limestones of the Rocky Bay and Belmont Formations are better cemented but still retain a primary granular texture, like beach sand. Increasingly, in the Upper and Lower Members of the Town Hill Formation and the Walsingham Formation, the grains become corroded and more tightly cemented.

2.3 Hydrogeology

Predictions of the possible effects of climate change on the groundwater resources, soils and infrastructure of Bermuda will require an understanding of natural systems of formation of the geologic framework of the islands and how this framework has influenced the distribution of fresh and saline groundwater. In addition, understanding the significant changes that have occurred to the natural systems because of anthropomorphic changes since Bermuda was first settled is important to modify these predictions.

In many ways the small size of the land area of Bermuda is a substantial constraint to environmental protection, which is the norm in other developed countries with larger land areas. Significant fresh groundwater lenses occur on the island but to use these for drinking water (and other domestic uses) requires treatment since the accepted way of disposing of human waste is by way of cesspits underlying each house, hotel or resort; this constitutes a relatively rapid transport pathway for untreated waste to enter the freshwater lenses.

Sewage discharged to the sea and nutrients leaching from cesspits and other waste treatment systems into the groundwater can cause observable impacts to Bermuda's environment. Figure 2.4 is a sketch of the various sewage disposal practices in Bermuda.

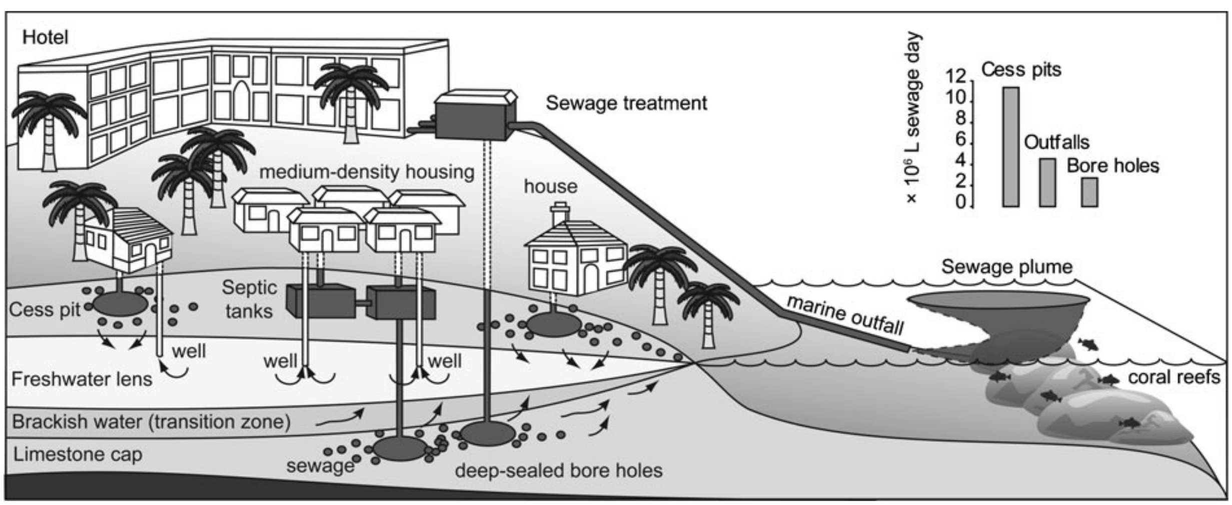


Figure 2.4 Sketch of the various sewage disposal practices in Bermuda, showing cess pits (11.4 × 106 L day−1), septic tanks (4.6 × 106 L day−1), deep-sealed bore holes (injection wells; 2.7 × 106 L day−1), and marine outfalls, relative to freshwater and brackish water lenses (Jones R. &., 2010)

Figure 2.5 shows the outfall and groundwater sources of wastewater that end up in the sea. Some impacts have been partially mitigated but phosphates in the groundwater could exceed the absorptive capacity of the limestone leading to leaching of phosphate to the nearshore environment. This could cause algal growth, which could negatively affect coral growth.

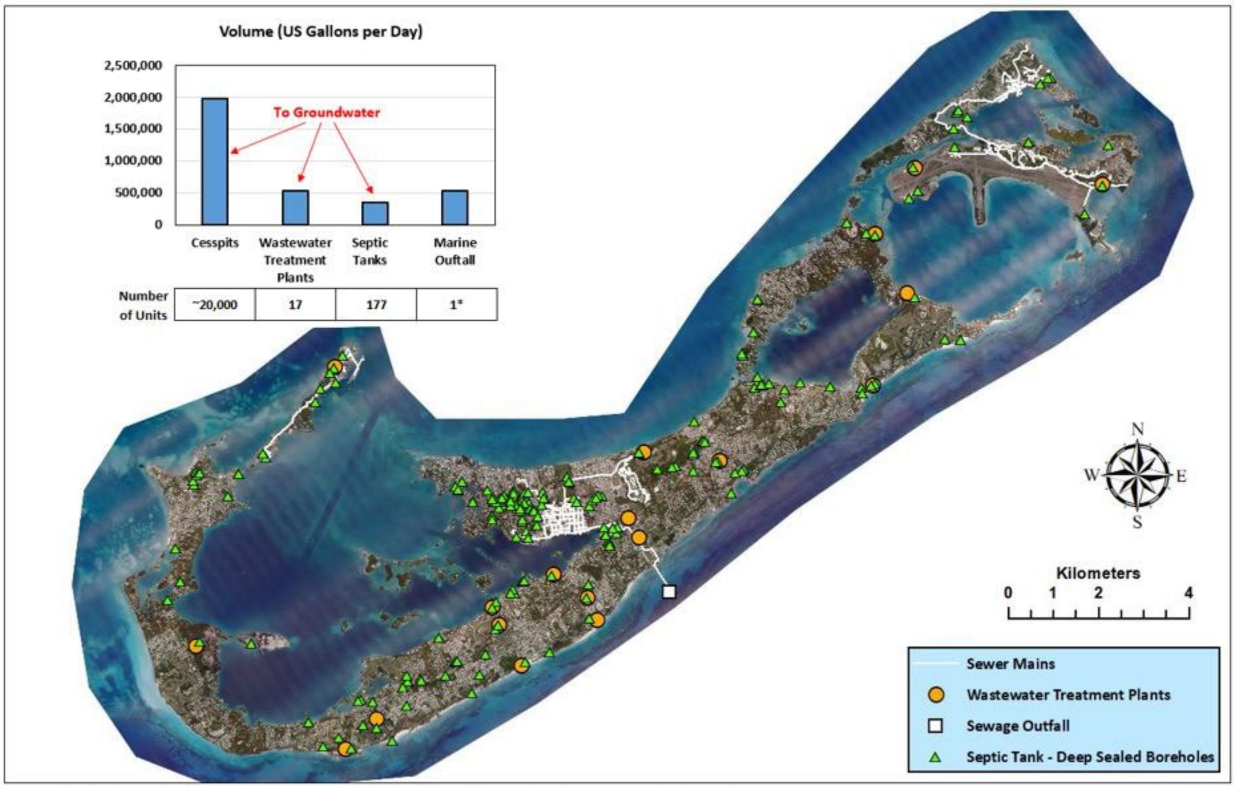


Figure 2.5 Wastewater generated in Bermuda *(Source: The State of Bermuda's Waters: A Snapshot of Bermuda's Exclusive Economic Zone From the Coastline to 200 Nautical Miles, Government of Bermuda, Ministry of Home Affairs – Bermuda Ocean Prosperity Programme)*

The Government of Bermuda is currently working to increase the coverage of sewage mains, and to redirect sewerage from St George's to a deep sealed borehole; both efforts will reduce the amount of discharge entering the sea. However, discharge of sewage waste via cesspits (with the water derived from rooftop harvesting of rainwater) is a vital component of the recharge to groundwater which maintains the volume of the groundwater lenses. Redirecting sewage to deep sealed boreholes will reduce this recharge. Therefore it is important to understand the dynamics of the groundwater lenses and the effects of anthropomorphic activities on the balance of recharge and discharge from the lenses.

The disposal of domestic and commercial waste is a problem because of minimal land area for sanitary landfills. The waste generates leachate flowing from the landfill in the predominant groundwater flow direction and leachate may discharge along the shoreline into the ocean. The contaminating lifespan of a landfill is over 300 years. The current practice of 'sea fill' with refuse and other material could compromise the health of reefs nearby.

Water treatment by reverse osmosis (RO) is practiced. Two plants were visited during the week of March 21-25, 2022. Both plants, run by the Bermuda Waterworks Limited, use brackish water in the process and this requires significant filtering and disinfection prior to producing drinking water. Other plants are under construction. 'There are several other water treatment plants being operated in Bermuda. Currently Bermuda Works & Engineering operate three brackish RO plants and two seawater RO plants. There are additional RO plants run by private entities' (Christopher, 2022).

In the Southampton and Rocky Bay Formations, groundwater is present and is constrained to move only between the sand grains that comprise the rock. In Belmont rocks, as the grains themselves are partly corroded in the process of conversion to more stable carbonate mineral species, and as the rock is partially dissolved, thus containing pencil size solution channels and small caves, water flows through a larger and more connected pore space. In the Walsingham rocks, the solutional openings are coalesced into room-sized caves and the intervening rock is tightly cemented, so that water flows largely though underground channels. The Town Hill Formation rocks are characterized by alteration between that of the Belmont and Walsingham Formation. The permeability (hydraulic conductivity) of Bermudian rocks ranges upward from that of well-sorted sand to that of a rock with an anastomosed network of well-defined open channels.

There is a stratigraphic partitioning of the upper saturated zone. According to current nomenclature [Rowe, (1991); Vacher et al., (1995)], the partitioning involves two hydrostratigraphic units: the Langton Aquifer and the Brighton Aquifer. The Langton Aquifer consists of the Southampton, Rocky Bay and Belmont Formations of the lithostratigraphic classification and, therefore, is the younger body of rock. The Brighton Aquifer consists of the upper and lower members of the Town Hill Formation.

The underlying Walsingham Formation is characterized, in terms of groundwater, as a saltwater aquifer. The Langton Aquifer comprises the youngest limestone and is where the important freshwater lenses are centred. The Brighton Aquifer does contain significant fresh and brackish water but not as extensively as the Langton.

The hydraulic conductivity of the Langton Aquifer is some 30-120 m/day. The hydraulic conductivity of the Brighton Aquifer is on the order of 1,000 m/day, a number that clearly reflects increased secondary porosity. In addition to these two aquifers, there is a hydrostratigraphic unit corresponding to the Walsingham Fm. This unit does not usually figure in discussions of Bermuda hydrogeology because it is highly cavernous and occupied by salty groundwater.

The freshwater lenses are localized in the Langton Aquifer. Groundwater in the Brighton Aquifer is generally brackish at the water table. Where fresh groundwater does occur in the Brighton Aquifer, it is usually an extension of a lens centred in the Langton Aquifer. The distribution of rock types affects the flow of groundwater. Several marshes occur in an approximately east-west direction along the contact of the Langton and Brighton Aquifers. North of the marshes the Central Lens is in the Langton Aquifer, and south of the marshes the lens is in the Brighton Aquifer.

The value of Bermuda limestone as a ground water aquifer is dependent on the inter-granular porosity (porosity between the grains) and hydraulic conductivity (permeability to water). To be capable of storing and retaining infiltrating precipitation, primary porosity must be high and the permeability must be low, as in the youngest formations. As limestone age their pore spaces fill with cement and channels (secondary porosity) are opened up by ground water flow, a process which causes a large increase in permeability, and ultimately creates caves. This process is called karstification. The oldest limestones, with their high permeability, are therefore susceptible to sea water intrusion and are for the most part occupied by saline ground water. It is the youngest formations, particularly the volumetrically dominant Rocky Bay Formation, within which the nuclei of significant "fresh" ground water bodies, known as "lenses", have formed. The four main lenses that have accumulated in this way and have been exploited for public water supply are the Somerset Lens (most of Somerset Island west of Beacon Hill Road, area 1.2 km^2), the Port Royal Lens (previously called the Southampton Lens, West of Middle Road, in the vicinity of Port Royal Golf Course, in western Southampton and southern Sandys Parishes - 1.1 km^2), the Central Lens of Pembroke and Devonshire (previously called the Warwick and Devonshire Lenses, elongate body just north of South Road in eastern Southampton Parish, around Horseshoe Bay, and in Devonshire, Western Smith's and northern Pembroke Parishes -7.2 km^2) and the St. George's Lens (0.38 km^2). At its peak, sustainable abstraction of low salinity ground water for public water supply exceeded $4.55x10^6$ L/day.

The ideal Ghyben-Herzberg (G-H) lens (named after the hydrogeologists who first explained the dynamics) is the basic model for a freshwater lens. Its upper surface is the water table that separates the aerated zone (vadose zone plus unsaturated zone) from the underlying saturated zone. Its lower surface is the interface separating fresh groundwater from underlying sea water.

In the simplest case, the lens is in hydrostatic equilibrium, so that the elevation of the water table above sea level, and the depth of the interface below sea level are mutually related. The relationship is the Ghyben-Herzberg Principle (G-H) and involves the depth of the interface below sea level, the elevation of the water table, the densities of sea water and fresh water. The densities of fresh water and sea water are such that the Ghyben-Herzberg balance equals 40 (the actual ratio can vary depending on the temperature of the water as density varies with temperature). This means that at any point the interface below sea level is 40 times the difference between the height of the water table at that location and sea level and the thickness of the lens at that point is 41 times the height of the water table at that location. The portion that is below sea level is 41 times the difference between the elevation of the water table at that location and sea level. The volume of fresh water that is below sea level is 40/41 (97.6%) of the volume of the lens.

As an example, suppose the top of the lens is 1m above sea level (asl). The bottom of the salt water/freshwater interface is therefore 40m below sea level (bsl). The volume of fresh water below sea level is 40/41 of the volume of the lens. Saline ocean water can permeate through the limestones relatively easily. Fresh water from precipitation infiltrates from the surface and forms lenses 'floating' on the saline water. The interface between the fresh and saline water is not sharp and tends to migrate up and down depending on precipitation, storm events, tides etc. The location of the midpoint of the interface can be calculated by the Ghyben-Herzberg equation for steady-state conditions. The long-term average high position of the water table in the Central Lens (groundwater) was between 0.35-0.40m above sea level during the period 1975-1982.

This relationship does not describe the elevation of the water table, only the position of the interface relative to the position of the water table. The position of the water table depends on the amount of fresh groundwater circulating through the lens and the time for water to migrate to the shoreline where it is discharged to the ocean.

The G-H relationship is based on the supposition that fresh and salty water are not miscible and are separated by a surface of zero thickness. In real world situations, the water table and the interface are continually fluctuating, so that in the neighbourhood of the interface the two bodies alternately and repeatedly invade each other, and the waters do mix. Thus, a transition zone of mixed, brackish water is present between the overlying unmixed fresh groundwater and the underlying undiluted salty groundwater. In the transition zone, the chemical composition of the groundwater changes progressively with depth, from the composition of the overlying fresh water to that of the underlying salty groundwater, which is essentially equivalent in chemical composition to sea water.

The midpoint of the transition zone is the interface of the idealized no-mixing lens. The real-world lenses have three volumes of groundwater that are distinct: (i) the interface-bounded lens with the water table as the upper surface and the lower surface is the position of the 1:1 mixture of fresh and salt water; (ii) the transition zone with gradational upper and lower boundaries which are placed (conveniently and arbitrarily) at the position of the 1% (99 parts fresh groundwater and 1 part seawater) and 99% blends respectively; and (iii) the fresh water nucleus of which the upper surface is the water table and the lower surface is arbitrarily placed at the 1% blend.

Currently in Bermuda, Shaun Lavis, hydrogeologist, is continuing the practice of measuring the thickness of the lens to the 3% mixing zone, the value above which groundwater is no longer considered "fresh" in Bermuda (Lavis, 2022). The first two volumes of groundwater described above can be considered fundamental and independent bodies in that their size and geometry depend on different fundamental hydrologic phenomena, which include the circulation through the island of rain-derived fresh water, and the efficiency of the blending caused by the up and down motion of the interface. The geometry of the third volume is dependent on the other two above it i.e., the freshwater nucleus is the interface bounded lens minus the upper half of the transition zone.

Relative salinity is indicative of the amount of mixing in the transition zone and is expressed as the percentage of one of the end members in the mixing blend, either fresh water or seawater. This can be measured using electrical conductivity probes which are linearly dependent on the total concentration of dissolved solids. Thus the RO plant operated by Bermuda Waterworks Limited can operate with a salinity of 5000ppm but the preferred salinity is 3000 ppm (Rance, 2022). Relative salinity ranges from zero in the freshwater nucleus to 100% in undiluted seawater. The groundwater monitoring program carried out by the government hydrogeologists included over a hundred drilled boreholes in 1991. Most of the boreholes penetrate into the seawater beneath the freshwater lenses and underlying transition zone. Salinity profiles have been measured with an electrical conductivity probe.

The salinity profiles give information on the structure of the transition zone and the quantity of recharge-derived water in the lens. The salinity data generally produce straight lines when relative salinity is plotted on a probability scale vs. depth on an arithmetic scale. These probability-paper plots indicate a simple error-function variation of relative salinity vs. depth, which is consistent with one-dimensional dispersion models. The error-function variation also means that the depth of particular percentiles of relative salinity can be read easily from the graphs. One of these, where the relative salinity is 50%, is taken as the position of the "interface", that is, where the base of the freshwater lens would be if there were no mixing. The thickness between the water table and this 50% datum provides a measure of the "meteoric water inventory"; the (smaller) thickness of freshwater from a water-resources standpoint, of course, is given by the break in slope at the top of the transition zone.

Across the island, the depth of the interface (50% relative salinity), the thickness of the transition zone (1% to 99%), and the thickness of the freshwater lens (depth to 1% relative salinity) all vary with the hydrostratigraphy and illustrate the geologic control on the distribution of fresh and brackish groundwater. Compared to the Brighton Aquifer, the lower-permeability Langton Aquifer impedes the escape of recharge-derived fresh groundwater. Also, tides and other sea-level variations are less effective in mixing the freshwater and saltwater in the Langton Aquifer than in the Brighton Aquifer. The transition zone decreases in thickness inland in both units but more rapidly per unit distance in the Langton Aquifer than in the Brighton Aquifer.

Recharge has been evaluated in a variety of ways and, over the years, has been repeatedly revised upwards. In the early study Vacher (1974) and Plummer et al. (1976) used a water-budget accounting method to estimate recharge and actual evapotranspiration from monthly averages of rainfall and potential evapotranspiration and ignored the unnatural contributions; the result was about 18cm/year (12% of the annual rainfall of 150cm/year). Rowe (1981) applied a conceptually similar scheme but coupled it to a land zonation based on percentage coverage by housing, roads and marshlands; by including such processes as road runoff and recharge through cesspits, the recharge result increased to about 30 cm/year. Vacher and Ayers (1980) obtained values of 35-45 cm/year from three independent methods: evaluation of outflows and change in storage (hence inflows, by difference) in an area of diversion around a major development area; fitting of the lens geometry by G-H equations with independently inferred values of K; and the ratio of the Cl- concentration in rainfall to that in the freshest part of the lenses. In his summary paper on the Central Lens, Rowe (1984) indicated that the earlier values from the water-budget accounting for natural surfaces were too low, because they were derived from monthly rather than daily values. Rowe (1984) suggested that the actual value for recharge including the unnatural contributions, may range up to 55-65 cm/year in some places.

The most recent estimate of recharge is in connection with a steady-state model of the Central Lens (Thomson, 1989) developed as part of a U.N. study. In that model, the recharge is a distributed parameter which varies according to percentage of rooftop coverage. In Bermuda, most households capture water from their roofs and then dispose of it in soakaways. Thomson (1989) calculated cell-by-cell recharge as a weighted average of 90% of the rainfall that falls on impervious surfaces (roofs and roads) and the somewhat high figure of 25% of the annual rainfall that falls on natural surfaces. With these assumptions, combined with the percentage coverage by paved surfaces (5-40%), Thompson obtained recharge rates of 40-75 cm/year. The same assumptions, of course, imply that in areas where the percentage coverage by pavement exceeds 22%, more than half of the recharge is obtained by recycling from these paved surfaces (with the total recharge being about 39% of the rainfall). This includes a significant fraction of the area of the Central Lens.

2.3.1 Transient Behaviour

Except for dug wells in some of the marshes, all the dug wells and boreholes in Bermuda are tidal, and most are strongly tidal. For a given distance inland of the shoreline, the tidal fluctuation is markedly larger in the Brighton Aquifer than in the Langton aquifer, indicating greater dampening in the latter unit. The water table fluctuation is not a simple scaled down version of ocean tides: The semidiurnal inequality is significantly enhanced in the water table fluctuation, indicating that the diurnal component passes through more easily than the semidiurnal component.

Hydrographs taken from the marshes show a non-tidal water level variation related to changes in freshwater storage. The marsh levels rise rapidly in response to rainfall, decay exponentially after the rainfall, and fluctuate with a diurnal periodicity in response to evapotranspiration-driven withdrawal.

In contrast, recharge events due to rainfall are not at all evident in hydrographs from boreholes in the limestone. As already noted, the dominant water table fluctuations correlate with changes in sea level, not with volumetric changes in the lens. Attempts to subtract out the sea-level variation to look at volume-related residuals have been frustrated by the uniqueness of the sea-level influence at each borehole (Rowe, 1984).

Comparison of yearly averages reveals variations due to recharge (Rowe, I984). Maps of the annual average water table in the Central Lens are now available for several decades. During wet years, the reduced water levels can be 50% higher than those of dry years. The interface (50% relative salinity), however, is not in Ghyben-Herzberg equilibrium with this interannual variation. In a single borehole, the ratio of water table elevation to depth of interface can vary from 1:25 in wet years to 1:58 in dry years. Thus the interface lags in its response to these water-table changes (Rowe, 1984). These results argue against the use of G-H models to simulate transient variation of the meteoric water inventory stored in the lens.

The long-term averages of eight years of data indicate that under steady-state conditions the Central Lens configuration supports the Ghyben-Herzberg theory. On a yearly average basis, however, the degree of disequilibrium is substantial. The water table is shown to be far more responsive to variations in recharge than is the interface and possible causes for this are discussed below. On less than a yearly average basis the water table levels are dominated by the influence of sea level (tides and barometric fluctuations). Demonstration of a relatively stable lens thickness, below sea level, allows a less cautious approach to management of pumping rates than previously taken. A maximum permissible thinning of the lens is considered as 45% in fresh areas and 60% in brackish areas. Under these conditions it is calculated from Henry's equation (Henry, 1964) that ~ 75% of recharge could be abstracted.

Consistent with the Ghyben-Herzberg principle, the Bermuda groundwater lenses float in the sea water almost entirely below sea level. Their maximum thicknesses range from 3m to 10m. The lenses have been developed for water supply purposes, through wellfields operated by the Bermuda Government and by private water companies using wells, horizontal tunnels and infiltration galleries. Following treatment by reverse osmosis, this ground water is delivered to the public via a limited network of "mains" pipelines and by "water truckers".

All the groundwater lenses correlate with occurrences of the Langton Aquifer rocks. The interface bounded lens tends to swell in the Langton Aquifer and thin in the Brighton Aquifer because of the hydraulic conductivity contrast. In the Central Lens, as it crosses the Langton/Brighton Aquifer contact, the midline of the transition zone rises abruptly and levels off at a lesser depth in the Belmont. The Langton Aquifer acts as a dam, and the Brighton Aquifer as a drain. The transition zone thins in the inland direction and does so at a greater rate per unit distance from the shoreline in the Langton Aquifer than in the Brighton Aquifer. The result is that at a given distance inland from the shoreline, the transition zone is considerably thicker in the Brighton Aquifer than in the Langton Aquifer. In the Prospect section, the transition zone attains its least thickness in the Langton Aquifer. Southward, as the transition zone crosses the Langton/Brighton contact the relative salinity surfaces diverge abruptly. This thickening and thinning of the transition zone is related to the considerably greater dampening of tidal and other oscillations of the water table in Langton Aquifer as opposed to Brighton

Aquifer. Thus the geographic distribution of fresh and brackish groundwater in Bermuda reflects the hydraulic characteristics of the rocks on the thickness of the interface-bounded lens and the thickness of the transition zone. These two effects, though mutually independent, are each dependent on hydraulic conductivity and oppose each other. As the lens crosses from relatively low hydraulic conductivity Langton Aquifer that occur on the north side of the island into relatively high hydraulic conductivity Brighton Aquifer that occur on the south side of the island, the interface-bounded lens thins abruptly and the transition zone thickens abruptly. As the thickness of the freshwater nucleus is the thickness of the interface-bounded lens minus the thickness of the upper half of the transition zone, the effect of the distribution of rock types of contrasting permeability on the thickness of fresh groundwater is pronounced.

The result of this pronounced geologic control is that the interface-bounded lenses and the fresh-water nuclei are not symmetric, as they would be if the island were composed of a single, homogeneous rock type. Instead, there is a pronounced asymmetry such that the axis of any particular lens or freshwater nucleus is displaced from the centreline of the island toward the shoreline composed of younger formations. This phenomenon could be important in the prediction of future climate changes on the groundwater regime.

2.3.2 Central Lens

866 ha. of the land surface are underlain by unmixed fresh water, and of that 340 ha. have 6m or more fresh water, 73 ha. have more than 10.7m of fresh water. The volume of rock that is saturated with fresh groundwater is 50x 10^6 m^3. Assuming a conservative porosity of 20%, the volume of fresh water in the Central Lens is estimated at $1.0x10^7$ m^3. In 72% of the area where a freshwater layer occurs, it is greater than 3m thick, in 28% of the area of naturally occurring fresh groundwater, the nucleus is 3-6m thick, in 56% of the area in which there is fresh groundwater the thickness is less than 6m. More than 10.7m of fresh groundwater occurs in the Prospect area over an area of 80 ha., or less than 10% of the area of naturally occurring fresh groundwater.

There is a zone of brackish water bounded by surface of the 1% and 10% relative salinity. This zone represents the appropriate composition for desalination by some RO plants and electrodialysis plants that use brackish water. The volume of this brackish zone in the central lens is about $4.6x10^6$ m^3.

2.3.3 Groundwater in Bermuda

The occurrence of fresh and brackish groundwater can be summarised as follows:

- Fresh groundwater is presently being extracted from five separate areas comprising approximately 1,012 ha. or 20% of the area of Bermuda
- The largest area is that underlain by the Central Lens.
    - It contains about $9.1x10^5$ m^3 of fresh water (Vacher H. , 1974).
    - It attains its maximum thickness, about 15 m, in the Prospect area.
    - It covers an area of some 870 ha. about 75% of which is presently yielding fresh water to household wells.
- Slightly brackish groundwater laterally surrounds and lies beneath the freshwater nuclei. This slightly brackish water is a mixture of fresh groundwater and seawater, the percentage of the

latter component ranging from 1% to 10% with a Total Dissolved Solids range of 600-3300 ppm.

  - the aureole of slightly brackish water associated with the Central Lens contains about 4.6x106m^3 water.
  - the area from which water of this quality is presently (1974) being produced by household wells in the Main Island is more than 1,200 ha.

- The distribution of fresh and brackish groundwater is orderly both geographically and in three dimensions and it bears a systematic relation to the occurrence of geologic units.

The two key variables that together determine the nature of the groundwater at a given locality are:

i) The thickness of the interface-bounded lens i.e., the depth below the water table of the midline of the transition zone; and

ii) The thickness of the upper half of the transition zone i.e., the depth range between groundwater of 1% and 50% salinity.

For example, where the thickness of the interface-bounded lens exceeds the thickness of the upper half of the transition zone, there is a layer of unmixed fresh groundwater, and its thickness is given by the difference of the two. Where the thickness of the interface-bounded lens is less than the thickness of the reconstructed upper half of the transition zone, the groundwater at the water table is brackish, and its composition can be determined approximately by the difference. Further, the increase in relative salinity with depth, that is, the composition of the groundwater at a particular position above the midline of the transition zone depends on the overall thickness of the zone.

The geometry of the interface-bounded lens and the transition zone, and hence the geographic distribution of fresh and brackish water, reflects the fact that relatively low permeability limestone of the Langton Aquifer occurs on the north side of the island and relatively high permeability limestone of the Brighton Aquifer occurs on the south side of the island. Importantly:

i) The interface-bounded lens swells in the Langton Aquifer and thins in the Brighton Aquifer.

ii) The transition zone, which, in general, thins in the inland direction, does so at a greater rate in the Langton Aquifer than in the Brighton Aquifer.

iii) The net result is that the various freshwater nuclei are mostly or entirely in the Langton Aquifer.

The continuity equation for hydrologic elements is called the Hydrologic Equation and gives a water budget for the reservoir. The equation states that if the amount of water entering the component at a given instant in time exceeds the amount of water leaving that component (i.e., the groundwater regime), at that time, then the amount of water stored there is increasing.

The concept of safe yield used to mean that extraction at the rate of recharge would maintain the groundwater reservoir. Extraction greater than recharge begins depletion of the reservoir. However, in the case of fresh water lenses the upper and lower boundaries of the lenses are movable surfaces;

their position in space is dictated by the volume of flow and its route within and through the lens. The following analysis illustrates the water budget elements before and after human caused development.

Before development: total inflow (recharge) = total outflows + change in volume

Total outflow = shoreline discharge + total pumping

Therefore, before development recharge = shoreline discharge

In the final adjusted state:

Shoreline discharge = recharge-pumping

During the transitional state:

Shoreline discharge steadily decreases to reach its final lower rate. Therefore, total outflows exceed recharge so the volume of the lens steadily decreases. The volume of the lens that is adjusted to the imposed extraction is less than the volume prior to the extraction. The result of the extraction (in this case assuming the use is consumptive and is not returned to the ground) is that the lens decreases to a lesser volume. Therefore planning for decreases of fresh groundwater in storage and how much decrease can be tolerated is essential. The framework for these kinds of considerations involves the relationship of the volume of the lens to the internal routing of water within it.

This assessment requires a quantitative hydrologic budget for each groundwater lens. The exercise must include an evaluation of the amount of rainfall and evapotranspiration as well as the assessment of the quantities of water that flow through the soil zone into the underlying rock and through the subsystem that includes household tanks and cesspits. The recharge to the groundwater table is a key variable affecting the distribution of fresh and salty groundwater, the chemistry of the fresh groundwater, the vertical fluctuations of the water table, and the drawdown of the water table in response to pumping.

The paths through which water passes from atmosphere to the groundwater in Bermuda are as follows:

1) *Rainfall lands on vegetated soils.* A portion of rainfall is absorbed by vegetation and transmitted back to the aquifer by evapotranspiration. Some runs off to natural depression where it either evaporates from the soil, is transpired by plants or infiltrates into the underlying limestones entering the aerated or vadose zone. The water moves downward under the influence of gravity but is resisted by capillary forces within the pore space. The water the pore spaces do not hold percolates downward through the aerated zone and enters the water table as groundwater recharge.
2) *Rainfall lands on the marshes.* As the marshes represent outcroppings of the groundwater reservoir, there is direct hydraulic continuity between the groundwater in the marshes and groundwater in the limestones. Water is, therefore, continuously available to plants in the marsh. Some of the rain that falls on the marshes is directly transmitted back to the atmosphere by evaporation from the water surface and evapotranspiration from vegetation. During the period in which water levels in the marsh are higher than in the surrounding limestone, the remaining water (that is the amount of rainfall that exceeds

evapotranspiration) flows from the marsh into the limestone reservoir. During periods when the rainfall cannot satisfy the needs of the plants in the marsh, the marsh acts as an evapotranspiration-driven pump. Water flows back into the marsh from the limestone reservoir and the water surface in the marsh is lower than the water table in the surrounding limestone. On an annual basis there is overall recharge of the groundwater reservoir from the marshes.

3) *Pembroke Marsh East* was Pembroke's waste disposal site and now serves as a composting site. Calculations indicate some 2.55×10^4 m^3 per year infiltrate the waste and enter the reservoir. This water then flows both north and south becoming progressively diluted by clean groundwater in the lens as it discharges into the ocean.

4) *Anthropogenic sources of water* (rainfall that short-circuits the natural elements of the infiltration process) include buildings that have a constructed catchment area on the roof where the water is routed to individual storage tanks for domestic use. Nearly all households use cesspits for human waste disposal. In some areas (Hamilton and Prospect) the wastewater is carried in a sewer system to be discharged in the ocean, in some cases after a septic system stage.

5) *Constructed waterproof surfaces* are drained (in some cases) by wells drilled to the water table. In other areas water runs off from roads and infiltrates into the soil, is then evapotranspirated by plants or is evaporated from the road surface. In most cases the new routes water takes are short cuts in the hydrologic cycle. These short cuts represent significant alteration of both the quantity and quality of the infiltrating water. Under natural conditions nearly 90% of the water that infiltrates the soil is transmitted back to the atmosphere by evapotranspiration before reaching the water table. In contrast to this, it has been estimated that 80% of rainfall that lands on roof catchments goes through a cesspit and enters the groundwater reservoir. For water that falls on roof catchments and is discharged to a sewage which discharges into the ocean, the rainwater bypasses all natural storage functions. It is estimated that 10% of rainfall is lost from storage in the aquifers underlying built-up areas with roof catchments where the sewage is collected (and not discharged into cesspits and from there into groundwater) and discharged into the ocean via a piping system.

6) *Water that is extracted from the groundwater reservoir by wells, tunnels and infiltration galleries:* The characteristics of the various routes and their effect on the overall water budget depend on the use and subsequent fate of the pumped water. Water that is extracted for gardening use or crop irrigation goes back into the soil and a significant portion of it is evapotranspirated back to the atmosphere. This is net outflow from the reservoir. Water that is extracted for human use in sewered areas goes into the ocean and is consumptive use, an outflow from the reservoir. Some water is extracted from the reservoir and transported by pipeline or truck and represents an outflow from the reservoir.

The first calculation of recharge over the 688 ha. Central Lens was approximately 16% of the rainfall that falls on the area (18 cm/year average) was done by (Vacher H. , 1974). Vacher and Ayers (1980) obtained values of 35-45 cm/year using three independent methods. Rowe (1981) calculated 30cm/year but included road runoff and infiltration through cesspits. Rowe (1984) calculated 55-

65cm/year recharge including unnatural contributions such as infiltration through cesspits. Thompson obtained recharge rates of 40-75 cm/year using a steady-state model (Thomson, 1989).

From the water budget calculations, it was estimated that the average water use by Bermudians is 136 L/day.

About one quarter of the water that passes through the saturated zone of the Central Lens has passed through a cesspit. This practice of capturing rooftop rain has increased the flow into the reservoir by 4.41×10^5 m^3/year. The use of sewers and discharge to the ocean reduces the water entering the reservoir. There is no estimate of this annual flow.

Approximately 2.55×10^4 m^3/year of recharge from precipitation flows through the Pembroke Dump waste and into the reservoir. No information on the leachate plume from the Pembroke dump appears to be available. It is not known what the concentrations of leachate related parameters are or whether there are any organic contaminants of consequence in the plume and whether the leachate is attenuated naturally by dilution, dispersion and diffusion and retardation or emerges on the shoreline to discharge into the ocean.

The Central Lens appears to be shrinking according to Vacher (1974) because of the large amount of water exported from the area. This is, however, being offset by the significant volume of water that is directly recharged through the cesspits.

2.3.4 Water Table

The water table is a surface where the water pressure is equal to atmospheric pressure and is the top of the saturated zone of the aquifer. The elevation of the water table at any location represents the hydraulic head at that location. Hydraulic head is the potential energy per unit mass of the flowing groundwater. Groundwater flows from areas of high hydraulic head (high elevation of the water table) to areas of lower hydraulic head, ultimately sea level following Darcy's Law, $Q=KiA$. Q is the groundwater flow rate, i is the horizontal hydraulic gradient which is the elevation difference in the water table between two points divided by the distance between those two points. A is the cross-sectional area through which the groundwater flows. The shape of the water table surface is not constant and varies with topography as well as with recharge or lack of it. In addition, there are fluctuations from changing atmospheric pressure as well as from daily tidal fluctuations. The tidal influence results in seawater moving inland under the island which raises and lowers the freshwater lenses. As the freshwater lens rises the groundwater flow from the centre of the lens toward the shoreline increases and decreases once the elevation of the water table decreases. There is a lag time between periods of high tide and the maximum rise of the water table depending on how far from the shoreline the maximum rise occurs.

Hydraulic heads of groundwater are described by the elevation of the free water surface (water table) in observation wells. When these elevation heads are contoured, they show groundwater flow direction perpendicular to the contours and the horizontal hydraulic gradient measured as the head difference divided by the distance between observation points.

The groundwater hydraulic heads and horizontal hydraulic gradient to the west side of the City of Hamilton taken from old water level measurements (1981) show that there would be about 10cm of head or less above sea level at Gorham Road. The contour maps consistently show a predictable flow of groundwater towards the coast, with contours parallel to the coastline. The gradients depend on permeability. At Gorham Road the limestone of the Brighton Aquifer is characterized by low hydraulic gradients with relatively high flow. The hydraulic gradient is calculated using 0. m/distance to the harbour in metres. The groundwater flow velocity is hydraulic conductivity K times the horizontal hydraulic gradient divided by the effective or connected porosity, which is equivalent in most cases to the specific yield.

The hydrographs of wells penetrating the lenses show three superimposed fluctuations of different periods:

(i) A seasonal oscillation with a period measured in months in the decimetre range;

(ii) An irregular oscillation reflecting barometric pressure changes with a variable period measured in days; and

(iii) A regular oscillation due to astronomical tides and composed mainly of semi-diurnal and diurnal components.

2.3.5 Effects of Climate Change on Hydrogeology

Long term effects of climate change may result is changes in recharge to the groundwater lenses. In addition, rising sea levels will raise the freshwater lenses and increase the groundwater flow from all parts of the lens to the receding shoreline. The water table may rise to intercept the ground surface in places resulting in groundwater spring emerging in places where they have not been observed previously. These will likely be seasonal in nature at first.

Understanding the physical and chemical components of groundwater lens formation and dynamics and the elements of natural and anthropomorphic changes forms the groundwork for predictions of the effects of climate change. Analytical equations have been developed to predict the response of the lenses to changing conditions.

Since the characteristics of tropical and semi-tropical islands are different, the climate change adaptations will likely be different in some aspects among different island locations. For instance, the islands of Bermuda and Great Exuma in the Bahamas are similar in that they are both composed of Quaternary marginal-marine, calcarenitic limestones which are predominantly eolianite. Topographic depressions between eolian ridges are locally lower than present sea level; consequently, the ground water is coupled to inland marshes and ponds. The islands differ climatically. Rainfall in Bermuda exceeds potential evapotranspiration by about 0.1m/year, while in Great Exuma potential evapotranspiration exceeds rainfall by some 0.5 m/year. As a result, the inland ponds of Great Exuma are brackish to hypersaline, and fresh-water lenses are localized beneath the topographic highs between the ponds and the shoreline. In contrast, the marshes of Bermuda are not strong discharge sites, and the surrounding fresh-water lenses are geologically rather than topographically controlled. Ghyben-Herzberg modelling indicates that if the climates of Bermuda and Great Exuma were reversed, the characteristics of their fresh-water lenses would be reversed as well. This comparison indicates that climate, as reflected in the water budget, is one of the important controlling variables in the occurrence and geometry of fresh-water lenses in low-lying subtropical islands.

Photos and notes from the site visit by the team's hydrogeologist are included in Appendix A.

2.4 Flora

Bermuda was once dominated by forests of Bermuda cedar (*Juniperus bermudiana*) with mangrove swamps on the coast. The low-lying peat marsh basins above Bermuda's groundwater lenses also supported mixed forest, including Bermuda cedars. The shipbuilding industry had denuded the forests, but in some areas these recovered. Another important component of the original forest was Bermuda palmetto (*Sabal bermudana*), a small palm tree. They grew, historically, in the low-lying peat marshes, which are vulnerable to sea level rise. If the peat becomes saturated with standing water, seedling recruitment will likely be problematic and mature palmettos may drown or have difficulty standing in hurricanes. A higher water table will also make these marshes less supportive of Bermuda cedars (Copeland, 2020).

Other trees and shrubs include Bermuda olivewood (*Elaeodendron laneanum*) and Bermuda snowberry (*Chiococca alba*). The climate allows for the growth of other palms such as royal palm (*Roystonea spp.*) and coconut palm (*Cocos nucifera*), although the lack of very warm temperatures does not usually allow coconuts to fruit properly. Bermuda is the farthest north location in the Northern Hemisphere where coconut palms will grow naturally. Among the many introduced species are the Casuarina (*Casuarina equisetifolia*) and Suriname cherry (*Eugenia uniflora*). Casuarina tree roots embed themselves into the rocks, leading to erosion of beaches and unstable rock formations. They also out-compete or inhibit native vegetation.

Bermuda has three endemic ferns. They include Bermuda maidenhair fern (*Adiantum bellum*), Bermuda Shield Fern (*Thelypteris bermudiana*), and Governor Laffan's fern (*Diplazium laffanianum*). The latter is extinct in the wild but is being reintroduced. The endemic flora of the island also includes two mosses, ten lichens and forty fungi.


Figure 2.6 Bermuda Sedge (Copeland, 2020)

The Bermuda sedge *(Carex bermudiana),* which grows on Bermudian forest floors and in peatmarshes, is also endemic to the islands of Bermuda. This relative of grass (Figure 2.6) has become rare due mostly to the clearing of forest habitats, e.g., for development, and because of competition from invasive plants. It was listed as *Endangered* on the International Union for Conservation of Nature (IUCN) Red List of Threatened Species in 2014, though even as far back as 1918 it was "very rare and presumably on the verge of extinction" (Government of Bermuda Department of Environment and Natural Resources, n.d.). In an assessment of Bermuda's endemic plant and fern species between 2013 and 2016 counts of mature Bermuda Shield Fern, Bermuda Sedge and Wild Bermuda Pepper were slightly higher than the estimates published in the species recovery plans. Of the 350 Bermuda Sedges mapped, 82% were growing within nature reserves. That study made recommendations for the propagation of the species from seed, rat control, habitat management, planting of Bermuda Sedge of private property, and ongoing monitoring (Copeland, 2020).

Other coastal vegetation includes bay/sea grape (*Coccoloba uvifera*), box-briar (*Randia aculeata*, also known as white indigoberry/goat horn or inkberry). Box briar is often used in coastal landscaping due to its high tolerance to salt spray). There is also the Jamaican Dogwood (*Ddonaea viscosa*) and two species of mangrove; namely the Red mangrove (*Rhizophora mangle*), the Black mangrove (*Avicennia nitida*) and the closely related Buttonwood (*Conocarpus erectus*).

Paget Marsh, now protected by the Bermuda National Trust and the Bermuda Audubon Society, is one of the best places to see what Bermuda looked like when settlers first arrived. It is one of the few remaining inland freshwater ponds on the island and supports a variety of flora and fauna The entire Paget Marsh basin is less than 2m above sea level. Periods of raised sea levels brought on by warm water eddies from the Gulf Stream raised the water table in Paget Marsh for extended periods of time in 2002 and 2011 drowning many Bermuda Cedars in the marsh. A similar event in 2017 lasted from September until December of that year (Copeland, 2020).

Figure 2.7 Box-briar (Randia aculeata) (https://www.flickr.com/photos/samfrasersmith/3761738819/)

Seven-year apple (*Casasia clusiifolia*) is a salt-tolerant shrub that grows along Bermuda's sand dunes near the ocean. Shrubby fleabane (*Pluchea odorata*, also known as sweetscent, shrubby camphorweed and saltmarsh fleabane) is a flowering native that inhabits wetlands and moist inland areas and is used traditionally as a medicinal herb. The Tassel plant or Bay Cedar (*Suriana maritima*) is a medium size shrub that grows in sand dunes and rocky shores. Due to its high tolerance of drought and salt, it is also used in the horticultural industry for coastal plantings[3].

[3] (www.levypreserve.org)

Bermuda is home to one of the most northerly and healthiest coral reefs in the world. They ring the entire Bermuda Platform and play a critical role in protecting the island from increasingly strong storms. According to one study (Sarkis S. , et al., 2013), the reefs contribute an estimated USD722 million a year to the economy, largely through tourism and in coastal protection value. This is roughly equivalent to 12% of Bermuda's GDP. Some of the more tangible ecosystem services provided by the reefs are: (1) Coral reef-associated tourism, (2) Reef-associated fisheries, (3) Amenity or reef-associated surplus value on real estate, (4) Physical coastal protection, (5) Reef-associated recreational and cultural values, and (6) Research and education value. The 2013 study area was approximately 400km^2, including the reefs of the Bermuda Platform, but not those of the outer edge of the North Lagoon (Figure 2.8).

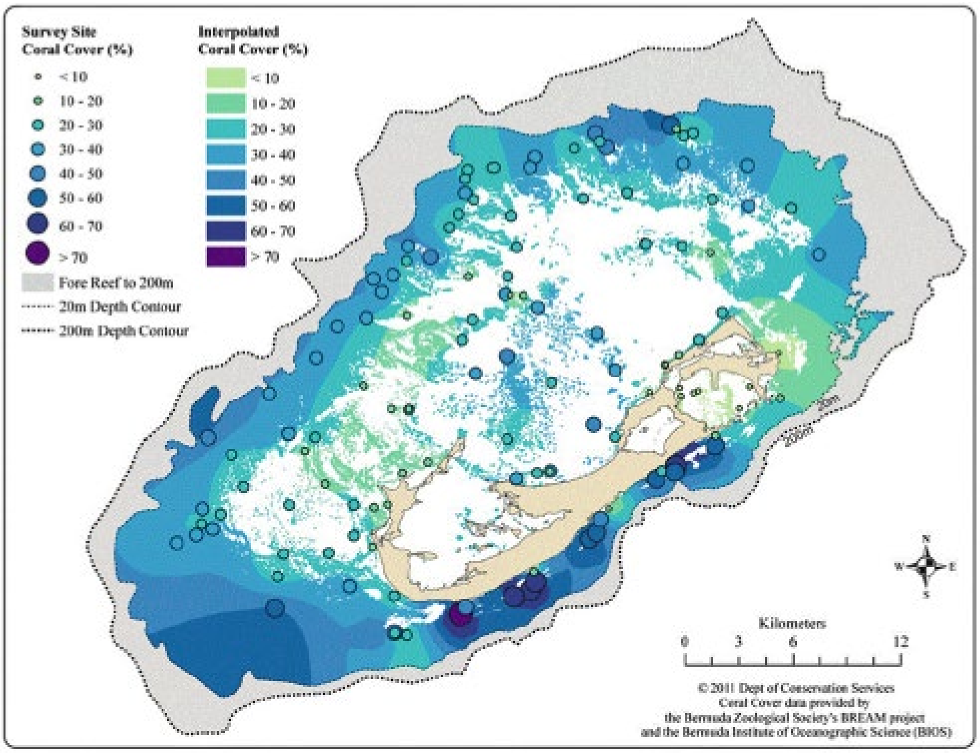


Figure 2.8 Bermuda's known coral reef cover including hard and soft coral species [Source: (Sarkis, van Beukering, & McKenzie, 2010)

The Bermuda Platform supports four species of tropical marine seagrasses, including *Thalassia testudinum* (turtle grass), *Syringodium filiforme* (manatee grass), *Halodule* sp. (shoal grass), and *Halophila decipiens* (paddle grass) (Fourqurean et al., 2019). Seagrass communities are invaluable to the fisheries industry as they provide essential habitat and forage for fish, regulate water quality and help to combat beach erosion (Orth, 2006). Over the years, shoreline development, dredging, propellers, ocean dumping and land reclamation have all affected Bermuda's nearshore seagrass meadows. In a 2007 study (Murdoch, et al., 2007) it was estimated that of the approximately 2100 hectares of seagrass meadows visible in a 1997 georeferenced mosaic of aerial photographs, 475 hectares were either reduced to sandy areas with dead and decaying rhizomes or had very sparsely distributed shoots of turtle grass, manatee grass or shoal grass by 2004. More recently, the green turtle has been responsible for the further decline of seagrass meadows through overgrazing (Figure 2.9

Figure 2.9 Presence, absence and average percent bottom cover of seagrass based on 530 benthic transects of 50m by 0.5m, extract from Coates et al. (2013)

Figure 2.10 Red mangrove (Rhizophora mangle)

Remnant patches of mangrove swamp can be found around the coast and at some inland sites, including Hungry Bay Nature Reserve and Mangrove Lake (**Figure 2.10**). The black (*Avicennia germinans*) and red mangrove (*Rhizophora mangle*) in Bermuda are the northernmost mangroves in the Atlantic. Mangroves are important for moderating the effects of storms and providing nursery for juvenile fish. Unfortunately, most of the stands in Bermuda have been lost to coastal infrastructure and property development. There are ongoing efforts to plant mangroves on Truck Island in Harrington Sound as part of a "living classroom" project there.

The inland swamps are particularly interesting as mangroves thrive in salty water; the saltwater arrives through underground channels rather than the usual tidal wash of coastal mangrove swamps. Areas of peat marsh include Devonshire, Pembroke, and Paget marshes.

2.5 Fauna

Approximately 250 species of birds have been recorded in Bermuda, of which about 20 are residents. There are two endemic species that cannot be found anywhere else in the world: the Bermuda Petrel (or Cahow) and the white-eyed Vireo. Of great relevance to this study are the Cahow and the White-tailed Tropicbird (or Longtail), both of which nest in holes and crevices in the soft limestone coastal cliffs and islands of Bermuda.

Believed to have been extinct for some 300 years, the Cahow was rediscovered in 1951 on four small offshore islets. Thanks to an intense program to protect the rare bird, it is making a slow recovery and, as of the 2019 Recovery Program report, there were 131 breeding pairs. The Longtail is widespread in the tropics and spends most of its life flying, coming only to land when nesting. There are an estimated 3500-4000 nesting pairs in Bermuda, but their numbers have been declining due to coastline development, predation, and competition with pigeons and mourning doves for nests. Higher sea levels, increasing coastal erosion and human efforts to mitigate erosion threaten both species of bird.

Other endemic species include the Bermuda Skink, the Buckeye Butterfly, Bermuda Cicada, Bermuda Cave Shrimp, and Bermuda snails. Bermuda was one of the first countries in the world to enact conservation legislation: the Bermuda petrel has been protected since 1616, and sea turtles and parrotfish have been protected since 1620 and 1977 respectively. Parrotfish are a keystone species for Bermuda's reefs. They feed by scraping algae and seaweed off the rocks, and this in turn ensures that corals do not become overwhelmed by the algae. They also produce beach sand when they excrete the excess rock they have ingested, making them an important factor countering beach erosion.

Nonsuch Island is a highly specialized nature reserve and one of the earliest ecological restoration sites in the world. It began as a place to conserve the endangered Cahow and is now home only to native and endemic plants and animals. On Nonsuch Island these plants and animals can thrive without human interference. It took many years of re-planting efforts, and great effort to prevent introduced species from reaching the island.

3 Site Inspections

Site visits by land and by boat were conducted during the weeks of February 28th – March 4th and March 22nd – 25th 2022. Figure 3.1 shows the areas visited which can be divided into:

- Sandy coasts - Several beaches/sandy coasts of importance were visited based on the findings of the previous study as well as their significance to the DOP.
- Areas of environmental significance – area of ecological importance were visited based on the findings of the previous study as well as their significance to the DOP
- Areas of hydrological significance – photos from site visits and meetings with relevant personnel are provided in Appendix A.
- Critical assets - Based on factors such as historical significance, importance to the road network, proximity to the coast, and value to distribution networks for oil, gas, water, and electricity, several sites were identified as critical during the initial desktop inspection. These are described in section 10; a detailed structures inventory was also done for these sites.

This section describes the beaches/sandy coasts and areas of environmental significance visited by the team.

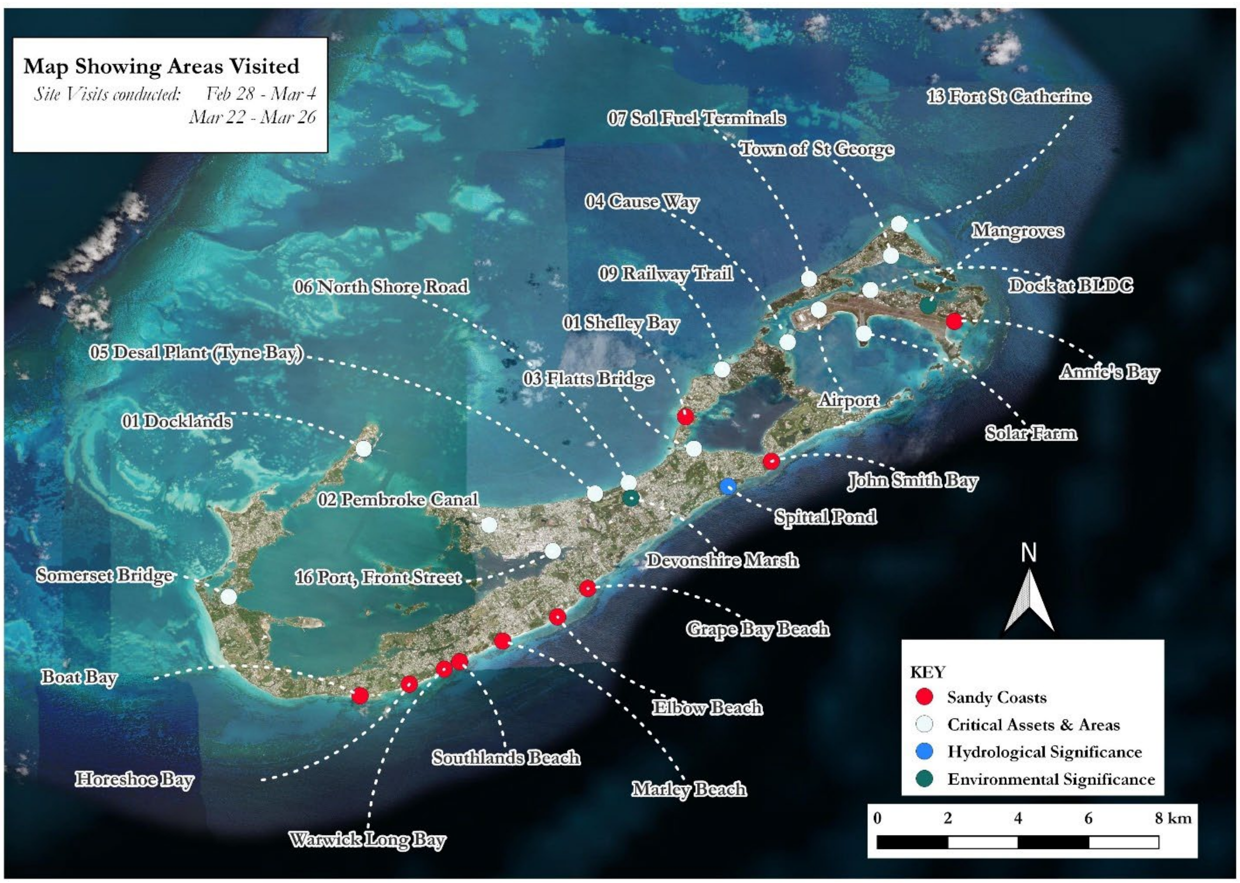


Figure 3.1 Areas visited

3.1 Sandy Shores

Shelley Bay

The beach is protected in parts with rock-filled gabion baskets. The gabions are in good condition despite being over 10 years old. A rocky shoreline protects a footpath connected with aluminium bridges in places. The rocky shoreline is disjointed with the gaps allowing wave energy to penetrate the shoreline. Shoreward of the beach/footpath lies the main arterial road. There is evidence of recent (and imminent) failure of the roadway slipping seaward, repaired with a concrete seawall. Apparently two brush islands existed within the bay, which were cut for firewood.

Figure 3.2 Shelley Bay Beach

Marley Beach

Marley Beach appeared to be one of the more exposed beaches on the south shore, evidenced by relatively large waves (~1m high) on the shore and the presence of a surfer.

At Marley Beach, approximately 0.5m of ground cover (organic soil) sits on top of a relatively weak sandstone formation that is easily crumbled by hand. There are some "columns" of harder rock, thought to be fossilized tree roots.

A large coastal cliff failure has occurred under a new development of three apartment blocks. A concrete seawall was built at the toe of the cliff to protect from further erosion.

Figure 3.3 Marley Beach

John Smith Beach

John Smith Beach is a sandy beach formed within a crenulate bay. The beach itself appears quite healthy with a well-defined vegetated upper dune. However, there is evidence of undercutting of the sandstone rock in the cliff face, presumably caused by wave action during storm events.

Figure 3.4 John Smith's Beach

Annie's Bay

The eastern end of the airport runway terminates with a roadway that is protected by a low revetment. This gets covered with sand and debris during passing hurricanes and requires heavy machinery to clear the road.

Figure 3.5 Annie's Bay

Horseshoe Bay

Horseshoe Bay has a wide crenulate shape beach. The beach is divided by a cliff headland that recently experienced cliff failure. The rock/reefs offshore offer significant protection to the sandy beach.

Figure 3.6 Horseshoe Bay

Grape Bay Beach

At the Grape Bay Beach, even though there's a wide beach area, the cliffs at the back of the beach show evidence of erosion: a walkway atop of the cliff recently collapsed.

Figure 3.7 Grape Bay Beach

Elbow Beach

Similarly, at Elbow Beach there's evidently of cliff erosion.

Figure 3.8 Elbow Beach

Southlands Beach

The Southlands beach is a small pocket beach. This beach has a significant number of rock outcrops, many of which have invasive Casuarina trees growing out of them. The casuarina trees out-compete or inhibit native vegetation and the roots embed themselves into the rocks, both of which ultimately lead to erosion of beaches and unstable rock formations.

Figure 3.9 Southlands Beach

Warwick Long Bay

At the time of the visit, wave conditions at this beach were aggressive and significant wave run-up was observed. There is a high cliff at the back of the beach, with less erosion than other beaches visited.

Figure 3.10 Warwick Long Bay

Boat Bay Beach

This is a natural pocket beach created by two headlands.

Figure 3.11 Boat Bay Beach

3.2 Environmentally Significant Areas

Airport Waste Management Facility

The Airport Waste Management Facility is licenced (under the Clean Air Act 1991) to receive 'inert' materials but including construction debris, drained road vehicles, tyres, white goods, non-recyclable e-waste, PVC and incinerator ash-concrete - as $1m^3$ blocks or as capping pours. Wood waste, other organic waste and hazardous waste is prohibited. The site appears to be subject to ad-hoc reclamation, with fill being pushed into the shallow nearshore area.

Figure 3.12 Landfill site

Mangroves

The mangroves in Bermuda are the most northerly in the Atlantic. Prior to human settlement, mangroves covered as much as 60 acres of Bermuda. Over the past two centuries, nearly 30% of the mangrove habitats in the Bermuda Islands have disappeared: in-filled as garbage dumps or drained when marsh-breeding mosquitoes spread deadly diseases such as yellow-fever. Development, erosion and rising sea levels related to climate change have also affected the remaining mangrove habitats.

Figure 3.13 Mangrove stands

Spittal Pond

Rising sea levels will likely cause the pond to connect with the sea eventually. During high water events (e.g., mesoscale eddies) the connection to the sea is already evident. Other impacts of rising waters may result in the roots of Bermuda palm being exposed to seawater.

Figure 3.14 Spittal Pond

Devonshire Marsh

There are concerns about rising sea levels causing salt intrusion into this marsh and affecting the Bermuda palms.

Figure 3.15 Devonshire Marsh

Casuarina Trees

The Casuarina was introduced to Bermuda in the 1940s following the decimation of the Bermuda Cedar forest by a scale insect (also introduced). It has since become an invasive species and is crowding out native and endemic species such as Buttonwood and the remaining Bermuda Cedar. Casuarinas grown near the edge of the cliffs send roots down into the cemented sandstone, which contributes to spalling and erosion along cliff faces (Figure 3.16). There are several locations along Bermuda shorelines where casuarina trees are now being cleared.

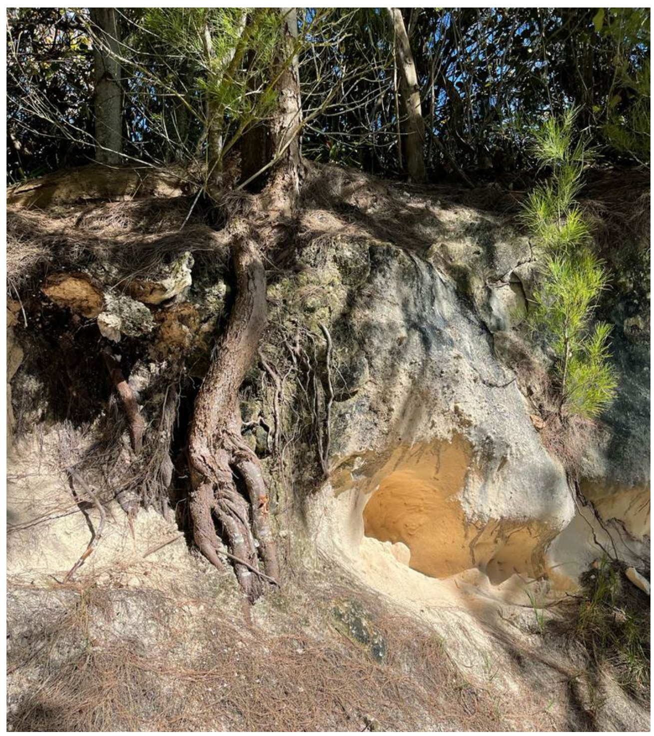


Figure 3.16 Casuarina roots along cliff face

Salt Marsh

Rising mean sea levels have eroded the soil away from several salt marshes, leaving very few thriving salt marshes. The white line along the rocks in the images below (Figure 3.17) delineates areas that were recently filled with soil and supported vegetation, including the locally rare native plant Sea Lavender (*Limonium carolinianum*). Increased wave action and high water levels swept away the soil and vegetation. Coastal erosion and storm damage are the biggest threats to salt marsh habitats, and are likely to worsen due to climate change and the associated increase in sea level and hurricane activity. Coastal development has also been a threat and, without appropriate intervention, will continue to threaten any remaining pockets of salt marsh. The largest salt marsh in Bermuda is at the eastern end of Spittal Pond (bottom end of photo in Figure 3.18).


Figure 3.17 Former salt marsh

Figure 3.18 Spittal Pond *(photo from the Royal Gazette archives)*

4 Bathymetry and Topography

The islands of Bermuda are oriented roughly south-west to north-east, with a length of 30 km and a width of 3 km. The island chain encompasses the lagoon-type features of Castle Harbour, Harrington Sound and Great Sound. These features, along with a highly indented shoreline, create a long coastline compared to the land area.

The topography of Bermuda is defined by rolling hills that reach an elevation of 80m with most of the remaining land at about 30m. There are no well-developed drainage lines and there are low lying depressions in the interior that form small ponds.

LiDAR Data from 2019 was obtained and the process of extracting the data has started. Based on the data received, it appears separate flights were done for bathymetry and topography. The bathymetric data was collected on a 0.6m grid spacing while the topography was on a 1m grid spacing. As a result, the data required several filtering routines to output useable data. The LiDAR data ranges from 77m down to -46m. The offshore reef platforms are clearly defined and play an important role in dampening the waves; we expect to see this clearly during the modelling activities (Figure 4.1).

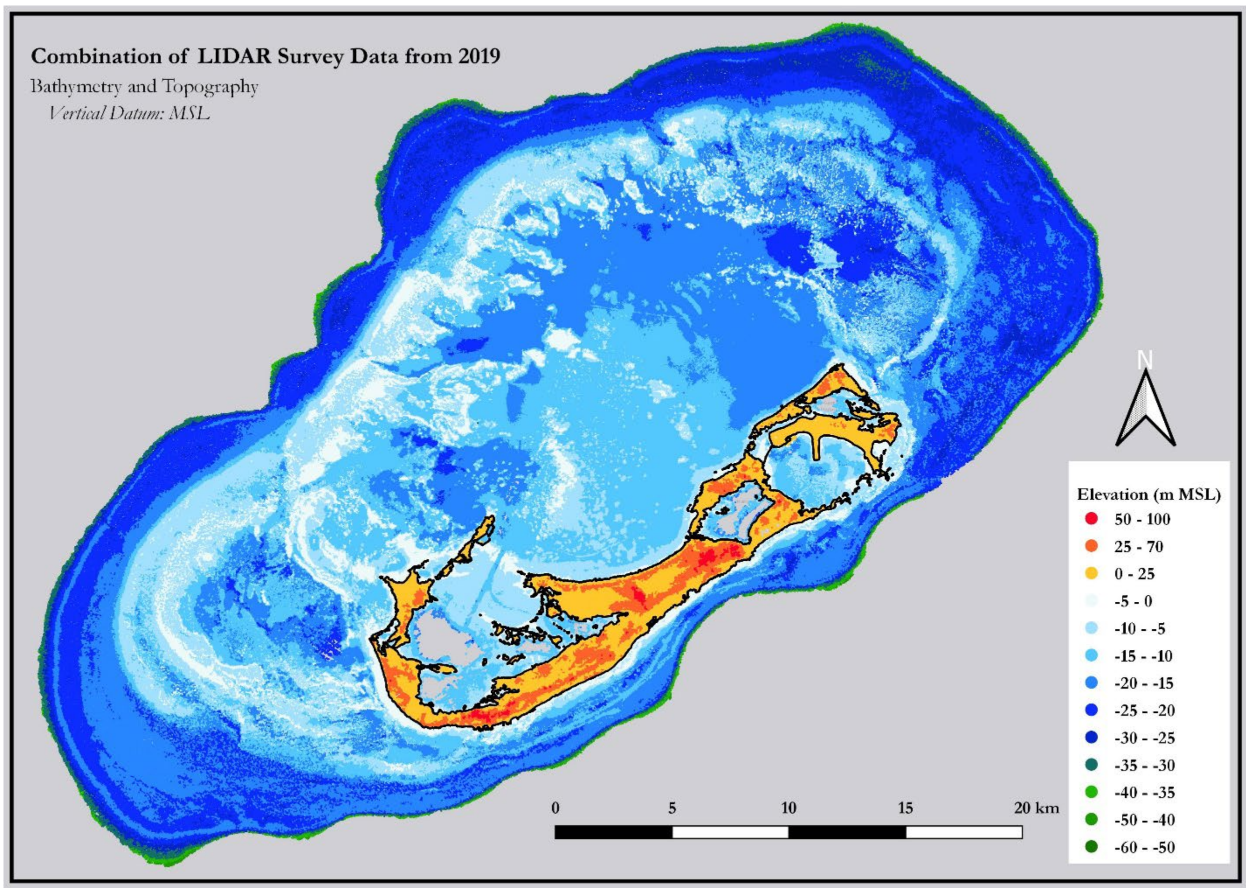


Figure 4.1 2019 LiDAR Data

5 Aerial Imagery

Aerial images were captured during a 2019 LiDAR campaign. The images were divided into 1391 tiles (1km x 1km each) that span the archipelago and the reef platform. These images have relatively high resolution with pixel sizes of less than 0.5m. At this high resolution, the conditions of the coastal structures in critical areas could easily be evaluated. Figure 5.1 is an example of the details visible from the images at the Ferry Dock at Front Street, Hamilton. A total of 30 tiles were extracted from the dataset and combined with onsite observations to create a detailed site inventory (see section 10).

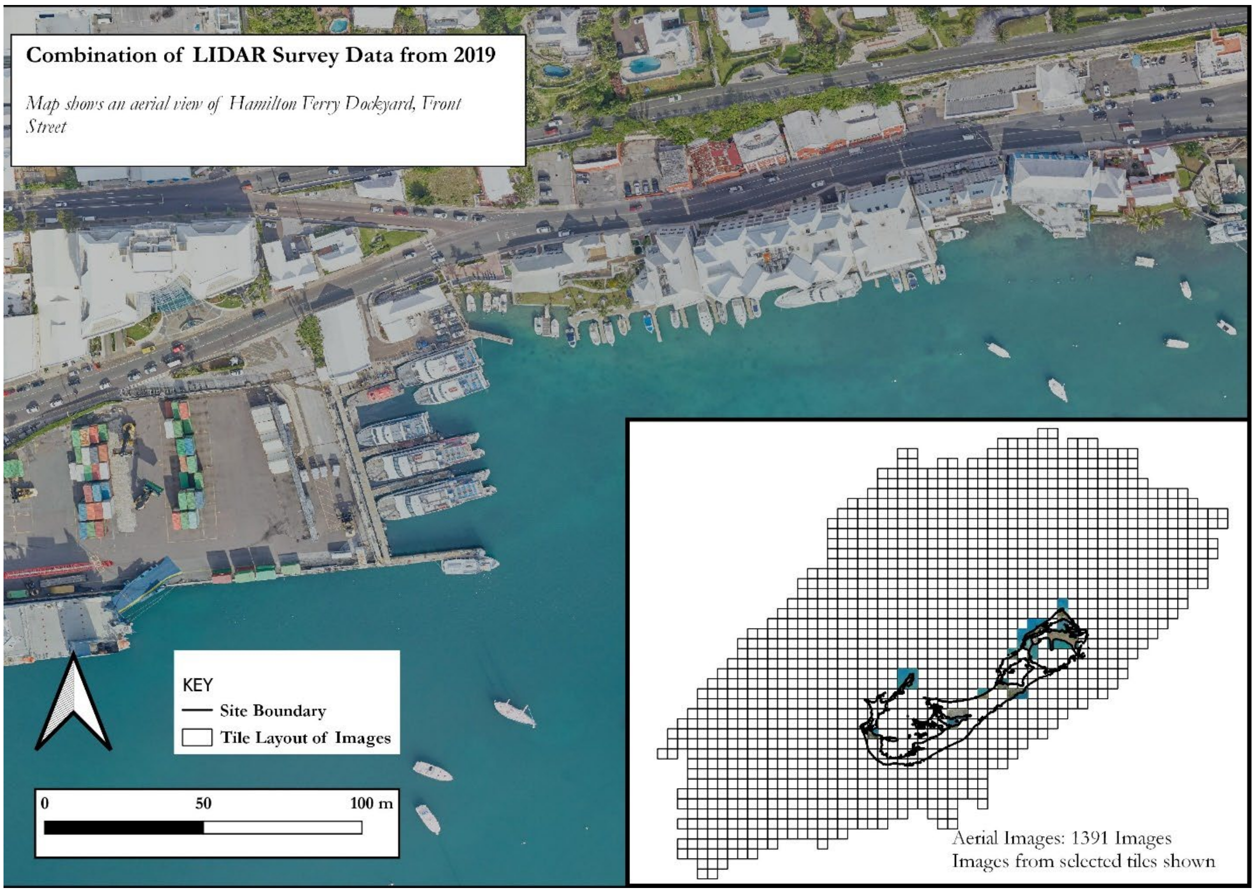


Figure 5.1 Example of the details visible from LiDAR images at the Ferry Dock at Front Street, Hamilton

6 Sea Floor Classification

The maps below show the seafloor classification for seagrass, corals and sand. These maps and information from them will be used in the modeling of climate change impacts, so knowing the baseline information is important.

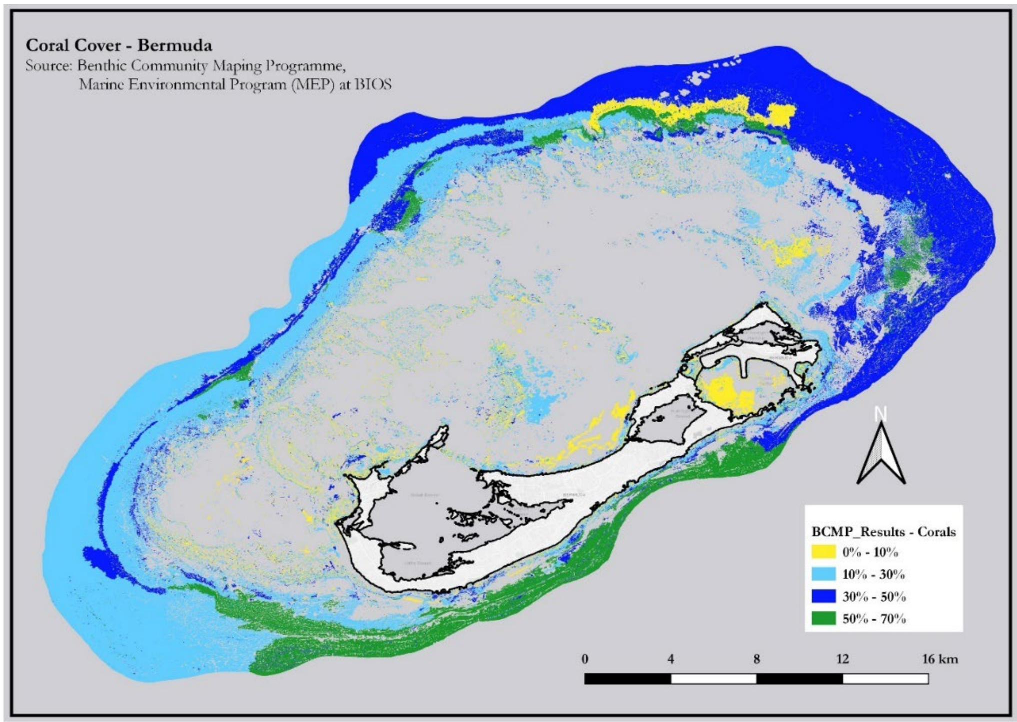


Figure 6.1 Seafloor: Corals

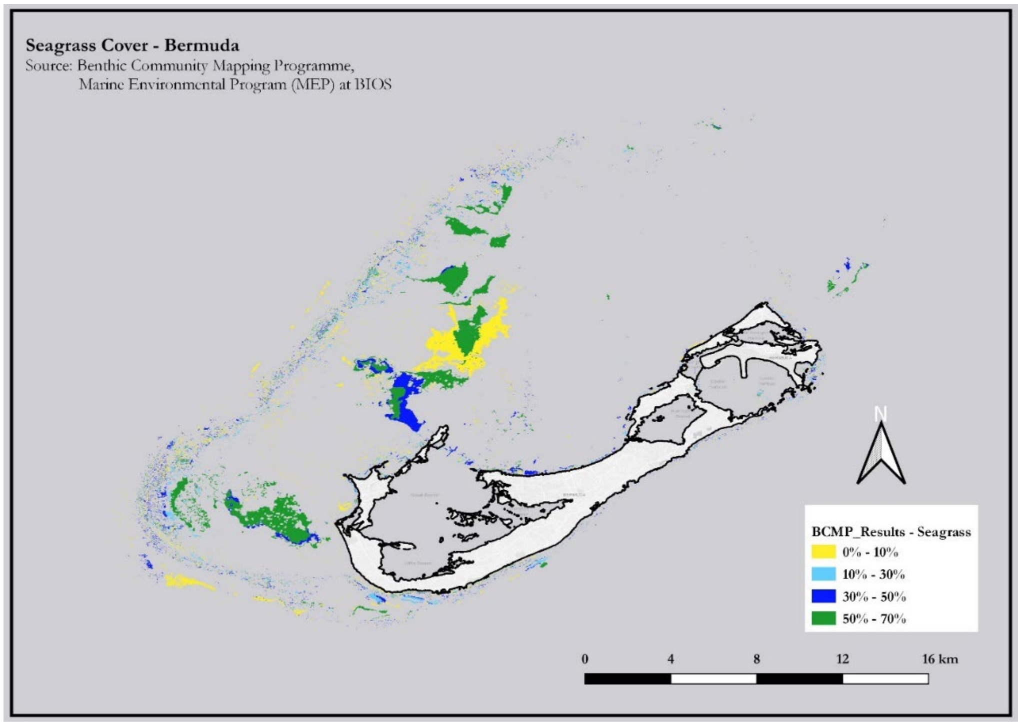


Figure 6.2 Seafloor cover: Seagrass

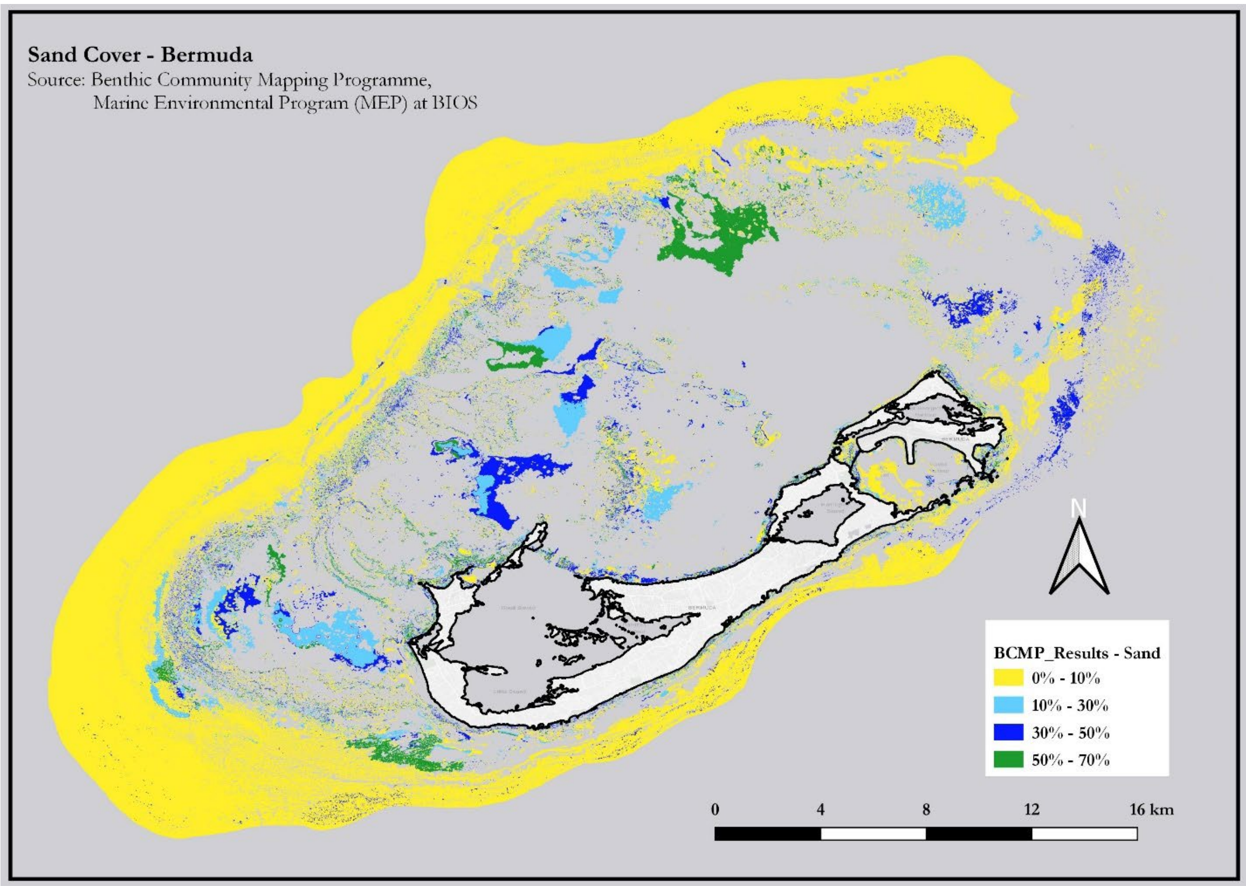


Figure 6.3 Seafloor Classification: Sand

7 Land Use Mapping

EOMAP proposed a satellite-based interrogation of land use by interpreting an aerial image from 2021. The classification includes land use/land cover such as road networks (transportation), buildings (residential / commercial, industrial), agricultural areas, forest, meadows, bare ground (open land), inland water, wetland, marina, etc. The results of the assessment are shown in Figure 7.1 to Figure 7.4. Approximately 70% of the island is covered by vegetation, both high and low canopy.

It should be noted that while the assessment suggests high percentage of vegetation cover, land use may vary on the ground. For instance, the low canopy vegetation may be on land space on some type of development. Nonetheless, this assessment gives a good assessment of areas where there is high density development. As the map below shows, the City of Hamilton, some areas of St George as well as the Royal Naval Dockyard are highly developed areas. This would have implications for developing setbacks and zones when the climate change assessment is complete.

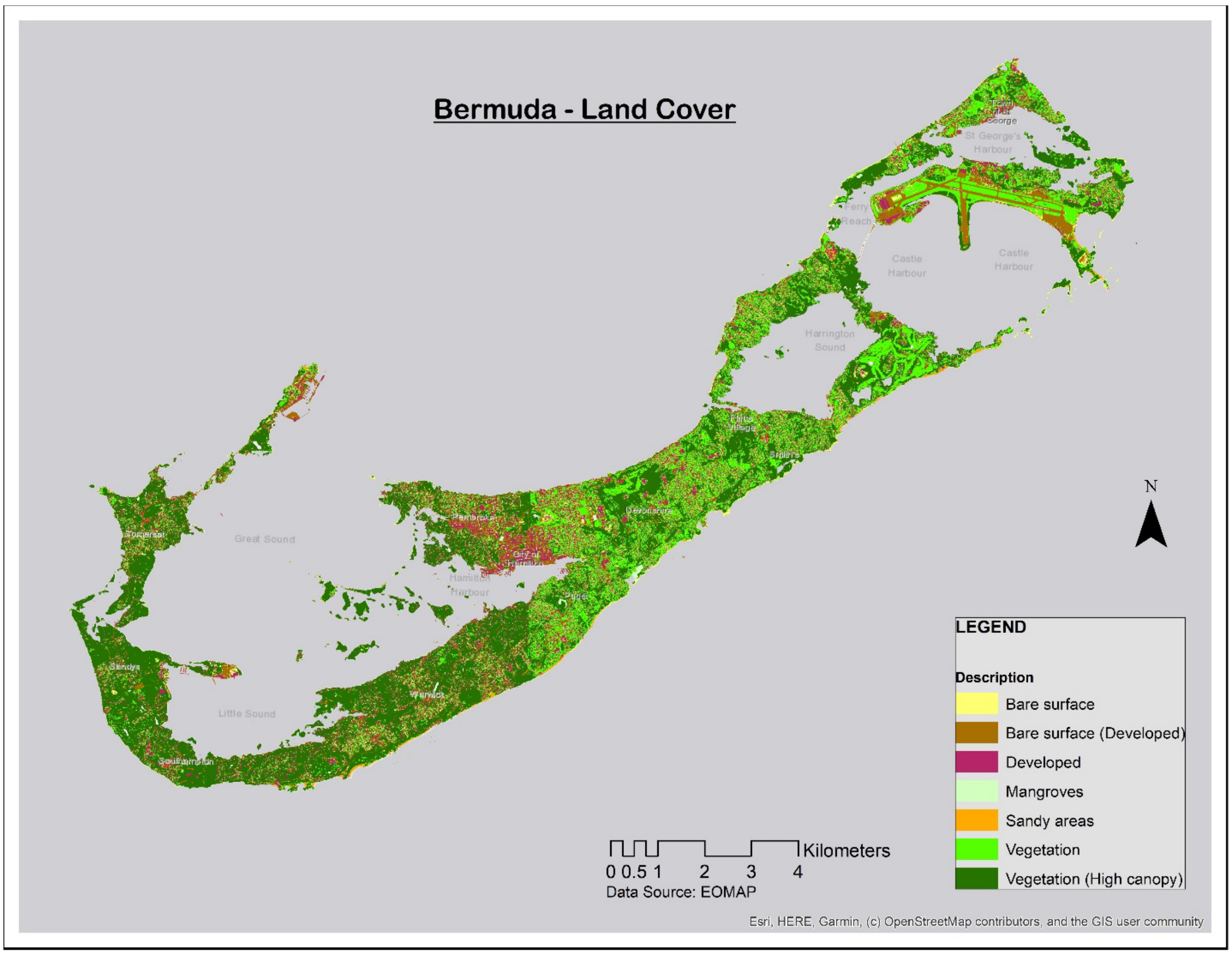


Figure 7.1 Land cover patterns for Bermuda

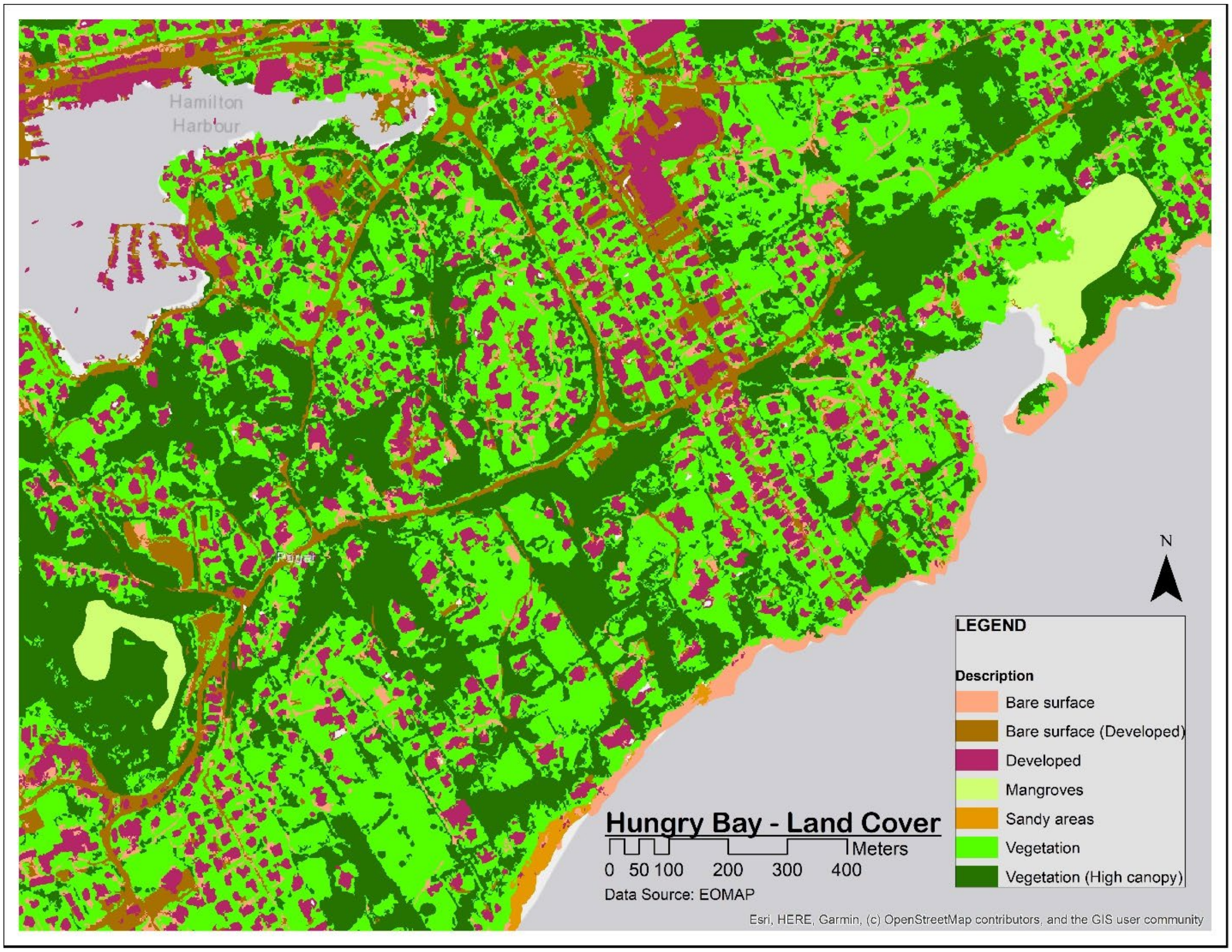


Figure 7.2 Land cover for Hungry bay

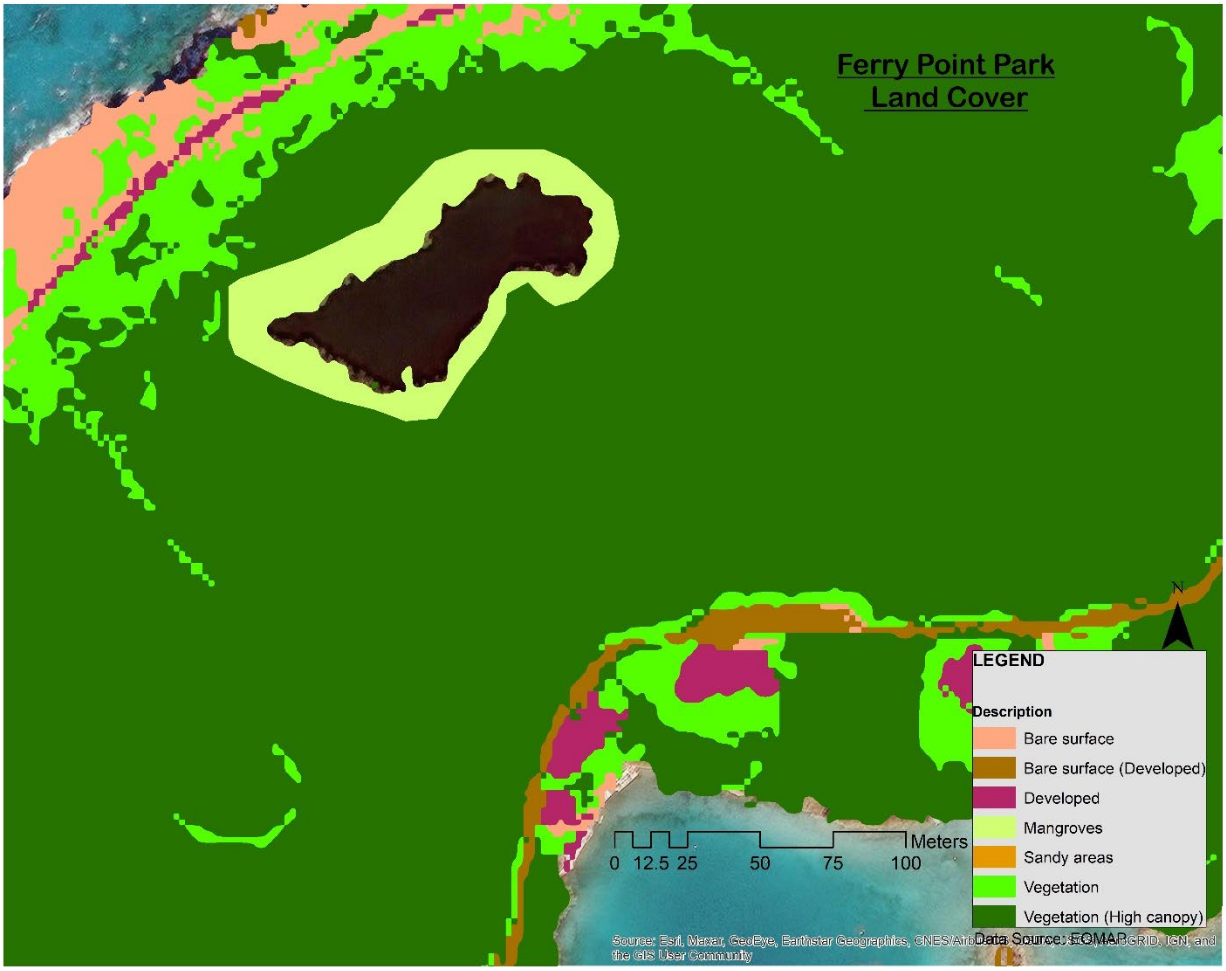


Figure 7.3 Land cover for Ferry Point Park

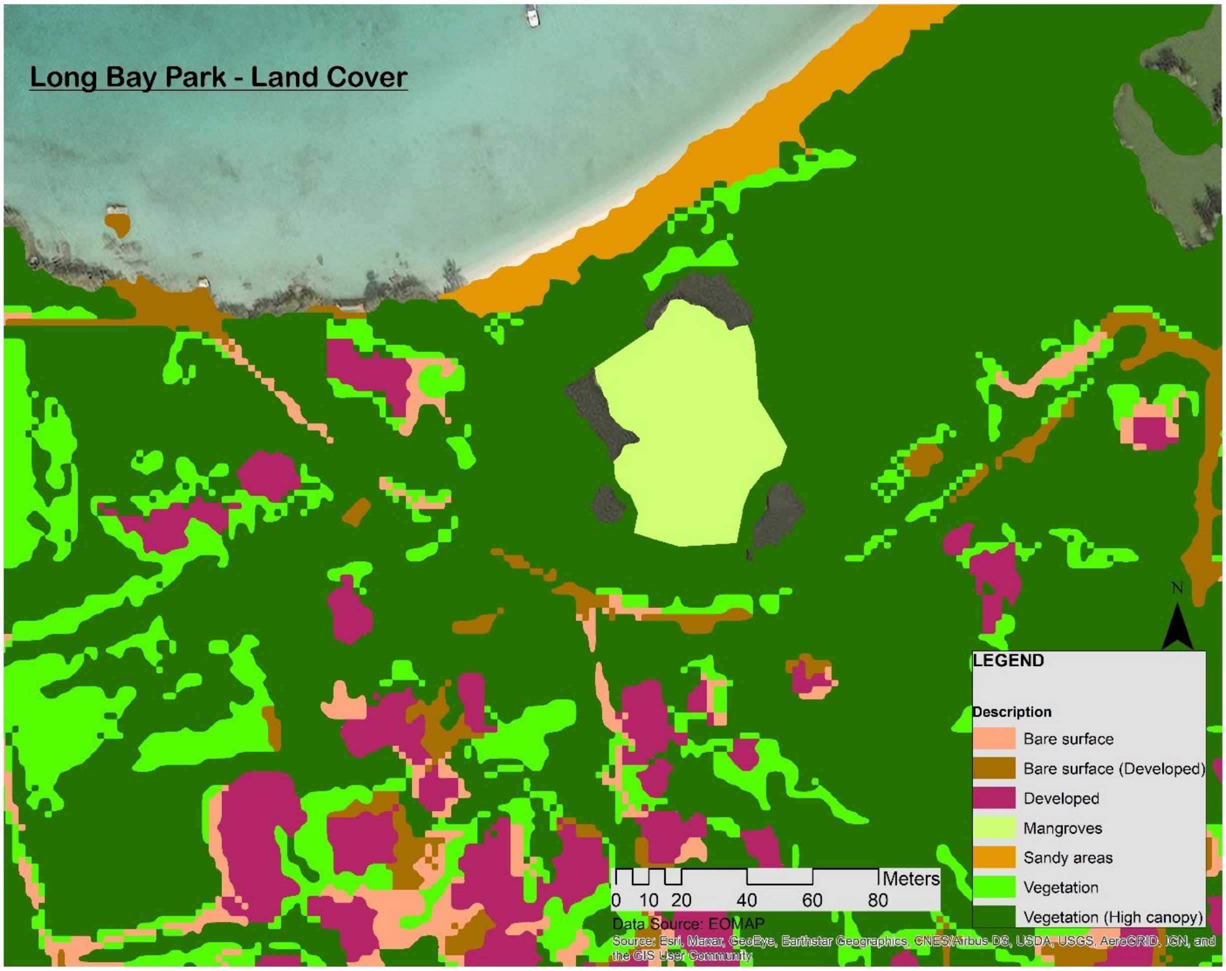


Figure 7.4 Land cover for Long Bay Park

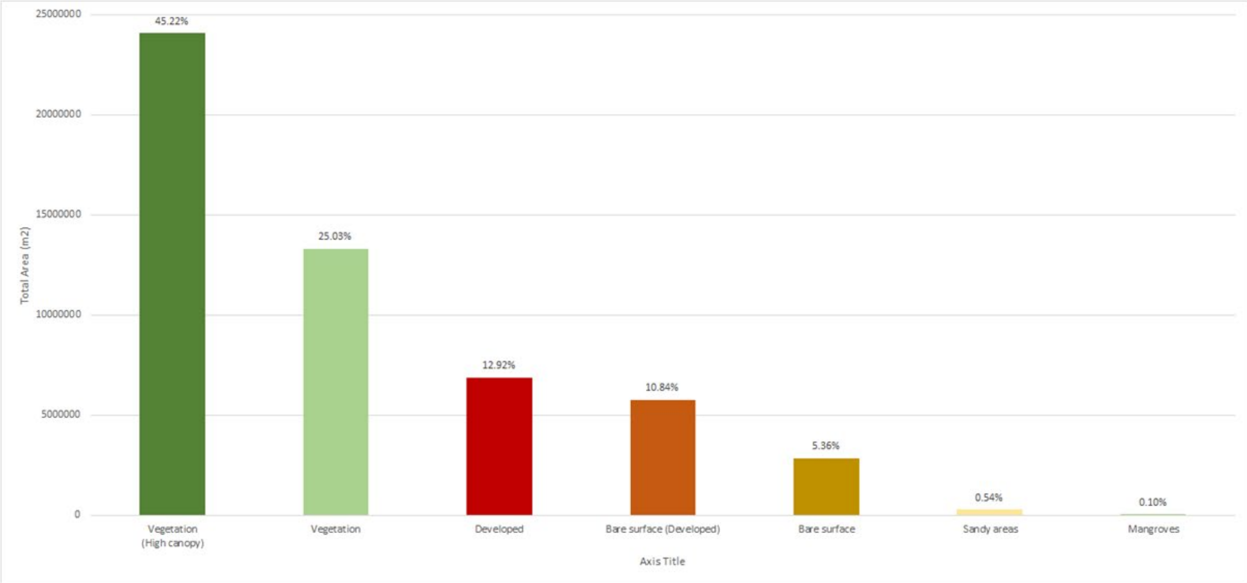


Figure 7.5 Distribution of land cover patterns

8 Delineation of Shoreline Types

Bermuda's coastline is long and indented, winding around islets, lagoons, and other indentations. The coastline is largely made up of exposed rock with pockets of beach in some places, allowing it to be divided into two broad categories: rocky and sandy coastline. The rocky shorelines can be further broken down as high cliffs, low cliffs, and flat rocky coastline. High cliffs are vertical rock faces greater than 7m high and low cliffs are steep rock faces 1-7m high. Low lying, relatively flat rocky coastline between sea level and 1m meter high is referred to as flat rocky coastline.

The sandy shorelines are mainly located on Bermuda's South Shore, with rocky shoreline features distributed around the island and more concentrated on North Shore areas. The following images represent typical shoreline features.

Figure 8.1 Example of sandy shore

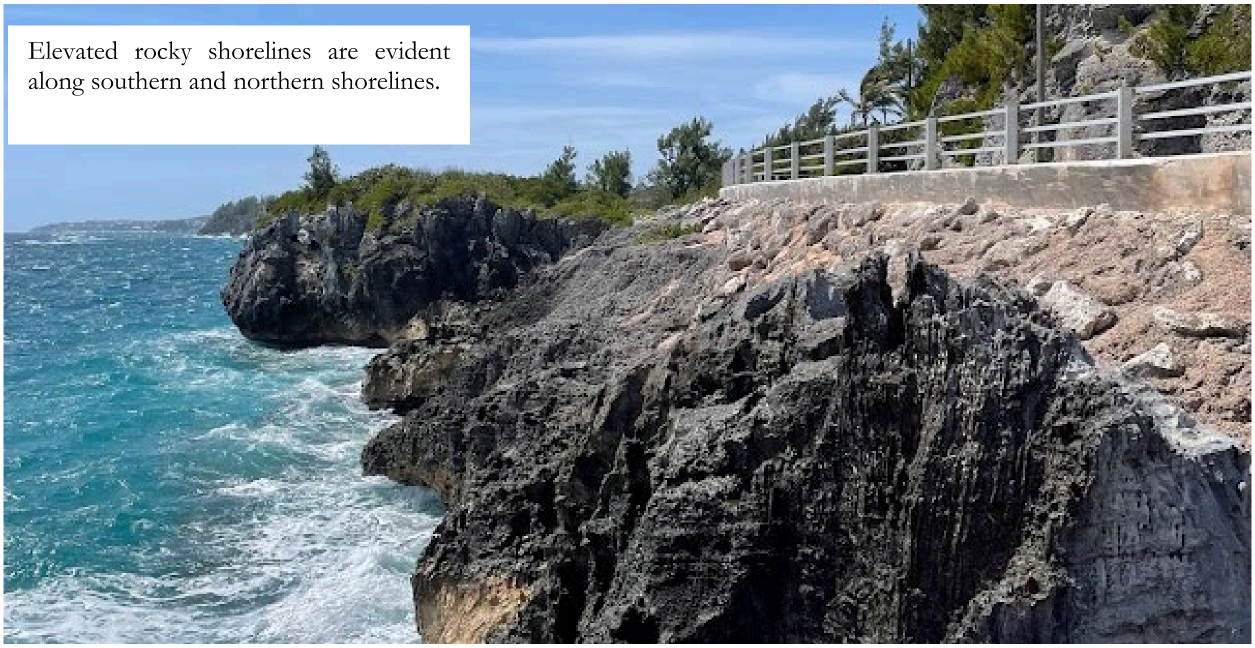


Figure 8.2 Example of low cliff area

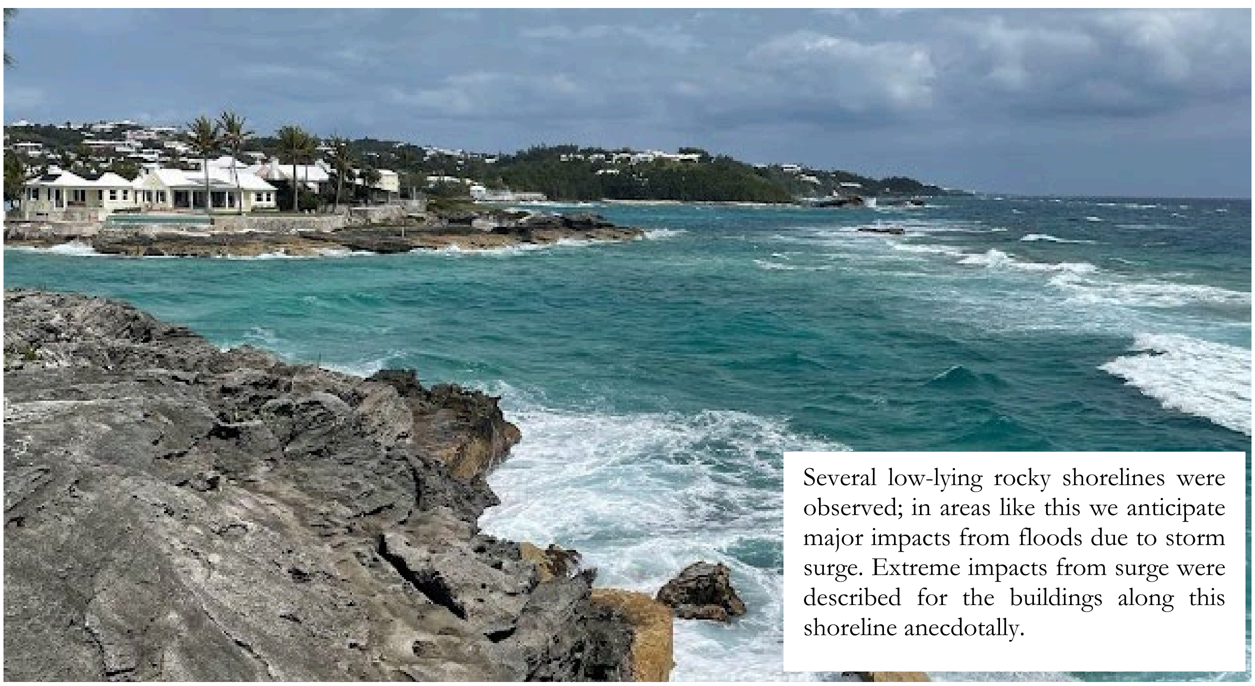


Figure 8.3 Flat rocky coastline

Figure 8.4 Example of low-lying rock shoreline in Devonshire

Figure 8.5 Example of high cliff in Southlands, Bermuda

In the 1998 Environmental Sensitivity Coastline Index, Bermuda's shoreline was divided into 10 categories (Figure 8.6 and Figure 8.7). Based on this breakdown, 34% of the Bermudian coastline is unprotected from the impact of oceanic waves. Approximately 24% of this total can be classified as high relief or cliff side formation. As a result, these areas would be more vulnerable to the effects of hazards such as hurricanes and land slippage. Further, approximately 30% of the shoreline is sheltered, having natural protection due to its location within a natural sound or in the lee of other smaller islands. Sandy beaches account for 9% of the shoreline and are further classified as high wave energy beaches (3%), low wave energy beaches (3%), and pocket beaches (3%). As expected, most of the high energy sandy coasts are concentrated on the south shore. Development along these shorelines should be mindful of the wide range of shoreline widths and should be set back sufficiently.

For approximately 11% of the shoreline, protection has been added in the form of sea walls and boulders. These are typically found near ports, marinas, and airports.

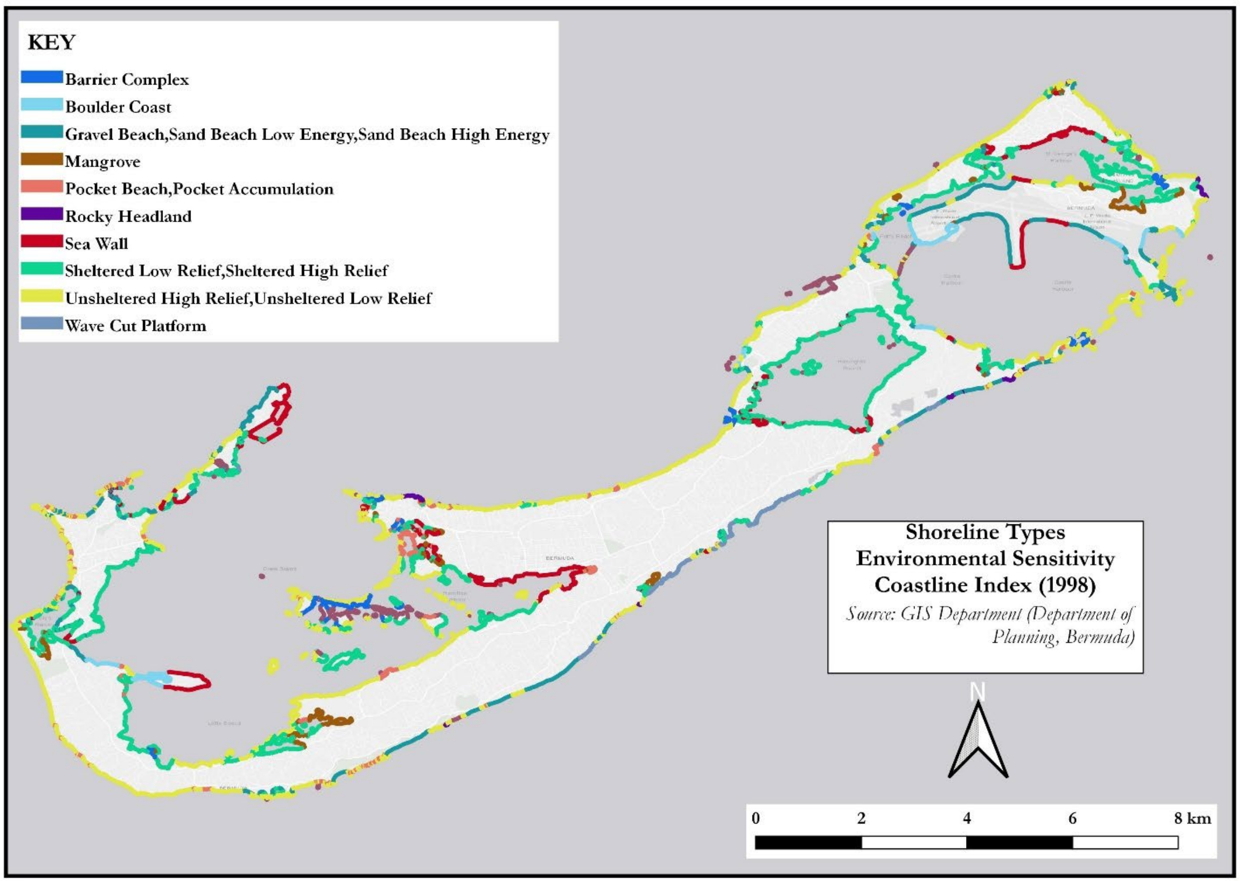


Figure 8.6 Delineation of shoreline types (1998, Department of Planning, Bermuda)

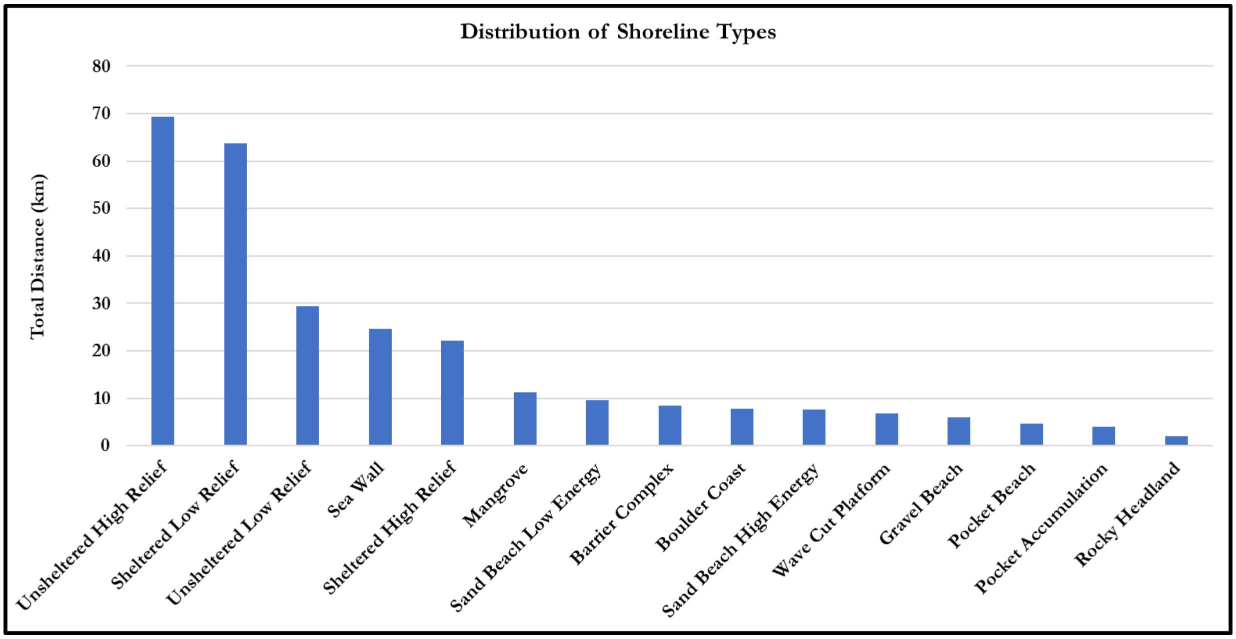


Figure 8.7 Total length of various shoreline types across the island

New (2021) satellite data obtained from EOMAP (Germany) was used to classify the backshore, coastline, and foreshore of the project shoreline. EOMAP used object-based geomorphological classification according to texture and spectral characteristics, linking this to identified classes of geomorphological units along the shorelines of the islands in the archipelago. The conditions at the coastline (i.e., at the waterline), at the backshore (immediately landward of the waterline) and at the foreshore (immediately seaward of the waterline) were delineated and grouped into classes as outlined below. Figure 8.9 to Figure 8.10 show the classifications of the backshore, coastline and foreshores of Bermuda.

Backshore (5 classes)	Coastline (5 classes)	Foreshore (7 classes)
Artificial,	*Anthropogenic or high built-up density*	*Mudflat*
Rock Dominated	*Rocky shores*	*Rock Dominated*
Vegetation Dominated	*Mangroves and vegetated areas*	*Sediment Dominated*
Beach	*Fine-grained sand beach*	*Macroalgae Dominated*
Dune	*Mixed sand and gravel beach*	*Seagrass Dominated*
		Artificial
		Coral Dominated

The results show that 39% of the Bermuda backshore area may be characterised by manmade structures (Figure 8.8), which typically include seawalls of varying height, coastal revetments, etc. The second and third most common backshore types may be classified as vegetation dominant (30%) followed by rocky shorelines (26%). Only 5% of the backshore area can be classified as sandy coasts.

For shoreline classification, and based on the EOMAP assessment, 39% of the shoreline is classified as rocky, while 44% of the shoreline shows the impact of anthropogenic influences, whereby they exhibit high built-up density. Only approximately 6% of the coastline is classified as being sandy, while the remaining 11% is mangrove and other vegetation.

For the foreshore, or area adjacent to the shoreline and underwater, a majority of the foreshore is dominated by sediments (~50%) and 38% of the foreshore is dominated by rocks.

The results of the work from this investigation will be used to aid the qualification and understanding of the risk of coastal erosion and flooding within the various morphological cells, or Shoreline Management Units (SMU's). As a significant amount of the shoreline is rocky in nature, a detailed assessment of the stability of the cliffs will aid an assessment of the risks of cliff failure. In addition, and based on observations made during our site visits, comments will be made as to the success (or not) of the various man-made structures that have been employed in Bermuda, against ocean waves and storm surges. Recommendations will also be made as to the most appropriate types of erosion mitigation measures that may be implemented, within each SMU.

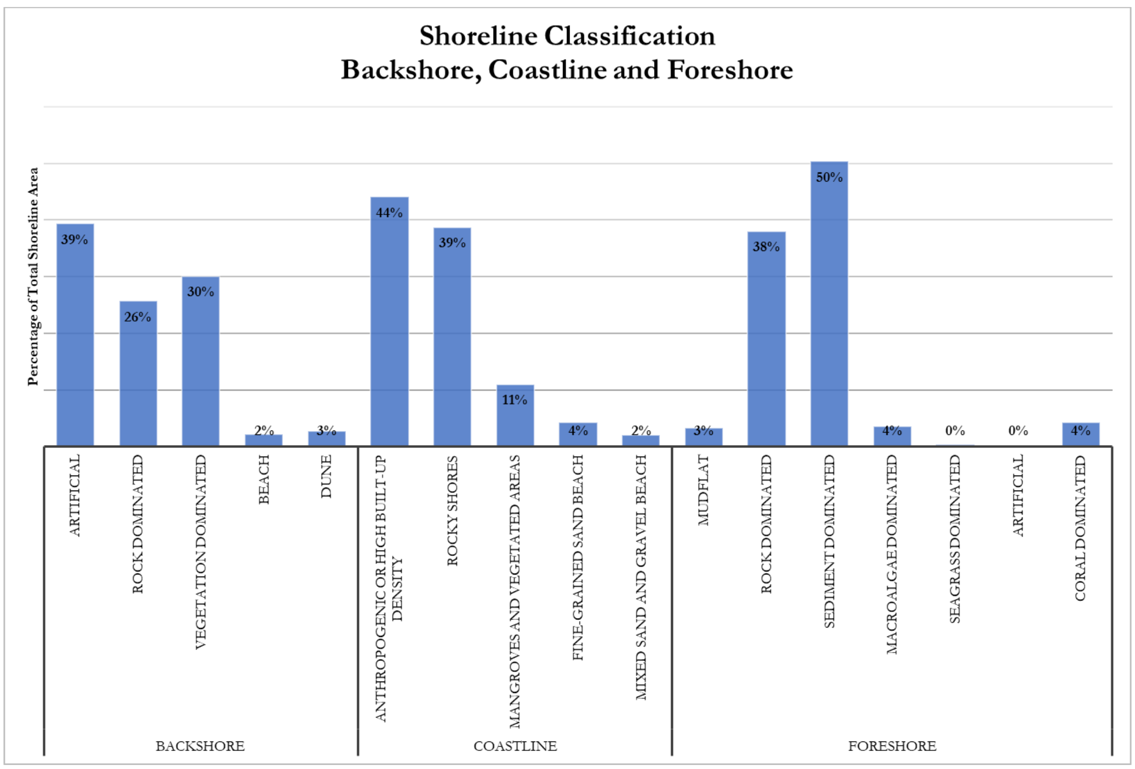


Figure 8.8 Delineation of shoreline types

It should be noted that the "Coastline" class called "Rocky shores" would encompass cliffs as well as boulder coasts. However, as the transition is smooth (i.e., 2-dimensional), it's hard to tell where a rather steep coast becomes a cliff...

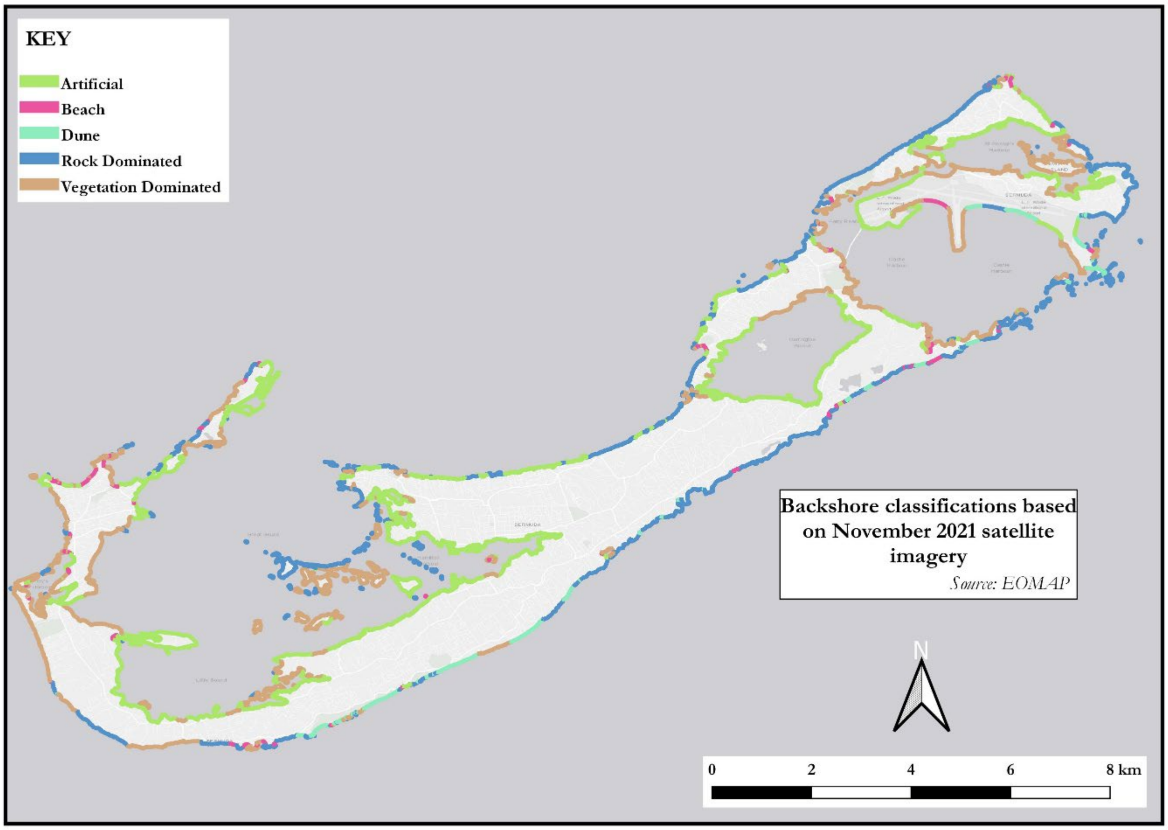


Figure 8.9 Backshore classifications based on 2021 satellite imagery

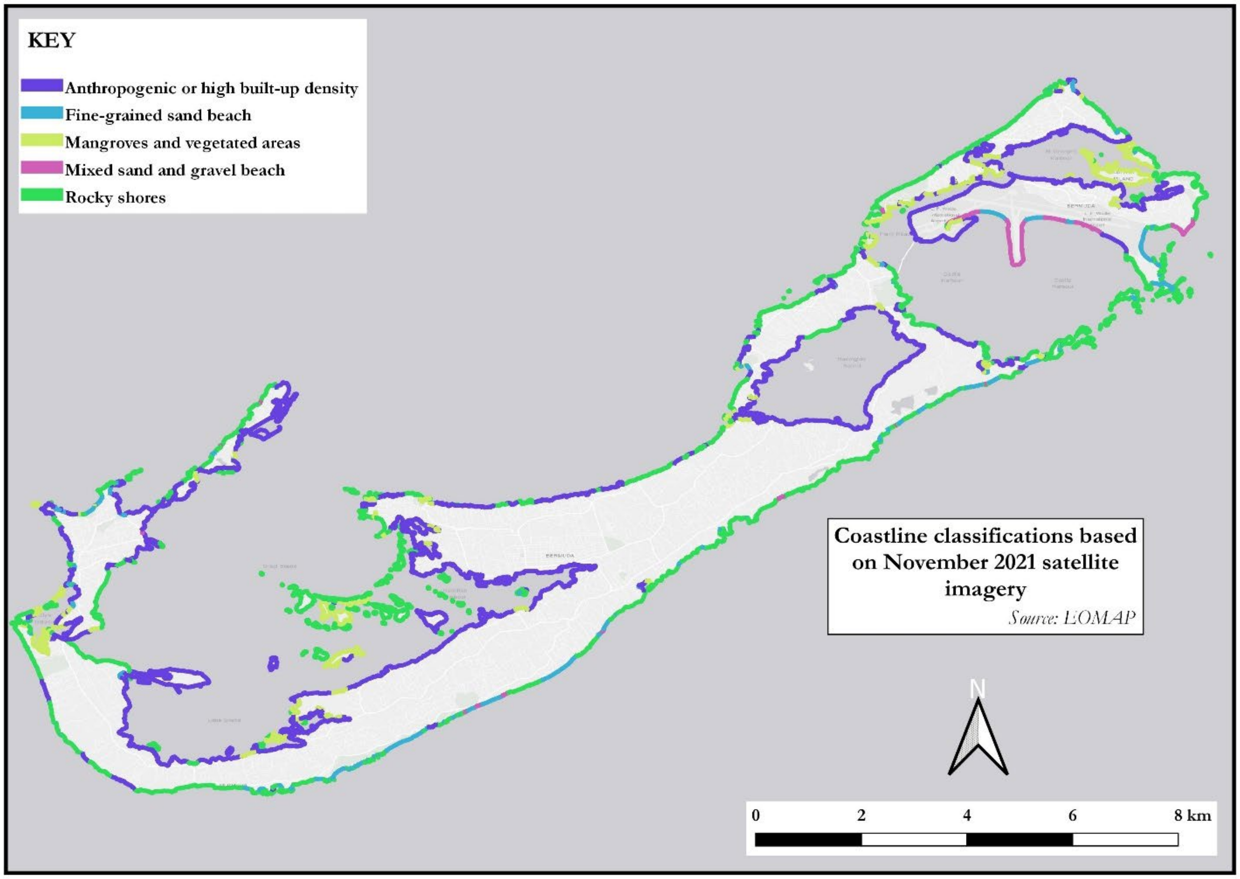


Figure 8.10 Coastline classifications based on 2021 satellite imagery

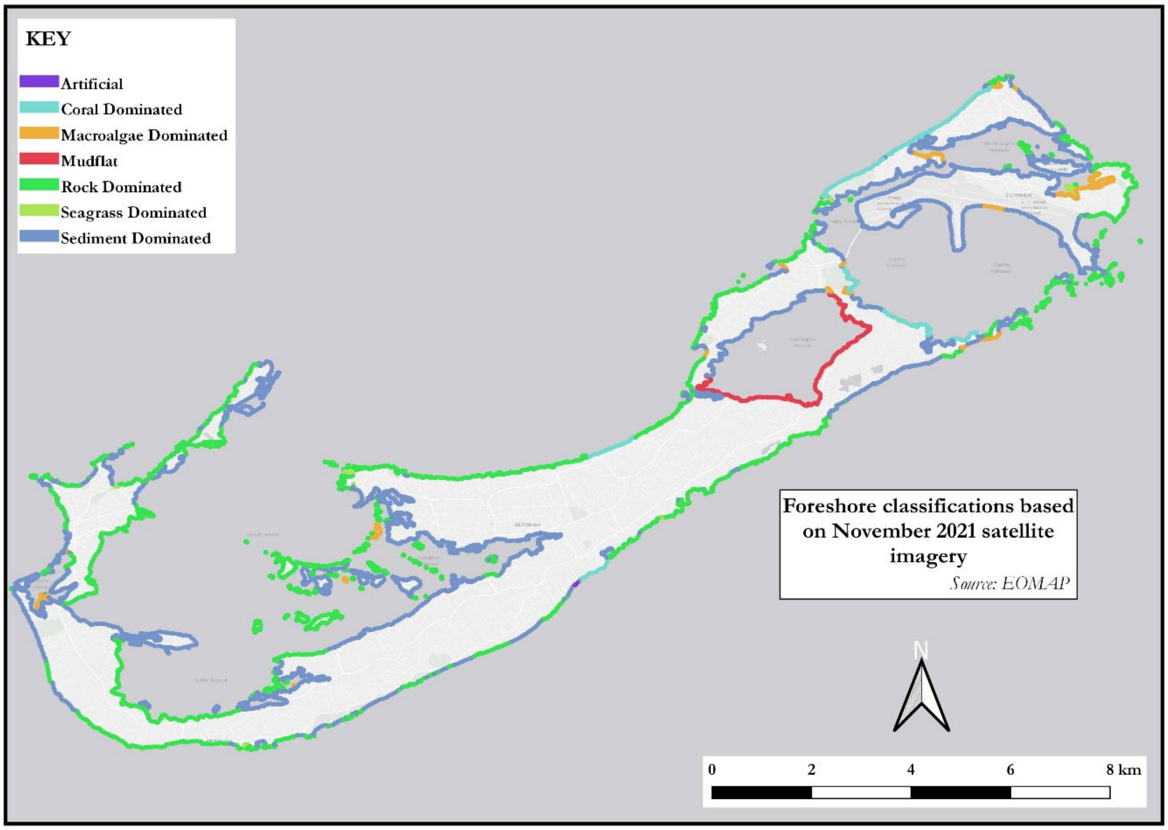


Figure 8.11 Foreshore classifications based on 2021 satellite imagery

9 Historical Cliff and Shoreline Changes

9.1 Coastal Cliffs

Wingate and Talbot (2003) suggest rocky coast comprises more than 90% of the Bermuda coast. Coastal cliffs outcrop at several locations and their erosion and retreat threaten coastal infrastructure. Coastal cliff erosion is broadly attributed to marine and subaerial (including subsurface) erosion mechanisms (Trenhaile, 1987); (Sunamura, 1992). Subaerial mechanisms (e.g., groundwater processes, rilling, slope wash, bioerosion), can act over the entire cliff face, and beneath the surface. In contrast, marine processes (e.g., wave-driven impact pressures and abrasion) act directly only at the cliff base, and only when tides and other water level fluctuations allow waves to reach the cliff (Young A. P., 2016). While marine and subaerial processes drive cliff erosion, geologic conditions dictate cliff resistance and failure mode.

The coastal cliffs of Bermuda are composed primarily of Pleistocene (12,000 – 2.58 million years ago) dune calcarenites (aeolianites) and associated beach calcarenites. Minor outcrops of fossil soils (paleosols) also exist interbedded with the limestones and often separating various formations. The aeolianite deposits include five main formations with the older and harder rocks lower in the rock column. Taller cliffs are primarily located on the eastern and south-eastern areas of the island. The present cliffs formed as the Pleistocene rocks were cut back during the Holocene transgression and subsequent sea level still stand. The cliffs are fronted by a shore platform and sometimes calcareous beaches composed of sand, gravel, and coral fragments. In some areas, beaches are absent and the cliffs are in constant contact with the ocean. Discontinuities such as fracturing within the rock mass create localized relatively weak zones and are subject to accelerated erosion. Bedding plane orientation and local differences in lithology can also influence cliff morphology. The cliffs exhibit karstic weathering and complex morphology (Bird, 2010) including caves, notches (Moses, 2013), (Neumann, 1966), and arches. In some locations, seawalls, revetements, notch fills, and other engineering measures have been installed to prevent erosion and improve slope stability.

The cliffs are exposed to physical, chemical, and biological processes (including boring organisms and root wedging by Casuarina trees). Wave-cliff interaction is influenced by nearshore bathymetry and the fronting beach volume. A protective shelf and shallow reefs help limit wave exposure on the northern coast cliffs, while the southern coast cliffs are exposed to relatively higher wave energy. Smith Warner International Limited (SWI) (2004) describe erosional processes in Bermuda including wave cut notches, large block failures driven by storm events, spalling of small blocks from bioerosion, and horizonal arch formation (mostly on the north shore) likely caused by solution of rock. Bioerosion by boring organism occurs largely in the inland waterways (e.g., Harrington Sound), while root wedging by Casuarina trees occurs island wide.

The evolution of coastal cliffs capable of supporting deep notches (observed in the study area) has been generally conceptualized as a three-stage cycle. In Stage 1, waves erode the cliff base, causing notch development and reducing cliff stability. Eventually, in Stage 2, a slope or block failure occurs, depositing talus material at the cliff base. The talus temporarily protects the cliff from direct wave action until the talus is removed during Stage 3, restoring direct wave attack, and completing the cycle (Young A. P., 2009). The time span of the cycle and persistence of the talus material is unknown.

SWI (2004) found wave-driven processes were the primary driver of erosion in Bermuda, with bioerosion acting as the second most important process, and that the south side of Bermuda was the most vulnerable to elevated wave action and erosion. Comparing historical topographic maps and photos, SWI (2004) also concluded that cliff retreat rates from day-to-day wave action were relatively low and that wave action during storm events was the primary driver of coastal erosion. These observations are consistent with Wingate and Talbot (2003) who suggest the Bermuda coast is primarily shaped by rare catastrophic events, rather than ongoing weathering processes. However, the long term, continuous day-to-day erosional processes such as weathering may help weaken the cliffs and facilitate cliff failures triggered by these high magnitude episodic events. In addition, the day-to-day wave action may promote notch development, particularly when sediment is present and can act as an abrasive (Sunamura, A wave tank experiment on the erosional mechanism at a cliff base, 1982) (Kline, 2014), and thus decrease overall cliff stability (Kogure, 2006) (Young A. P., 2008).

Detailed quantitative assessment of cliff retreat rates in Bermuda are not available. However, several significant cliff failure events have been documented. For example, in 2003 the eye of Hurricane Fabian passed about 80 km to west of Bermuda and generated sustained wind speeds of 190km/h over the land. The hurricane caused extensive damage including seawall failures, structural damage, and coastal erosion including cliff failures (SWI, 2004). SWI (2004) documented numerous cliff failures and noted several wave-driven erosional processes including cliff overstepping from basal erosion, surface stripping exposing softer, more erodible cliff material, and high-pressure water jets extending to high cliff elevations helping to trigger upper cliff failures. Jones (2012) reported two major cliff collapses just east of the Grand Atlantic development and at Southlands Beach prior to the arrival of Tropical Storm Leslie in 2012. Neumann (1966) measured profiles in the steep cliffs of Harrington Sound (a location with limited wave action) and observed notches 4-5m deep and estimated retreat rates of 14mm/year caused by bioerosion.

Airborne LiDAR surveys conducted in 2004 and 2019 provide an opportunity to quantitatively analyze coastal change, including cliff retreat, over this period. The 2004 LiDAR dataset is relatively sparse, with a density of about 0.06 points/m^2 (1 point per 17m^2) and spans about 24km along the southern side of Bermuda and about 2.7km in the cross-shore direction. The dataset includes the offshore bathymetry to depths of about 60m (Figure 9.1). The point density is suitable to generate a 4m resolution elevation model and could be compared to the 2019 LiDAR data (Figure 9.2) to detect large scale cliff failure and retreat on the south site of Bermuda.

Photos and notes from the cliff expert's site visit are included in Appendix B.

Figure 9.1 2004 lidar coverage of Bermuda; orange and reds are land area data coverage (i.e. the points above sea level) and light blues are bathymetric data coverage

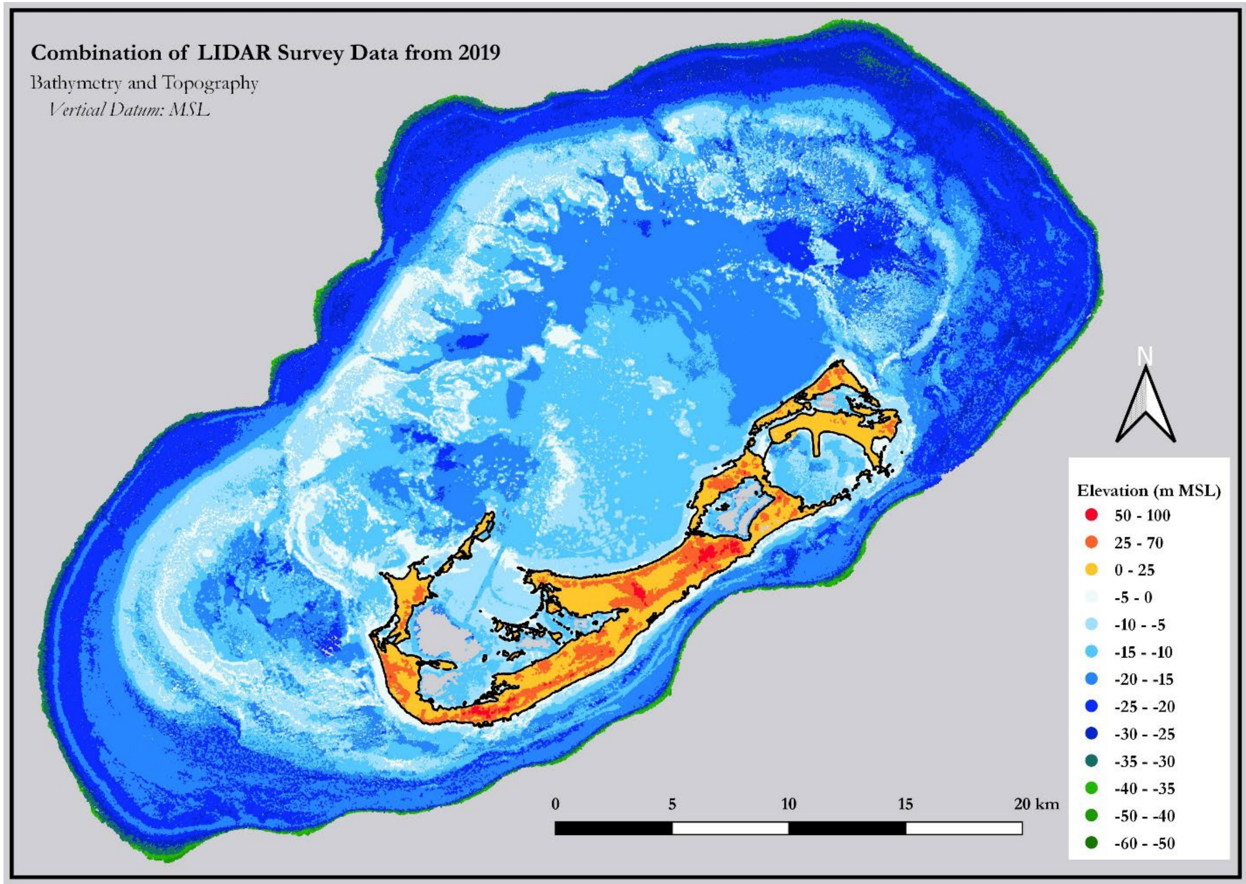


Figure 9.2 2019 LiDAR coverage of Bermuda; orange and reds are land area data coverage (i.e., the points above sea level) and blues / greens are bathymetric data coverage

9.2 Shoreline Changes

The changes along Bermuda's shorelines are due mainly to three types of weathering processes: physical, chemical, and biological. These are described in more detail in Figure 9.3. The overall morphology of the shoreline may be a combination of all three of these processes, but one process sometimes dominates the movement of sediment in an area.

The coastline of Bermuda can be divided into two regions in terms of general exposure to wave action, with the southern coast experiencing higher wave energy than the northern coast. This is mainly due to the absence of a protective shelf along the southern coast, and which is present along the northern coast as an extensive shallow reef covered area.

This means the sand beaches, which are mostly along the southern shore, are affected by incoming wave energy. This was confirmed by SWI in 2004 (Figure 9.4). Littoral transport is the term used to describe the transport of non-cohesive sediments, mainly sand, in the littoral zone along the shoreline primarily due to the action of breaking waves.

Physical Erosion – This refers to the gradually movement of soil/sediments due to applied forces from waves (mainly), wind and gravitational forces, etc. that affect the shoreline. For example, as waves approach a shoreline there is an amount of energy that causes sediment to move from one point to another. This causes a shoreline to reshape to a new equilibrium based on the incident waves. Additionally, gravitational forces may cause the movement of sediment that leads to land slippages as shown in the photo at right.

Biological Erosion - Rocks can be impacted by plants and animals. Roots burrow into the rock's structure, weakening it until it breaks away. Plant roots can find their way into even the tiniest cracks in the rock. The cracks get bigger as the roots grow. Small pieces of rock break away as a result of this. The Casuarina trees located along the cliffs of Bermuda cause significant erosion because of their roots.

Chemical Erosion - Rainwater and seawater can be weakly acidic. Over time, a coastline made up of rocks such as limestone or chalk can become dissolved by the acid in the water. This causes the formation of fissures in the rocks, which weakens them thus making it easier for the other processes.

Figure 9.3 Three main types of weathering processes

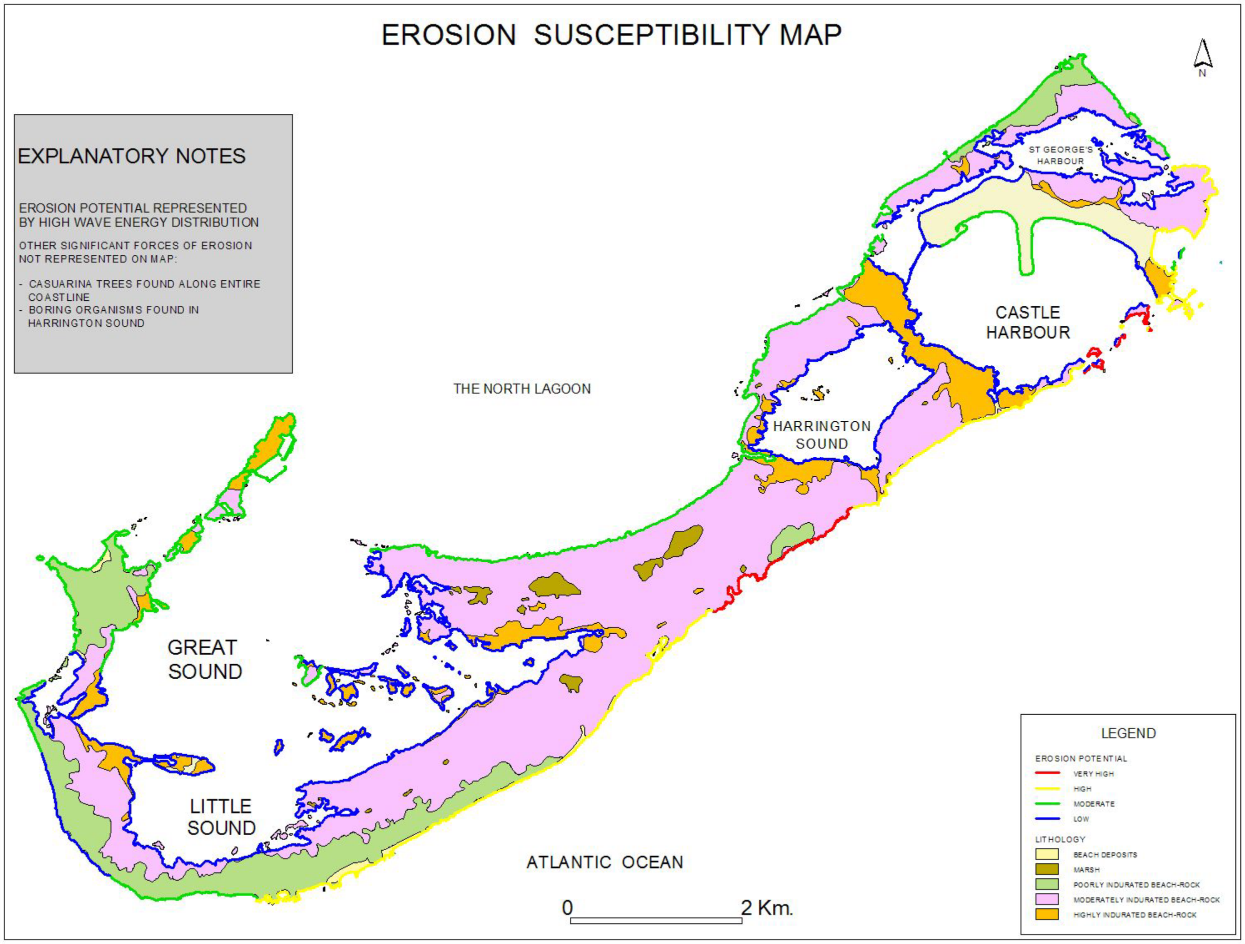


Figure 9.4 Erosion Susceptibility Zones (extracted from the 2004 Coastal Erosion Study)

The shoreline shape is impacted by the nearshore wave climate it is exposed to. A shoreline may accrete when sediment volumes being transported to the beach are larger than those leaving the beach. Conversely, a shoreline may also erode when sediment volumes being transported to the beach are less than those leaving the beach.

The historical movement of a shoreline is a valuable tool in obtaining an initial understanding of the long-term changes of the shoreline. Shoreline morphology can be extracted from historical maps or surveys, or by observing changes along a coastline by examining aerial images such as drones or satellite imagery. For this project, satellite imagery was downloaded from Google Earth Pro. Prior to download we ensured the imagine was clear and free from cloud cover.

The images were then georeferenced using the ESRI software, ArcMap 10.8.1. On completion of georeferencing we traced/digitized the shoreline in each of the images to accurately represent it at the time of the image capture.

Fixed points of interest were selected, and measurements taken from said reference point for each shoreline that was digitized from the satellite imagery. The rate of erosion or accretion was then computed using the formula: sum product (erosion rate and change in time)/sum (change in time).

There are limitations to this method and uncertainties that mostly centre on the nature of the shoreline position at the time a satellite image is captured. Possible errors that could limit the accuracy of the analysis are summarized in the text box below.

Errors that could limit the accuracy of shoreline change analysis

- Seasonal error - Many beaches have seasonal cycles of erosion and accretion. Because high resolution satellite images are limited for areas like the Caribbean and Bermuda, images cannot be selected on seasonal time frames;
- Tidal fluctuation error - The satellite images were obtained without regard to tidal cycles, which can result in inaccuracies on the digitized shoreline;
- Digitizing error - The error associated with digitizing the shoreline;
- Pixel error - The pixel size in orthorectified images is 0.5m, which means anything within 0.5m cannot be resolved;
- Rectification error – Satellite images are corrected, or rectified, to reduce displacements caused by lens distortions, Earth curvature, refraction, camera tilt, and terrain relief using remote sensing software.

This assessment was done for the following sandy shores:

1. Horseshoe Bay (shown in Figure 9.5 and Figure 9.6)
2. Elbow Bay
3. Fort St Catherine
4. John Smith Bay
5. Mid-Ocean Beach
6. Sam Hall Bay
7. Shelly Bay
8. Surfside
9. Warwick Long Bay
10. Grape Bay

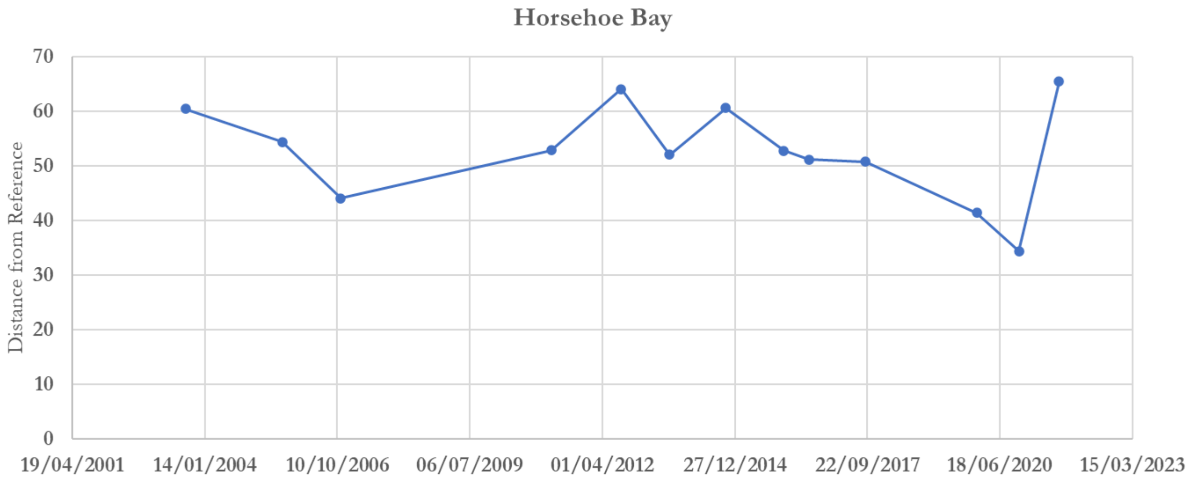


Figure 9.5 Beach width fluctuations over time at Horseshoe Bay

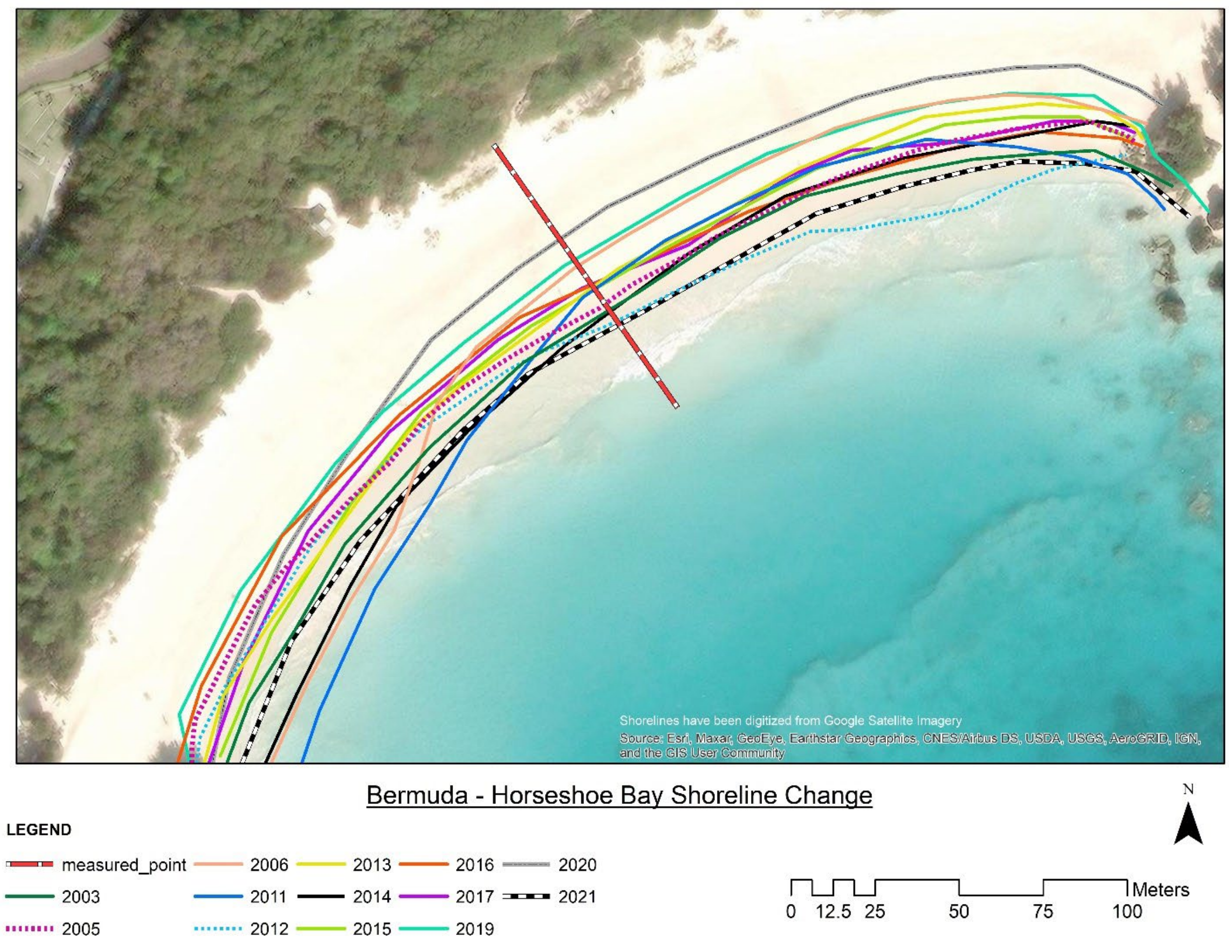


Figure 9.6 Shoreline change from 2003 to 2021 at Horseshoe Bay

Detailed shoreline change maps for the remaining sites are included in Appendix C.

The results indicate that along the south-western coast the shoreline has the potential to have variations in width between 29 and 42m. Along the south-eastern coast the shoreline change is between 16-18m. The sandy beaches at the north see less change with only 9-12m of beach width movement.

There is no clear trend of erosion or accretion when looking at the beaches on a large scale. As Figure 9.7 shows, there is erosion and accretion at all the beaches, both on the south and north shores.

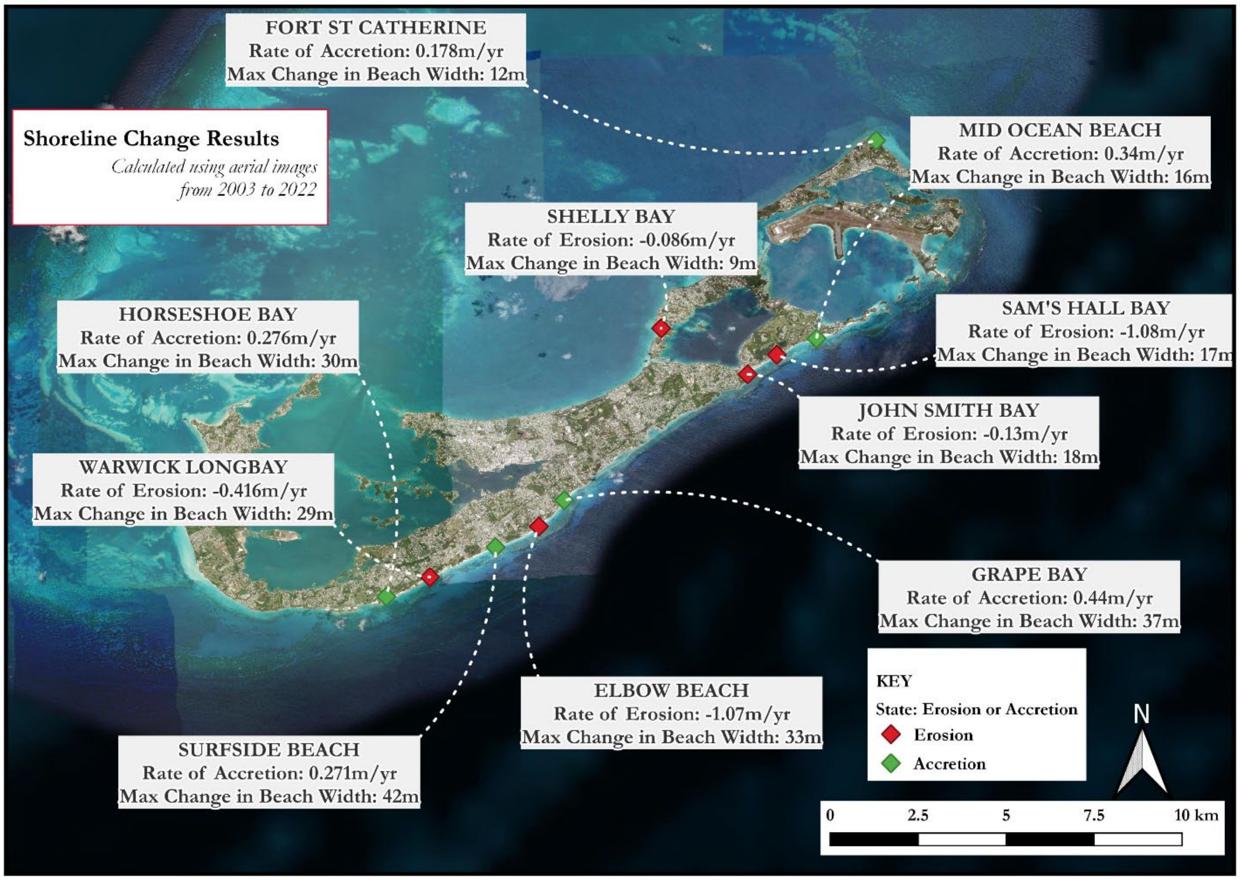


Figure 9.7 Summary for shoreline change assessment

10 Inventory and Condition of Critical Assets

Sixteen locations and/or infrastructure components were identified as being in critical areas and/or of key significance from a perspective of risk/vulnerability. These locations were selected based on several criteria, including:

- Historical significance;
- Importance to the transportation network (i.e., roads, bridges, ferry terminals);
- Importance to water and fuel distribution network;
- Importance to economic wellbeing; and
- Importance to disaster response efforts

Structures were classified according to their function (structure class), the construction material and (approximate) dimensions were determined where possible, and their condition was assessed according to the rating system provided in "The Condition Assessment Manual" (UK Environment Agency, 2012). For visual inspection methods, the manual establishes a grade of condition ranging from "Very Good" to "Very Poor", which was used to the assess the coastal structure inventory. A graphic describing these ratings is shown below.

Grade	Rating	Description
1	Very Good	Cosmetic defects that will have no impact on performance
2	Good	Minor defects that will not reduce the overall performance of the asset
3	Fair	Defects that could reduce the performance of the asset
4	Poor	Defects that would significantly reduce the performance of the asset. Further investigation needed.
5	Very Poor	Severe defects resulting in complete performance failure.

Visual inspections were made using ortho-rectified images and oblique photographs. This information was augmented using some ground-level photos and available Google-Earth imagery. A detailed inspection of the underwater components, foundations and other features not visible from the imagery was not undertaken and this limits the extent of the assessment.

For each structure that was assessed, a geo-referenced identification was established that has been entered into the geo-database. A comments section is provided that describes the structure condition and any defects that were noted from the visual inspection. A baseline photograph is included that shows the structure. The full detailed inventory is attached as Appendix D. The structures that were assessed are described briefly below.

Dockyard Cruise ship Pier and King's Wharf

- The cruise ship facility includes docks on steel sheet piling, with mooring dolphins. Portions also include historical cut-stone blocks.
- A small drydock/ramp exists for hauling Marine and Ports ferries. There is a small storage area inland.
- Along the docking area there are several warehouses and a cement silo. Plans include relocation of various activities to divide the area into a tourism and light industrial area. This may involve moving the Marine and Ports workshop into the warehouse area.
- At the southern end a landfill area has been created using sheet piling to contain spoil dredged from the channels. This area was already protected by a breakwater. Although not overtopped by recent hurricanes, it may indeed be below design water levels.
- On the northwest coast there is a dump that has been raised with fill. Shoreline erosion is evident. Conversion of these lands from a dump to residential or recreational will require shoreline stabilization.
- The mini-golf lands appear to be built on landfill and require shoreline stabilization. In its current usage upgrades to the shore protection would not be cost effective.

Figure 10.1 Dockyard Cruise ship Pier and King's Wharf

Pembroke Canal, Hamilton

- The visit was conducted at 9:30am, approximately 1 hour after high tide. Water level in the canal is at the level of the road, with some pooling of water onto the road in lower elevations.
- Sparse mangroves exist at the downstream side of the canal leading to the bay.

Figure 10.2 Pembroke Canal, Hamilton

Flatts Bridge (Road Network)

The Flatts Bridge connects the North Shore Road to the airport and towns like St Georges. Though there are alternative routes, this is the main route used by drivers. The bridge goes over a noted tidal inlet with an aggressive tidal flow. There is evidence of bioerosion undercutting the banks, especially on the bay side.

Figure 10.3 Flatts Bridge

Causeway (Road Network)

The causeway connects the mainland of Bermuda to the airport and Banjo Island and is considered vital infrastructure for medical emergencies and air-related evacuations. It is approximately 150 years old and failed in parts during the last major hurricane. During subsequent repairs, a layby was built that included protection using gabion baskets. Due to its low-lying nature and fragile condition, the causeway is closed during severe storm events such as the passage of tropical storms. A proposal to replace the causeway with a pier structure was considered in 2010.

Figure 10.4 Causeway

Tyne's Bay Waste to Energy Plant (Solid Waste Disposal) and Tyne's Bay Seawater Reverse Osmosis Plant

The infrastructure associated with the waste to energy plant and the desalination plant appears to be quite elevated.

Figure 10.5 Desalination plant at Tyne's Bay

Sol Fuel Terminal (Fuel Supply)

The fuel terminal appeared to be in good working condition. The infrastructure at the shoreline showed signs of corrosion from wave action.

Figure 10.6 Sol Fuel Jetty

Railway Trail

Sections of the railway trail were inspected. Some areas showed signs of erosion, and others are exposed to potential wave damage. It was not clear where the Sol pipeline is located along all segments (awaiting mapping from Sol). At various points the trail is exposed to coastal erosion and wave damage. Periodic inspections by Sol have revealed pipeline corrosion, which leads to shoreline reinforcement and/or pipeline replacement.

Figure 10.7 Railway Trail

North Shore Residences

The condition along the North Shore varies. Some areas are on high ground with residences set back from the shoreline, while other areas are low-lying and require protection from the sea with seawalls. Some residences on the North Shore were subject to wave action on their protective seawalls. Other buildings are built directly on the shoreline and fitted with boat docks. However, with a changing wave climate and rising sea levels, the viability of these dwellings will be compromised.

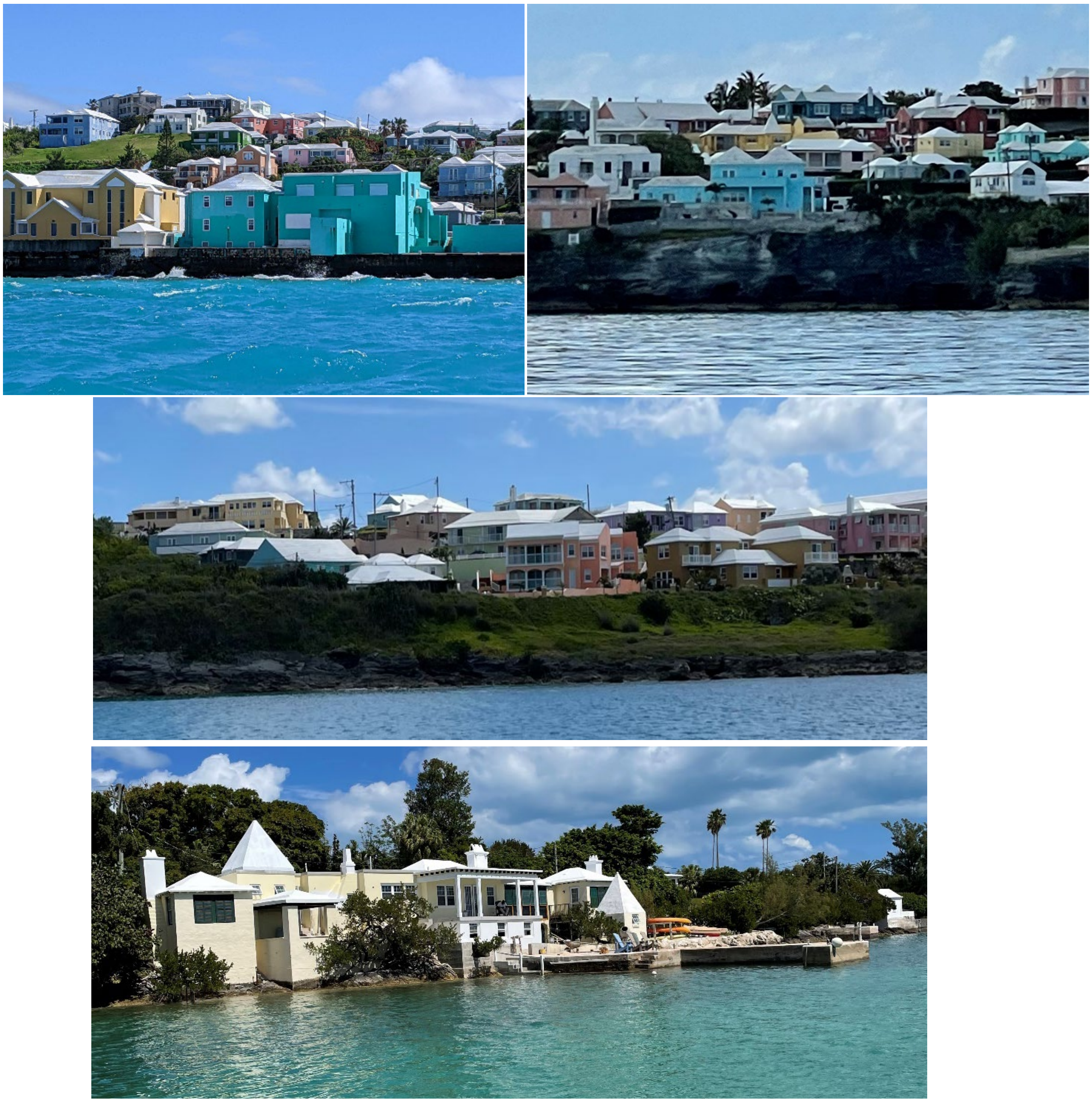


Figure 10.8 Residences along the North Shore

South Shore Residences and Businesses (Noted Coastal Cliff Failures)

The south coast shows the impact of a more aggressive wave climate. Several coastal cliff failures were seen from afar; some appeared to be very close to residences and infrastructure.

Figure 10.9 South Shore cliff failure

St David's Lighthouse

A large coastal cliff failure occurred close to the lighthouse on the eastern end of St David's Island just east of the end of the airport runway.

Figure 10.10 Cliff failure

Fort St Catherine (Historical Significance)

There was some erosion of the cliffs at the historic Fort St Catherine. A recently constructed St. Regis Hotel sits just to the south of these eroded walls at the back of a sandy beach.

Figure 10.11 Fort St Catherine's eroding seawalls (top) and the Residences at The St Regis (bottom)

Dock at Bermuda Land Development Company

The docks across from St. George's are presently used for light industry. It is a potential site for relocation of the main cargo port, which would likely require significant infrastructure. The existing marina appears unused. A small boat ramp is reportedly used occasionally by the boatyard to launch small vessels. The bridge is derelict. Seagrass cages have been installed to protect the blades from foraging turtles.

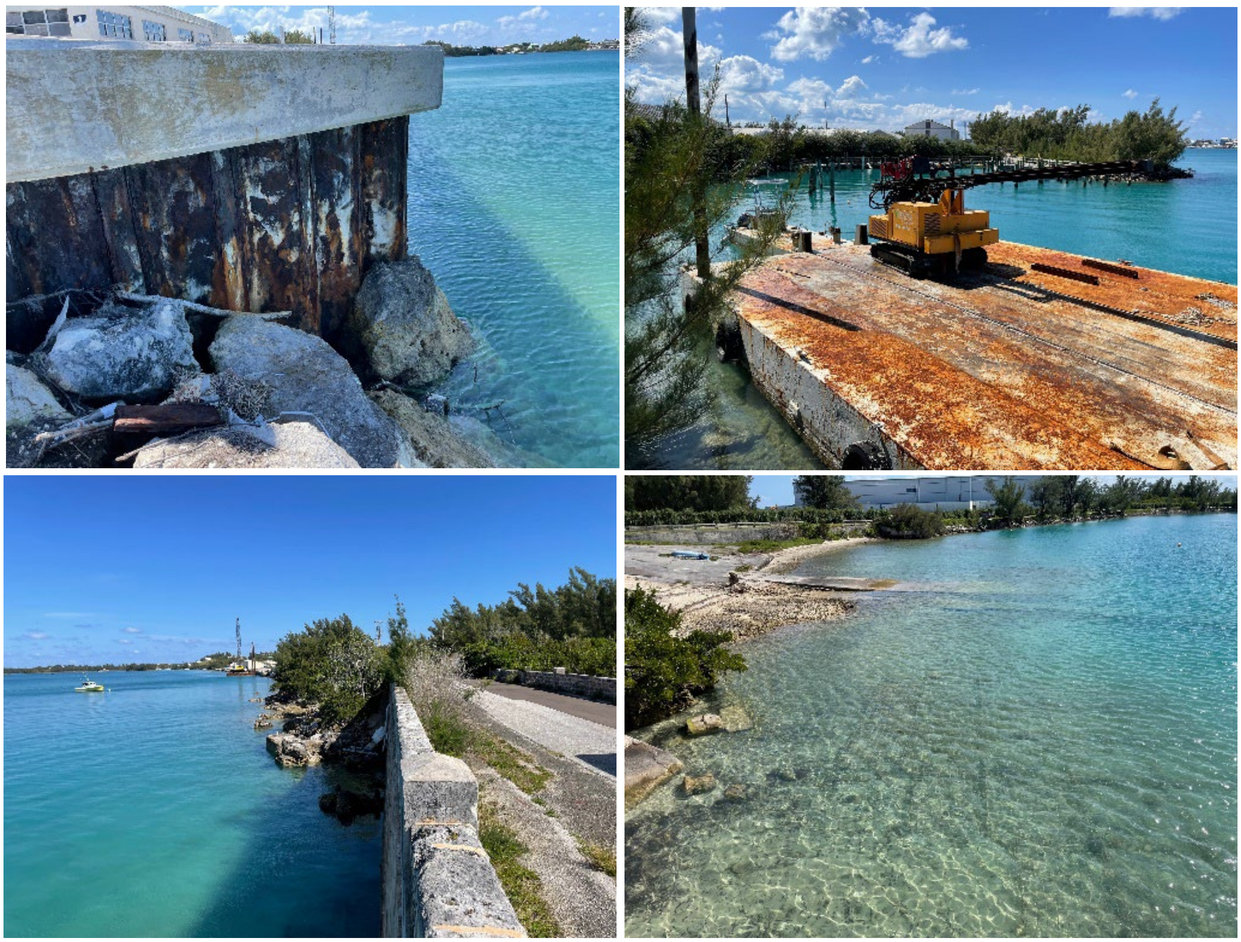


Figure 10.12 Observations at the BLDC, St George's

Town of St George

The town appears to be low-lying with streets and seawalls that are overtopped and flooded during storms. It is evident that drainage issues exacerbate this problem, again likely due to the low-lying nature of the area.

Figure 10.13 Town of St George

Front Street (Port & Ferry Terminal)

The Ferry terminal at Front Street appears to be too low for the changes in sea level and the fuel storage facility needs to be relocated. There is no storage for ferries. With more frequent extreme wave conditions expected, the current facility will require more storage.

Figure 10.14 Ferry terminal

Somerset Bridge

The somerset bridge is the only connection to Sandys Parish. It is known as the smallest drawbridge on the island. The area is affected by fast currents as the water squeezes through the small area. Rock revetments were used for further protection from currents and boat loads.

Figure 10.15 Somerset bridge (top) and rock revetment adjacent to bridge (bottom)

11 Existing & Collected MetOcean Data

This section presents the data collected and reviewed since the start of the study. It should be noted that the sections below are not comprehensive as there are still data being collected.

11.1 Wind

Wind data from the Bermuda Weather Service is available from 2006 to 2022. On average the wind speeds are approximately 9.7m/s at the L.F. Wade International Airport. Additionally, the mean direction is from the Southwest. However, there is a notable portion of the wind energy that comes from the north-east. This is indicative of a seasonal variation of the wind patterns in the area. This was confirmed by a longer study by Bates (2007) that looked at wind patterns from 1984 to 2006 (Figure 11.1).

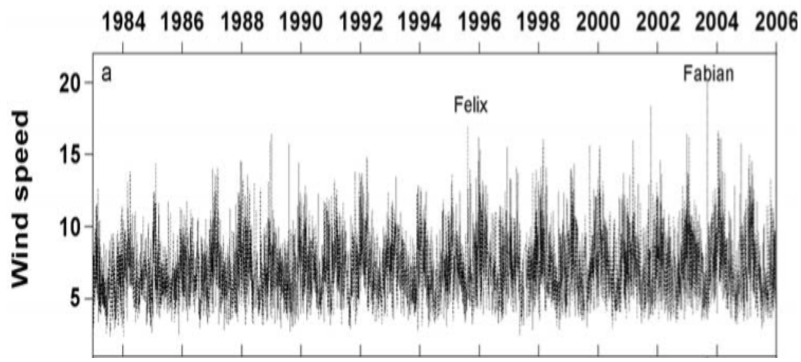


Figure 11.1 Modified from Bates 2007 showing wind speeds in m/s from the NCEP mode

Data review (weather spark.com) indicates that the highest average wind speeds at the L.F. Wade International Airport occur in February, and the lowest in September. The following Figure 11.2 shows that the windiest period is from 21 October – 18 April, with winds higher than 6.6m/s. The calmest period of the year is between 18 April and 21 October, with August showing as having the lowest winds (4.8m/s).

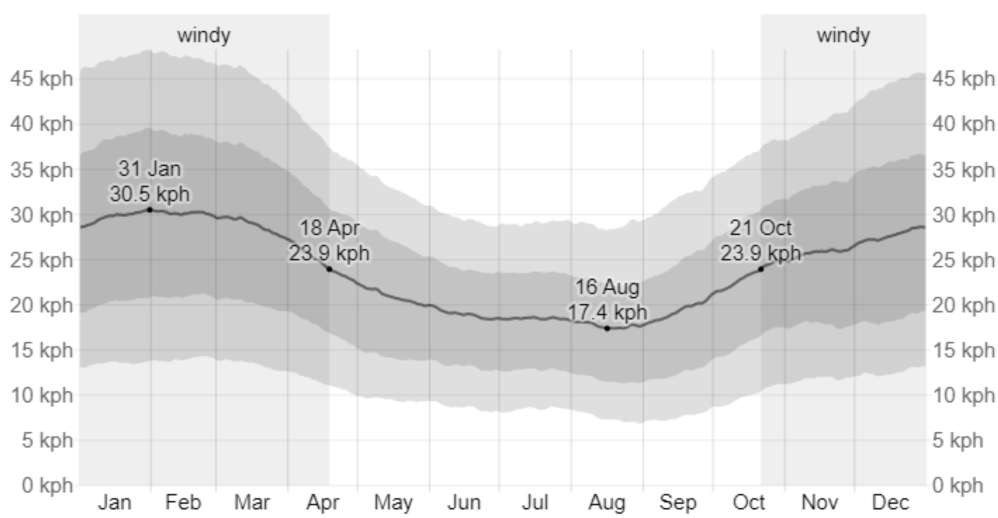


Figure 11.2 Hourly average wind speeds at L.F. Wade International Airport (10m above ground)

With respect to wind direction, the following Figure 11.3 (weather spark.com) shows that winds out of the south-to-west sector occur from January through August, with frequencies typically between 60% - 80% of the time. During the months of September to November, winds are predominantly from the east-to-north sector, with frequencies of typically 0% - 59% of the time.

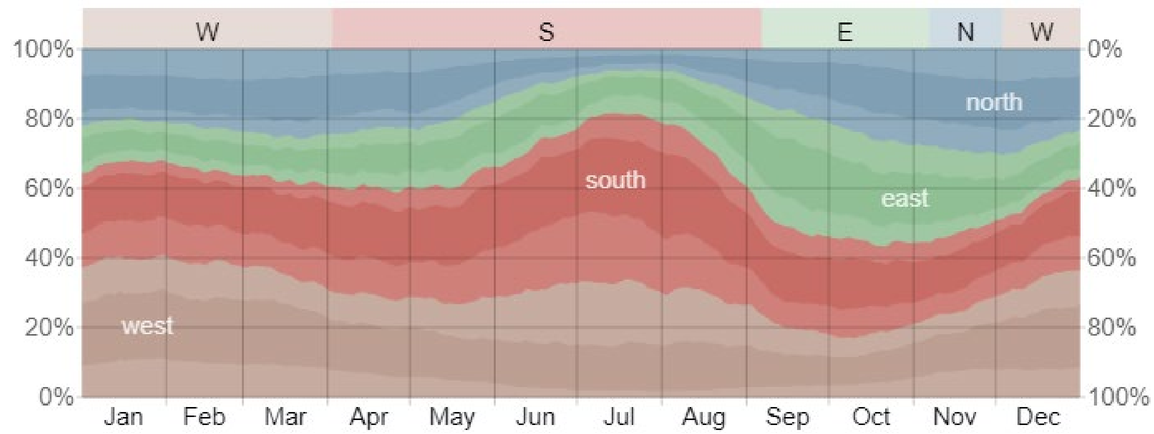


Figure 11.3 Hourly average wind directions at L.F. Wade International Airport (10m above ground)

11.2 Water Levels and Tides

Bermuda experiences semi-diurnal tides, with a mean range of ~0.76 m and a maximum range of ~1.00m [Coates et al., (2013), and from measurements in 2022]. Tide heights are infrequently affected by the slow passage of mesoscale eddies that can elevate or attenuate tidal heights by up to 25cm. Harrington Sound, an enclosed body of water with a single, restricted, surface entrance, has incomplete tidal loading and unloading, resulting in a reduced tidal range of about 0.20–0.25m and delays in maximum tide levels of about 30 minutes.

Data obtained from the National Oceanic and Atmospheric Administration (NOAA) indicates an almost 1m range of sea levels (Figure 11.4), which concurs with field measurements collected under this 2022 project. Analysis of the long-term water level data indicates a trend of rising Mean Sea Level of approximately 2.2 mm/year (Figure 11.5).

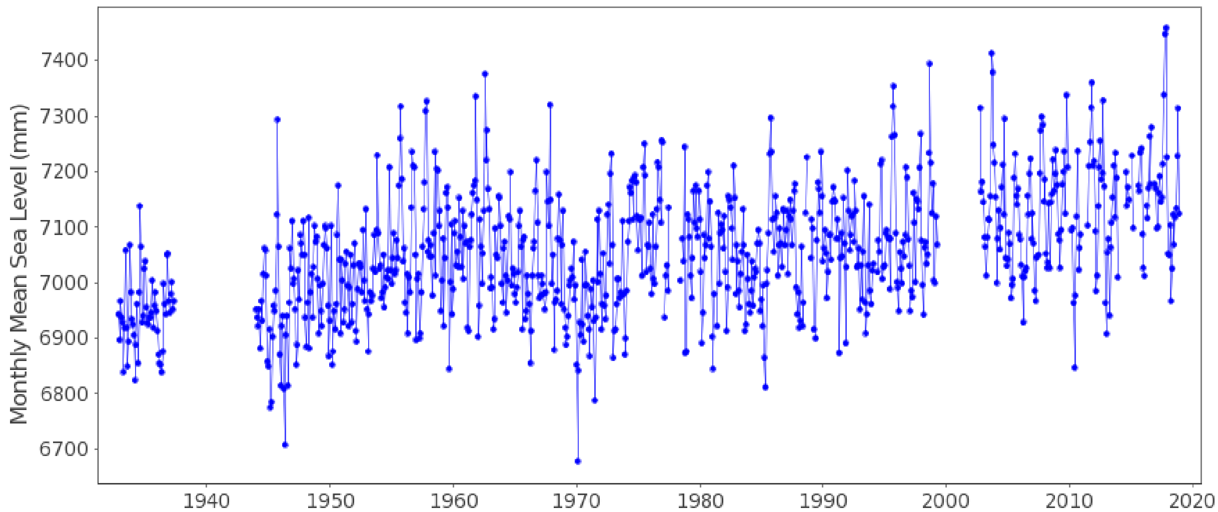


Figure 11.4 Monthly Sea levels: Data from NOAA tide gauge and sourced from https://www.psmsl.org/data/obtaining/stations/368.php (St George's Station)

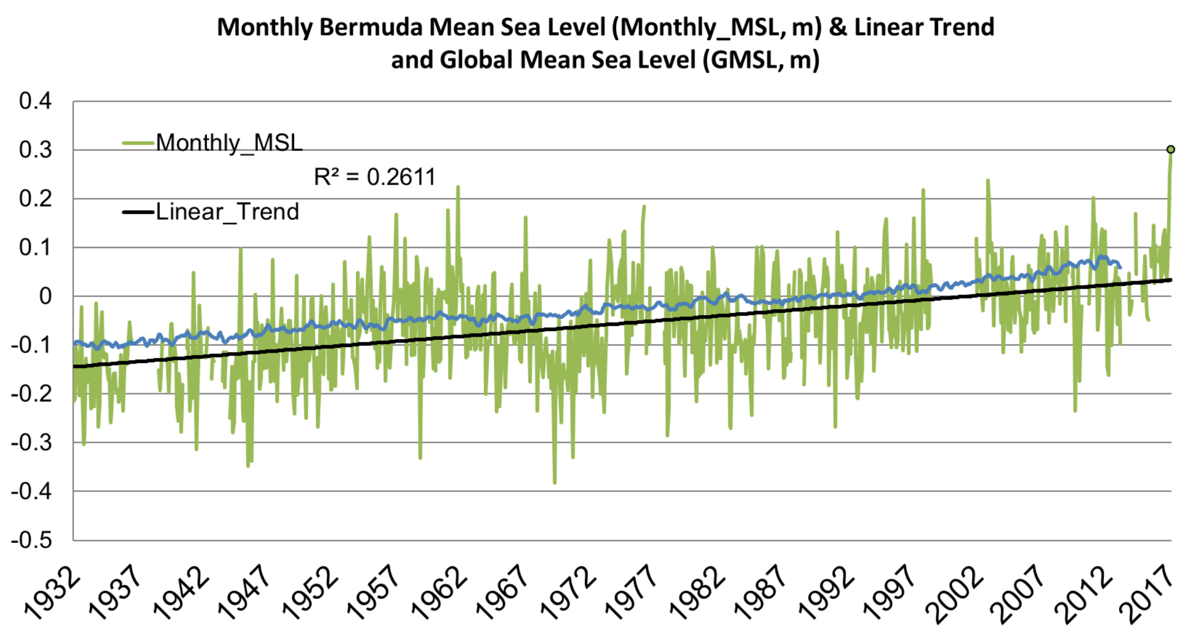


Figure 11.5 Sea level changes over 85 years (sourced from NOAA, based on tide gauge measurements: https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=2695540)

11.3 Waves

The operational wave climate at the project site is characterized by (a) day-to-day, relatively calm conditions; and (b) seasonal winter swells (December to May). The day-to-day conditions are primarily generated by the north-east Trade Winds. The swells, however, are generated by north Atlantic cold fronts and these waves approach the site from the north and north-west sectors.

In the previous study in 2004, wave conditions were assessed using data from Oceanweather Inc.'s AES40 database. This database was a project for the Atmospheric Environment Service (now Meteorological Service of Canada) which produced the first 40-year wind and wave hindcast of the North Atlantic. Figure 11.6 shows the wave climate offshore Bermuda from 1998 to 2003.

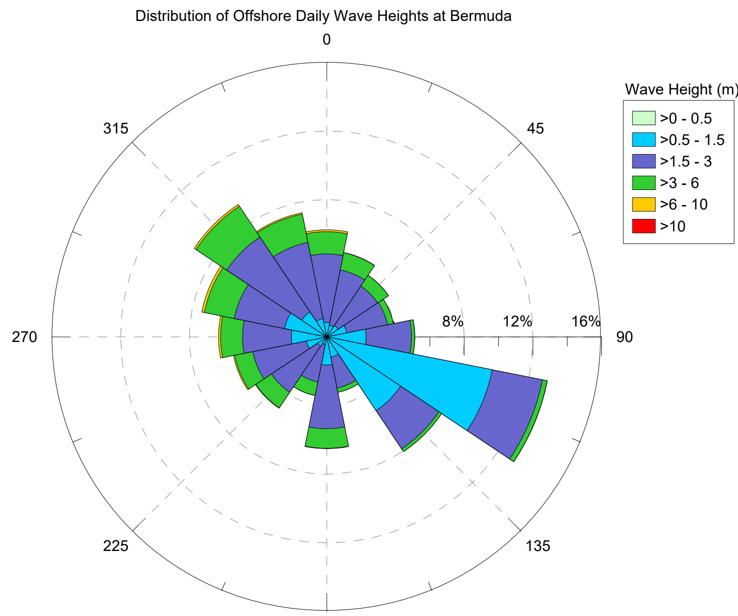


Figure 11.6 Directional Distribution of AES-40 Wave Database

Wave direction is defined as **the direction that waves are coming from** (which is the same as the standard definition of wind direction). Each segment also shows the range of wave heights. For example, the most common wave condition appears to be waves between 0.5 and 1.5m in height coming from the east-south-east, which account for approximately 10% of the database. By contrast the sectors from west to north appear to occur less frequently but consist of larger wave heights (between 6 and 10m in height).

From an examination of the wave database at that time, a seasonal variation in the wave conditions was found. It is quite clear that there is relative calm during the summer months when wave heights in deep water are typically less than 2.0m. This correlates well with the wind data presented earlier. By contrast, during the remainder of the year, and particularly in the winter months, wave heights offshore are between 6-8m.

Based on this information, two seasons were derived, which appear to characterize the seasonality in wave conditions. The period May-September appears to be dominated by lower waves from the east-south-east, whereas larger waves from the north-west appear to dominate during the remaining time (October to April).

The final plot of these day-to-day wave simulations (Figure 11.7) has been derived from the individual direction plots and each grid point represents the maximum wave height from all eight direction sectors. When looked at in this light, there was not a significant difference in wave height values between the north and south shorelines, however, the inshore areas, such as Great Sound, Harrington Sound and Castle Harbour are well sheltered and experience smaller wave heights than the outer shorelines.

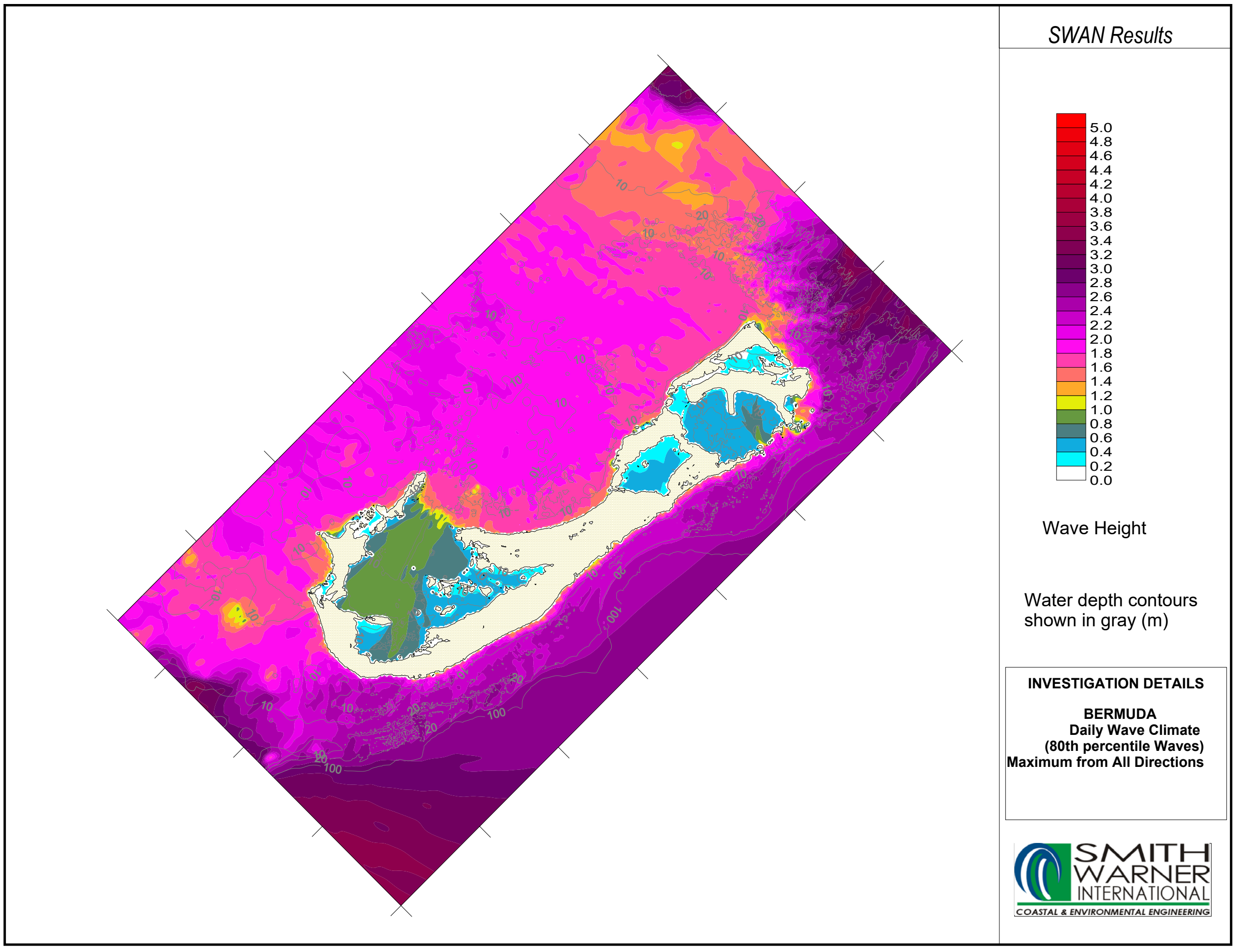


Figure 11.7 SWAN Modelling – maximum daily wave heights

For this study, the data used to assess the operational wave climate of Bermuda was procured from the ERA 5 global reanalysis model. Figure 11.8 shows a wave rose plot (wave heights and frequency of occurrence) at each of one of four nodes that bracket the offshore area of Bermuda. The European Centre for Medium-Range Weather Forecasts (ECMWF) produced the ERA5 reanalysis which, once completed, will embody a detailed record of the global atmosphere, land surface and ocean waves from 1950 onwards. Currently, data from 1979 to 2020 is available for use. ECMWF in 2016, implemented significant resolution upgrades and introduced methodology improvements to facilitate high-resolution forecasts (HRES). HRES is now performed using a transform grid with a nominal grid point spacing of 9 kilometres (0.08 degrees) and is carried out with IFS (Integrated Forecast System) model cycle CY41r2. ERA5 thus benefits from a decade of developments in model physics, core dynamics and data assimilation. In addition to a significantly enhanced horizontal resolution, ERA5 has hourly output throughout, which is an improvement on most wave data publicly available.

The wave rose shown in Figure 11.6 was developed from nodal information developed at 64ºW 33ºN. The wave rose may therefore be compared with the ERA5 nodes shown in Figure 11.8. Such a comparison confirms the presence of frequent, but less energetic, waves from the south-east, as well as less frequent, but more energetic waves from the west to north-west sector.

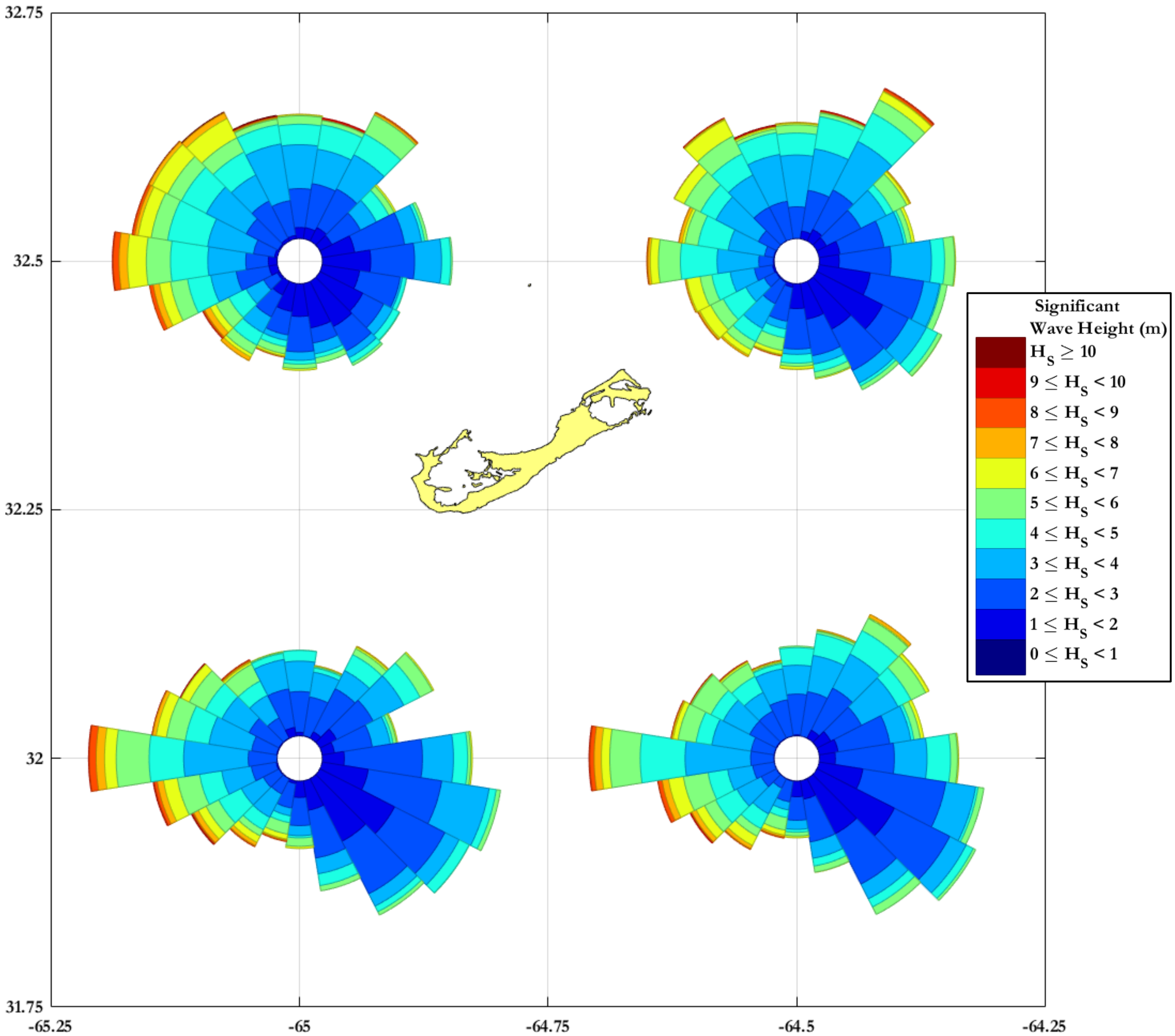


Figure 11.8 Distribution of Wave Heights from the ERA5 Reanalysis (1979 to 2021)

11.4 Extreme Winds and Storm Surge

11.4.1 Hurricanes

The Caribbean and, by extension, the North Atlantic Ocean are so frequently attacked by hurricanes and tropical storms that there is an established "hurricane season" that starts in June and ends in November each year. This phenomenon applies great strain to countries within the region because they are all predominantly low-lying islands with most of their populations and development residing in coastal regions. Dramatic and abrupt changes to coastlines often occur because of these storms.

Anecdotal information about storms that have affected Bermuda has been archived by the Bermuda Weather Service (BWS)[4]. The BWS document refers to wind speeds and gusts with reported conditions at the airport, St. George's and other locations. The points of reference for how and where sustained winds or gust measurements were taken do not appear to be consistent.

Table 11-1 shows the most intense storms that have passed within a 300km radius of Bermuda extracted from NOAA's National Hurricane Center (NHC) Hurricane Database (HURDAT). The storms are ranked by intensity based on only the storm data occurring within the 300km radius around Bermuda. It presents the maximum wind speeds attained (and thereby intensities) within that search radius only. The table also includes estimates of distance of the storms from Bermuda.

The NHC measurements are taken by dropwindsondes that are dropped into strategic points in a storm's centre from "hurricane hunter" aircrafts. The instruments continuously transmit critical weather data back to the plane, including pressure, humidity, temperature, wind direction and wind speed. This data is relayed from the plane to a satellite and then to NHC where hurricane specialists put it together to assess the cyclone's strength, motion, and size.

It should be noted that the BWS document does not include some of the storms listed in the NHC's HURDAT and the HURDAT doesn't include some of the storms listed in the BWS document. The discrepancies between the NHC and BWS information are likely because of the different methods and locations of measurement used by each agency. The storms listed in Table 11-1 are those storms that fall within a 300km radius of the site based solely on the NOAA NHC database. Figure 11.9 shows the paths of the worst five storms that have passed within a 300km of Bermuda since 2003.

Subtropical cyclones also affect the Bermuda coasts. Subtropical storms can be a forecasting problem for locations such as Bermuda because of the potentially rapid cyclogenesis of the storm close to landfall. This increases vulnerability as there is limited time to prepare.

Historical hurricane information, dating from 1850 to 2020, procured from the NHC database, was analysed using HurWave (an in-house computer program). All hurricanes passing within a 300 km radius of Bermuda were extracted from the database. The results show that since 1850 (over the past 169 years), 149 hurricanes and tropical storms have passed within this distance (Table 11-2). The total number of storms can be broken down according to the categories described by the Saffir Simpson scale. The numbers show that the study area was more frequently hit by tropical storms (76) and was affected by strong hurricanes (category three and higher) less frequently (23). Figure 11.10 shows the temporal distribution of storms and suggests their frequency has increased from about 1930 to the present.

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[4] http://weather.bm/tropicalArchiveDocuments/Summary%20And%20Miscellaneous/Tropical%20Climatology%20-%20Timeline%20_updated_17Aug2021.pdf

Table 11-1 20 most intense hurricanes within 300km radius of Bermuda based on NHC Hurricane Database (in descending order of severity)

Storm Name	Maximum Recorded Within 300km Search Radius			Data Recorded Closest to the point of Interest	
	Max Wind Speed (knots)	Category	Distance from Point (km)	Wind Closest Point (knots)	Distance Of Closest Point (km)
Nicole 2016	120	4	234	105	5
Ophelia 2011	120	4	218	115	202
Not Named 1939	117	4	240	115	71
Not Named 1948	115	4	225	110	98
Frances 1961	115	4	164	115	158
Not Named 1930	110	3	211	107	114
Not Named 1880	110	3	240	110	200
Not Named 1933	110	3	234	110	204
Not Named 1949	110	3	237	110	112
Humberto 2019	110	3	139	110	102
Gonzalo 2014	107	3	248	95	5
Not Named 1870	105	3	191	100	45
Not Named 1947	105	3	232	100	99
Not Named 1916	105	3	214	102	160
Fabian 2003	105	3	250	102	45
Not Named 1899	105	3	187	105	18
Not Named 1906	105	3	207	105	82
Not Named 1915	105	3	214	105	37
Not Named 1917	105	3	243	105	192
Not Named 1926	105	3	138	105	11
Erin 2001	105	3	183	105	171

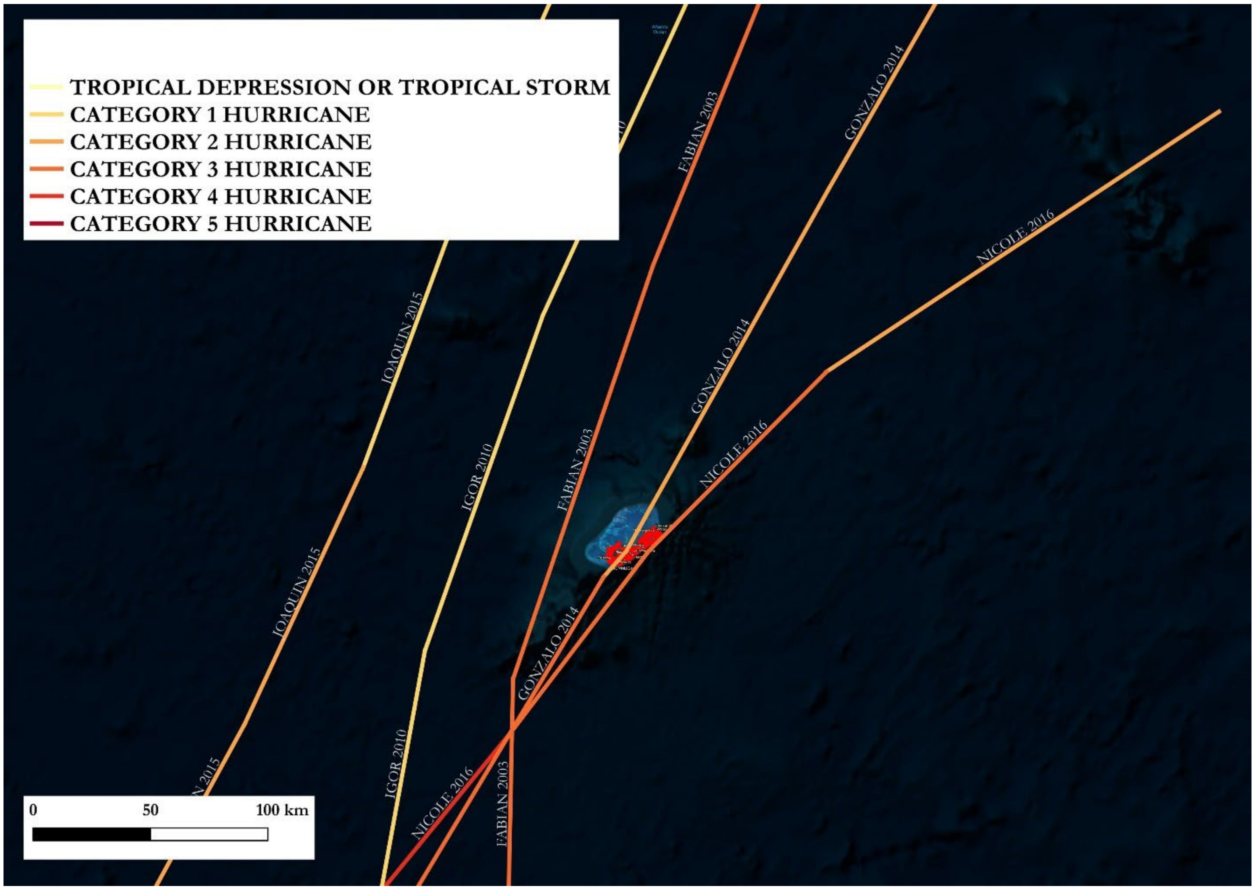


Figure 11.9 Worst five storms since 2003 passing withing 300km of Bermuda

Table 11-2 Distribution of storm events according to the Saffir Simpson Scale

Cyclone Category	Wind Speed		Number of Events
	(m/s)	(km/h)	
Tropical Storm	18 – 33	64 – 118	76
1	33 – 43	119 – 154	19
2	44 – 49	155 – 178	31
3	50 – 58	179 – 210	17
4	59 – 70	211 – 250	6
5	> 70	> 250	0
		Total:	**149**

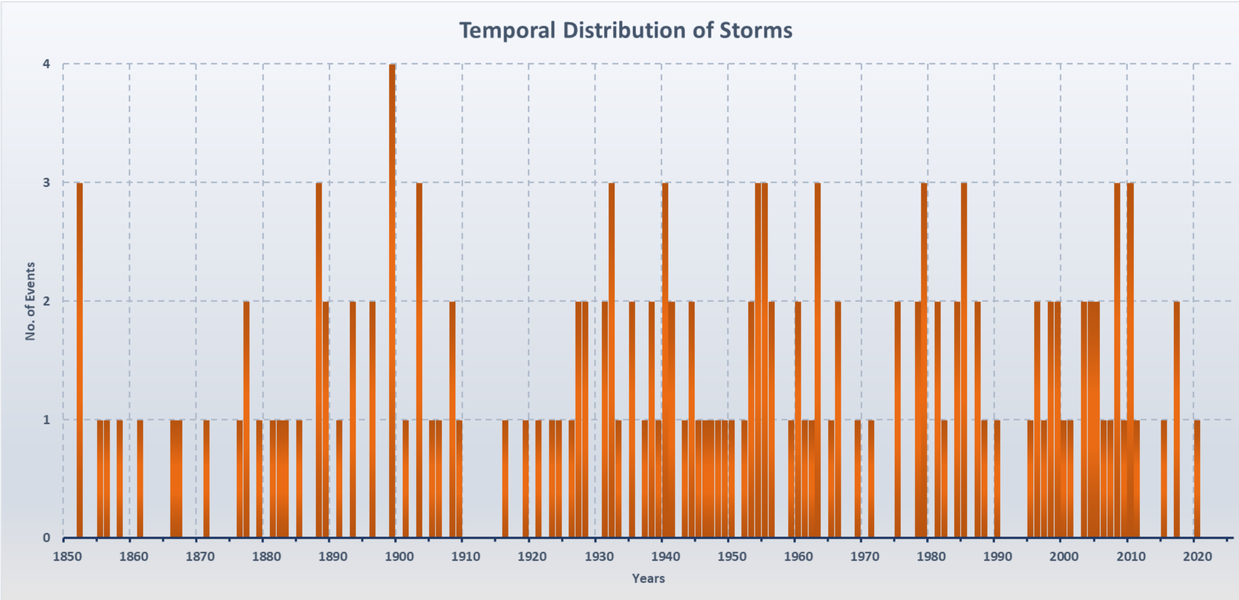


Figure 11.10 Temporal distribution of storms passing near Bermuda (300 km radius) since 1850

Observations of wind speed profiles in hurricanes have been made by numerous researchers in an attempt to improve the prediction capabilities of models that are used to simulate the distribution of hurricane wind patterns. One of the more promising models (Willoughby et al., 2006) uses two different distributions to predict: (a) the steep ascent in wind speeds from the storm centre to the eye wall; and (b) the more gradual fall off of wind speeds moving away from the zone of maximum winds. That predictive model was correlated with Hurricane Hunter measurements from 493 hurricanes between 1977 and 2000, in the Atlantic and Eastern Pacific basins. The model predictions showed very good correlation with the average wind speed values of the measured storms.

The model and measurement comparisons indicate that the typical distance from the centre of the cyclone to the zone of maximum winds is 20km – 30km. The typical distance from the centre of the cyclone to the zone of gale force winds (approximately 18m/sec) is approximately 140-160km. We typically set our modelling zone radius of inclusion around a location of interest (for hurricanes) at 300km. This ensures that we include the area of maximum winds, and that our area of consideration is not so narrow as to exclude storms that could have an impact. Further, from our observation of Hurricane Lenny in 1999 ("Wrong-Way-Lenny"), which originated in the Western Caribbean and exited the Caribbean basin in the vicinity of Antigua & Barbuda, we are aware that swells from that event were able to wreak havoc on shorelines as distant as 500km away (in St Lucia). We therefore attempt to strike a balance by setting a 300km radius of interest, although in some instances we may increase this to 400km in order to obtain a larger number of storms on which to perform an extremal analysis.

Finally, there is some evidence (Holland, 1980) that more intense storms (with larger Vmax values) are typically more tightly packed. It is therefore unusual to see a very intense and very wide storm occurring in the North Atlantic basin.

11.4.2 Mesoscale Eddies

Mesoscale eddies are common features of the world's oceans, with a typical scale of about 100km and lifespan lasting between tens and hundreds of days (Shcherbina, 2010). These eddies can rotate anti-clockwise or clockwise and the gradients associated with their density fields drive ocean currents in much the same way that high- and low-pressure systems in the atmosphere force the wind field. Bermuda is affected by mesoscale eddies that result in both increased and lowered water levels. As shown in Figure 11.11 these eddies result in water level conditions that can cause worse flooding than some tropical storms. Conversely, these eddies can also cause unusually low tides, as occurred over several months in 2010.

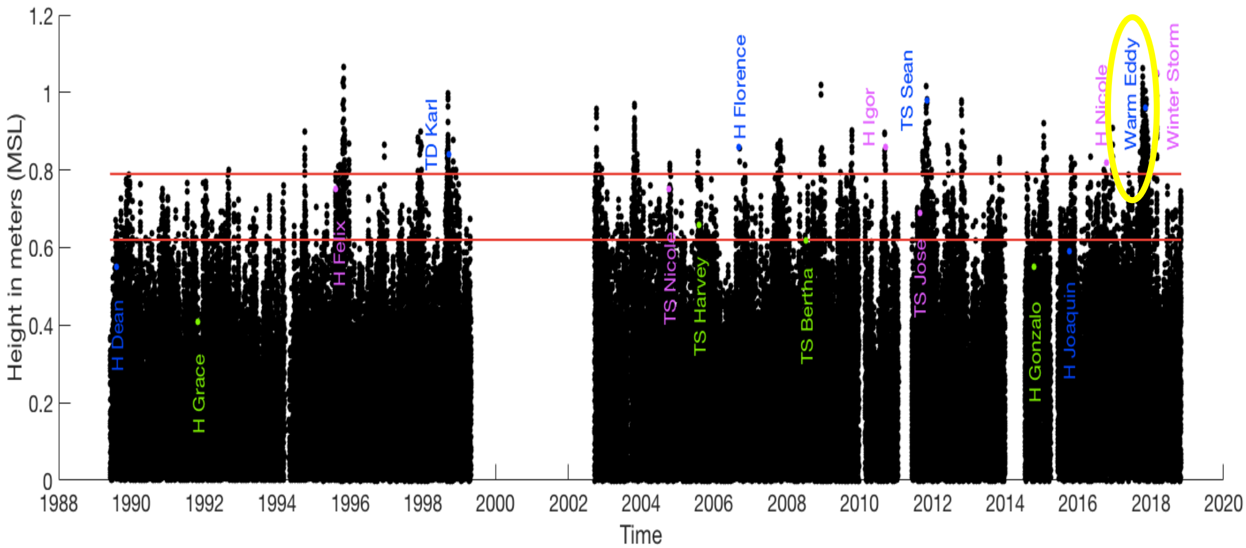


Figure 11.11 Extreme water level recorded at the St George's Station (*Source: Bermuda Institute of Ocean Sciences)*

11.5 Collected Oceanographic Data

11.5.1 Instruments Used

Currents were measured under this project using two Teledyne/RDI Acoustic Doppler Current Profilers (ADCP's). Instruments were deployed in varying water depths so that an overall understanding of the wave-induced currents could be achieved. A description of each deployment and the instruments used is presented below.

Two Teledyne/RDI Acoustic Doppler Current Profilers (ADCP) were deployed in the study area. An ADCP operates using acoustic signals and determines the current speed and direction by detecting the Doppler shift of reflected acoustic signals, which bounce off tiny particles moving within the water. Using multiple acoustic "pings", it is possible to divide the water column into distinct layers and simultaneously determine the speed and direction of the water movement within each layer as shown in Figure 11.12.

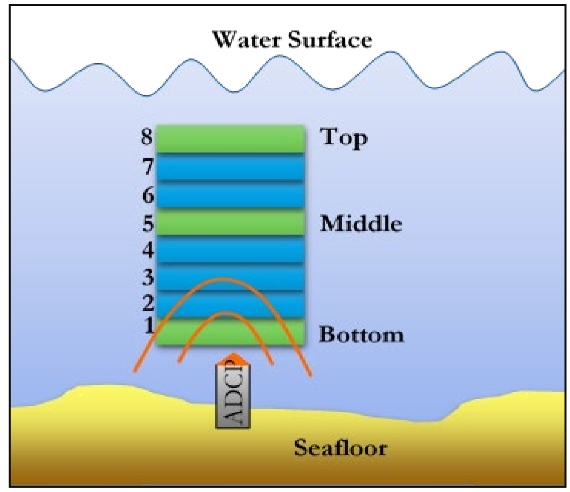
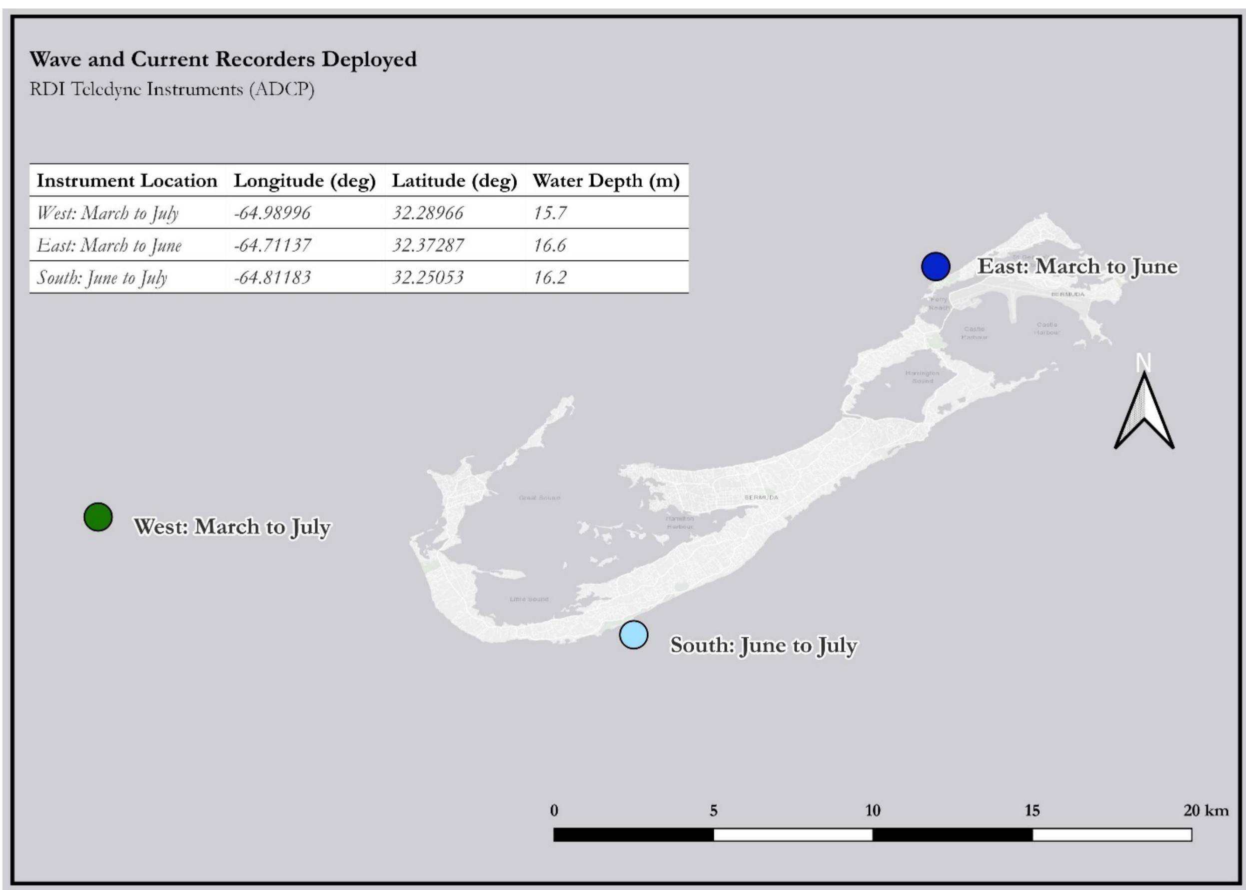


Figure 11.12 Description of binning

In the first deployment, an ADCP was placed west of the island and another placed east of the island, at depths of 14m and 16m respectively. For the second deployment, the "West" recorder was kept in its original location, while the "East" recorder was moved to the South, in a water depth of 16.1m (Figure 11.13).



Instrument Location	Longitude (deg)	Latitude (deg)	Water Depth (m)
West: March to July	*-64.98996*	*32.28966*	*15.7*
East: March to June	*-64.71137*	*32.37287*	*16.6*
South: June to July	*-64.81183*	*32.25053*	*16.2*

Figure 11.13 Locations of instruments

11.5.2 Method of Deployment

The offshore ADCPs were mounted in aluminium frames (Figure 11.14) and deployed on the seabed in water depths ranging from 14m to 16m. Sandbags were used to keep them anchored. Each ADCP instrument was set to record current speed and direction in nine vertical bins, each 2m thick. Readings were made every 30 minutes, along with the tide level and the water temperature at the seabed. In addition to the current measurements, the ADCP can determine wave characteristics. These readings were made every hour for the duration of the monitoring program. Recorded wave conditions are described later in this section.

Figure 11.14 Deployed ADCPs

11.5.3 Results of Deployment

Tides and Temperatures

Both instruments recorded tidal ranges between -0.4m to 0.6m for spring tides and -0.2m to 0.23m for neap tides (Figure 11.15). This is typical for the area and corresponds with literature found for the area. Both instruments show a steady increase of the mean sea temperature, showing a temperature range of 19.5°C - 25°C. The instrument to the East (closer to land) shows slightly higher temperatures with an average difference of approximately 0.7°C -1°C.

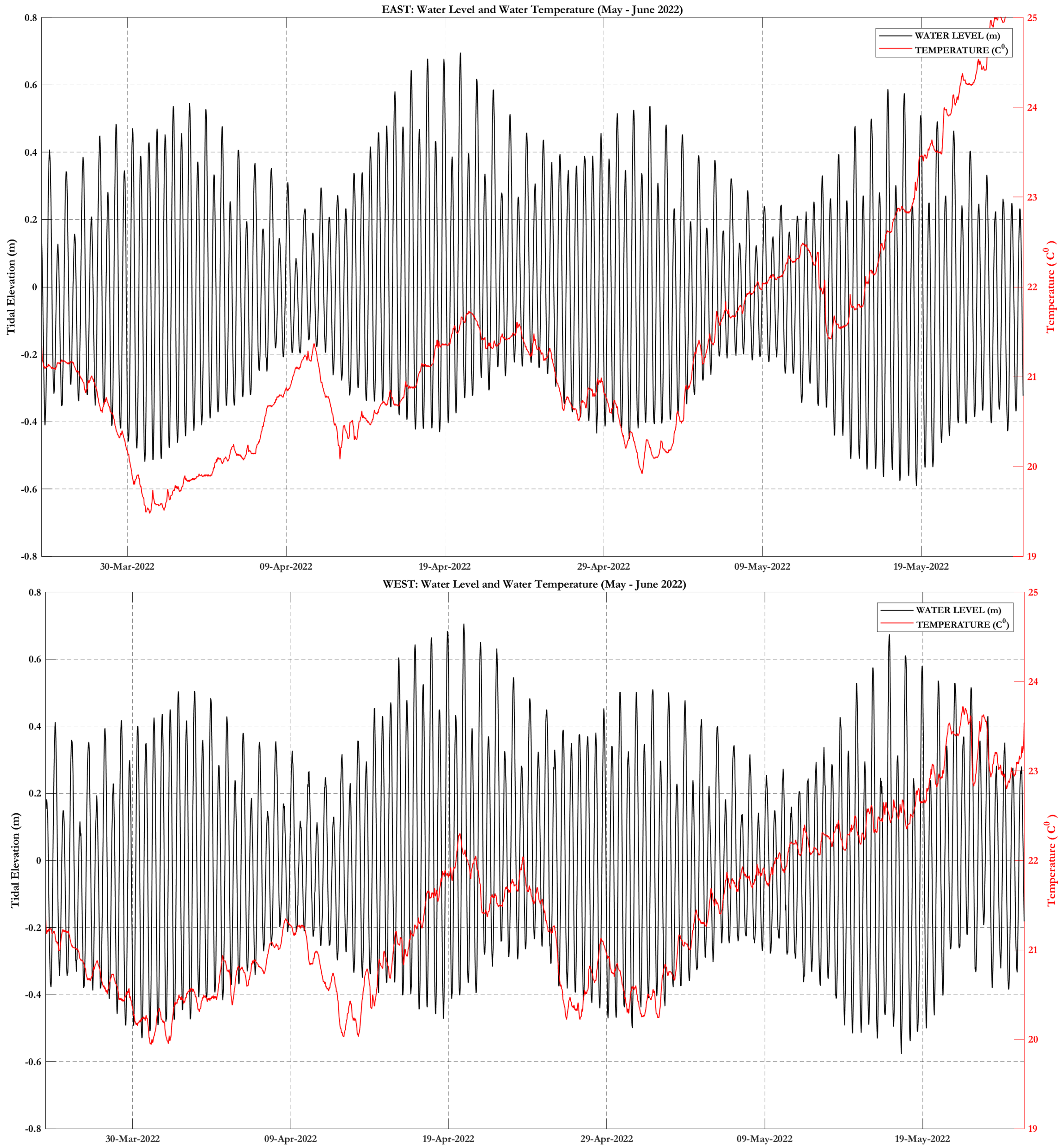


Figure 11.15 Tidal variations and sea temperatures for the East and the West locations

Figure 11.16 shows temperature data for March 2023 to the end of July 2023 from the Bermuda Weather Service. It confirms the sudden increase in sea surface temperature exhibited in Figure 11.15, with both the sea surface temperature and mean air temperature increasing.

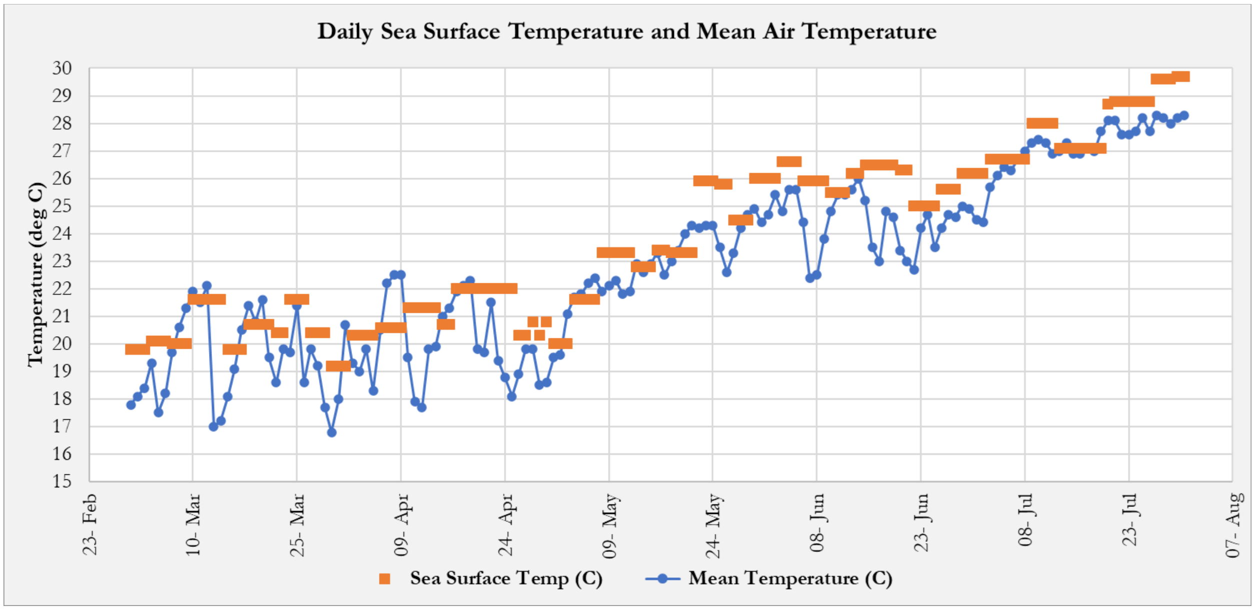


Figure 11.16 Daily sea surface and mean air temperature for Bermuda *(Source: Bermuda Weather Service)*

Currents

The current direction at the East location was primarily to the east-north-east (shore parallel), with speeds up to 0.2m/s (Figure 11.17). The currents are influenced by tides and show a reversal in directions, accompanied by slower speeds (less than 0.15m/s). The instrument to the West exhibited a broader range of directions from south to north. The currents have speeds ranging from 0.2 to 0.3m/s. The current directions are also influenced by the tides and reverse when the tides change. The current speed when it comes from the north is less than 0.2m/s.

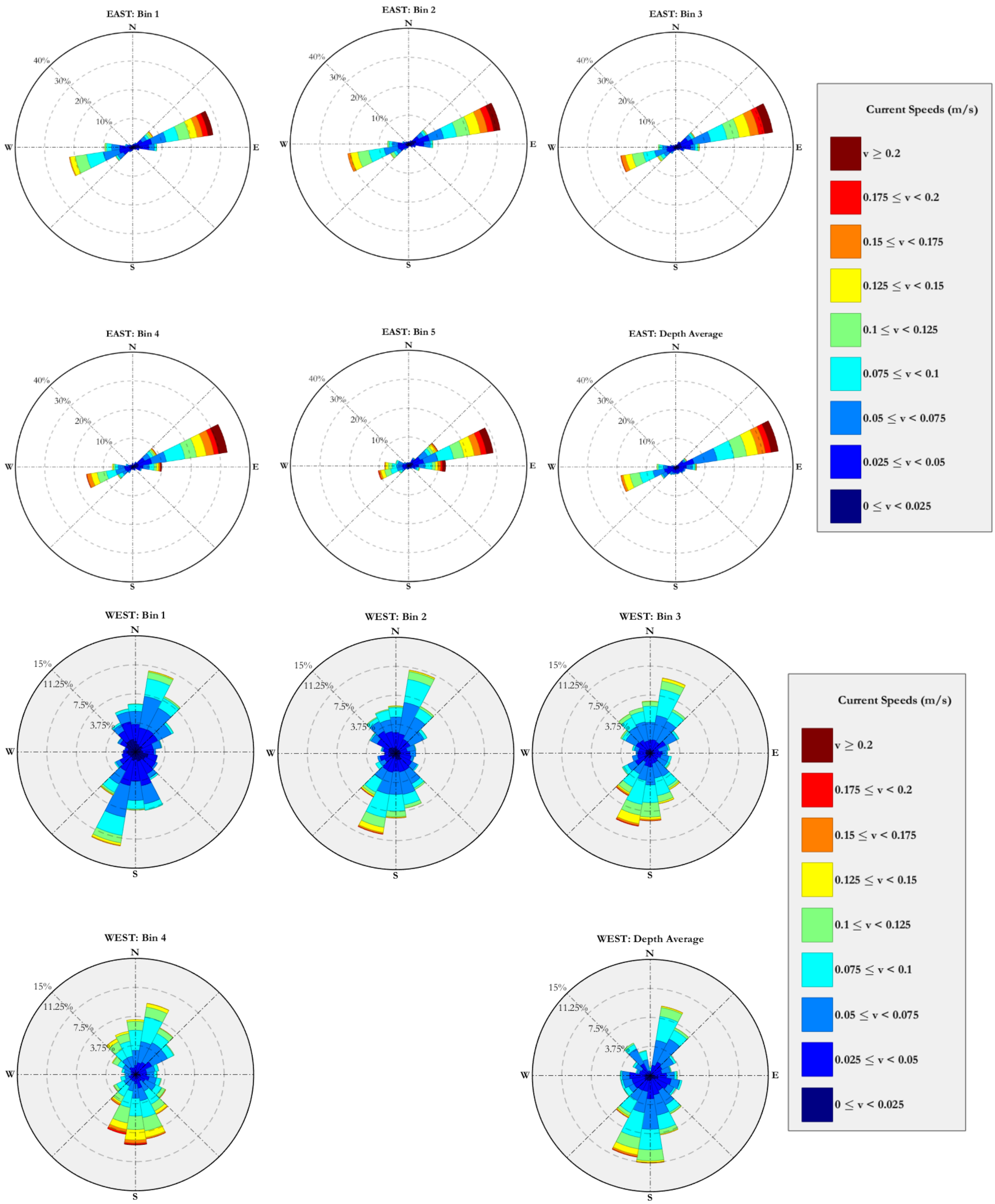


Figure 11.17 Measured current speeds and directions for east and the west and the depth average

Figure 11.18 shows the three-dimensional distribution of the measured currents within each (vertical) bin and through the water column. The U (East-West) and V(North-South) components of velocities for the respective bins through the water column are shown. The plots show that for the East instrument there is a relatively narrow band of UV point cluster, which means that most of the currents are flowing in one direction from the NE to the SW. The colour shows that there is a stronger current coming from the NE. This would have implications for the flow of sediments or other suspended particles. The results at the West instrument show a wider shape of the point cluster, which indicates the flow of the current is more multidirectional. This may be due to the influence of the stronger waves that affect this area and which are also multidirectional. Having said that, both figures have very similar shapes for all the bins. This indicates that there is little variation in the currents as one descends through the water column. Ultimately, in terms of the numerical modelling campaigns, there will be no need to model the hydrodynamics in 3D because the measured data confirms that there are no major differences in current patterns with depth throughout the water columns.

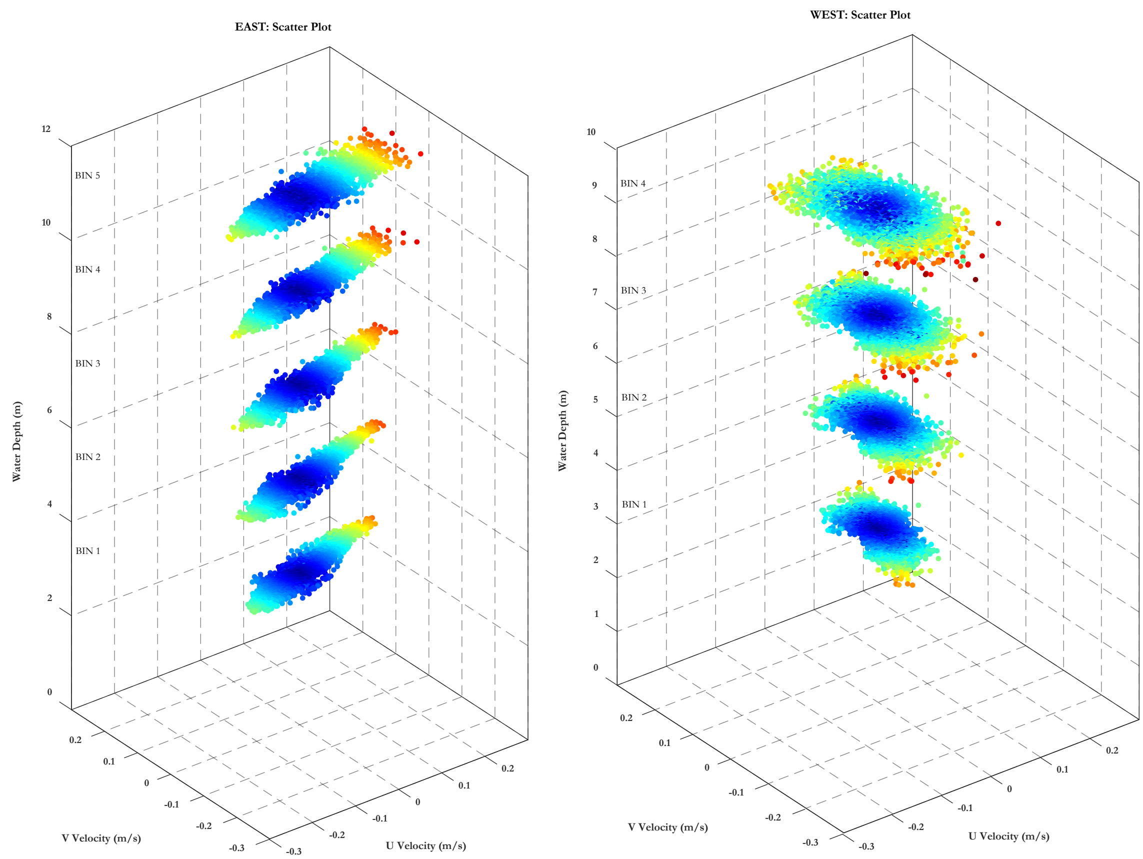


Figure 11.18 U and V Velocities through the Bins for the east (left) and the west (right)

Waves

As expected, the West instrument shows higher waves, with values up to 2.4m and a mean of approximately 1.2m. On the East, the maximum wave height value recorded was 1.5m with a mean of approximately 0.7m. During the period of measurement the dominant wave direction was from the west for both instruments, however for the East instrument, there was a notable occurrence of waves from the north-east (Figure 11.19 and Figure 11.20).

It should be noted that the wide spectrum of wave conditions as a result of the influence of the open ocean will present challenges for the calibration of numerical models.

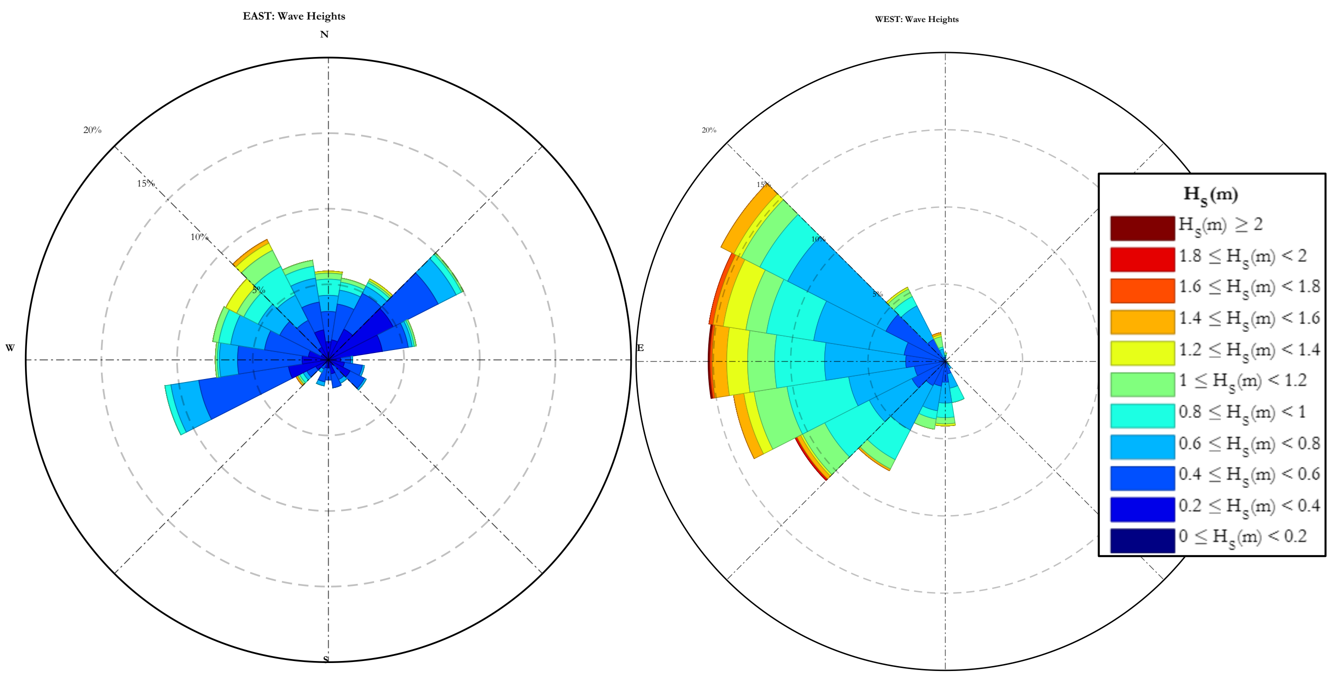


Figure 11.19 Recorded Wave Data

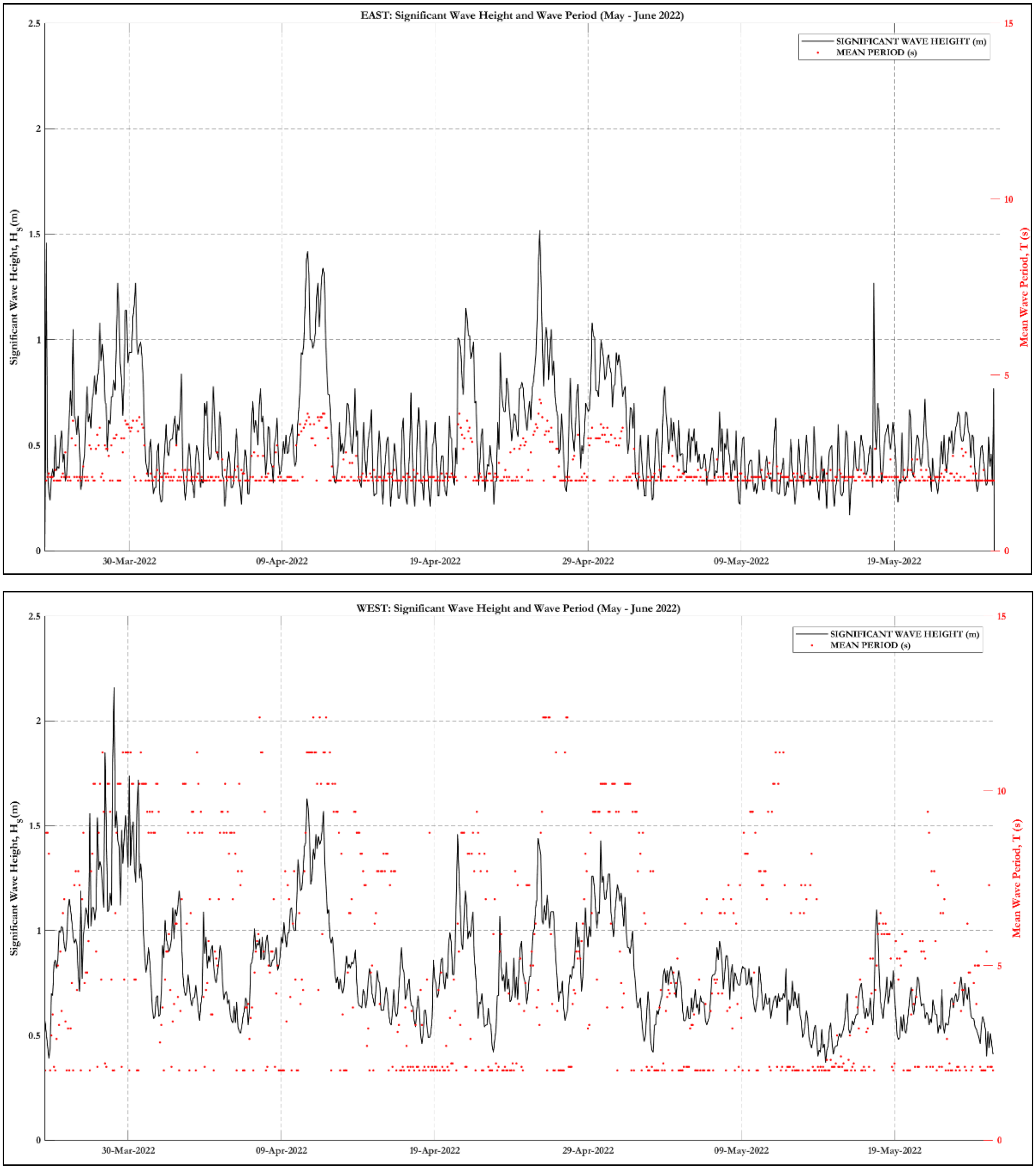


Figure 11.20 Wave heights and periods for East (top) and West (bottom) Instruments

11.6 Sediments

Understanding the movement of sediment along the shoreline is important in understanding the long-term stability of the various beach areas. This insight will be garnered from historical mapping of the shoreline as well as from grain size analysis. Sediment samples were collected at the locations shown in Figure 11.21 and have been sent for dry sieve analysis. As at the writing of this report results were not yet available.

Figure 11.21 Locations of sediment sampling

12 Stakeholder Meetings

SWI visited Bermuda twice between February 28 and March 25, 2022. During each visit the team met with several high-level stakeholders. Table 12-1 summarises the main concerns and actions required for the current study. Detailed description of the meetings are presented in Appendix E.

These comments have been noted and will guide the study as the work progresses.

Table 12-1 Summary of stakeholder meetings

Stakeholder	*Participants*	*Actions Required/Main Concerns*
Department of Public Lands and Buildings (PLB)	S. Patterson, PLB V. Pereria, DOP D. Smith, SWI	LiDAR data was obtained and will be used as the main input to create the elevation model for Bermuda. Tsunami risk should be commented on.
Bermuda Weather Services (BWS)	M. Guishard, BWS D. Smith, SWI M. Harris, SWI P. Warner, SWI	There has been recent flooding in the square of St George's due to tidal excursions and rainfall. The effect of hurricane winds on buildings should be understood. A wave model was developed for BWS and used for the predication of wave conditions. The data from the BWS will be used in the calibration of numerical models.
Department of Environment & Natural Resources (DENR)	G. Smith, DENR S. Lavis, DENR P. Hollis, DENR V. Pereria, DOP D. Smith, SWI	Underground storage tanks are believed to be in the hazard zones, and these will be highlighted by the numerical modelling proposed for this project. Nitrates from cesspits are affecting coastal zones and water table. The effect of climate change on the solar farm should be assessed. Seafloor mapping was done under the Bermuda Ocean Prosperity Programme (BOPP) and should be used in the assessments.
Department of Planning	K. Campbell, DOP P. McDonald, DOP M. Shailer, DOP D. Smith, SWI	Inclusion of the flood risk mapping with storm surge and rainfall combined is necessary. Return periods of interest are 50yr, 100yr, and 200yr.
Ministry of Home Affairs	Hon. W. Roban, MHA PS R. Azhar, MHA J. Nikolai, MHA V. Pereria, DOP	The vulnerability of the coastline limits the potential for expansive development which may cause discomfort to developers. Coastal retreat analysis needs to be tailored based on the context of each shoreline type. The study

Stakeholder	*Participants*	*Actions Required/Main Concerns*
	D. Smith, SWI E. Albada, SWI	should identify the critical areas and indicate prioritization for action based on vulnerability.
Tynes Bay Industrial Complex Desalination and RO Plants	JT Christopher, MPW V. Pereria, DOP D. Smith, SWI E. Albada, SWI	There are 4 desalination/RO plants on Bermuda under Government control. The main plant (other than the coastal infrastructure) is located approximately 6m above sea level
Bermuda Institute of Ocean Sciences	B. Curry, BIOS V. Pereria, DOP P. Warner, SWI	NOAA sea level gauge data goes back 80 years and trend analysis shows a 2.17mm/year rise. Mesoscale eddies have impacts on water levels in Bermuda.
Sol Bermuda	N. Ball, Sol A. Bonamy, SOL S. Simons V. Pereria, DOP P. Warner, SWI	Sol imports gas, diesel, jet-fuel, heavy fuel, and LPG, and is the main importer for the island. This infrastructure is therefore critical. Repairs to main pipeline are frequently done when problems arise, and studies or engineering designs are not typically done.
Bermuda Electrical Company	V. Pereria, DOP P. Warner, SWI J. Nikolai, MHA	The main generating facility is in a potential flood zone. BELCO indicated that maintenance of the canal will ensure adequate drainage.
Marine and Ports Services	R. Cann, M. Bailey, V. Pereria, DOP P. Warner, SWI M. Harris, SWI	Issues arise during storm surge events as the fendering systems are not high enough. Cruise ships and other vessels rely on the tugs for berthing. Hurricane tracking information means cancellations are done earlier.
West End Development Company, WEDCO	A. Dais, WEDCO P. Warner, SWI M. Harris, SWI	Critical facilities, such as the water treatment plant, desal facilities, water storage tanks, warehouses, cement storage silos, and others were observed.

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Appendix A Hydrological Assessment

This memo details notes and observations made during the project visit to Bermuda by Smith Warner International (SWI) representative David Ruttan. Field visits were conducted between March 22, 2022 and March 27, 2022 to view the geological conditions, the coastlines and infrastructure that may be vulnerable to climate change. Meetings were arranged by Shaun Lavis, Hydrogeologist with the Bermuda Environment Department and Dr. Lavis accompanied Mr. Ruttan on all occasions.

	Meeting Particulars	Attendees
1	**Dr. Shaun Lavis, Hydrogeologist, Dept. of Environment & Natural Resources** Date: 22 March 2022	David Ruttan P.Eng., Hydrogeologist, SWI

- Discussion of the geology and hydrogeology of Bermuda
- Examination of various geological and hydrogeological reports and maps as well as the evolution of understanding of the geology and hydrogeology; changes in nomenclature were discussed
- General tour of island geology and location of groundwater lenses
- Visit Spittal Pond, nature reserve and south coast rock, shoreline and reefs

2	**Dr. Shaun Lavis, Hydrogeologist, Dept. of Environment & Natural Resources** **Date:** 23 March 2022	Mr. Alan Rance, P.Eng. Managing Director, Bermuda Waterworks Limited David Ruttan P. Eng., Hydrogeologist, SWI

- Tour of Bermuda Waterworks Limited RO plant which treats brackish water
- Salinity maximum 5000 ppm
- Significant pretreatment because water sources are fresh water lenses of various water quality which is compromised by recirculation of human waste by cesspits
- Water collected by wells and by horizontal tunnels and infiltration galleries
- Discussion of fire fighting requirements indicates lack of capacity
- Plant capacity 420,000 Igpd, with production of 380,000 Igpd processed water
- Salinity kept below 5000 ppm, ideally 3000 ppm by mixing water types

3	**Dr. Shaun Lavis, Hydrogeologist, Dept. of Environment & Natural Resources** **Date:** 24 March 2022	Mr. Derek Woolley, Managing Director ROCON David Ruttan P.Eng., Hydrogeologist, SWI

- Visited the RO plant at Tynes Bay Incinerator site
- Toured plant with explanations of operations
- Visited wells on sea shore, there are three wells on top of the cliff near the sea shore. The wellheads are approximately 6 m above sea level.
- These are equipped with 18" diameter PVS casing and 16" diameter PVC screens
- Minimum pretreatment of sea water by sand filtration prior to RO treatment
- Can process 960,000 Igpd, produce 38% fresh water

4	**Dr. Shaun Lavis, Hydrogeologist, Dept. of Environment & Natural Resources** **Date:** 27 March 2022	David Ruttan P.Eng., Hydrogeologist, SWI

- Field visit of Horseshoe Bay to examine the Rocky Bay Formation and rock outcrops

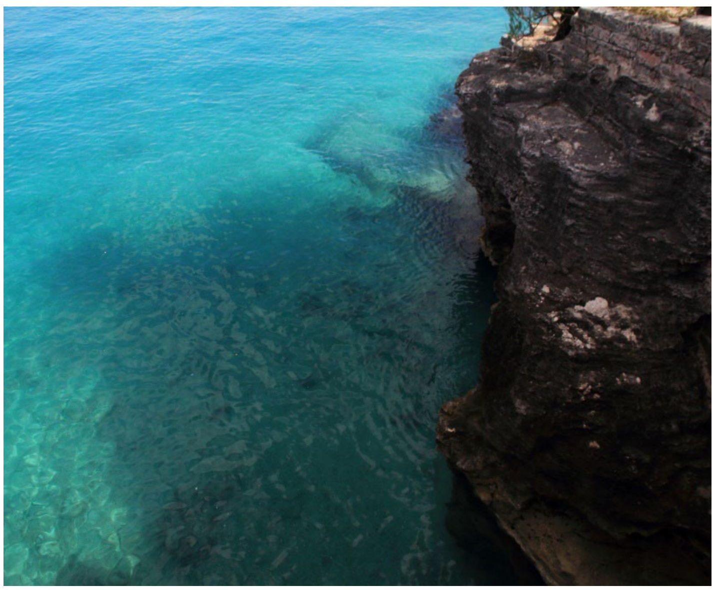
5	**General Touring Observations** 22-27 March 2022	David Ruttan P.Eng., Hydrogeologist, SWI

- Drive and walk by views of rooftop water collection systems and water storage tanks, one at the Botanical Gardens and the other at the residence of Dr. Lavis
- General viewing of shoreline infrastructure on north and south coasts and in Hamilton
- Observation of low lying area around Pembroke Canal, Hamilton being dredged
- Observation of Flatts Bridge, Hamilton, with strong tidal flow

Limestone tile roof top with guides to channel rainwater to storage

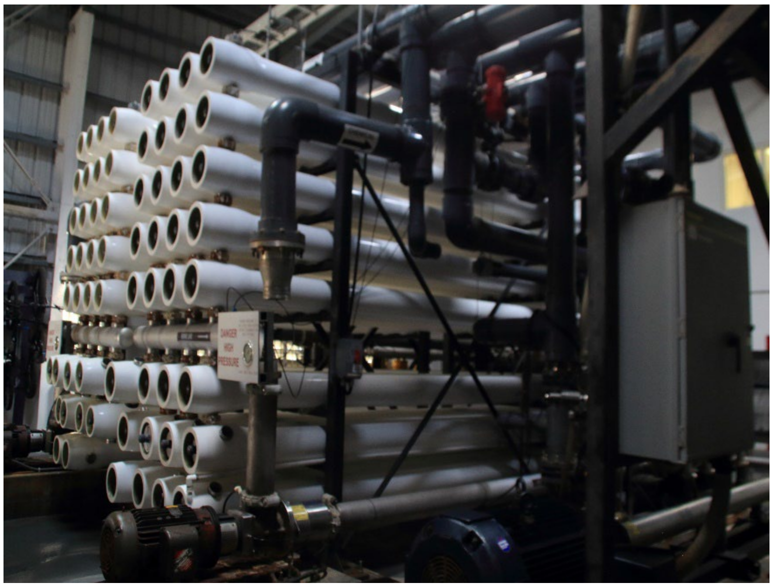
Spittal Pond

Bermuda south shore south of Spittal Pond



Cliff at ROCON RO plant

Seawater extraction well at Tynes Bay SWRO plant, SWRO plant and incinerator Plant in background, Incinerator is behind trees



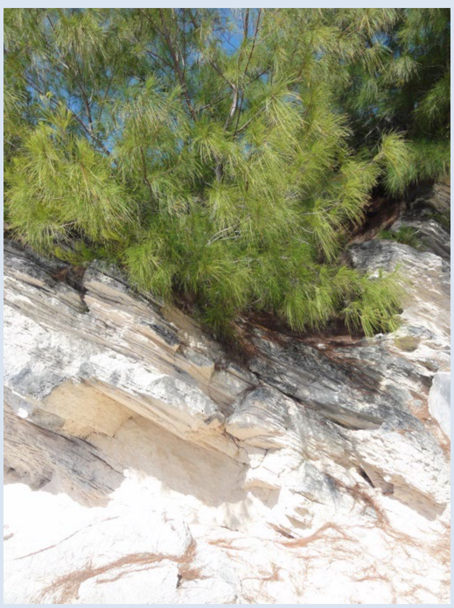
Seawater extraction well at Tynes Bay SWRO plant, SWRO plant and incinerator Plant in background, Incinerator is behind trees

Rocky Bay Formation at Horseshoe Bay

Rocky Bay Formation at Horseshoe Bay

Appendix B Cliff Assessment

	Representative Photos	Observations
Site visit conducted via land on 18 May 2022		
1.		**John Smith Bay** - Preliminary site visit - Pictures taken
2	 	**Spittal Pond** - Preliminary site visit - Pictures taken
Site visit conducted via land 19 May 2022		

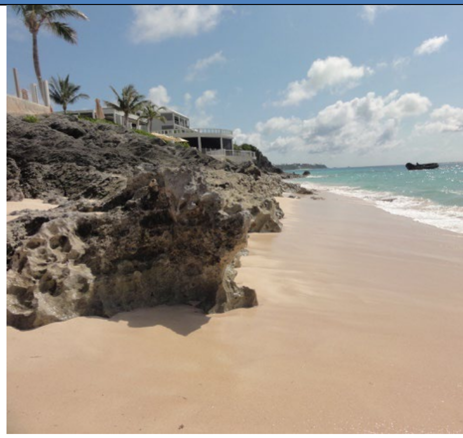
	Representative Photos	Observations
3	  	**Horseshoe Bay** **Middle Beach** **Angle Beach** - 10:15, started at Horseshoe Bay, collected 3 Schmidt hammer measurements at different heights on a limestone block with different coloration. First the lowest rock in contact with the ocean, then a layer of gray/black limestone above the water, and then a layer of whiter limestone above that. - Walked NE to Middle Beach. Observed a low seawall NE of the main beach at Horseshoe Bay. - Extensive limestone blocks in this area - Abundant examples of Casuarina root-wedging - In many locations, weathered (gray and pockmarked) limestone hardness could not be measured with the Schmidt hammer; the material simply crumbled and no measurements registered on the instrument. - Farther along the coast at Middle Bay and Angle beach, 3 additional Schmidt hammer measurements were recorded on shore platform rock and a 4th measurement was recorded from the base of a limestone cliff in contact with the ocean, and another was collected inside a cave on recently exposed, fresh limestone. - Many limestone blocks in the water were observed to be undercut. - Four additional Schmidt hammer measurements were collected from a small cove at the SW of Horseshoe Bay, at varying heights above the water. - GPS waypoints 1077-1084

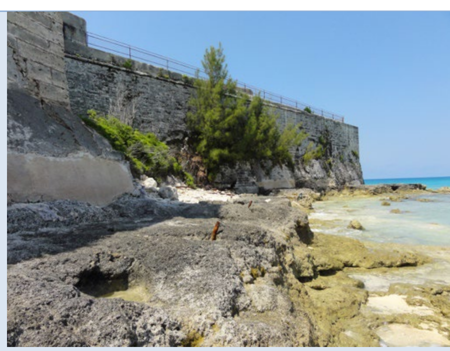
	Representative Photos	Observations
4		**Warrick Long Beach** **Jobson's Cove** Took photos
5		**Astwood Park Overlook** Took photos at the overlook only, no access to beach
6		**Marley Beach** **Bermudiana Beach** **Surf Side Beach** **Azura Bermuda Resort** - 15:05 Accessed Marley beach at a small beach park, walked towards SW first - Observed large cave with freshly exposed limestone and roots hanging from ceiling - Observed a layer of soft material at the back of the beach below the limestone above, probably a paleosol - Collected 7 Schmidt hammer measurements of different types of material at this site (limestone in contact

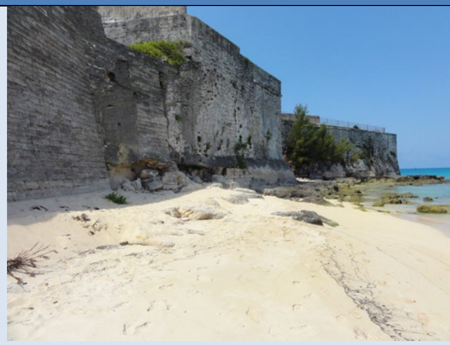
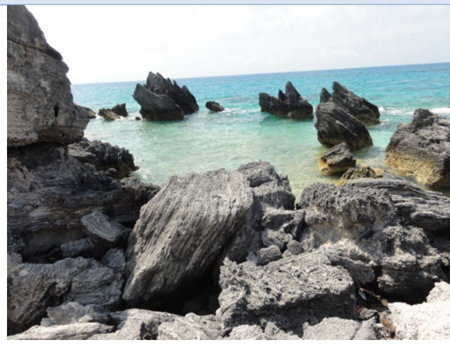
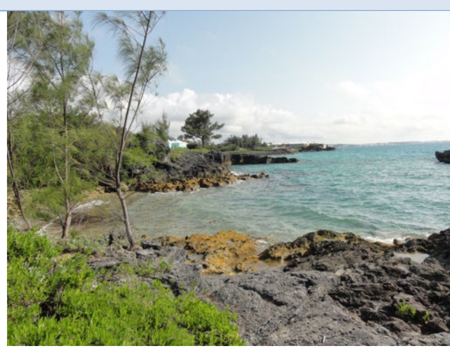
	Representative Photos	Observations
	 	with water, weathered, freshly exposed, paleosol, etc.) - Beach scarp observed - Walked NE to site below the Bermudian. Observed a low seawall at the base of the cliff below the development. To the SW of the seawall, a soft paleosol layer was observed similar to that observed at Marley Beach. Collected a Schmidt hammer measurement on this material. - Surveyor Jeffery Roach was conducting a high resolution total station survey of the cliff face and provided his business card. - Observed chunks of gray limestone crust on the sand below the cliff, and fresh cliff erosion south of the seawall. - Collected a Schmidt hammer measurement on shore platform fronting seawall. - Continued NE to Surf Side Beach, collected 3 Schmidt measurements at various locations. - Cliffs at SW side of Surf Side Beach NE of Bermudian are undercut and appear primed to fail. - Continued walking up the beach to the Azura Bermuda Resort. This area also has a low seawall at the base of the cliff possibly where the same soft paleosol layer is located. The upper cliffs also look primed to fail, with large vertical cracks. - Schmidt measurement on freshly exposed limestone at a recent failure did not register. - Collected one Schmidt measurement at the base of the cliff below the high tide line.

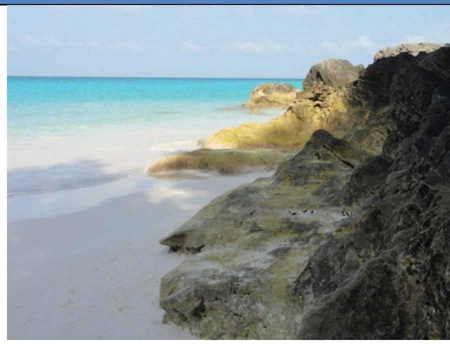
	Representative Photos	Observations
7	  	**Elbow Beach** **Coral Beach** - 16:00 Began at the Lido resort and walked SW along the beach - Just NE of a set of former access stairs, now destroyed, Schmidt hammer could not register hardness. - One Schmidt hammer measurement was collected about 2 feet above the sand on a low cliff at the back beach. - Beach is wide and sandy, with few to no limestone cliff blocks. Cliffs at the back of the beach are low and soft, and appear comprised of paleosol material. Schmidt hammer could not register hardness. This appear to be a vulnerable coastal location. - Further SW down the beach, limestone cliff material returns and the beach narrows. Walls are built into the limestone for resorts above. Sand height (water level to back beach) varies by about 10' in this area. - Collected 3 Schmidt measurements on limestone in this area, one of which was on a secondary deposit of calcium carbonate that formed a very hard crust on the limestone material.
Site visit conducted via land 20 May 2022		

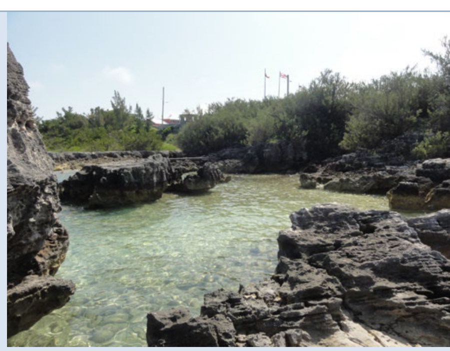
	Representative Photos	Observations
8		**Devonshire Bay Park** - 8:55 Limestone here has nearly flat bedding, but slopes a little bit toward the water. - Collected 3 Schmidt hammer measurements - Observed apparent tree trunk (palm?) fossil traces in the limestone here - Erosion mechanisms observed at this site include wave undercutting, bioerosion by marine organisms such as chiton, rainwater dissolution, and casuarina root-wedging - The low lying rocks here suggest the area may be subject to overtopping during storms. - Bedding measurement
9		**Spittal Pond** 9:28 Visited Checkerboard rocks, collected Schmidt measurements on each of the layers of limestone (oldest, Checkerboard; middle, and youngest layer, above paleosol)
10		**John Smith Bay** - 9:56 Low cliffs back this beach, with very weathered rocks on NE side of the bay - Cliffs are very undercut and soft at the back beach - Collected 3 Schmidt measurements on rocks at NE side of bay, and 1 at rocks on SW side of bay - Bedding measurement

	Representative Photos	Observations
11		**Pink Beach West** - 10:16 Cliffs are low and dip away from the water - Collected 1 Schmidt measurement on limestone just above the water - Bedding measurement
12	 	**Rosewood Beach** - 10:37 Wide sandy beach with high limestone cliffs at each end - Back beach has signs saying "unstable cliff" but appears to be a dune, possibly an artificial dune to protect low cliffs? - Cliffs at NE side of beach are pretty jointed, with caves, and dip toward water, cliffs at SW dip away from water - Root wedging - Collected 3 Schmidt hammer measurements

	Representative Photos	Observations
13		**Clearwater Beach** **Long Bay Beach** - 11:50 Collected 5 Schmidt hammer measurements from limestone material backing beaches around Cooper's Island - Very little infrastructure here to be threatened by future erosion
14		**St. David's Head** - 12:52 Huge vertical and very undercut cliffs with caves below the battery - Collected one Schmidt measurement on limestone about 20' above the water at the base of stairs leading down from the top of the headland
15		**Just north of Building Bay Beach** - 15:00 Rock very solid, not fractured, but appears weathered by rain and bioerosion from marine organisms at the water's edge. Very little layering apparent in rock. - Collected one Schmidt measurement at the top of an undercut, about 3' above the water.
16		**St. Catherine's Beach** - 15:14 Stairs to the beach north of the fort damaged and closed, no access to beach - Observed sea stacks in water and vertical cliffs around this beach, from top of damaged stairs. - Accessed beach on south side of fort near St. Regis. Damage to fort walls apparent along bottom of external walls. Soft paleosol layer visible.

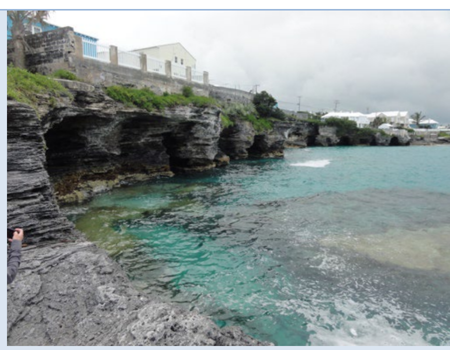
	Representative Photos	Observations
		- Beach has shells, coral, and bits of tiny volcanic cobble washed up, contrasting with other beaches visited so far, that did not have material washed up on sand. - Collected one Schmidt hammer measurement on the shore platform, which was quite broken up
17		**Tobacco Bay** - 15:37 Observed quite thick paleosol, limestone very broken up - Collected 3 Schmidt hammer measurements, one about 1 foot above waterline, one about 3 feet above water on gray weathered limestone, and one above 15 feet above water on freshly exposed limestone
18		**Railway Trail near Callen Glen Dr.** - 16:52 Small coves with stairs cut into limestone/poured with concrete to access water - Collected 3 Schmidt hammer measurements from limestone near water and on top of shore platform
19		**Railway Trail near Lynwood Dr.** - 17:00 Low cliffs and wide shore platform in this area - Collected 3 Schmidt measurements, at waterline, about 1.5 feet above, and 5 feet above waterline - Observed water flowing out of apparent underground tunnels – possibly water from Harrington Sound draining to ocean
Site visit conducted via land 21 May 2022		

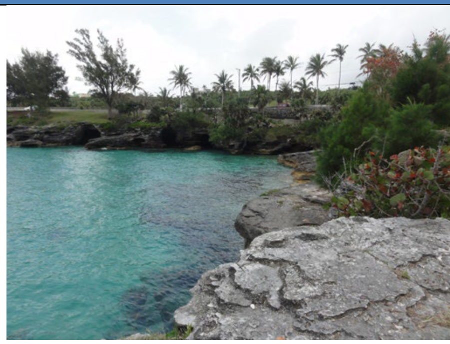
	Representative Photos	Observations
20		**West Whale Bay Park** - 8:51 Small pocket beach, limestone bedding dips away from the water - Abundant casuarina at the west side of beach - Collected 2 Schmidt hammer measurements, one on yellow limestone in contact with water and one on gray limestone about 3 feet above water - Bedding measurement
21		**Hog Bay Park** - 9:27 Very little/no sand, "beach" is instead comprised of flat slabs of beach rock - Block detachment observed and photographed - Coastline setting appears relatively uniform for some distance along the coast in this area – beach rock and no sand at the coast, sand is offshore underwater instead - Collected 2 Schmidt measurements, one on clean beach rock and one on gray weathered limestone not in contact with water - Bedding measurement
22		**Pocket Beach at 8 West Side Rd** - 9:54 Collected one Schmidt measurement on bioeroded limestone above one foot above water surface - Cliffs low, bedding approx. horizontal - Paleosol exposed at north side of pocket beach, limestone is undercut/arched/full of caves where the paleosol is eroded

	Representative Photos	Observations
		- Paleosol is not visible at S side of beach, where entire cliff has been engineered/covered by a seawall
23		**Daniels Head** - 10:07 Abandoned resort, beach on N side of headland blocked by a fence. - Accessed beach on S side of headland, collected 1 Schmidt measurement on gray limestone about 1 foot above water. - Water was a bit cloudy; first experience of water that was not perfectly clear - Coral and shells were washed up on beach.
24		**Long Bay Beach** - 10:20 Murky water, coarse sand with sargassum washed up, rubbish - Very low cliffs observed at ends of long beach, and chunks of beach rock at the north end of the beach. Collected one Schmidt measurement on yellow limestone with algae. - "Cliffs" behind beach appear to be comprised of old trash - Seawalls occur at the south end of the beach
25		**Dockyard Beach** - 10:44 Rock is fractured, layered, has some arches and areas with beach rock. - Paleosol layer observed at the back beach; observation of these paleosol layers/pockets suggests that beaches may form where paleosol layers are near sea level - Collected 3 Schmidt measurements including one on weathered portion of

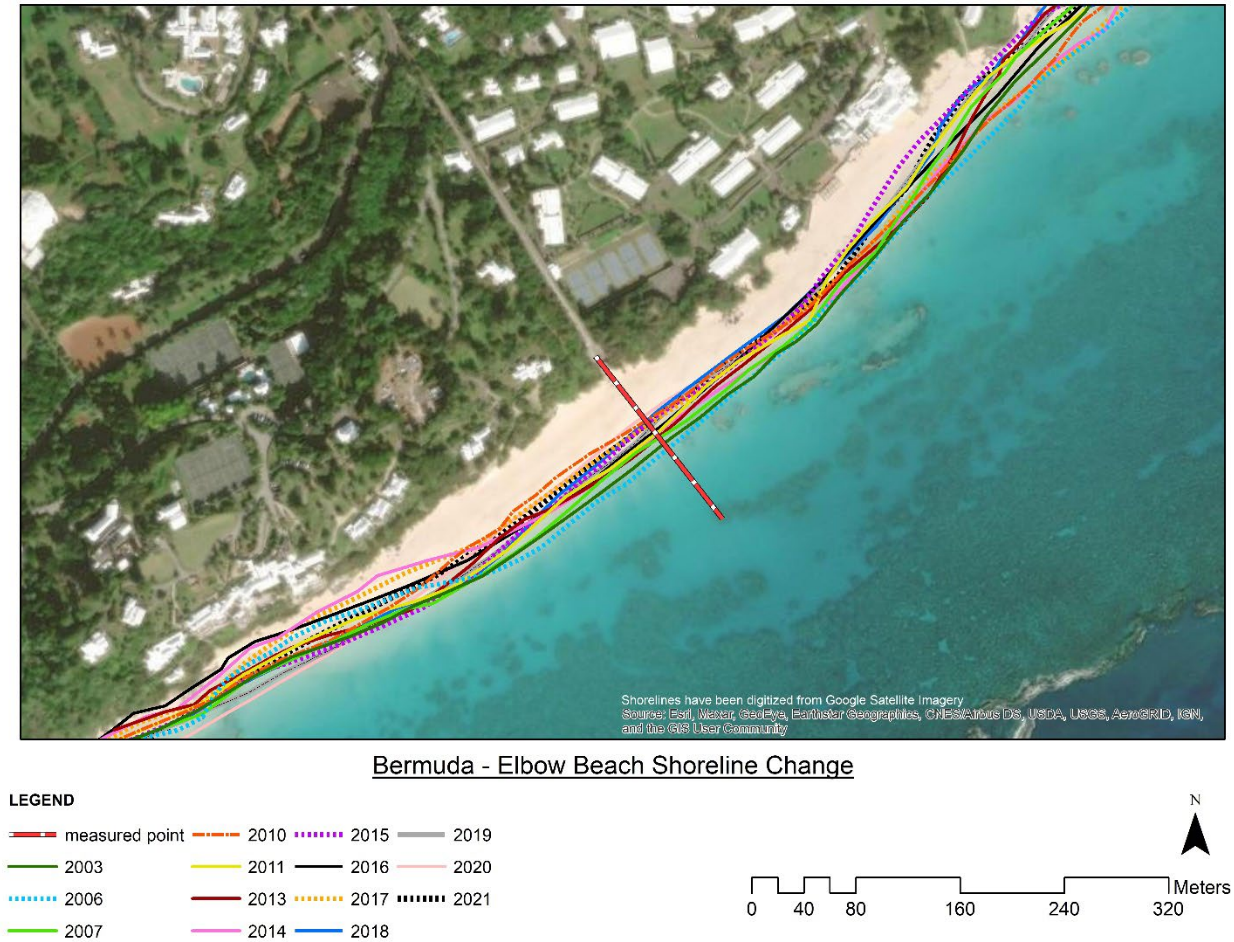
	Representative Photos	Observations
		paleosol; freshly weathered paleosol area did not register with Schmidt hammer - Bedding measurement
26		**Theo's Cove** - 11:09 Low limestone cliffs with several small pocket beaches and a low hill at the back beach - Collected Schmidt hammer measurement on (marine) bioeroded limestone about foot above water. - Bedding measurement
27		**Reefs Resort Beach** - 12:05 Collected 1 Schmidt measurement at base of gray limestone ~4 feet above water - Paleosol observed at back beach at lower part of cliff - Bedding measurement

	Representative Photos	Observations
28		**Church Bay Beach** - 13:17 Variable bedding, limestone layers change a lot and contain paleosols - Thick paleosol at the back beach - One Schmidt measurement on limestone, one on paleosol at the top of the back beach just above the sand (~10 feet above water level)
29		**Spanish Point Park** - 14:48 Limestone bedded thinly, and approximately horizontal - Very little sand accumulated in embayments - Rocks offshore contain arches and seacaves - Variable rock hardness appears to be causing complex erosion patterns - Collected 2 Schmidt measurements on gray limestone, one about 1 foot above and one about 3 feet above water; additional measurement on yellow limestone at water level was too soft to register.

	Representative Photos	Observations
30	 	**Clarence Cove** **Admiralty House Park** - 15:30 Big cliffs with caves facing N, pocket beach (Clarence cove) w/seawall along north side of beach behind these large cliffs. - Cliffs inside the cove are undercut and full of caves. Bedding is approximately horizontal and thin, looks like a stack of cards with weathered material between each "card". Flat beach rock pieces observed underwater in cove. - Evidence of recent cliff failures - Very erodible - Schmidt did not register on many rocks, collected one measurement on freshly exposed limestone about 2 feet above water. - Top of limestone not pitted/sharp here, as in other locations
31		**Ducking Stool Park** - 15:54 Very large undercut caves beneath park - Bedding ~horizontal, lots of pitting/sharp parts on top surfaces. Lots of holes in limestone exposed to air. - Fresh failures evident - Collected Schmidt measurement on yellow limestone about 1 foot above water

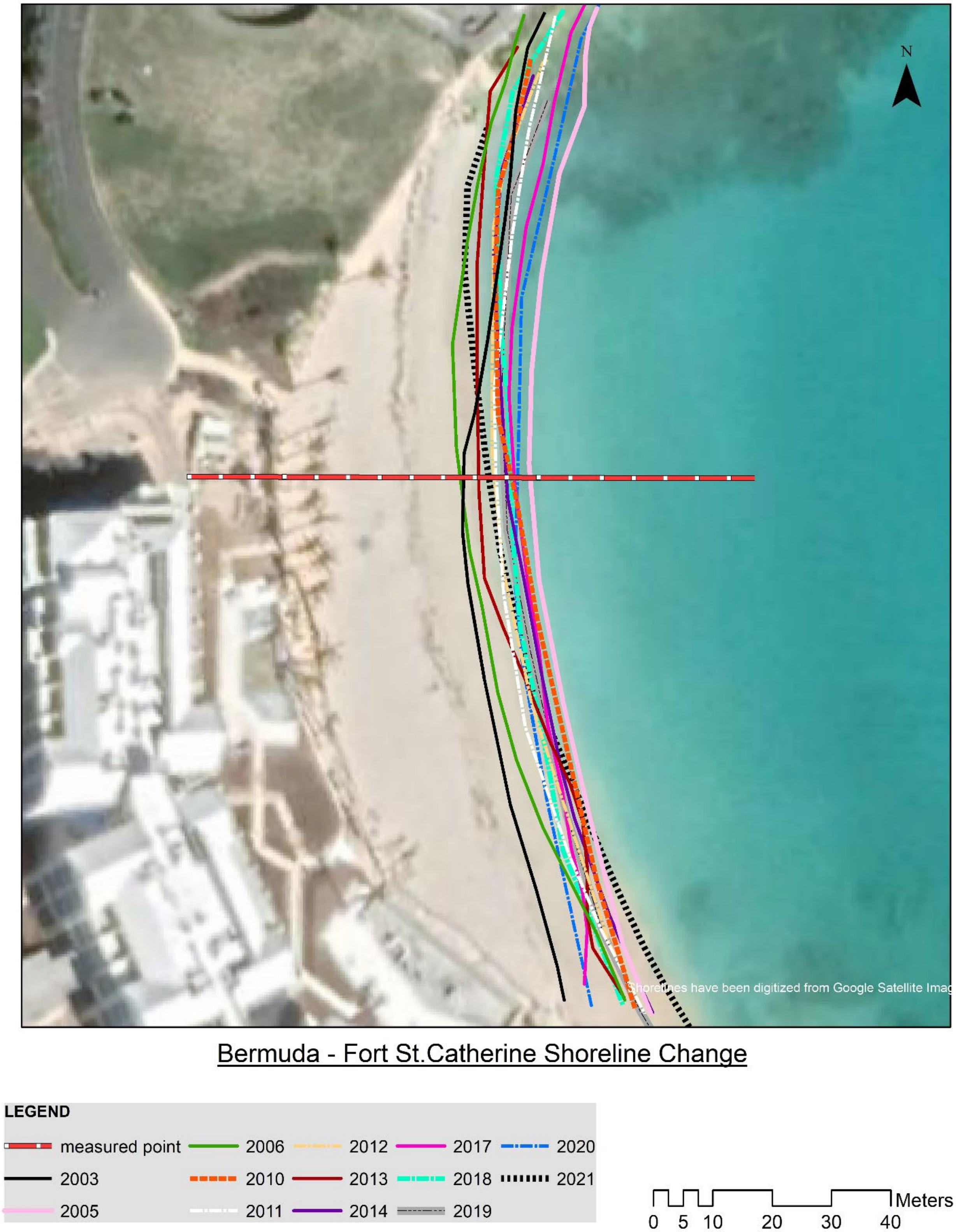
	Representative Photos	Observations
32		**Robinson Bay Park** - 16:15 Friable layers of limestone and caves like other locations along this stretch of coast, but cliffs lower overall - Schmidt measurement on limestone about 2 feet above water - Bedding measurement
33		**Penfurst Park** - 16:29 Schmidt measurement on yellow limestone ~1 foot above water, on spot cleared of algae by marine life - Schmidt hammer did not register on rocks higher up – sounded hollow
Site visit by kayak 22 May 2022		
		Harrington Sound -Southern half of Harrington Sound visually inspected -Almost fully enclosed interior water body with a few islands. Strong currents at Flatts Village -Many plunging cliffs with undercutting and some seacaves -No photos taken

Appendix C Shoreline Change Maps

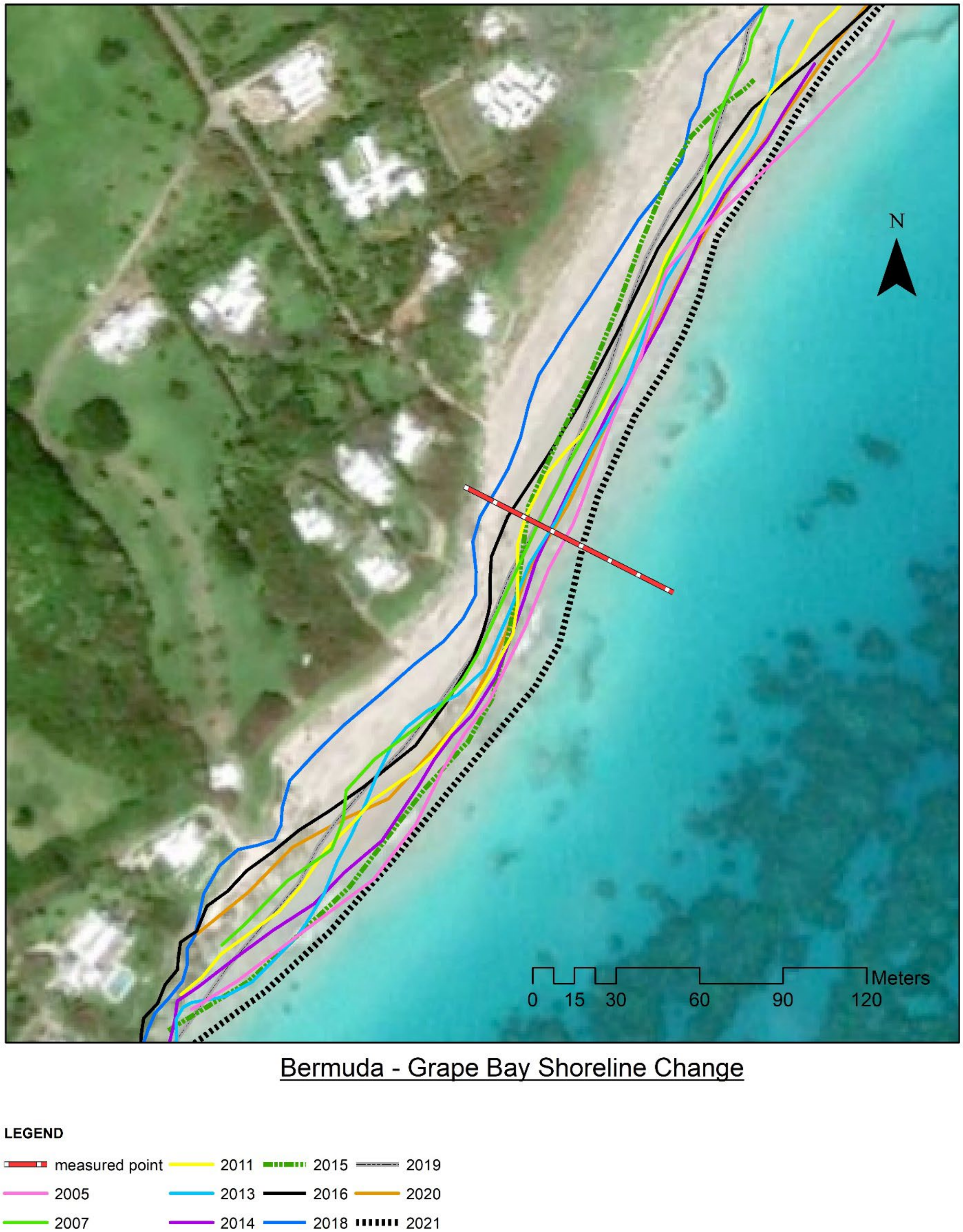


		ELBOW BAY	
		PROFILE 1	
Date of Image Capture	**Time Change**	**Distance**	**Erosion Rate**
	(years)	**(m)**	**(m/yr)**
8/22/2003		84.982	
3/27/2006	2.595482546	91.799	2.626486551
3/17/2007	0.971937029	80.34	-11.78985845
9/21/2010	3.515400411	62.357	-5.115491238
3/24/2011	0.503764545	74.859	24.81714946
3/15/2013	1.976728268	78.538	1.861156163

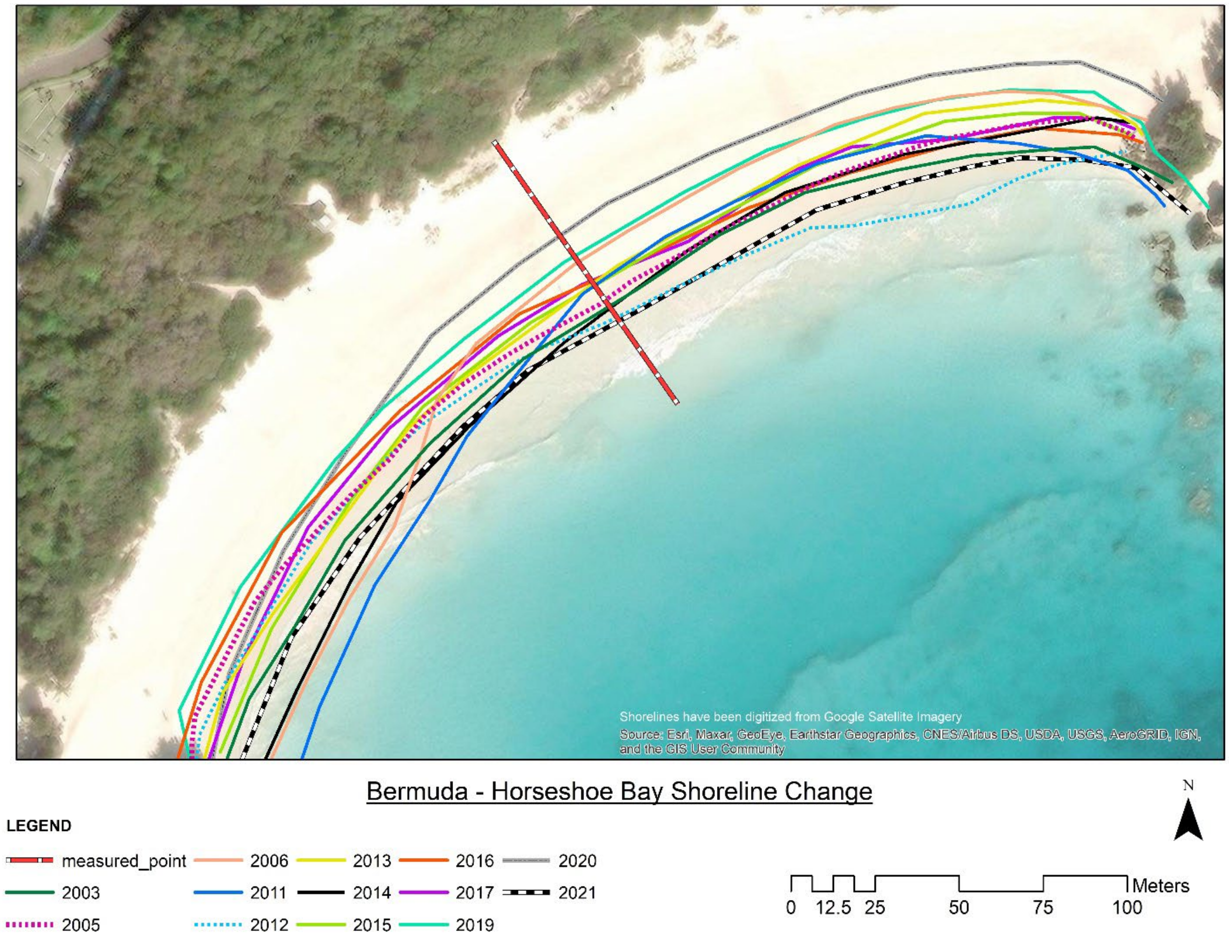
8/28/2014	1.453798768	75.698	-1.953502825
12/30/2015	1.338809035	67.512	-6.114389571
7/8/2016	0.5229295	73.303	11.07415052
9/8/2017	1.169062286	65.98	-6.263994731
9/15/2018	1.018480493	63.251	-2.679481855
12/26/2019	1.278576318	68.839	4.370486081
12/11/2020	0.960985626	58.447	-10.81389744
12/1/2021	0.971937029	65.409	7.163015493
Weighted Rate of Erosion/accretion (m)			**-1.070856538**


N
Shorelines have been digitized from Google Satellite Imag
Bermuda - Fort St.Catherine Shoreline Change
LEGEND
measured point
2003
2005
2006
2010
2011
2012
2013
2014
2017
2018
2019
2020
2021
0 5 10 20 30 40 Meters

		FORT ST.CATHERINE	
		PROFILE 1	
Date of Image Capture	**Time Change**	**Distance**	**Erosion Rate**
	(years)	**(m)**	**(m/yr)**
9/2/2003		47.784	
9/15/2005	2.036960986	58.216	5.121354839
11/6/2006	1.141683778	45.455	-11.17735072
9/21/2010	3.874058864	54.98	2.458661661
3/24/2011	0.503764545	52.44	-5.042038043
3/15/2012	0.977412731	51.382	-1.08244958
3/15/2013	0.999315537	49.238	-2.145468493
3/10/2014	0.985626283	53.816	4.6447625
8/18/2017	3.441478439	55.403	0.461139021
9/15/2018	1.075975359	54.239	-1.08180916
4/13/2019	0.574948665	53.604	-1.104446429
7/11/2020	1.245722108	57.415	3.05926978
3/12/2021	0.668035592	50.921	-9.721038934
Weighted Rate of Erosion/accretion (m)			**0.179001601**

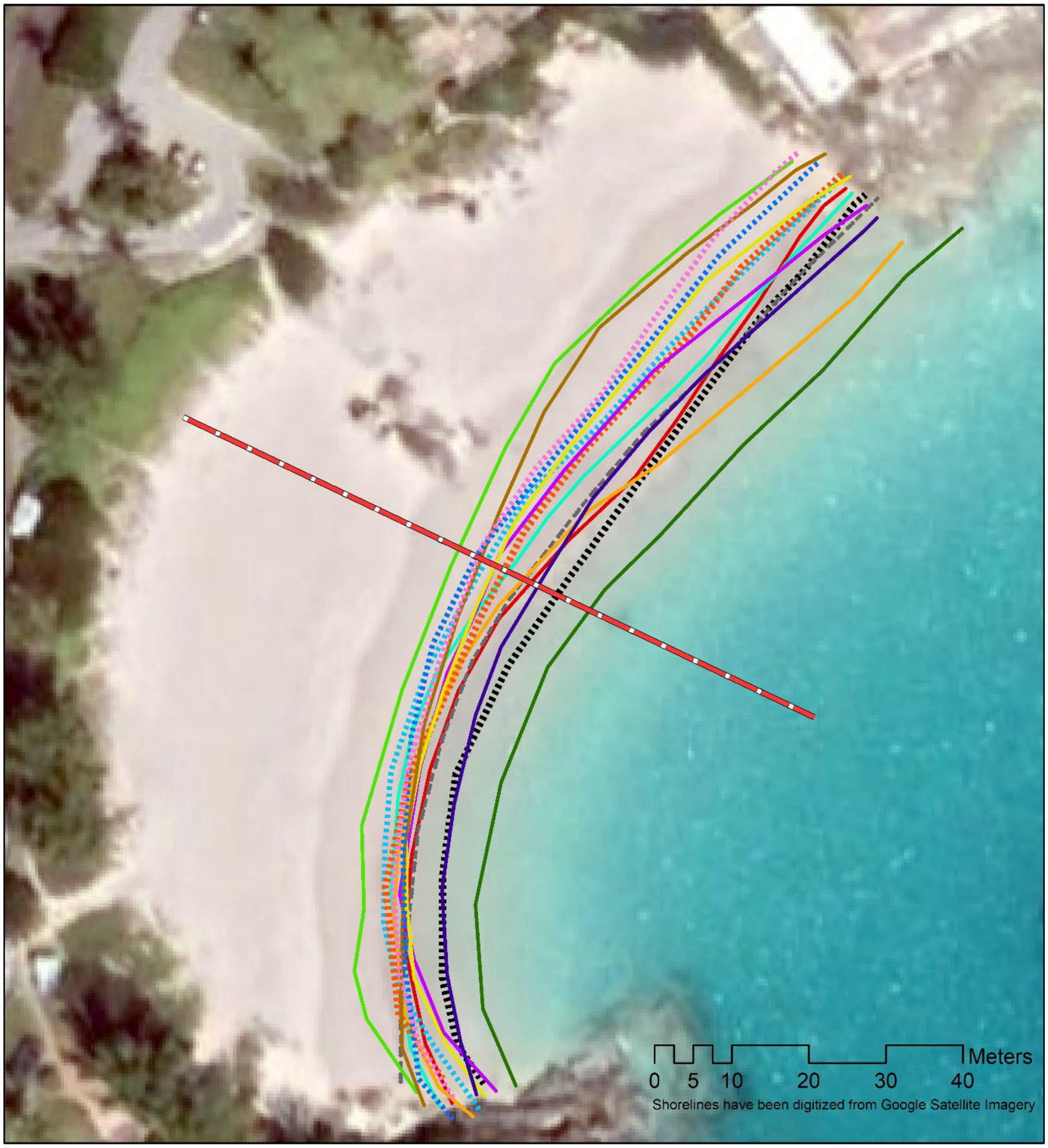

N
0 15 30 60 90 120
Meters
Bermuda - Grape Bay Shoreline Change
LEGEND
measured point
2005
2007
2011
2013
2014
2015
2016
2018
2019
2020
2021

		GRAPE BAY	
		PROFILE 1	
Date of Image Capture	**Time Change**	**Distance**	**Erosion Rate**
	(years)	**(m)**	**(m/yr)**
7/18/2005		40.631	
3/17/2007	1.661875428	29.815	-6.50830972
3/24/2011	4.019164956	24.692	-1.274642881
3/15/2013	1.976728268	35.202	5.316866343
3/10/2014	0.985626283	34.549	-0.662522917
12/30/2015	1.80698152	21.367	-7.295038636
7/8/2016	0.5229295	19.139	-4.260612565
1/3/2018	1.489390828	10.514	-5.79095818
4/13/2019	1.273100616	29.248	14.71525484
4/22/2020	1.026694045	36.087	6.661186
4/5/2021	0.952772074	47.612	12.09628233
Weighted Rate of Erosion/accretion (m)			**0.444217814**



		HORSESHOE BAY	
		PROFILE 1	
Date of Image Capture	**Time Change**	**Distance**	**Erosion Rate**
	(years)	**(m)**	**(m/yr)**
8/22/2003		60.424	
8/21/2005	1.998631075	54.351	-3.038579795
11/6/2006	1.210130048	44.05	-8.512308258
3/13/2011	4.34770705	52.816	2.016235202
8/21/2012	1.442847365	64.04	7.779062619
8/22/2013	1.002053388	52.023	-11.992375
10/19/2014	1.158110883	60.594	7.400845745
12/30/2015	1.196440794	52.764	-6.544410755
7/8/2016	0.5229295	51.138	-3.109405759

9/8/2017	1.169062286	50.753	-0.32932377
12/27/2019	2.299794661	41.397	-4.068189286
11/8/2020	0.8678987	34.409	-8.051630915
9/5/2021	0.824093087	65.405	37.61225581
Weighted Rate of Erosion/accretion (m)			**0.276113257**



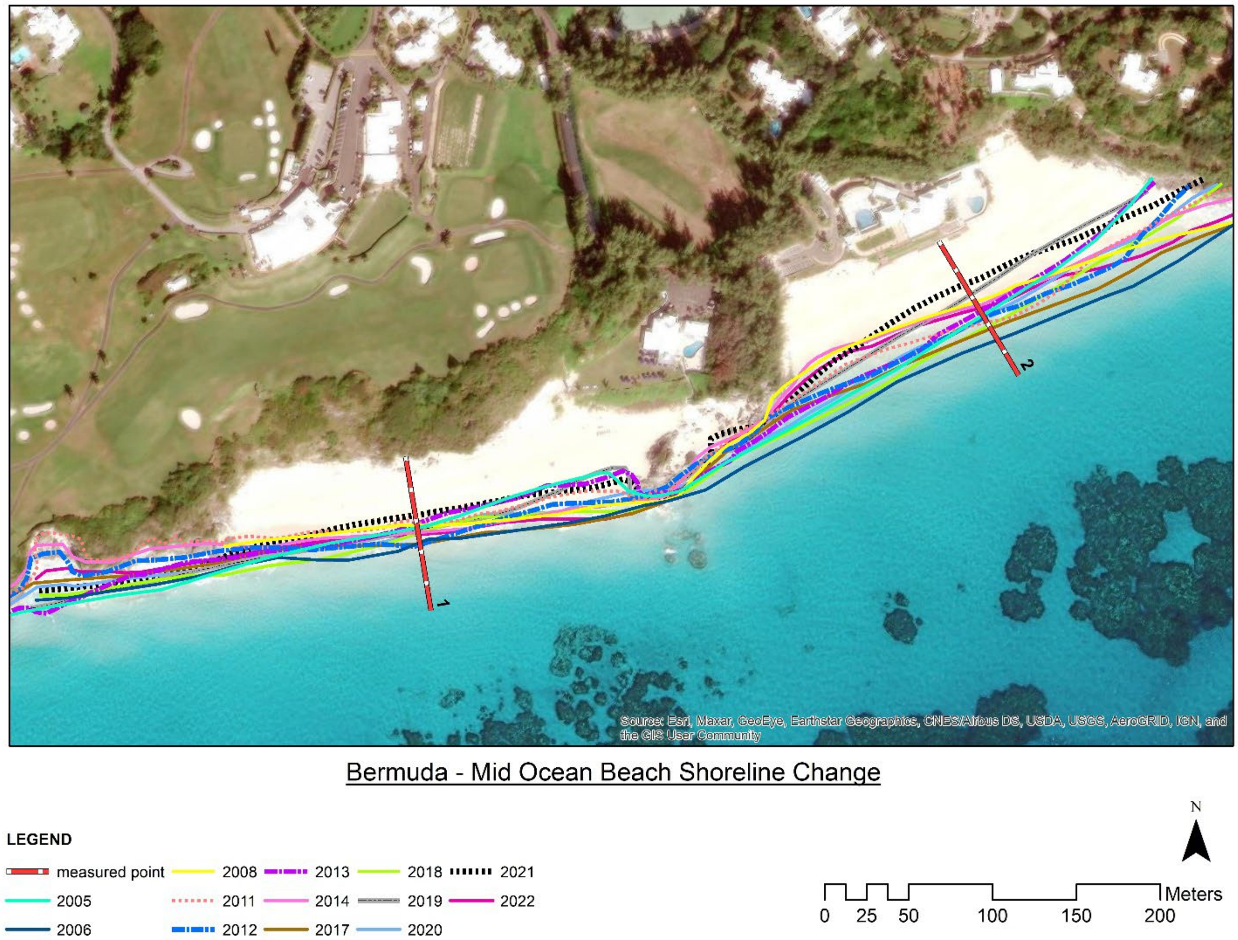
Bermuda - John Smith's Bay Shoreline Change

LEGEND

measured point	2010	2015	2019
2005	2011	2016	2020
2006	2013	2017	2021
2008	2014	2018	2022

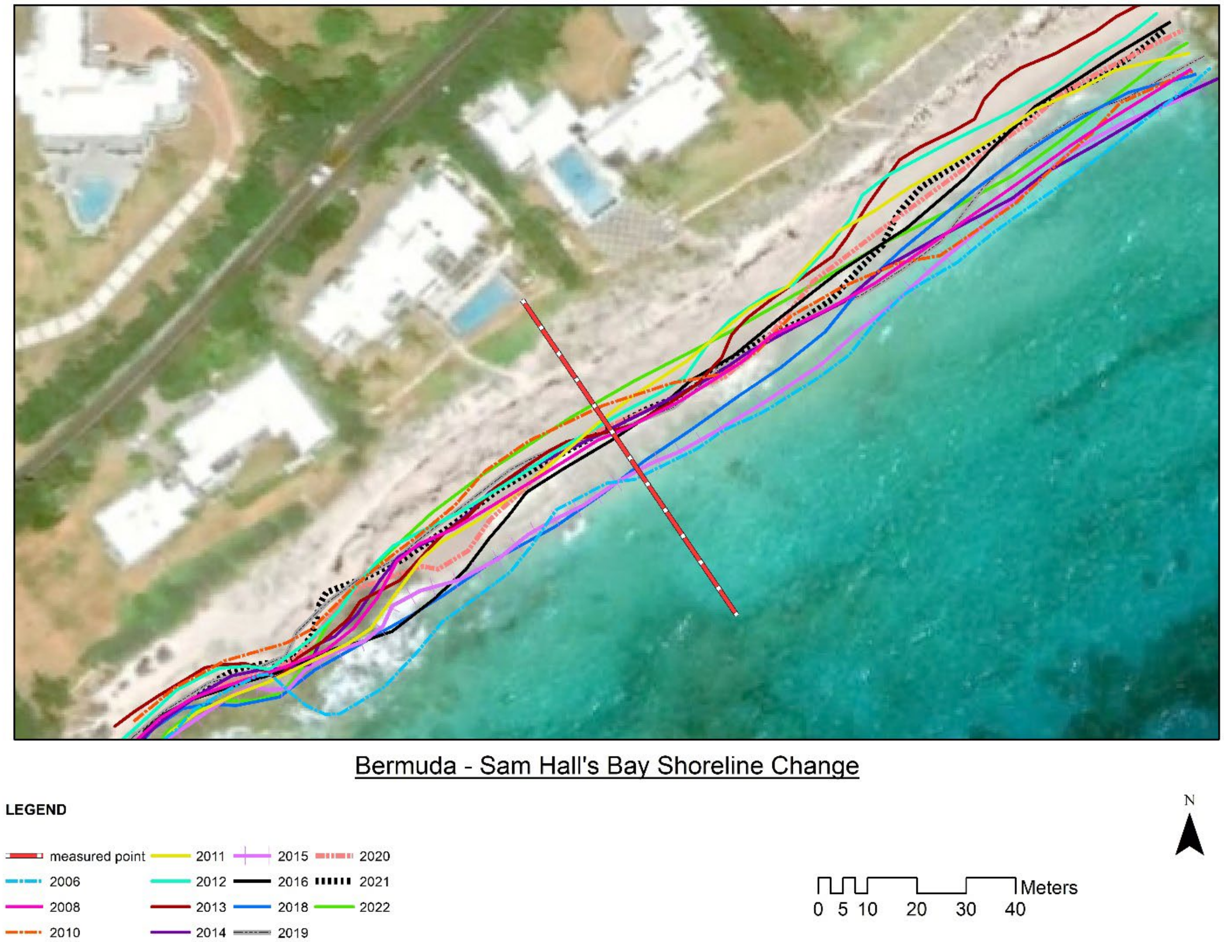
N

		JOHN SMITH'S BAY	
		PROFILE 1	
Date of Image Capture	**Time Change**	**Distance**	**Erosion Rate**
	(years)	**(m)**	**(m/yr)**
9/15/2005		52.308	
11/6/2006	1.141683778	42.507	-8.584688849
5/12/2008	1.514031485	44.048	1.017812387
9/21/2010	2.360027379	42.706	-0.568637471
3/24/2011	0.503764545	45.168	4.887203804
8/20/2012	1.409993155	43.038	-1.510645631
3/15/2013	0.566735113	39.726	-5.844
3/10/2014	0.985626283	44.799	5.14698125
12/30/2015	1.80698152	45.263	0.256781818
8/10/2016	0.613278576	43.529	-2.827426339
8/18/2017	1.021218344	48.896	5.255487265
6/3/2018	0.791238877	46.8	-2.649010381
8/6/2019	1.174537988	49.073	1.935229021
5/3/2020	0.741957563	58.662	12.92391974
4/5/2021	0.922655715	53.868	-5.19587092
3/1/2022	0.90349076	50.032	-4.245754545
Weighted Rate of Erosion/accretion (m)			**-0.138297954**



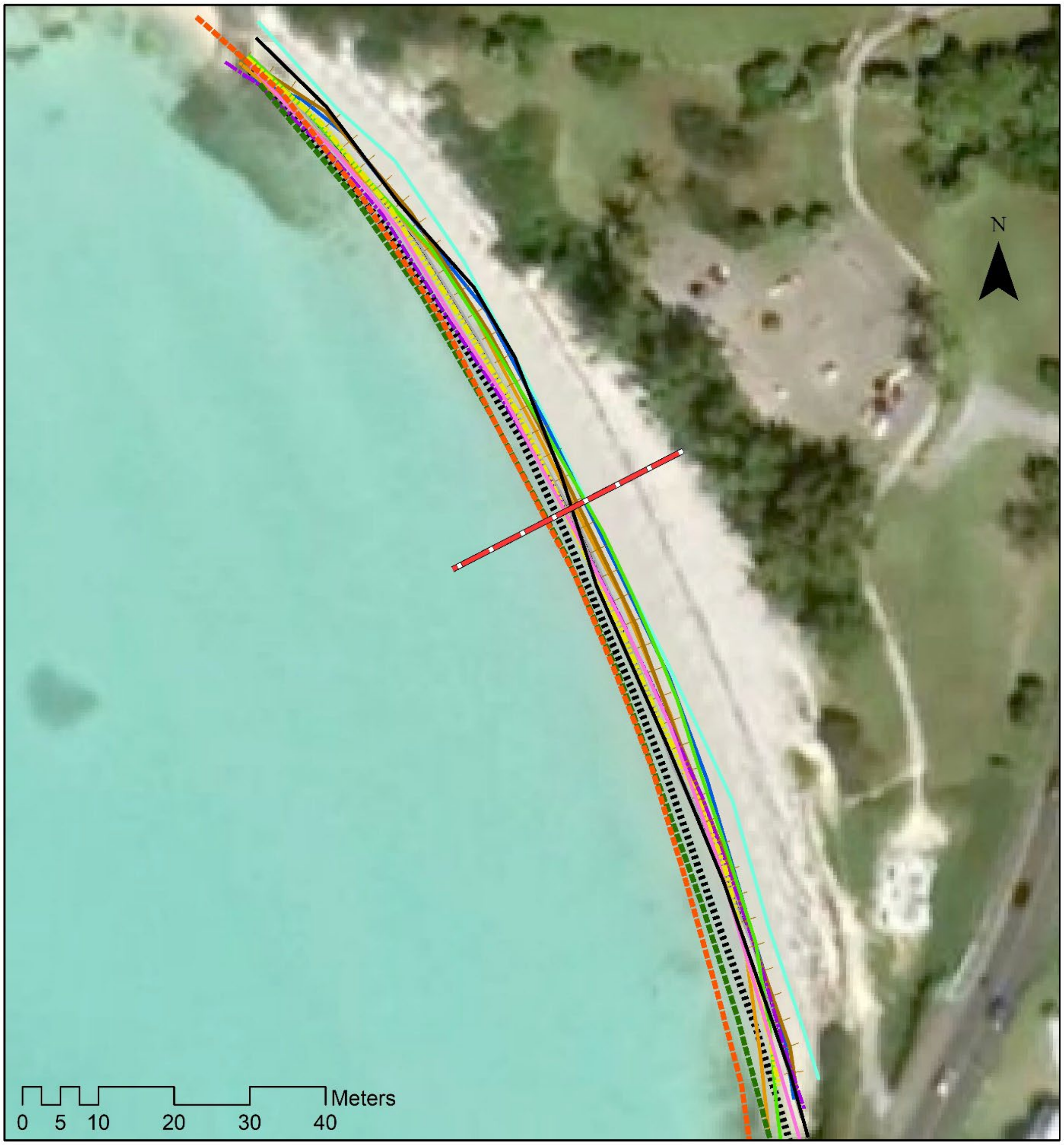
		MID OCEAN BEACH			
		PROFILE 1		**PROFILE 2**	
Date of Image Capture	**Time Change**	**Distance**	**Erosion Rate**	**Distance**	**Erosion Rate**
	(years)	**(m)**	**(m/yr)**	**(m)**	**(m/yr)**
9/15/2005		41.711		51.232	
7/8/2006	0.810403833	51.912	12.58755152	67.811	1.317094907
5/12/2008	1.845311431	36.753	-8.214873516	34.871	4.009800021
3/24/2011	2.863791923	39.711	1.032896272	56.622	21.05826171
8/20/2012	1.409993155	52.586	9.13125	52.141	-0.490732375
8/22/2013	1.004791239	40.814	-11.71586649	48.749	0.289521906
3/10/2014	0.547570157	46.127	9.70286625	44.705	-0.416784061

8/18/2017	3.441478439	52.968	1.987808473	61.045	8.220107835
8/10/2018	0.977412731	46.481	-6.636909664	58.958	0.314453579
12/27/2019	1.379876797	45.061	-1.029077381	37.178	21.16458918
6/5/2020	0.440793977	42.298	-6.268234472	51.358	-2.262199996
11/1/2021	1.407255305	35.97	-4.496696498	30.189	4.707678183
3/1/2022	0.328542094	47.366	34.686575	47.138	0.48863285
Weighted Rate of Erosion/accretion (m)			**0.343618158**		**8.004597298**



		SAM HALL'S BAY	
		PROFILE 1	
Date of Image Capture	**Time Change**	**Distance**	**Erosion Rate**
	(years)	**(m)**	**(m/yr)**
7/8/2006		42.799	
5/12/2008	1.845311431	31.048	-6.368030786
9/21/2010	2.360027379	27.059	-1.690234629
3/24/2011	0.503764545	29.341	4.529894022
8/20/2012	1.409993155	29.397	0.039716505
8/22/2013	1.004791239	32.388	2.976737738
8/28/2014	1.015742642	31.947	-0.434165094
12/30/2015	1.338809035	42.384	7.795734663
8/10/2016	0.613278576	33.854	-13.90885045

8/10/2018	1.998631075	41.287	3.719045548
8/6/2019	0.988364134	32.595	-8.79432964
8/4/2020	0.996577687	30.632	-1.969741071
11/1/2021	1.242984257	31.69	0.851177313
4/1/2022	0.413415469	25.791	-14.26893874
Weighted Rate of Erosion/accretion (m)			**-1.081129829**

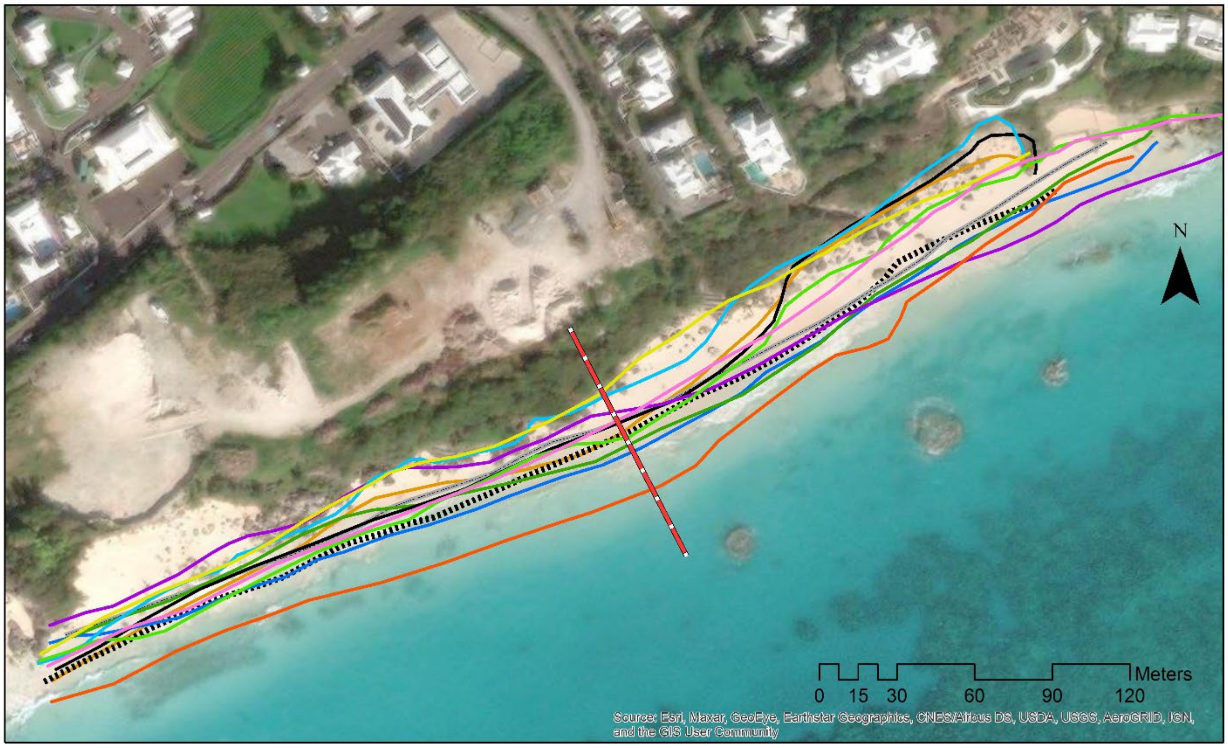


Bermuda - Shelly Bay Shoreline Change

LEGEND

measured_point
2005
2008
2010
2011
2012
2013
2014
2015
2016
2018
2019
2020
2021

		SHELLY BAY	
		PROFILE 1	
Date of Image Capture	**Time Change**	**Distance**	**Erosion Rate**
	(years)	**(m)**	**(m/yr)**
9/15/2005		20.096	
5/12/2008	2.655715264	16.883	-1.209843557
9/21/2010	2.360027379	17.79	0.384317575
3/24/2011	0.503764545	17.569	-0.438697011
3/15/2012	0.977412731	20.367	2.862659664
3/15/2013	0.999315537	19.341	-1.02670274
3/10/2014	0.985626283	17.151	-2.2219375
12/30/2015	1.80698152	15.019	-1.179868182
8/10/2016	0.613278576	16.155	1.852339286
10/15/2018	2.179329227	14.831	-0.607526382
11/10/2019	1.070499658	16.982	2.009342072
10/6/2020	0.906228611	10.749	-6.877955438
10/5/2021	0.996577687	18.705	7.983321429
Weighted Rate of Erosion/accretion (m)			**-0.086640987**

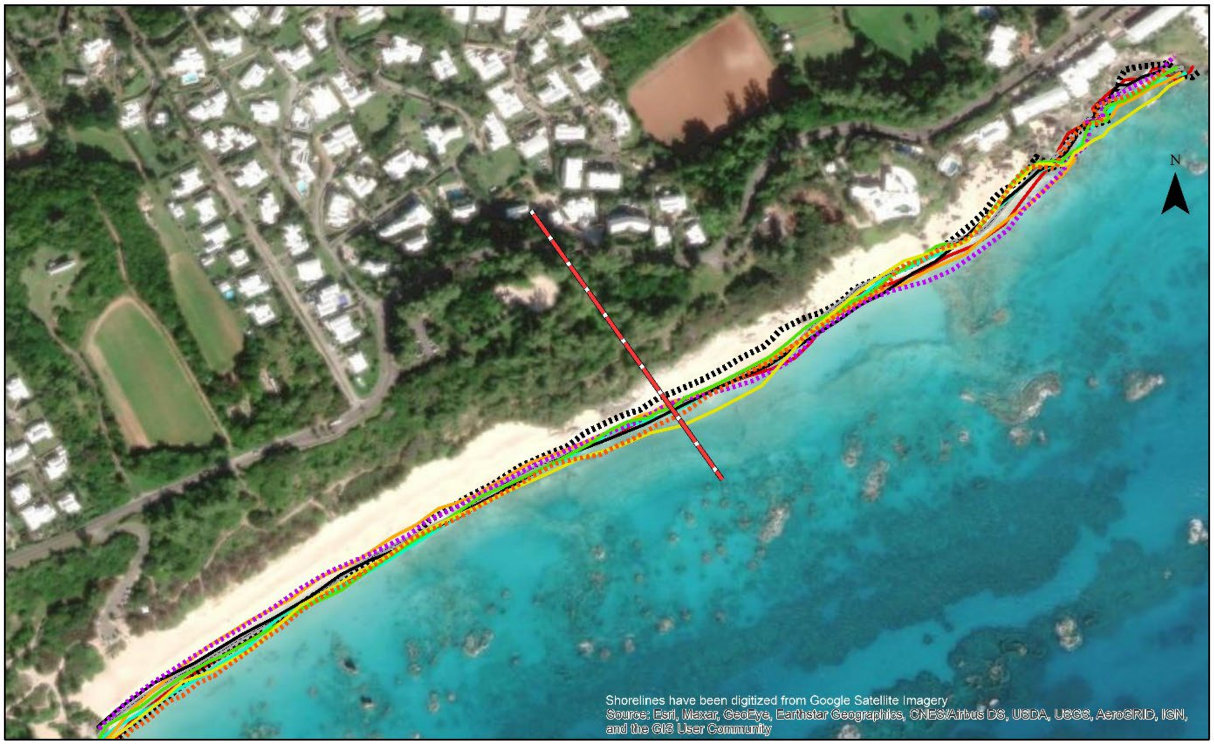


Bermuda - Surfside Beach Shoreline Change

LEGEND

measured point, 2003, 2006, 2007, 2011, 2013, 2014, 2016, 2017, 2018, 2019, 2021, 2022

		SURFSIDE BEACH	
		PROFILE 1	
Date of Image Capture	**Time Change**	**Distance**	**Erosion Rate**
	(years)	**(m)**	**(m/yr)**
8/22/2003		40.04	
7/8/2006	2.877481177	69.913	10.38164914
3/17/2007	0.689938398	47.44	-32.57247321
3/13/2011	3.989048597	27.594	-4.975121139
8/22/2013	2.444900753	29.646	0.839297872
8/28/2014	1.015742642	36.799	7.04213814
4/29/2016	1.67008898	41.225	2.650158197
3/17/2017	0.881587953	50.613	10.64896584
6/3/2018	1.212867899	53.558	2.428129233
7/5/2019	1.086926762	40.638	-11.88672544
7/15/2021	2.028747433	46.163	2.723355263
4/1/2022	0.711841205	45.076	-1.527025962
Weighted Rate of Erosion/accretion (m)			**0.270619244**



Bermuda -Warick Long Bay Shoreline Change

		WARICK LONG BAY	
		PROFILE 1	
Date of Image Capture	**Time Change**	**Distance**	**Erosion Rate**
	(years)	**(m)**	**(m/yr)**
8/22/2003		191.328	
7/8/2006	2.877481177	205.112	4.790300666
3/17/2007	0.689938398	194.47	-15.42456548
3/13/2011	3.989048597	202.835	2.096991249
8/22/2013	2.444900753	185.751	-6.987604703
8/22/2014	0.999315537	183.163	-2.589772603
12/30/2015	1.35523614	181.608	-1.147401515

7/8/2016	0.5229295	188.263	12.72638089
9/18/2017	1.196440794	182.047	-5.195409611
8/10/2018	0.892539357	189.658	8.527355061
7/5/2019	0.900752909	185.853	-4.224243921
9/3/2020	1.166324435	183.47	-2.043170775
10/1/2021	1.075975359	175.374	-7.524335878
1/1/2022	0.251882272	183.676	32.95984239
Weighted Rate of Erosion/accretion (m)			**-0.416712837**

Appendix D Critical Structures Inventory & Assessment

Location: Dockyard

Structure Characteristics:

Structure Class:	**Cruise Pier and Wharf**
Material:	**Concrete/Steel Sheet Piling/Stone Blocks**
Condition:	**3 (Fair)**
Coordinates (UTM 20):	**327255 m (Easting)** **3577940 m (Northing)**

Structure Dimensions:

Running Length:	**820 m**	Width:	**30 m**

Description of Structure:

- Docks on sheet piling, with mooring dolphins
- Small drydock/ramp for hauling Marine and Ports ferries
- Storage areas including wharehouses and a cement silo

Location: Pembroke Canal, Hamilton

Structure Characteristics:

Structure Class:	**Drainage Canal**
Material:	**Reinforced Concrete**
Condition:	**3 (Fair)**
Coordinates (UTM 20):	**330521 m (Easting)** **3575181 m (Northing)**

Structure Dimensions:

Running Length:	**400 m**	Width:	**5 m**

Description of Structure:

- Major drainage conduit for a commercial section of Hamilton
- Subject to frequent flooding, with spillover into the adjacent roadways
- Sparse mangrove stand at the outflow end of the drain

Location: Flatts Bridge


Structure Characteristics:

Structure Class:	**Road Bridge**
Material:	**Reinforced Concrete**
Condition:	**2 (Good)**
Coordinates (UTM 20):	**336543 m (Easting)** **3577564 m (Northing)**

Structure Dimensions:

Running Length:	**65 m**	Width:	**5.5 m**

Description of Structure:

- Connects Norths Shore Road to the airport and to towns such as St Georges
- Main route used frequently by many drivers
- Bridge spans a tidal inlet that exhibits very strong tidal flow velocities
- Evidence of bioerosion undercutting the banks, particularly on the bay side

Location: Causeway


Structure Characteristics:

Structure Class:	**Road Bridge**
Material:	**Cut stone blocks**
Condition:	**3 (Fair)**
Coordinates (UTM 20):	**339251 m (Easting)** **3581023 m (Northing)**

Structure Dimensions:

Running Length:	**1000 m**	Width:	**15 m**

Description of Structure:

- Connects Mainland of Bermuda to the airport and Banjo Island
- Vital infrastructure for tourism/business, medical emergencies, air-related evacuations
- Structure is ≈ 150 years old, and partially failed in last major hurricane
- In subsequent repairs, a layby was built that included gabion basket protection
- Due to its low-lying natiure, the causeway is closed during severe storm events

Location: Tyne's Bay SWRO Plant

Structure Characteristics:

Structure Class:	**Utility – Water Supply Plant**
Material:	**Reinforced Concrete Block**
Condition:	**1 (Very Good)**
Coordinates (UTM 20):	**333793 m (Easting)** **3576003 m (Northing)**

Structure Dimensions:

Running Length:	**200 m**	Width:	**150 m**

Description of Structure:

- Currently largest desalination plant for Bermuda (750K Imperial Gallons per Day)
- Imfrastructure elements are significantly elevated above Mean Sea Level
- Reduced risk from storm surge at present-day sea levels

Location: Sol Fuel Terminal

Structure Characteristics:

Structure Class:	**Utility – Fuel Terminal**
Material:	**Reinforced Concrete Block**
Condition:	**2 (Good)**
Coordinates (UTM 20):	**339965 m (Easting)** **3583105 m (Northing)**

Structure Dimensions:

Running Length: **130 m** Width: **5 m**

Description of Structure:

- Main fuel receptor terminal for Bermuda
- Infrastructure appears to be in generally good condition
- Infrastructure at the shoreline (jetty, conveyor belt, etc.) shows signs of corrosion

Location: Railway Trail




Structure Characteristics:

Structure Class:	**Cultural/Historical – Walking Trail**
Material:	**Natural Ground**
Condition:	**3 (Fair with signs of deterioration)**
Coordinates (UTM 20):	**338570 m (Easting)** **3581519 m (Northing)**

Structure Dimensions:

Running Length: **m** Width: **m**

Description of Structure:

- Some sections of trail show signs of erosion and exposure to potential wave damage
- The Sol pipeline is located along some sections of the trail
- Periodic inspection by Sol have revealed pipeline corrosion, which has led to shoreline reinforcement and/or pipeline replacement

Location: North Shore Residences

Structure Characteristics:

Structure Class:	**Residential Housing**
Material:	**Concrete Block,**
Condition:	**2 (Good)**
Coordinates (UTM 20):	**m (Easting)**
	m (Northing)

Structure Dimensions:

Running Length: **m** Width: **m**

Description of Structures:

- Conditions along the north shore vary
- Some areas are on high ground and well set back from the sea, while others are low lying and require protection by seawalls
- Some buildings are located directly on the shoreline and accommodate small craft vessels which dock against the seawalls. With sea level rise, the long term viability of these residences and their functionality will be compromised.

Location: Fort St Catherine

Structure Characteristics:

Structure Class:	**Seawall**
Material:	Concrete
Condition:	**3 (Fair)**
Coordinates (UTM 20):	**342485.17 (Easting)** **3584977.62 (Northing)**

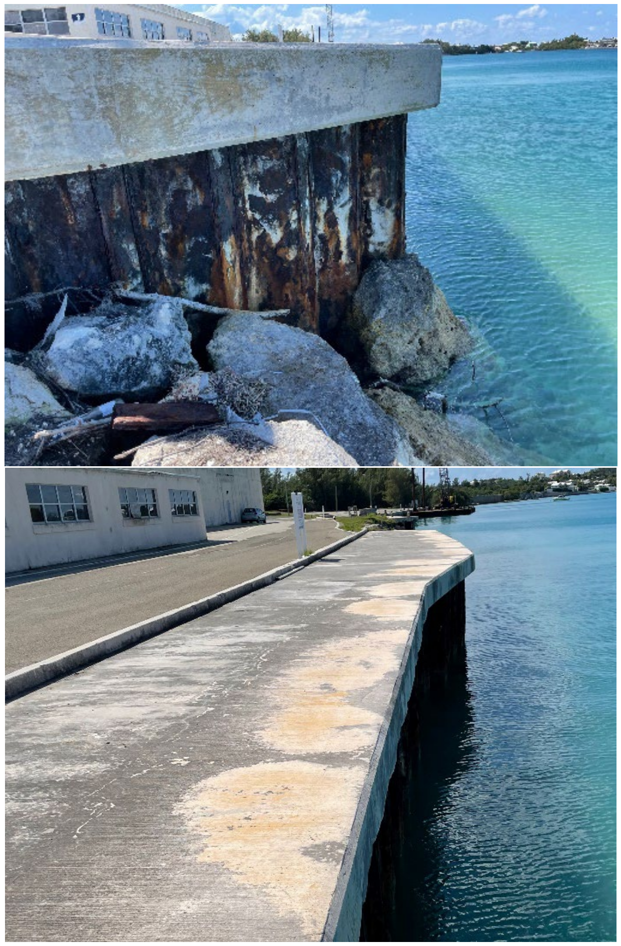
Structure Dimensions:

Running Length: **~190m** Width:

Description of Structure:

- Concrete wall with a foundation in sand rock.
- Vertical segments of the wall intact.

Location: Dock at Bermuda Land Development Company (BLDC)



Structure Characteristics:

Structure Class:	**Seawall**
Material:	Concrete and Sheet piles
Condition:	**2 (Good)**
Coordinates (UTM 16):	**341881.53 (Easting)** **3582790.23 (Northing)**

Structure Dimensions:

Running Length: **~45m** Width: **~3m**

Description of Structure:

- Metal sheet piling appears undermaintained, with evidence of rust.

Location: Dock at Bermuda Land Development Company (BLDC)

Structure Characteristics:

Structure Class:	**Rubble Mound Revetment**
Material:	Boulders
Condition:	**4 (Poor)**
Coordinates (UTM 16):	**341881.53 (Easting)** **3582790.23 (Northing)**

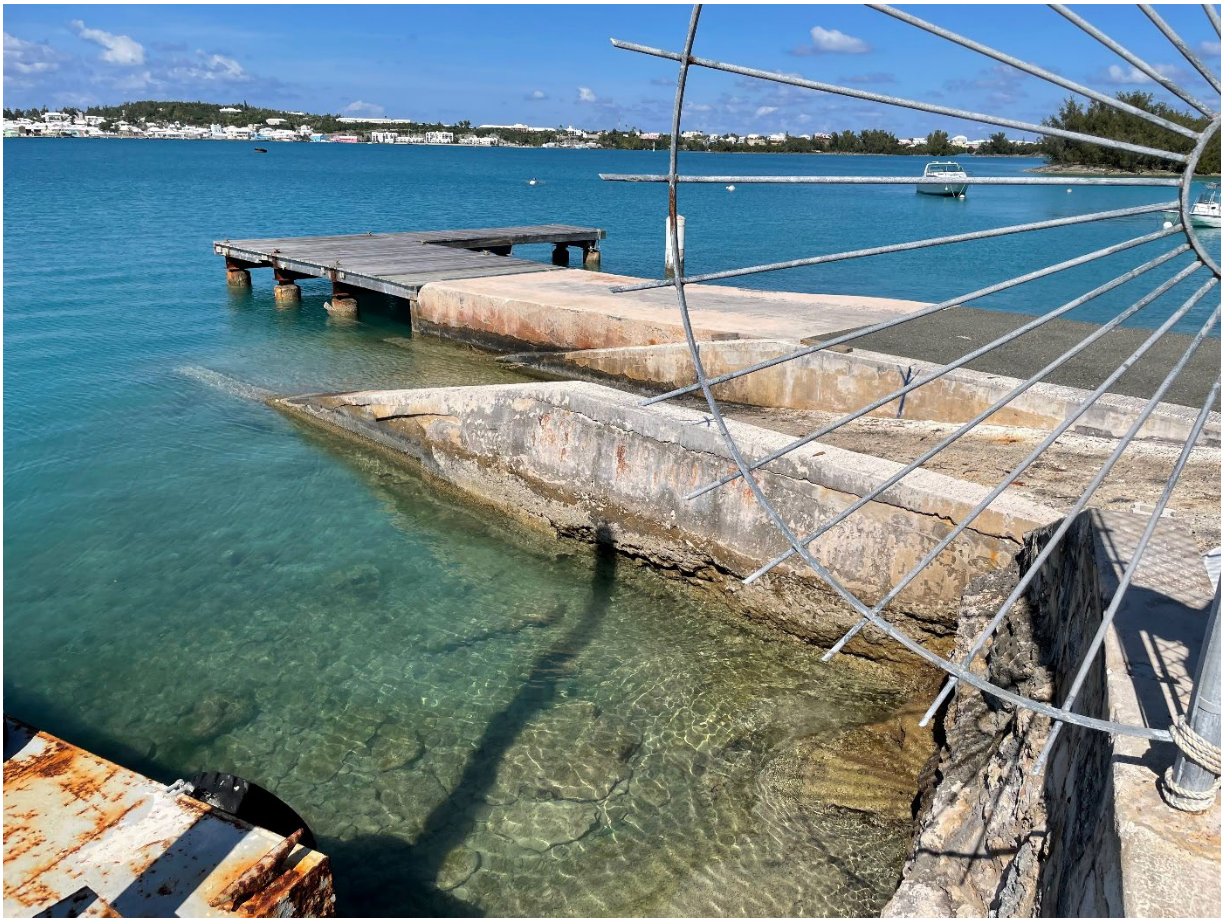
Structure Dimensions:

Running Length: **~45m** Width: **~3m**

Description of Structure:

- Several displaced stones
- Needs to be repacked.

Location: Dock at Bermuda Land Development Company (BLDC)



Structure Characteristics:

Structure Class:	**Boat Dock and Ramp**
Material:	Boulders
Condition:	**2 (Good)**
Coordinates (UTM 16):	**342209.81 (Easting)** **3582718.54 (Northing)**

Structure Dimensions:

Running Length: **~26m** Width: **~3m**

Description of Structure:

- Evidence of scraping at the foundation of structures.
- Piles are intact, with no evidence of failure.

Location: Dock at Bermuda Land Development Company (BLDC)

Structure Characteristics:

Structure Class:	**Bridge**
Material:	Concrete
Condition:	**4 (Poor)**
Coordinates (UTM 16):	**341365.43 (Easting)** **3582887.07 (Northing)**

Structure Dimensions:

Running Length: **~40m** Width: **~6m**

Description of Structure:

- Derelict bridge.

Location: Sea Defence, Town of St George's

Structure Characteristics:

Structure Class:	**Seawall**
Material:	Concrete
Condition:	**2 (Good)**
Coordinates (UTM 16):	**342123.53 (Easting)** **3583817.77 (Northing)**

Structure Dimensions:

Running Length: >400m   Width: **~6m**

Description of Structure:

- Low elevation wall used for retaining land for residential and commercial properties.

Location: Sea Defence, Airport

Structure Characteristics:

Structure Class:	**Revetment**
Material:	Concrete Units and Boulders
Condition:	**2 (Good)**
Coordinates (UTM 16):	**339979.45 (Easting)** **3581544.96 (Northing)**

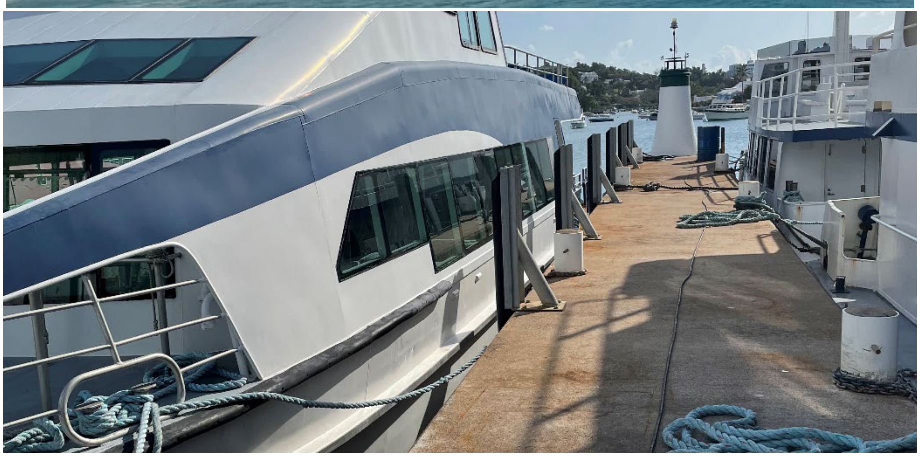
Structure Dimensions:

Running Length: >1600m Width: **undetermined**

Description of Structure:

- Rubble structure held together by concrete grout which reduces the permeability of the structures.
- The elevation of the structure is set about 2m above sea level.

Location: Front Street (Ferry Terminal)



Structure Characteristics:

Structure Class:	**Seawall and Floating Dock**
Material:	Concrete
Condition:	**2 (Good)**
Coordinates (UTM 16):	**332667.79 (Easting)** **3574299.94 (Northing)**

Structure Dimensions:

Running Length: >150m   Width: **undetermined**

Description of Structure:

- Concrete seawall that is used as the cruise berths.
- The dock is relatively low and can likely be flooded under storm events.
- A few of the fenders along the berths have failed used to repeated collisions.

Location: Somerset Bridge

Structure Characteristics:

Structure Class:	**Bridge**
Material:	Concrete
Condition:	**3 (Fair)**
Coordinates (UTM 16):	**323316.01 (Easting)** **3572828.95 (Northing)**

Structure Dimensions:

Running Length: >150m Width: **undetermined**

Description of Structure:

- This is a drawbridge that connects the parish of Sandy's.
- Rubble revetment is used to stabilise the banks of the channel.

Appendix E Meetings

February 28 – March 4, 2022
This memo details notes and observations made during the initial project visit to Bermuda by Smith Warner International (SWI) representatives David Smith and Edward Albada. Two field visits were conducted on 2 March 2022 by land and by sea and on 3 March 2022 by land to view coastal areas and infrastructure vulnerable to climate change and exhibiting evidence of coastal erosion. Meetings were also held throughout the entire visit with key stakeholders.

	Meetings Details	Attendees
1	**Sean Patterson, Chief Land Surveyor** Date: 1 March 2022	• Victoria Pereira, Director, Department of Planning • David Smith, SWI

- The new LiDAR data set has revealed previously uncovered shipwrecks.
- Topographic data is referenced as Land Datum, and bathymetric data are referenced as Marine Datum. The two datum references are to be harmonized.
- A 4TB external drive was identified as being required to download the LiDAR dataset.
- This dataset also contains aerial photography at a 10cm pixel resolution, as well as contour data at 2m contour intervals. More detailed resolution may be extracted from the raw data.
- It was noted that the seabed around Bermuda was mapped (benthic mapping) under the Bermuda Ocean Prosperity Programme (BOPP). This data is to be obtained.
- It was noted that a Chinese fishing vessel, the Xing Da, had been sunk off the north-west coast of the island to provide a dive destination. The currents at that location proved to be so strong that the vessel was torn apart within a year and reduced to a pile of metal plates.
- To the best knowledge, current meters have not been deployed offshore Bermuda.
- There used to be a tide gauge on the Esso pier, run by NOAA. This was in operation for 19.5 years. It was decommissioned and relocated within the lagoon at the Bermuda Institute of Ocean Sciences (BIOS) station. Data from this gauge can be obtained online from the NOAA website.
- The UK Hydrographic Office gave the Survey Department two (2) tide gauges. One on Ordnance Island, St George's and the other by Summerset Bridge (although this was not properly related to a datum).
- It was mentioned that NOAA has been looking at re-establishing the tide gauge on the Esso pier.

- The Survey Department does not have a copy of the Tennex Lads LiDAR data from 2004 and would like to receive a copy from SWI. This data set is to be brought to Bermuda by Philip Warner on 20 March 2022.
- We should note building footprints from the recent LiDAR data, as well as observed hurricane flooding locations.
- Has tsunami risk been examined for Bermuda? A tsunami exercise was modelled by NOAA in 2016. This may be seen on the NOAA Natural Hazards Viewer.

2	**Mark Guishard, Director Bermuda Weather Services** **Date:** 1 March 2022	• Victoria Pereira, Director, Department of Planning • Jeanie Nikolai, Dir. Of Energy • David Smith, SWI

- There has been recent flooding in the square of St George due to tidal excursions and rainfall.
- The Island Resiliency Action Challenge has been working on a Resiliency Scorecard that can be applied to Bermuda to better assess risk for investors. The work is ongoing and currently seeks to identify and address the 'gaps between the 'ordinary' cost of infrastructure and that which is necessary to build for resilience in the face of climate change. The work is being done through the Caribbean Renewable Energy Forum.
- SWI to have a chat with people from Building Services. How resilient are buildings (offices and residences) to hurricane winds? The Building Code is being updated.
- The wave model used by the BWS is applied in a predictive mode. It was written expressly for the BWS.

3	**Dr Geoff Smith, Director Dept. of Environment & Natural Resources** **Dr Shaun Lavis** **Patricia Hollis** **Date:** 1 March 2022	• Victoria Pereira, Director, Department of Planning • Jeanie Nikolai, Dir. Of Energy • David Smith, SWI

- The Dept. of Environment & Natural Resources has a lot of information and operate as regulators.
- Many underground storage tanks are believed to be within the hazard zone.
- A recent study by Princeton University stated that Nitrate-nitrogen from cesspits has been detected within the structure of corals off the north shore. [We need to obtain the Princeton study].
- Treated effluent is typically discharged to the sea.

- Dr Geoff Smith agreed to send their PowerPoint presentation to the Department of Planning for sending on to us.
- We will also get from the DENR the metadata base of GIS shape file coverages and we can indicate the areas of interest.
- We should include the solar farm installation.

4	**Victoria Pereira, Director, Department of Planning** **Date:** 1 March 2022	• Kenny Campbell, Snr. Planning Officer; Paul McDonald, Development Manager; Mandy Shailer, GIS • David Smith, SWI

- There is a desire to see flood risk mapping for storm surge and for rainfall inundation.
- There is a Coastal Development Policy.
- There is a Climate Change Report from the National Trust.
- There is a Sustainable Drainage Policy, which mirrors the policy approach adopted by the UK.
- The concept of sustainable return periods (e.g. 1:50, 1:100 and 1:200 etc.) should be examined.
- GIS department (Mandy Shailer) can get us the ESRI shapefiles that we want. They have an Enterprise License with ESRI.

5	**Minister and Permanent Secretary in the Ministry of Home Affairs** **Date:** 2 March 2022	Attendees: • The Hon. Walter H. Roban, JP, MP, Minister of Home Affairs • Rozy M. Azhar, Permanent Secretary, Minister of Home Affairs • Victoria Pereira, Director, Department of Planning • David Smith, SWI • Edward Albada, SWI

- Hon. Minister Roban and PS Azhar welcomed SWI and expressed enthusiasm for the coastal study.
- Hon. Minister Roban identified that some of the owners of the coastal lots acquired these lots via inheritances from relatives who purchased (or were granted) lots at a much less value than they are today. With the appreciation in the value of the land over time, the present owners seek to develop on the lots as a means to improve their financial standing. However, recent understanding of the vulnerability of the coastlines in light of climate change (through this study, for example) may lead to planning

constraints on developments (e.g. within nature reserves or with footprints too close to the coast), thereby minimizing the return potential. The new planning constraints may create discomfort to these developers.

- Given that much of Bermuda's infrastructure has been developed throughout history in the coastal zone, a blanket approach of coastal retreat to all areas is neither feasible nor a viable consideration. There may be areas where other mechanisms should be considered, such as coastal hardening/protection or adaptation.
- PS Azhar identified some important areas of the study including the effects of coastal climate change on the water table, agriculture, subsea infrastructure, fuel tanks, fibre optic cables, etc. The study should identify the critical areas and indicate prioritization for action based on vulnerability.
- Hon. Minister Roban accepted that the study would not necessarily result in a "quick fix" solution, and the intent it that the study will be applied for longer term planning purposes.
- Public awareness opportunities were discussed to raise enthusiasm for the project.

6	**Tynes Bay Industrial Complex** **Date:** 3 March 2022	Attendees: • J. Tarik Christopher, Principal Engineer, WSS, Ministry of Public Works • Victoria Pereira, Director, Department of Planning • David Smith, SWI • Edward Albada, SWI

- There are 4 desalination/RO plants on Bermuda under Government control:
  - Tyne's Bay SWRO where water is produced using energy derived by the adjacent WTE plant
  - Fort Prospect WTP
  - Tudor Hill WTP
  - Containerized RO (Currently located at BLDC, Southside)

Of these, only Tyne's Bay has coastal infrastructure and extracts seawater.

- Another private producer of RO water exists, Watlington Waterworks. The infrastructure for Watlington Waterworks is separate from Tyne's Bay.
- Concerns of coastal-related climate change with regard to Tyne's Bay include the potential for impact on:
  - Tyne's Bay three seawater wells, which are on the coast adjacent to the plant.

- The approximately 200 freshwater wells scattered throughout the island.
- Tyne's Bay cooling water intake and discharge infrastructure.

- The Government recently completed a demand forecast as part of a waste and Water Utility business Case, part of a Water and Wastewater master plan.•
- The Tyne's Bay WTE and SWRO main plants (other than the coastal infrastructure) is located approximately 6m above sea level.'

Meetings: March 22 - 24, 2022
This memo details notes and observations made during the project site visit to Bermuda by Smith Warner International (SWI) representative Philip Warner. Field visits were conducted on March 22, 23, and 24. Meetings were also held throughout the entire visit with key stakeholders.

	Meetings Details	Attendees
7	**Bermuda Institute of Ocean Sciences** Bill Curry, President • Date: 22 March 2022	• Victoria Pereira, Director, Department of Planning • Philip Warner, SWI

- BIOS main focus is on offshore, deepwater research and data collection. Funding arrangements have facilitated a long time series of deep ocean measurements.
- NOAA sea level gauge data goes back 80 years and trend analysis shows a 2.17mm/yr rise.
- Coastal research and data collection has been done, but not through a long-term funding arrangement. This has resulted in ad hoc programmes.
- Two researchers were identified who may have collected information on nearshore currents and have done circulation modelling; Rod Johnson and Tim Noyes. Email contact has been established with these individuals.
- Mesoscale eddies have impacts on the water levels in Bermuda. These extend through the photic zone and move through the area at 4 km/d, typically raising (if counter clockwise rotation) or lowering (clockwise) for several weeks at a time.
- Potential to share data from the four-month data collection program was discussed. VP to verify that the data could be shared (This was later confirmed, but limited to BIOS researchers).
- Coral reefs are "healthy" and not subject to bleaching events. This may be due to the temperature variations they are exposed to. Growth is slower than corals in warmer waters.

8	**Sol Bermuda** Nick Ball, Alcindor Bonamy, Stephanie Simons **Date:** 22 March 2022	• Victoria Pereira, Director, Department of Planning • Philip Warner, SWI

- Facilities include the 500' pier, tank farm, and 8.3mile long pipeline that supplies BELCO, tank farm, and a jet fuel facility at the airport. Sol imports gas, diesel, jet-fuel, heavy fuel, and lpg, and is the main importer for the island. This infrastructure is therefore critical.
- Pipeline dates from 1972 and is inspected every 5 years using an internal instrument that evaluates wall thickness to detect corrosion. Results from these surveys are used to guide repairs and replacement programs.
- The pipeline is owned by Sol, but is on government lands. Much of the route follows the Railway Trail, a public footpath along the north coast.
- Past work has been done to stabilize eroding sections of the footpath where the pipeline is at risk from erosion or storm damage. Sol carries out this work to protect their asset, with permission/knowledge of government. Repairs are frequently done when problems arise, and studies or engineering designs are not typically done. Contractors suggest solutions to pressing problems, due to time and access constraints.
- Pipeline has three water crossings. Sol to provide an annotated drawing showing the pipeline and notes of historical repair works and issues along the route.
- NOAA water level gauge on the Sol pier, but it has not been working since 2019.
- Pier was extended in 2005 and revised in 2012. Recent survey conducted in 2019. Moffat Nichols prepared the engineering design.
- Sol has a hurricane contingency plan, including shut-off valves on both ends of water crossings, and filling BELCO tanks.
- Tsunami modelling done for 10m and 20m wave. (On subsequent meetings with BWS the nature of the modelling was revealed to be a simple doubling of offshore tsunami wave height, rather than hydrodynamic wave propagation modelling).

9	**BELCO** President, Managers of Production, Transmission, Distribution, Safety, and Communications Officer Date: 22 March 2022	• Victoria Pereira, Director, Department of Planning • Jeanie Nikolai, Dir. Of Energy • Philip Warner, SWI

- BELCO has made many preparations to accommodate climate change. All transmission lines are buried. There is only one substation that is at risk and plans exist to relocate.

- BELCO is planning on a major shift to renewable energy, and therefore the reliance on the Sol fuel pipeline will be reducing over time.
- The main generating facility is located in a potential flood zone. BELCO indicated that maintenance of the canal will ensure adequate drainage.

10 Marine and Ports Services

- Rudy Cann, Malcolm Bailey

Date: 23 March 2022

- Victoria Pereira, Director, Department of Planning
- Philip Warner, Miles Harris, SWI

- Marine and Ports operates 21 vessels including ferries, tugs and workboats. The main docking area is adjacent to the port. Other facilities are located at Dockyard and at other ferry terminals.
- Marine and Ports is responsible for the vessels, the docks are maintained by Public Works.
- Issues arise during storm surge events as the fendering systems are not high enough.
- Cruise ships and other vessels rely on the tugs for berthing. Hurricane tracking information means cancellations are done earlier.
- Project on stream to relocate fuel system from its present location to put tanks on higher ground. Awaiting lease finalization with other involved parties.
- Marine and Ports to supply maps showing ferry routes.
- SWI to provide coordinates of instruments so that M&P can issue marine advisory to avoid anchoring in the vicinity.

11 Bermuda Weather Service

Mark Guishard

Date: 23 March 2022

Attendees:

- Philip Warner, Miles Harris, SWI

- BWS started primarily as aviation support, but has expanded to marine (wave model) and also issues hurricane warnings, etc.
- MG expressed support in on-going measurement programme and a desire to continue afterwards.
- MG explained the tsunami modelling that was undertaken and its limitation to a simplified approach.
- Rainfall data is available on BWS website and additional radar acquired images may be available 6-hourly accumulations.
- Maps of mesoscale eddies are available from satellite altimetry.

- MG to provide links to tsunami and storm surge animations from Steve Ward.

12	**West End Development Company** **Andrew Dias** **Date:** 23 March 2022	Attendees: • Philp Warner • Miles Harris, SWI

- A site tour was undertaken visiting the dock areas, recent America's Cup landfill area, the dump area and along the mini golf lands.
- Critical facilities, such as the water treatment plant, desal facilities, water storage tanks, warehouses, cement storage silos, and others were observed.
- Due to the nature of this coastal development, it is exposed to climate change risks from increased storm surge and increased frequency of severe hurricanes.
- Photographs of the site visit are provided below.

13	**Corporation of Hamilton, Port Facilities** **Patrick Cooper** **Date:** 24 March 2022	Attendees: • Victoria Pereira, Director, Department of Planning, • Kenneth Campbell, Planning Officer • Philip Warner, SWI

- After a brief safety discussion, a tour of the port facilities was undertaken. No photos were allowed on the tour.
- Observations indicate that the dock height is adequate for the present water levels. Significant increase in the mean sea level would have to happen to force any upgrades to the port facilities. The overall condition of the dock structures (concrete cap on steel sheet piling) indicate that a major rebuild is not anticipated in the near term (<30 years).
- Concerns were voiced about protecting cranes and forklifts from water damage during storm surge events.
- Other factors, such as changes to 40' containers, may affect port operations before climate change impacts are felt. Stevedoring is a challenge due to the port being long and narrow in shape. Upgrades to the x-ray facility are anticipated to liberate deck space, along with some relocation of workshop and offices.
- Drainage from the City of Hamilton pass through the site.
- Discussions on the possible relocation of the port facilities to other sites were held, including logistical and cost implications.

14	**Lands and Surveys Department** **Sean Patterson** **Date:** 24 March 2022	Attendees: • Victoria Pereira, Director, Department of Planning, • Philip Warner, SWI

- A Zoom meeting was held to discuss available mapping. The LiDAR data is able to provide a high level of detail, perhaps enough to delineate areas of "rough" and "smooth" reef.
- Holes in the LiDAR coverage were discussed and there are plans to fill in those areas using multi-beam echo soundings. The timing of those surveys means that the modelling for this project will have to utilize existing bathymetric chart data.
- Holes were identified in Great Sound, Little Sound, Granaway Deep, Mills Creek, Harrington Sound, St. George's Harbour and adjacent to the port facilities in Hamilton.
- Using the topographic LiDAR to measure cliff erosion were discussed. Areas to examine could include Bailey's Bay and east of Spittal Pond, where SP had observed erosion.
- The nature of the Boiler Reefs were discussed, and the potential linkage to gaps and corresponding erosion pockets on land.
- Recreational areas of note, where storm surge and wave run-up were identified and included Pampas and Devonshire Bay.
- Coastal erosion at the solar farm has been estimated from aerial imagery to be ~1ha.