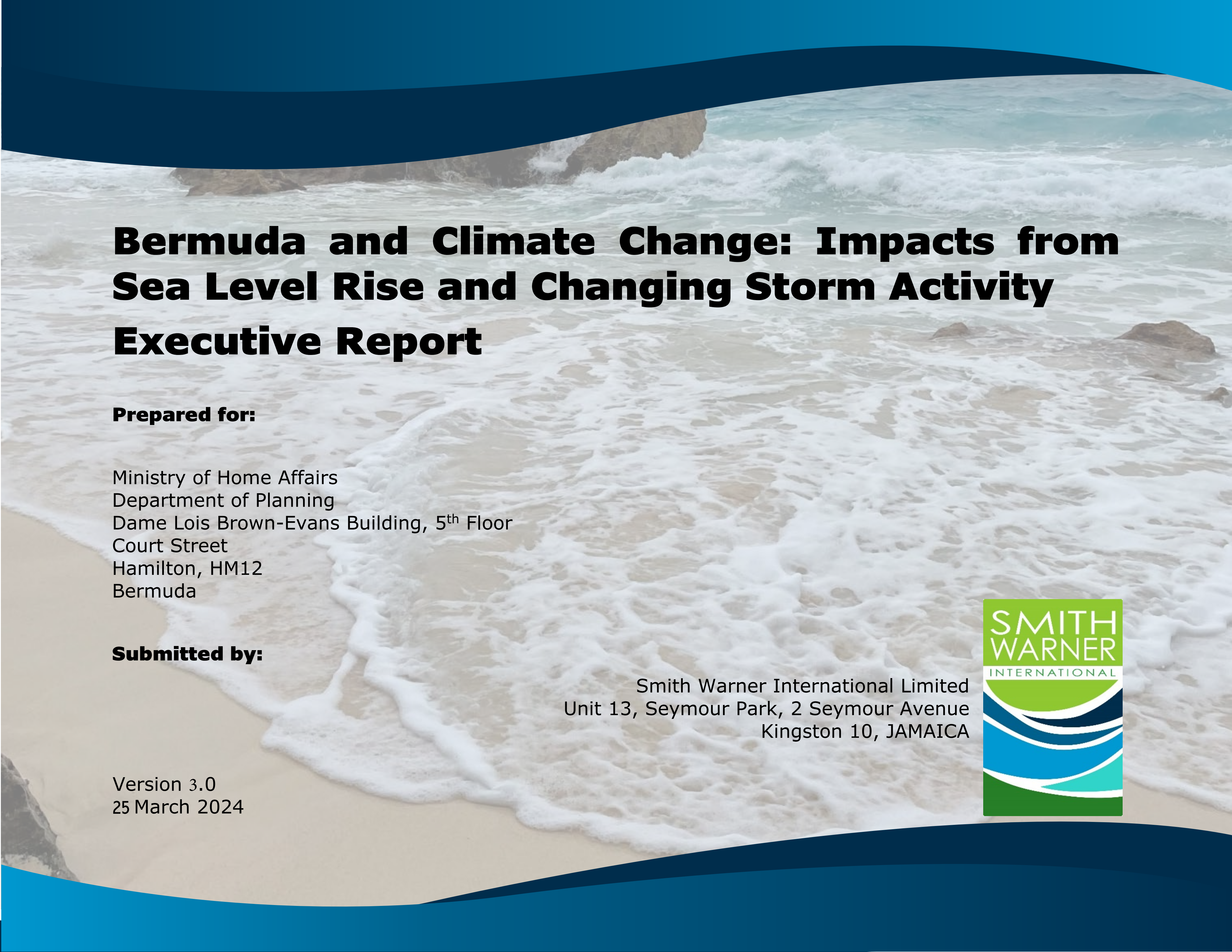

Bermuda and Climate Change: Impacts from Sea Level Rise and Changing Storm Activity

Executive Report

Prepared for:

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Contents

List of Abbreviations

GIS	Geographic Information System
IPCC	Intergovernmental Panel on Climate Change
LiDAR	Light Detection and Ranging
RCP	Representative Concentration Pathways
SLR	Sea Level Rise
SMU	Shoreline Management Units
SSP	Shared Socio-economic Pathways
SST	Sea surface temperature
SWI	Smith Warner International

Introduction

Purpose and Scope

The coastal and marine zones of Bermuda are dynamic: they are in a state of constant change. This, combined with a unique range of human and natural pressures presents challenges to sustainable long-term management of the coastline. These challenges are made worse by potential global climate change. Variations in key climate change parameters such as air/sea temperatures, hydrometeorological hazard patterns and sea level rise (SLR), influence physical processes (e.g., flooding and erosion) in the coastal and marine environments, which affect patterns of flooding and erosion, hydrodynamics, water quality and habitats. These changes can all have significant implications for the planning and operation of existing and future uses of these areas.

Planning Outlook Selections

When planning guidelines include responses to extreme events such as coastal flooding, a statistical approach to climate change that covers most of the risk and unknowns and provides sustainability is often adopted. The selection of a recommended planning outlook for Bermuda was based on an assessment of the various permutations of scenarios, and ultimately is divided into:

    - The *Planning time horizon*, or period of time under consideration, is assumed as **100-years**, in keeping with accepted planning benchmarks for flood studies.
    - The *Return period of the extreme event* is the severity of the event, typically analysed through a statistical risk occurrence process. A common benchmark is to apply a (present day) **1:100-year return period event**. However, recent findings suggest that for flooding events today's predictions of extreme events will become more common in the future. Hence a more robust **1:150-year event** is recommended for a coastal storm (for both waves and storm surge).
- The *Emission pathway*, or climate change scenario, is the selection of the greenhouse gas emission scenario applied in the study, which principally effects the Sea Level Rise (SLR) parameter. Recent (2023) scientific data has measured an increased rate of SLR, primarily from thermal expansion of oceans and enhanced meltwater contributions from the Greenland and Antarctic ice sheets; the more pessimistic Shared Socio-economic Pathways (SSP) 5-8.5 (≈ RCP8.5) emissions scenario (detailed in the **Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report, AR6) is therefore recommended for use in Bermuda.**

Bermuda's Climate Change Predictions

An important part of assessing Bermuda's coastal vulnerability is the most recent projections of climate change, based on the latest understanding and research on the expected scenarios of the earth's environment. The table[1] below summarises the parameters considered and changes observed, as well as the projections, based on historical data and climate change models respectively.

Parameter	Historical Trend	Projection
Temperature	Air temperature varies through the year with highest temperatures from July - September and lowest in January - March. Mean monthly temperature has been increasing between 0.22°C and 0.6°C per decade. Hot days & nights have also been increasing at a rate of 4% & 3% per decade, respectively.	Temperature is expected to keep increasing with global warming. In the medium term (2040-2060) the projected annual increase is between 0.6 & 1.7℃. In the long term (2070-2090) the projected annual increase is between 0.6 & 3.2℃. Hot days & nights are increasing & will account for nearly 100% of days by end of the century (under RCP 8.5). Heatwave durations are increasing & will reach near 60 days by the end of the century (under RCP 8.5). The World Meteorological Organization (WMO) defines a heat wave as a period during which the daily maximum temperature exceeds for more than five consecutive days the maximum normal temperature by 5℃, the normal period being defined as 1961–1990.
Rainfall	The island's climatology exhibits a bimodal rainfall pattern with peaks in January and September, and with the September peak receiving more rainfall.	The RCPs suggest no real varying trend toward the end of the century. In the medium term (2040-2060) mean annual rainfall projected change is 4 - 11%. In the long term (2070-2090) mean annual rainfall projected change is 3 - 48%. Extreme events will be characterised by significant interannual variability. However, rainfall indices reflect no real overall trends with, for example, projected change in consecutive dry days (CDD) of between 0.1 & 0.2 days/decade & changes in consecutive wet days (CWD) of 0.0 & 0.2 days/decade.
Sea Surface Temperature (SST)	SSTs are highest between August - September & coolest from December - April. SSTs are increasing at a rate of 0.26 ℃ per decade.	SSTs are projected to increase at a rate of 0.43 ℃ per decade (under RCP 8.5). In the medium term (2040-2060) monthly projected increase ranges from 1.0 – 2.3 ℃ (for RCP 8.5). In the long term (2070-2090) monthly projected increase ranges from 2.5 – 4.0 ℃ (for RCP 8.5).
Sea Level Rise	Bermuda lies in an area that has experienced sea level rise of more than 3.84 mm/year.	For Bermuda, there is good consensus across the two mapping tools examined about SLR. By 2100, mean SLR is projected to be approximately 0.69-0.82m for SSP5-8.5 (more than the global SLR estimate of 0.77m). However, this estimate does not include revised Antarctic ice-sheet contributions, incorporation of which may result in a worst-case SLR of up to 1.46m for Bermuda ("low confidence" SSP5-8.5 scenario). For this study, the median SSP5-8.5 scenario was applied, with a SLR rate of 10.5 mm/year.
Hurricanes	Over the last 4 decades there were 21 storms passing within 50km of Bermuda. 5-8 storms passed per decade except for 1991 to 2000 when no storms were recorded passing within 50km.	The future will likely be characterized by more intense hurricanes (Categories 3, 4 and 5) with corresponding high winds and greater rainfall. A likely increase in rainfall rate of between 20% and 33% is projected, particularly near the hurricane's core, by the end of the century.

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[1] Clarke, L., Taylor, M. & Maitland, D. 2022. "Climate Profile and Projections for the Island of Bermuda", Climate Studies Group Mona, University of the West Indies, Mona, Jamaica.

Coastal Hazards that were Assessed

Wave & Surge Dynamics

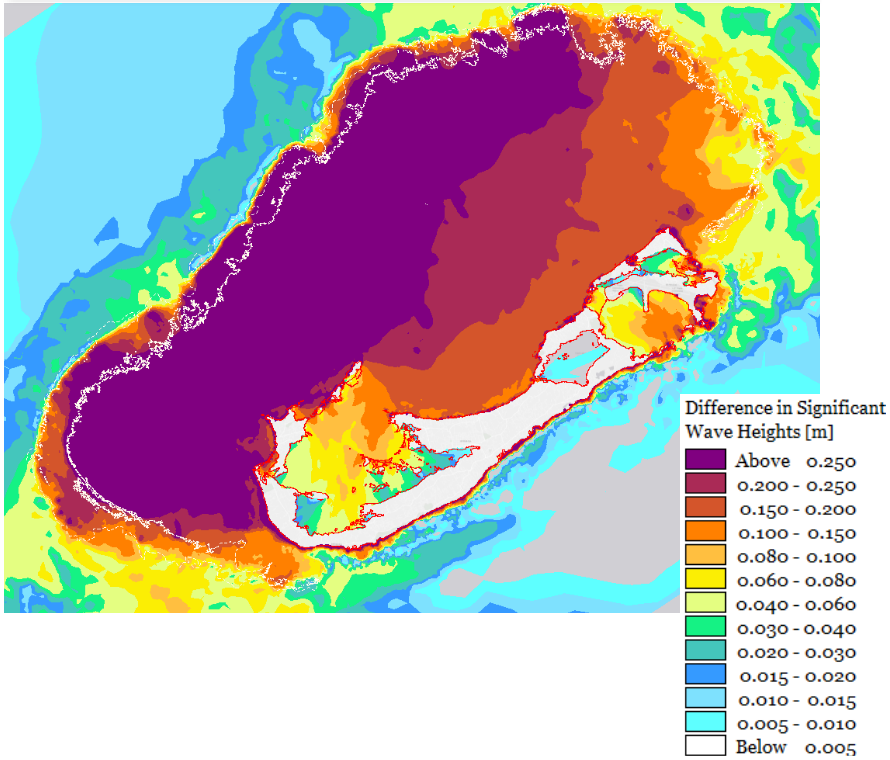
Regular (Yearly/Operational) Wave Events

Bermuda's coastline is largely protected from storm waves by the outer reefs, which act as a natural barrier against incoming wave energy. With SLR, the water depth over the reef crest increases, diminishing the outer reef's function as a breakwater, and allowing additional wave energy to propagate over the reef structure and into the lagoon. This results in more impact on the shorelines.

The increase in wave energy due to SLR will be more prominently felt on Bermuda's northern coastline, particularly on the Somerset Village's northwest shore, where wave heights will increase by more than 0.25m. The Dockyards area is also at risk of greater wave energy hitting the shoreline, which may have implications for the maritime activities there: disturbances to cruise ships and ferries, general shipping, and navigation in the area.

The southern coastline has a less pronounced outer reef structure and is therefore already more exposed to severe waves. The change between present-day and 100 years into the future (with SSP5-8.5) is therefore quite small. For example, nearshore wave heights in the Long Bay Beach area are expected to increase by only up to 0.15m (approximately 10% increase) from 1.5m to 1.7m.

Change in significant wave heights between Yearly Maximum (99th percentile) Operational wave conditions from Present-Day (no SLR) and what is expected with 100-year SLR (SSP5-8.5)



Storm Surge and Elevated Water Levels

Storm surge refers to the increase in water level at the shoreline due to a passing storm. Elevated water levels are also manifested from SLR and oceanographic effects such as mesoscale eddies. Descriptions of some of these components are given below.

- ***Tide Level***
  Tides are the rise and fall of sea levels caused by gravitational forces exerted mainly by the moon and sun.

- ***Inverse Barometer Effect (IBR)***
  The atmosphere constantly exerts pressure on the earth and its oceans. A tropical storm has low pressure in its centre, which results in a localised sea level rise, called the inverse barometer effect.

- ***Sea Level Rise (SLR)***
  The SLR associated with the median SSP5-8.5 emissions scenario, adapted for Bermuda's waters was applied (10.5mm/year).

- ***Wind Set-up***
  As the wind blows over the water surface, it pushes water ahead of it, which piles up against the shoreline. The stronger the wind, the more energy is available to be transferred, and the longer the wind blows the more time that is available for the energy transfer to occur. Wind set-up is minimal over shorter fetches, however, Bermuda's waters are open to very long fetches.

- ***Mesoscale Eddies***
  Mesoscale eddies are large rotational gyres or currents within the world's oceans that can result in both increased and/or lowered water levels. Bermuda experiences mesoscale eddies that offshoot from the Gulf Stream current. Increased water levels from these eddies can contribute to coastal flooding. Smith Warner International Limited (SWI) analysed 25 years of measured tidal data at Bermuda Weather Service's St. George's Station to estimate the maximum superelevation resulting from mesoscale eddy effects in Bermuda's waters.

A summary of the water level contributions is given in the table below.

Parameter	Value	Notes
Highest Astronomical Tide (m)	0.84 m	Historical analysis
IBR (m)	0.49 m	Statistical hindcasting analysis
SLR by year 2124 (100-year horizon)	1.05 m	Adopted SSP5-8.5 SLR projection for Bermuda (10.5 mm/year)
Mesoscale eddies contribution	0.48 m	Tide gage analysis
Wind set-up	≈ 0.25m	Exact values differ by geographic location, determined through modelling

Extreme Storm Conditions

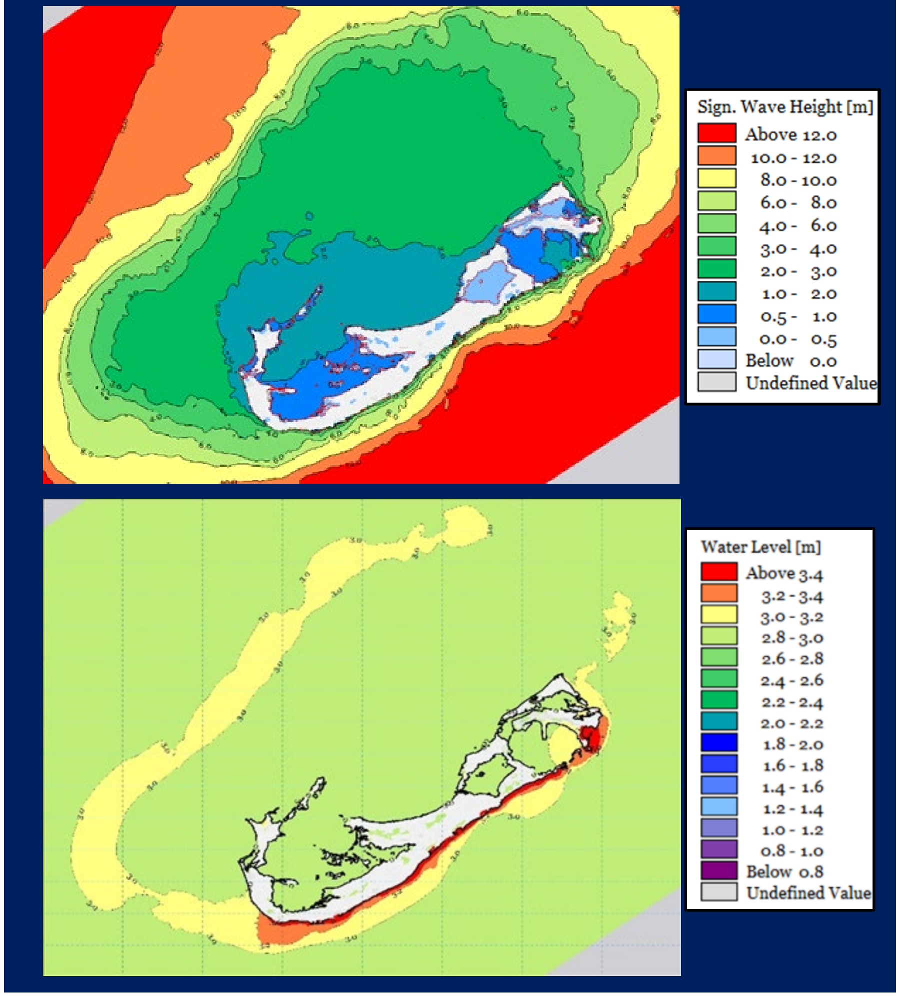
Extreme (tropical) storms can cause catastrophic damage to shorelines and coastal infrastructure through storm surge, wave impact, and wind. Interestingly, the statistical analysis on historical wave heights in the waters around Bermuda shows a decreasing average long term (40+ years) trendline. However, tropical storms themselves are documented to occur more frequently and with greater intensity over time. These storms will generate higher waves with elevated storm surge, and Bermuda's coastline is expected to be increasingly threatened.

Despite an elevated water surface from storm surge (including a mesoscale eddy), the reef effectively protects the North Shore from hurricane waves: wave heights are reduced from 10m (in deep water) to approximately 2m (inside the reef). Despite this reduction, waves of 2-3m on the North Shore can affect the shoreline, along with storm surge of approximately +3.0 m.

Unlike the North Shore, the South Shore has less protection from an outer reef. As a result, waves immediately offshore are 8-10m in height during a hurricane, with storm surge of more than +3.2m. The most vulnerable areas to a coastal storm include:

- The town of St George's;
- The Airport;
- Dockyard;
- Castle Harbour; and
- The islands of the Great Sound.

Wave Heights and Storm surge for 150-year RP, 100-year horizon, SSP5-8.5 SLR (includes Mesoscale Eddies)



Inland Flooding - Storm Surge and Rainfall

The Mill Creek and Pembroke Marsh catchment is recognized as one of the more vulnerable areas in Bermuda to rainfall-induced flooding due its low-lying terrain, seaward drainage, and potential for surge amplification. A model capable of representing concurrent surge and rainfall demonstrates the flood risk (right).

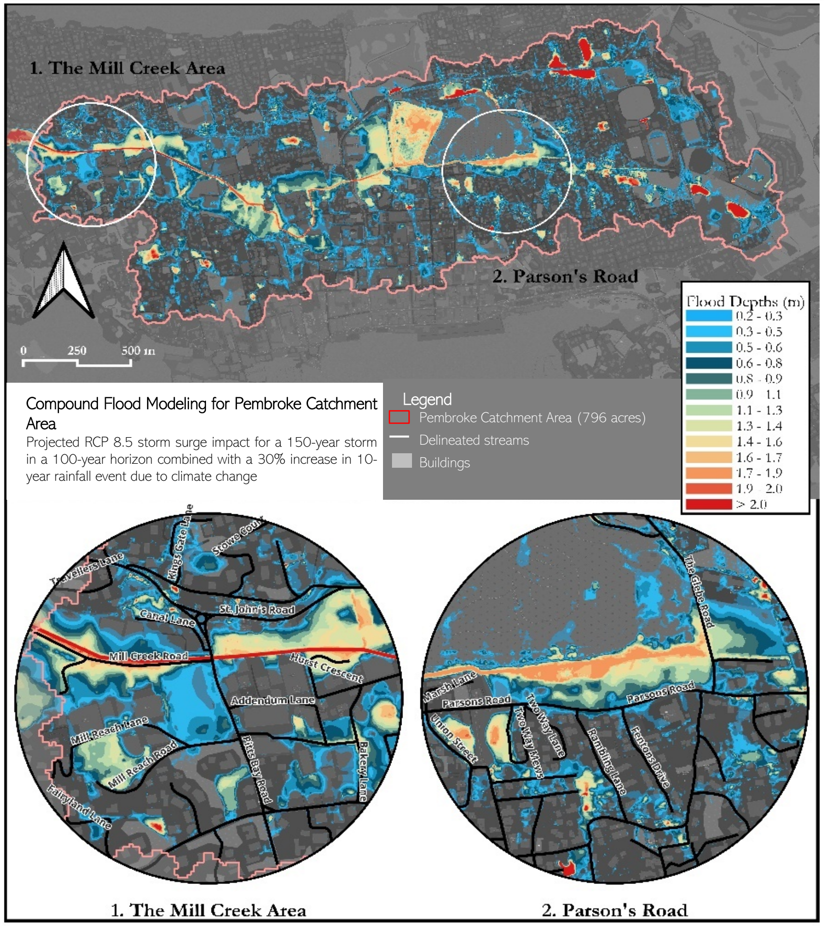
Notable areas of concern include:

- Properties along St. Johns Road, Mill Creek Road, and Pitts Bays Road, which filter to Baker Lane, where flood depths are up to 1.5m deep;
- Western Stars Sports Club (Dandy Town) along channel bank;
- Bermuda Athletic Association (Goose Gosling Field);
- Channel overflow by Laffan Street/Saltus Grammar School, with 0.4 -1.2m flood depths;
- Dellwood Middle School; and
- Pembroke Marsh Playground and North Street (1.5 - 1.7m flood depths).

Notable areas with pocket flooding include:

- To the northeast of the catchment along Palmetto/Roberts Avenue, where flooding reaches up to 3m;
- Bermuda Arboretum;
- Land next to Kings, Curving Avenue, and Curving Court;
- Old Rectory Lane;
- Cedar Avenue; and
- Along Palmetto Road (2.6 - 2.8m flood depths).

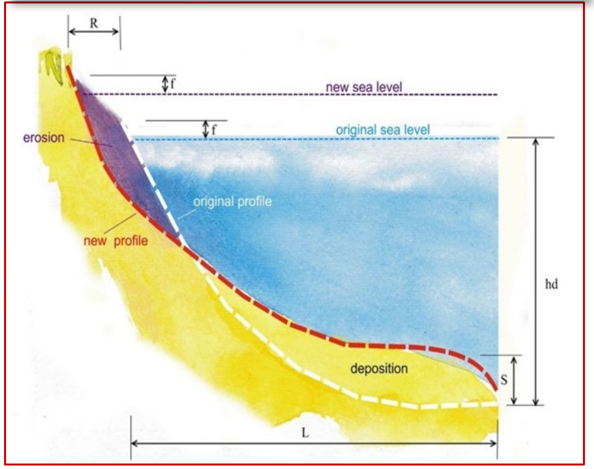
Storm surge + associated rainfall flood levels for 150-year RP, 100-year horizon, SSP5-8.5 SLR, [Surge combined with present-day 10-year rainfall increased 30% to account for effects of climate change]



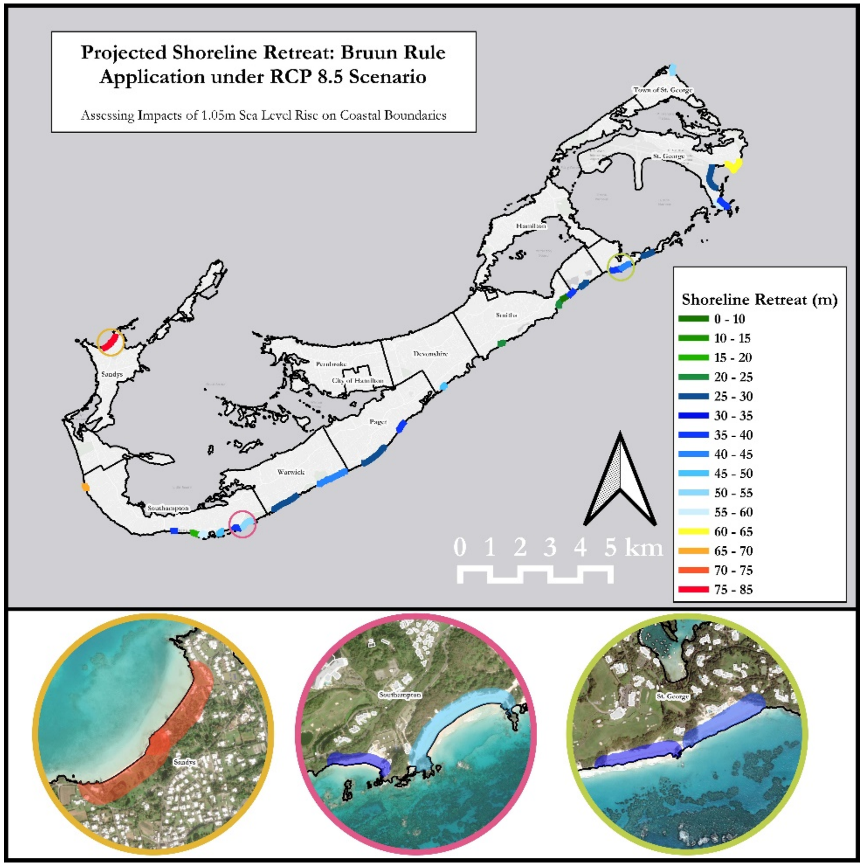
Beach Erosion

The first and best-known model relating shoreline retreat to an increase in local sea level was that proposed by Per Bruun (1962). The Bruun rule is applied to correlate SLR with beach erosion, as it estimates the response of the shoreline profile to SLR using the mean annual wave climate (IPPC 1998) including both daily and swell waves. Simply stated, the Bruun Rule asserts that a typical concave-upward beach profile erodes sand from the beach face and deposits it offshore to maintain constant water depth.

Definition sketch of the Bruun Rule applied to determine coastal retreat on sandy shorelines



Sandy shorelines longer than 50m were assessed. The figure (right) shows that under the SSP5-8.5 scenario by the year 2100 the southern beaches will have receded 30-65m.



Horizontal shoreline retreat considering 100-year time horizon for SSP5-8.5 SLR

Along the South Shore, Horseshoe Bay is predicted to retreat 60m and Warwick Long Bay 40m by 2100. The maximum retreat calculated is 75-85m close to the Dockyards, in an area with a wider zone of active transport.

The Brunn Rule has some limitations in that each sandy location would have site-specific conditions that affect the retreat. For example, the nearshore wave conditions could be affected by the presence of reefs and rock formations. The retreat would also be limited by hard substrates such as a cliff face. Erosion of a cliff face would, in turn, act as a supply of sediment to the beach. Anthropogenic influences such as properly designed coastal protection measures could limit the shoreline retreat in the future.

Cliff Erosion

Bermuda's coastal cliffs can be divided into two main categories: those with and without a fronting beach. Cliffs with fronting beaches mostly occur on the South Shore. Beaches of sufficient volume can provide protection to wave-driven cliff erosion. However, the beach-fronted cliffs around Bermuda were often observed to have a weak rock layer (paleosol) near the cliff base that is susceptible to erosion. As sea levels rise, the expected increase in wave heights and beach retreat (as modeled) make these cliffs particularly vulnerable to climate change and increased rates of erosion.

Conversely, low or moderate increases in future erosion rates are expected at sites with relatively small forecast changes in wave conditions, such as on the north coast, and where cliffs plunge directly into deep water (e.g., headlands). The modeled increase in day-to-day wave conditions was highest on westerly coastlines, suggesting a potential moderate acceleration of future cliff retreat rates at those sites.

Future retreat was estimated using the modified SCAPE model (Walkden and Dickson, 2008) which assumes cliff erosion is primarily driven by wave action. The modified SCAPE model assumes future cliff retreat depends on historical cliff retreat, and historical and future sea level rise. Based on the chosen SLR scenario, the future cliff erosion rate is projected to be 55 cm/year. SWI applied the modified SCAPE results to map potential retreat for cliffs greater than 2m in height. Some caveats of the analysis include:

- There is a paucity of available cliff erosion data. Measurements of historical cliff erosion are based solely on the Bermudiana Beach Resort on Marley Beach (where the historical erosion rate is calculated as 33 cm/year).
- If sea level rise causes waves to interact with a paleosol layer (or other weak layer) that is not currently actively eroded by waves, erosion rates would likely accelerate. The elevation and locations of the paleosol layers varies along the coastline and are not currently mapped in sufficient detail to allow geographic analysis of this factor.
- Additional observations such as high-resolution LiDAR (**li**ght **d**etection **a**nd **r**anging) and/or imagery are also needed to develop a detailed inventory of quantitative coastal cliff changes in Bermuda, to calibrate and develop robust models of coastal cliff evolution under future climate scenarios.

Strategic Infrastructure Vulnerability Mapping

The project modelling output is shown in vulnerability mapping of coastal erosion (through either sandy shores/beaches or coastal cliffs), coastal flooding from extreme storm events, and saltwater intrusion effects from rising sea (and groundwater) levels. The study geographically encompasses the immediate coastline as well as interior areas where groundwater elevations are expected to impact critical receptors. The Mill Creek and Pembroke Marsh catchment is also separately assessed due to its sensitivity to rainfall-induced flooding.

The receptors considered in this study are divided into "built infrastructure" (buildings, road network, and other critical infrastructure), and "reserve areas" (coastal, nature, and agricultural).

The following sections provide indicative mapping for one of the shoreline management units in the St. George's area for the more extreme SSP5-8.5, 100-year time horizon, 150-year event, as an example of the geographic information system (GIS)-based exercise for the "built infrastructure" receptors. The full mapping, including reserve receptors, is provided as GIS layers and featured in a convenient GIS-based web application here: https://arcg.is/0yTniT.

Shoreline Management Units

To make the assessment more accessible, the shoreline was divided into Shoreline Management Units (SMUs). These units are typically created by local authorities and agencies responsible for coastal management and are used to guide the development of policies and strategies for protecting the coastline and its communities.

The concept of SMUs recognizes that different areas of the coast have unique characteristics and require specific approaches to management. For example, a sandy beach may require different management strategies than a rocky coastline. SMUs are typically defined based on: (i) the physical characteristics of the coast, such as the type of shoreline, the presence of cliffs or dunes, and the degree of erosion and flooding risk; (ii) the exposure to wave action (i.e., the orientation of the shoreline relative to predominant wave directions); and (iii) the existing shoreline use.

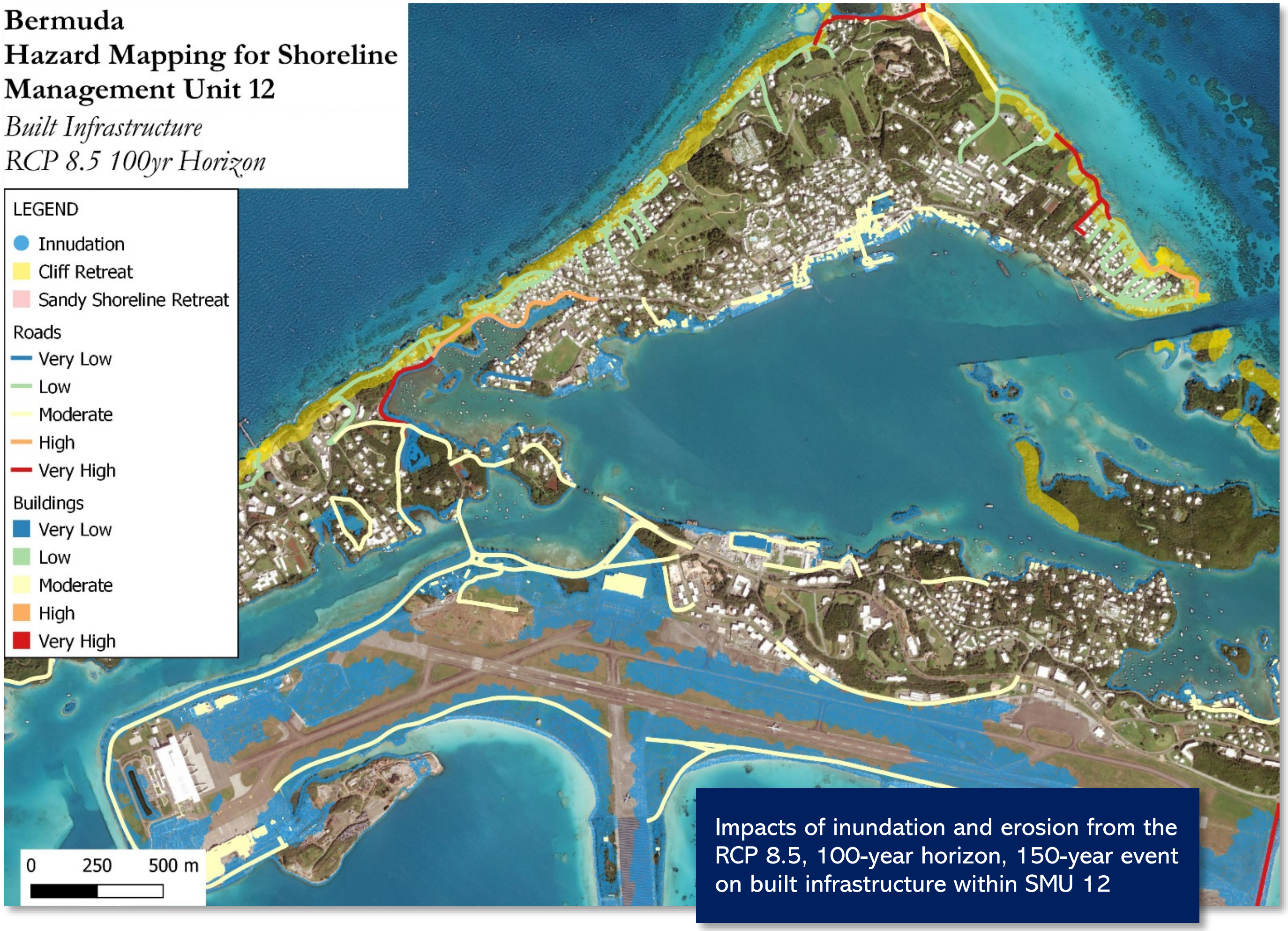
Hazard Mapping

Built Infrastructure

Flooding and Erosion

The graphic on the right shows the impacts of the hazards on built infrastructure - namely buildings and road infrastructure - that are under threat from inundation, shoreline or cliff retreat. The hazards are shown in the figure as inundation in blue, cliff retreat in yellow and sandy shoreline retreat in pink. Buildings and roads impacted by these hazards are colour-coded to the degree of vulnerability.

Under this scenario, buildings and roads in low-lying coastal areas are particularly vulnerable to flooding, notably in St. George's and the airport perimeter. Cliff erosion will likely threaten buildings on the northern coastline.



Impacts of inundation and erosion from the RCP 8.5, 100-year horizon, 150-year event on built infrastructure within SMU 12

Saltwater Intrusion

The figure at right shows the impacts of saltwater intrusion (based on expected groundwater elevations) on the built infrastructure, namely buildings and roads. The expected groundwater elevation (which has a different elevation from coastal to inland pond areas) is shown as a blue "saltwater intrusion" area. The affected assets are colour coded from blue (very low vulnerability) to red (very high vulnerability).

As expected, saltwater intrusion is expected in the lower lying areas along the coast, with a notable cluster in St. George's and the coastal road network around the airport.

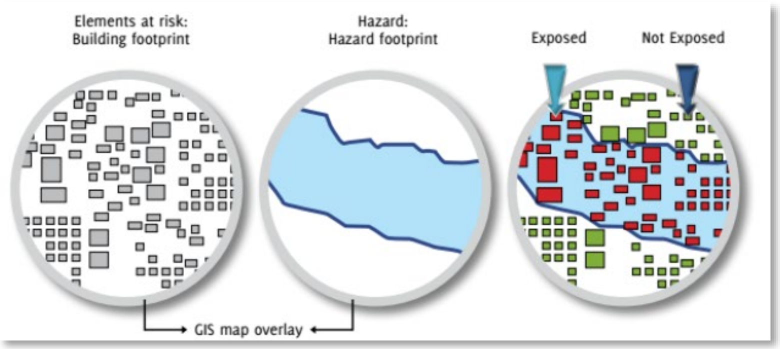
Impact of saltwater intrusion from the RCP 8.5, 100-year horizon on built infrastructure within SMU 12

Coastal Vulnerability Index Mapping

Once the hazards affecting various assets were identified, Bermuda's shoreline vulnerability was quantified in a simplistic "Coastal Vulnerability Index" (CVI). The index identifies individual locations at risk and clusters where remediation or corrective action should be taken.

The CVI approach involves a spatial geoprocessing technique that identifies the levels of exposure of those assets (ranked as Very High' to 'Very Low') to specific hazards, and those assets that are not exposed to the risks of flood and erosion.

Exposed elements at risk to flood hazard using CVI approach. Source: Jamaica's Office of Disaster Preparedness and Emergency Management (2016)



The following steps were used to generate the CVIs for each asset:

(1) Collect data for each hazard to which the asset in question is exposed.

(2) Flag the data for each variable for each location impacted. Assign "0" for no impact and "1" for an impact.

(3) Weight the variables in order of importance. Inundation (from a storm surge event) is considered highly important as there is little forewarning with impactful consequences, and thus is assigned a weighting of 50%. Cliff erosion also occurs with little/no warning and can be catastrophic; it is therefore assigned a 30% weighting. In comparison, shoreline retreat and saltwater inundation tend to develop more gradually and thus are assigned an equal weighting of 10% each.

(4) Calculate the Coastal Vulnerability Index using the following formula:

$$\begin{aligned} CVI = \; & (0.50 \times CVI_{inundation}) \\ & + (0.30 \times CVI_{saltwater\ intrusion}) \\ & + \left(0.10 \times CVI_{cliff\ retreat}\right) \\ & + (0.10 \times CVI_{shorelineretreat}) \end{aligned}$$

The resulting CVI values classify the coast into different vulnerability categories, such as low, moderate, high, or very high vulnerability.

Built Infrastructure

For ease of presentation of the CVI, each receptor within the "built infrastructure" is plotted separately. Hence, independent mapping is provided for buildings apart from the road network.

Buildings

The figure at right presents the CVI for buildings. Each building impacted by any of the hazards under consideration is colour coded in accordance with the severity of risk. A building impacted by only one hazard is shown as green, with progressive colouring from yellow, orange to red with increasing hazard impacts.

As expected, the low-lying buildings of St. George's (including the ferry and cruise terminals), the residences at Cut Road and Barry Road on the headland by Gate's Fort, and the residences around Railway Trail/Suffering Lane adjacent to St. George's Harbour are at greatest risk from the hazards under consideration. The earlier mapping shows that these areas are expected to be affected by both inundation and saltwater intrusion.

Building vulnerability index for the RCP 8.5, 100-yr Horizon, 150-yr event in SMU12

Road and Bridge Network

The figure at right presents the CVI for the road network. The roads affected by any of the hazards considered are colour coded in scale from blue to red in accordance with the severity of risk.

The roads around Cut Road and Barry Road on the headland by Gate's Fort are the most at risk from the hazards presented. These roads are predicted to be impacted by inundation, cliff retreat and saltwater intrusion. Other roads notably at risk include the airport perimeter roads, Mullet Bay Road and Bridge, Railway Trail and Ferry Road around Ferry Point Park.

Road vulnerability index for the RCP 8.5, 100-yr horizon, 150-yr event in SMU12

Coastal Vulnerability Index Summary

Buildings

- 326 buildings are classified with High to Very High Exposure. The Town of St George's is particularly susceptible to hazards, in particular saltwater intrusion and inundation. Several properties within the Great Sound, Harrington Sound and Castle Harbour areas are also very susceptible to coastal hazards. Buildings on the South Shore are less affected by the hazards, owing to higher property elevations.
- Only five buildings are affected by all hazards assessed in the long-term. These buildings are characterized as having "very high" vulnerability with a CVI between 0.8 – 1. These buildings are located:
    - In Sinky Bay (2);
    - Southwest end of Long Bay Beach, Somerset (2);
    - Northeast end of John Smith Bay Beach (1).

Road Network

- The main roadways affected are located within St George's Parish. Select roadways within the towns of St George's, Hamilton, and Sandys have CVI indices greater than 0.6, and the Causeway, Coney Island Road, and Somerset Bridge as having "Moderate Vulnerability".
- Along the South Shore, roadways are relatively safe. Only two roadways show vulnerability to hazards (namely from cliff erosion and/or beach erosion). These roadways are South Road (from Church Road to Rock Sound Road, and also by Harbour View Drive); and Sinky Bay Road (where it runs at the back of Cross Bay Beach).
- Along the North Shore, the shorelines of Pembroke, Devonshire, and Smiths are vulnerable to cliff retreat. The roadways near Flatts are also moderately vulnerable (mainly due to inundation effects) within the next 20 years.

Reserves

- Agricultural reserves are relatively safe from the effects of climate change, with only 55 reserves (~60 acres) rated as low to moderately vulnerable.
- Nature reserves are mostly moderately affected, with 90% of the reserves under no exposure to moderate vulnerability. Approximately 11% (28 reserves totalling 5.6 acres) are considered highly vulnerable.
- Coastal reserves are most at risk given their proximity to the coastline. Approximately 96.5% of coastal reserves are categorized with "very high" vulnerability.

Saltwater Intrusion

- Sea level rise effects will result in upward movement of saline water into the subsurface at the coast and inland for some distance. This intrusion will be felt further inland on the South Shore than on the North Shore due to the hydraulic conductivity contrast of the bedrock between the Brighton and Langton Aquifers.

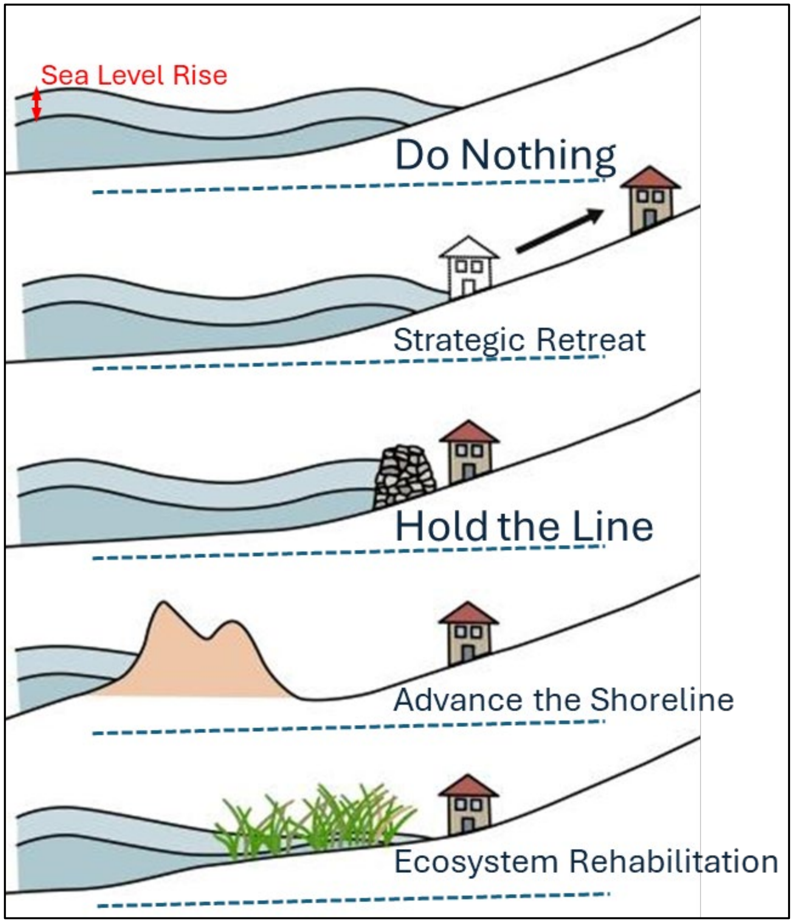
Recommendations

Shoreline Management

Appropriate interventions typically decided at the planning level include the following standard options:

1. *Hazard Preparedness Measures:* Alerting population to impeding coastal events. Advise on best practice responses (relocate to shelters, etc.)
2. *Strategic Retreat:* Relocation of receptors away from areas of coastal risk.
3. *Hold the line:* Prevention of further retreat of the shoreline using sea defences.
4. *Advance the Shoreline:* Beach nourishment, submerged breakwaters, buried revetments and land reclamation.
5. *Ecosystem Rehabilitation:* Use of nature-based components to promote sustainable coastal protection (e.g., planting of mangroves, seagrasses, etc.).

The general long-term strategy for much of Bermuda's low-lying areas or cliff-facing shoreline is for *Hazard Preparedness* followed by *Strategic Retreat*. The expected threats from sea level rise coupled with an increase in both frequency and intensity of storms will render traditional hardened shoreline solutions either economically unsustainable and/or environmentally unsound for large scale resilience or adaptation measures.



Where critical infrastructure already exists, a *Hold the Line* or *Advance the Shoreline* approach can be justified, including for example the major commercial centres of Hamilton and St. George's, the Great Sound, West End Development Corporation, Westgate Correctional Facility, various marine terminals and piers, the airport, Fort St. Catherine, North Shore Road, and the Tyne Bay facility. All critical infrastructure should be elevated above predicted inundation levels, with appropriate upland drainage provisions.

Sandy beaches offer the opportunity to *Advance the Shoreline* through beach nourishment. Where possible, retaining structures such as submerged breakwaters or headlands can be considered to optimise (i.e. reduce) the frequency of beach maintenance needed.

At locations where *Ecosystem Rehabilitation* or a nature-based adaptation solution is applicable, this should be encouraged, in particular mangrove re-establishment. Possible locations include The Lagoon, Castle Harbour, Harrington Sound, and the areas outside the town of St. George's.

Saltwater Intrusion / Groundwater Table

- Restoring coastal wetlands, coral reefs, marshes and mangroves provides a nature-based defence against coastal flooding and storm surge and will also protect near-coast groundwater from downward moving saline recharge during an inundation event.
- The effects of salinisation on infrastructure can be mitigated by installing shallow vertical or horizontal wells depressing the water table. Buried electrical systems in areas where sea level rise and saltwater intrusion will occur should be housed in waterproof structures.
- Vertical or horizontal wells can be used to depress the water table under and around heritage buildings, and rainwater collected from roofs could be directed to French drains surrounding the building foundations.
- The Bermuda Electric Light Company plant near the Pembroke Canal is in a low-lying area that will be seriously impacted by saltwater intrusion. Experts in design and construction of buildings in challenging environments should be consulted in this regard. Pumping to depress the water table may be a viable alternative in the short to medium term.
- Maintaining recharge from cesspits with an appropriate buffer distance to the water table is essential to maintain horizontal flow in the lenses and restricting horizontal movement inland of the interface zone.
- In agricultural areas, practises that should be encouraged include wastewater reuse for irrigation purposes, drip irrigation, changing crop varieties to drought resistant or heat tolerant ones, and adopting cultivation practices such as "no-till" and organic methods characteristic of regenerative agriculture.

Recommendations for critical data gaps:

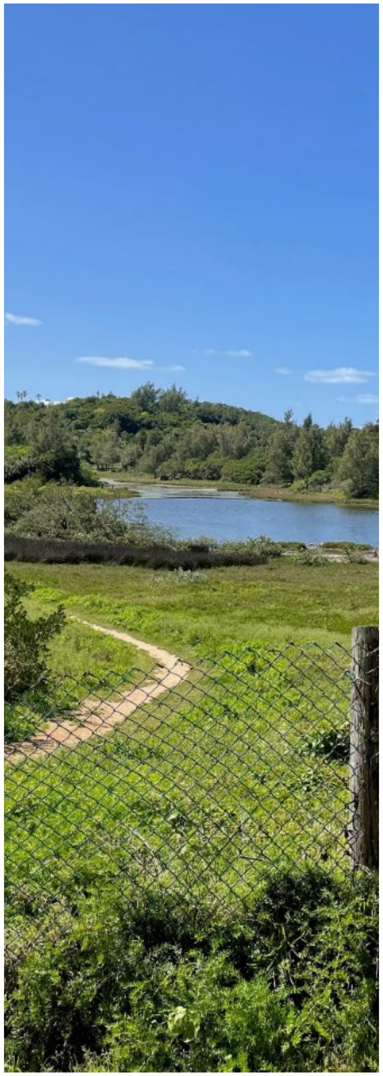
The estimates for cliff erosion in this analysis are likely conservative. The estimates were extracted from sparse LiDAR data measured at the Bermudian development area where a relatively soft rock layer exists. As cliff hardness varies widely across Bermuda, susceptibility to erosion processes will also vary widely. **Cliff surveys that target the cliff face should be completed before and after cliff failures to accurately document the extent of the cliff erosion throughout Bermuda.** High resolution oblique and/or orthorectified nadir photos could also help.

Quantifiable impacts on environmental assets in the risk and vulnerability analyses should be expanded on and included. For example, modelling can be applied to estimate the protection offered by these habitats and importantly the loss in protection if the habitats were degraded or destroyed. To do this, aerial or satellite surveys of critical habitat areas, specifically mangroves, seagrasses and coral reefs will require surveys at an appropriate scale to assess larger scale changes that may be related to climate change effects. Given the importance of the marine and coastal environment of Bermuda, this addition would be considered to provide a more comprehensive representation of the potential impacts of climate change. Of note, with modern technology these benthic surveys can be conducted on existing imagery in archives collected 20+ years ago.

Other variables that may be affected by climate change, such as temperature, rainfall and sea surface temperature (SST) should be incorporated in any data gathering exercise. Sea level rise and storm surge are probably the greatest impacts of climate change for Bermuda; however, the addition of other climate change variables would provide for a more comprehensive analysis of impacts.

Find and organize existing data on water table elevations, groundwater models, pumping tests, chemical analyses of groundwater etc. in order to allow easy access to data that was not available for this study. A continuing program should be initiated to collect and collate data and produce annual reports of the water table and thickness of the lenses, location of the saltwater interface, precipitation, water use and other hydrologic data.

Conduct a study on nutrient (nitrogen and phosphorous) release to groundwater in soils and phosphate in the carbonate aquifer as salinification increases.



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