Coastal Vulnerability Index and Recommendations Report

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

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Contents

List of Abbreviations

BELCO	Bermuda Electric Light Company
CC	Climate Change
CVI	Coastal Vulnerability Index
GIS	Geographic Information System
IPCC	Intergovernmental Panel on Climate Change
LID	Low impact development
LIDAR	Light Detection and Ranging
MSL	Mean Sea Level
NHC	National Hurricane Centre
NOAA	National Oceanic and Atmospheric Administration
PFAS	Perfluorooctyl Sulfonate
PFOA	Perfluorooctanoic Acid
OD	Ordinance datum
RCP	Representative Concentration Pathways
RO	Reverse osmosis
SLR	Sea Level Rise
SMU	Shoreline Management Units
SSP	Shared Socioeconomic Pathways
SST	Sea surface temperature
SWI	Smith Warner International
UKHO	UK Hydrographic Office

Executive Summary

In 2004, the Government of Bermuda (GoB) assessed Bermuda's vulnerability to coastal erosion. The 2004 study, carried out by Smith Warner International Limited (SWI) 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.

This updated assessment builds on the results of the 2004 study to assess Bermuda's vulnerability to climate change. Coastal erosion, whether observed on either sandy shores/beaches or coastal cliffs, remains a focal point of the assessment. In addition, the analysis herein considers areas that are vulnerable to flooding from extreme storm events and saltwater intrusion effects from rising sea (and groundwater) levels.

The vulnerability of the island's shoreline is quantified in a simplistic "Coastal Vulnerability Index" (CVI) which identifies individual locations at risk and clusters where remediate or corrective action should be taken. The CVI is developed from a combination of datasets and analyses available (in particular those presented in the SWI *Final Modeling Report*, March 2024) to provide a 'normalized' presentation of the potential impacts of future flooding and erosion hazards across the study area. This is a geographic information systems (GIS) based exercise, whereby the projected future flood and erosion hazard areas are overlain on the available 'receptor' mapping, and the resultant 'risk' is aggregated into a grid. The future hazard impacts – flood, erosion, and saltwater intrusion – are therefore 'normalized' relative to present day conditions.

The study geographically encompasses the immediate coastline, as well as interior areas where groundwater elevations are expected to impact critical receptors. The receptors considered in this study are divided into "built infrastructure" (buildings, critical infrastructure and road/bridge networks), and "reserve areas" (coastal, nature, and agricultural). In addition, impacts to environmental receptors are discussed in general terms.

The selection of the representative event for application in the CVI is based on the latest Intergovernmental Panel on Climate Change (IPCC) guidelines, precedence from other respected jurisdictions as well as consideration of what is most appropriate for small island nations within the North Atlantic/Caribbean area. The events selected to assess effects of climate change hazards through the CVI included:

- RCP4.5, 50 year horizon, 150-year storm event
- RCP8.5, 100 year horizon, 150-year storm event

The CVI assessment yields the following salient summarized points:

- Buildings:
    - Based on the CVI analysis, approximately 12% of all buildings in Bermuda are affected by coastal hazards (RCP8.5 100yr event horizon, 150yr storm event).
    - The governing factors determining the degree of vulnerability of a building is elevation and the distance from the shoreline. Buildings that are sufficiently elevated and set back from the shore are not typically affected by the coastal hazards that have been considered.
    - For the RCP4.5 50-yr horizon scenario, no buildings mapped are classified as being at High to Very High Exposure. This number increases to 3 for the RCP8.5 100-yr horizon scenario.

  - Within the RCP 4.5 50-year and RCP 8.5 100-year horizon scenarios, there are 503 and 918 buildings, respectively, categorized as having moderate to high exposure. This comprises 1.4% and 2.6% of all buildings in Bermuda. Notably, these buildings are all situated within a 100m distance from the shoreline.
  - Buildings on the south shore are less affected by the hazards, owing to higher property elevations occurring there.
  - 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 very susceptible to coastal hazards.
- Road and Bridge 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.
  - The CVI categorises the Causeway, Coney Island Road, and Somerset Bridge as having "Moderate Vulnerability".
  - Along the south shore, the roadways are relatively safe. Only two roadways show vulnerability to hazards (namely from cliff erosion).
  - Along the north shore, the shorelines of Pembroke, Devonshire, and Smiths are vulnerable to cliff retreat.
  - The roadways in the vicinity of Flatts are also moderately vulnerable (mainly due to inundation effects) within the next 20 years. These therefore require immediate attention.
- Reserves:
  - Very few of the agricultural reserves (approximately 15%) are indicated to be moderately vulnerable, notably in areas around Little Head Park on St. David's Island and Redcoat Lane N and Blue Meadows/Bayside Lane on St George's Island.
  - The most vulnerable nature reserve is Cooper's Island Nature Reserve, which may be susceptible to all four hazards considered. Other popular reserves include Tom Moore's Jungle, and Spittal Pond, which show high vulnerability grades. Discrete nearshore islands such as Nonsuch Island, Brangman's Fort Island, Castle Island, Charles Island, Rushy Island, and Smith's Island are also threatened. Of note, approximately 92% of all nature reserves are affected by inundation and shoreline retreat, with 78% being in the "Moderate" to "High" category.
  - While all coastal reserves are expected to be affected by climate change, the most vulnerable shorelines are shown as being located in Tucker's Town, Natural Arches, and along Ruth's Bay. Gravelly Bay, Newtown Bay and Pink Beach are also classified at the highest level of vulnerability. As expected, the hazards assessed affect approximately 100% of all coastal reserves, with 96% being in the "Moderate" to "Very High" vulnerability category.

- 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 further on the south coast than on the north coast due to the hydraulic conductivity contrast of the bedrock between the Brighton and Langton Aquifers.
  - Seasonal climate variations can affect the G-H balance (the ratio of water table elevation to the depth of the interface below sea level) which can vary from 1:25 in wet years to 1:58 in dry years.
  - Maintaining recharge from cesspits is essential to maintaining horizontal flow in the lenses and restricting horizontal movement inland of the interface zone. As contamination from sewage is a concern, an incentive program to install septic systems with nitrate treatment is recommended.
  - The minimum distance between the base of the proposed cesspit and the water table is currently 1.22m. Where the land surface remains approximately 5m above the water table's maximum height, this criteria can be maintained. No new cesspits should be installed where the water table maximum rise will be 3m or less below the land surface. For the zone in between these two areas, the location of new cesspits will depend on assessments of the land elevation and the water table maximum elevation projected for 100 years in the future.
  - The climate of Bermuda, with precipitation moderately exceeding evapotranspiration, is an important factor in maintaining the groundwater lenses. If the climate changes in favour of more droughts or extended periods of low recharge, impacts to the freshwater lenses such as thinning of the freshwater portion, and more upward moving saline groundwater inland from the coasts could occur. Increased upconing of brackish water may be a consequence of these influences. In addition, reduced rainfall means less water collected in tanks by domestic and commercial owners and less recharge through cesspits.
  - Restoring coastal wetlands, coral reefs, marshes and mangroves provides a nature-based defence against coastal flooding and storm surges. In addition, these will protect near coast groundwater from downward moving saline recharge from the inundation event.
  - In agriculture, proposed mitigation measures against saltwater intrusion include the encouragement of wastewater reuse for irrigation purposes, providing more irrigation water with the use of drip irrigation, changing crop varieties to drought resistant or heat tolerant ones, and modifying cultivation practices such as "no-till" and organic methods characteristic of regenerative agriculture.
  - The BELCO 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 to determine how to protect the existing building to make it waterproof and resistant to the corrosive effects of saline water. Pumping to depress the water table may be a viable alternative in the short to medium term. This would require a detailed hydrogeological study.
  - The effects of salinization 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.

- Heritage buildings are under threat by rising levels of saline water degrading the foundation materials. Vertical or horizontal wells can be used to depress the water table under and around the buildings and rainwater water collected from roofs could be directed to French drains surrounding the building foundations.
- There is opportunity for significant increased abstraction of the Central, Somerset, and St George's lenses to provide potable water feedstock, to reduce the need for energy-intensive seawater reverse osmosis and to provide a stable potable water supply for Bermuda. Expanded use of the lens during a period of climate change carries with it some uncertainties regarding the effects of increased abstraction rates during sea level rise and the expected increases in the length of dry spells. These risks can be managed by improving knowledge of:
  - the behaviour of the lenses on a "micro" scale (i.e. on a per pumping wells basis);
  - improving knowledge of the lenses on a "macro" scale (e.g. across a lens);
  - updating recharge estimates; and
  - by having accurate information on the rate of pumping from each abstraction well.

Consideration of two different climate scenarios for vulnerabilities from four different hazards over five areas of interest requires an inordinate number of maps. To assist in the mapping, the shoreline was divided into discrete Shoreline Management Units (SMUs).

The resulting CVI identifies several areas where coastal action or intervention is needed at present or in the foreseeable future. Appropriate interventions are typically decided at the planning level, and for coastal management plans the following are standard options:

1. ***Hazard Preparedness Measures:*** Alerting population to impending coastal events.
2. ***Strategic Retreat:*** Removal of receptors away from areas of coastal risk.
3. ***Hold the line:*** Prevention of further retreat of the shoreline using sea defence.
4. ***Advance the Shoreline:*** Beach nourishment, submerged breakwaters, buried revetments and land reclamation.
5. ***Ecosystem Rehabilitation:*** Use of the natural environment to promote sustainable coastal protection.

This report identifies and recommends the most appropriate management option for each shoreline management unit based on short-, medium- and longer-term timescales. These draft recommendations are intended to serve as a basis for a discussion as to the appropriate treatment of the shorelines for future climate change impacts from an outside consultant's perspective and thus will require careful consideration by the Department of Planning prior to finalization.

Additional recommendations are suggested to fulfilling the data gaps identified within this study to better assess the coastal risk and vulnerabilities. The following are of particular importance to future work (see recommendations chapter for full descriptions):

- The estimates for cliff erosion in this analysis is 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 also varies 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.

- Expansion and inclusion of quantifiable impact on environmental assets in the risk and vulnerability analyses. 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 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.
- Incorporation of other variables that may be affected by climate change, such as atmospheric temperature, rainfall and sea surface temperature (SST). Sea level rise and storm surges are probably the greatest single impact of climate change for Bermuda; however, the addition of other climate change variables would provide for a more comprehensive impacts analysis. The benefits of this addition would need to be balanced against the additional analysis and uncertainties that these further variables would generate.
- Find and organize existing data on water table elevations, pumping tests, chemical analyses of groundwater etc. in order to allow easy access to data that was not available for this study. Assess the data and data gaps. If additional data from the 1970s and before 2020s can be found, it will help assess the rate of sea level rise to the present. 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 salt water interface, precipitation, water use and other hydrologic data. In order for mitigation and adaptation to be carried out, the characteristics and geometry of the fresh water lenses must be monitored over time.
- Locate the 1989 Thomson groundwater model and supporting data and examine the assumptions and expand on the model or adapt it to new modelling software. A long-term form of the model or a new steady-state model would be the optimum way of simulating the rate of change of the freshwater lenses and sea level rise.
- Groundwater monitoring recommendations:
    - Locate areas where mangrove forests yield to buttonwood trees (*Conocarpus erectus*) (perhaps at Hungry Bay). This indicates a change from saline conditions to non-saline conditions in the soil. Install piezometers to monitor daily water level fluctuations using data loggers. Install instruments to monitor electrical conductivity in soil profiles. This may involve hand auguring boreholes or possibly drilling. Install tensiometers and electrical conductivity sensors to monitor the vadose zone as salinity can increase in this zone by capillary rise and diffusion of saline contaminants upward. Chloride can be accurately determined using field equipment, either wet chemical methods or selective ion electrodes.

- Conduct on nutrient (nitrogen and phosphorous) release to groundwater in soils and phosphate in the carbonate aquifer as salinification increases. The change in salinity may release phosphate in the soils and carbonate aquifer which will be mobilized and flow to the sea and likely cause algal blooms along the coast. This could be carried out at the mangrove monitoring site but should also be done on an agricultural area where fertilizers are applied as well as high density residential unit areas with cesspits.
- Continue monitoring the interface zones in the four groundwater lenses especially near the coasts. The data available for this study included an annual listing of the average thickness of the water table to 3% sea water/97% fresh water interface zone for approximately 20 years. Given the fluctuations of local sea level from various influences, monitoring of the interface zone should occur much more frequently with several data loggers in each fresh water lens.
- Monitoring of water levels and salinity in the internal fresh and saline ponds on a regular basis is recommended.
- Monitoring of the discharge at Foot of the Lane and at Mill Creek/Pembroke Canal would help to determine if the discharge represents a drain for the Central Lens or not and whether this discharge is increasing with sea level rise. As the Central Lens rises, these areas may see an increase in discharge with the possible increase in horizontal hydraulic gradients.
- Monitoring of the water table and its fluctuations plus salinity levels in the vicinity of agricultural areas, infrastructure and built heritage areas will determine which of those areas will require mitigation (lowering of the water table, infiltration of rainwater) in the short term and which will require mitigation in the medium and long term. Some highly impacted areas nearest the coast may undergo a change in function. For example, agricultural areas may be abandoned to allow mangrove forests to retreat inland. In areas other than agricultural areas, and where possible, mangroves should be encouraged to develop and advance inland. This will involve an assessment of possible areas where this could happen and a program of land acquisition by the government.
- Watersheds should be delineated across the islands with a study of the potential to use runoff from precipitation to flush salt from impacted soils and for the installation of infiltration galleries to maintain the lens margins at the coasts.
- Monitor Perfluorooctyl Sulfonates (PFAS) and Perfluorooctanoic Acids (PFOA) as well as other persistent organic chemicals (Polychlorinated biphenyls, etc.) in the groundwater lenses in selected wells. It is likely that these chemicals are removed during the reverse osmosis (RO) process, however, they may be accumulating in the lenses and since the groundwater in the lenses slowly discharges into the sea, these chemicals may be a long-term threat to the reef organisms. There are no safe concentrations of these chemicals for organic life. It is unknown if these chemicals are adsorbed onto the limestone.
- Monitoring wells should be equipped with TCD (temperature, conductivity pressure) transducers to monitor changes to the lenses at sufficient resolution to resolve sub-diurnal changes in tides, recharge etc. Multiple transducers could be used in select wells. Data can be transmitted via the cellular network to decrease labour time.

- Abstraction wells should be equipped with flow rate meters and the data made available to the regulator so that responses of the lenses to pumping can be accurately characterised.
- Additionally, it should be pointed out that since Bermuda is sinking at a rate of 0.9 mm/yr, and ordnance datum (OD) was set at Mean Sea Level in 1963, then the land mass has sunk 53mm since 1963 assuming the rate of subsidence is constant. This means that the ordnance datum location has sunk 53mm since 1963. The wells that Vacher used in his 1974 report were surveyed for elevation of a measuring point in order to relate groundwater levels to OD. Given that measurement of water table elevations are a challenge due to the various oscillations that occur, and if the well measuring points have dropped 5cm (approximately), comparing data from 2022 to that in the 1974 will present an additional challenge. It will be necessary to resurvey to sub-centimetre accuracy the location and elevations of all existing wells and infiltration galleries.

- Groundwater modelling recommendations:
  - Map lichen species near the seashore. Some species are tolerant to salt and others are not[1] and establishing sites to observe the change in lichen species will help understand the increasing salt water intrusion and salt water spray.
  - 3D geological mapping: the currently un-cased monitoring wells are well suited to downhole geological logging using downhole cameras and equipment to detect the saline water gradient. Better understanding of the 3D distribution of the Brighton and Langton aquifers will enable better understanding of the behaviour of the lens on micro and macro scales.
  - Rehabilitation of monitoring wells: after downhole logging, existing monitoring wells of sufficient depth should be completed with appropriate casing to preserve them for the long-term. Partially collapsed wells should be re-drilled to penetrate the lens and be completed with the appropriate casing.
  - Expansion of monitoring well network: monitoring wells that have collapsed or have been lost should be replaced and completed with appropriate casing. Additional geological modelling should also be carried out for each new well.
  - The hydraulic connection between the marshes and aquifers should be investigated and the results used to better constrain the water balance and hydrogeological model (see below).
  - 3D geological modelling: results from surface and downhole geological modelling should be used to create a 3D geological model, showing the locations of potential confining layers (e.g. paleosols, base of marshes, etc.) as well as the aquifers.
  - Re-appraisal of groundwater recharge should be carried out using the results of new data collected from high quality monitoring wells and modern GIS techniques.
  - The information from the above recommendations should be used to create a hydrogeological model, using modern software that can be used to manage abstraction from the lenses and respond to the changes in weather patterns and steady increase in sea levels expected over the next few decades. The model can also be used to investigate hydrogeologic controls on salinization due to the long timescale over which changes in climate and sea level occur. Computer

[1] https://www.nationalobserver.com/2023/03/07/news/worried-about-sea-level-rise-lichens-got-your-back

modelling in other jurisdictions has been employed in several studies to investigate this and provide a resource for methods that would be useful.

Attention was also given to the assessment of the vulnerability of specific key infrastructure, the hazards to which they are most exposed, and the recommended vulnerability reduction methods that could be employed over the short, medium and long terms. The vulnerability reduction responses that were developed have been prioritized over differing time scales, and this listing is presented in the following table.

Short Term (0-20 years)		**Medium Term (20-50 years)**		**Long Term (50+ years)**	
Asset	**Suggested Approach**	**Asset**	**Suggested Approach**	**Asset**	**Suggested Approach**
Airport Parking lots	Elevate	Airport Runway	Elevate	Sol Fuel Storage	Elevate
Causeway	Rebuild	Airport Perimeter Roads	Elevate	King Edward VII Memorial Hospital	Protect
Somerset Bridge	Rebuild	Longbird Bridge	Rebuild		
St George's Harbour	Elevate (short term)	Flatts Bridge	Rebuild		
Dockyard	Elevate (short term)	Coney Island Bridge	Rebuild		
Oil Docks Terminal	Cliff protection, Rebuild for storm conditions	Swing Bridge	Rebuild		
BELCO Power Station	Elevate, Protect	Hamilton Harbour Ferry Terminal	Elevate		
Tyne's Bay Plant	Cliff protection	Hamilton Harbour Container Docks	Elevate		
Watlington Waterworks	Cliff protection	St George's Harbour	Strategic Retreat		
		Dockyard	Strategic Retreat		
		BELCO Solar Installation	Rebuild, elevate		

1 Coastal Vulnerability Index

1.1 Background

Coastal cities around the world are increasingly being exposed to hazards due to climate change and its impacts on storm activity, rising sea levels and increasing sea surface temperatures. Assets and infrastructure near the coast are likely to have been developed without regard to these changes in climate and are largely now at risk.

The Coastal Vulnerability Index (CVI) is a tool commonly used to assess the vulnerability of a coastal area to physical changes caused by sea level rise, storm surge, and other coastal hazards. It is a measure of the susceptibility of a coastal area to erosion and other hazards and is used to identify areas that are at risk and to develop strategies to protect them. It uses a numerical ranking system that considers factors such as the height of the land above sea level, the slope of the land, the type of shoreline (e.g., cliff, rocky, sandy), and the rate of erosion, *inter alia*.

The CVI is typically used by coastal zone managers and planners to identify areas that are at higher risk from coastal hazards and to prioritize actions intended to reduce the vulnerability of those areas. The index is calculated by assigning numerical values to the various factors that contribute to vulnerability and then combining those values into a single score. It is noted that the factors are weighted and combined to create a score that ranges from 0 to 1, with higher scores indicating greater vulnerability.

Some of the factors that are included in the CVI calculation are:

- Elevation of the land relative to sea level (e.g., cliff or beach);
- Slope of the land (e.g., gently sloped or steeply sloping);
- Type of shoreline (e.g., rocky or sandy);
- Historical erosion rates (significantly different for sandy versus cliff shorelines);
- Projected rate of shoreline position change (particularly relevant for erodible coastlines);
- Wave energy exposure (to both operational and extreme wave climate);
- Storm Surge exposure;
- Rainfall-induced flooding (in the Mill Creek area); and
- Saltwater intrusion.

The CVI can be used to identify areas that are at risk of flooding, erosion, or damage from other hazards, and to develop strategies to mitigate those risks. It can also be used to guide decisions about land use planning, infrastructure investments, and emergency preparedness. Overall, the CVI is a valuable tool for coastal managers and planners who are responsible for protecting coastal communities and natural resources from the impacts of coastal hazards.

1.2 Methodology

The variables involved in derivation of a CVI include hazard footprint(s), hazard intensity, the likelihood of the impact of the hazard, elements at risk at the location of assets, offshore bathymetric contours, topography and other physical factors. The output of a CVI is a model with colour schemes that aid the visualization of the range of exposure to these assets. For this study, the vulnerability score adopted ranges from 0 (least vulnerable) to 1 (most vulnerable). In this manner the assets, building and/or structures that are exposed to hazards are identified and comparatively quantified as to their level of exposure to hazards.

To determine the level of exposure of these assets and infrastructure from future hazards, a Coastal Vulnerability Index (CVI) – developed using the datasets and analyses available (and refined through the numerical modelling analyses) – provides a 'normalized' presentation of the potential impacts of future flooding and erosion hazards across the study area. This is a Geographic Information System (GIS) based exercise, whereby the projected future flood and erosion hazard areas are overlain on the available 'receptor' mapping, and the resultant 'risk' is aggregated into a grid. The future flood and erosion hazard impacts are therefore 'normalized' relative to present day development conditions.

The CVI model approach involved a spatial geoprocessing technique that identifies the levels of exposure of those assets (ranked as Very High' to 'Very Low' in exposure) to specific hazards, as well as those assets that are not exposed to the risks of flood and erosion (Figure 1.1).

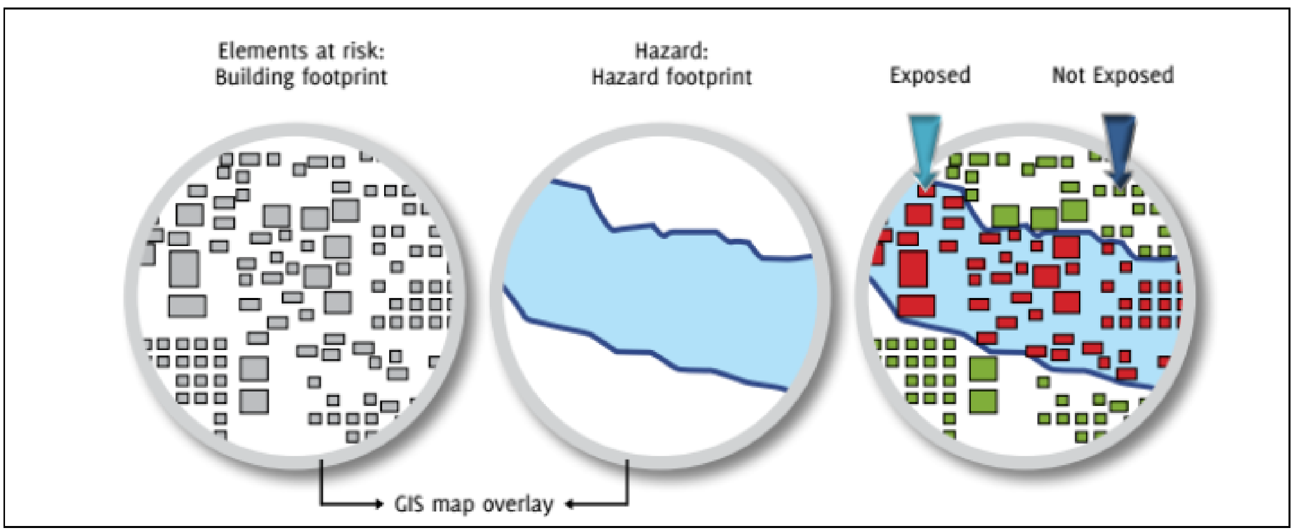

Figure 1.1 Exposed elements at risk to flood hazard. *Source: The Office of Disaster Preparedness and Emergency Management (2016)*

Impacts on the exposed elements vary based on direct exposure to the hazard. Vulnerabilities are related to the predisposition, susceptibilities, fragilities, weaknesses, and deficiencies of the exposed elements at risks (Cardona et al, 2012). For this study, we have focused on visualization of the vulnerabilities of building footprints, road networks, bridges, and major coastal infrastructure assets. Other critical infrastructure, such as the airport, ports, power plants, and water/wastewater treatment plants are discussed separately.

In mapping CVI for the areas of interest in Bermuda, it must be ascertained who or what will be at risk. First, all assets near the coast were identified in the GIS. A hazard model was then generated based on a multi-criteria evaluation and using various spatial and non-spatial data (e.g., inundation model, projected erosion model, modelled flood depths, terrain data, etc). Subsequently, the assets at risk were identified and the level of exposure determined (Figure 1.2).

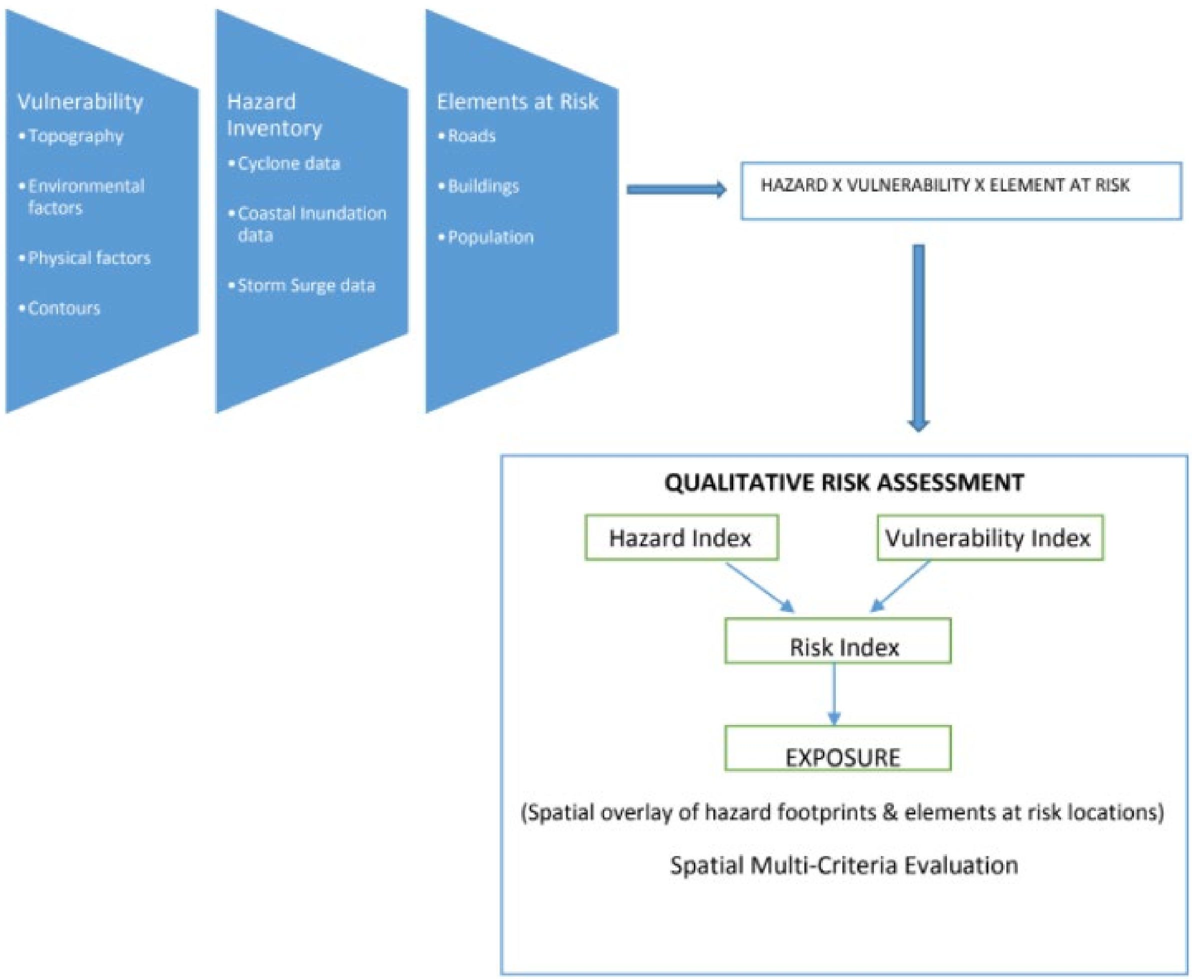

Figure 1.2 Aspects adopted from the framework of the use of GIS multi-hazard risk assessment (Van Westen, 2008)

Several precedents exist for the use of this methodology in coastal cities, where GIS combined with Coastal Vulnerability Index (CVI) were used to assess natural and socio-economic vulnerability, notably in Brazil (Barsley, et al., 2013). In that example, ArcGIS 3.2 was used to create a CVI score, which was then used to measure disparities within a community exposed to the identified hazards. For this study in particular, a vulnerability score range of 0 to 1 is applied, with 0 being the least vulnerable and 1 being the most vulnerable. With this method, the focus tends to be on physical vulnerabilities (Van Westen, 2013). According to Balica, et al., 2012, a 0 - 1 range of CVI values facilitates a global perspective that can be integrated to provide a coastal city flood vulnerability index.

The CVI output map of Bermuda identifies areas of greatest future risk from coastal flood and erosion hazards to determine a basis for prioritization of frontages for treatment or action in the development of risk management measures.

1.3 Datasets and Scenarios Modelled

Data needed in vulnerability mapping includes satellite-based information, flood data (frequency, magnitude, depth and/or distance of flooding), the probability of occurrence, and intensities of hazards. Table 1-1 lists the spatial data and the methodology sources applied to develop the CVI for this project.

Table 1-1 Spatial data with source information incorporated in developing a Coastal Vulnerability Index

Hazard	
Flood Depth – Coastal Storm Surge	SWI modelled with MIKE21 Hydrodynamic (HD) FM module (DHI, 2016) software, processed from grid to vector. (SWI Modelling Report, Chapter 5)
Flood Depth – Compound Flooding (Coastal Surge + Rainfall Inundation)	SWI modelled with HEC-RAS software with input from the MIKE21 HD FM module (above), processed from grid to vector. (SWI Modelling Report, Chapter 6)
Coastal Retreat – Sandy Shorelines	SWI computed from Bruun Rule (SWI Modelling Report, Chapter 7)
Coastal Retreat – Cliff Shorelines	SWI computed from the SCAPE Model and historical cliff retreat rates (Modelling Report, Chapter 8)
SLR	RCP4.5 and RCP8.5 values extracted from UWI Mona Report (2022)[2], which was in turn sourced from the Copernicus Marine Environment Monitoring Service (CMEMS), (SWI Modelling Report Chapter 2).
Saltwater Intrusion	SWI modelled (SWI Modelling Report Chapter 9).
Environmental factors	
Contours	SWI generated, from Government of Bermuda, Department of Planning data
Digital Elevation Model	SWI generated from Government of Bermuda data
Satellite Imagery	Worldview 3, 2m resolution, provided by EOMAP, Date of recording: 2021-09-26 15:09:00 UTC
Topography	Government of Bermuda, Department of Planning
Rainfall	Bermuda Weather Service
Assets	
Building Locations	Government of Bermuda, Department of Planning
Road Network	Government of Bermuda, Department of Planning
Bridges	Government of Bermuda, Department of Planning
Coastal Infrastructure	Government of Bermuda, Department of Planning, SWI Field visits

[2] 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.

2 Critical Assets

The Coastal Vulnerability Index (CVI) describes a ranking of severity of erosion and flood threats to assets along the coastline. These assets are generally grouped into the following spatial areas:

- Built Infrastructure
  - Buildings
  - Road Network
  - Bridges
- Major Coastal Infrastructure
- Nature Reserve Areas
- Ecological Significant Areas

2.1 Built Infrastructure

2.1.1 Buildings

The Department of Planning provided data for buildings, categorising them according to distance from the coast. Figure 2.1 shows a bar chart of the number buildings and their buffer zones from the shoreline. Notably, 13% of the buildings in Bermuda are located less than 100m from the shoreline. Of these buildings, approximately 333 of them, are government related. The ownership details for the government related buildings are further broken down and presented below in Table 2-1.

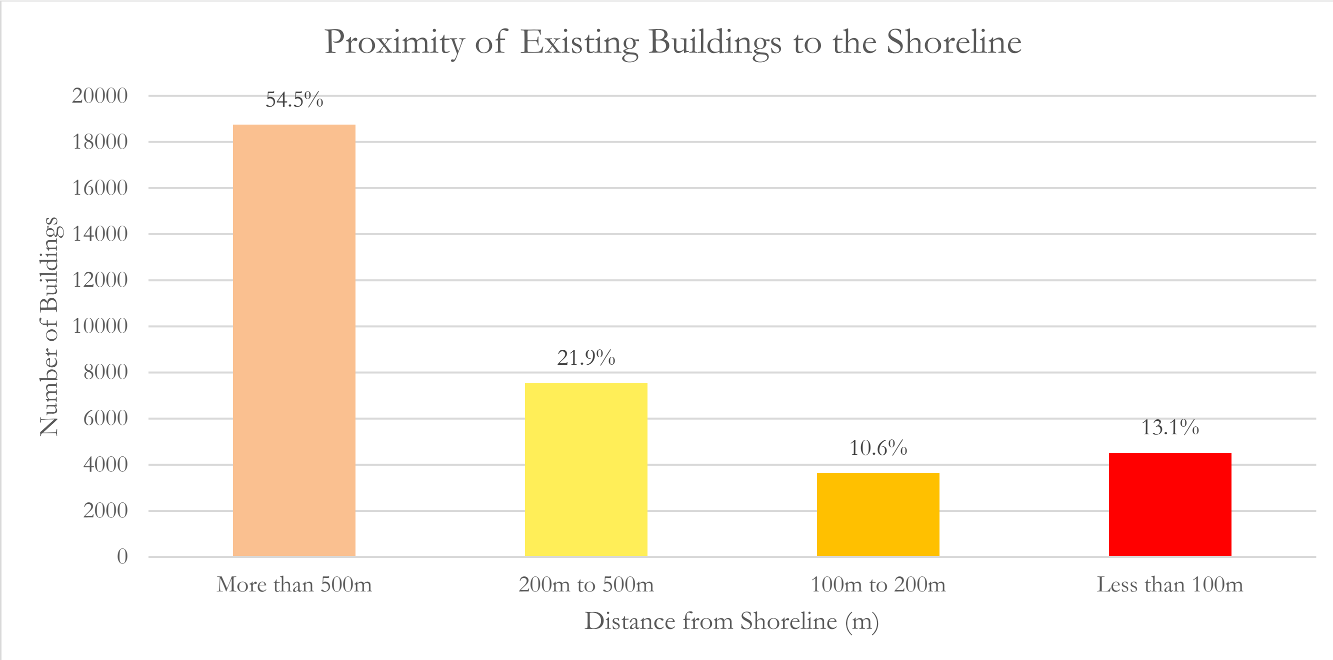

Figure 2.1 Distance away from shoreline for existing buildings

Table 2-1 Ownership of government-related buildings within 100m of the coastline

Government-Related Building Owners	Percentage	Number
Government of Bermuda, Parks and Roads	43%	143
WEDCO, BLDC Leasehold, BLDC	33%	112
Bermuda National Trust, Heydon Trusts	11%	38
Corporation of St Georges and Hamilton	6%	21
Bermuda Housing Corporation, Bermuda Housing Trust	3%	10
BELCO	1%	4
Bermuda College and Zoological Society	1%	5

2.1.2 Road Network

Coastal road networks link adjacent communities and, by extension, facilitate economic growth and serve as vital emergency thoroughfares. These roads, which have typically developed over the years from pedestrian walkways to horse trails to cart paths to paved roads, were likely conceived centuries ago in a time when future coastal vulnerability was not considered. These valuable and costly national assets lie close to the shorelines in many places and are now particularly vulnerable to the impacts of climate change, including sea-level rise, storm surge, saltwater intrusion, and coastal erosion. These impacts can cause damage to roads and other infrastructure, disrupt transportation networks, and pose risks to public safety.

The primary and secondary road networks are shown in Figure 2.2. The map shows that on the south shore, a strip of roadway in the south-west runs approximately 7-9 km very close to the shoreline. On the north shore, north of Hamilton to Flatts as well as from Flatts to Bailey's Bay, (approximately 9-10 km) is close to the sea. Overall, however, a significant percentage of the road infrastructure is set back from the coastline.

Figure 2.3 shows the percentage of the road network and their distances from the shoreline. Notably, 12% of the roads in Bermuda are located less than 100m from the shoreline. Conversely, 42% are located further than 500m from the coast. The remaining 48% are located within these two distance limits.

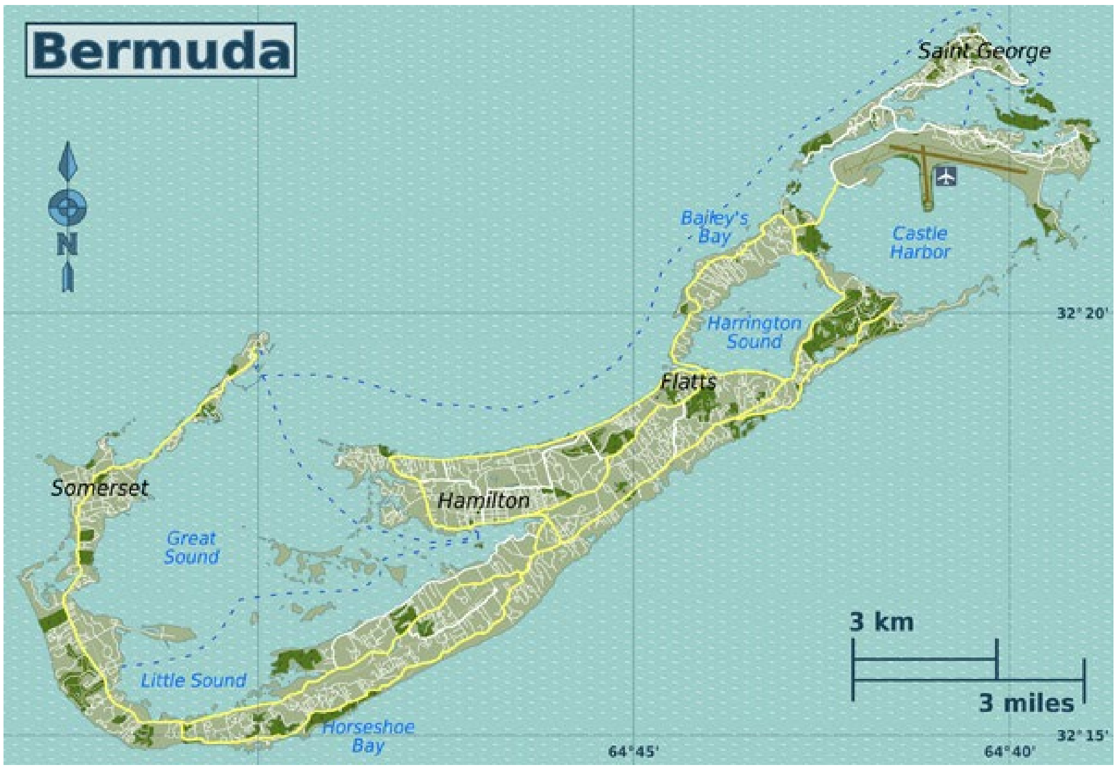

Figure 2.2 Bermuda road network (Main and Secondary roads) – Reference: OpenStreetMap

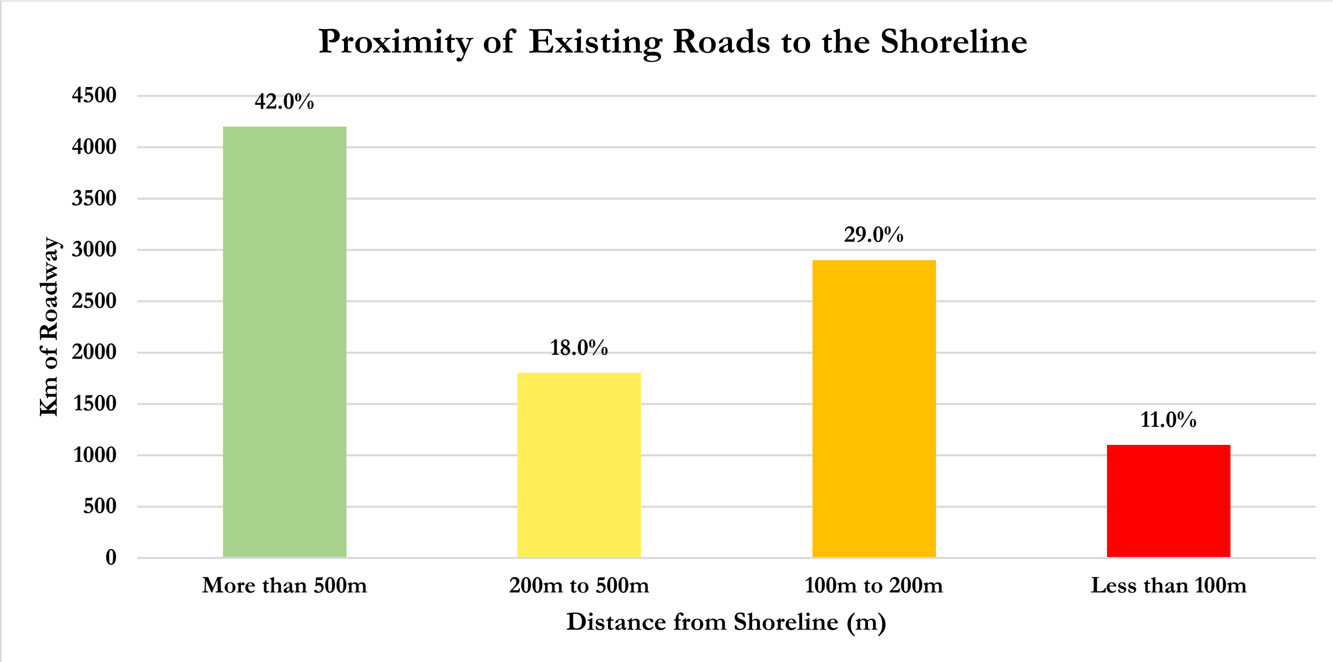

Figure 2.3 Distance away from shoreline for existing road networks

2.1.3 Bridges and Causeways

The network of bridges in Bermuda serve a critical function of facilitating transport (leisure, commercial and emergency) across different parts of the island. Some of these bridges are immediately adjacent to the ocean, some are further inshore. Some serve a more critical transport role than others. Below is a listing of the bridges that have been considered in our analysis.

- *The Glebe Road* – This road is adjacent to the Marsh Folly Composting Facility and is approximately 370 metres form the coastline. This structure is unlikely to be vulnerable to shoreline erosion or storm surge.
- *The Causeway* - This is a narrow strip of reclaimed land and bridges in the north of Bermuda linking Hamilton Parish on the mainland in the southwest and the L F Wade International Airport on St. David's Island in St George's Parish in the northeast, which are otherwise divided by Castle Harbour. It is a critical piece of infrastructure and has significant strategic importance for the island. Originally opened to traffic in 1871, it has been damaged by several successive hurricanes and rebuilt several times over the years. The last major damage

episode was in 2003 by Hurricane Fabian. Because of its low-lying nature, it is very prone to storm damage.

- *Swing Bridge* – This bridge connects St David's Island (L F Wade International Airport) to St George's Island (ST George's Parish). It is by virtue of its location, a critical piece of infrastructure.
- *Somerset Bridge* – Connects Southampton/Sandys to Sommerset island. It is a critical roadway connector and has exposure to storm wave effects.

- *Point Shares Road Bridge* – This is well protected from storm wave impacts within Fairyland Creek
- *Ordinance Bridge* – Connects St George's with Ordinance Island. It is generally well sheltered.
- *Malabar Road Bridge* – Connects Somerset Village with the islands of Moresby, Regatta and Ireland Island South. This bridge links are critical to the connectivity of this part of the island to the main centres of population, and therefore are important for emergency evacuation, etc.
- *Long Bird Bridge* – Has been out of commission since Hurricane Fabian damage in 2003, after which a a diversion section with twin Mabey Compact bridges was added at the airport-end of the Causeway.
- *Lagoon Bridge* – Connects roadway at the southern end of the Lagoon on Ireland Island South. This is not considered to be a critical connector, as there are existing alternative routes available.
- *Cockburn's Cut Bridge* – This is a short bridge over a narrow waterway that connects Ireland Island's North and South. It is a critical piece of infrastructure that facilitates access to both functional and historic tourism locales (Royal Naval Dockyard, National Museum of Bermuda).
- *Bailey Bridge* – Connects Coney Island with the Parish of Hamilton. It was first commissioned around 1624 and at that time must have served a critical connector function. Presently, it is in a quiet location which does not see much traffic. It is however, relatively exposed to open water.

2.2 Major Coastal Infrastructure

The Baseline Assessment identified sixteen critical locations and infrastructure components based on historical significance, transportation importance, water and fuel distribution, economic significance, and disaster response. Structures were categorized by function, material, dimensions, and condition, assessed visually using a rating system. Notably, the locations described below were highlighted.

Utilities and Infrastructure:

- Bermuda Electric Light Company Ltd. (BELCO);
- Fuel pipeline routes and landing points for heavy fuel transmission from fuel dock to the BELCO generating stations;
- Cables for telecommunications; and
- Water lines.

Marine Infrastructure:

- Tyne's Bay Waste to Energy Plant and Desalination Plant: Elevated to mitigate flood risks.
- St David's Lighthouse: Near a large coastal cliff failure.
- Sol Fuel Terminal: Shows corrosion from wave action at the shoreline.
- Fort St Catherine: Erosion of historic cliffs observed.
- Dock at Bermuda Land Development Company: Potential for infrastructure relocation, derelict bridge.

Transportation and Drainage Infrastructure:

- Docks, marinas, and commercial dock landing points.
- Pembroke Canal, Hamilton: Shows signs of flooding during high tide, with sparse mangroves downstream.
- Ferries and fish landing areas.

Coastal Facilities:

- Reverse osmosis intake and outfalls.
- Underwater fuel storage and septic tanks.
- Tourism and residential infrastructure:
  - Dockyard Cruise Ship Pier and King's Wharf: Key for tourism and industrial activities, needing shoreline stabilization and potential relocation plans.
  - Railway Trail: Vulnerable to erosion and wave damage, with pipeline corrosion concerns.
  - North Shore residences: Varying conditions, some requiring seawall protection.
  - South Shore residences and businesses: Experiencing coastal cliff failures due to aggressive wave climate.
  - Town of St George's: Low-lying with flooding issues during storms.

These locations represent critical areas that are vulnerable to various hazards and require attention for mitigation and adaptation measures.

2.3 Reserve Areas

Environmental reserves, also known as nature reserves, are areas of land or water that are designated as such and managed specifically for the conservation and protection of natural resources, including plants, animals, and ecosystems. These areas may be established by governments, private organizations, or individuals with the goal of preserving biodiversity, maintaining ecosystem health, and protecting natural habitats from human activities that can harm the environment.

Environmental reserves can take many forms, including national parks, wildlife refuges, protected areas, and marine sanctuaries. They may vary in size from small parcels of land to vast expanses of wilderness and are located in a variety of environments such as forests, grasslands, deserts, mountains, wetlands, and coastal areas.

The management of environmental reserves typically involves a range of activities, including monitoring and research, restoration and rehabilitation of degraded habitats, control of invasive species, and regulation of human activities to minimize impacts on the environment. The goal is to ensure the long-term health and sustainability of natural resources, while also providing opportunities for education, scientific research, and recreation.

There are several reasons why environmental reserves are created:

- Conservation of biodiversity: Environmental reserves are created to protect and conserve the diversity of plants and animals that live in the area. These reserves often contain unique or rare species that may be threatened or endangered, and creating a protected area can help ensure their survival.
- Preservation of ecosystem services: Ecosystems provide important services to humans, such as clean water, air, and soil. Environmental and coastal reserves help preserve these ecosystem services by protecting natural habitats, watersheds, and other critical ecosystem components.
- Mitigation of climate change: Environmental reserves can help mitigate climate change by storing carbon in trees and other vegetation, reducing greenhouse gas emissions from deforestation and land use change, and providing habitat for species that may be impacted by climate change.
- Education and research: Environmental reserves can be used for educational and research purposes, providing opportunities for scientists, students, and the public to learn about ecology, conservation, and sustainable land use practices.
- Recreation and tourism: Environmental reserves can provide opportunities for outdoor recreation and tourism, which can have economic benefits for local communities while promoting conservation and appreciation of natural areas. For example, in addition to the conservation reasons cited above, woodland reserves provide excellent opportunities for bird watching, and for access to historical sites in some instances.

Bermuda, like many other small islands, has recognized the importance of protecting its natural environment and has established several reserves. According to the World Database on Protected Areas (WDPA), Latin America and the Caribbean region have approximately 10,111 protected areas, which account for 24.29% of the total available land. In addition, 24.44% of the region's marine and coastal areas are also protected.

When compared to other island states, Bermuda's total area of protected reserves (expressed as a percentage) is similar to that protected in some Caribbean states (Table 2-2). However, some Pacific islands have exceeded this average by more than two times, indicating that there is still room for Bermuda to increase its conservation efforts.

Table 2-2 Reserve area comparison with other island nations

Country	Total Protected Area (sq. km)	Total Percent Cover (Terrestrial)	Total Percent Cover (Marine)
Bermuda (Source: *Calculated)*			
Bermuda	13.02	24.4%	-
Caribbean (*Source: WDPA)*			
Jamaica	2212	20%	0.77%
Bahamas	4930	36.63%	7.92%
Trinidad	1595	30.59%	0.05%
St Lucia	117	18.75%	0.22%
Other Regions (*Source: WDPA)*			
Palau (highest)	221	44.18%	100%
Maldives	7	2.3%	0.07%

Environmental reserves are important tools for protecting and preserving the natural world, and they serve many critical functions for both humans and the environment. Table 2-3 summarises the total area of reserves in Bermuda (agricultural, nature, coastal and woodland), and Figure 2.4 shows the locations of nature reserves in Bermuda.

Table 2-3 Total area of nature and agricultural reserves in Bermuda

Zones	Areas (acres)
Agriculture Reserves	737
Nature Reserves	775
Coastal Reserves	715
Woodland Reserves	989

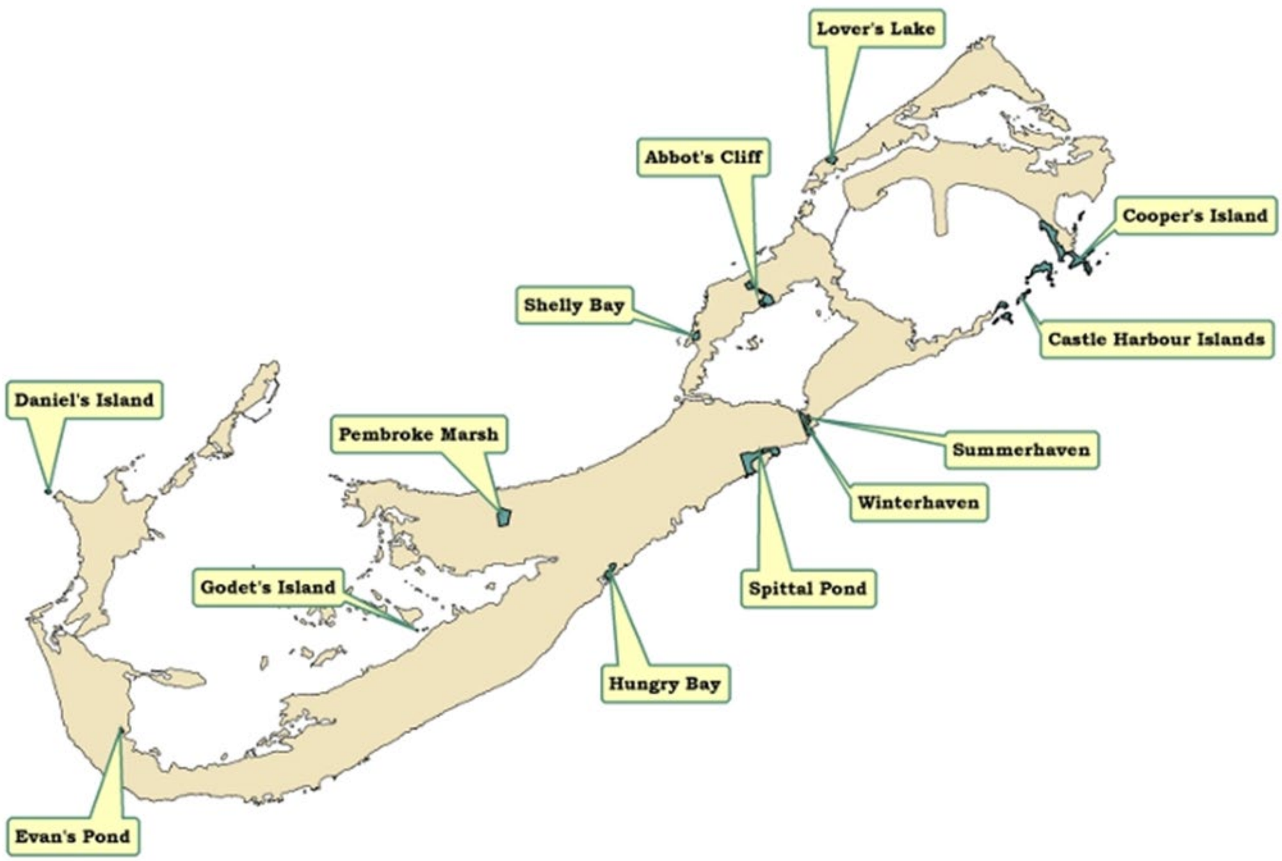

Figure 2.4 Nature reserves in Bermuda

2.4 Ecologically Significant Areas

Ecologically significant areas along a coastline refer to specific areas that have a high ecological value and importance for the conservation and preservation of biodiversity and ecosystem functions. These areas can be defined based on a range of ecological criteria such as the presence of unique habitats, rare or threatened species, high levels of biodiversity, and important ecosystem services.

Some examples of ecologically significant areas along the Bermudian coastline include:

Mangrove forests: These unique coastal ecosystems provide critical habitat for a wide range of species and help to protect coastlines from storm damage.

Seagrass meadows: These underwater meadows are important feeding and breeding grounds for many marine species, including sea turtles.

Coral reefs: These are important marine ecosystems that support high levels of biodiversity and provide important habitat for numerous fish and invertebrate species.

It is important to identify and protect ecologically significant areas along a coastline as they play a critical role in maintaining the health and resilience of coastal ecosystems and the services they provide to human communities. It is also important to note that all the ecosystems listed provide (in addition to key ecosystem services) important roles in the protection of the coastlines from destructive storm waves and surges. Finally, all three have a role to play in the capture and management of carbon dioxide, and so are important organisms in the management of climate change.

2.4.1 Mangrove forests

A total of 111 mangrove areas were identified in Bermuda. Most of these areas are less than 1,000m^2 in area (Figure 2.5). There are four areas where the mangrove areas exceed 9,000m^2: (i) Hungry Bay, (ii) Riddell's Bay, (iii) Shelly Bay and (iv) Mangrove Lake. It should be noted that 12 of the mangrove areas are located inland.

Remnant patches of mangrove swamp can be found around the coast and at some inland sites, including Hungry Bay Nature Reserve and Mangrove Lake. These were important for moderating the effects of storms and providing transition habitats. The black mangrove (*Avicennia germinans*) and red mangrove (*Rhizophora mangle*) in Bermuda are the northernmost mangroves in the Atlantic. 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. In addition to existing mangrove habitats, some areas of peat marsh exist, such as the Devonshire, Pembroke, and Paget marshes.

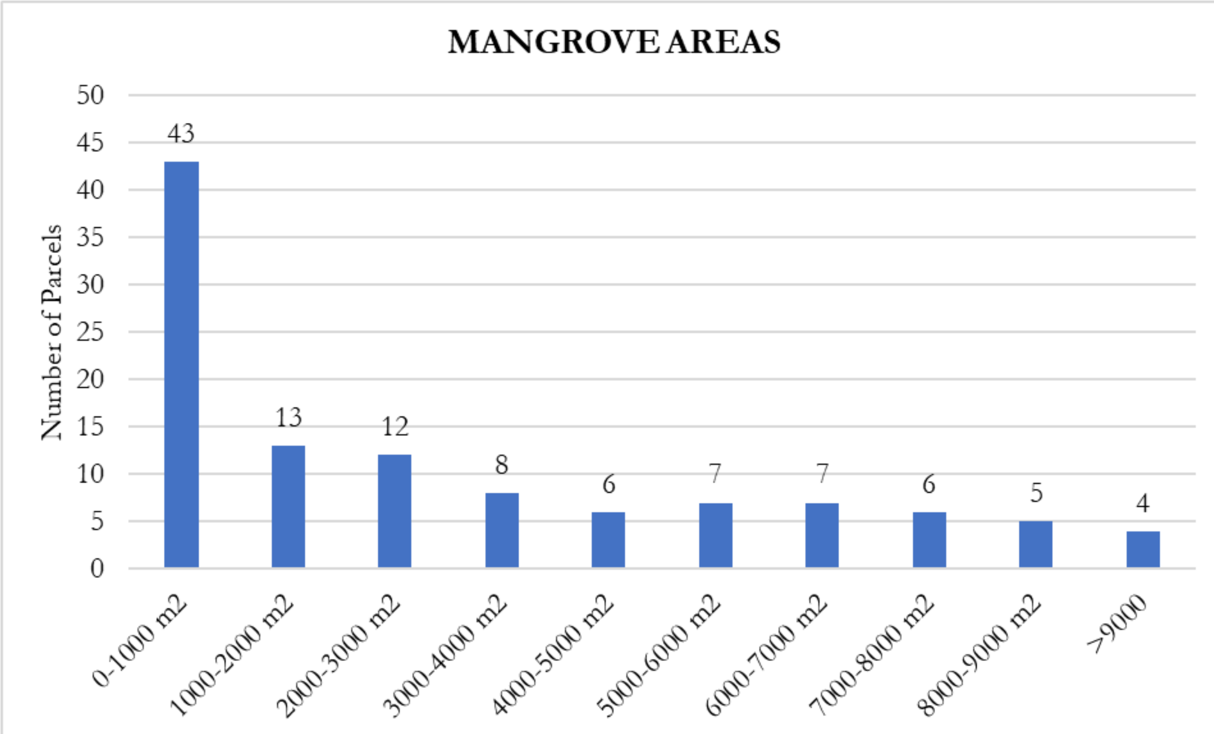

Figure 2.5 Mangrove Areas

2.4.2 Seagrass Meadows

The Bermuda Platform supports four communities of tropical marine seagrasses, including *Thalassia testudinum*, *Syringodium filiforme*, *Halodule* sp., and *Halophila decipiens* (Fourqurean et al., 2019). The seagrass communities are invaluable to the fisheries industry as they provide essential habitat and forage, regulate water quality and help to combat beach erosion (Orth et al., 2006, p. 20). Bermuda's seagrass meadows have declined in recent years in part due to overgrazing by the Green Sea Turtle (*Chelonia mydas*) (Fouqurean et al. 2019). Figure 2.6 shows the presence/absence and average percent bottom cover of seagrass, based on benthic transect site data (50m x 0.5m transects).

Figure 2.6 An excerpt from Coates et al. 2013 showing presence, absence and average percent bottom cover of seagrass based on 530 benthic transect sites of 50m by 0.5m

Figure 2.7 shows the seafloor classification for the seagrass. The data shows that seagrass can be found over approximately 11,000 acres of the seafloor around Bermuda with varying density (but primarily offshore the north shore). Approximately 38% of the seagrass has a coverage ranging between 50-70%, (Figure 2.8) notably in meadows located offshore of Bermuda's north and northwest coastlines. Along the shoreline of the north shore (Pembroke, Devonshire, and Smiths), the seagrass coverage is 10-50%.

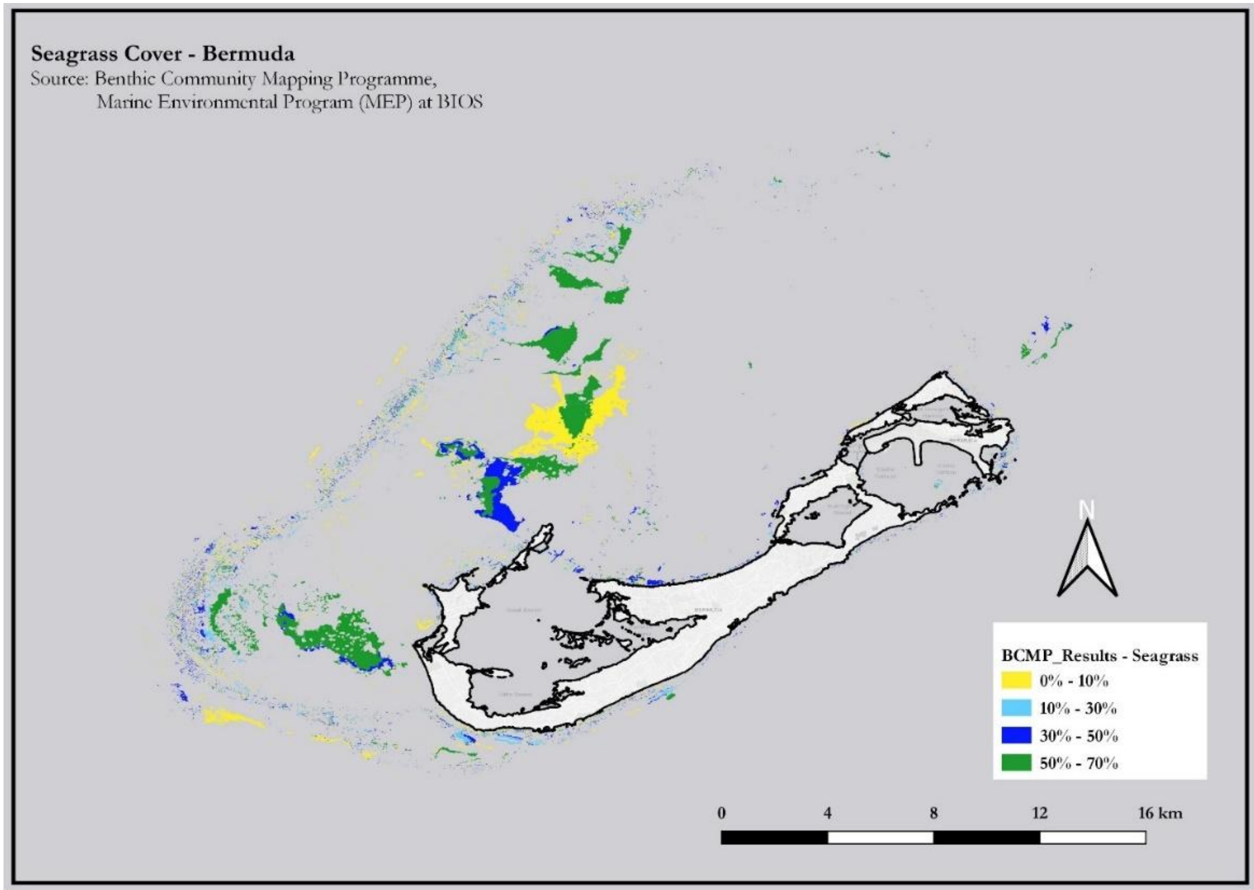

Figure 2.7 Seafloor Cover: Seagrass

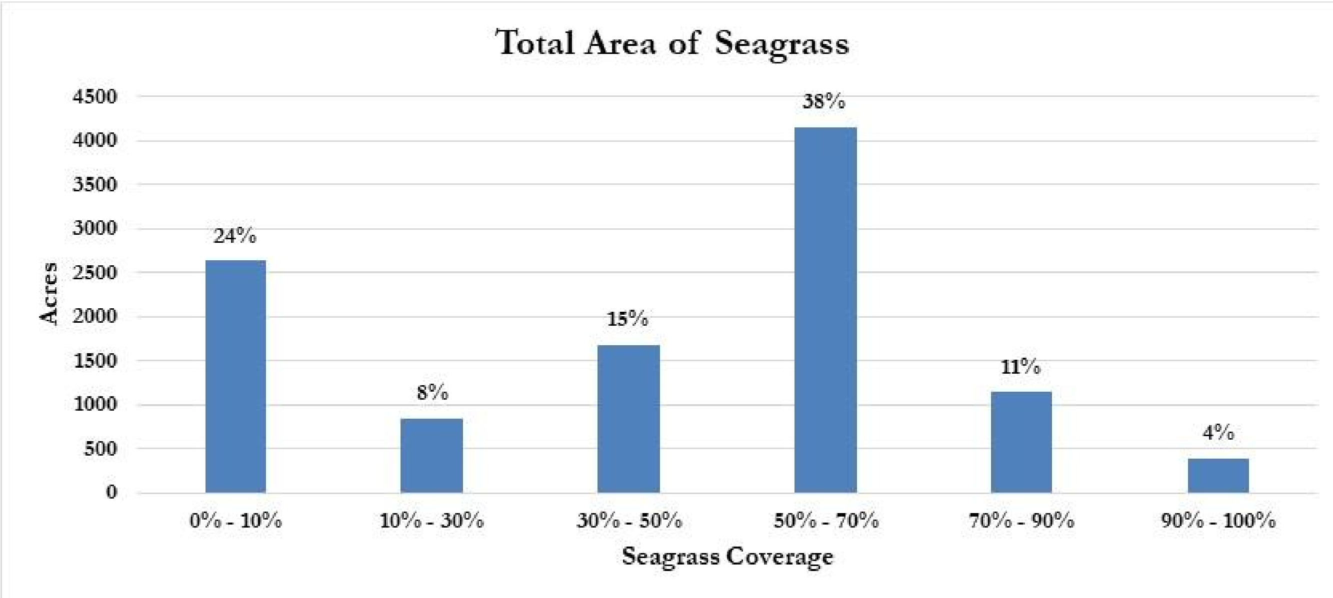

Figure 2.8 Seagrass coverage

2.4.3 Coral Reefs

Over recent decades, there has been a dramatic decline in coral reef health worldwide. Bermuda is one of the few remaining locations where the coral reef system remains relatively healthy. These reefs are considered to be the best preserved in the northern Caribbean-Western Atlantic region (Woodley et al., 2000). Great uncertainty exists, however, with respect to the capacity of Bermuda's slow growing corals to cope with rising sea levels and ocean acidification. It is therefore unknown whether the reef system will continue to deliver their valuable ecosystem services and essential economic benefits into the next century (Smith et al., 2013). On the positive side, however, Bermuda's high-latitude reefs have not experienced a major bleaching mortality event to date and may act as refuges for corals under global warming scenarios (Woodley et al. 2000; Smith et al. 2013). Figure 2.9 shows the seafloor coral cover, with most of the coral communities containing 10-50% coral coverage. The south coast has a particularly high coverage band of 50-70% and the rim reef shows coral coverages of between 10-30% (Figure 2.10).

Although the reef system has benefited from ongoing regulation and control of fishing and pollution, the nearshore environment and lagoon reefs are threatened by some existing and planned activities. Coastal development, including cruise ship ports, marinas and shipping channel expansion present significant potential threats by way of reef removal and sedimentation. Coral bleaching has occurred occasionally since the 1980's, in response to elevated seawater temperatures, but these events have not resulted in significant mortality in Bermuda. Coral diseases have prevailed at low levels of infection in a large number of species but do not appear to have caused significant mortality. The invasive lionfish (*Pterios volitans*) is present, and their population is growing, however a response to this has been the implementation of a culling and harvesting program. There is also great concern for the potential impacts of climate-related changes on these reefs, in particular from the impacts of ocean acidification. Bermuda's corals grow at reduced rates compared with similar Caribbean species and there is evidence that some corals are already growing slower, under the current condition of declining aragonite saturation state in reef waters. The potential for reduced coral and reef growth, in combination with rising sea level, may compromise the effectiveness of the reef as a natural barrier to storm waves, resulting in greater coastal erosion in the long term.

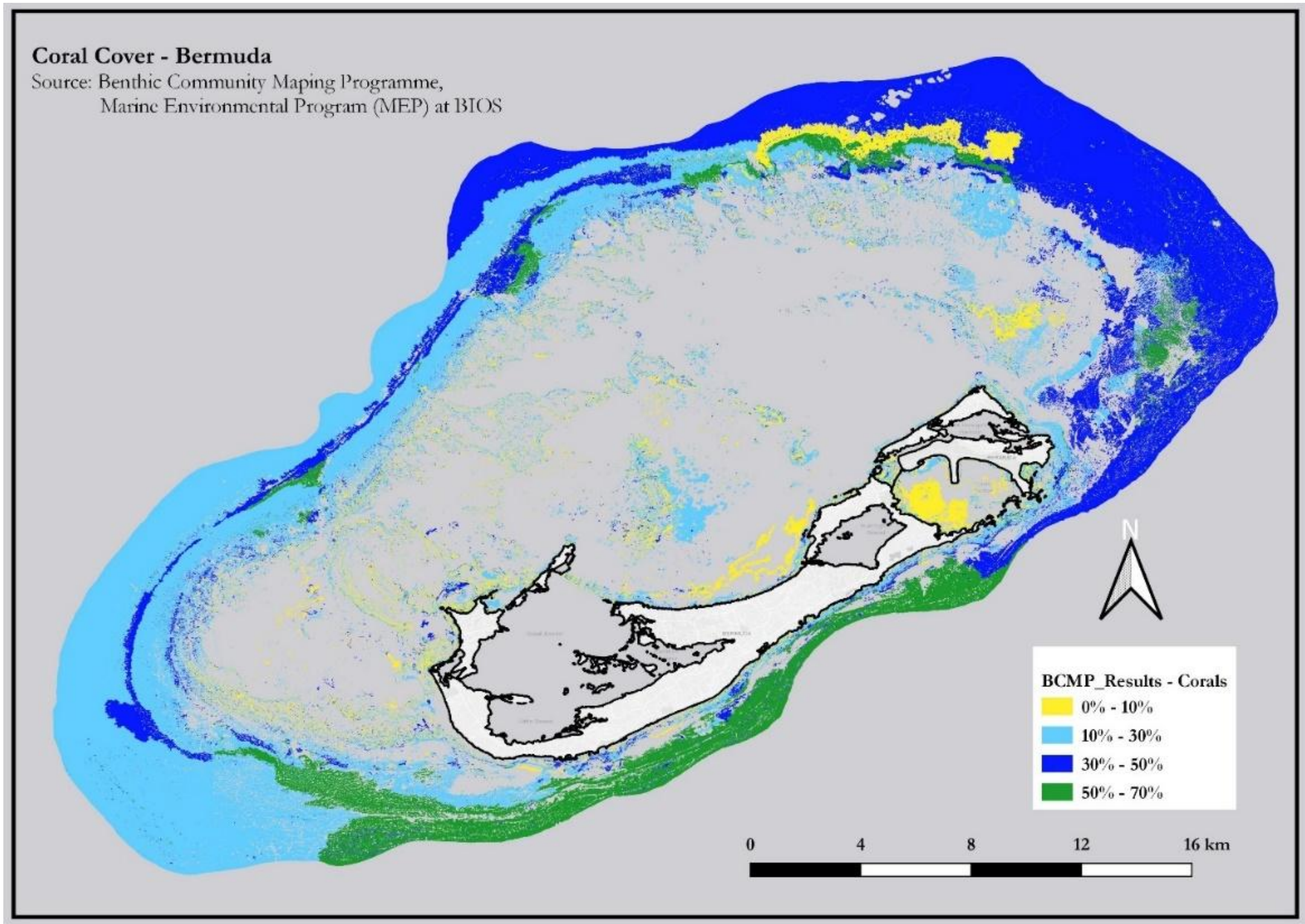

Figure 2.9 Seafloor: Coral cover

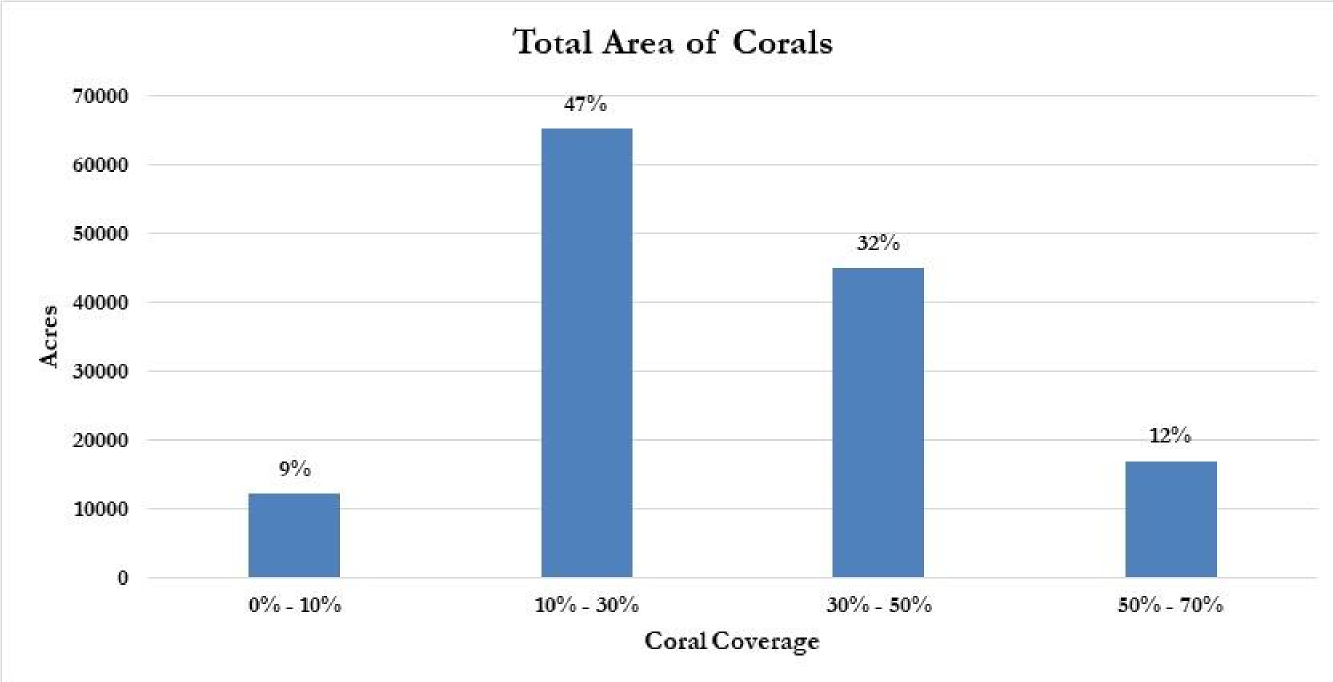

Figure 2.10 Breakdown of coral coverage

3 Hazards Exposure

Coastal hazards exposure refers to the risk of damage or harm to communities, infrastructure, and the environment that could result from natural hazards occurring in coastal areas. Typical hazards in the Caribbean and North Atlantic basin include storms, hurricanes, sea-level rise, saltwater intrusion, erosion, and flooding. Coastal areas are particularly vulnerable to these hazards as a result of their proximity to the sea and exposure to the forces of wind and water. With the effects of climate change, and as sea levels rise and weather patterns become more extreme, the risks associated with coastal hazards are expected to increase in the medium to long term.

Planning guidelines must strike the right balance that protects lives, the environment, and important infrastructure while at the same time ensuring that economic development is not stifled by overly protective measures and buffers.

3.1 Scenario Selection for Planning Development

In the development of appropriate planning guidelines, there are three different parameters that need to be evaluated and selected:

- *Planning time horizon*, which defines the time period under consideration,
- *Return period* of the extreme event, which describes the severity of extreme events typically analysed through statistical risk occurrence analyses (conversely this can be regarded as the level of risk that the society is prepared to take on in the face of known hazard occurrences), and
- *Emission pathway* (RCP or SSP), or climate change scenario.

3.1.1 Planning Time Horizon

Of these, the planning time horizon is the most important. When planning guidelines contend with extreme events such as coastal flooding, which are infrequent but damaging events, a statistical approach is typically adopted, which is traditionally based on the mathematical concepts of ergodicity and stationarity. However, doing this within a framework of uncertainty that is exacerbated by climate change brings significant additional challenges. The different scenarios of potential climate change, and in particular global sea level rise, vary considerably. Adopting a climate change scenario that is overly optimistic; one that relies on global emissions rapidly dropping, may result in lives, ecosystems, and assets being exposed to unacceptably high risks if that pathway is exceeded. Conversely, a more pessimistic outlook on global emissions may result in unnecessarily high costs for economic development and may appear to be overly conservative for the next few decades, as conditions are not as bad as planned for.

For engineering design purposes, the selection of an appropriate return period looks at the consequence of failure and then balances the initial capital cost against future possible maintenance costs. Typically, for shoreline protection and other non-critical infrastructure, a return period of 50 years is recommended so that the initial capital costs are kept within a reasonable range. A longer design return period is considered if the design involves critical infrastructure such as port facilities, power generation, essential transportation links, emergency installations, etc. or facilities that may require a longer design life.

Conversely, for planning purposes, extreme events that have a higher return period of at least 100 years are recommended. This is to avoid development of infrastructure in greenfield sites (or redevelopment of existing infrastructure) that may be overly exposed to the effects of climate change in the foreseeable future.

For the planning time horizon in this study, SWI relies on precedence established by recent climate change reports, coastal master plans, and other relevant studies. The generally accepted time horizon for climate change reports for sovereign nations is 100 years, identified in:

- Barbados' Integrated Coastal Zone Management Plan, where a 100 year time horizon is stated or inferred for "flooding" (SLR induced storm-surge and tsunami) and cliff erosion.[3]
- The Republic of the Marshall Islands has mandated that any coastal protection works (other than for a defined short-term purpose) should be designed to a 50 year planning horizon for short term interventions (with consideration on how it could be upgraded to withstand longer term outcomes) and a minimum 100 year horizon - or more - depending on the situation for longer term interventions[4].
- New York City has undertaken extensive flood mapping, which includes recent updates. Their online map portal shows three different time horizons including present day, 2050 and 2080[5].

Based on this, and accounting for SLR, beach and cliff erosion, SWI recommends a 50-year time horizon for short term planning and a 100-year time horizon for longer-term considerations.

3.1.2 Return Period of the Extreme Event

The calculation of the representative extreme event is typically done using historical climate data. Recent findings from the IPCC have suggested that for flooding events, climate change will result in today's predictions of extreme events becoming more common. What is estimated today as a 100-year flood event is predicted to occur more frequently in the future, such that it will eventually be considered a 30-year event, and eventually a 10-year event, and possibly an annual occurrence. The following figure from IPCC (2019) Special Report on the Ocean and Cryosphere depicts how Historical Centennial Events (HCE's, 100-year return period events) are predicted to transition to annual events (1-year events). The data for Bermuda appears to suggest this transition will occur in approximately the period 2040-2050 for both the RCP 2.6 and RCP 8.5 emission scenario.

[3] The Government of Barbados, Coastal Zone Management Unit (2022). Integrated Coastal Zone Management: The Barbados ICZM Plan (2020 to 2030), ICZM Plan Vol.2, October 2022, A1.2.1. The Coastal Zone Management Area

[4] Republic of the Marshall Islands, Tile Til Eo Committee (2023), RMI Sea Level Rise (SLR) Adaptation Policy – Cabinet Proposal Final, Office of Chief Secretary, Climate Change Division, 14 June 2023

[5] City of New York, 2023. Flood Hazard Mapper. Available at: https://www.nyc.gov/site/planning/data-maps/flood-hazard-mapper.page), accessed April 13, 2023.

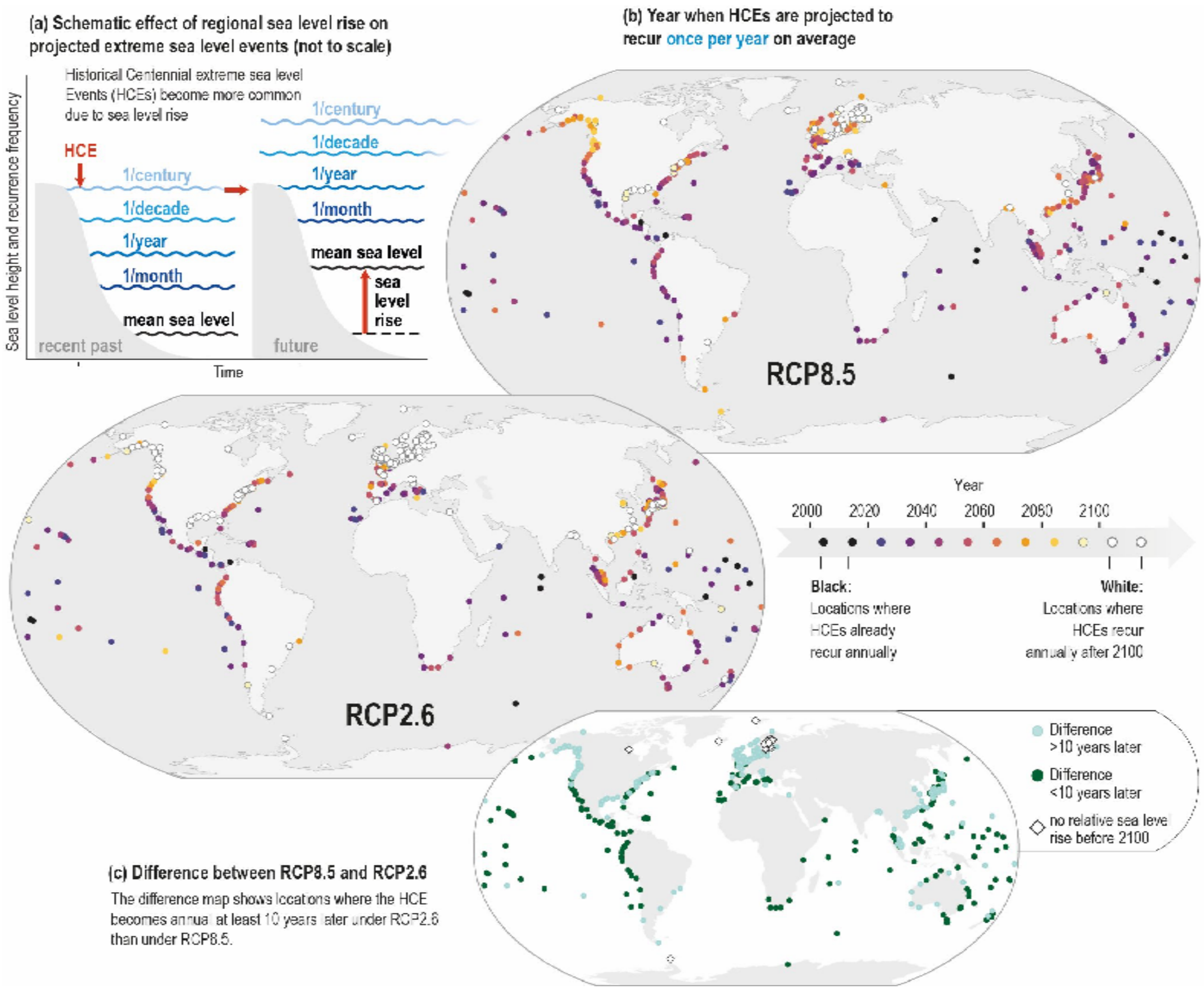

Figure 3.1 Graphical description of transition of Historical Centennial Events (HCE's, 100-year return period events) to transition to annual events (1-year events)[6].

As described in the preceding paragraph, climate change predictions indicate an increase in the frequency of extreme events, and SWI's analysis revealed an increase in the extreme wave heights by 1.5 – 2.5% in the next 50 years (SWI *Modeling Report*, March 2024).

[6] IPCC, 2022: Summary for Policymakers [H.-O. Pörtner, D.C. Roberts, E.S. Poloczanska, K. Mintenbeck, M. Tignor, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem (eds.)]. In: Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 3-33, doi:10.1017/9781009325844.001.

Given these parameters outlined above, and the uncertainty levels within each, it may be prudent to select an appropriate range of those parameters, rather than focus on a single value. Looking at how other jurisdictions have selected scenarios for consideration provides a useful benchmark analysis:

- For coastal flooding risk, the UK has adopted a range of risk levels that correspond to chance of flooding each year and the corresponding applicable return periods (Table 3-1)[7]. Mapping has been conducted that shows the present flooding risk and is available for the general public to see maps through a web-browser. However, future climate change scenarios are not presented in this format.

Table 3-1 UK guidance for climate change assessment.

Risk Level	Annual Probability of Exceedance (i.e. chance of flooding each year)	Return Period (yrs.)
High	x >3.3%	<30
Medium	1.0< x <3.3%	30-100
Low	0.1< x <1.0%	100-1,000
Very Low	x <0.1%	>1,000

- New York City has undertaken extensive flood mapping, which includes recent updates. Their online map portal shows the flooding for 100- and 500-year events for three different time horizons including present day, 2050 and 2080[8]. The sea level rise for the future scenarios is based on high climate change emission pathway estimates.
- In Barbados' Integrated Coastal Zone Management Plan, a 100 year return period is stated or inferred for surge modelling, extreme wave conditions, beach erosion, cliff erosion and tsunami inundation[9].
- The Hawai'i Sea Level Rise Report (2017) and Hawaii Sea Level Rise assumes a 1%-annual-chance coastal flood zone, equivalent to a 100 year return period event, to estimate coastal flood extents for wave-generating events including tropical storms, hurricanes, tsunamis, and other severe wave events with sea level rise.
- The City of Miami[10] has adopted a varying criteria for their level of assessment, which includes:

[7] UK Environment Agency, 2023. Available at: https://check-long-term-flood-risk.service.gov.uk/map, accessed April 13, 2023.

[8] City of New York, 2023. Flood Hazard Mapper. Available at: https://www.nyc.gov/site/planning/data-maps/flood-hazard-mapper.page), accessed April 13, 2023.

[9] The Government of Barbados, Coastal Zone Management Unit (2022). Integrated Coastal Zone Management: The Barbados ICZM Plan (2020 to 2030), ICZM Plan Vol.2, October 2022, A1.2.1. The Coastal Zone Management Area

[10] Comprehensive Stormwater Master Plan (B-30632A) Draft Executive Summary, March 2021

- Zero flooding over the crown of all roads in the 10-year recurrence interval design storm event, and no flooding for buildings for the 100-year design storm wherever practicable.
- Where it cannot be achieved, or where it is not economically feasible, the level of service is reduced to a 5-year recurrence interval design storm event; and temporary flooding is allowed of a safe predictable depth, for short durations of time, in known areas, for the 10-year event.

While most jurisdictions reference a (present day) 1:100 year return period event, SWI identified (above) that recent findings suggest that for flooding events, climate change will result in today's predictions of extreme events becoming more common[11]. **For this reason, SWI recommends that the 150-year return period storm event be applied to reduce the risk from future coastal flooding events.**

3.1.3 Climate Change Scenario

Despite the predictions relating to the intensity of storms and annual wave power, sea level rise is expected be the main driver for coastal flooding.

The latest IPCC report (AR6 Synthesis Report, 2023) provides some guidance for the selection of appropriate SLR scenarios for coastal flooding and erosion risk. Two important points are stressed here:

- Figure 3.2 indicates that between AR5 and AR6 new research has revealed that the risk/impacts for various "Reasons for Concern" have increased for the same level of global warming, or put another way, moderate to high risks/impacts are now predicted to occur at even lower global warming levels. Looking at extreme weather events, the newer science (2022 vs 2014) has revealed that high risks will occur at 1.5ºC warming, whereas in the AR5, this was above 2ºC.

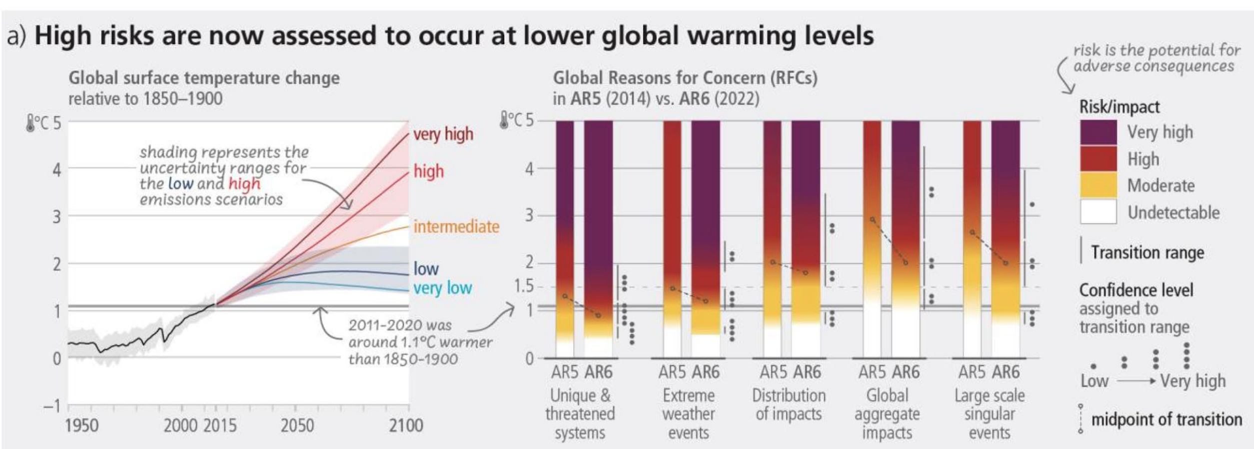

Figure 3.2 Increase in risk from IPCC's AR5 to AR6 reports for given global surface temperature change scenarios[12]

[11] SWI (2023), Coastal Vulnerability Index and Recommendations Report, Bermuda and Climate Change: Impacts from Sea Level Rise and Changing Storm Activity, Prepared for: Ministry of Home Affairs, Department of Planning, Bermuda.

[12] IPCC 2022. Figure 3.3.

- Figure 3.3 depicts how projected global mean SLR will vary with the response and actions taken to adapt to it. This figure may provide some comfort, as jurisdictions that have the potential, desire, and capacity to respond will have a risk profile that is potentially lower.

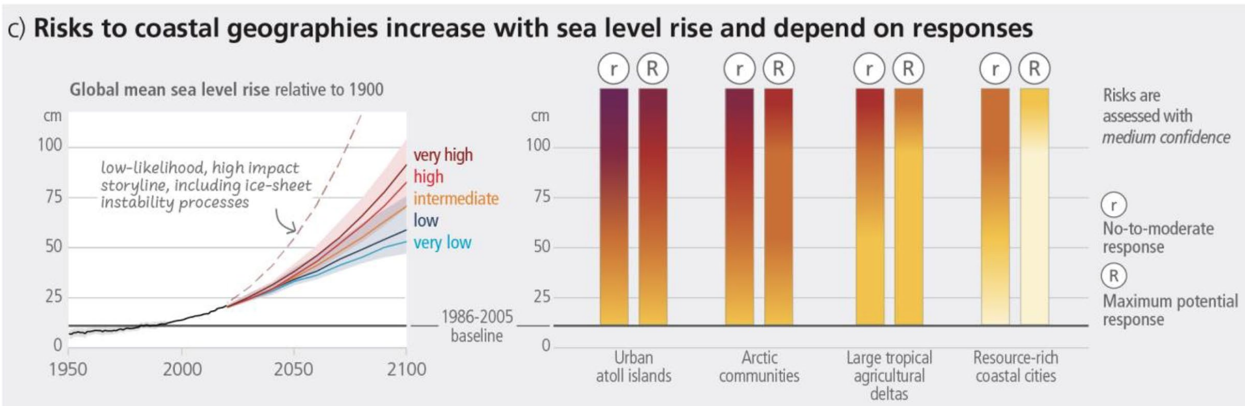

Figure 3.3 Risk profiles of jurisdictions based on response to sea level rise threat[13]

A comparison of the figures of temperature and mean SLR between 1950 and 2100 shows a rather disturbing correlation – even if a low emission pathway occurs, which could see global temperatures decrease in the latter half of this century, mean sea levels will continue to increase, and this is expected to continue well into the next century and beyond. AR6 includes the following figure, which accurately summarises the risks until the end of the century, and an assessment of the years beyond.

[13] IPCC 2022. Figure 3.3.

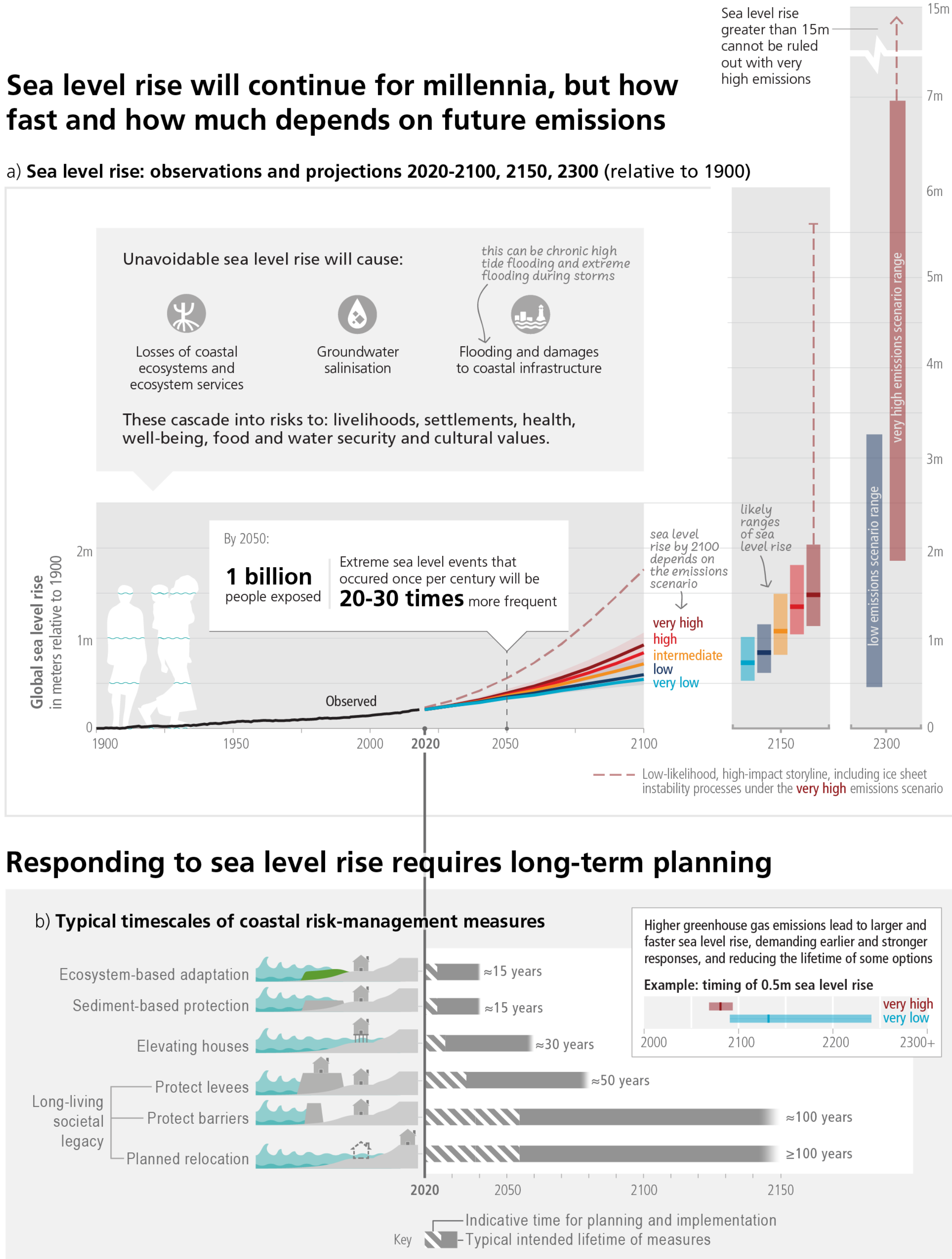

Figure 3.4 Summary of risks from sea level rise over the next century[14]

Regardless of the climate change scenario chosen, by the end of this century, mean sea level is predicted to be at least 0.5m above its present value. The intermediate climate change scenario has a median level that rises to 0.75m above present in 2100 and then above 1.0m by 2150. The slow and steady rising sea levels that appear to lag the rise in temperature suggest that a precautionary approach for sea level rise is appropriate.

For this report, SWI adopted the Representative Concentration Pathways (RCP) framework as presented in the 2014 IPCC climate change report. RCPs are factor amalgamated greenhouse gas emission (GHG) scenarios used by the IPCC, which categorize possible future climates of the world. Factors weighed into the scenarios include energy use, economic activity, and land use. There are four defined scenarios, namely RCP 2.6, 4.5, 6 and 8.5, each representing a future subjected to a specific radiative forcing value because of the predicted cumulative GHG emission quantities. **The chosen RCP scenarios include RCP4.5 and RCP8.5**:

- RCP4.5 is selected to represent a middle level of the RCPs, which has the largest number of Global Climate Model (GCM) simulations.
- RCP8.5 is the highest of the RCPs and with high climate sensitivity represents the greatest level of climate risk.

Of note, in the latest IPCC reports, the trend to describe climate change scenarios is one from RCPs to "Shared Socio-economic Pathways" (SSPs). SSPs are a new method of assessing future scenarios which seeks to combine the knowledge of the physical sciences of climate change with the societal impacts brought on by the vulnerability caused by climate change. SSPs incorporate adaptation and mitigation research to create a more holistic approach to future projections by combining them with future emission and concentration scenarios with socio-economic development pathways.

- SSP1-2.6 is described as the 'sustainability' development pathway. Under SSP1-2.6 global warming stays just below 2°C at the end of the century when compared to pre-industrial (pre-1900) levels.
- SSP2-4.5 referred to as the 'middle of the road' development pathway. SSP2-4.5 corresponds to emissions reductions which are roughly in line with the upper bounds of the latest Nationally Determined Contributions and global warming of around 2.7°C at the end of the 21st century.
- SSP3-7.0 referred to as 'regional rivalry' development pathway. SSP3-7.0 corresponds with a medium-high development pathway. Under this SSP no additional climate change policy is put in place and there are high non-CO2 related emissions which leads to a pathway that would be roughly in the middle of the previous RCP6.0 and RCP8.5
- SSP4-6.0 referred to as 'inequality' development pathway and which considers emissions peaking around 2040 and slowly declining thereafter (versus peaking in 2080 as predicted by RCP6).
- SSP5-8.5 described as a 'fossil fuel intensive' development pathway. (See Riahi et al., 2017 for more details on SSPs). SSP5-8.5 corresponds to very high emissions, no additional climate policy and intensive fossil fuel dependent development, which is the worst-case scenario pathway.

[14] IPCC 2022. Figure 3.4.

For Bermuda, there is good consensus across the two mapping tools examined about sea level rise[15]. Though RCPs and SSPs are not directly comparable, by 2050, mean SLR is projected to increase by 0.23m for RCP4.5 and 0.21m SSP2-4.5; while by 2100 mean SLR is projected to be at 0.53m for RCP4.5 and 0.56 for SSP5-8.5.

SWI's modelling report included the following table outlining the sea level rise scenarios.

Table 3-2 Sea level rise scenarios adopted for this study

RCP Scenario	Time Horizon (yr)	Rate (mm/yr)	Source	Projected SLR (m)
RCP4.5	20	5.7	SSP3-7.0 Rate 2040-2060	0.11
	50	7.7	SSP2-4.5 Rate 2080-2100	0.39
	100	7.7	SSP2-4.5 Rate 2080-2100	0.77
RCP8.5	20	6.6	SSP5-8.5 Rate 2040-2060	0.13
	50	10.5	SSP5-8.5 Rate 2080-2100	0.53
	100	10.5	SSP5-8.5 Rate 2080-2100	1.05

The uncertainty in modelled predictions, as well as the acceleration of future sea level rise, is inherent in the measured historical data. Between 1900 and 2018, sea levels rose approximately 200mm at a rate of 1.7 mm/yr over the entire time period. Breaking this down into discrete time periods, sea levels rose at 1.3mm/yr between 1900-1971, 1.9mm/yr until 2006, and thereafter almost doubled to 3.7mm/yr from 2006 to 2018. Satellite altimetry data confirms a global average rate of SLR exceeded 3.2 mm/yr since 1993. In 2022, the global average sea level set a new record high—101.2 mm above 1993 levels[16]. This increased rate, is consistent with the more aggressive climate change projections, and can be attributed to a variety of factors:

- The World Meteorological Organization (WMO) reports that 2023 was one of the hottest years on record, with global temperatures exceeding pre-industrial levels by an estimated 1.1°C[17].
- A 2023 study published in Nature Geoscience revealed that the Greenland ice sheet lost mass at an unprecedented rate between 2019 and 2022, exceeding earlier predictions[18]. Similarly,

[15] 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.

[16] Climate.gov (2022). Climate Change: Global Sea Level, published April 19, 2022, Available at: https://www.climate.gov/news-features/understanding-climate/climate-change-global-sea-level, Accessed February 21, 2024.

[17] World Meteorological Organization (2024). WMO confirms that 2023 smashes global temperature record

Published 12 January 2024. Available at: https://wmo.int/news/media-centre/wmo-confirms-2023-smashes-global-temperature-record, Accessed Feb 21 2024.

[18] Bochow, N., Poltronieri, A., Robinson, A. *et al.* Overshooting the critical threshold for the Greenland ice sheet. *Nature* **622**, 528–536 (2023). https://doi.org/10.1038/s41586-023-06503-9

research published in Science in 2021 indicates that the Antarctic ice sheet is contributing more significantly to SLR than previously estimated[19].

- The 2024 Copernicus Climate Change Service (C3S) reports that 2023 has seen record-breaking Sea Surface Temperatures (SSTs) around the globe, including the highest daily global SST in the ERA5 satellite record, and every month from April through to December saw global SSTs reach record levels for the time of year. High SSTs were particularly felt in the North Atlantic, with exceptional SSTs throughout June to December, where monthly anomalies well above average for the time of year were recorded and daily SST records were broken. The previous highest daily SST for the North Atlantic was 24.81°C, set in September 2022, and on 31 August 2023 the SST reached 25.19°C. The boreal summer months saw marine heatwaves across large sectors of the North Atlantic. The warm tropical Atlantic SSTs also contributed to an above-normal hurricane season, ranking 4th for the most named storms in a year since 1950 and seeing the most named storms of any El Niño influenced year[20].

These factors - thermal expansion of oceans and enhanced meltwater contributions from the Greenland and Antarctic ice sheets are driving this SLR increase.

In order to bracket the uncertainty of future climate change scenarios, a range of sea level rise scenarios is adopted for this study. The lower sea level rise recommended corresponds to the RCP4.5 scenario over a 50-year time horizon with a rise of 0.385m. The higher scenario recommended assumed the RCP8.5 predictions over a 100-year time horizon, resulting in a rise of 1.05m.

Of these two, SWI recommends that the GoB favour the latter RCP8.5 scenario for their long-term planning, which is consistent with recent practises in other jurisdictions, such as:

- Barbados' Integrated Coastal Zone Management Plan adopts a SLR rate corresponding to RCP8.5 scenario in 2100[21],
- Louisiana's Coastal Master Plan adopts NOAA Intermediate-High SLR curve with forcings from RCP 8.5 projections, as reported in their 2023 report[22],

[19] Sadai, S., Condron, A., DeConto, R., Pollard, D. (2020) Future climate response to Antarctic Ice Sheet melt caused by anthropogenic warming, Science Advances, 23 Sep 2020, Vol 6, Issue 39, DOI: 10.1126/sciadv.aaz116

[20] Copernicus Climate Change Service (C3S) (2024). The 2023 Annual Climate Summary, Global Climate Highlights 2023. Available at: https://climate.copernicus.eu/global-climate-highlights-2023, Accessed Feb 21, 2024.

[21] The Government of Barbados, Coastal Zone Management Unit (2022). Integrated Coastal Zone Management: The Barbados ICZM Plan (2020 to 2030), ICZM Plan Vol.2, October 2022, A1.2.1. The Coastal Zone Management Area

[22] Pahl, J. W., Freeman, A. M, Fitzpatrick, C., Jankowski, K. L., & White, E. D. (2023). 2023 Coastal Master Plan: Attachment B2: Scenario Development: Sea Level Rise and Additional Climate-Driven Variables. Version 2. (p. 43). Baton Rouge, Louisiana: Coastal Protection and Restoration Authority.

- Sea level rise exposure mapping in the 2017 Hawaiʻi Sea Level Rise Report and Hawaii Sea Level Rise Viewer is based on an upper-end projection in the 2013 IPCC 5th Assessment Report of 3.2 feet (0.98 m) of global mean sea level rise by 2100[23],
- The Republic of the Marshall Islands has mandated that IPCC 2021 SLR Scenario projections SSP1- 2.6, SSP2- 4.5 and SSP5-8.5 (adjusted for RMI and any future updates) should be used as the basis for updating future SLR planning projections[24].

3.1.4 Scenario Selection Summary

In summary, the selection of an appropriate planning time horizon is the most important aspect when considering coastal erosion and flooding in the framework of climate change. The increased frequency of coastal flooding is mainly affected by future sea levels, and to a lesser extent by changes in the climate that affect the wind and waves. Different climate change scenarios, (RCP or SSP) affect the timing of the rising sea levels; only in the longer time horizons is the extent affected.

For SLR, beach and cliff erosion, SWI has adopted a 50 year time horizon for short term planning and a 100 year time horizon for longer term considerations. Given the recent trend on climate patterns, the "moderate" (RCP4.5) and "aggressive" (RCP8.5) scenarios were selected (which are very similar to more updated SSP scenarios in AR6). For the anticipated increased frequency of extreme storm events (described earlier), SWI assumed the 150-year return period storm event to model coastal erosion and flooding events for both of these water level rise scenarios. The 150-year return period was chosen as an event with reasonable confidence based on statistical derivation in extreme value analysis processing from the available NOAA NHC hurricane record (Modelling Report, Sections 4.3 and 4.4) and 43 years of hindcast ERA-5 data (Modelling Report, Section 3.1), as well as inherent uncertainties in the climate change forecasts.

Table 3-3 presents the hazards considered for this project.

Table 3-3 Hazards considered in the assessment.

Timescale		Hazard Considered
Short Term	20-year Horizon	1. Inundation from Storms (150-year event) (RCP 4.5 and 8.5) 2. Cliff Erosion (Shoreline Retreat) (RCP 4.5 and 8.5) 3. Beach Erosion (Shoreline Retreat) (RCP 4.5 and 8.5) 4. Saltwater Intrusion from Sea Level Rise (RCP 4.5 and 8.5)
Medium Term	50-year Horizon	
Long Term	100-year Horizon	

Of these scenarios, the following have been selected for graphical analysis:

- RCP4.5, 50-year horizon, 150yr storm event
- RCP8.5, 100-year horizon, 150yr storm event

[23] Hawaiʻi Climate Change Mitigation and Adaptation Commission. 2017. Hawaiʻi Sea Level Rise Vulnerability and Adaptation Report. Prepared by Tetra Tech, Inc. and the State of Hawaiʻi Department of Land and Natural Resources, Office of Conservation and Coastal Lands, under the State of Hawaiʻi Department of Land and Natural Resources Contract No: 64064.

[24] Republic of the Marshall Islands, Tile Til Eo Committee (2023), RMI Sea Level Rise (SLR) Adaptation Policy – Cabinet Proposal Final, Office of Chief Secretary, Climate Change Division, 14 June 2023

3.2 Inundation from Storms

Storm surge and heavy rainfall associated with storms can lead to flooding and inundation in low-lying areas. In recent years, Bermuda has experienced several significant storms that caused widespread flooding and damage. For example, in 2014, Hurricane Gonzalo caused extensive damage, including power outages, downed trees, and significant flooding. Hurricane Gonzalo was the second tropical cyclone, after Hurricane Fay, to directly strike the island in a week in October 2014, and was the first Category 4 Atlantic hurricane since Hurricane Ophelia in 2011. At the time, it was the strongest hurricane in the Atlantic since Igor in 2010[25]. Gonzalo struck Bermuda less than a week after the surprisingly fierce Hurricane Fay. It is noted that 2014 was the first season in recorded history to feature two hurricane landfalls in Bermuda.

To develop estimates of inundation resulting from a strong hurricane and taking into account predictions of climate change over near- to long-term timeframes, the 1 in 150-year storm event was used with both RCP4.5 and RCP8.5 SLR forcing scenarios (Table 3-4). The modelling report (Section 4.4) details the extensive data analysis and numerical modelling undertaken to derive coastal storm parameters. The components for storm surge include Inverse Barometric Pressure Rise (IBR, which is related to hurricane statistics based on the HURDAT database), tide levels, effects from mesoscale eddies (unique to Bermuda), wind and wave setup from storms, sea level rise, and dynamic surge (run-up).

The findings (Table 3-4, Figure 3-5) suggest that over the near term (20 years), there will be a small change in the impact of hurricane inundation, with a 17% increase equating to 111 buildings under the RCP4.5 scenario, and a modest 20% rise to 133 buildings under the RCP8.5 scenario compared to the current situation. However, looking ahead to the medium term (50 years), the area affected by inundation for buildings during severe hurricanes is projected to increase by 66-86% for respective RCP scenarios. In the long term (100 years), the number of affected buildings is forecasted to surge by 126-169% compared to the present-day situation. One significant implication of these findings is the necessity to revise Building Codes to address this escalating threat in the medium to long term.

Table 3-4 Number of buildings affected by inundation during a 1 in 150-year storm event (percentage referenced to present day)

Horizons	RCP 4.5	RCP 8.5
Present Day	656	
20 years	767 (17%)	789 (20%)
50 years	1088 (66%)	1218 (86%)
100 years	1485 (126%)	1766 (169%)

[25] Atlantic Hurricane Best Track (HURDAT Version 2)" (Database). United States National Hurricane Center. September 19, 2022. Retrieved March 14, 2023.

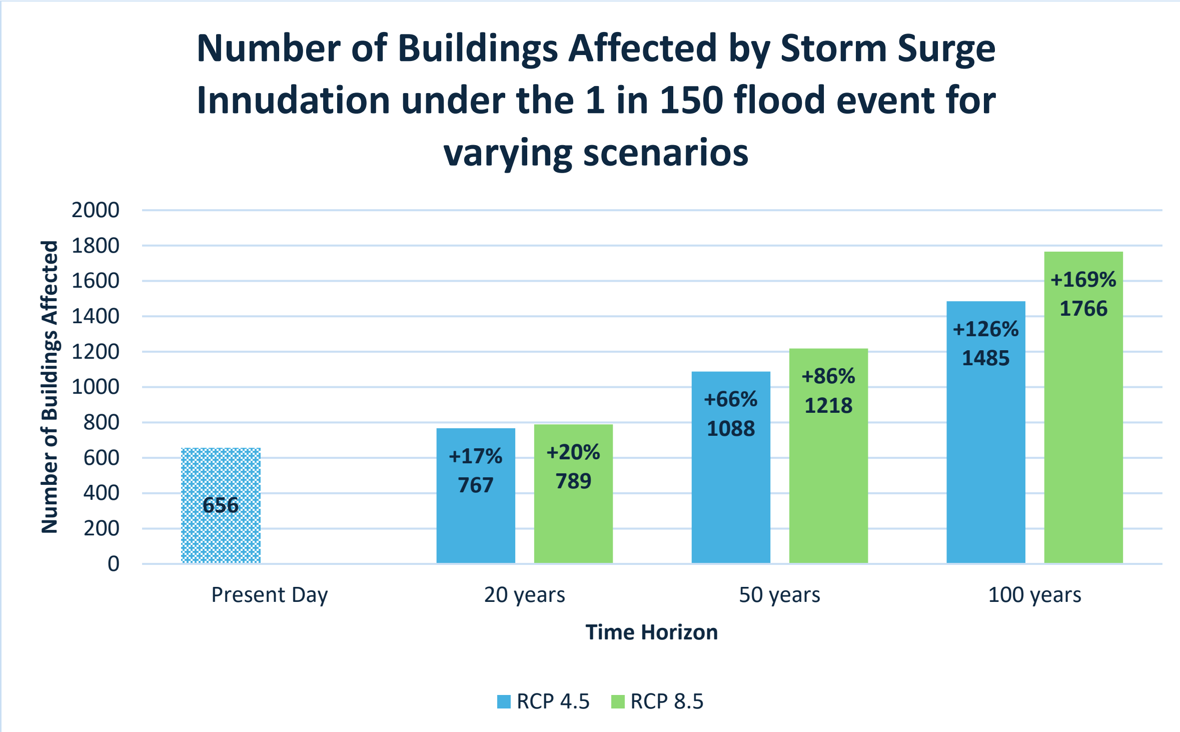

Figure 3.5 Buildings expected to be impacted by a 1:150-year storm event for different time horizons

The analysis also reveals a notable variation in the number of roads affected by inundation across different time horizons and emission scenarios. Presently, there are 244 roads affected by inundation. Looking ahead, under the RCP 4.5 scenario, the number of affected roads is projected to increase to 279 in the next 20 years, indicating a 14% increase, and to 359 and 490 in the next 50 and 100 years, respectively, representing percent changes of 47% and 101%, respectively. Similarly, under the RCP 8.5 scenario, the number of affected roads is forecasted to rise to 285 in the next 20 years, marking a 17% increase, and to 402 and 586 in the subsequent 50 and 100 years, with percent changes of 65% and 140%, respectively (Figure 3.6). These projections underscore the escalating threat of inundation to road infrastructure over time, highlighting the imperative for proactive adaptation measures to mitigate potential impacts.

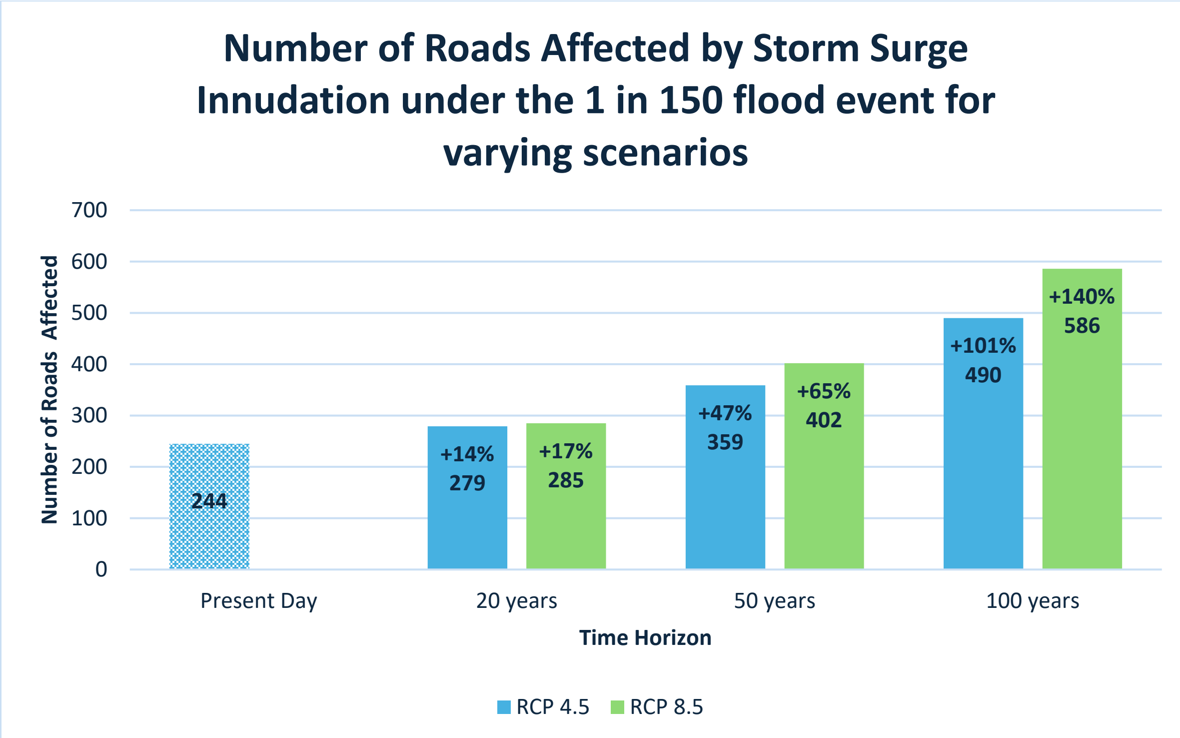

Figure 3.6 Roads expected to be impacted by a 1:150-year storm event for different time horizons

An analysis incorporating rainfall over the Pembroke Marsh catchment indicates a significant rise in the number of affected buildings across various scenarios. Presently, there are 2986 buildings within the catchment area are affected by rainfall (Figure 3.7). Looking ahead, projections for the 20-year timeframe show 3499 buildings (+17%) under RCP 4.5 and 3504 buildings (+17%) under RCP 8.5. For the 50-year period, the numbers increase to 3867 buildings (+30%) under RCP 4.5 and 3981 buildings (+33%) under RCP 8.5. In the 100-year outlook, the figures surge to 4710 buildings (+58%) under RCP 4.5 and 4988 buildings (+67%) under RCP 8.5. These findings underscore the pressing need for proactive measures to address the escalating risks posed by rainfall-induced inundation events within the catchment area.

While these results provide valuable insights into potential impacts within low-lying areas of Bermuda, it is important to note that the rainfall modelling did not consider the specific locations of manmade drainage infrastructure. Therefore, interpretation of the findings should be approached with caution. Nonetheless, these results offer a glimpse into potential scenarios and may guide decisions regarding the maintenance or enhancement of existing manmade structures in areas vulnerable to compound flooding scenarios.

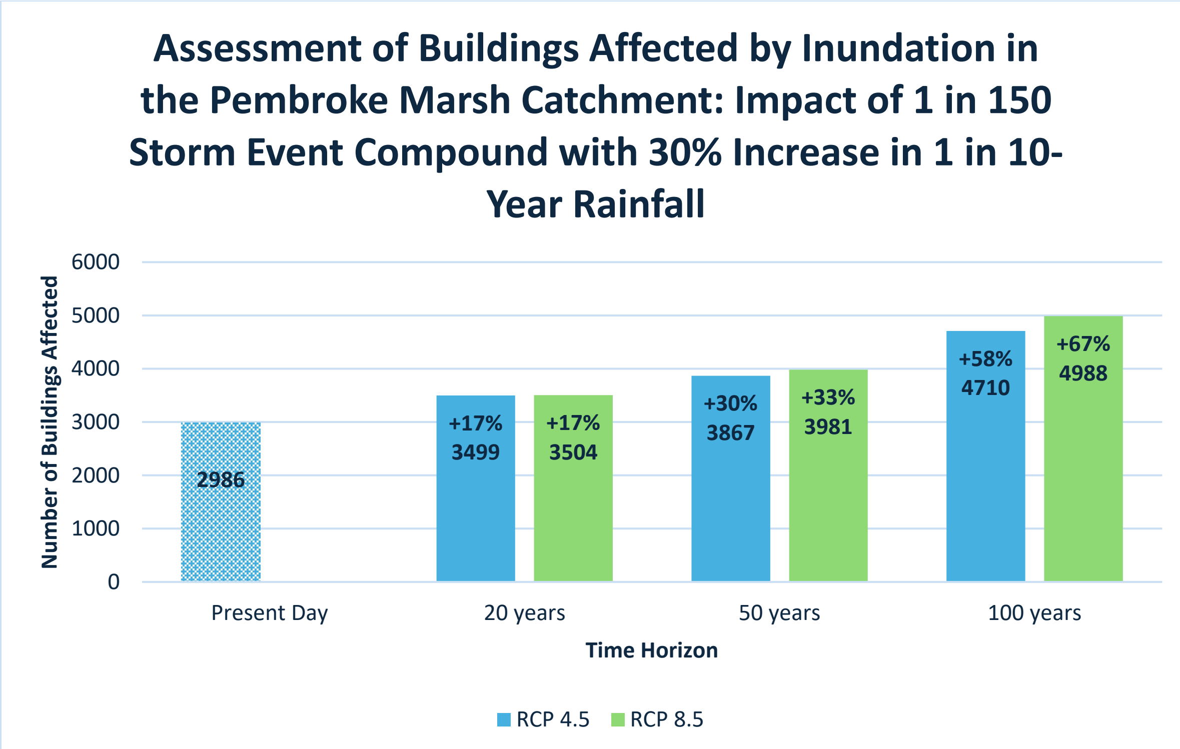

Figure 3.7 Buildings within the Pembroke Marsh Catchment area expected to be impacted by compound flooding from the 1:150-year storm event and the 1 in 10 year rainfall increased for different time horizons

3.3 Cliff Erosion

Bermuda's coastal cliffs are susceptible to erosion, particularly where soft strata exist. Future cliff retreat was estimated using the modified SCAPE (Soft Cliff and Platform Erosion) model (Walkden and Dickson, 2008; Ashton et al., 2011; Table 3-5), 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. The model, which is expressed as a relatively simple relationship, is derived from detailed process-based modelling of soft cliff coasts using the full SCAPE model version (*Soft Cliff and Platform Erosion*, Walkden and Dickson, 2008). Therefore, the modified SCAPE model is considered more physics-based than the other simplified coastal erosion models and is widely used to estimate erosion rates and provide valuable insights into the processes driving cliff retreat in many coastal areas.

Table 3-5 Modelled future cliff retreat rates for RCP 4.5 and 8.5 based on the modified SCAPE model for a range of potential historical cliff retreat rates

Future Retreat Rate (cm/yr.)

	RCP 4.5			RCP 8.5		
	SLR 5.7 mm/yr.	SLR 7.7 mm/yr.	SLR 7.7 mm/yr.	SLR 6.6 mm/yr.	SLR 10.5 mm/yr.	SLR 10.5 mm/yr.
Historical Retreat Rate (cm/yr.)	20 Year Horizon	50 Year Horizon	100 Year Horizon	20 Year Horizon	50 Year Horizon	100 Year Horizon
5	6	7	7	7	8	8
10	12	14	14	13	17	17
20	24	28	28	26	33	33
33	41	47	47	44	55	55

While the modified SCAPE model is considered a more physics-based approach to assessing future cliff retreat in Bermuda, it has some limitations. The SCAPE model relies on assumptions about wave energy, sediment supply, and cliff material properties, which may not always accurately reflect the conditions at a specific site. Additionally, the SCAPE model does not account for the effects of biological weathering. Furthermore, the modified SCAPE model uses historical data, which may no longer be available or accurate. In our mapping analysis, we applied a cliff retreat rate of 41-55 cm/year from the modified SCAPE model results under a range of SLR scenarios (Table 3-5), based on a historical retreat rate of 33 cm/year. This value extracted from sparse LiDAR data measured at the Bermudian development area where a relatively soft rock layer exists. Cliff hardness varies widely across Bermuda, as demonstrated in the measured Schmidt Hammer readings (Modelling Report, Section 8.7), and thus susceptibility to erosion processes also vary widely. Application of model results based on measurements from the Bermudian area are likely conservative (overestimate retreat) when applied elsewhere at Bermuda's harder rock cliffs. For example, Sunamura (1992) estimates limestone cliffs generally retreat on the order of 10^{-3} to 10^{-2} m/yr (1-10 cm/yr). However, locally high retreat rates are expected in areas with unfavourable geologic conditions and weak rock layers (i.e. the paleosols).

Cliff undercutting from wave action can lead to large episodic cliff failures. The 33 cm/yr cliff retreat at the Bermudian area includes a time period with a large episodic retreat event. The episodic nature of these events can significantly influence the observed retreat rates over various time scales. For example, a cliff averaging 25 cm/yr retreat might retreat very little for 20 years, then suddenly retreat 5m in an episodic event. Hence retreat rates will vary widely over space and time, and interpretation of these rates can vary depending on when sampling is carried out.

Therefore, while the modified SCAPE model provides a useful tool for estimating cliff retreat rates, it should be used with caution and in conjunction with other methods to gain a more comprehensive understanding of the local coastal cliff erosion processes and geologic conditions. The existing limitations highlight the need for more information on the various Bermuda cliffs and quantitative monitoring of cliff failure events and processes. Given the paucity of data on cliff erosion in Bermuda, a site-specific cliff erosion study that considers site-specific geologic and oceanographic conditions should be required for any development within the potential cliff erosion zone.

SWI applied the modified SCAPE results to map potential retreat for cliffs greater than 2m in height. The resultant mapping was analysed to quantify the number of existing buildings within the conservative cliff retreat zone, considering future sea level rise scenarios and compared to present-day baseline conditions. The results (Table 3-6) indicate that within 20 years there will be a potentially manageable number of buildings (212 - 237) impacted. However, in the 50–100-year timeframe, coastal retreat could result in major impacts with potentially 762 - 2031 buildings impacted. This highlights the need for critical assessment of setback criteria over those timeframes, and evaluation of potential future engineering options to reduce coastal retreat.

Table 3-6 Number of buildings affected by cliff erosion

Horizons	*RCP 4.5*	*RCP 8.5*
Present Day	Present-day conditions taken as the baseline for comparison	
20 years	212	237
50 years	762	920
100 years	1705	2031

3.4 Beach Erosion

The Bruun Rule is a model that relates an increase in local sea level to shoreline retreat and estimates the response of the shoreline profile to sea-level rise based on a concave-upward beach profile. Bruun (1962) proposed that under rising sea levels a beach's equilibrium profile (i.e., its average form) would be maintained while rising with sea level. It can be used to correlate sea-level rise with eroding beaches and estimate the surface of land loss due to erosion. The active slope of sand transport is required for the model, which starts from the depth of closure (the most landward depth seaward of which there is no significant change in bottom elevation and no significant net sediment exchange between the nearshore and the offshore) to the shoreline and can be estimated using data on the movement of sediment offshore or the effect of waves on sand movement. Table 3-7 and Figure 3.8 list the results of the Bruun Rule calculation for erodible beaches in Bermuda for different time horizons (20, 50, and 100 years) under two different sea level rise scenarios, RCP 4.5 and RCP 8.5 (SWI Modelling Report, Chapter 7).

Table 3-7 Bruun Rule estimates of shoreline retreat for RCP4.5 and RCP8.5

Scenario	**Expected Shoreline Retreat**		
	20 years	**50 years**	**100 years**
RCP 4.5	6.7m	22.6m	45.3m
RCP 8.5	7.8m	30.9m	61.2m

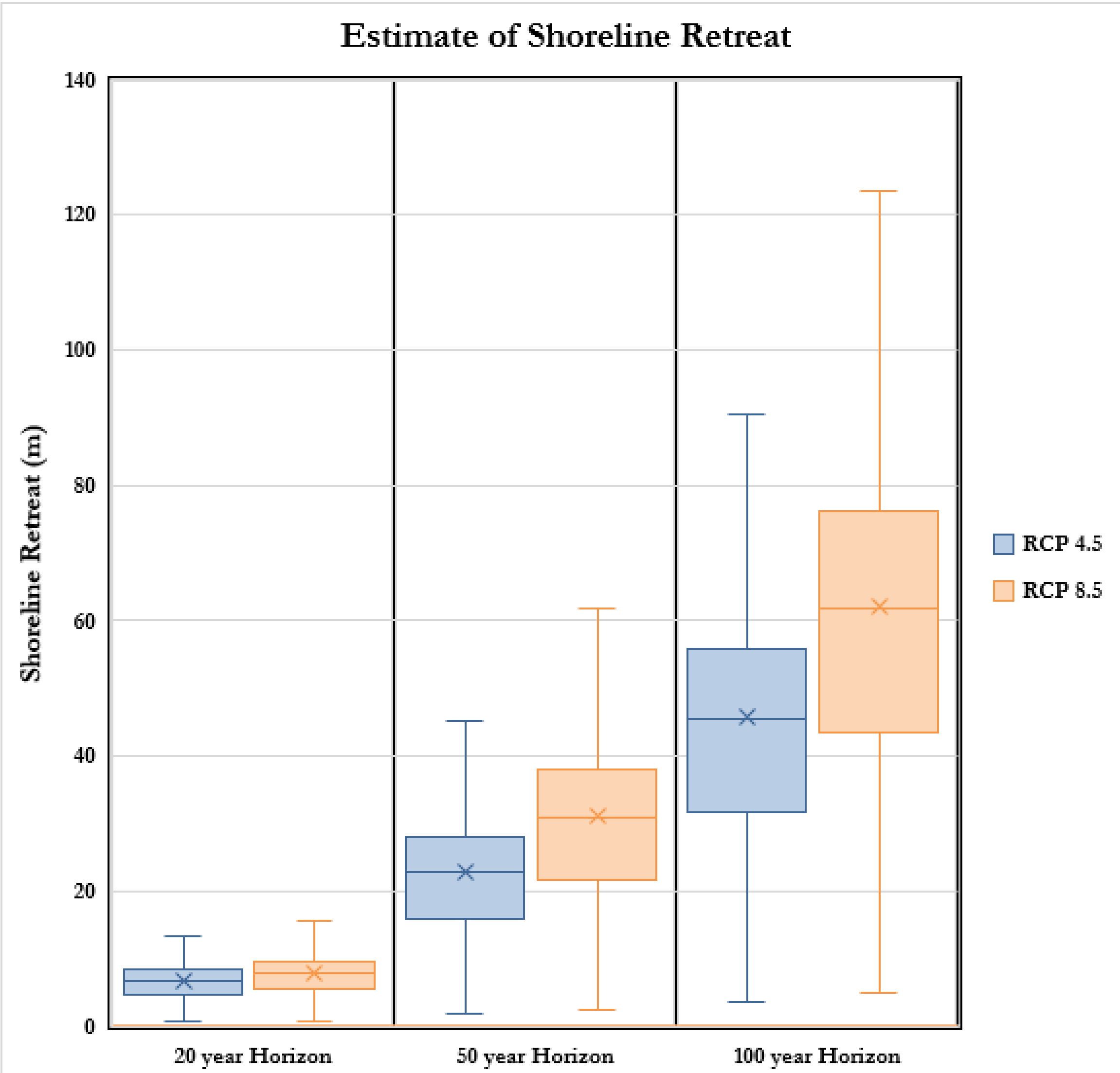

Figure 3.8 Shoreline retreat comparison between Bruun Rule estimates

Unfortunately, the Bruun Rule has limitations, especially in complex systems such as exist for Bermuda. Some of these limitations are noted in the assumptions inherent in its formulation, such as straight and parallel nearshore bottom contours, consistency in a sandy erodible beach throughout, no longshore transport, no cliff or hardened shoreline, etc. As such, the erosion profiles, which were applied only to beach areas as much as possible, should be considered with caution.

Shoreline retreat can have significant impacts on buildings and infrastructure located near the coast. As the shoreline moves landward, buildings that were once located on or near the beach may become increasingly exposed to wave action and storm surge, leading to increased risk of damage or destruction from coastal hazards. In addition, as the beach erodes, the foundation of buildings near the coast can become destabilised, leading to structural issues and potentially rendering them unsafe for occupancy. The retreat of sandy shorelines is expected to affect a total of 12-13 buildings within the next 20 years. This number is projected to increase to 37 buildings for RCP 4.5 and 55 buildings for RCP 8.5 within the next 50 years. The number of affected buildings is expected to increase significantly over the next 100 years, with 123 buildings projected to be affected by retreat under RCP 4.5 and 210 buildings under RCP 8.5.

Table 3-8 Number of buildings affected by shoreline retreat

Horizons	RCP 4.5	RCP 8.5
Present Day	Present-day conditions taken as the baseline for comparison	
20 years	12	13
50 years	37	55
100 years	123	210

3.5 Sea Level Rise and Saltwater Intrusion

Impacts of rising sea level on the hydraulic balance between aquifers and the ocean will likely threaten freshwater resources, aquatic ecosystems, and infrastructure for some distance inland in small oceanic islands such as Bermuda. It is vital to understand the vulnerability of groundwater systems to these rising sea levels and saltwater intrusion and to assess and understand the factors that determine the magnitude of system response.

Sea water (or saltwater) intrusion is defined as the lateral landward migration of the sea water-fresh water interface in the subsurface. Vulnerability in this context is defined by the rate and magnitude of salinization (or salinification) of coastal aquifers and changes in groundwater flow to the sea. Salinization can occur from lateral saltwater intrusion at depth and infiltration from surface due to coastline transgression and storm surge inundation. Changes in groundwater flux to the ocean can affect groundwater discharge and circulation of saltwater through the offshore subsurface. This can alter both ocean aquatic ecosystems and ocean chemical composition.

Sea level rise will occur in Bermuda's subsurface as the same rate as in the surrounding ocean due to the strong hydraulic connection between the shore and the interior of the island. In addition to sea level rise, oscillations from tidal effects, the local steric anomaly, and meso-scale effects will translate more or less to the interior of the island under the freshwater lenses with the tidal effects experiencing the most damping (Vacher, 1974).

At the coast, and for some distance inland, saline water will rise into the pore spaces to the same extent as SLR plus transient oscillations and a portion of the saline water will remain within the pores. Some of the water will drain under the influence of gravity and some will be diluted by infiltration of precipitation.

The vadose zone is the unsaturated zone above the water table and can be contaminated by upward moving saline water resulting from chemical diffusion mechanisms. Controlling factors for this phenomenon are vertical hydraulic gradients, unsaturated hydraulic conductivity, texture of the rock or soil (soil or rock composition, percentage of gravel, sand, silt and clay sizes in soil), and soil-water characteristic curves. Coarse grained soils and rock have low water retention and high conduction facilitating downward moving of meteoric water whereas fine grained soils have high water retention (and therefore will retain saline water) and low downward conduction. Coarse materials in wetter climate such as exists in Bermuda are expected to have higher water gain at the ground surface and larger downward advective flux values.

Flow and transport of groundwater and contaminants in fine-textured soils are more dependent on the climate type. For arid climatic conditions, net water loss conditions exist for fine-grained soils. This is the result of the infiltrating meteoric water, being held in soil layers closer to the ground surface due to higher retention and lower conduction of fine-grained soils. Although such soils restrict the downward migration of the solute, upward transport to the root zone is probable. Therefore, for fine-grained materials and arid climatic conditions, it can be concluded that the vertical upward solute displacement from a diffusion-dominated transport process can contaminate near-surface soil layers. For wetter climates, the upward migration of salt in fine-grained soils is less probable. Even very small quantities of water gain at the ground surface can induce enough downward advection to limit any upward diffusion (Eeman, 2017).

Only when the groundwater level reaches a certain critical depth can salts accumulate on the surface of the ground. This depth depends on the hydraulic properties of the subsurface combined with the effect of rising sea levels and transient effects discussed previously. Salts migrate upward more readily under the capillary effect, especially when the groundwater salinity is high and the groundwater level is shallow.

Bermuda is characterised as a wet climate with precipitation marginally higher than evapotranspiration. Thus, it would be expected that for fine and coarse soils, downward moving infiltrating meteoric water would flush the salt from the pores of the soil or rock. However, if droughts become common because of climate change, or precipitation falls below evapotranspiration, then upward movement of saline water to the root zone is possible to probable.

3.5.1 Impact of Saltwater Intrusion on Built Infrastructure

Groundwater in Bermuda will rise with increasing sea levels around Bermuda. Where the topography is less than 3m above sea level, saline groundwater may impact infrastructure buried in the soil or the foundations of infrastructure due to the mechanisms discussed above. Saline water increases corrosion of metal especially where two different metals are connected. This galvanic response can rapidly increase corrosion of metal structures.

Saltwater intrusion will lead to corrosion of steel and concrete as well as degradations to road and runway foundations, bridges and ports. Rising temperatures increase expansion and materials degradation of concrete joints, steel, asphalt, protective cladding, coatings, sealants, timber and masonry. In addition to reducing life expectancy, there will be increased maintenance costs and potential structural failure during extreme events (Glasspool, 2008).

Impact of Saltwater Intrusion on Populated Areas

It is noted that while all residences are required to collect rainwater from roof catchments with associated underground cisterns, one source of supplementary potable water continues to be from groundwater extracted from wells. The intrusion of saltwater into groundwater can make it unsuitable for drinking or irrigation purposes. Saltwater intrusion can have several negative effects on groundwater in populated areas, particularly in coastal communities where the groundwater is susceptible to saltwater intrusion. This can pose a serious health risk to humans and animals and can also impact crop yields and local economies that depend on agriculture.

In addition, saltwater intrusion can damage water supply infrastructure, including wells and treatment plants. This can result in increased costs for repairs and maintenance, as well as disruptions to water service for residents and businesses. Further, saltwater intrusion can also contribute to soil erosion and subsidence, which can further exacerbate issues related to groundwater availability and quality.

Overall, saltwater intrusion is a serious issue that can have far-reaching effects on both natural ecosystems and human communities. Efforts to mitigate saltwater intrusion, such as improved management of freshwater resources and development of new technologies to desalinate seawater, are critical to ensuring the health and well-being of both natural and human systems.

Impact of Saltwater Intrusion on Power Generation

The majority of the island's energy is provided and distributed by BELCO at their 9.3 hectare Cemetery Road plant in Pembroke. In addition to the main power plant BELCO has 34 substations across the island, some of which are on low-lying land. Energy-related infrastructure at risk from SLR includes 217 km of underground transmission cable and 193 km of high voltage underground distribution cable (as of 2008) (Glasspool, 2008).

The BELCO Plant is situated in a low-lying area near the Pembroke Canal that is prone to flooding. The projected saline groundwater rise and inland saltwater intrusion in this area could affect the building structure and power-related infrastructure due to corrosion.

In addition, extreme storm events with storm surge and flooding may cause significant damage to electricity transmission infrastructure and services as well as the acceleration of the degradation of materials and structural integrity of power generation and transmission equipment including underground cables. The combination of increased wind and lightning, storm surges and flooding could damage transmission lines and structures.

3.5.2 Impact on Reserves

Saline water upward migration will affect low-lying reserve areas and natural vegetation near the ocean where the ground surface is less than approximately 3m above the sea level. As sea levels rise, the line between the areas affected and not impacted will gradually move inland. However, rising topography will ensure that the salinity impacts will remain in the subsurface and in higher areas these impacts will not occur in near surface soils.

Reserve areas with natural vegetation will likely have plant species with deeper root systems. Salinity increases in the groundwater will impact deeper rooted species and may result in these dying out in some areas. Shallower rooted species may survive depending on the topographical distance between the root zone and the highest incursion of saline water.

The predictive estimates (presented below) indicate that for the agricultural reserves, the impact of saltwater intrusion will be amplified between the medium- and long-term timeframes. By contrast, for the nature reserves the saltwater intrusion impacts appear to taper off over the long term. The explanation for this difference may be found in an examination of land use and topography. Agricultural areas in Bermuda are more workable if they are relatively flat or gently rolling with adequate topsoil. Nature reserves on the other hand tend to be clustered near the coasts, and are characterized by variable and often steep topography, often with swamps or ponds in coastal embayments. There may be other relevant characteristics, but in summary these areas have not been developed for housing or agriculture on an island with high competition for such resources because they are not suitable for cultivation (too rocky or too little topsoil or too marshy). A saltwater rise in steep topography would only affect a small area, so the long-term effect on nature reserves seems to diminish relatively. Agricultural areas, being relatively flat, will see an increasing effect in the long term i.e., more land on the periphery of such areas being affected until topographical rises truncate the effect.

Agriculture Reserves

In agricultural lands, saltwater intrusion can render soil unsuitable for crops, resulting in reduced yields or complete crop failure. It can also increase the salinity of groundwater, which can limit the availability of freshwater for irrigation. This can be particularly problematic in areas that rely heavily on agriculture, as it can have significant economic impacts on farmers and communities. Table 3-9 shows the area of agricultural reserves expected to be affected by saltwater intrusion in various climate change scenarios.

Table 3-9 Area of Agricultural Reserves (acres) affected by saltwater intrusion / % increase over present day

Horizons	RCP 4.5	RCP 8.5
Present Day	7.7 acres	
20 years	8.9 (+16%)	8.9 (+16%)
50 years	10.8 (+40%)	13.0 (+69%)
100 years	19.4 (+150%)	25.0 (+225%)

Coastal Reserves

The intrusion of saltwater can lead to the loss of critical freshwater resources, disrupting the ecological balance of the region and affecting local flora and fauna. Additionally, saltwater intrusion can affect the quality of water in the reserve, making it unsuitable for human consumption and other uses. It can also cause soil salinization, making it difficult for plants to grow and reducing the overall productivity of the reserve. Table 3-10 shows the area of coastal reserves expected to be affected by saltwater intrusion under various climate change scenarios.

Table 3-10 Area of Coastal Reserves (acres) affected by saltwater intrusion / % increase over present day

Horizons	RCP 4.5	RCP 8.5
Present Day	713.74 acres	
20 years	713.87 (+0.02%)	713.87 (+0.02%)
50 years	714.29 (+0.08%)	714.99 (+0.08%)
100 years	714.99 (+0.18%)	715.01 (+0.18%)

Nature Reserves

Within nature reserves, saltwater intrusion can alter soil and water chemistry, which in turn can harm or kill plant and animal species that have adapted to freshwater environments. It can also affect the migration patterns of aquatic species, which can have ripple effects throughout the food chain. Additionally, saltwater intrusion can lead to the loss of wetlands, which are critical habitats for a variety of species. Table 3-11 shows the area of nature reserves expected to be affected by saltwater intrusion under various climate change scenarios.

Table 3-11 Area of Nature Reserves (acres) affected by saltwater intrusion / % increase over present day

Horizons	RCP 4.5	RCP 8.5
Present Day	237 acres	
20 years	260 (+10%)	261 (+10%)
50 years	281 (+19%)	284 (+20%)
100 years	285 (+20%)	296 (+25%)

4 Hazard Mapping

The hazard mapping results from a GIS exercise display the impacts various hazards have on important receptors, including the built infrastructure (buildings, road network, bridges, major coastal infrastructure) and various reserves (agricultural, coastal and nature).

This chapter presents a delineation of Bermuda's coastline into Shoreline Management Units (SMUs) to better define the mapping required at the scale needed for reasonable inspection. The next sections provide indicative mapping in one select management unit for the more extreme RCP8.5, 100-year horizon, 150-year event only. The full mapping for Bermuda for both scenarios considered are provided as GIS layers and featured in a convenient GIS-based web application (https://arcg.is/0yTniT). A user guide for this web application is attached as Appendix A.

4.1 Application of Shoreline Management Units

Shoreline Management Units (SMUs) are defined areas of the coast that are used as the basis for managing coastal erosion and flooding. 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 different characteristics and require different approaches to management. For example, a sandy beach may require different management strategies than a rocky coastline. SMUs are typically defined based on:

- 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;
- the exposure to wave action (i.e., the orientation of the shoreline relative to predominant wave directions);
- the existing shoreline use.

Within each SMU, coastal management plans can be developed that aim to balance the requirement for shoreline protection with the needs of shoreline users. These may include consideration of activities such as recreation, fishing, and wildlife conservation. The plans may include a range of measures, such as beach nourishment, sea defences, managed retreat, and land-use planning, depending on the specific needs of the area.

In the context of this chapter, the SMUs are used for the hazard mapping. Later chapters use the same SMU delineation for presentation of the CVI mapping and recommendations and consideration for coastal planning.

Based on the conditions assessed for the Bermudian coastline, a total of 16 SMUs are presented in Table 4-1 and shown in Figure 4.1 through Figure 4.3.

Table 4-1 Proposed Shoreline Management Units

SMU	Location Description	Starting UTM	Ending UTM
SMU1	Islands of the Great Sound		
SMU2	City of Hamilton	330914.0,3573034.6	328933.3,3575774.3
SMU3	Great Sound – Little Sound and Sandy's	325045,3575715	330885,3573062
SMU4	Great Sound – Dockyards/WEDCO	327430,3578474	325116,3575786
SMU5	West Coast – Sandys/Dockyards	327207.9,3578447.7	325107.0,3575857.2
SMU6	West Coast – Sandys/Somerset	324964.6,3575741.4	322971,3571442
SMU7	South Coast – South Warwick and Southampton	322873,3571433	331739,3571504
SMU8	South Devonshire and Paget	331704,3571575	336030,3575350
SMU9	South Smith's and Hamilton	336048,3575332	342475,3579231
SMU10	Castle Harbour		
SMU11	East Coast - St Georges	344540.4,3580139.1	343436.5,3583486.3
SMU12	St George's Harbour		
SMU13	North Shore – St Georges	343534,3583691	338514,3581911
SMU14	North Shore – Hamilton Parish	338584.9,3581603.5	336127.9,3577668.8
SMU15	North Shore (Pembroke and Devonshire)	336599.7,3577535.2	329024,3575951
SMU16	Harrington Sound		

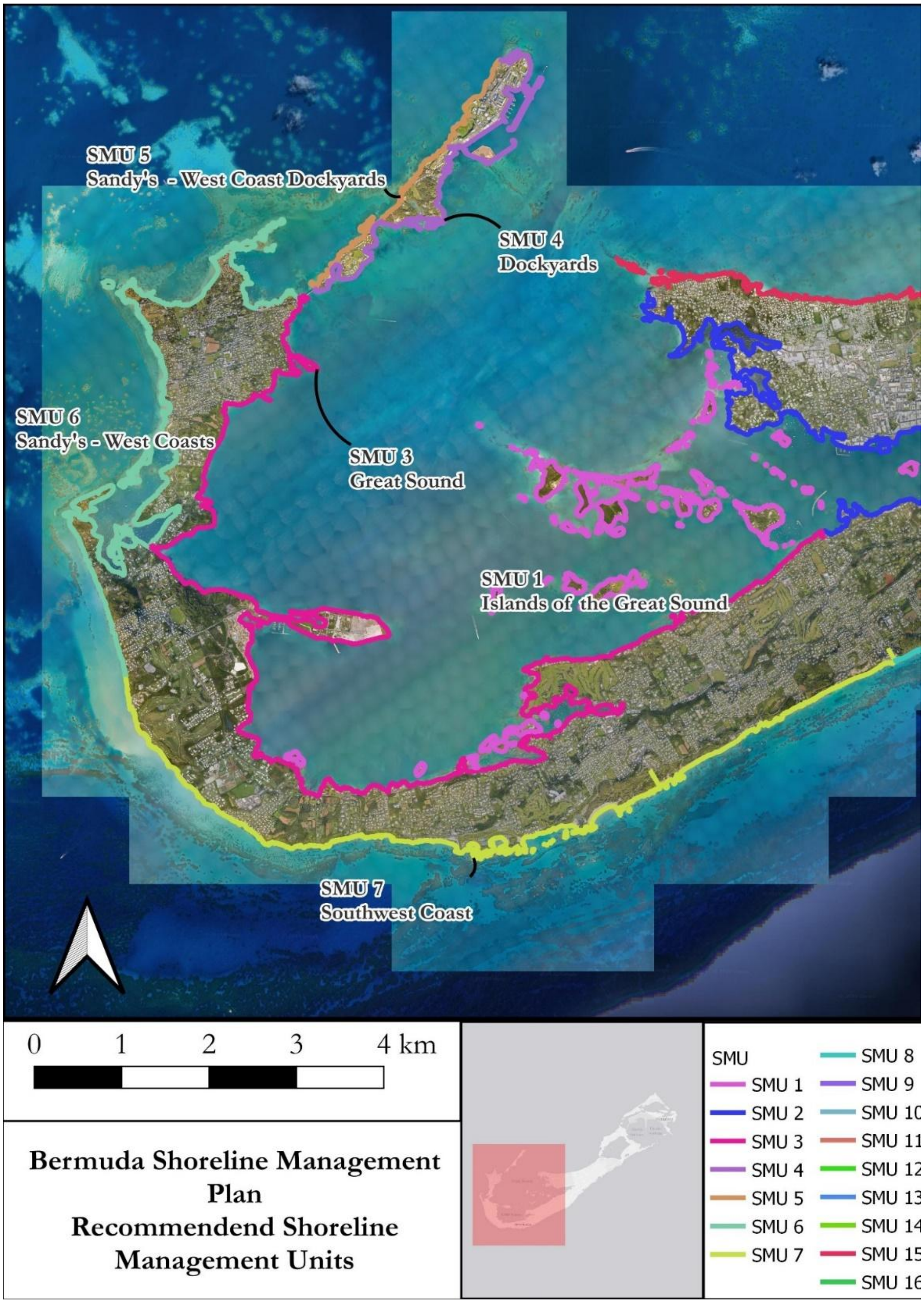

Figure 4.1 Recommended Shoreline Management Units 1, 3, 4, 5, 6, 7

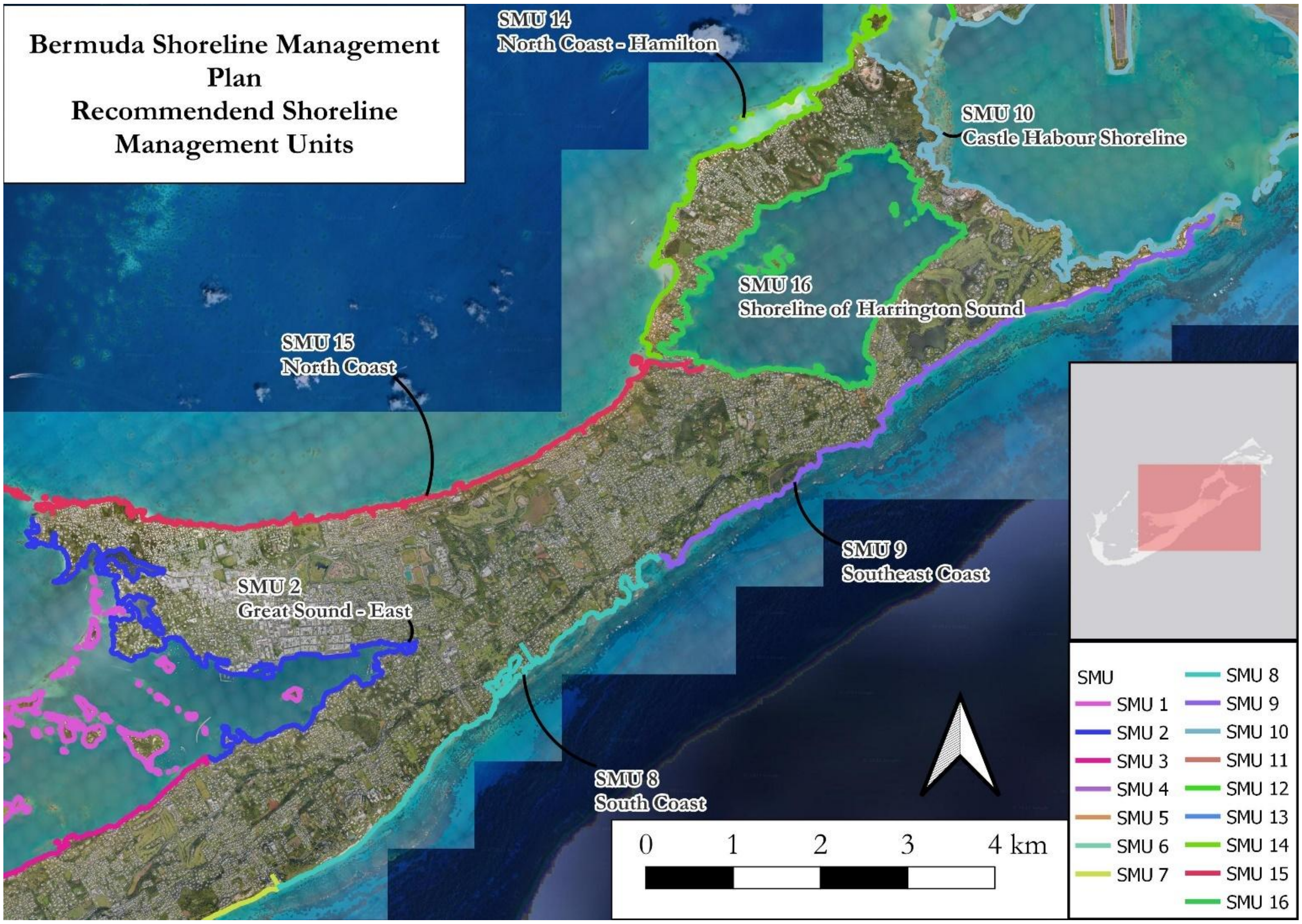

Figure 4.2 Recommended Shoreline Management Units 2, 8, 9, 10 (partially), 14, 15 and 16

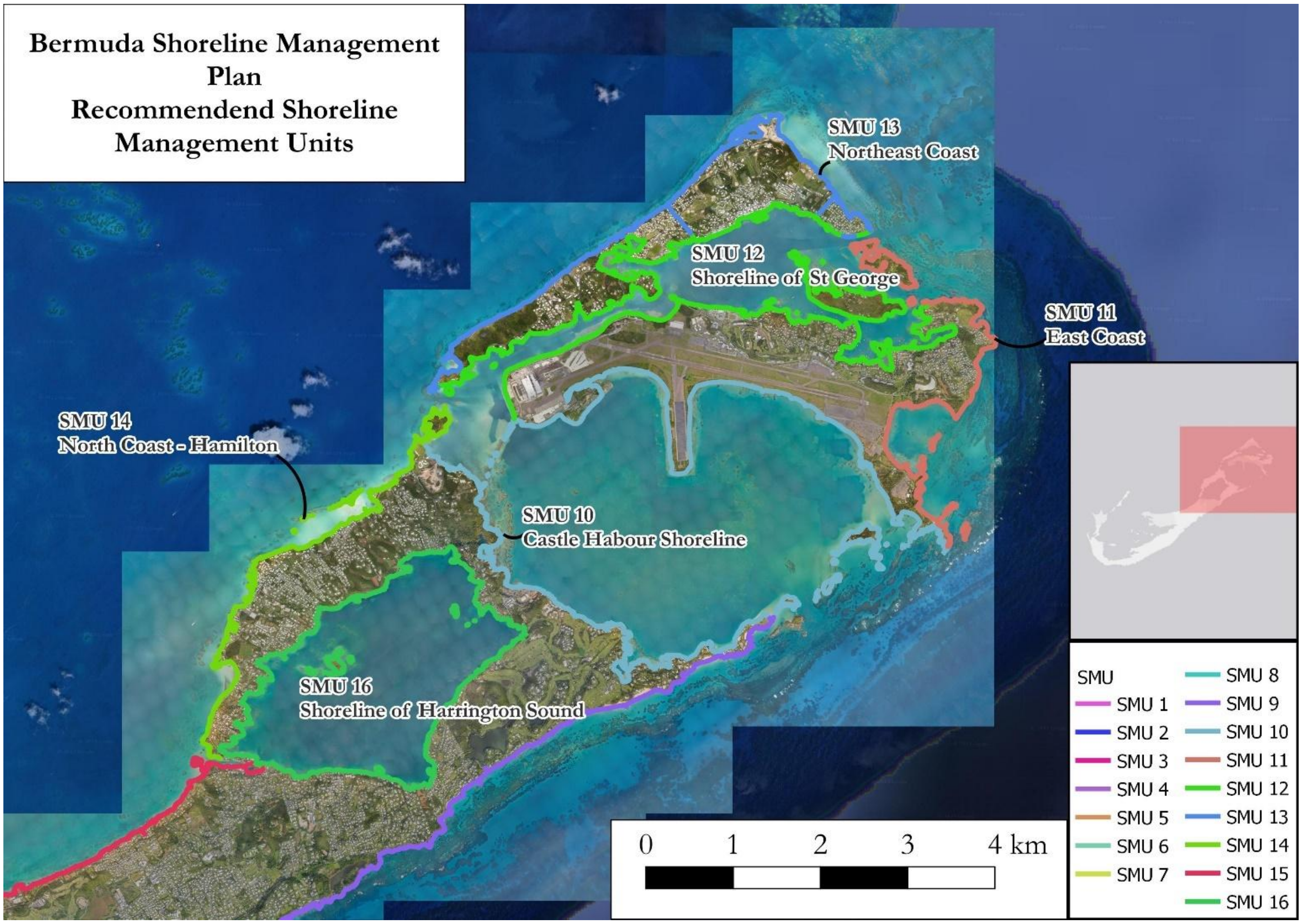

Figure 4.3 Recommended Shoreline Management Units 10, 11, 12, 13

4.2 Receptor and Hazard Classes

Given the complexity of mapping multiple receptors over different climate change scenarios, separate maps were produced for the “built infrastructure” and for the “reserves”. For this study, the “built infrastructure” refers to buildings, road network and bridges, and critical infrastructure. “Reserves” describes the existing coastal, nature and agricultural reserves established in Bermuda.

Similarly, the hazards posed by environmental forcing (as a result of climate change) are grouped together. Inundation and erosion effects (flooding, shoreline and cliff erosion) will impact the coastal areas, hence these hazards are mapped together. Saltwater intrusion as described by predicted groundwater elevations can affect both coastal and inland areas, hence separate mapping is shown for this hazard.

The maps presented in the following figures present a high level overview of the level of information contained in the detailed mapping. With regards to flooding depths however, the detailed maps show flood depths in ranges, whereas the maps following present flooding as either “flooded” or “dry”.

4.3 Built Infrastructure

4.3.1 Inundation and Erosion (Flooding, Shoreline and Cliff Erosion)

Figure 4.4 shows an example of the impact of the hazards on the built infrastructure - namely buildings and road infrastructure - that are under threat from inundation, shoreline or cliff retreat for the RCP8.5, 100-year horizon combination scenario. The hazards are shaded (inundation is shown in blue, cliff retreat in yellow and sandy shoreline retreat in pink). Buildings and roads that are 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 in the perimeter of the airport. Cliff erosion will likely threaten buildings on the northern coastline.

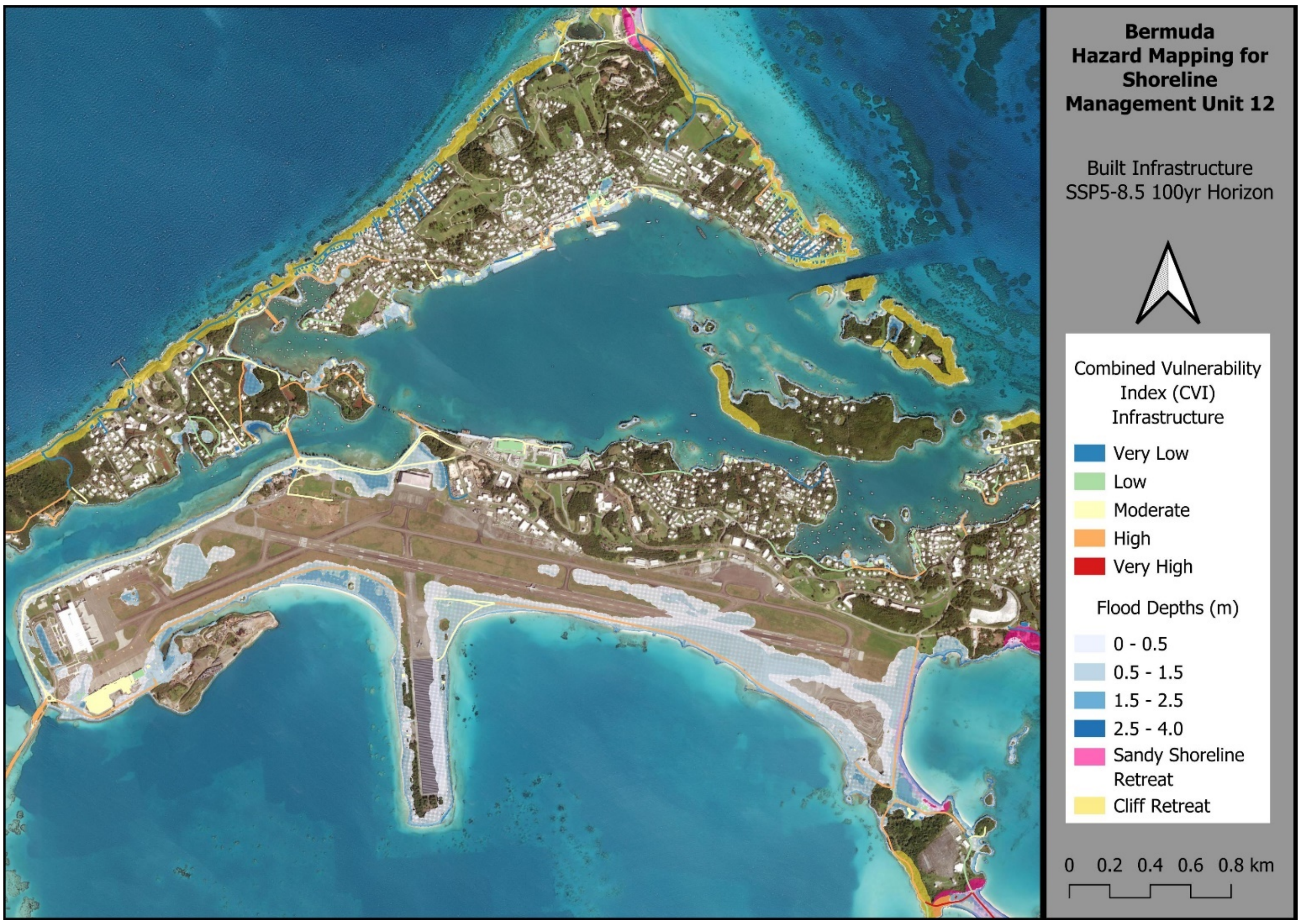

Figure 4.4 Impact of inundation and erosion from a RCP8.5, 100yr Horizon, 150yr event on Built Infrastructure within Management Unit 12

Buildings and roadway network elements that are vulnerable can be clearly seen from this mapping. For example, roadways on the north-eastern tip of St George's are at risk, while a significant part of the LF Wade International Airport associated area is vulnerable to flooding under this planning scenario.

Based on the numerical modelling conducted in HECRAS for the Mill Creek area, the end of the Pembroke March catchment, it is evident that there is increased vulnerability to inundation resulting from a combination of rainfall, runoff, and storm surge when utilizing the HEC model. As anticipated, the termination point of the catchment experiences heightened inundation, impacting several buildings in the vicinity. However, the presence of pocket flooding throughout the catchment creates localized areas of ponding, further exacerbating vulnerability by affecting roads and structures. These pockets are notably situated near Cemetery Road, the stadium, and Parsons Road, underscoring the susceptibility of specific areas to flooding. These findings serve as valuable indicators for lower-lying regions across Bermuda, where similar pockets are likely to contribute to varying degrees of vulnerability. Consequently, proactive measures such as diligent maintenance and timely upgrades to drainage systems are imperative to mitigate the impacts of significant flood events.

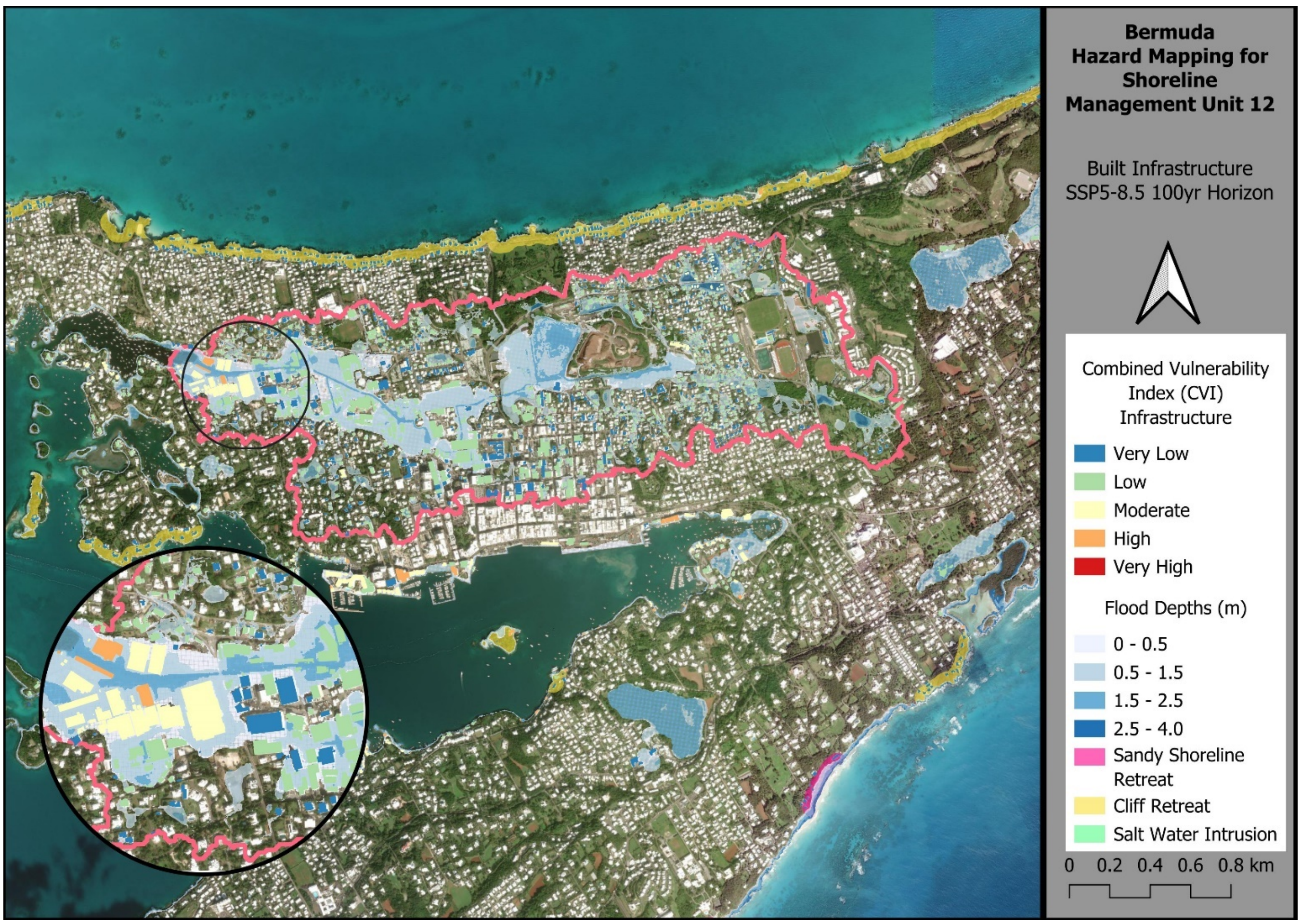

Figure 4.5 Impact of inundation from a RCP8.5, 100yr Horizon, 150yr event on built infrastructure within Mill Creek

4.3.2 Saltwater Intrusion (Groundwater Elevation)

Figure 4.6 shows an example of the impact of saltwater intrusion based on expected groundwater elevations on the built infrastructure, namely buildings and road infrastructure in the RCP8.5, 100-year horizon. The expected groundwater elevation (which has a different elevation from coastal to inland pond areas) is shown shaded as a blue "saltwater intrusion" area. As per the inundation and erosion plots above, the affected assets are shown colour coded from blue (very low vulnerability) to red (very high vulnerability). Within this SMU, there is one stretch of roadway that is labelled as being at very high risk.

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

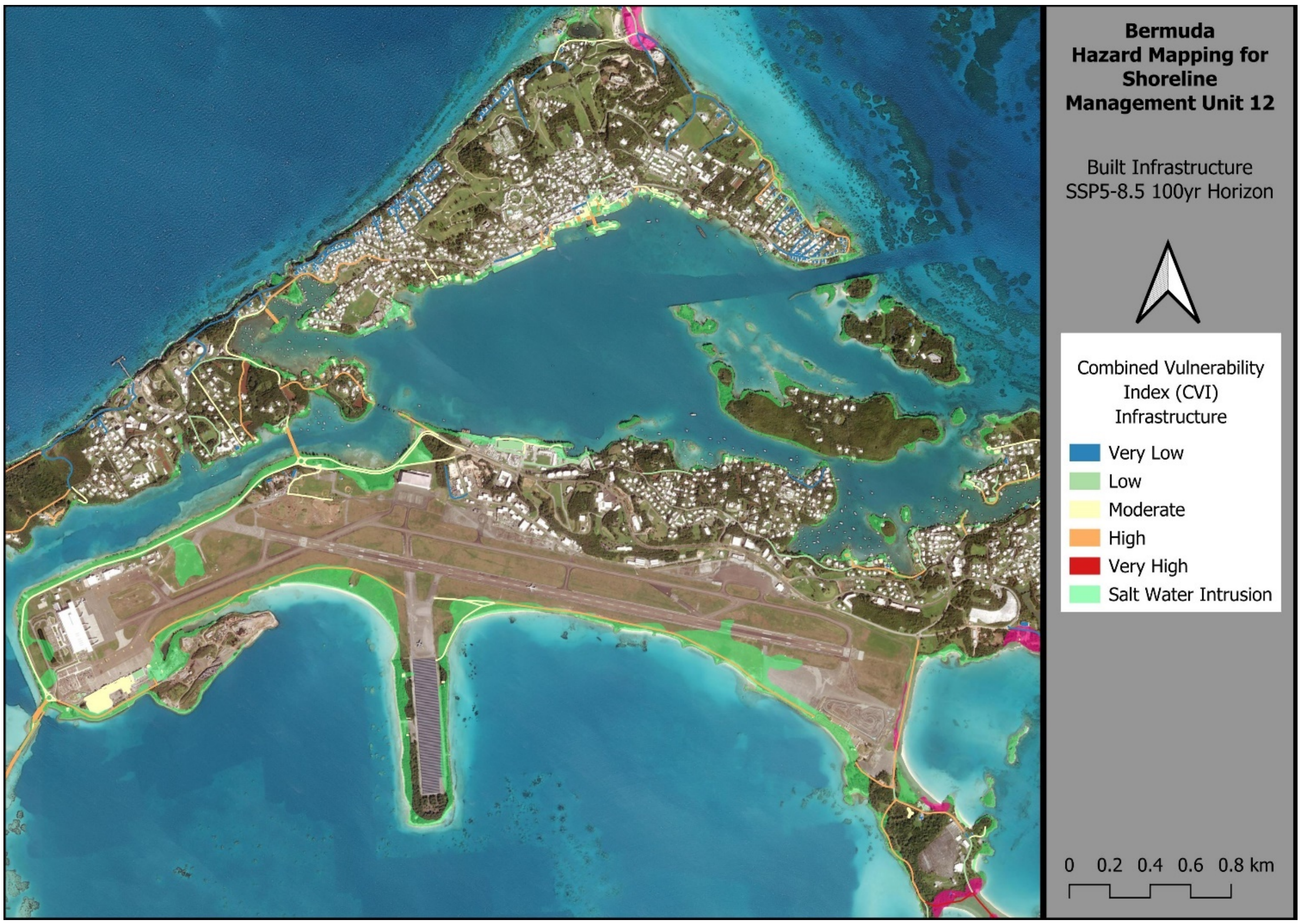

Figure 4.6 Impact of saltwater intrusion from a RCP8.5, 100yr Horizon event on built infrastructure within Management Unit 12

4.4 Reserves

4.4.1 Inundation and Erosion (Flooding, Shoreline and Cliff Erosion)

Figure 4.7 shows an example of the impact of the hazards on various reserves under threat from inundation, and shoreline or cliff retreat for the RCP8.5, 100-year horizon in SMU12. The reserves impacted by inundation or erosion are shown in solid shading for Agriculture (green), Nature (Orange) and Coastal (Pink). Almost all coastal reserves are impacted by one or more of the hazards, given their proximity to the shoreline.

Figure 4.7 Impact of inundation and erosion from a RCP8.5, 100yr Horizon, 150yr event on Reserves within Management Unit 12

4.4.2 Saltwater Intrusion (Groundwater Elevation)

Figure 4.8 shows an example of the impact of the hazards on various reserves under threat from possible saltwater intrusion for the RCP8.5, 100-year horizon. The reserves impacted by inundation or erosion are shown in solid shading for Agriculture (green), Nature (Orange) and Coastal (Pink).

Figure 4.8 Impact of saltwater intrusion from a RCP8.5, 100yr Horizon event on Reserves within Management Unit 12

None of the agricultural reserves in this SMU are shown as being impacted by saltwater intrusion. A few of the nature reserves are, as is the case for the coastal reserves.

5 Combined Multi-hazard Vulnerability

The sections below present the CVIs for the buildings, road networks, reserves and ecological areas in Bermuda. The CVI is calculated based on exposure to the four variables presented in the preceding sections: shoreline erosion, cliff erosion, storm surge inundation and saltwater intrusion.

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

(i) Collect data for each hazard and for the asset in question as discussed in Section 3.

(ii) Normalize the data for each variable to a scale of 0 to 1, with 0 being the least vulnerable and 1 being the most vulnerable. The scales are measured in accordance with the Table 5-1 below.

Table 5-1 Scaling assigned for each hazard within the CVI

Criteria	Scale	Notes
Inundation	0 – 1, normalized by the maximum inundation depth modelled. Any asset (building, road, bridge, critical infrastructure) that is subject to the maximum flood depth for the given simulation will be assigned a scale of 1. Any flood depths less than maximum are assigned a corresponding fraction between 0 to 1 as outlined following. Flood Depth — CVI Score 0m — 0.00 0.0<h<0.5m — 0.25 0.5<h<1.5m — 0.50 1.5<h<2.5m — 0.75 h>2.5m — 1.00	For example, • If the maximum flood depth for the RCP8.5, 100-year time horizon, 150-year Return Period storm event is +3.0m, • Scale is assigned **1.00** for assets affected by maximum flood depths of +2.5m or greater, • Scale is assigned **0.50** for assets affected with flood depths of +1.0m, • Scale is assigned **0.00** for assets with no flooding +0.0m.
Saltwater intrusion	0 = no impact 1 = impact	The saltwater intrusion assessment doesn't quantify varying levels of saltwater intrusion.
Cliff Retreat	0 = no impact 1 = impact	Cliff retreat is usually an inadvertent, spontaneous event that can vary in magnitude. It would be inappropriate to attempt to scale the risk of a cliff collapse.
Shoreline Retreat	0 = no impact 1 = impact	The shoreline retreat magnitudes are finite distances for each time horizon based on Bruun Rule parameters.

(iii) Weight the variables in order of importance:

- Inundation (from a storm surge event) is considered high importance and is assigned a weighting of 50%. This high weighting stems from the lack of forewarning offered in advance of a storm, which is typically predicted 3-4 days out of the storm's arrival, as well as the potential damage inflicted in a given area.

- Cliff erosion similarly occurs without warning and can be quite catastrophic and is 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.

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

$$CVI = (0.50 \times CVI_{innudation}) + (0.30 \times CVI_{saltwater\ intrusion}) + (0.10 \times CVI_{cliff\ retreat}) + (0.10 \times CVI_{shorelineretreat})$$

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

5.1 Built Infrastructure

To avoid "cluttering" of information in the presentation of the CVI, each receptor within the "built infrastructure" is plotted separately. Hence independent mapping is provided for buildings separate from the road network.

5.1.1 Buildings

Figure 5.1 presents the CVI for buildings for the RCP8.5, 100-year horizon, 150-year event within SMU 12. Each building that is impacted by any of the hazards under consideration is colour coded in accordance with the severity of risk. A building that is impacted by only one hazard is shown as green, with progressive colouring from yellow, orange to red with increasing number of applicable hazard impacts.

Figure 5.1 Building vulnerability index for the RCP8.5, 100yr Horizon, 150yr event in SMU 12

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

All Areas

Based on the CVI analysis, approximately 12% of all buildings in Bermuda are affected by coastal hazards (RCP8.5 100yr event horizon, 150yr storm event). In summary:

- The governing factors determining the degree of vulnerability of a building is elevation and the distance from the shoreline. Buildings that are sufficiently elevated and set back from the shore are not typically affected by the coastal hazards that have been considered.
- For the RCP4.5 50-yr horizon scenario, no buildings mapped are classified as being at High to Very High Exposure. This number increases to 3 for the RCP8.5 100-yr horizon scenario.

- Within the RCP 4.5 50-year and RCP 8.5 100-year horizon scenarios, there are 503 and 918 buildings, respectively, categorized as having moderate to high exposure. This comprises 1.4% and 2.6% of all buildings in Bermuda. Notably, these buildings are all situated within a 100m distance from the shoreline.
- Buildings on the south shore are less affected by the hazards, owing to higher property elevations occurring there.
- 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 very susceptible to coastal hazards.

A breakdown of the number of buildings in the various vulnerability rankings for the RCP 4.5 and RCP 8.5 scenarios is presented in Table 5-1 and Table 5-2 and in Figure 5.2.

Table 5-1 CVI Ranks: Buildings (RCP 4.5 – 50 year horizon)

Location	Vulnerability Category	CVI - Rank	Number of Buildings in Category	Buildings in Category %
CVI 50yr Horizon				
	No Exposure	0	32365	93.60%
	Very Low	0.0 - 0.2	854	2.64%
	Low	0.2 - 0.4	712	2.20%
	Moderate	0.4 - 0.6	387	1.20%
	High	0.6 - 0.8	116	0.36%
	Very High	0.8 - 1	0	0.0%
Buildings Exposed		6.40%		

Table 5-2 CVI Ranks: Buildings (RCP 8.5 – 100 year horizon)

Location	Vulnerability Category	CVI - Rank	Number of Buildings in Category	Buildings in Category %
CVI 100yr Horizon				
	No Exposure	0	29886	88.24%
	Very Low	0.0 - 0.2	2014	5.95%
	Low	0.2 - 0.4	1050	3.10%
	Moderate	0.4 - 0.6	589	1.74%
	High	0.6 - 0.8	329	0.97%
	Very High	0.8 - 1	3	0.01%
Buildings Exposed		11.77%		

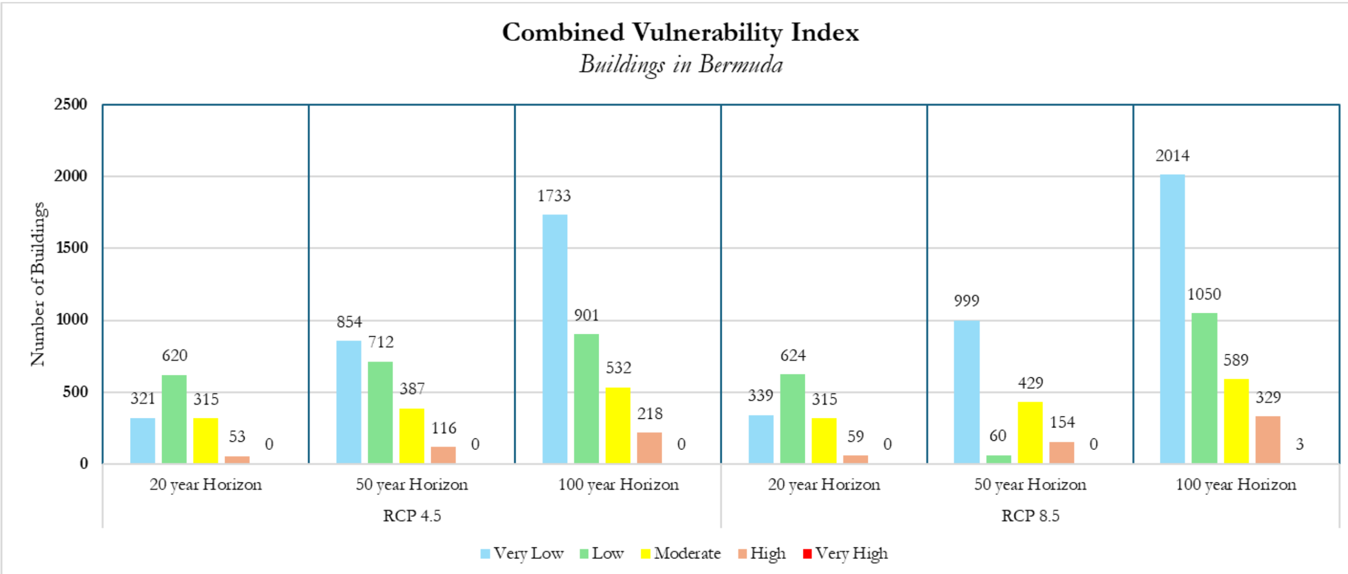

Figure 5.2 CVI index for RCP 4.5 (top) and RCP 8.5 (bottom) scenarios

Pembroke Catchment

As expected, the vulnerability of this area is most pronounced at the termination point of the catchment, where inundation significantly impacts nearby buildings. Moreover, the prevalence of pocket flooding within the catchment exacerbates vulnerability, creating localized ponding that affects roads and structures. Particularly near Cemetery Road, the stadium, and Parsons Road, these pockets highlight specific areas that are highly susceptible to flooding. These observations provide crucial insights for lower-lying regions across Bermuda, where similar pockets of vulnerability are anticipated. Therefore, it is imperative to implement proactive measures such as thorough maintenance and timely upgrades to drainage systems to mitigate the impacts of significant flood events.

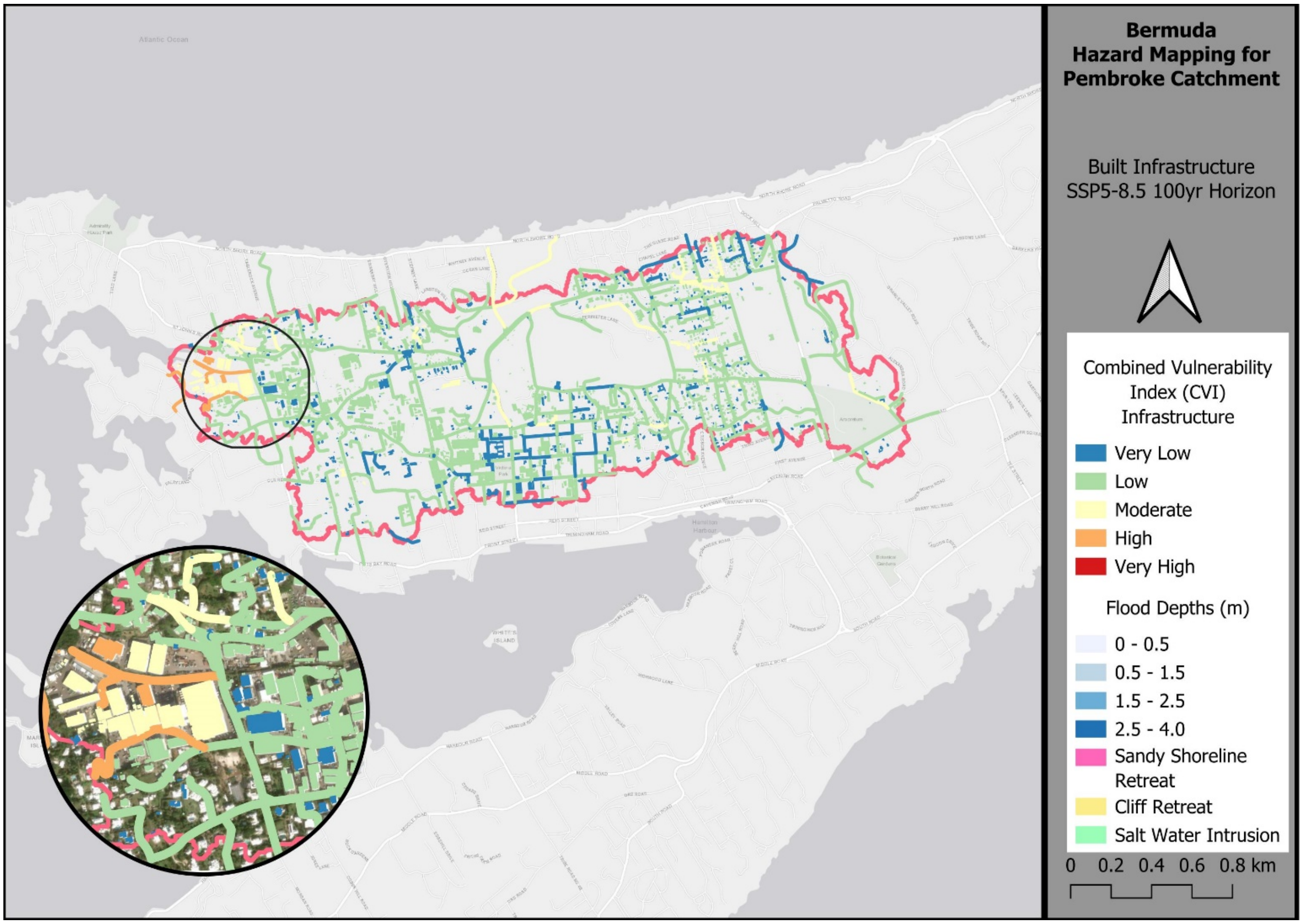

Figure 5.3 Pembroke Marsh Catchment

Parishes

Table 5-3 following shows the number of buildings that are affected in each parish.

Table 5-3 Breakdown of CVI score per parish (Long-term – RCP 8.5)

Parishes	Number of Buildings	No Exposure	Very Low	Low	Moderate	High	Very High
Southampton	3187	89.1%	0.6%	4.8%	1.6%	3.6%	0.3%
Warwick	4280	93.1%	0.4%	2.7%	1.7%	1.7%	0.5%
Sandys	3919	76.9%	0.9%	12.4%	4.0%	2.7%	3.1%
City of Hamilton	824	91.1%	0.5%	0.0%	6.7%	1.7%	0.0%
Smiths	3231	91.6%	0.0%	4.3%	1.8%	1.2%	1.1%
Hamilton	2814	73.3%	1.3%	10.6%	4.7%	5.8%	0.8%
St George's	2711	76.1%	1.3%	11.0%	4.9%	6.0%	0.8%

Parishes	Number of Buildings	No Exposure	Very Low	Low	Moderate	High	Very High
Devonshire	3577	93.5%	0.0%	2.8%	2.9%	0.1%	0.6%
Paget	3623	93.5%	0.6%	1.5%	1.5%	2.5%	0.3%
Pembroke	5332	82.3%	0.9%	6.2%	7.2%	3.0%	0.5%
Town of St George's	936	79.7%	0.4%	7.5%	4.5%	7.6%	0.3%

Government Assets

Table 5-4 shows the most critical government assets that will require urgent consideration ("High Vulnerability" ranking under the 150-year storm event with the RCP 8.5 scenario). In total, 84 government assets will be affected by coastal hazards over the next 100 years.

Table 5-4 Government assets with a high vulnerability ranking

Owner	Location	Full Address
High Vulnerability		
Government of Bermuda Park	Gates Fort Park	2 Barry Road, St George's
Government of Bermuda	Gates Fort Cottage	56 Cut Road, St George's
Government of Bermuda	Staff Cottage	9 Lagoon Road, Sandys
Government of Bermuda	Former Church (Government Land)	41 Malabar Road, Sandys
Government of Bermuda	Watford Bridge Ferry Wharf	1A Mangrove Bay Road, Sandys
Government of Bermuda Park	Shelly Bay Park	55 North Shore Road, Hamilton
Government of Bermuda Park	John Smith's Bay Park	92A South Road, Smiths
Government of Bermuda	Somerset Bridge Wharf	4 Wharf Drive, Sandys
Government of Bermuda Park	Clearwater Beach Park	181 Cooper's Island Road, St George's
Government of Bermuda Road	Road	12 Evans Bay Road, Southampton
Government of Bermuda	LeFroy House	7 Lagoon Road, Sandys

5.1.2 Road and Bridge Network

Figure 5.4 presents the CVI for the road network for the RCP8.5, 100-year horizon, 150-year event within SMU 12. The roads impacted by any of the hazards under consideration are colour coded in varying 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 notable roads at risk include the airport perimeter roads, Mullet Bay Road and Bridge, Railway Trail and Ferry Road around Ferry Point Park.

Figure 5.4 Road infrastructure vulnerability index for the RCP8.5, 100yr Horizon, 150yr event in SMU 12

The following points summarise the main observations regarding the road and bridge networks:

- 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.
- The CVI categorises the Causeway, Coney Island Road, and Somerset Bridge as having "Moderate Vulnerability".
- Along the south shore, the roadways are relatively safe. Only two roadways show vulnerability to hazards (namely from cliff erosion).
- Along the north shore, the shorelines of Pembroke, Devonshire, and Smiths are vulnerable to cliff retreat.
- The roadways in the vicinity of Flatts are also moderately vulnerable (mainly due to inundation effects) within the next 20 years. These therefore require immediate attention.

Figure 5.5 shows the CVI index for roads for RCP 4.5 and 8.5.

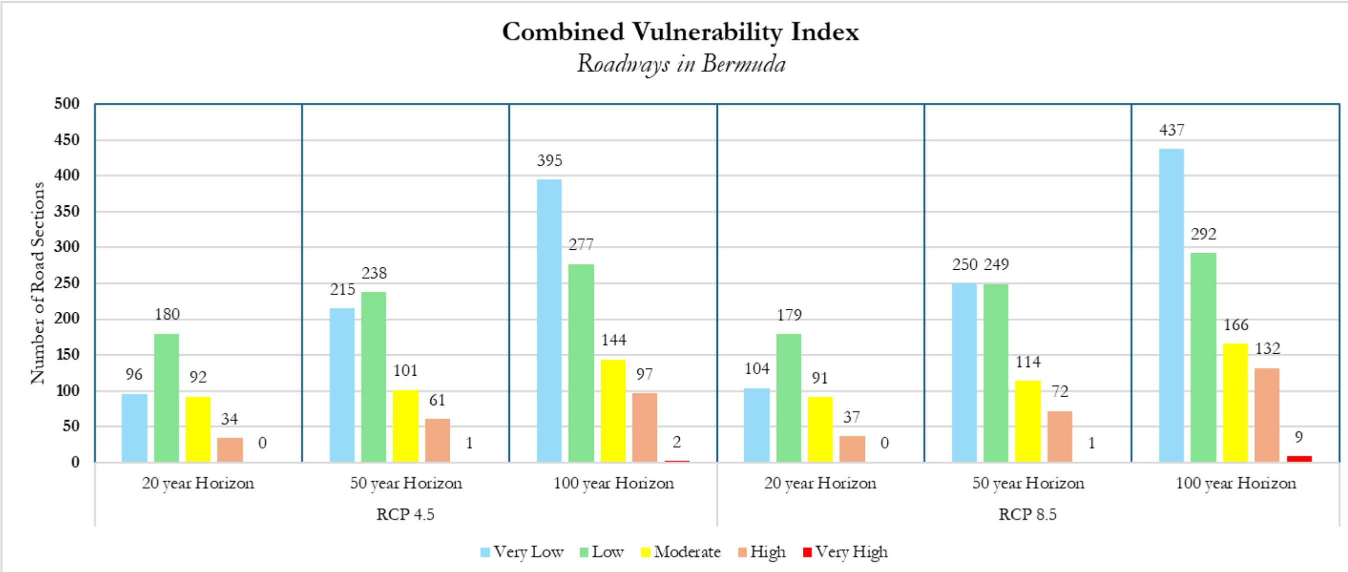

Figure 5.5 CVI index for roadways for RCP 4.5 and 8.5 scenario

5.2 Reserves

5.2.1 Agriculture Reserves

Saltwater intrusion on agricultural lands occurs when saltwater from the ocean or saline groundwater infiltrates and contaminates the soil and water used for crop irrigation. This can happen when groundwater levels drop due to overuse or drought, allowing saltwater to seep in from nearby coastlines or saltwater aquifers. With sea level rise, the groundwater lenses will also rise with the water table moving closer to the ground surface. This may marginally reduce the overall storage capacity of the aquifer in the long term.

The presence of salt in the soil can have several negative impacts on agricultural production. Excessive salt in the soil can reduce plant growth, yield and quality, as well as make crops more susceptible to pests and diseases. High levels of salt can also reduce the availability of nutrients and water to plants, leading to water stress and nutrient deficiencies.

Figure 5.6 shows an example of the agricultural reserve vulnerability index mapping for north-eastern Bermuda for the RCP8.5 100-year horizon scenario. Very few of the reserves are indicated to be moderately vulnerable, notably in areas around Little Head Park on St. David's Island and Redcoat Lane N and Blue Meadows/Bayside Lane on St George's Island.

A full breakdown of vulnerability scores for agricultural reserves across Bermuda is given in Table 5-5.

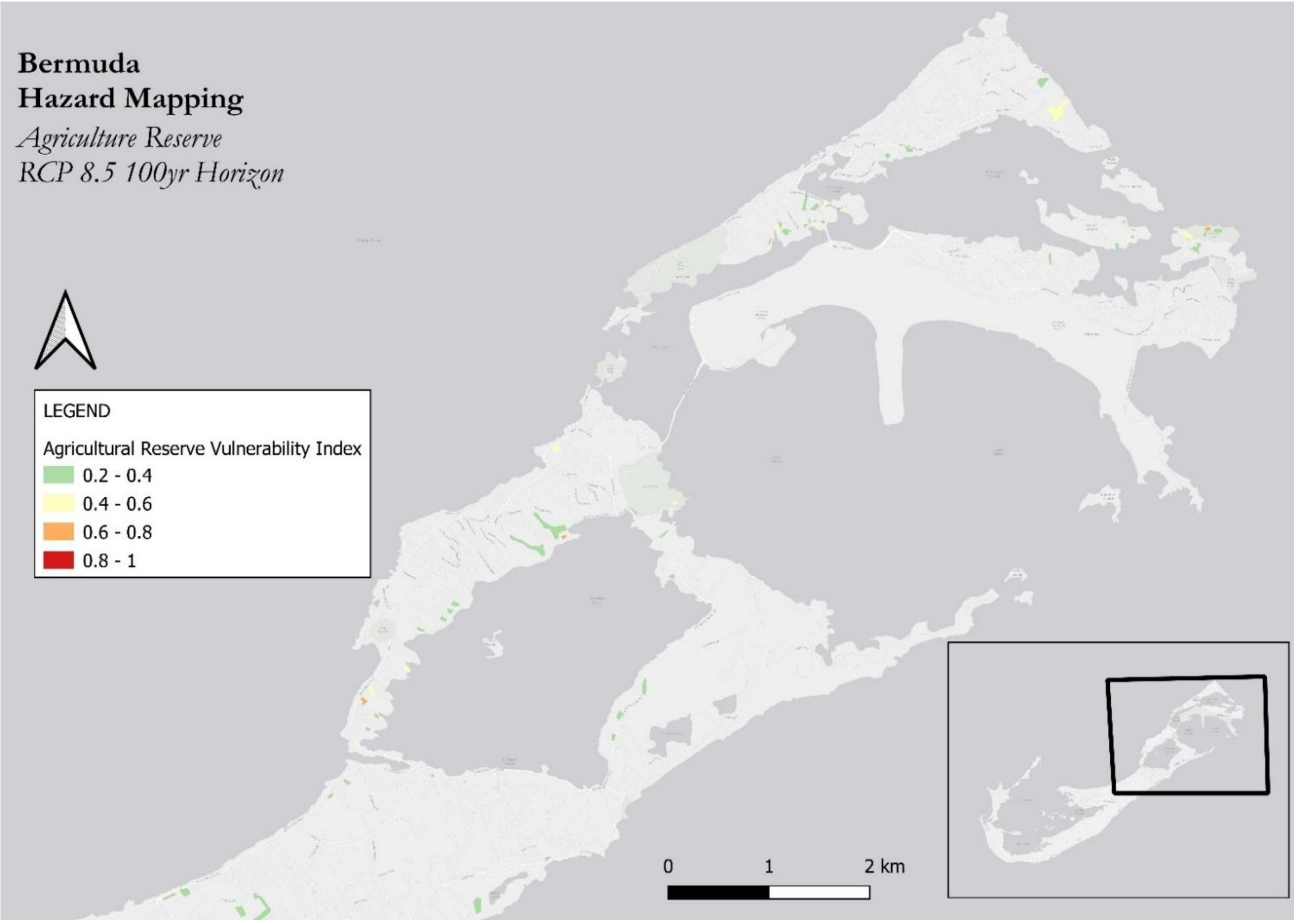

Figure 5.6 Agricultural reserve vulnerability index (RCP8.5 100-Year horizon, 150-Year return) for north-eastern Bermuda

Table 5-5 Breakdown of CVI score for agricultural reserve areas (Long-Term: RCP 8.5 with the 100horizon and 150yr event)

Location	Vulnerability Category	CVI - Rank	Number of Plots Exposed	Reserves Exposed %
Bermuda (All Areas)				
	No Exposure	0	1071	84%
	Very Low	0.0 – 0.2	0	0%
	Low	0.2 - 0.4	48	4.2%
	Moderate	0.4 - 0.6	114	10.1%
	High	0.6 - 0.8	9	<1%
	Very High	0.8 – 1.0	7	<1%
Agriculture Reserves Exposed		≈ 16%		

There are several strategies that can be used to manage saltwater intrusion on agricultural lands. These include:

- Implementing water conservation practices to reduce overall water use and minimise groundwater depletion.
- Implementing irrigation practices that minimise the amount of saltwater used for crop irrigation.
- Using crops that are tolerant to salt, such as certain varieties of rice, wheat, and vegetables.
- Applying gypsum, mulching with organic materials and hydrogels to the soil to reduce the concentration of sodium ions in the soil, which can improve soil structure and reduce salt damage.
- Implementing drainage systems to remove excess saltwater from the soil.
- Implementing soil management practices, such as deep ploughing[26] or soil flushing, to remove accumulated salt from the soil.

Overall, managing saltwater intrusion on agricultural lands requires a combination of measures that are tailored to the specific conditions and needs of the affected area.

5.2.2 Nature Reserves

The Bermuda Development Plan designated five Conservation Base Zones, for which two require the (mandatory) submission of Coastal Management Plans to facilitate any development proposals. These are the Coastal Reserve and the Nature Reserve.

Nature Reserves are intended to demarcate areas of special environmental significance and/or ecological, biological, geological, and scientific value. These areas include mangroves, marshlands, bird sanctuaries, cave and rock formations, islands and other wildlife habitats. These reserves support critical aspects of Bermuda's natural heritage, since they comprise some of the few remaining areas that support native flora and fauna.

In summary, the benefits of these reserves include:

Protection of natural habitats: The reserves protect against pollution, erosion, and other negative impacts from adjacent human development, helping to preserve critical habitat for plants and animals.

Reduction of human-wildlife conflicts: They can provide a transitional area between human development and wildlife habitat, reducing the likelihood of conflicts between humans and wildlife.

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[26] Deep plowing is only recommended for areas where hardpan has developed. Hardpan is a layer of soil so dense that air, water, and roots can barely move through it. Hardpan can occur naturally, and it can be caused by human actions. It occurs by compressing layers of minerals into an impenetrable slab. It is possible that hardpan can occur in Bermuda when plowing, digging, or rototilling are done each year to the same depth in wet soils with some clay in them. This can compact the underlying soil so much that it becomes hardpan. Heavy traffic, heavy chemical use, which kills beneficial soil microorganisms, extended drought, and improper watering can also cause hardpan. Soil pH and soil structure are major factors in the development of hardpan. Acidic soils are far more likely to cause calcium and iron to form hardpan layers, than alkaline soil. Clay particles are very small and already tend to become compacted. In clay soil, rain or irrigation followed by high temperatures can also create hardpan. Therefore soil deep ploughing should only be used in Bermuda where testing shows hardpan has occurred. Unlike compacted soil, which is a general condition of soil that doesn't have enough macropores and micropores for roots, air, and water to move through, hardpan is a distinct layer that stops everything.

Promotion of sustainable resource use: The reserves can be managed to maximise sustainable resource use, such as fishing or forestry, providing economic benefits to local communities while maintaining the integrity of the reserve.

Enhancement of recreational opportunities: A reserve can provide opportunities for low-impact recreational activities such as hiking, birdwatching, and nature photography, providing additional benefits to local communities.

Figure 5.7 shows an example of the nature reserve vulnerability index mapping for north-eastern Bermuda for the RCP8.5 100-year horizon scenario. The most vulnerable reserve is Cooper's Island Nature Reserve, which may be susceptible to all four hazards considered. Other popular reserves include Tom Moore's Jungle, and Spittal Pond, which show high vulnerability grades. Discrete nearshore islands such as Nonsuch Island, Brangman's Fort Island, Castle Island, Charles Island, Rushy Island, and Smith's Island are also threatened.

A full breakdown of vulnerability scores for nature reserves across Bermuda is given in Table 5-6. Of note, approximately 92% of all nature reserves are affected by inundation and shoreline retreat, with 78% being in the "Moderate" to "High" category (Table 5-6).

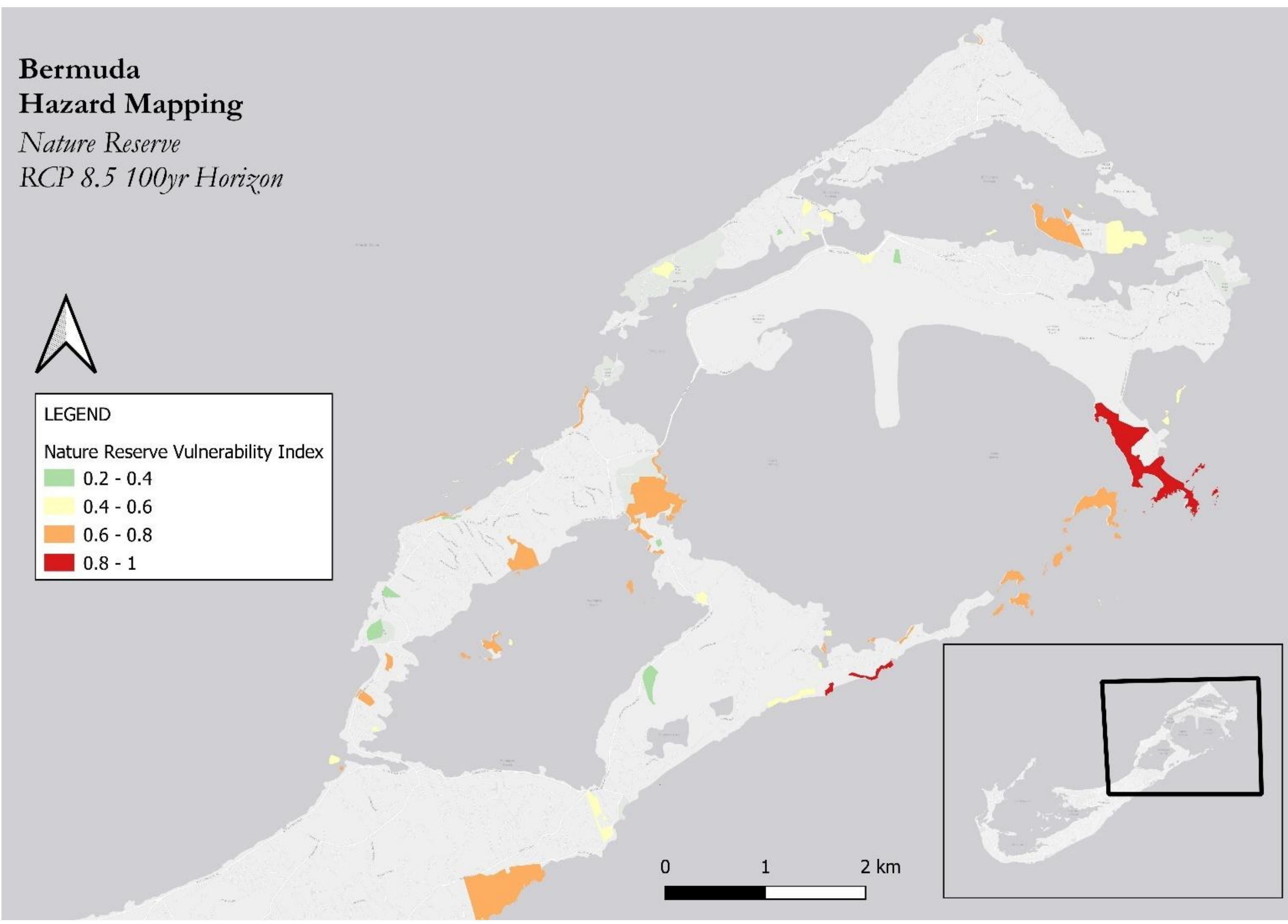

Figure 5.7 Nature reserve vulnerability index (RCP8.5 100-Year horizon, 150-Year return) for north-eastern Bermuda

Table 5-6 Breakdown of CVI Score for Nature Reserve Areas (Long-Term – RCP 8.5)

Location	Vulnerability Category	CVI - Rank	Number of Plots Exposed	Nature Reserves Exposed %
Bermuda (All Areas)				
	No Exposure	0	18	7.2%
	Very Low	0.0 – 0.2	7	2.8%
	Low	0.2 - 0.4	25	10%
	Moderate	0.4 - 0.6	111	44.4%
	High	0.6 - 0.8	3	<1%
	Very High	0.8 – 1.0	86	34%
Nature Reserves Exposed		≈ 92%		

5.2.3 Coastal Reserves

Coastal reserves are intended to provide protection to woodlands, beaches, caves, habitats, and natural features such as rock formations, cliffs, and dunes. As so described, coastal reserves are situated on or near the coastlines, hence they are more likely to be impacted by the changing coastal climate than other class of reserves.

Figure 5.8 shows an example of the coastal reserve vulnerability index mapping for north-eastern Bermuda for the RCP8.5 100-year horizon scenario. While all coastal reserves are expected to be affected by climate change, the most vulnerable shorelines are shown as being located in Tucker's Town, Natural Arches, and along Ruth's Bay. Gravelly Bay, Newtown Bay and Pink Beach are also classified at the highest level of vulnerability.

A full breakdown of vulnerability scores for coastal reserves across Bermuda is given in Table 5-7. As expected, the hazards assessed affect approximately 100% of all coastal reserves, with 93% being in the "Very High" vulnerability category (Table 5-7).

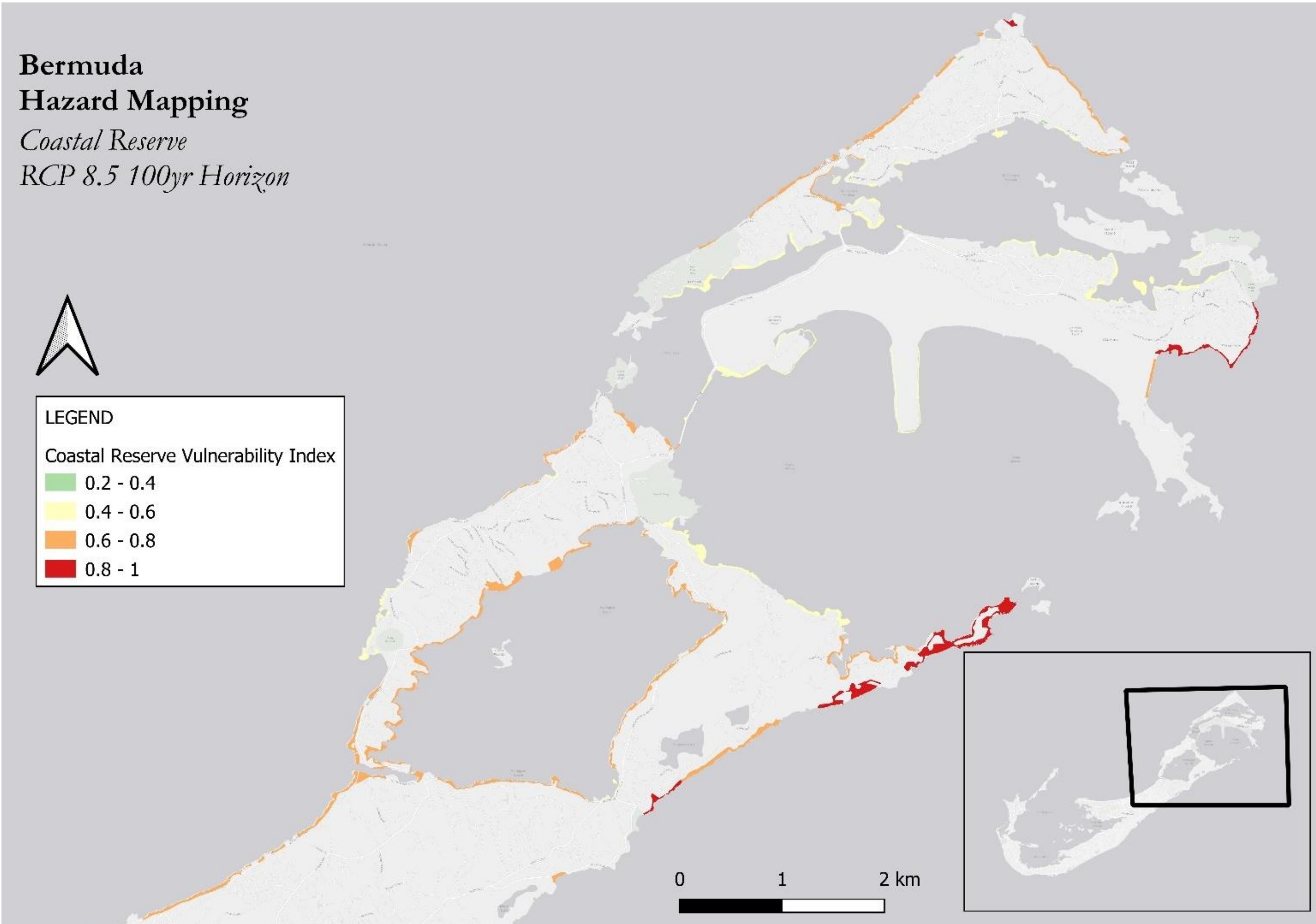

Figure 5.8 Coastal reserve vulnerability index (RCP8.5 100-Year horizon, 150-Year return) for north-eastern Bermuda

Table 5-7 Breakdown of CVI Score for Coastal Reserve Areas (Long-Term – RCP 8.5)

Location	Vulnerability Category	CVI - Rank	Number of Plots Exposed	Coastal Reserves Exposed %
Bermuda (All Areas)				
	No Exposure	0	0	0%
	Very Low	0.0 – 0.2	5	<1%
	Low	0.2 - 0.4	3	1.3%
	Moderate	0.4 - 0.6	109	47.5%
	High	0.6 - 0.8	1	<1%
	Very High	0.8 – 1.0	111	48.5%
Coastal Reserves		100%		

6 New Development Areas of Concern

The CVI offers the opportunity to identify "clusters" of hazards, essentially areas where hazards will pose development problems in the future. Some identified areas of concern include:

- St George's
    - Residences on the North and East of St George's Island, where cliff erosion is the main threat. **Recommendation: Setbacks to be imposed**.
    - St George's Harbour area, seaward of Duke of York Street/Barrack Hill. **Recommendation: Protection of vital assets only; restrict new development; plan for strategic retreat in the medium-term.**

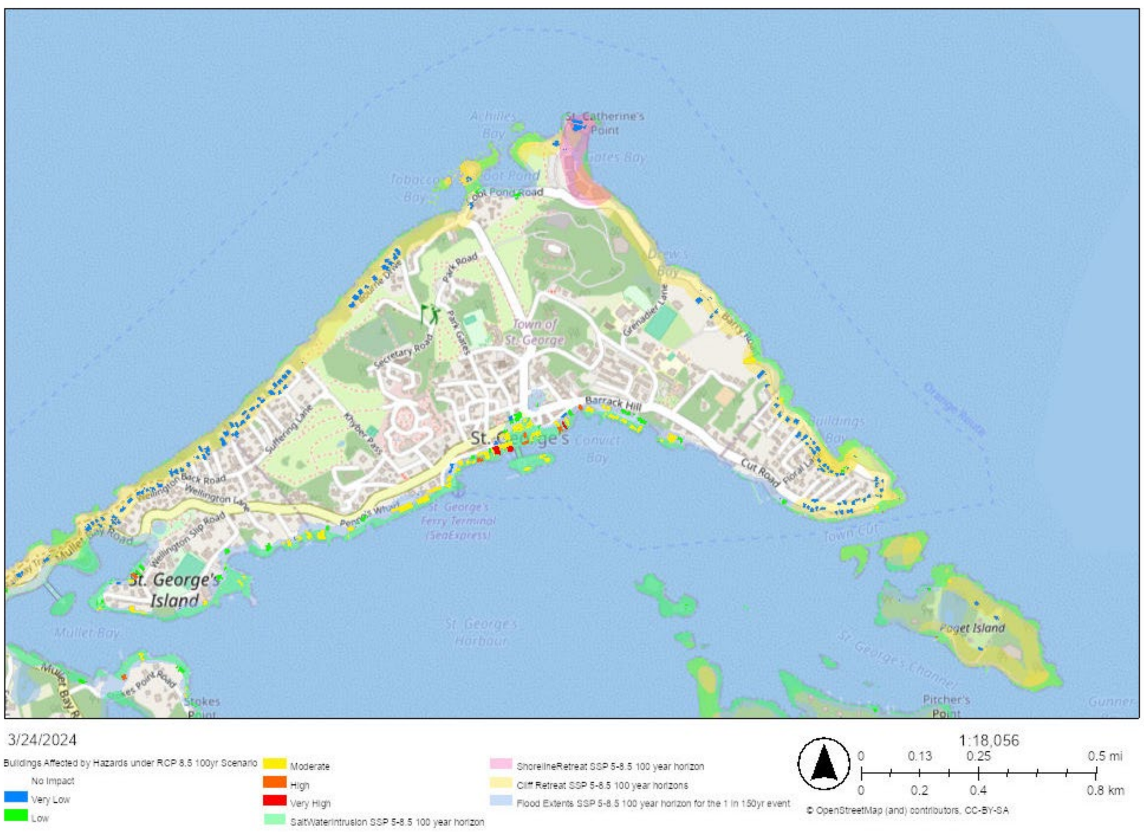

Figure 6.1 St George's – Areas of Concern

- Tucker's Town
    - Tucker's Town Peninsular, where cliff erosion is the main threat. **Recommendation: Setbacks to be imposed.**
    - Residences along John Smith Bay, Canton Bay, Sam Halls Bay, where beach erosion is a threat. Recommendation: Setbacks to be imposed.

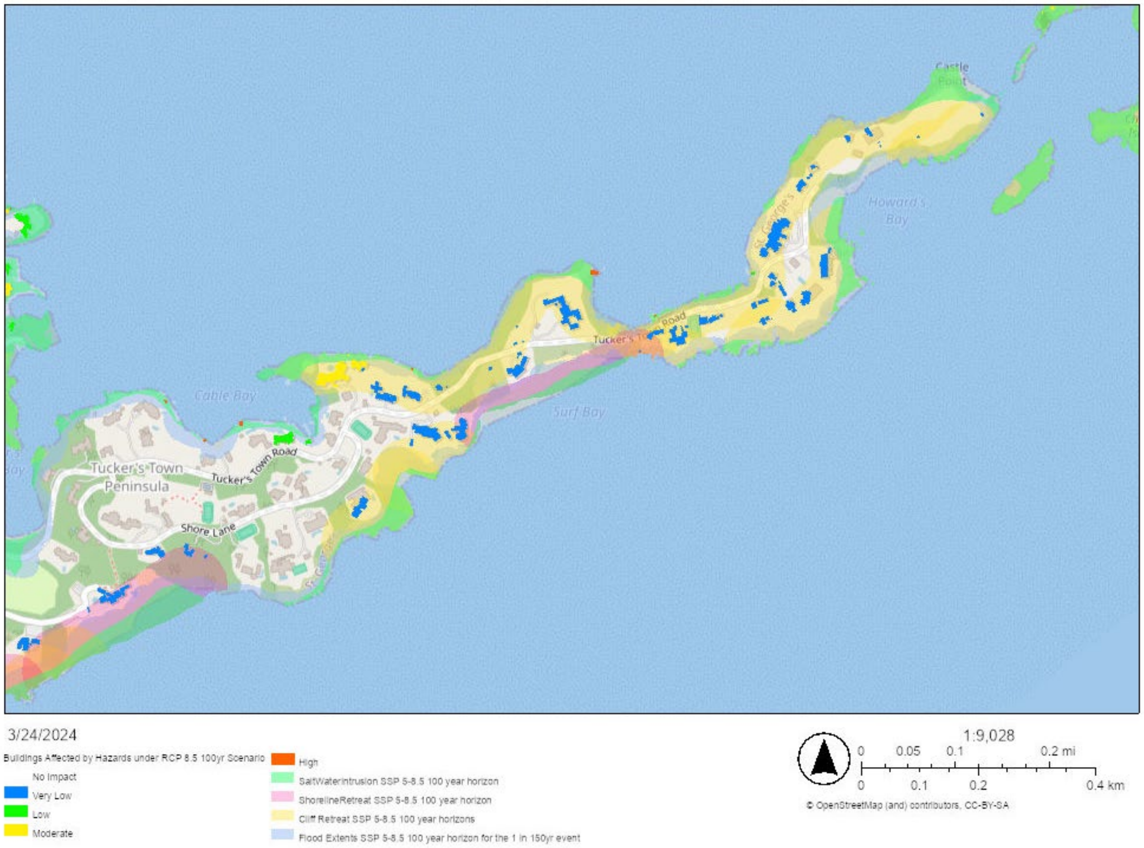

Figure 6.2a. Tucker's Town – Areas of Concern

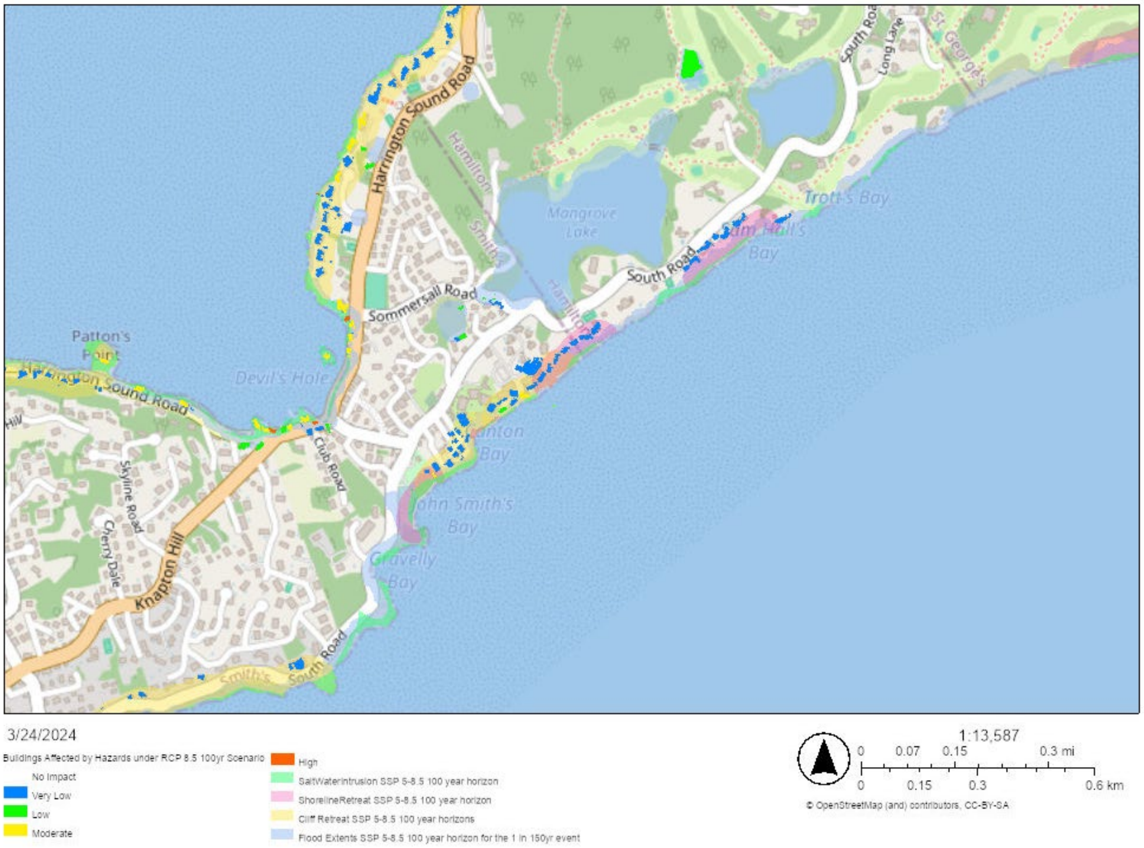

Figure 6.2b Tucker's Town – Areas of Concern

- Hamilton Parish
    - Residences on the North and South coasts, where cliff erosion is the main threat. **Recommendation: Setbacks to be imposed.**

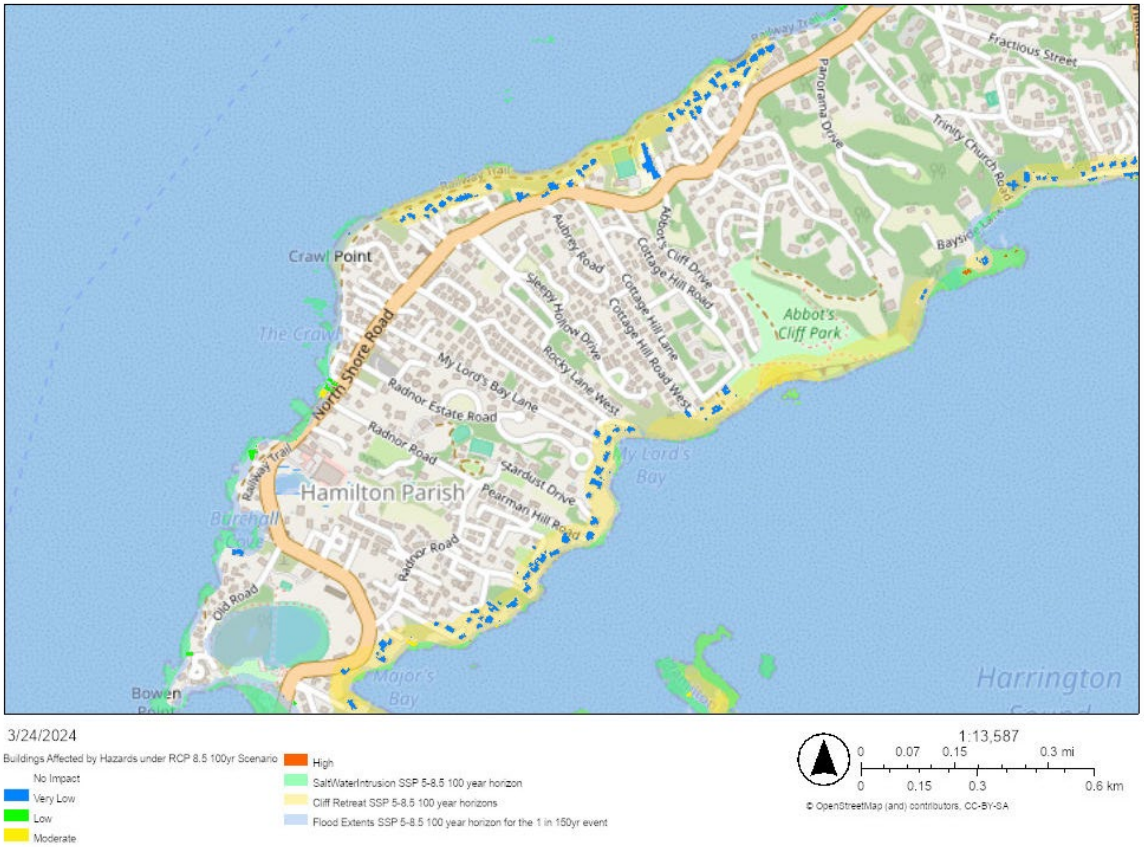

Figure 6.3 Hamilton Parish – Areas of Concern

- Lower Mill Creek / Pembroke Canal – flood risk. **Recommendation: Protection of vital assets only; restrict new development; plan for strategic retreat**.
- North Shore Road, where cliff erosion is the main threat. **Recommendation: Setbacks to be imposed.**

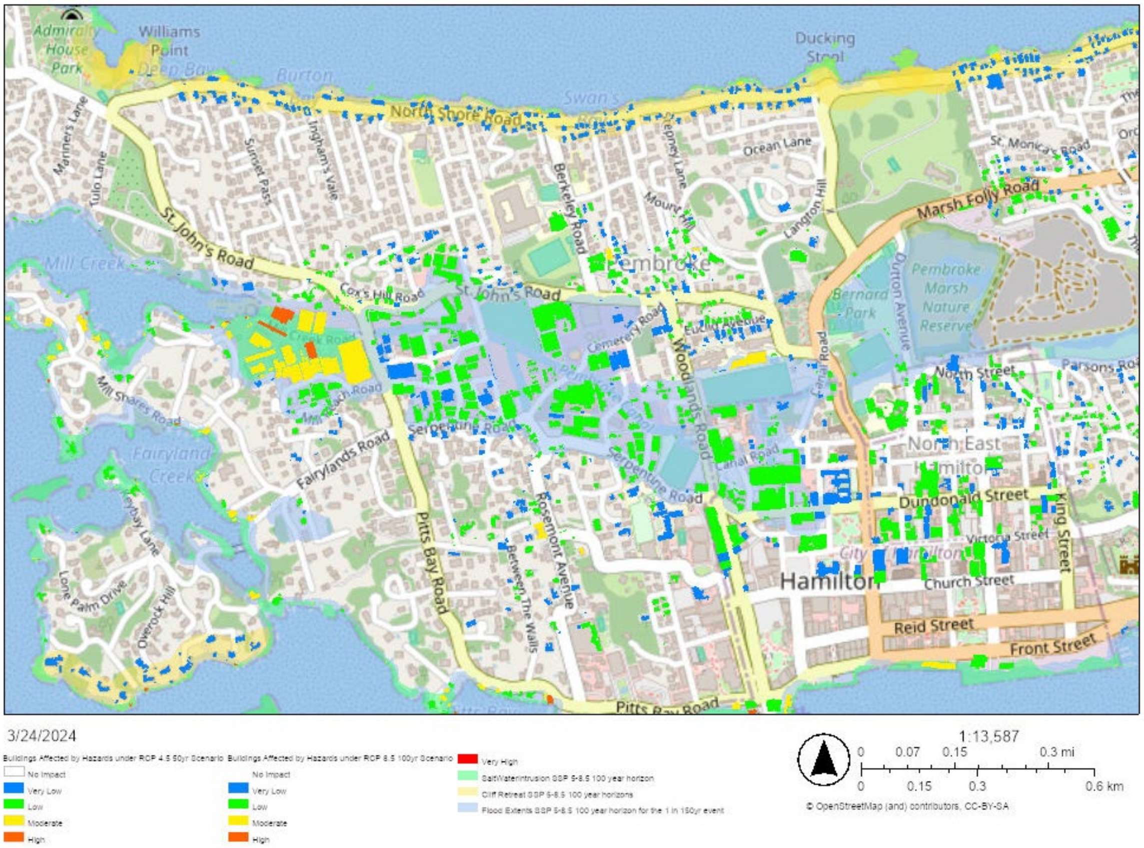

Figure 6.4 Lower Mill Creek / North Shore Road – Areas of Concern

- Sandy's & Somerset
  - Coastal residences, where cliff erosion is the main threat. **Recommendation: Setbacks to be imposed.**
  - North of Somerset Road (Pinkhouse Lane, Acacia Lane, Daniel's Head Road, Spice Lily Lane, Cambridge Road, etc.), where a variety of hazards pose cumulative risks. **Recommendation: Setbacks to be imposed.**

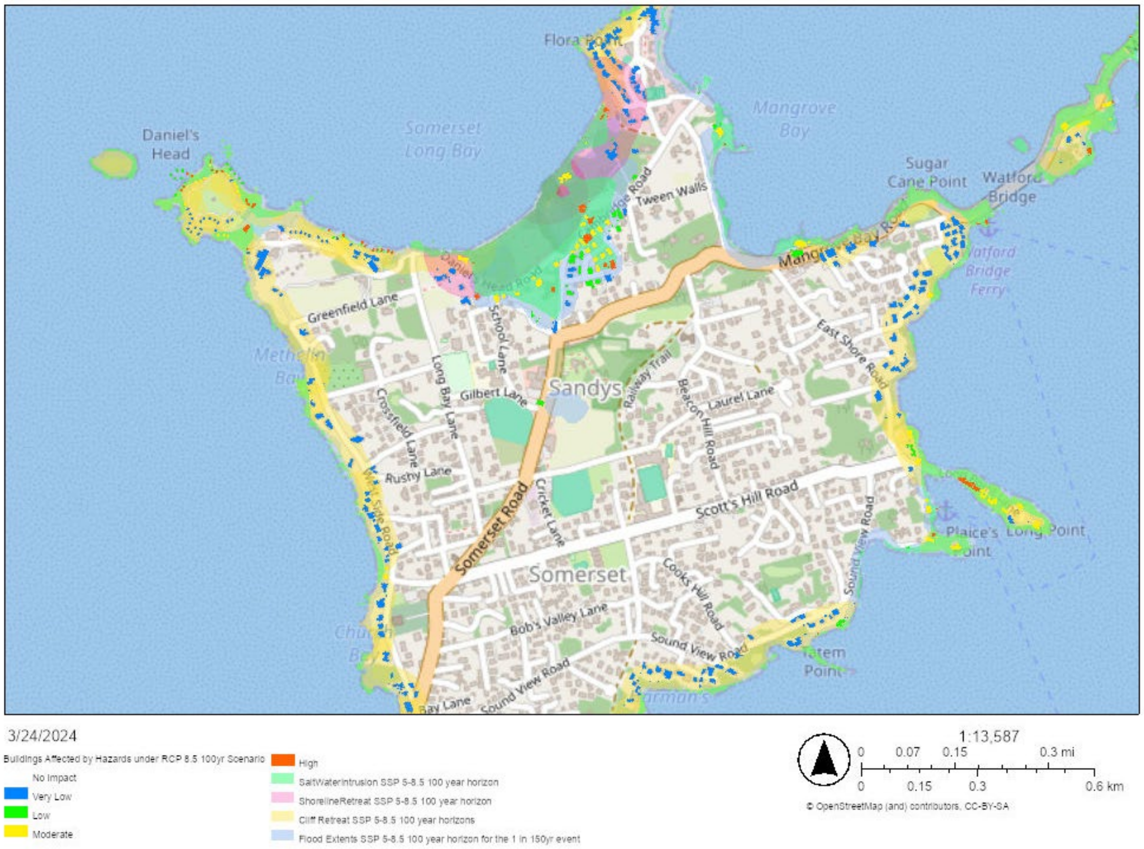

Figure 6.5 Sandy's and Sommerset – Areas of Concern

- Dockyards, where flooding and saltwater intrusion combined with exposure to surge plus wave events. **Recommendation: Protection of historical and vital assets; restrict new development; develop options for "hold the line" protection.**

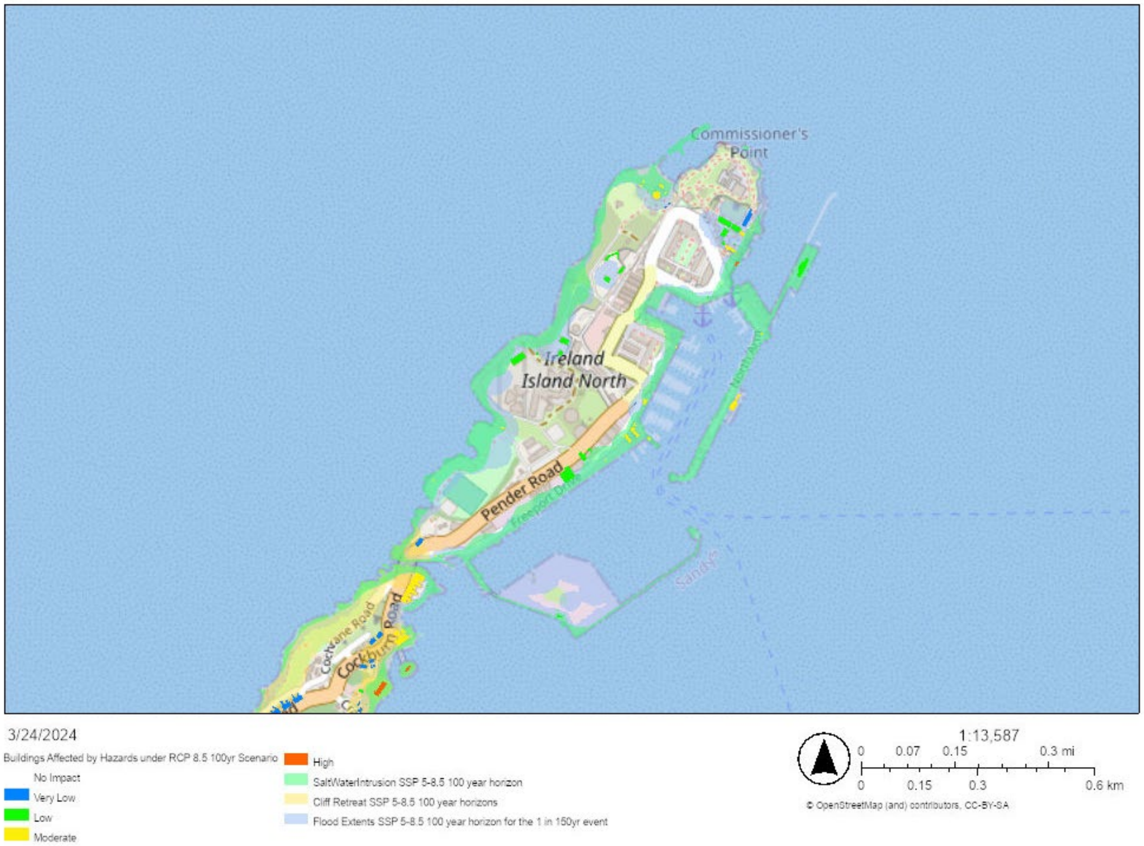

Figure 6.6 Dockyards – Areas of Concern

7 Impact of Climate Change on Ecology

Bermuda's continued resilience as a nation can be expressed through social, financial, and environmental considerations, among others. The preceding chapters, including the development of the CVI, are based primarily on the vulnerability of built assets and resources to coastal hazards. However, it is also recognised that the natural environment is equally as valuable as the built environment. Impacts on the ecology therefore need to be considered in future assessments of climate change impacts in the coastal zone.

Bermuda's coastal zone includes a variety of ecosystems including coral reefs, mangroves, seagrass beds, beaches, mudflats, estuaries, lagoons, littoral woodlands and rocky shores. This coastal zone with its variety of key ecosystems makes it a very productive area that provides valuable resources for the people and the economy of Bermuda.

Ecologically significant areas refer to specific areas that have a high ecological value and importance for the conservation and preservation of biodiversity and ecosystem functions. These areas can be defined based on a range of ecological criteria such as the presence of unique habitats, rare or threatened species, high levels of biodiversity, and important ecosystem services.

Some examples of ecologically significant areas along the coastline that are addressed herein include:

- **Coral reefs:** These are important marine ecosystems that support high levels of biodiversity and provide important habitat for numerous fish and invertebrate species. Coral reefs also provide a first line of defence against storm waves.
- **Seagrass beds:** These underwater meadows are important feeding and breeding grounds for many marine species, e.g., sea turtles. They also provide a physical function of stabilising the seabed substrate and reducing wave energy in the nearshore zones.
- **Mangrove forests:** These unique coastal ecosystems provide critical habitat for a wide range of species and help to protect coastlines from storm damage.

This chapter presents a qualitative discussion on a select range of impacts resulting from key climate change factors. More focus is provided for example, on the impact that increasing wave heights may have on key coastal and aquatic ecosystems, given the overall theme of the project and with regard to general vulnerabilities on the coastline. Other climate change related factors such as temperature, rainfall, and wind, are not included but may also have an adverse effect on coastal and marine environments and processes.

7.1 Impacts on Coastal Reefs

Bermuda's reef system is the most northerly in the world, supported by the prevailing warm oceanic conditions from the Gulf Stream current. However, as a northerly outpost, coral species diversity is limited in Bermuda with a reduced suite of only 22 shallow water hard coral species occurring. Surprisingly, calcareous algae are Bermuda's main reef builders, with corals and vermetid worm shells (a snail) performing a secondary role. Covering an area of 550 km^2, Bermuda's reefs (Figure 7.1) not only provide a physical protective barrier but also a suite of other ecosystem services and are an essential natural resource asset to the economy (Glasspool, 2008).

Bermuda's reefs have certainly experienced the spectrum of human-related stresses and contemporary challenges to their health (e.g., pollution, sedimentation, diseases, bleaching, over-exploitation and fishing); (Cook et al. 1994). Yet despite this, Bermuda's reefs seem to be quite resilient, exhibiting relatively limited change over the past three decades, a fact attributed in part to pro-active management aimed at reducing deleterious anthropogenic impacts, especially fishing pressure (Smith et al. 2013).

The added stressor effects related to a changing climate are expected to impact Bermuda's sensitive ecosystems further in a negative manner. As Bermuda's location is isolated within the open North Atlantic waters, climate change effects on the island will essentially be affected by larger regional and global climate variability such as the North Atlantic Ocean's stratification and circulation patterns. For example, increases in water/air temperature, CO2 and sea level rise (SLR) will alter the composition of species (by affecting tolerance levels) and threaten the diversity of marine ecosystems such as the extensive coral reefs in the area. Within the upper 400m of waters surrounding Bermuda, temperature and salinity are increasing at rates of ~0.01°C/year and 0.002/year respectively (Smith et al. 2013).

Sea level rise effects are expected to contribute to increased coastal flooding and run-off and its associated salinity reduction. Excessive sedimentation and turbidity would stress the corals and make them more vulnerable to bleaching once sea surface temperatures increase. High sediment inputs accompanying floods can have significant impacts on coral reefs by adversely affecting their structure and function through alterations of physical and biological processes. Nutrient (e.g., nitrogen and phosphorous) inputs into the coral ecosystem can result in enhanced eutrophication, resulting in algal blooms that can either smother the corals (causing death) and/or reduce light penetration. With increased vessel movement (cargo, pleasure vessels and cruise), careful monitoring of potential sedimentation and pollution is recommended for Bermuda's four channels for ship passage into Bermuda's ports (North Channel, South Channel, Town Cut and Two Rock Passage).

Some species of corals currently live at or near their thermal limits (due to their narrow temperature tolerances). Projected increases in sea surface temperature suggest the thermal tolerance of reef-building corals will be exceeded within the next few decades with incidences of bleaching also rising rapidly (IPCC reports).

Hurricanes have been more frequent and intense due to increasing sea surface temperatures. The coral reef systems are also an integrated part of the coastal system where they dissipate wave energy, influence currents, and provide a source of sediment (coraline sand). The stability of the beaches in the areas of coral reefs are generally dependent on the functioning of the coral reef.

As mentioned above, this assessment focussed on the change in wave heights that could be expected to occur over the reefs (as a result of climate change) with possible associated impacts. The modelling and analysis presented in the preceding chapters of this report demonstrates that an increase in wave heights is expected over the coral reef systems.

There are a few possible benefits to an increase in wave height over coral reefs. As more energy is distributed within the water column, the circulation of nutrients and oxygen to corals and seagrass may improve, which can potentially enhance coral growth and health. In addition, as waves can help disperse seeds and spores, increased wave heights have the potential to promote the colonization and growth of new coral and seagrass populations.

However, it is more likely that increased wave heights will have a net negative effect on corals. Excessively high waves, such as those expected during storm events, can cause physical damage to seagrass and corals by breaking off branches, uprooting plants, or dislodging coral fragments and leaving them vulnerable to disease and predation. Seagrass beds and coral reefs act as natural barriers that help absorb wave energy, but when wave heights exceed their ability to absorb energy, the seagrass and corals can suffer significant damage. Corals require sunlight to grow and thrive. Increased wave heights can stir up sediment and reduce the amount of light reaching the seafloor, which in turn can affect the growth and survival potential of the corals. Increased sedimentation rates can smother corals and seagrass, while changes in nutrient availability can promote the growth of harmful algae that can outcompete seagrass and damage coral reefs. Waves can also disrupt the nutrient cycle in seagrass beds and coral reefs. High waves can cause nutrient-rich water to be flushed away, leaving behind water that is low in nutrients. This can lead to nutrient depletion and reduced growth rates for corals.

In summary, while increases in wave heights can have some positive effects on corals and seagrass, they can also have negative impacts on these important marine ecosystems.

It is important to monitor changes in wave patterns and their impacts on marine ecosystems, and to take action to mitigate the negative impacts of increasing wave heights where possible.

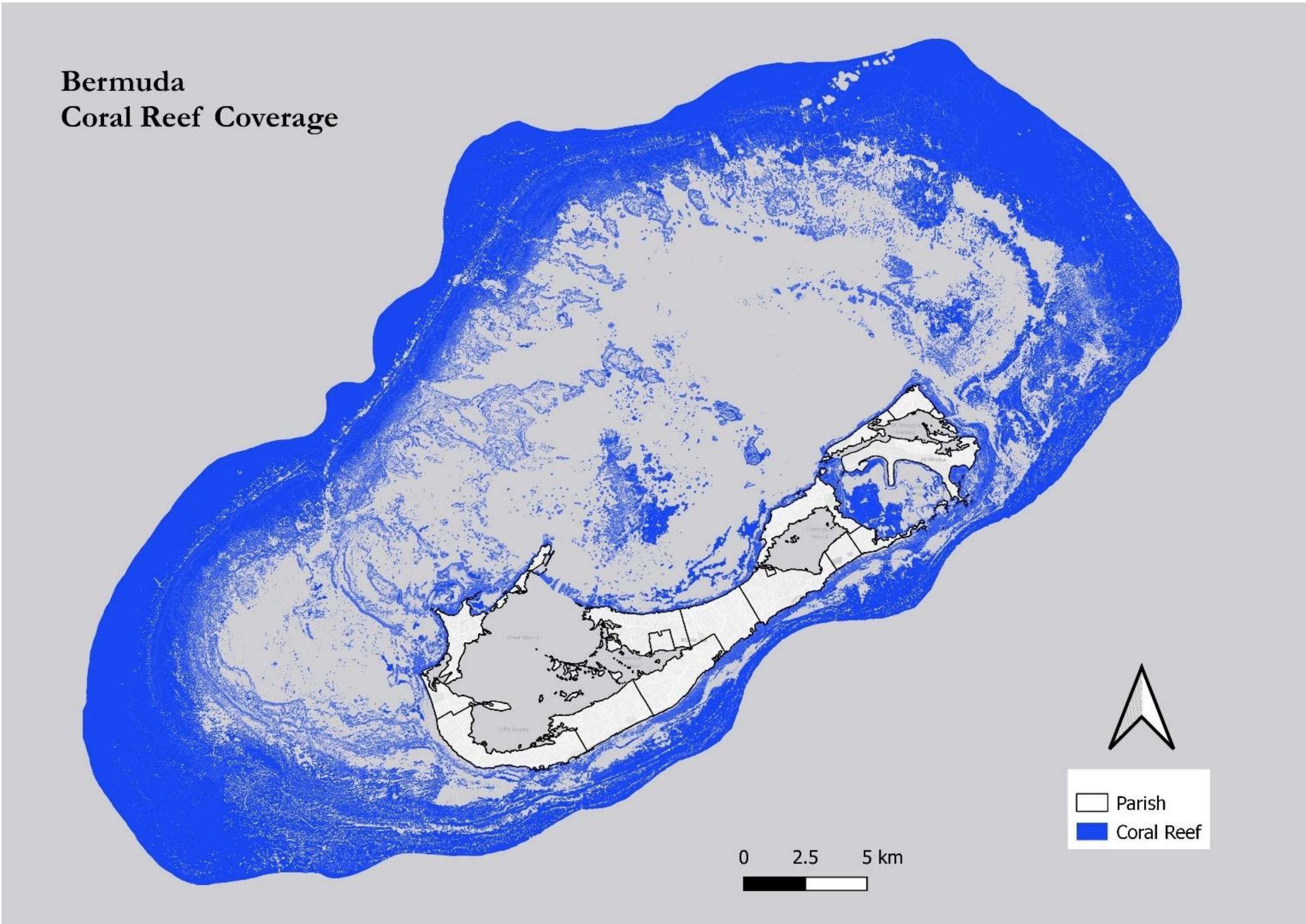

Figure 7.1 Coral reef coverage around Bermuda (Benthic Community Mapping Programme)

7.2 Impacts on Seagrass Beds

Seagrasses are coastal ecosystems with several ecological benefits, including provision of essential food for marine animals, a nursery and shelter habitat for a variety of economically important species of fish, snails and crustaceans. At the same time, seagrasses tend to stabilise bottom sediments by trapping additional sediments and reduce wave velocity, providing coastal protection services. Seagrasses also produce organic matter (e.g., their decaying leaves) that supports (i.e., is food for) a diversity of fauna. They absorb carbon dioxide from the water column and convert it to oxygen through photosynthesis.

Bermuda is home to five different species of seagrass within the various aquatic bays and lagoons, including *Thalassia testudinum* (turtle grass), *Syringodium filiforme* (manatee grass), *Halodule sp* (shoal grass), and *Halophila decipiens* (paddle grass). *Ruppia maritima* (widgeon grass) is also found in most Bermuda ponds. In total, Bermuda has approximately 1,600 hectares of seagrass (Government of Bermuda, 2023) as shown in Figure 7.2. As of 2008, 23% of Bermuda's seagrass beds had died in the previous decade (Glasspool, 2008).

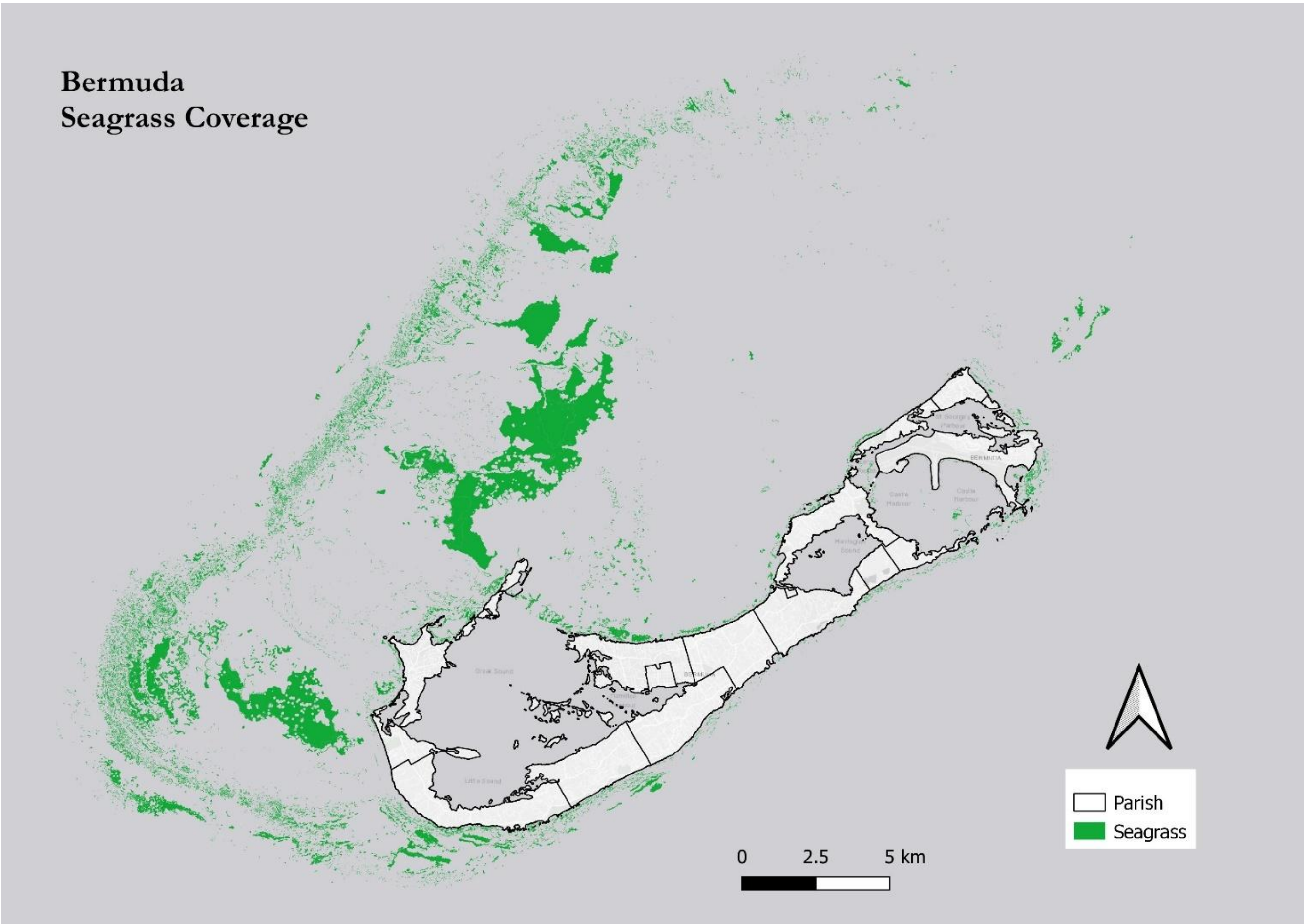

Figure 7.2 Seagrass coverage around Bermuda (Benthic Community Mapping Programme)

Much of the same considerations of the effects of climate change on coral reefs apply to seagrass meadows. Increased flood waters and land run-off can bring elevated sediment loads to shallow, nearshore environments. Benthic or bottom living communities are often directly affected by sedimentation. The primary effects of sedimentation are smothering or burial of seagrasses in shallow water and reduced light penetration and stress to the photosynthesising seagrasses in deeper water. At the same time, reduced light penetration reduces the primary productivity of phytoplanktonic organisms, thereby reducing overall productivity of the ecosystem. High suspended sediment loads also tend to impede faunal feeding abilities because of lower light levels and reduced visibility.

Contaminants like trace metals can, through bioaccumulation, result in impact on associated trophic assemblages thereby causing death and reduced biodiversity. Increased nutrient loads also enhance eutrophication causing seagrass loss, while toxic nutrients and sediment anoxia may also contribute to seagrass mortalities.

Studies have also shown that seagrass shoot mortality and recruitment rates can be negatively influenced by higher temperatures. However, Glasspool (2008) contends that as three of the species of seagrasses are at the most northerly limit of their geographical range, a higher water temperature may actually promote growth and productivity, as long as the seagrasses can compete with algal growth. Glasspool also suggests that seagrasses may be well suited to adapt to climate change if the effects are not overly abrupt.

Within the context of this study, the more pertinent consideration is the damage or uprooting of seagrass beds by strong waves, leading to loss of habitat and reduced food availability for many marine species.

It is important to monitor changes in wave patterns and their impacts on marine ecosystems, and to take action to mitigate the negative impacts of increasing wave heights where possible.

7.3 Impacts on Mangroves and Wetlands

Due to its unique location and proximity to the warmer waters of the Gulf Stream currents, Bermuda has the northern-most mangroves within the Atlantic Ocean (Gov't. of Bermuda, 2023). Mangrove coverage is approximately 17.5 hectares (Anderson *et al.*, 2001), which is reportedly a fraction of what they were over the last two centuries. Many of Bermuda's mangroves and wetlands were either in-filled as garbage dumps or drained in the 19th Century when marsh-breeding mosquitoes spread deadly diseases such as yellow-fever (Hallett 2009). Notably, human modifications to the coast inadvertently created thriving mangrove marshes – at Morgan's Point, and The Lagoon on Ireland Island (Hallett 2009).

Only two species of mangrove tree are found locally: the red mangrove (*Rhizophora mangle*), which is commonly found in the seaward part of coastal swamps (Figure 7.3) and the black mangrove (*Avicennia nitida*), which inhabits a more landward position. Overall mangrove coverage for Bermuda is shown in Figure 7.4.

Figure 7.3 Red Mangrove in Bermuda

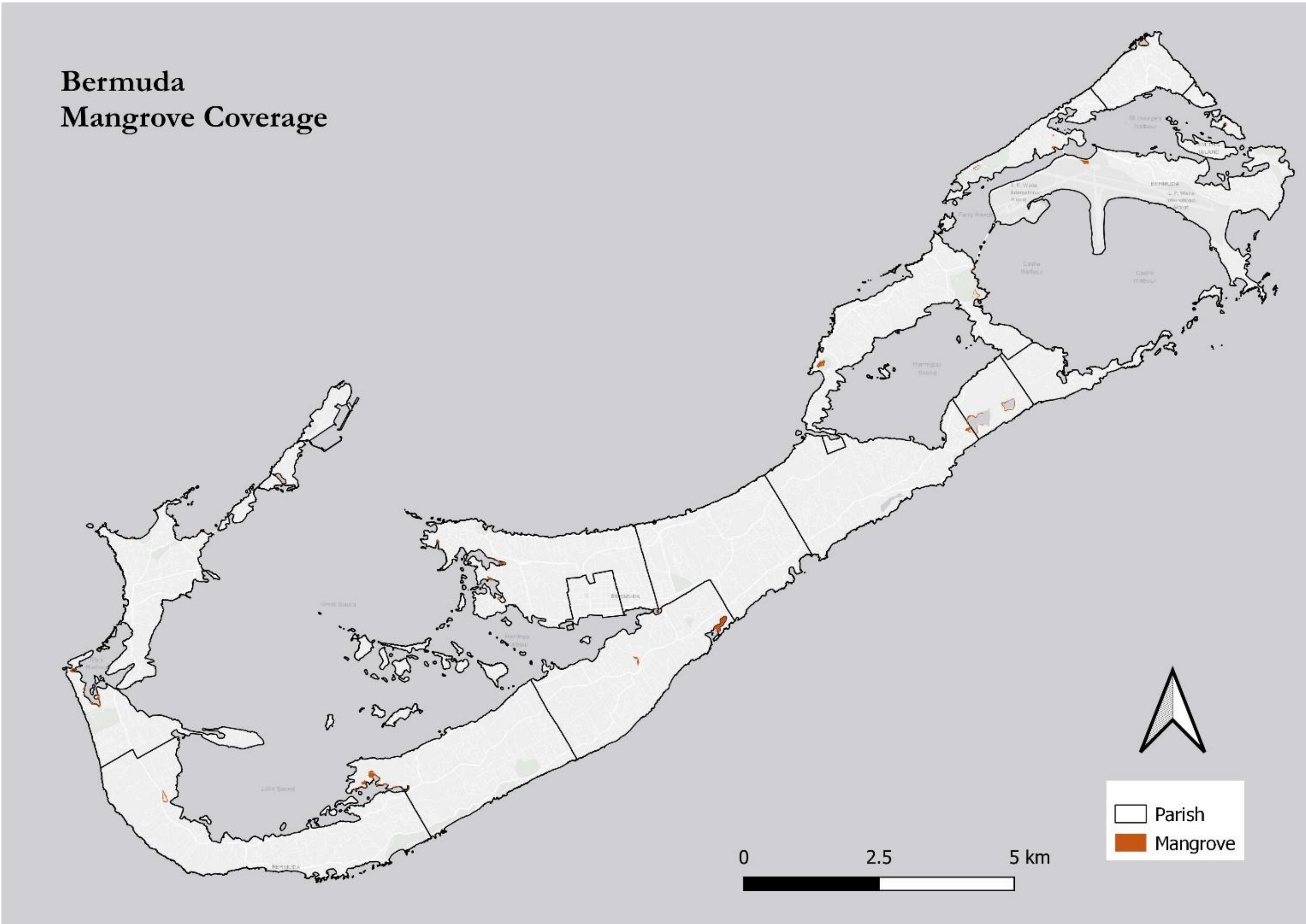

Figure 7.4 Mangrove coverage around Bermuda (Benthic Community Mapping Programme)

Wetlands and mangrove ecosystems are extremely productive and provide a variety of goods and services. These include nursery areas, shelter and feeding grounds for a variety of economically important species of fish. At the same time mangroves add to coastal biodiversity and provide food and nutrients for a variety of mangrove fauna (arboreal, aquatic, and terrestrial). Mangrove forests also provide socio-economic functions including the provision of protection against storms and hurricanes.

Like the argument proposed for Bermuda's seagrasses, the unique northern location of Bermuda's mangroves may mean that they will be tolerant to increased sea temperatures.

SLR is reportedly the most significant climate change threat to the survival of mangroves. There is varying research as to whether mangroves can keep pace with sea level rise. Ellison and Stoddart (1991) showed that on low islands, mangroves could only keep pace with a sea level rise of up to 8cm/100 years, but not at rates over 12 cm/100 years. Tide gauge records from Bermuda since 1932 show sea-level rise occurring at a rate of 28 cm/100 years. The largest mangrove area (6.26 acres) at Hungry Bay has for the last 2000 years been building peat at a rate of 8.5 to 10.6 cm/100 years (Glasspool, 2008). The inability of mangroves to tolerate increased water depth through sea level rise has been more attributed to loss of the seaward edge of mangroves in some instances. However, if accommodation space is available landward, mangroves may be able to keep pace with slow sea level rise by migrating inland.

While some mangrove organisms can tolerate a wide range of salinities (euryhaline), most are limited within a narrow range (stenohaline). When organisms are faced with salinities outside their optimal range, they may lose their ability to regulate internal ion concentrations, which may lead to death. However, decreased salinity in a fringe mangrove system can enhance productivity of the system, and although there might be a change in the fauna composition, it does not necessarily translate to decreased biodiversity.

The mangrove forests in Bermuda are mostly tidally influenced fringe systems, so they would be more likely to be impacted by sea level rise rather than decreased salinity. Glasspool (2008) suggested that the fringing mangroves along Ferry Reach and Mullet Bay will be threatened by SLR. The analysis herein indicates that low island mangroves will experience problems with the rates of sea-level rise predicted for the foreseeable future.

Mangroves are located in relatively sheltered locations with calm daily wave conditions. Mangroves can also tolerate storm conditions to a certain extent and are promoted as a natural form of coastal protection for upland areas. However, hurricanes and tropical storms can inflict catastrophic damage to mangrove areas to which they may not recover. To this end, increased frequency of these storm events poses a risk to Bermuda's mangrove sanctuaries.

The exacerbated conditions associated with climate changes such as SLR and increased storms and hurricanes is expected to cause a decrease in mangrove cover, fauna and flora and those marine organisms that use mangroves as nursery grounds (e.g., juvenile fish).

8 Recommendations - Overview

8.1 Options for Shoreline Management

Under existing climatic conditions, tropical cyclones already pose several hazards for coastal zones in Bermuda, including storm surge flooding, extreme wave forces and coastal erosion. The gently sloping beaches of Bermuda are relatively narrow and there is often little horizontal or vertical setback available within the intensely developed coastal zone, which accommodates human settlements and infrastructure such as hotels, roads and other critical facilities. Increases in sea level will therefore encroach into these intensely developed areas and exacerbate the potential for erosion and flooding, and is expected to negatively impact space suitable for development planning. It is therefore critical that the Government of Bermuda considers at this time, how, when (in the context of future timelines) and which sections of their coastlines will need to be protected from this increasing risk.

8.1.1 Traditional Approaches

Bermuda is faced with the challenge of developing appropriate strategies to deal with coastal risks in a unique environment, considering climate change impacts. In this regard, it is recommended that benefit may be derived from a selection process that considers all of the feasible strategies to address coastal zone management issues.

The standard shoreline intervention strategies include:

1. ***Do Nothing / Hazard Preparedness Measures:*** Essentially, hazard preparedness strategies are geared at quickly alerting individuals living in hazard prone zones about potential risks to livelihoods. This is done using adequate early warning systems and evacuation plans. This strategy does not solve the physical problems, however from a management standpoint it can support informed decisions about building zones, maintenance schedules and particularly vulnerable areas.

2. ***Strategic Retreat:*** Projected sea level rise will cause the retreat of sandy shorelines and cliffs, creating several places where the scarping causes land slippage and ultimately leads to infrastructural damage. The erosion is usually caused by swell waves that occur frequently in the winter, however the damage from the swells develops in a cumulative way. When hazards are less imminent, such as with coastal erosion, people living close to the hazard are often unwilling to relocate. As a result, it may be difficult to garner support for the expense of relocating residents and/or the roadway. Relocating people is likely to have negative socio-economic implications, which may not garner political support. Further, given the limited space of the hinterland areas, pushing back the road and building is likely to be a major challenge in the context of the Bermuda landscape. Strategic retreat may also take the form of setbacks (vertical and horizonal). Spatial planning can define a buffer between the coastline and urban development to reduce the risk of coastal flooding and maintain the resilience and natural appearance of the coastal zone in the long term. An effective measure entails defining a minimum distance from the shoreline to where new buildings or infrastructure can be developed (setbacks). Another measure applicable to Bermuda would be cliff reshaping. This measure aims to slow down the erosion of steep cliffs by re-shaping them to a slope with an angle of less than 15º. A smooth profile may dissipate wave energy more gradually, reducing or even halting coastline retreat.

3. ***Hold the line:*** The traditional term used for hard structures that prevent further retreat of the shoreline is *sea defence* – these are typically seawalls and rock armour protection (revetments). These types of structures have been widely and successfully applied to protect coastal areas. There have already been successful applications of this method in Bermuda.
4. ***Advance the Shoreline:*** Beach nourishment, submerged breakwaters, buried revetments and land reclamation are some of the strategies that could have a place in Bermuda. These strategies create additional land in selected nearshore zones. Typically, these solutions are done in an area with gentle slopes and/or sediment-rich areas that support the success of these methods.
5. ***Ecosystem Rehabilitation:*** The coastal ecosystems (seagrass beds, mangroves, dune vegetation, and corals reefs) contribute to reducing negative impacts of climate variability and change. They act as defences against wave action and storm surge, protecting coastal populations and infrastructure. Reinforcing mangroves and other coastal vegetation is a practice that has been proven to reduce erosion and wave energy. For areas where there are highly energetic wave climates, the growth of coastal vegetation is often not supported.

These strategies may be applied in a complementary manner, which would help to increase resilience and reduce vulnerability in the target areas. They are shown schematically in Figure 8.1.

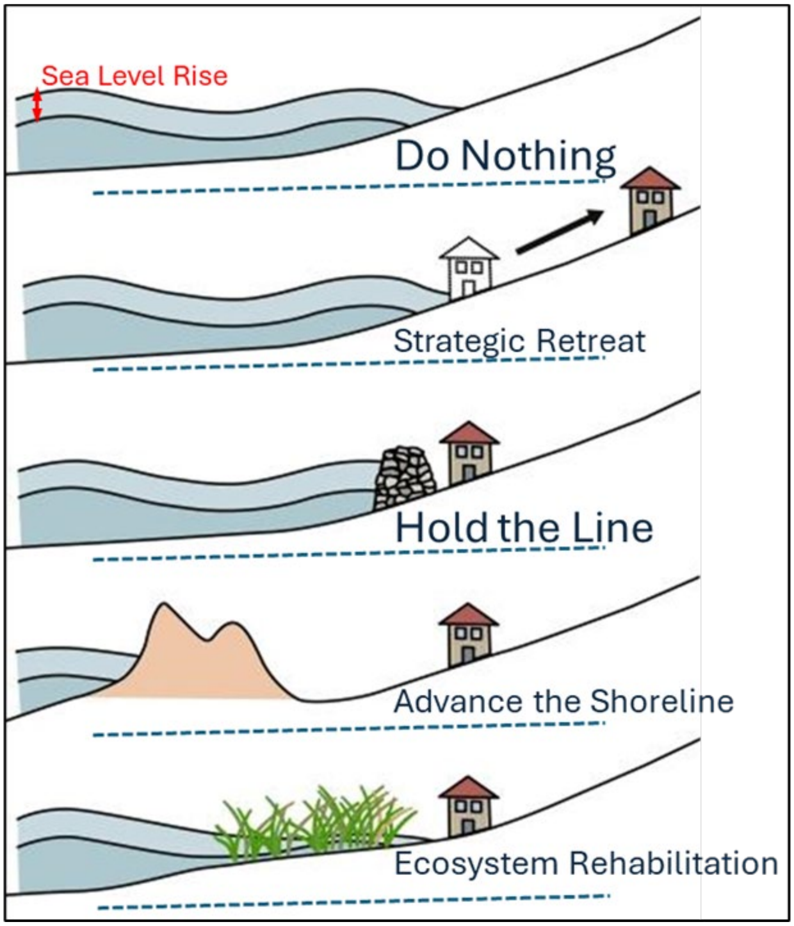

Figure 8.1 Coastal strategies for reacting to the impacts of sea level rise (adapted from Dronkers et al., 1990)

8.1.2 Considerations combining "Hold-the-Line" or "Advance the Shoreline" with "Ecosystem Rehabilitation"

While traditional "grey" infrastructure such as seawalls, rock revetments, and concrete barriers can offer absolute protection from storms and erosion, ecosystem rehabilitation (or "nature-based solutions") are increasingly favoured for their long-term benefits. These solutions, for example restored wetlands or coral /oyster reefs, mimic natural coastal features, buffering against waves and floods while fostering healthy ecosystems. Not only are they more adaptable to a changing climate, but they also provide additional advantages like improved water quality, habitat creation, and even economic gains through increased tourism and recreation. The drawback to ecosystem rehabilitation (or nature-based solutions) is that it generally requires additional time, space, and budget to be successful.

Ecosystem rehabilitation refers to nature-based coastal solutions that apply natural systems and processes to manage and protect coastal areas from the impacts of climate change and other threats. While these concepts can be designed as stand-alone projects (such as rehabilitation of a pre-existing mangrove swamp), modern coastal engineering increasingly strives to include elements of ecosystem rehabilitation into traditional infrastructure defences. Some examples of nature-based coastal solutions, as well as "hybrid" schemes that integrate Ecosystem Rehabilitation concepts into "Hold the Line" or "Advance the Shoreline" strategies include:

Mangrove restoration: Mangroves are salt-tolerant trees and shrubs that grow in intertidal zones of tropical and subtropical coastlines. Restoring mangroves can help reduce the impact of coastal erosion and protect coastal communities from storm surge and tsunamis.

The root systems of mangroves stimulate sedimentation and work to prevent erosion. The rehabilitation of mangroves requires the restoration of hydrology and salinity conditions, replanting of trees and restoring the sand barrier in front of the mangrove forest, or implementing a hard protective structure in front of the replanted trees. Hungry Bay Mangrove Swamp, the largest example of the most northerly mangrove swamp in the Atlantic, which has significantly degraded from the effects of sea level rise, damage from hurricanes, and the dredging of a boat channel some 40-50 years ago (Ramsar, 2021) may be a candidate for such remediation work.

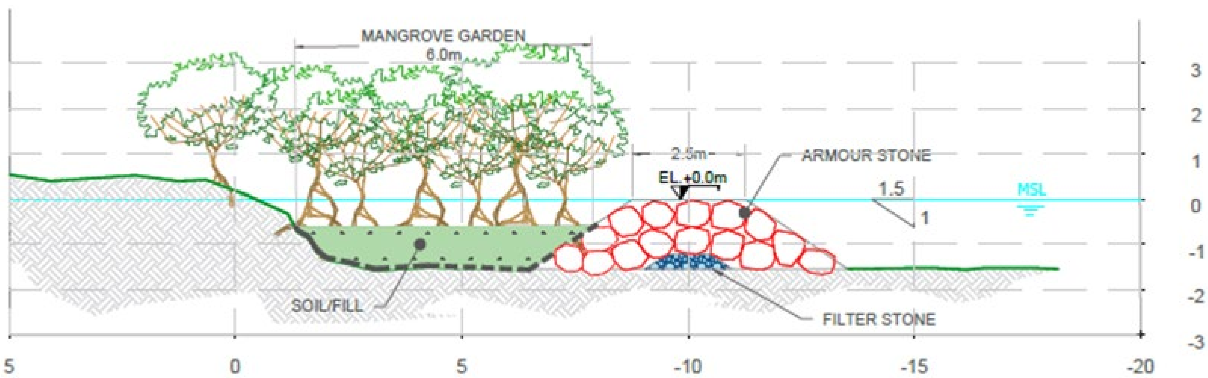

Figure 8.2 Cross-section through manmade mangrove garden in revetment

Beach nourishment: Beach nourishment involves the addition of sediment to beaches to restore and maintain their natural functions. It can help protect coastal communities from the impact of storm surges and sea-level rise. Sand nourishment aims to recover the sediment balance by supplying beaches and shore faces with sand from the island/continental shelf or, alternatively, from inland sandstone quarries. Sand nourishment can help to restore beaches and can reduce storm damage to coastal structures.

The various shipping and navigational channels of Bermuda's harbours require maintenance dredging where large volumes of sediment may be disposed of in deep water, rendering it lost for supply to the coastal system. The dredged material from both maintenance dredging and capital dredging projects could be used to help fill the sediment supply needs of the coast. There is precedent for this type of project integration, for example, recently (2015-2017), the dredging of the North Channel, intended to widen it to facilitate the entry of Quantum class cruise vessels, was integrated with the creation of a commercial marina facility on what is known as Cross Island. This project involved the dredging of approximately 300,000m^3, which was then used to create a 4.5 hectares reclaimed land facility. For beach nourishment applications, such usage would first require that a sediment contaminant analysis be carried out to ensure that the dredged material is safe for use in a recreational setting.

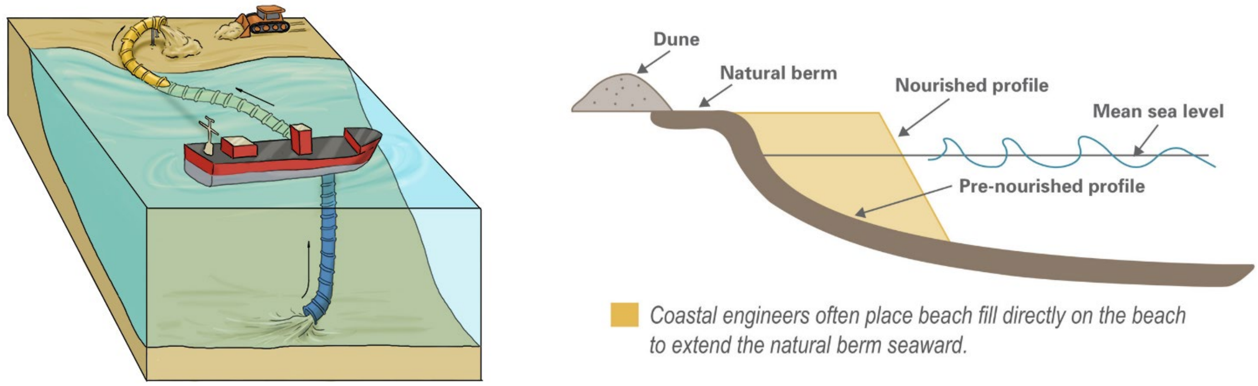

Figure 8.3 Beach nourishment

Living shorelines: Living shorelines are engineered systems that use natural materials such as sand, rock, and vegetation to stabilise shorelines and protect them from erosion. Living shorelines can provide habitat for wildlife, help maintain the natural function of coastal ecosystems, and depending on emplacement location can be used to push out a shoreline.

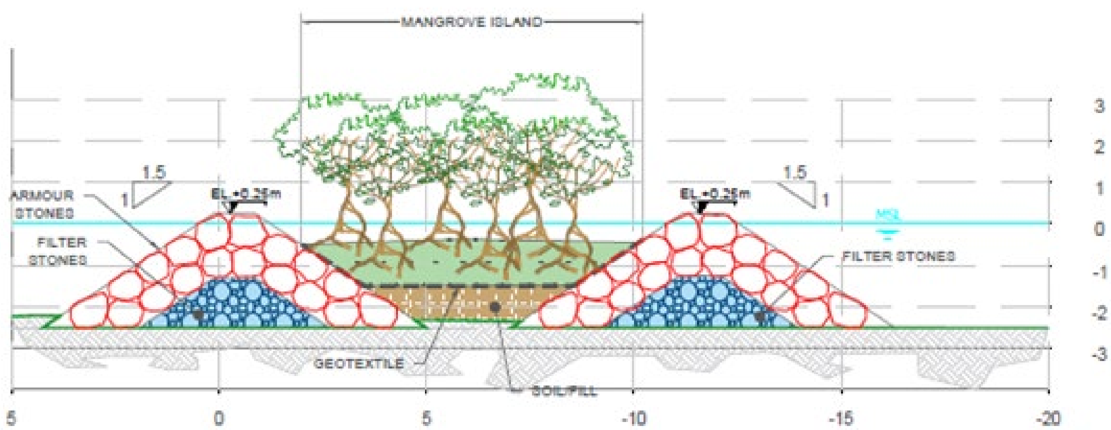

Figure 8.4 Example of living shoreline nearshore breakwater system

Coral reef restoration: Coral reefs are important coastal ecosystems that provide many benefits, such as protection from wave energy and habitat for marine biodiversity. Restoring coral reefs can help protect coastal communities from the impacts of storms and sea-level rise.

Hard structures (like wrecks) on the sea bottom can provide a suitable settlement substrate for coral polyps. Reefs provide a complex habitat to a wide variety of marine species, including fish. The development of coral reefs to reduce erosion is however, a long-term solution, but one that has the potential to keep pace or slowly lag sea level rise (Figure 8.5).

Nature-based coastal solutions can provide many benefits over traditional coastal protection measures, such as being more cost-effective, providing additional ecological benefits, and being more adaptable to changing environmental conditions.

Figure 8.5 Coral reef restoration efforts

8.1.3 Management Strategy Options

Table 8-1 summarises the recommended management strategy options and comments on the strengths and weaknesses of each.

Table 8-1 Summary of recommended management strategies options

Management Strategy	Strengths	Weaknesses
Hazard Preparedness	Complementary to all selected strategies. Sensitizes society to the oncoming threats of climate change.	Does not solve the issues.
Strategic Retreat (SR) ● Purchase or acquire land ● Relocate roads, utilities, and facilities ● Relocate residents ● Compensate land and business owners ● Can incorporate ecosystem protection measures ● Apply Horizontal and Vertical Setbacks ● Establish No Build Zones	Creates a natural hazard buffer area Can be used to promote the creation of intertidal habitat by being used in combination with ecosystem enhancement strategies Removes valuable and/or critical assets from harm's way	Local topography may preclude it; available land area is already at a premium Stakeholders' reluctance, e.g.: • heritage • socio-economic • political Potentially significant cost Valuable land is "sacrificed"
Hold the Line (HtL) ● vertical walls ● revetments (buried or exposed) ● boardwalks ● short groynes ● nearshore breakwaters ● Nature based and/or hybrid protection	Well-established design methods ensure project success Stakeholders recognise this as an accepted method Local job-creation during construction Creates security for planning and development in the short-term	Short project lifespan if climate change projections are underestimated Fewer tangential benefits Capital intensive
Advance the Shoreline (AtS) ● armoured land fill ● beach nourishment ● long groynes ● breakwater systems ● Nature-based protection plus hard solution	Provides buffer area against hazards Protects existing infrastructure Provides additional space for recreation Buffer guards against future erosion and climate change impacts Local job-creation during construction	Potential impact to alongshore sediment balance Capitally intensive
Ecosystem Rehabilitation ● mangrove planting ● coral reef habitat creation ● seagrass bed restoration ● manage sediment supply ● Integrated coastal zone management	Complementary with SR, HtL and AtS strategies Works with "nature" Can be done using low-skilled labour and equipment May improve marine conditions, fishing and recreation Local job-creation during construction.	Only partial protection from coastal hazards Requires on-going maintenance Ecosystem may degrade in the future

8.2 Shoreline Management Strategies and Recommended Solutions for SMUs

The tables from 8.2.1 to 8.2.16 offer a comprehensive overview of drafted strategies tailored to manage and mitigate shoreline hazards across different Shoreline Management Units (SMUs). These tables are structured to present a clear comparison between key infrastructure and shoreline use, the key issues faced, and the recommended approaches for each SMU. By categorizing the shoreline into distinct units, the tables facilitate an organized assessment of each area's unique characteristics, main uses, and challenges. For each SMU, it delineates the primary hazards, such as inundation from storm surges or cliff erosion, and recommends strategic interventions ranging from short-term hazard preparedness to long-term strategies like 'Hold-the-Line' or Strategic Retreat. This structured presentation not only simplifies the identification of relevant strategies for stakeholders but also enhances the decision-making process for effective shoreline management tailored to the specific needs and vulnerabilities of each area.

Below is a guide to interpreting the tables:

1. Key Infrastructure: This column lists the primary infrastructure and shoreline use within each Shoreline Management Unit (SMU). This provides insight into the types of properties and areas affected by coastal hazards.

2. Main Hazards: The next two columns present the main hazards expected over different timeframes: short term (next 20 years) and long term (next 50-100 years). These hazards are color-coded as shown below for easy reference, helping to highlight the severity and urgency of each risk.

Inundation	Cliff Retreat	Sandy Shore Retreat	Extreme Wave Conditions	Saltwater Intrusion

3. Recommendations: Following the hazards, short-term and long-term recommendations are provided. These recommendations are tailored to address the identified hazards and mitigate risks. To fully understand these recommendations, it's important to grasp the strategies outlined earlier in the document, which include options such as strategic retreat, hold-the-line, advance-the-shoreline, ecosystem rehabilitation, and hazard preparedness measures.

The recommendations on shoreline management herein are intended to serve as a basis for a discussion as to the appropriate treatment of the shorelines for future climate change impacts from an outside consultant's perspective and thus will require careful consideration by the Department of Planning prior to finalisation.

Ideally, the work conducted, and the recommendations put forth will be presented to government stakeholders as well as the public for their wider perspective. Once the recommendations have been vetted, they would be drafted as policy within a dedicated Shoreline Management Plan. This Shoreline Management Plan could then, in turn, be considered for statutory documentation status.

8.2.1 SMU 1 - The islands of the Great Sound

	Key Infrastructure and Shoreline Use	Key Issues	Recommended Approaches
SMU 1 The islands of the Great Sound	The islands of the Great Sounds Main Uses: *Residential* *Marinas* Other areas affected: *Ridell's Is.* *Perot Is.* *Five Star Is.* *Bartlett's Is.* *Franks Bay* *Saltus Is.* *Agar's Is.* *Point Shares (NW, NE, and SW extremities)* *Block's Is.* *Long Is.* *Darrel Is.*	Inundation from storm surge: *Short Term* *1.8 – 2.0m MSL* *Medium/Long term* *2.7 – 3.0m MSL* Threats to coastal reserves, housing	Short-term Intervention: Strategic Retreat - Apply Horizontal and Vertical Setbacks - Establish No Build Zones
		Cliff erosion (secondary) Threats to building infrastructure (base data in need of verification)	Medium/Long-term Intervention: Hold-the-Line using "grey" infrastructure, or a combination of nature-based solutions (NbS) + Hard infrastructure

8.2.2 SMU 2 - City of Hamilton

	Key Infrastructure and Shoreline Use	Key Issues	Recommended Approaches
SMU 2 City of Hamilton	Port of Bermuda Ferry Terminal Pembroke Canal	Inundation (Storm Surge and Rainfall) *Short Term* *1.8 – 2.0m MSL* *Medium/Long term* *2.7 – 3.0m MSL* Threats to City of Hamilton buildings, road infrastructure, Port, Ferry, marinas, residential buildings. Major vulnerability to coastal reserves Threats to Salt Kettle Isthmus, residential housing. Industrial Areas surrounding the Pembroke Canal Mill Creek BELCO	Hazard Preparedness Early Warning Systems should be tailored to address maritime navigation issues. Areas should be identified for the relocation of vessels and other assets during extreme events. **City of Hamilton:** ***Short/Medium/Long Term: Hold the Line*** - **Significant waterfront infrastructure investment in and around the City of Hamilton.** - Comparatively little environmental assets remaining, and little potential for ecological recovery. - **All critical infrastructure should be elevated above the calculated SLR and Storm Surge Inundation levels.** - **This includes increasing the elevation of the quay walls and fuel containers.** **Pembroke Canal:** ***Medium/Long Term*: Hold the Line** - Installation of storm surge barriers. **Outside City of Hamilton:** ***Short/Medium/Long Term:* Strategic Retreat (SR)** - Particularly for areas such as the Salt Kettle isthmus, where there are a number of residential buildings.

8.2.3 SMU 3 - Great Sound – Little Sound and Sandy's

	Key Infrastructure and Shoreline Use	Key Issues	Recommended Approaches
SMU3 Great Sound – Little Sound and Sandys	Main Use: Mainly Residential	Inundation Threat to buildings, roads infrastructure. In particular to: Current Is. Cavello Bay Caroline Bay Causeway Morgan's Point Cliff Retreat In the short to medium term, we can anticipate the high relief cliffs to retreat by up to 8-53 meters. This retreat will affect some roads like the Middle Road and Railway Trail.	Hold the Line (HtL) All critical infrastructure should be identified and protected by revetments and seawalls to reduce the likelihood of retreat. In addition, ground elevations should be raised to provide protection against anticipated SLR. Strategic Retreat (SR) Any new infrastructure should be set back by up to 53m from the shoreline depending on the tolerable risk. Where existing buildings are to be relocated, this must be done in a strategic manner. For facilities for which relocation would be problematic, SR will not be an option in the short to medium term. For residences, typically on small islands that are threatened by inundation, SR should be considered for implementation in some form. Short/Medium Term: Hold the Line Long Term: Strategic Retreat and Hold-the-Line as appropriate.

8.2.4 SMU 4 - Great Sound – WEDCO

	Key Infrastructure and Shoreline Use	Key Issues	Recommended Approaches
SMU4 Great Sound – WEDCO	Main Use and Notable Assets: Commercial Cruise Terminal Oil Docks Royal Navy Dockyard National Museum The Lagoon Regatta Island	**Cliff Retreat** In the short to medium term, we can anticipate the high relief cliffs to retreat by up to 8-53 meters. **Inundation** Significant vulnerability of buildings and road infrastructure to SLR and storm surge induced inundation. Namely, the Freeport Drive	Hold-the-Line All critical infrastructure should be elevated above the calculated SLR and Storm Surge Inundation levels. This includes increasing the elevation of the quay walls and fuel containers. For environmental assets such as The Lagoon, a Hold-the-Line approach may be adopted, wherein mangrove ecosystem rehabilitation is practiced. Short/Medium Term: Hold-the-Line; Strategic Retreat as applicable. Long term: Strategic Retreat (Relocation)

8.2.5 SMU 5 - West Coast – Sandys

	Key Infrastructure and Shoreline Use	Key Issues	Recommended Approaches
SMU5 West Coast – Sandys	Main Use and Notable Assets: Westgate Correctional Facility	Inundation *Short Term* *1.8 – 2.0m MSL* *Medium/Long term* *2.7 – 3.0m MSL* Waves (1-2m)	Hold-the-Line All critical infrastructure should be elevated above the calculated SLR and Storm Surge Inundation levels. This includes increasing the elevation of quay walls, fuel containers and shoreline fronting critical facilities such as the correctional facility. Short/Medium/Long Term: Hold-the-Line; Strategic Retreat as applicable

8.2.6 SMU 6 - West Coast – Sandys/Somerset Island

	Key Infrastructure and Shoreline Use	Key Issues	Recommended Approaches
SMU6 West Coast – Sandys	Main Use and Notable Assets: Somerset Village Long Bay Beach Residential Buildings Golf Course	Cliff Retreat (8-65m landward) Inundation (isolated buildings, roads) Waves (1-3m) Sandy Shoreline Retreat	Advance the Shoreline (AtS) In these locations, and in particular for Long Bay Beach, the recommendation is made to advance the sandy shoreline with sand nourishments. In any areas where these may be applicable, submerged breakwaters can be constructed. Short/Medium/Long Term: Strategic Retreat particularly for roads as applicable. Hold-the-Line through ecosystem restoration as applicable.

8.2.7 SMU7 - South Warwick and Southampton

	Key Infrastructure and Shoreline Use	Key Issues	Recommended Approaches
SMU7 South Warwick and Southampton	Boat Bay Horseshoe Bay Warwick Long Bay Southlands Beach Marley Beach Sinky Bay Beach Cross Bay Beach	Cliff Retreat (8-65m landward) Inundation (isolated buildings, roads) Waves (1-3m) Sandy Shoreline Retreat	Advance the Shoreline In these locations, the proposal is made to Advance the sandy shorelines with sand nourishments. To also reduce the wave energy incident on the cliffs at the back of the beaches, submerged breakwaters could also be considered. Hold-the-Line All critical infrastructure should be identified and protected by revetments and seawalls to reduce the likelihood of retreat. Any new infrastructure should be set back by up to 65m from the shoreline depending on the tolerable risk and space available. Where possible, existing buildings should be relocated (Strategic Retreat). Short Term: Hold-the-Line with the aid of beach nourishment Medium/Long Term: Hold-the-Line through the implementation of offshore breakwaters; Strategic Retreat over time (i.e., the next 50 years) relocating buildings that are within the cliff erosion line.

8.2.8 SMU8 - South Devonshire and Paget

	Key Infrastructure and Shoreline Use	Key Issues	Recommended Approaches
SMU8 South Devonshire and Paget	Elbow Bay Grape Bay Spittal Pond	Cliff Shoreline Retreat (8-65m landward) Sandy Shoreline Retreat Extreme Waves (3-5m)	Advance the Shoreline In these locations, we have proposed Advancing the Sandy Shorelines with sand nourishment. In the medium to longer term, submerged breakwaters could be considered for implementation, to reduce the incoming wave energy that would be incident on the cliffs at the back of the beaches. Hold-the-Line All critical infrastructure should be identified and protected by revetments and seawalls to reduce the likelihood of retreat. Any new infrastructure should be set back by up to 65m from the shoreline depending on the tolerable risk and available space limitations. Strategic Retreat Where possible, over the next 50 years or longer, efforts should be made to relocate existing buildings. Short Term: Advance the Shoreline - for the major beaches in this SMU. Medium/Long Term: Strategic Retreat - for buildings threatened by cliff erosion.

8.2.9 SMU 9 - South Smith's and Hamilton

	Key Infrastructure and Shoreline Use	Key Issues	Recommended Approaches
SMU9 South Smith's and Hamilton	Spittal Pond John Smith Bay Sue Wood Bay Pink Bay Rosewood Beach Windsor Beach	Cliff Shoreline Retreat (8-65m landward)	Advance the Shoreline For some of these locations where major sandy beaches are to be found, it is proposed to Advance the Sandy Shorelines with Sand Nourishments. To provide an added degree of protection to this nourishment, and to reduce the energy of incoming waves on the cliffs at the back of the beach, it is recommended to implement submerged breakwaters.
		Sandy Shoreline Retreat	Hold-the-Line All critical infrastructure should be identified and protected by revetments and seawalls to reduce the likelihood of retreat. Any new infrastructure should be set back by up to 65m from the shoreline depending on the tolerable risk.
		Extreme Waves (3-5m)	Strategic Retreat Where possible and where it is required, existing buildings should be relocated over the medium term. Short Term: Advance the Shoreline and Hold-the-Line Medium/Long Term: Strategic Retreat

8.2.10 SMU 10 - Castle Harbour

	Key Infrastructure and Shoreline Use	Key Issues	Recommended Approaches
SMU10 East of St Georges	Castle Harbour Airport The Causeway Solar Farm Coopers Island Nature Reserve	Inundation (1.44 – 3.03m MSL) Saltwater Intrusion Sandy Shoreline Retreat	Advance the Shoreline In general, for the beaches within this SMU, it is proposed that the preferred strategy should be Advancing the Sandy Shorelines with Sand Nourishment. To increase the longevity of this intervention, it is recommended that submerged breakwaters be installed offshore, to reduce the incoming wave energy. Airport & Road Network: Hold-the-Line Significant and vital emergency infrastructure investment. Comparatively little environmental assets remaining, and little potential for ecological recovery. All critical infrastructure should be elevated about the calculated SLR and Storm Surge Inundation. Outside Airport: Short Term: Hazard Preparedness Early Warning Systems should be tailored to maritime navigation. Areas should be identified for the relocation of vessels and other assets during extreme events. S5 Ecosystem Rehabilitation (Mangroves) Medium/Long Term: Strategic Retreat (Relocation) over the medium to long term.

8.2.11 SMU 11 – East Coast - St Georges

	Key Infrastructure and Shoreline Use	Key Issues	Recommended Approaches
SMU11 Castle Harbour	St David's Head Smith's Island Paget Island Great Oswego Island	Inundation Extreme Waves (2-4m)	Short Term: Hazard Preparedness Measures (setbacks, do nothing) Medium/Long Term: Strategic Retreat – for areas subject to cliff erosion

8.2.12 SMU 12 – St George's Harbour

	Key Infrastructure and Shoreline Use	Key Issues	Recommended Approaches
SMU12 South St Georges, Smiths, and Hamilton	Town of St George's Sol Fuel Terminal Cruise Ship Terminal St George's Ferry Terminal	Inundation (1.44 – 3.03m MSL) Roads and Buildings	Within City of St George's and Sol Terminal Short/Medium/Long term: Hazard Preparedness Early Warning Systems tailored to maritime navigation. Areas should be identified for the relocation of vessels and other assets during extreme events. Hold-the-Line Significant waterfront infrastructure investment in and around the City of St George's. Comparatively little environmental assets remaining, and little potential for ecological recovery. All critical infrastructure should be elevated about the calculated SLR and Storm Surge Inundation. This includes increasing the elevation of the quay walls and fuel containers. Outside City of St George's and Sol Terminal: Short Term: Hold-the-Line – Through Ecosystem Rehabilitation (Mangroves) Medium/Long Term: Strategic Retreat

8.2.13 SMU 13 – North Shore – St Georges

	Key Infrastructure and Shoreline Use	Key Issues	Recommended Approaches
SMU13 South Devonshire and Paget	Fort St Catherine Oil docks pier	Inundation (around Rocky Hill Park)	Around Rocky Hill Park: Hold-the-Line Very little landward opportunity to relocate. All critical infrastructure should be elevated about the calculated SLR and Storm Surge Inundation. Around Fort St Catherine: Hold-the-Line – Secure the cliff at the back of beach adjacent to the fort foundations. Elsewhere: <u>Short Term:</u> Hazard Preparedness Measures (setbacks, do nothing) <u>Medium/Long Term:</u> Strategic Retreat – for areas threatened by cliff erosion
		Waves (1-2m)	

8.2.14 SMU 14 – North Shore – Hamilton Parish

	Key Infrastructure and Shoreline Use	Key Issues	Recommended Approaches
SMU14 South Warwick and Southampton	Shelley Bay Beach Railway Trail Residential	Waves (1-2m) Inundation (Road around Eve's Pond)	Road network around Eve's Pond: Hold-the-Line Very little landward opportunity to relocate. All critical infrastructure should be elevated above the calculated SLR and Storm Surge Inundation. Or protected by seawall or hybrid structure. Elsewhere: <u>Short Term:</u> Hazard Preparedness Measures (setbacks, do nothing) <u>Medium/Long Term:</u> Strategic Retreat – for places threatened by cliff erosion

8.2.15 SMU 15 - North Shore (Pembroke and Devonshire)

	Key Infrastructure and Shoreline Use	Key Issues	Recommended Approaches
SMU15 West Sandys	North Shore Road Desalination Plant (Tyne Bay)	Waves (1-2m) Buildings, Road Infrastructure Cliff Retreat	<u>Short Term:</u> Hold-the-Line Very little landward opportunity to relocate. All critical infrastructure should be elevated about the calculated SLR and Storm Surge Inundation. <u>Medium/Long Term:</u> Hold-the-Line – for threatened roadways, using combinations of hard and "green" protection methods. Strategic Retreat – if possible, for the places threatened by cliff erosion

8.2.16 SMU 16 – Harrington Sound

	Key Infrastructure and Shoreline Use	Key Issues	Recommended Approaches
SMU16 Harrington Sound	Harrington Sound Residential Flatts Bridge	Cliff Retreat (8-65m landward) Inundation (isolated buildings, roads)	<u>Short Term:</u> Hazard Preparedness Measures (setbacks, do nothing) Hold-the-Line – through ecosystem rehabilitation. <u>Medium/Long Term:</u> Hold-the-Line

8.3 Hydrogeologic Considerations

This report presents the results of data compilation and literature searches of a complex geologic setting. Significant data gaps were present in the information supplied to the SWI hydrogeologist, and it is possible that data errors or errors in interpretation also occurred in the supplied and researched material. It was beyond the scope of this project to review each data measurement and infill all gaps. Analytical models constructed from this data are limited by the quality and completeness of the information available at the time the work was performed. Analytical models represent a simplification of the actual geologic conditions. The applicability of the simplifying assumptions may or may not be valid to a variety of applications.

This report does not exhaustively cover an investigation of all possible environmental conditions or circumstances that may exist in the study area. If a service is not expressly indicated, it should not be assumed that it was provided. It should be recognised that the passage of time affects the information provided in this report. Environmental conditions and the amount of data available will change. Discussions relating to the conditions are based upon information that existed at the time the conclusions were formulated.

Specifically:

1) The assessment of sea level rise was based on IPCC projections and does not consider the cataclysmic breaking off of very large pieces of glaciers into the sea or the melting of glaciers such as the Thwaites Glacier in Antarctica and the ice cover of Greenland, which could cause almost instantaneous sea level rise on the order of metres throughout the world.
2) The complex response of the groundwater lenses underlying Bermuda to sea level fluctuations depends on many factors affecting sea level (daily tidal fluctuations, meso scale anomalies, storm response, the local steric anomaly and the fact that Bermuda is slowly sinking[27]) and the many factors in the hydrogeological environment such as the hydrogeological characteristics of rock type, recharge from precipitation, evapotranspiration and pumping for water supply as well as tidal damping and the dynamic nature of the interface between fresh and underlying saline water. As such it is very challenging to comprehend the overall response of the lenses to ongoing, climate change-induced sea level rise and to make predictions of the magnitude of that rise and the areal extent of Bermuda that will be affected by salinification in the future.

Despite the challenges, useful predictions on the potential for salinity intrusion have been produced for specific areas in Bermuda. The following sections discuss recommendations to address the challenges faced ahead.

8.3.1 General Mitigation/Adaptation Recommendations

Sacrificial anodes should be investigated to mitigate corrosion of sensitive metal structures in the short term. Where the infrastructure is onshore, and not likely to be inundated but may be within the range of saline groundwater rise, waterproofing of the structure may be an option. Where waterproofing is not an option, wells could be used to depress and maintain the water table so that saline water will not impact the structures. In addition, or instead of wells, fresh rainwater plus grey water normally channelled to a cesspit under or near the buildings or structure could be channelled to French drains surrounding the infrastructure to maintain a hydraulic head above the water table that will flush saline water away from the structure.

Sea water affects concrete specifically by the actions of sulphate and chloride. Chloride causes the corrosion of reinforcing rods made of steel; sulphate deteriorates the concrete itself. The compressive strength of concrete is its predominant property for construction purposes. Concretes in marine environments suffer deterioration that may be due to chemical reactions of saline constituents with the cement hydration products, alkali-aggregate expansion which occurs when reactive aggregates are present, crystallisation pressure of salts within concrete when one face of the structure is subject to wetting and others to drying conditions (Uneke et al, 2018). In new construction sulphate-resistant concrete should be used. Where possible, depression of

[27] See the Modelling Report pg 113 (pg 124 of 331 pdf), where the subsidence rate is referenced as 0.9 mm/yr from satellite GPS vertical motion velocity data published by the Jet Propulsion Laboratory. This subsidence has been taken into account in the calculations of coastal inundation and in relation to the rise of the groundwater lenses. This subsidence has been added to the total sea level rise in Table 8.3 in the modelling report.

the water table should be used to control upward movement of saline water. As above, rainwater and greywater could be channelled to French drains around the foundations and the downward migration of the freshwater will flush out the saltwater. For the waste management sea filling, sulphate-resistant concrete should be used to immobilise the ash from the Tynes Bay Incinerator.

Low impact development (LID) methods should be implemented in new construction. These methods include (i) pervious concrete and pavement to reduce runoff and increase infiltration, (ii) the incorporation of infiltration galleries where runoff is concentrated. This will allow runoff to more rapidly infiltrate to the water table.

In the past few years, the concept of spongier cities has been developed. Sponginess refers to the ability of cities to allow more infiltration to the groundwater from precipitation and reduce runoff thereby reducing the likelihood of floods. For instance, in 2016, work began to restore a creek that often flooded in the centre of Aukland, New Zealand to a more natural, meandering shape. Its banks are now lush with native vegetation including filtering wetland plants. The changes have increased this part of the city's ability to absorb excess rainfall and increase sponginess. Auckland was recently named the most spongy global city thanks to its geography, soil type, and urban design (Arup, 2022). As the planet warms, intense rainfall and flash flooding are predicted to significantly increase[28]. The spongier a city is, the more resilient it will be in the face of those threats. Solutions will involve politicians, planners, developers and individuals.

High-rise New York City, for example, has introduced thousands of vegetation-filled planter boxes to city sidewalks. Planting trees in sidewalks, unused lots or private gardens, and changing planning regulations to encourage the use of gravel rather than concrete in car parks and driveways can all help to change the map from grey to green.

Building or restoring nature-based flood-prevention infrastructure like mangroves, swales and wetlands costs around 50% less than traditional infrastructure (such as concrete seawalls) while delivering similar outcomes in cities (International Institute for Sustainable Development, 2021). And if well-designed, natural infrastructure can have repercussions that flow well beyond stormwater, like reducing air pollution, storing carbon dioxide, or boosting tourism.

Nature-based solutions are affordable and scalable. These solutions, which increase resilience to climate impacts such as more frequent and intense storms, excess heat and flooding, also have the benefit of supporting the regeneration of ecosystems. These nature-based solutions are an evolution over the so-called hard approaches traditionally used by built environment practitioners.

Site-specific solutions include maintaining or creating green spaces, rainwater gardens, and permeable paving. These nature-based solutions can be incorporated into traditional infrastructure at a pace dictated by available monetary resources.

In Bermuda's case, and especially for the City of Hamilton, increasing recharge to the underlying fresh water Central Lens will both maintain water levels in the lens and reduce the intensity of flash floods during storms. Much of Bermuda could be described as ex-urban and the approaches outlined here apply to those areas as well.

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[28] https://www.metoffice.gov.uk/about-us/press-office/news/weather-and-climate/2021/future-extreme-rainfall-more-extreme-than-first-thought

Conversion of air conditioning and heating systems to those based on heat pumps will significantly decrease energy needs for the island. Consideration of, and supporting studies, should be given to using groundwater as a source for heating and cooling using heat pumps.

Strategies to improve the sponginess of cities are based on these principles adapted to the Bermuda environment include:

- Integrated: a country-wide approach but also taking into consideration local plans and strategies across government and city departments. These include existing city and environs management of flooding, water management and current development plans.
- Systems Approach: Changes should be implemented across the interconnected systems that comprise the water supply. These include:
    - Governance: a system for strategy development and implementation such as the enforcement of sponge city planning guidance and design standards, regulations, incentives, information sharing and encouragement of collaboration.
    - Green infrastructure such as surface structures to increase storage and improve water quality, as well as reduce flooding at the source using parkland, meadows, recreation areas, street trees, green roofs and walls and sustainable urban drainage systems. In Bermuda these would likely be mostly miniature installations on private land that could be encouraged by government programs.
    - An integrated modelling approach for blue infrastructure including the existing pumps and infiltration galleries, pumping stations and underground piping systems, the inland ponds and the groundwater lenses.
    - Grey infrastructure including sewage systems, pumps and storage facilities and storm sewage treatment and injection into the groundwater lenses.
- An adaptive approach with flexibility to address future uncertainty and new understandings. This would include phased strategies with an incremental approach to scenarios along with planning large infrastructure investments.
- Strategies should be based on robust data acquisition and integrated analysis in all areas including groundwater modelling. These strategies should optimise the existing infrastructure and comprise planning scenarios with detailed monitoring programs focussing on local conditions but also considering innovative global solutions.
- In Bermuda's case, and especially for the City of Hamilton, increasing recharge to the underlying fresh water Central Lens will both maintain water levels in the lens and reduce the intensity of flash floods during storms.

8.3.2 Agricultural Mitigation/Adaptation Recommendations

The projected future salinization effects due to SLR will affect the coastal areas of Bermuda with a much greater impact than those areas inland due to relatively steeply rising topography in most areas. Agricultural areas at or near the coast that are characterised by a ground elevation within approximately 3m of the current sea level elevation will likely experience an increase in soil salinity at some time in this century. The effects of this can be delayed using powdered gypsum (calcium sulphate), which binds with calcium rather than sodium making sodium mobile and able to be flushed with recharge from precipitation. Adding gypsum to the soil reduces erosion by increasing the ability of soil to soak up water after precipitation, thus reducing runoff. Gypsum application also improves soil structure, soil aeration and water percolation through the soil profile. Powdered gypsum, applied to agricultural fields, is known to reduce phosphorus movement from the soil to groundwater or during storm runoff.

Another technique to reduce salt concentrations in soil is swamping fields with fresh water. However, the practice can use significant amounts of freshwater. Research shows it can take 300 to 400 litres of freshwater to flush just 1 litre of saltwater out of the soil[29].

More research is needed on an individual property basis and in entire coastal regions to delineate the local water balances to determine if infiltration from precipitation plus runoff plus pumping and/or rainwater harvesting using solar energy is feasible. Pumping fresh groundwater on a scale needed to mitigate the effects of salinization may deplete the freshwater lens.

Crops that are bred to be more drought and/or more saline-water tolerant should be investigated. Organic and regenerative methods of agriculture should be promoted. These methods, employing natural fertilizers and compost, along with no-till systems, cover crops and seed drilling, application of gypsum reduce nutrient loading to runoff and recharge as well as reduced soil erosion from runoff. Soil erosion is likely to increase under present systems of agriculture because intensity of rainfall is likely to increase.

Salinization is known to alter nutrient cycling rates in freshwater ecosystems (Megonigal and Neubauer 2009). Several mechanisms could account for nutrient loss from salinified soils. First, enhanced availability of sulfate in salt-impacted anoxic soils results in desorption of sediment phosphate through sulfide and iron interactions as well as increased microbial metabolism and mineralization of nitrogen (N) and phosphorus (P) by providing an alternative electron acceptor. In addition, increased ionic strength in pore water can desorb exchangeable soil and sediment ammonium and phosphate. Finally, increases in the amount and nutrient content of detritus inputs associated with plant stress or mortality could stimulate microbial nutrient mineralization in soils,

However, more studies are required regarding biogeochemical cycling in various shoreline ecosystems to predict their response to salinification.

It is hypothesised that salinification will increase both N and P mineralization fluxes in the soils of nearshore ecosystems as sea levels rise and salinification increases inland. Mobilisation of phosphate in the underlying limestone could also occur. The goals of the studies should be to quantify changes in N and P soil mineralization along a longitudinal salinification gradient from continuously freshwater to heavily salt impacted locations as well as to compare the possible mechanisms associated with changes to N and P mineralization fluxes due to salinification of impacted soils. We recommend drilling two new wells with rock coring as part of a larger project to repair and update the monitoring well network to obtain limestone samples for testing, with laboratory-based studies to investigate how much P the carbonate can adsorb (and/or react to form apatite) as well as the effects of salinity on mobilisation. Measurement of N and P concentrations in

[29] https://yaleclimateconnections.org/2022/09/fighting-for-inches-in-the-southeasts-struggle-with-salt/

the nearshore ocean should also be included as increasing nutrient concentrations will cause increases in algal blooms and depletion of dissolved oxygen thus impacting fish and other marine life as well as coral reefs.

N and P uptake is so rapid in seawater that it is not possible to detect free nitrate and phosphate in seawater using conventional analytical techniques. Perhaps analysing for isotopes of N and P could be used to determine if these chemical components originate in the Bermuda soils or limestones or another species might serve as a tracer for N and P.

8.3.3 Water Supply Mitigation/Adaptation Recommendations

Restricting Contamination of Drinking Water

Bermudians are required to harvest rainwater from roofs for drinking water. Discharging this water to cesspits is an important component of recharge to the groundwater lenses and will aid in mitigating the effects of salinization. Some persistent organic chemicals such as PCBs and PFAS are easily transported through the atmosphere worldwide and reach the ground via precipitation in all areas of the Earth. This will also occur in precipitation on Bermuda even though it is a relatively isolated landmass.

PFAS (per- and polyfluoroalkyl substances) have been in use for 70 years as non-stick and waterproofing agents. They are commonly found in non-stick cookware, waterproof cosmetics, firefighting foams, water-repellent fabrics and products that resist grease and oil.

Since PFAS do not biodegrade or are otherwise attenuated they have become ubiquitous in the environment, bioaccumulate in marine and land organisms and are found in rainwater throughout the world. PFAS has been detected in the blood of 97% of the U.S. population. Although the health effects are not yet fully understood, PFAS exposure is strongly associated with decreased fertility, developmental effects in children, increased risks of various types of cancer, reduced immunity to fight infections and increased cholesterol levels. The U.S. Environmental Protection Agency recently declared several PFAS as unsafe, even at sub parts per trillion levels.

PFAS can be removed from drinking water with the use of activated carbon and ion exchange but, when the filters are spent, they become contaminated. Disposal of these filters in landfills (or seafills) will not result in destruction of PFAS. It is possible that PFAS are impacting coral reef organisms and landfilling or seafilling spent filters could exacerbate that impact.

Up until recently there has not been a method to destroy PFAS. A recent study found that heating the PFAS (from one of the largest classes of PFAS) in dimethyl sulfoxide with sodium hydroxide destroyed part of the PFAS molecule leaving behind a reactive portion of the molecule and the process subsequently converted the fluorine atoms to relatively safe fluoride. There are other classes of PFAS that will require a different method of degrading the molecule.

In this study, 10 perfluoroalkyl carboxylic acids (PFCAs) and perfluoroalkyl ether carboxylic acids (PFECAs), including perfluorooctanoic acid (PFOA) and one of its common replacements, known as GenX—two of the most prominent PFAS compounds, were degraded. The US EPA, however, has identified more than 12,000 PFAS compounds (Trang et al, 2022).

Another method of treatment for PFAS has been discovered, which uses a UV/sulfite+iodide system which degraded other PFAS, such as the frequently reported eight-carbon PFOA and PFOS, with ease. The addition of iodide also enabled the system to destroy concentrated PFAS in brine solution, which is a practical challenge for groundwater remediation. Ion-exchange systems are used to clean the groundwater, but the PFAS chemicals captured in the resin need to be washed out and destroyed in a cost-effective way (Liu, Z et al, 2022).

Until recently it was commonly believed that PFAS would eventually wash off into the oceans where they would dilute over decades. Cousins et al, (2022) claim this is not true, and instead maintain that the presence of PFAS in oceans can worsen the situation. They claim ocean-bound PFAS can be significantly enriched on sea spray aerosols and transported in the atmosphere back to shore where they will be deposited and contaminate freshwaters, drinking waters and surface soils.

PCBs, especially the higher molecular weight species, and related chemicals, are highly resistant to breakdown and degradation in any environment and are easily transported through the air due to volatilisation. Once airborne, they are adsorbed by airborne particulate matter and transported by weather systems and deposited on land and sea through precipitation. They can also result from dumping and leakage from ships. The PCBs from ships would likely be mixed with oil, mix with surface slicks and would likely be subject to uptake by plankton. PCBs are chlorinated hydrocarbons and bioaccumulate in food chains and are likely carcinogenic.

According to the estimates made in this paper (Nisbet and Sarofim, 1972), the PCBs released into the north American and adjacent coastal environment in the past are now concentrated in three major compartments in the environment: (a) buried in landfill dumps (roughly 3×10^5 tonnes, without allowing for degradation); (b) attached to sediments in rivers and the Great Lakes (roughly 2×10^4 tonnes); (c) attached to sediments on the continental shelf (roughly 10^4 tonnes). A further substantial quantity (of the order of 2×10^4 tonnes) has been widely distributed over the land and sea by aerial fallout and by disposal from ships. These are order of magnitude estimates and may have increased substantially since 1972.

Transfer of PCBs within the environment is expected to take place by the following main routes: (a) volatilisation, aerial transport on particulates, and fallout; (b) leaching from dumps; (c) sediment transport in rivers and in the shallow sea; (d) sedimentation in the ocean. Uptake and transport by the biota are probably quantitatively unimportant routes of transfer of PCBs but are of major biological significance. The rate of transport by any of these routes is likely very slow. In particular, PCBs in sediments in rivers and lakes are likely to move downstream and augment those in the shallow sea for a long period into the future.

Therefore, it would be prudent to test rainfall and ocean spray during storm events on Bermuda for PCB and related chemical concentrations.

As a precaution, it is recommended that rainwater collected from rooftop systems should be pretreated with activated carbon filters and ion exchange systems before drinking and other personal uses. The spent filters should be collected and stored because of the threat of PFAS and PCB contamination until the experimental method of degradation becomes commercially viable.

The concentrations of these persistent chemicals should be monitored in the groundwater lenses. Some attenuation of these chemicals may occur as the infiltration from precipitation passes through the soil but they are unlikely to be attenuated in the underlying rock.

Another reason for filtering rainwater from roofs is to capture microplastics, which are prevalent the world over and likely to be present in precipitation. While the health effects of ingestion of microplastics are unknown, it is best to err on the side of caution. These particles leach out toxic chemicals, including carcinogens. Their rough surfaces snag other toxins and microbes, transporting them to new environments and into bodies. Small creatures like plankton and insects mistake microplastics for food, so they get less nutrition, grow less, reproduce less, and sicken more easily, with effects that can cascade all the way up the food chain. Microplastics have been shown to alter gene expression and endocrine systems in various animals. Plastic microfibers can get deep into lungs, causing a kind of damage similar to that from asbestos.

Maintenance of Recharge from Cesspits

Discharge from domestic uses to the cesspits near or under each dwelling in Bermuda is an important component of recharge to the groundwater lenses. Continued maintenance of this recharge is important to maintain integrity of the lenses and, by maintaining water table levels, control saltwater intrusion. However, discharge of untreated human waste to cesspits contributes to contamination of the lenses with bacteria and viruses associated with human waste, as well as nutrients (nitrate and phosphate) in the liquid effluent. While phosphate tends to bind to the soil and carbonate bedrock, nitrate can migrate easily with the velocity of the groundwater and is not retarded or adsorbed by soil or rock. Dilution is the only mechanism to reduce nitrate concentrations. Increasing nitrate in the freshwater lenses will eventually discharge to the ocean and cause the growth of algal blooms and may affect coral reefs. It would be prudent to introduce some form of septic treatment system that can also reduce nitrate and phosphate to acceptable concentrations. Composting toilets, as discussed previously, could also be used. Infrastructure to collect the waste and process it for fertilizer should be investigated.

8.3.4 Hydrogeologic Conclusions

- Human-caused climate change has triggered a significant rise in global sea levels since the Industrial Revolution. IPCC and University of the West Indies forecasted sea level rise plus daily, weekly, monthly and seasonal ocean fluctuations around Bermuda is causing and will cause saltwater intrusion into freshwater aquifers underlying Bermuda in coastal areas in the future. Sea level rises under the most extreme scenario are predicted to be up to 2.47m in 100 years including the transient oscillations noted above. This will result in upward movement of saline water into the subsurface at the coast and inland for some distance. This intrusion will be further on the south coast than on the north coast due to the hydraulic conductivity contrast of the bedrock between the Brighton and Langton Aquifers.

- The bulk of this assessment deals with the Central Lens, the largest groundwater reserve. There was little available data for the other, smaller freshwater lenses, however, the conclusions apply to the smaller lenses as well.

- Seasonal climate variations can affect the G-H balance (the ratio of water table elevation to the depth of the interface below sea level) which can vary from 1:25 in wet years to 1:58 in dry years.

- Maintaining recharge from cesspits is essential to maintaining horizontal flow in the lenses and restricting horizontal movement inland of the interface zone. As contamination from sewage is a concern, an incentive program to install septic systems with nitrate treatment is recommended. Effluent should still be directed to the local subsurface. It would be prudent to redirect sewage flow that currently is piped to the ocean to a treatment system that captures nitrate and phosphorous and discharges the effluent into the subsurface. Rainwater contains significant concentrations of PFASs which are toxic at the parts per trillion level. Rainwater should not be consumed without filtration (activated carbon and ion exchange), which can be accomplished by household systems or by countertop units. The spent cartridges should be collected and stored for when treatment systems with chemical methods that break down PFASs become available.

- The climate of Bermuda, with precipitation moderately exceeding evapotranspiration, is an important factor in maintaining the groundwater lenses. The climate is generally characterised as having more or less equal precipitation all year, with increased evapotranspiration in the summer months. If the climate changes in favour of more droughts or extended periods of low recharge, impacts to the freshwater lenses could occur such as thinning of the freshwater portion, and more upward moving saline groundwater inland from the coasts. Increased upconing of brackish water in pumping wells may be a consequence of these influences. In addition, reduced rainfall means less water collected in tanks by domestic and commercial owners and less recharge through cesspits.
- Restoring coastal wetlands, coral reefs, marshes and mangroves provide a nature-based defence against coastal flooding and storm surges. In addition, these will protect near coast groundwater from downward moving saline recharge from the inundation event. These defences will also reduce salt spray during heavy storms with high winds. Mangroves and buttonwoods (which occur landward of mangroves and are salt-intolerant) can be used to monitor saltwater intrusion over the years. Mangroves build up soil in response to rising sea levels and will retreat landward as sea levels rise if they have the land available to do so. Mapping of lichen species can also be used to monitor the advance of saltwater intrusion.
- In agriculture, proposed mitigation measures against saltwater intrusion include the encouragement of wastewater reuse for irrigation purposes, providing more irrigation water with the use of drip irrigation, changing crop varieties to drought resistant or heat tolerant ones, and modifying cultivation practices such as "no-till" and organic methods characteristic of regenerative agriculture. Harvesting water from the atmosphere powered by renewable energy sources should be explored. In those agricultural areas at the edge of areas where inundation or upward moving saline water is likely to occur, increasing recharge of fresh water will slow the increasing salinization of the soil. Identifying those agricultural areas that may be at immediate risk for salinization and installing vertical or horizontal wells to depress the water table sufficiently that saline water cannot reach the root zone will protect the soil. Those areas at risk in the medium or long term can be studied as to most efficient methods to depress the water table with lessons learned from mitigating those areas already instrumented with vertical or horizontal wells. Well pumps could be powered by sustainable energy sources such as wind, solar and tidal.
- The effects of salinization on infrastructure can be mitigated by installing shallow vertical or horizontal wells depressing the water table. Numerical or analytical modelling will be useful in assessing the spacing and depth of wells. The BELCO 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 to determine how to protect the existing building to make it waterproof and resistant to the corrosive effects of saline water. Pumping to depress the water table may be a viable alternative in the short to medium term. This would require a detailed hydrogeological study. Buried electrical systems in areas where sea level rise and saltwater intrusion will occur should be housed in waterproof structures.

- Heritage buildings are under threat by rising levels of saline water degrading the foundation materials. Vertical or horizontal wells can be used to depress the water table under and around the buildings and rainwater water collected from roofs could be directed to French drains surrounding the building foundations. However, the system of recharging with fresh water must consider hydrostatic uplift from the upward pressure applied to a structure that could raise it relative to its surroundings, and cause cracks in the basement. Parging or cladding of below grade foundations could be explored. It may be possible to replace old concrete or other building materials in basements with sulphate resistant concrete. This will protect from moisture entering the building materials.
- A campaign to educate the public on the fragility of fresh water should be increased. Bermudians, with their long history of collecting rainwater with roof structures, are well aware of the scarcity of this resource. Water saving devices such as low flow shower heads and toilets should be actively encouraged. New toilet designs should be investigated such as the prototype from Samsung Electronics with the Bill & Melinda Gates Foundation. The core technologies developed by Samsung include heat-treatment and bioprocessing technologies to kill pathogens from human waste and make the released effluent and solids safe for the environment. The system enables the treated water to be fully recycled. Solid waste is dehydrated, dried and combusted into ashes, while liquid waste is treated through a biological purification process. The Canadian company, Lystek has technology that can hydrolyse biosolids and residuals into a multipurpose product beneficial for enhancing nutrient and energy recovery. Lystek THP's product is a pathogen free, high-solids liquid Class A quality biosolids fertilizer, called LysteGro. A mechanism to collect human waste via a sewer system is a prerequisite.
- Another company, DC Water, a sewage plant in Washington DC processes the "output" of the entire US capital. It renders sewage harmless of all pathogens by simmering it at 300F (148C) and compressing it to six times atmospheric pressure. The cooked sludge is pumped into biodigester tanks in which various bacteria eat through it for several weeks, converting it into a consistency of mud. The mud is then dried out for three weeks until it reaches the consistency of potting soil, becoming a fertiliser product that is sold by a local non-profit. This could be adapted to the Bermuda situation.
- Education and public consultation should be sought regarding ways to conserve water, treat sewage, distribute water, handle domestic and industrial waste, reduce pollution and solicit ideas on natural and constructed coastal defences, protection of infrastructure, remediation of salt impacted soils etc. The public should be encouraged to get involved by establishing a community spirit, increasing individual agency, stressing the idea that we are all in this together, and incorporating both top down and bottom-up approaches. Bergkamp et al, (2003) stressed that *"What is needed is a new approach that would be characterized by flexibility and building adaptive capacity in the face of uncertainty. It would draw on existing approaches, techniques and expertise to create a new blend of strategies, styles and means to innovate and implement concrete adaptation measures. It would represent a middle way between planned and top-down technocratic management and the more laissez-faire reliance on spontaneous actions. Adaptation in this sense would be used to strengthen more progressive elements in the water sector. The new threat of climate change and its attendant uncertainties would thus help to propel innovation, and make the required changes more visible and salient. In this way it would support the changes that are occurring in the water sector at present and create opportunities for taking a more integrated and sustainable approach to water management."*

- There is increasing evidence that limits to adaptation are being reached or soon will be reached due to the speed of effects of climate change and other constraints that, in Bermuda, include limited land area, coastal development, ecosystem degradation, lack of resources including financial constraints, and lack of understanding of the general public regarding the seriousness of the problem.
- Conversion of air conditioning and heating systems to those based on heat pumps will significantly decrease energy needs for the island. Consideration of, and supporting studies, should be given to using groundwater as a source for heating and cooling using heat pumps.
- There is opportunity for significant increased abstraction of the Central, Somerset, and St George's lenses to provide potable water feedstock, to reduce the need for energy-intensive seawater reverse osmosis and to provide a stable potable water supply for Bermuda. Expanded use of the lens during a period of climate change carries with it some uncertainties regarding of the effects of increased abstraction rates during sea level rise and the expected increases in the length of dry spells. These risks can be managed by improving knowledge of:
    - the behaviour of the lenses on a "micro" scale (i.e. on a per pumping wells basis);
    - improving knowledge of the lenses on a "macro" scale (e.g. across a lens);
    - updating recharge estimates; and
    - by having accurate information on the rate of pumping from each abstraction well.

9 Vulnerability of Specific Key Infrastructure

This section discusses specific infrastructure that is considered vital to Bermuda's functionality and long-term sustainability. Each asset is described with regard to its vulnerability to the four hazards assessed, with guidance provided for the importance of action needed to address these hazards based on the two scenarios modelled:

- 50yr event horizon considering SSP2-4.5 SLR, and a 150yr RP storm event ("50yr SSP4.5")
- 100yr event horizon considering SSP5-8.5 SLR, and a 150yr RP storm event ("100yr SSP8.5")

Of note, consistent in this section for observations and recommendations to all infrastructure, is the need to closely monitor the climate change trends in the coming decade. As stated in the preceding sections of this report, recent data suggests that the world is on track to experience the more aggressive SSP5-8.5 climate change scenario, which we recommend for longer term (100yr) planning decisions. Some inference on timing of interventions or related actions is also provided based on the 50yr SSP2-4.5 model results, although this assumes more moderate changes to climate. Given the different scenarios modelled, care must be taken to the recommendations, which may change based on the actual trajectory of future climate change.

9.1 LF Wade International Airport

Bermuda's only airport, the LF Wade International Airport, is located on reclaimed land on St David's Island. The airport can handle large commercial aircraft despite having a single runway. The runway measures 2,950m and was constructed during World War II (1941-1943) by levelling Long Bird Island (and others), which were added to connect to (and enlarge) St David's Island. The LF Wade International Airport underwent a significant redesign that culminated with a new terminal opening in December 2020. The airport is connected by a Causeway to Hamilton Parish.

9.1.1 Runway

Although the more modest 50yr SSP4.5 model shows inundation and saltwater intrusion onto the airport property boundary, the runway itself is unaffected. Under the 100yr SSP8.5 event, both inundation (up to 1.5 m depths) (Figure 9.1) and saltwater intrusion (Figure 9.2) are predicted in areas along the eastern half of the runway. Wave heights during this event are less than 1m high (Modelling Report, Figure 5.10), owing to the airport's protection by adjacent land mass.

As a functional airport is considered vital for emergency management, careful monitoring is required on the rate of SLR and other climate change parameters to ascertain whether these predictions are accurate. If future climate change is aligned with these present predictions/modelling, consideration should be given to elevating affected sections of the runway in a 50yr timeframe.

Saltwater intrusion affects concrete specifically by the actions of sulphate and chloride - chloride causes the corrosion of reinforcing rods made of steel; and sulphate deteriorates the concrete itself. In new construction sulphate-resistant concrete should be used. Where possible, depression of the water table should be used to control upward movement of saline water. Rainwater and greywater could be channelled to French drains around the runway and the downward migration of the freshwater will flush out the saltwater.

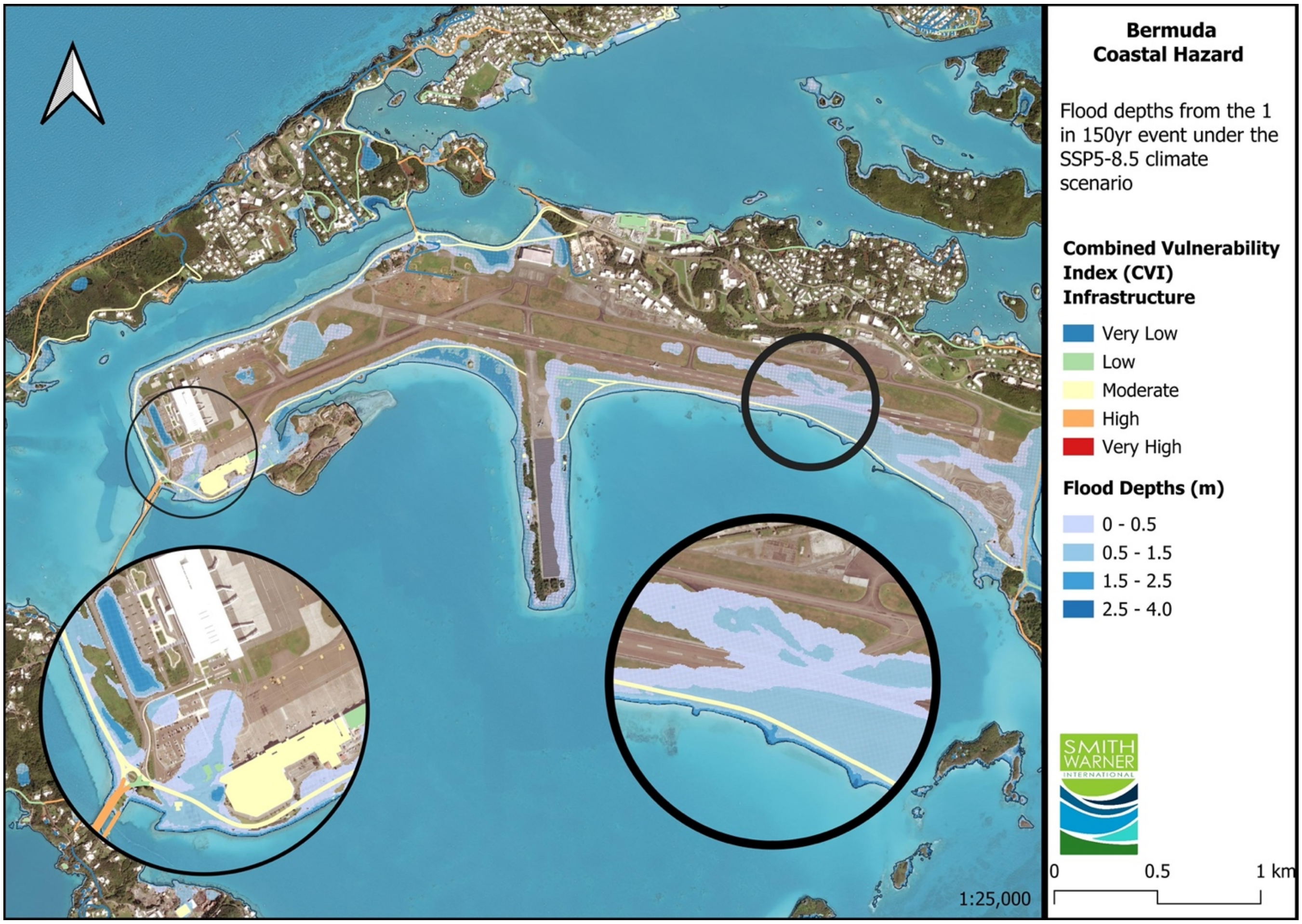

Figure 9.1 Airport runway areas flooded for the SSP5-8.5 100yr scenario

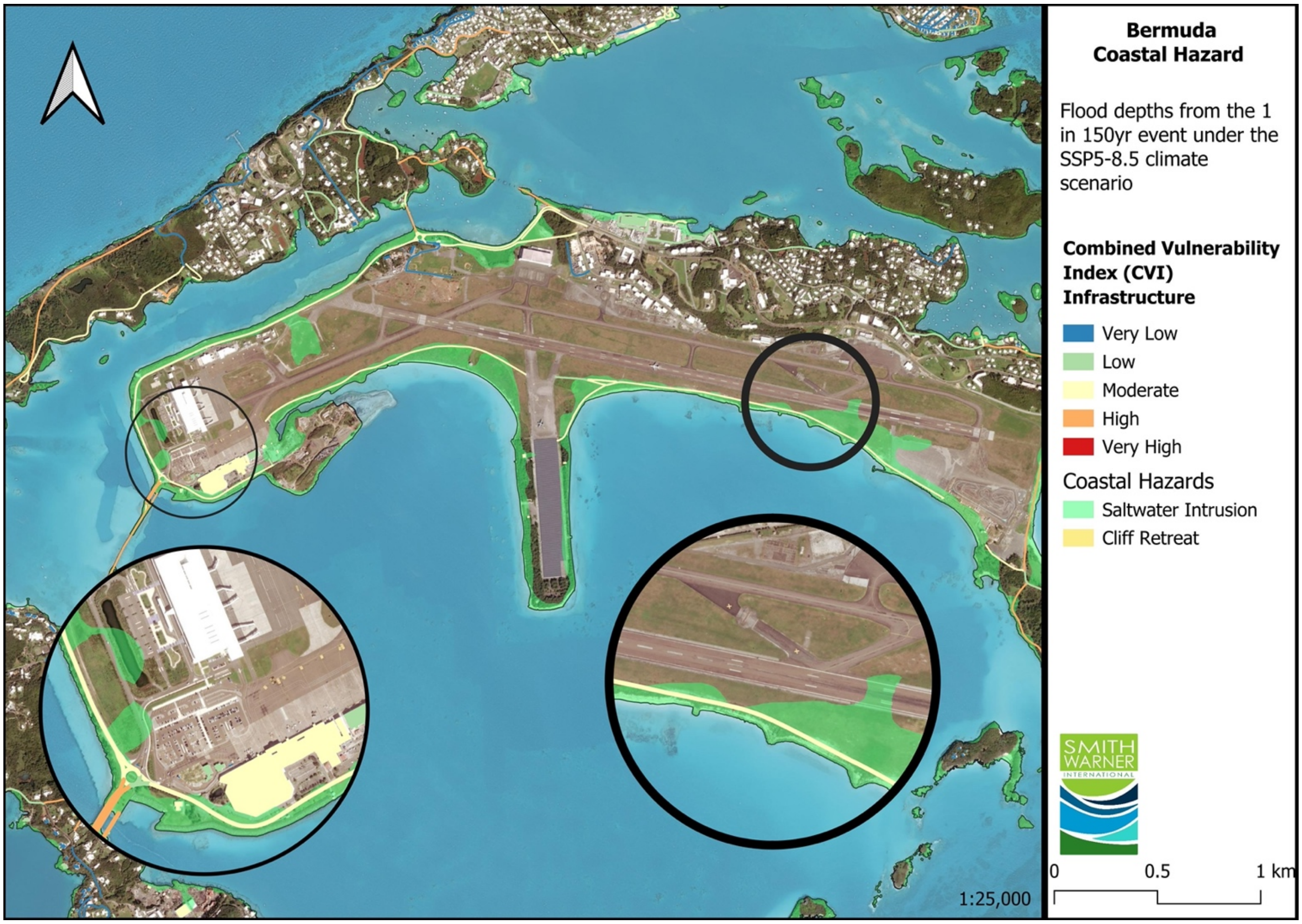

Figure 9.2 Airport runway areas affected by saltwater intrusion for the SSP5-8.5 100yr scenario

9.1.2 Terminal

The main terminal is not impacted by the 50yr SSP4.5 event (although some flooding occurs in smaller adjacent buildings such as the courier building). Under the 100yr SSP8.5 event, both inundation (0.5m depths) (Figure 9.3) and saltwater intrusion (Figure 9.4) is predicted for the terminal as well as the parking lots (up to 2.5m depths). Wave heights during this storm event are less than 1m (Modelling Report, Figure 5.10).

Consideration should be given to adding protection from flooding to the terminal and elevating the parking lots in a 50yr timeframe. Waterproofing of the terminal building is also an option to combat saltwater intrusion.

Figure 9.3 Airport terminal areas affected by flooding for the SSP5-8.5 100yr scenario

Figure 9.4 Airport terminal areas affected by saltwater intrusion for the SSP5-8.5 100yr scenario

9.1.3 Perimeter Roads

The airport's perimeter roads (e.g., Cahow Way, Kindley Field Road, St David's Road) are impacted from both inundation (Figure 9.5) as well as saltwater intrusion (Figure 9.6) from both the SSP2-4.5 50yr and the SSP5-8.5 100yr events. This is unsurprising given the proximity to the shoreline and low-lying elevations. Wave heights are less than 0.5m for the SSP5-8.5 100yr event (Modelling Report, Figure 5.10).

Some of the perimeter roads may survive an occasional storm event with little damage or may not be needed during the passage (or some days after) a storm event; for these roads, little to no action is required. A more detailed consideration (e.g., discussion with the Airport's Authority) is required to ascertain which of these perimeter roads are deemed as vital (e.g. emergency access to the terminal and/or runway), and protective measures applied to these.

In new construction sulphate-resistant concrete should be used. Where possible, depression of the water table should be used to control upward movement of saline water. Rainwater and greywater could be channelled to French drains around the runway and the downward migration of the freshwater will flush out the saltwater.

Figure 9.5 Airport perimeter roads affected by inundation during the SSP5-8.5 100yr scenario

Figure 9.6 Airport perimeter roads affected by saltwater inundation during the SSP5-8.5 100yr scenario

9.1.4 Sol Fuel Storage and Supply Facility

The airport fuel storage facility is located on the north side of the airport[30].

There is minor impact from the scenarios modelled for the SSP2-4.5 50yr event. The fuel storage yard, the tanks, and fuel lines are expected to be flooded (0.5m water depths) in the SSP5-8.5 100yr event (Figure 9.8)

Wave heights are less than 0.5m high for the SSP5-8.5 100yr event (Modelling Report, Figure 5.10). To avoid this inundation, the facility should be elevated above flood levels.

Sacrificial anodes should be investigated to mitigate corrosion of sensitive metal structures in the short term.

Figure 9.7 Sol Fuel Storage and Supply Facility (OBMI, 2024)

[30] OBMI (https://bermuda.obmi.com/project/fuelfarm/

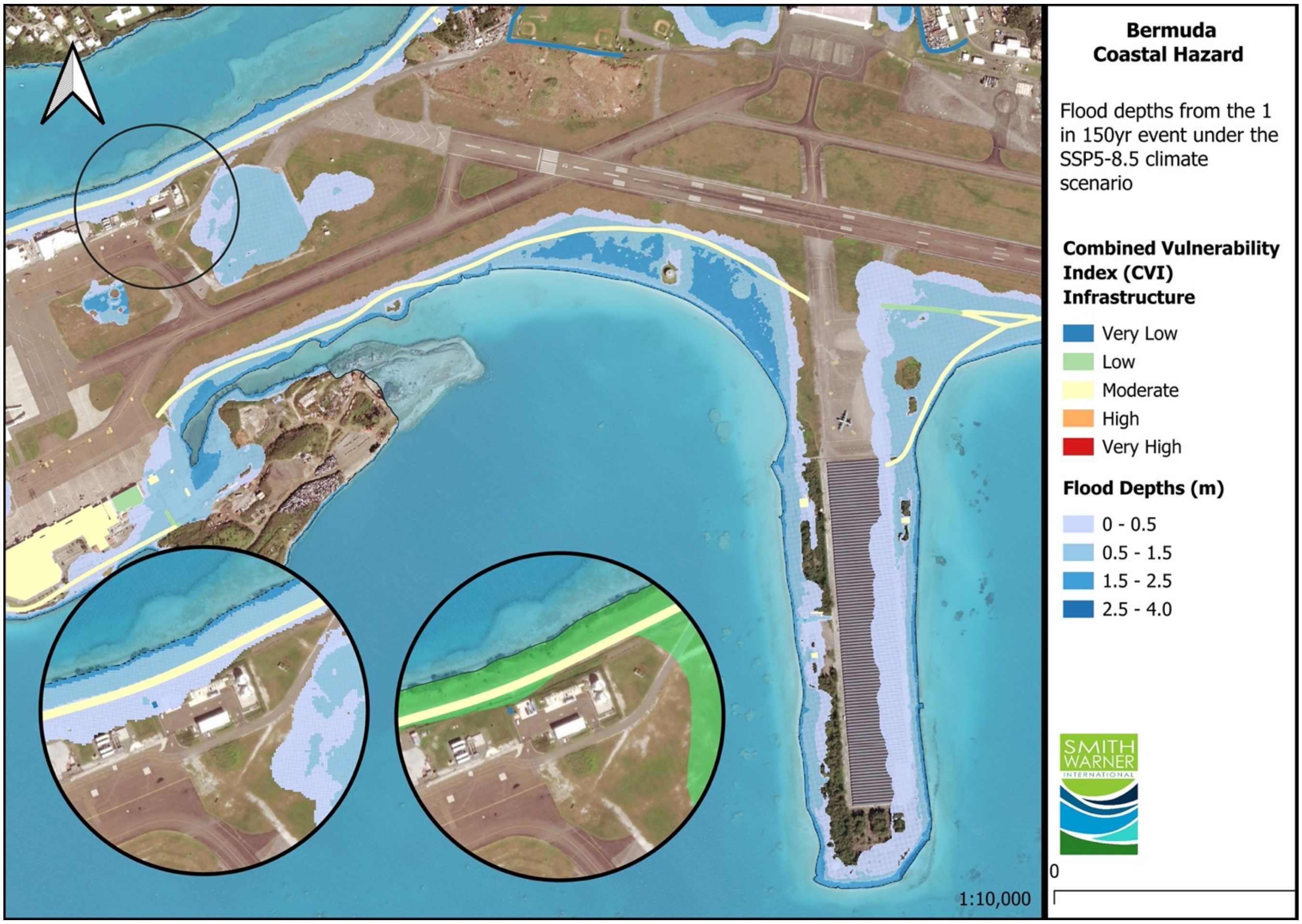

Figure 9.8 Sol Fuel Storage affected by inundation during the SSP5-8.5 100yr scenario

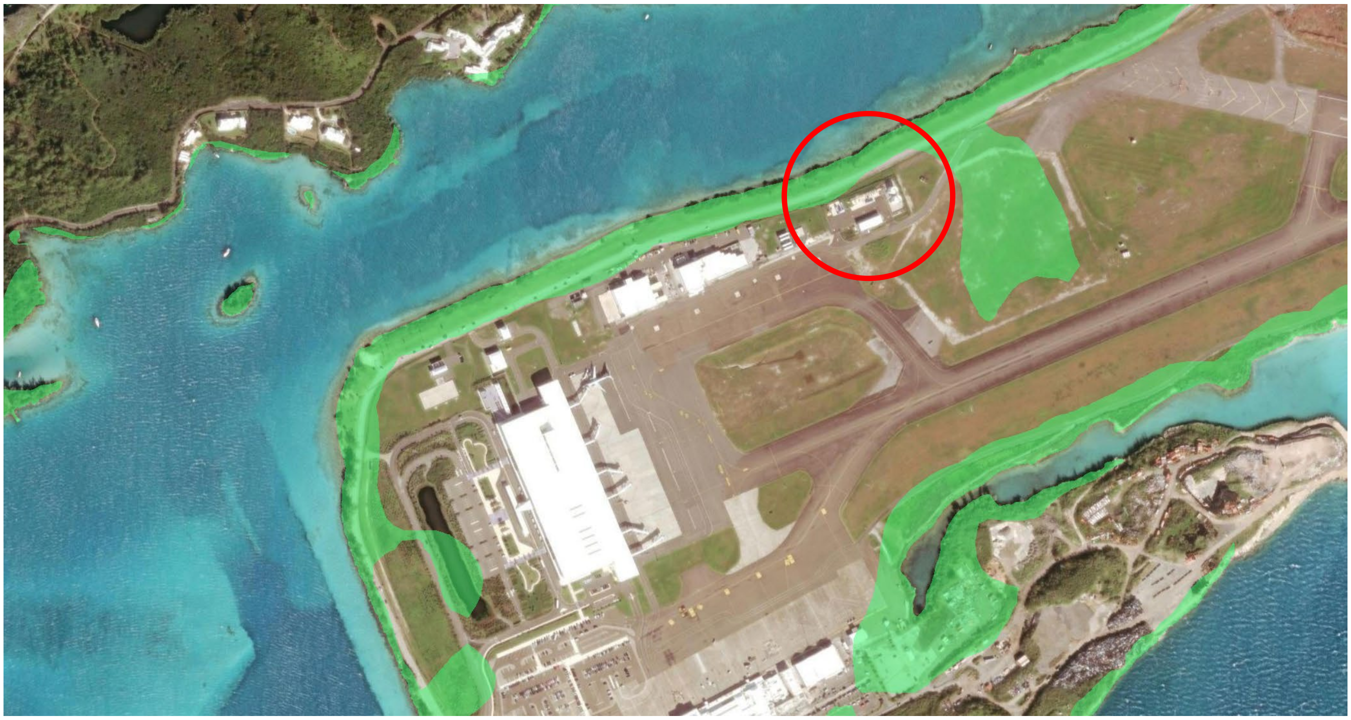

Figure 9.9 Sol Fuel Storage affected by saltwater inundation during the SSP5-8.5 100yr scenario

9.2 Major Bridges

Bridges are essential to Bermuda's connectivity of its various islands and islets, and were first developed in the 1600s. There are over 42 bridges according to the latest government register of bridges[31]. This section discusses the vulnerabilities of some of the larger, more critical bridges.

Of note, the LiDAR survey provided did not include deck elevations. Hence certain inferences were required on the modelling results to ascertain overtopping during surge events. This was achieved by observing pictures of bridges. For the most part, Bermuda's bridges are relatively flat with little vertical grade – and hence the (known) elevations of the abutments and roads leading to the bridge (provided by the LiDAR survey) could be considered as the bridge deck elevation.

9.2.1 The Causeway / Longbird Bridge

The Causeway is vulnerable to both simulated events, from both inundation as well as saltwater intrusion. This is unsurprising given the Causeway's low-lying elevation. The Causeway has been historically fraught to damage from hurricanes. According to Bermuda Online, on September 1, 1880, the Causeway was wrecked by "the great storm. It was rebuilt following the original design, which stood until 14 September 1899, when three-fourths of a mile of the bridge was ravaged by another powerful hurricane. Afterwards, the causeway

[31] Jones, E. (2024). "The Bridges of Bermuda". The Bermudian, March 23, 2024. Available at: https://www.thebermudian.com/heritage/heritage-heritage/the-bridges-of-bermuda/. Accessed March 23, 2024.

was rebuilt of stone block."[32] The Causeway also sustained major damage during Hurricane Fabian in 2003 (Figure 9.10), which required extensive repairs.

Aerial pictures indicate that the Causeway bridge sections are approximately the same elevation as the approach roads and abutments. Hence with these structures flooded, it is surmised the bridge will also be inundated for the SSC4-8.5 100yr event.

Note that lesser events will likely damage the Causeway as well. The combination of surge plus wave action can exert tremendous lateral and uplift forces on the superstructure that will likely result in damages similar to those experienced in Hurricane Fabian.

As the causeway is critical for an airport connection, raising of the causeway's elevation should be considered in the short term (less than 20 years). Given that the causeway was first constructed in 1871, a full replacement of this structure may be the most prudent solution.

Longbird Bridge is at the northern end of the Causeway. From the modelling results, it appears the existing structure is sufficiently high to avoid flooding, although the effects of surge plus wave action may still damage the superstructure. Longbird Bridge is being redesigned, as a "twin tied-arch structure" (Figure 9.13)[33]. Details of the basis of design for the new bridge were not available.

For both assets, wave heights are expected to be approximately 1.0m for the SSP5-8.5 100yr event (Modelling Report, Figure 5.10).

For the reconstruction of the Causeway and Longbird Bridge, sulphate-resistant concrete should be used to combat saltwater intrusion.

[32] Jones, E. (2024).

[33] Knight Architects (2024). Available at: https://www.knightarchitects.co.uk/bridges/bermuda-bridges, Accessed 23 March 2024.

Figure 9.10 Damage sustained to the Causeway during Hurricane Fabian in 2003

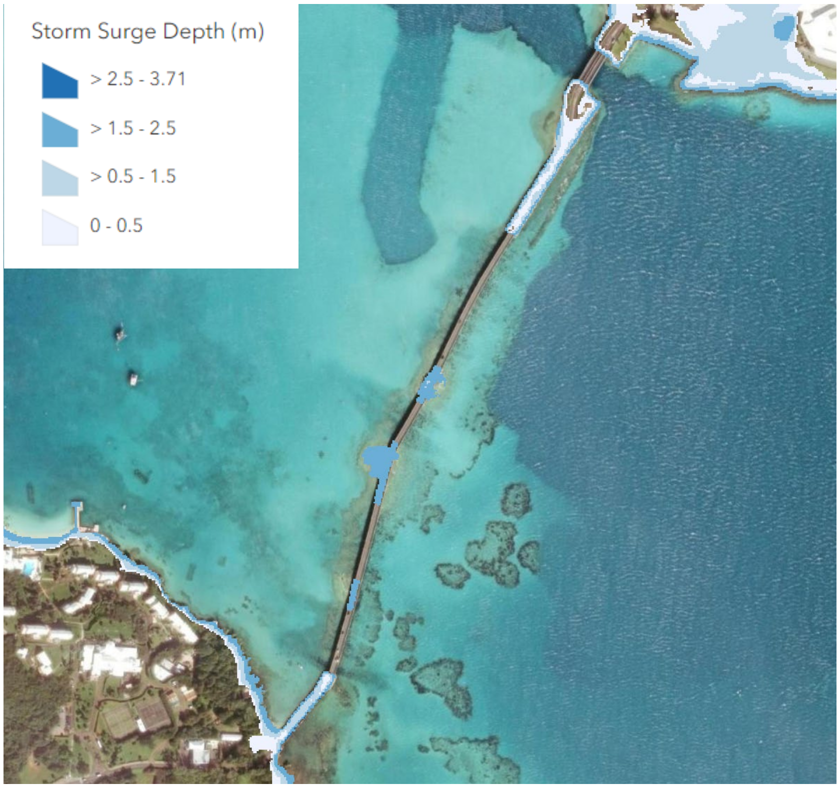

Figure 9.11 Causeway/Longbird Bridge affected by inundation during the SSP5-8.5 100yr scenario (Note: data is not shown for suspended bridge deck sections)

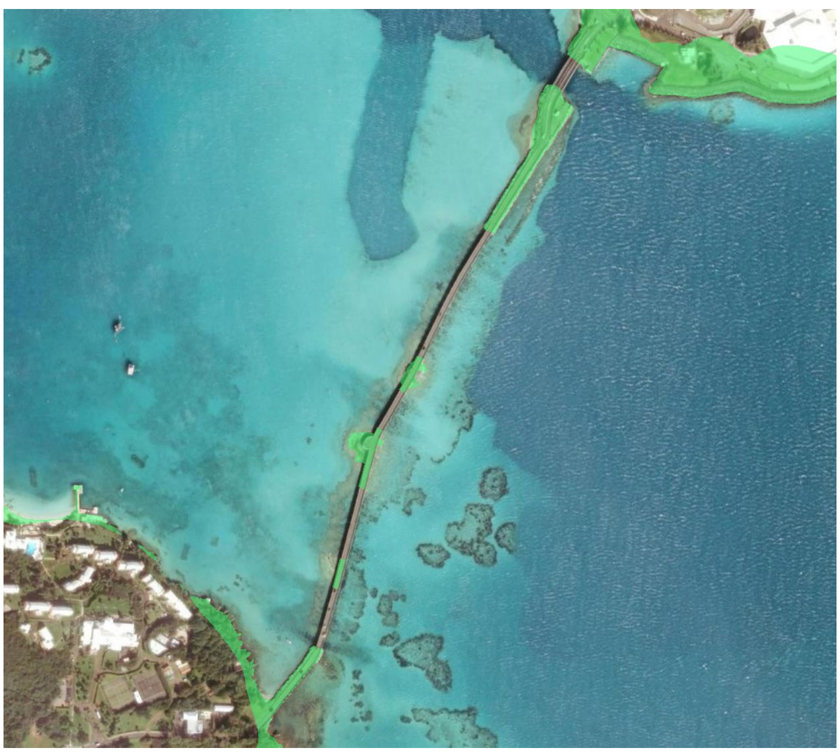

Figure 9.12 Causeway/Longbird Bridge affected by saltwater inundation during the SSP5-8.5 100yr scenario (Note: data is not shown for suspended bridge deck sections)

Figure 9.13 Architect's concept for the replacement of Longbird Bridge (Knight Architects (2024))

9.2.2 Flatts Bridge

Flatts Bridge in Bermuda is a bridge spanning Flatts Inlet, connecting the parishes of Hamilton and Smith's. It is rumoured to be the oldest bridge in Bermuda, first constructed as a wooden footbridge in the 1600s. It was rebuilt in steel and concrete in the 1960s.

Flatts Bridge is seen to be vulnerable to the climate change scenarios modelled. The bridge will be impacted by inundation and saltwater intrusion for the the milder SSP2-4.5 50yr event, as well as the SSP5-8.5 100yr event. Wave heights are approximately 1.0 m high for the SSP5-8.5 100yr event (Modelling Report, Figure 5.10).

Given Flatt's Bridge's importance to connectivity between the parishes of Hamilton and Smith's, the bridge is recommended for replacement. Sulphate-resistant concrete should be used to combat saltwater intrusion.

Figure 9.14 Flatts Bridge

Figure 9.15 Flatts Bridge affected by inundation during the SSP5-8.5 100yr scenario (Note: data is not shown for suspended bridge deck sections)

Figure 9.16 Flatts Bridge affected by saltwater inundation during the SSP5-8.5 100yr scenario (Note: data is not shown for suspended bridge deck sections)

9.2.3 Somerset Bridge

Reputedly the world's smallest working drawbridge, Somerset Bridge connects Somerset Island to the Bermuda mainland in Sandy's parish. The bridge has tremendous historical significance, built in 1620 with limestone masonry that remains from its original construction.

Figure 9.17 Somerset Bridge showing a maximum deck elevation at the opening

Unfortunately, Somerset Bridge is under threat from the effects of climate change. The bridge will be impacted by inundation and saltwater intrusion for the the milder SSP2-4.5 50yr event as well as the SSP5-8.5 100yr event. Wave heights are approximately 1.0 m high for the SSP5-8.5 100yr event (Modelling Report, Figure 5.10).

Given Somerset Bridge's importance to connectivity the bridge is recommended for immediate replacement. Sulphate-resistant concrete should be used to combat saltwater intrusion.

Figure 9.18 Somerset Bridge affected by inundation during the SSP5-8.5 100yr scenario (Note: data is not shown for suspended bridge deck sections)

Figure 9.19 Somerset Bridge affected by saltwater inundation during the SSP5-8.5 100yr scenario (Note: data is not shown for suspended bridge deck sections)

9.2.4 Coney Island Bridge

Originally built in the 1600s (and rebuilt in 1958), Coney Island Bridge connects St George's Island to Coney Island. The bridge will be impacted by inundation and saltwater intrusion for the the milder SSP2-4.5 50yr event as well as the SSP5-8.5 100yr event. Wave heights are 1.0-2.0 m high for the SSP5-8.5 100yr event (Modelling Report, Figure 5.10).

Coney Island itself, which has recreational and historical significance but little infrastructure, will also be greatly impacted by these hazards. These considerations will have to be taken into account when considering the type, value and timing of the bridge's replacement. Sulphate-resistant concrete should be used to combat saltwater intrusion.

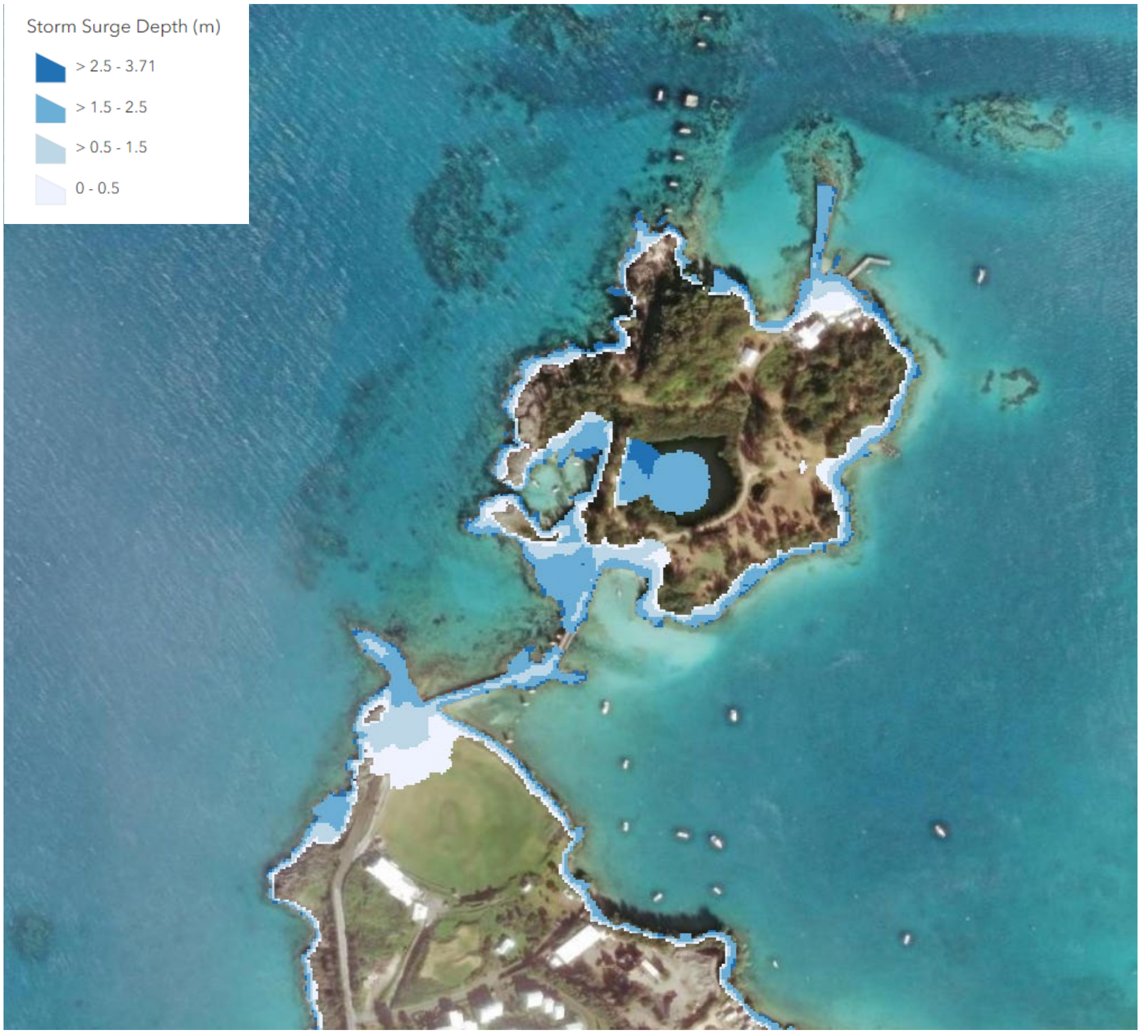

Figure 9.20 Coney Island Bridge affected by inundation during the SSP5-8.5 100yr scenario (Note: data is not shown for suspended bridge deck sections)

Figure 9.21 Coney Island Bridge affected by saltwater inundation during the SSP5-8.5 100yr scenario (Note: data is not shown for suspended bridge deck sections).

9.2.5 Swing Bridge

The Swing Bridge, opened in 1871 in conjunction with the Causeway, links Long Bird Island with St George's and is the 2nd connection to the airport. The Swing Bridge revolves "on a circular pier leaving two water passages for boats 50 feet wide."[34]

[34] Jones (2024)

Figure 9.22 Swing Bridge

Given its protected location, wave heights are less than 0.5 m high for the SSP5-8.5 100yr event (Modelling Report, Figure 5.10).

The Swing Bridge is presently being redesigned and will consist of "a multi-span structure with a central bascule lifting section" (Figure 9.25)[35]. Details of the redesign of the Swing Bridge were not available. However, recent press indicates that the construction phase has been halted due to funding issues[36].

The existing Swing Bridge is reasonably elevated to avoid impacts of inundation and saltwater intrusion. However the combined effects of surge plus waves may cause damage to the superstructure.

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35 Knight Architects (2024)

36 Johnston-Barnes, O. (2023). "New RFP issued for Swing Bridge repairs". The Royal Gazette, September 7, 2023. Available at: https://www.royalgazette.com/general/news/article/20230907/new-rfq-issued-for-swing-bridge-repairs. Accessed: March 23, 2024.

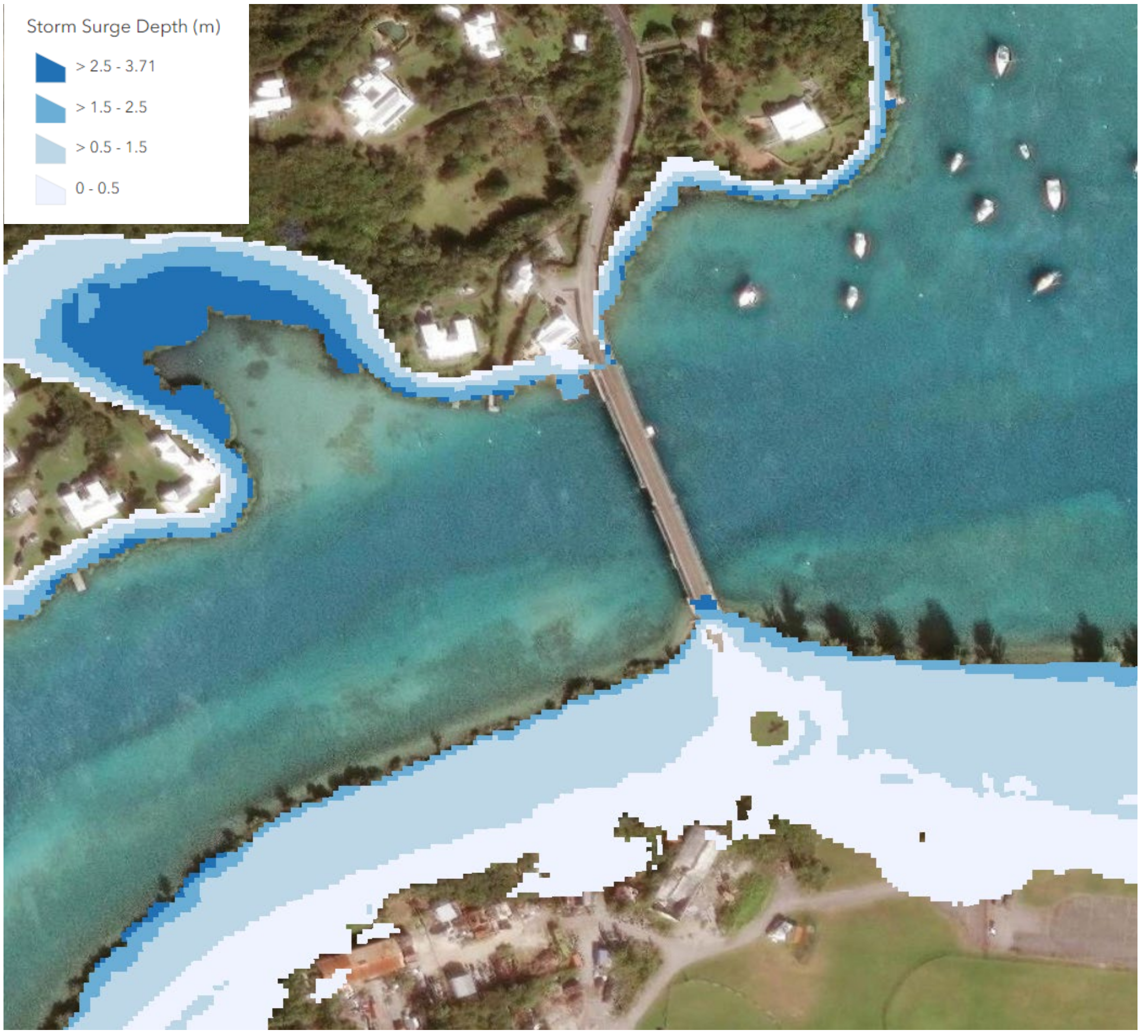


Figure 9.23 Swing Bridge affected by inundation during the SSP5-8.5 100yr scenario (Note: data is not shown for suspended bridge deck sections)

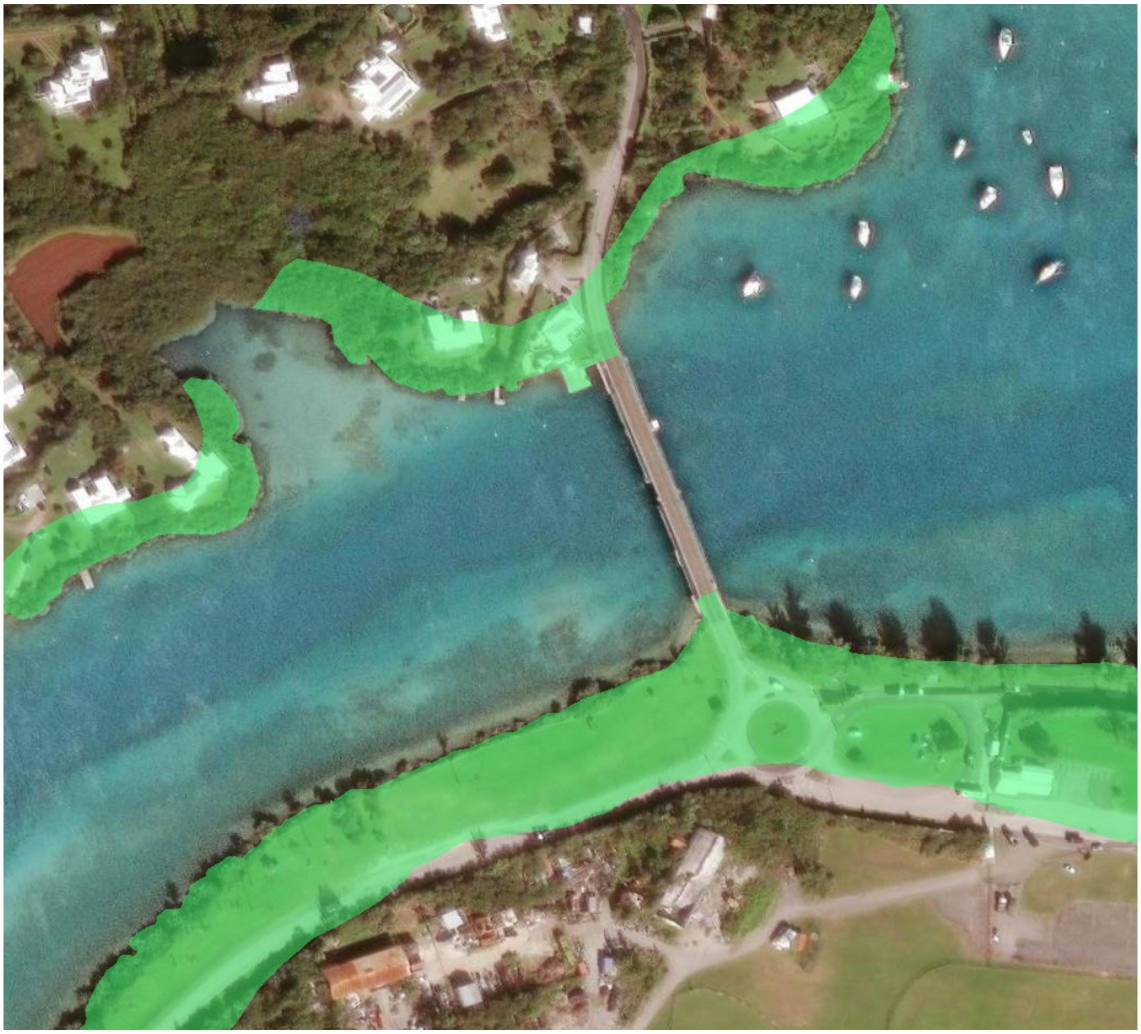


Figure 9.24 Coney Island Bridge affected by saltwater inundation during the SSP5-8.5 100yr scenario (Note: data is not shown for suspended bridge deck sections).

Figure 9.25 Architect's concept for the replacement of the Swing Bridge (Knight Architects (2024))

9.3 Major Marine Infrastructure

9.3.1 Hamilton Harbour

Hamilton Harbour, a natural arm of the Great Sound, serves as the heart of Bermuda's capital city, Hamilton. This is the main harbour in Bermuda, serving cruise ships, ferries, and recreational vessels. Some of Hamilton Harbour's main marine infrastructure includes:

- Container Terminals: Hamilton Harbour is the main harbour for cargo shipping in Bermuda. It features container terminals equipped to handle the loading and unloading of container ships carrying a wide range of goods for import and export.
- Cargo Piers: Several piers are designated for general cargo vessels, facilitating the import and export of various non-containerized goods.
- Ferry Terminals: Ferry services connect Hamilton to other parts of Bermuda, including Dockyard, St George's, Somerset, and Ireland Island. Dedicated ferry terminals within the harbour provide docking facilities and passenger amenities for these services.
- Cruise Ship Facilities: While not the primary location for cruise ships in Bermuda, Hamilton Harbour can accommodate smaller cruise ships at designated piers. These facilities might offer limited docking space compared to the larger facilities at Dockyard.
- Marina: Hamilton Harbour also has a marina area with docking facilities for private yachts, pleasure boats, and fishing vessels.

Hamilton Harbour is generally mildly affected for the SSP2-4.5 50yr event, notably with minor flooding and saltwater intrusion in Barr's Bay Park, and the area around Foot of the Lane, including Pembroke Hall, Crow Lane Park, Waterville (Bermuda National Trust), and Pomander Road. Saltwater intrusion is seen to affect the Container Docks as well. These hazards are magnified in the same general areas for the SSP5-8.5 100yr event, with inundation (Figure 9.26) and saltwater intrusion (Figure 9.27) affecting adjacent roads such as Front Street, Crow Lane, The Lane, Pomander Road, and Harbour Road. Wave heights in Hamilton Harbour are less than 1 m for the SSP5-8.5 100yr event (Modelling Report, Figure 5.10).

Of the public marine infrastructure affected within Hamilton Harbour, the Ferry Terminal and the Container Docks should be elevated within a 20-50yr timeframe.

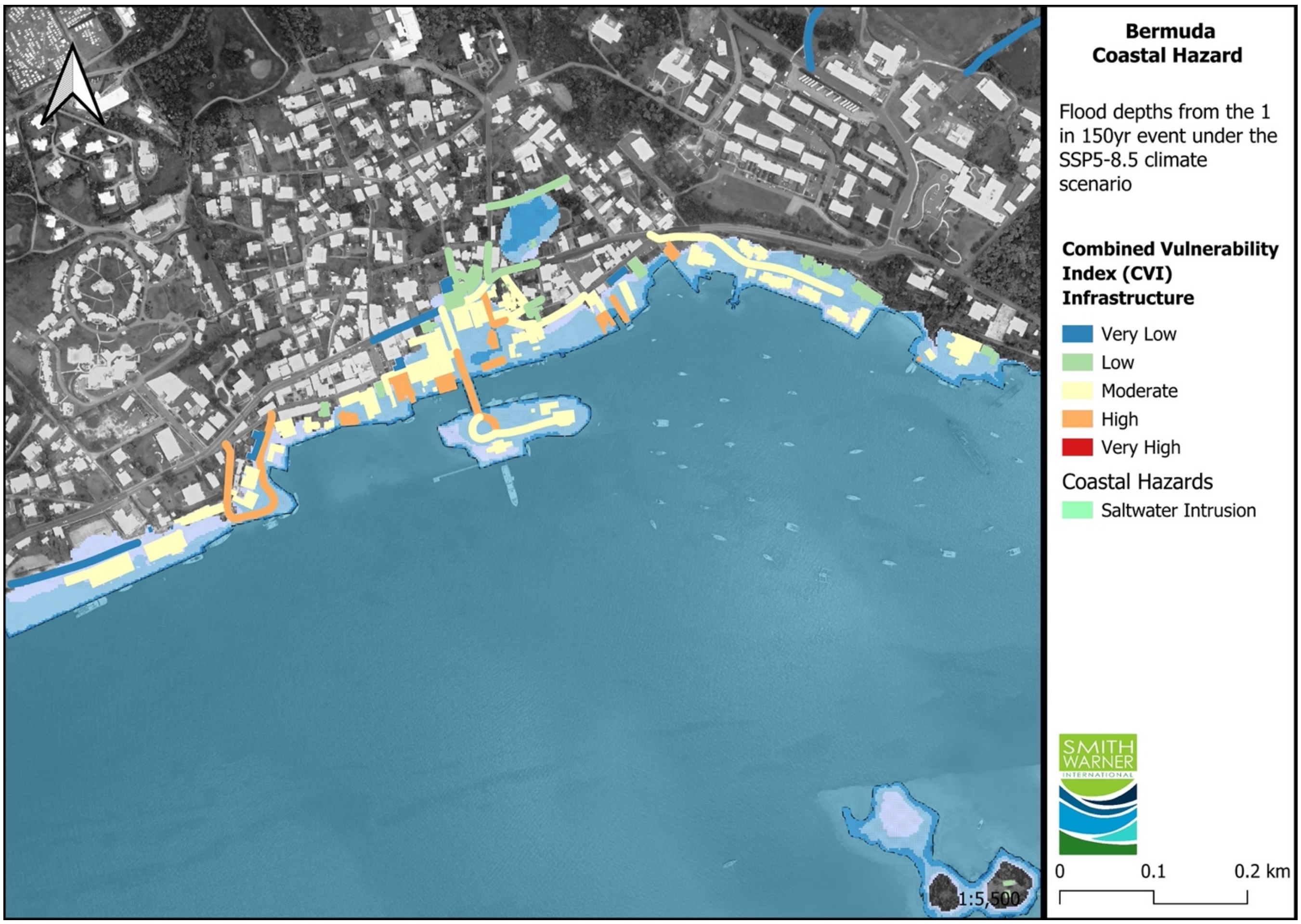


Figure 9.26 Hamilton Harbour and surrounds flooding (SSP5-8.5 100yr scenario)

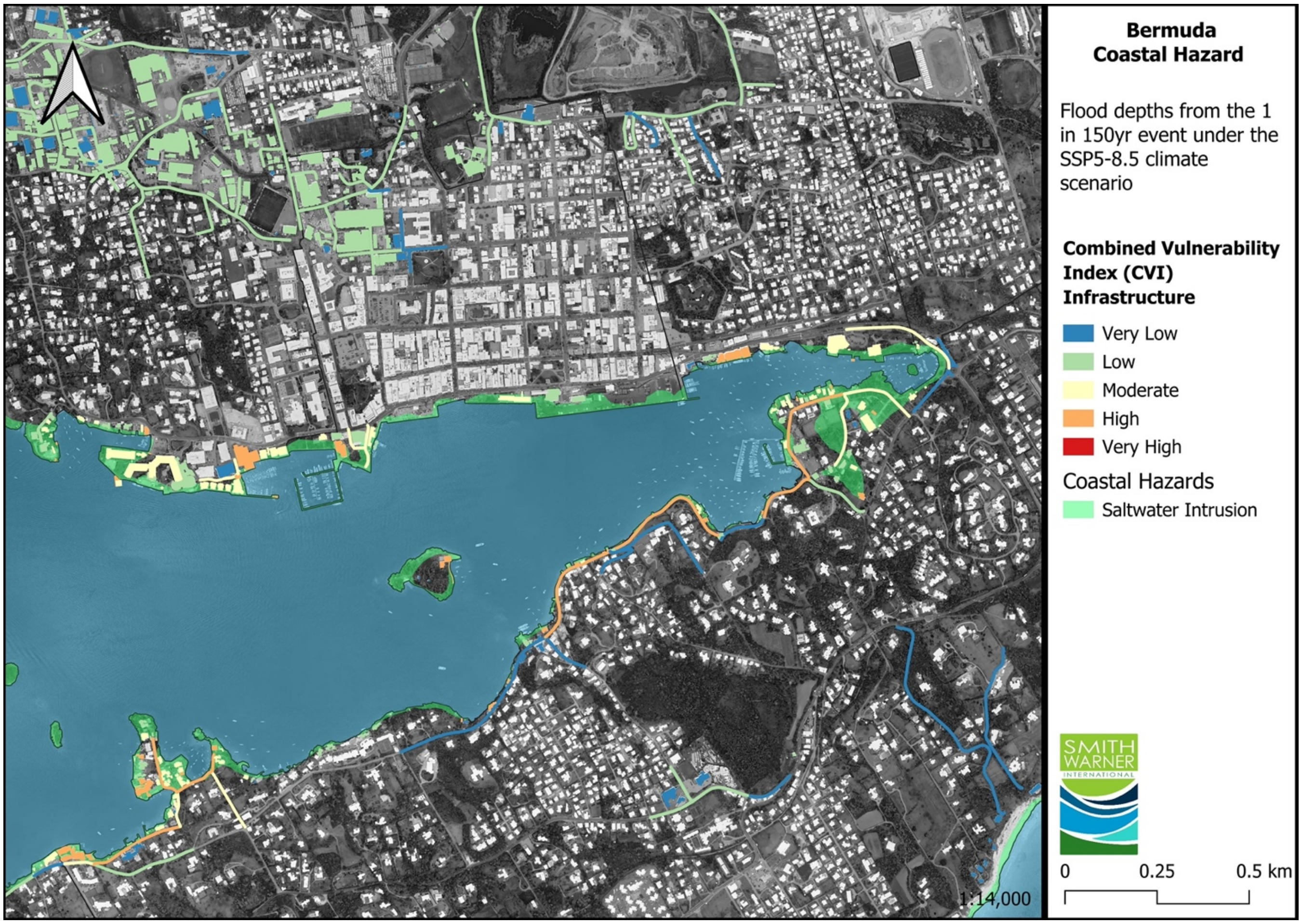


Figure 9.27 Hamilton Harbour and surrounds saltwater inundation (SSP5-8.5 100yr scenario)

9.3.2 St George's Harbour

St George's Harbour, a UNESCO World Heritage Site, boasts a rich history as the island's first official port for centuries. Today, it primarily serves pleasure craft and ferries.

St George's Harbour is exposed to hazards of flooding and saltwater intrusion for the milder SSP2-4.5 50yr event. All main marine infrastructure – Penno's Wharf, Ferry Terminal, Cruise Ship Terminal, and Boatyard are affected, with flooding impacting into Water Street and Convict Bay Lane. These hazards extend further for the SSP5-8.5 100yr scenario, with flooding also experienced into the Duke of York Street and Barrack Hill. Wave heights in St George's Harbour are less than 1 m for the SSP5-8.5 100yr event (Modelling Report, Figure 5.10).

The modelling indicates that the entire shoreline of St George's is vulnerable. Elevating key infrastructure may suffice for the short term, however with such a large reach being threatened, long term planning for strategic retreat should be considered.

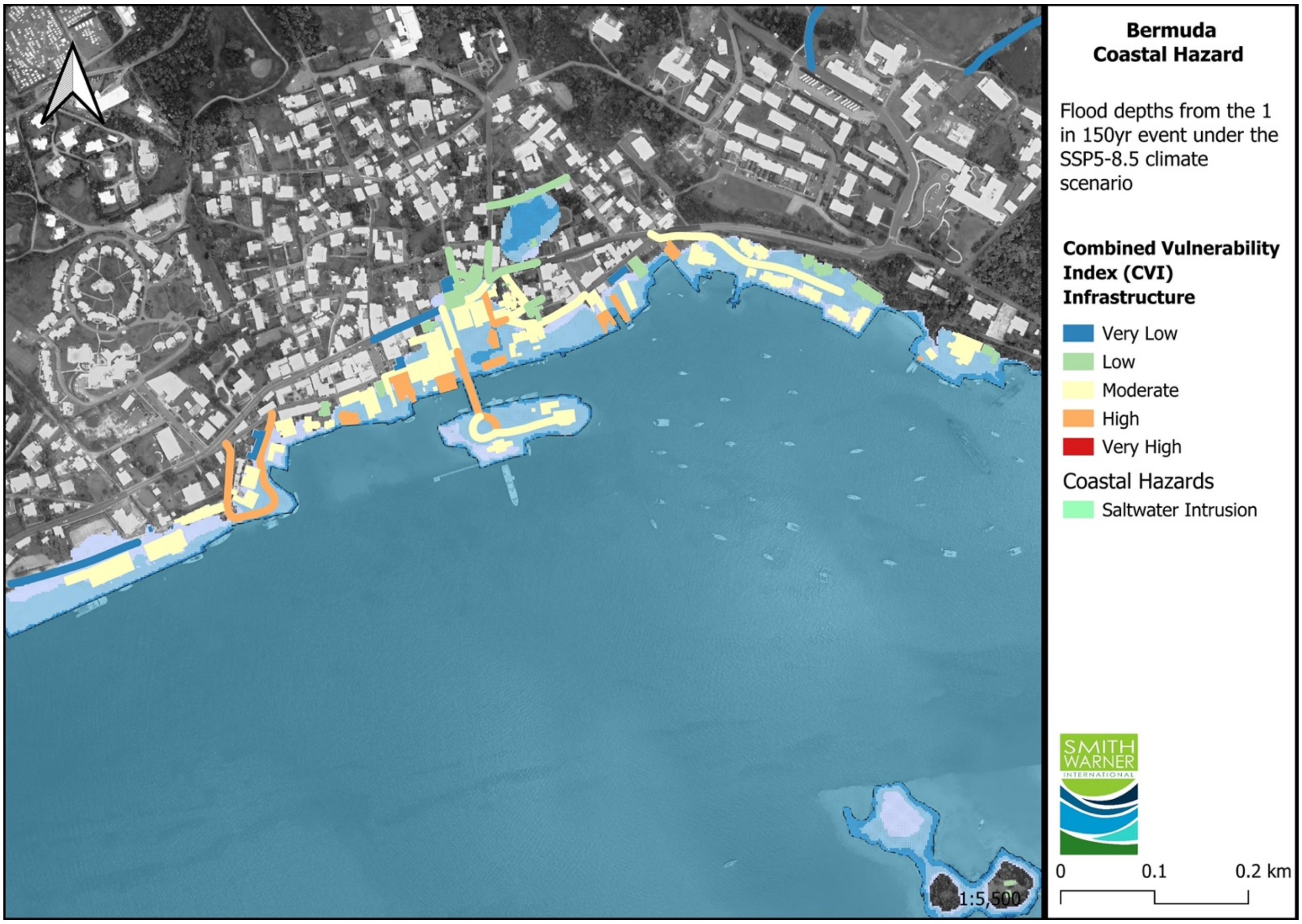


Figure 9.28 St George's Harbour and surrounds flooding (SSP5-8.5 100yr scenario)

Figure 9.29 St George's Harbour and surrounds saltwater inundation (SSP5-8.5 100yr scenario)

9.3.3 Dockyard

The Dockyard was originally a Royal Navy shipyard and now serves as a cruise ship port, marina, and entertainment complex. Key marine infrastructure includes:

- **Cruise Ship Piers:** The Dockyard is a major port of call for large cruise ships in Bermuda.
- **Ferry Terminal:** A ferry terminal provides connections to other parts of Bermuda, including Hamilton and St George's.
- **Marina:** The Dockyard has a well-developed marina with numerous slips and docking facilities for a variety of recreational vessels, including yachts, catamarans, and sportfishing boats.
- **Historical Docks:** Some remnants remain of the Dockyard's past as a Royal Navy facility, such as older piers or dry docks used for ship maintenance.

The Dockyard is susceptible to flooding and saltwater inundation for both scenarios modelled. In the SSC 2-4.5 50yr event, saltwater inundation impacts the majority of the perimeter, notably along Freeport Drive, Westgate Correctional Facility, and the run of the cruise pier. Flooding also occurs in these areas, as well as several historical buildings (Foster Cooper Building, Shell House, Shifting House, etc.). Flooding and saltwater inundation extends further into the interior of the Dockyards for the SSC5-8.5 100yr event. Waves are expected to be 1-2 m high for the SSC5-8.5 100yr event (Modelling Report, Figure 5.10).

Similar to St George's, the modelling indicates that the entire shoreline of Dockyards is vulnerable. Elevating key infrastructure may suffice for the short term, however with such a large reach being threatened, long term planning for strategic retreat or holding the line should be considered.

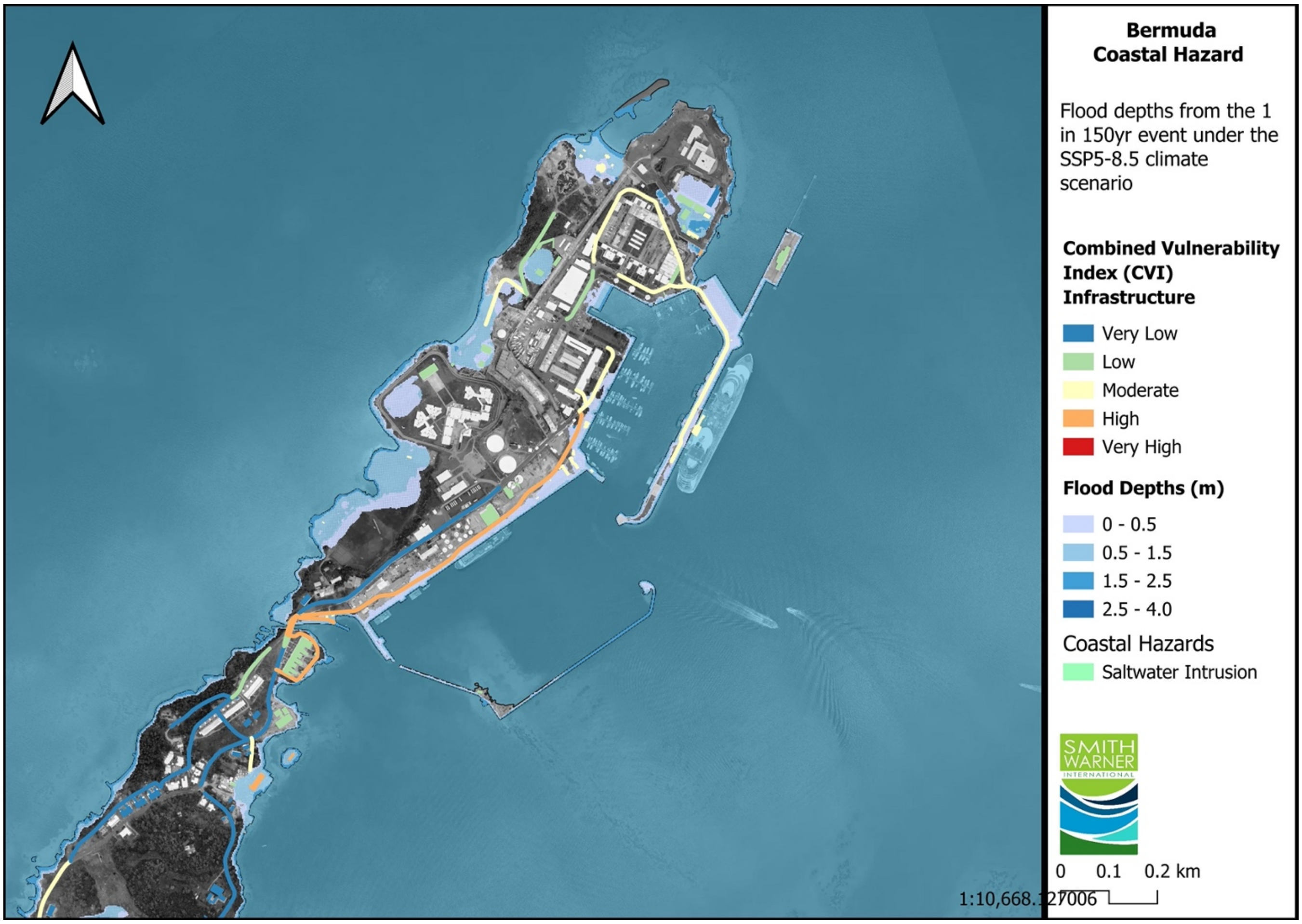


Figure 9.30 Dockyard and surrounds flooding (SSP5-8.5 100yr scenario)

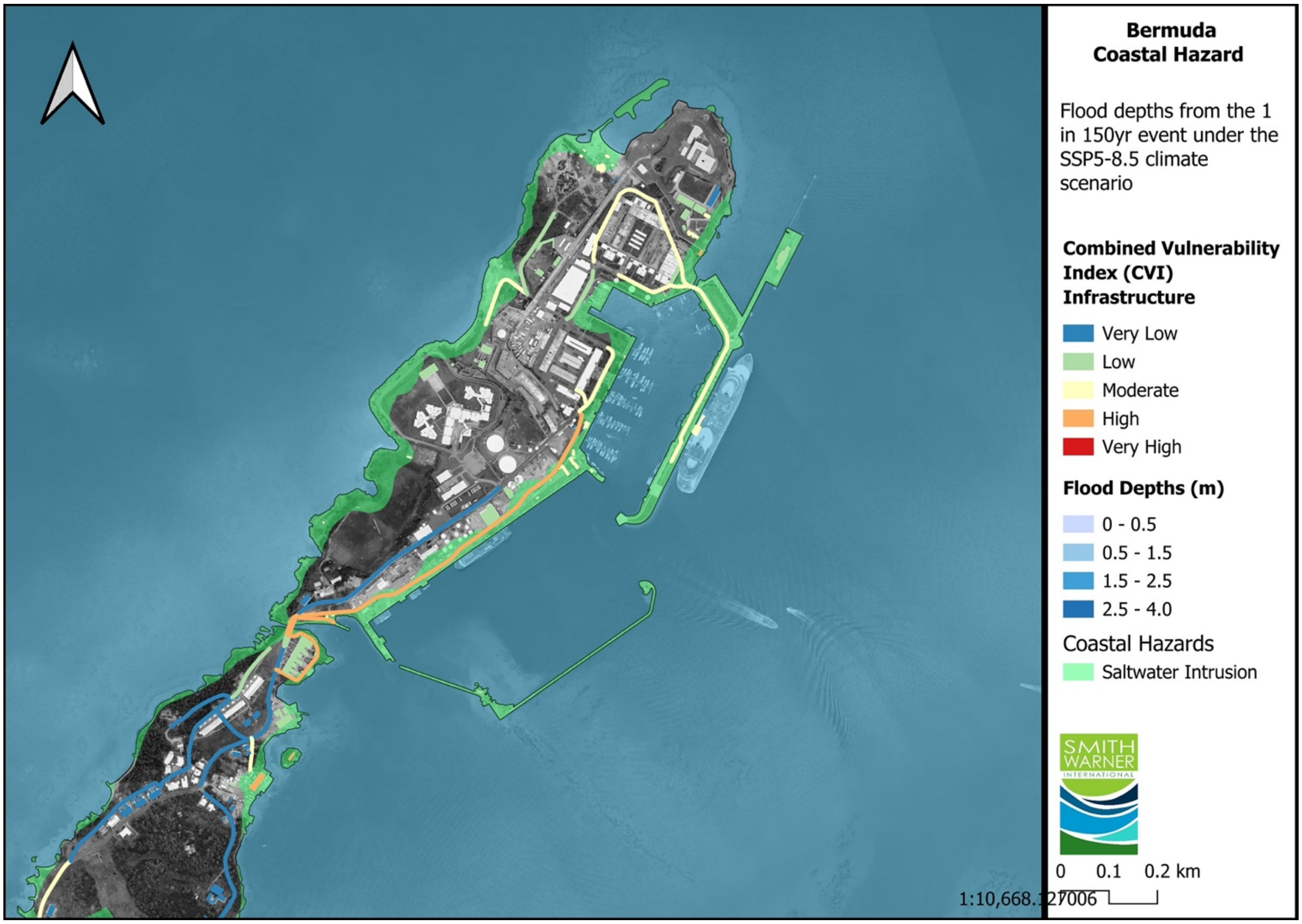


Figure 9.31 Dockyard and surrounds saltwater inundation (SSP5-8.5 100yr scenario)

9.3.4 Oil Docks Terminal

The Oil Docks Terminal in Bermuda is a crucial facility for the island's energy needs. The Oil Docks Terminal serves as the primary import point for the heavy fuel oil and diesel used by BELCO, Bermuda's electricity company.

Oil Docks is only marginally impacted by flooding and saltwater intrusion along a narrow strip of the coastline. The main risks to the Oil Docks pier include cliff failure (Figure 9.34), common along the North Coast cliffs, and wave impact from future storm events. The shoreline should be monitored over the next few decades to observe signs of erosion from waves and cliff toe protection added as necessary; rock (boulder) protection is likely the most cost-effective mechanism in this location. The pier itself should be analysed for its ability to withstand a future storm event; wave heights are expected to be in the 2-3m range with 2.8-3.0m elevated storm surge for the SSP5-8.5 100yr scenario.

Sacrificial anodes should be investigated to mitigate corrosion of sensitive metal structures in the short term.

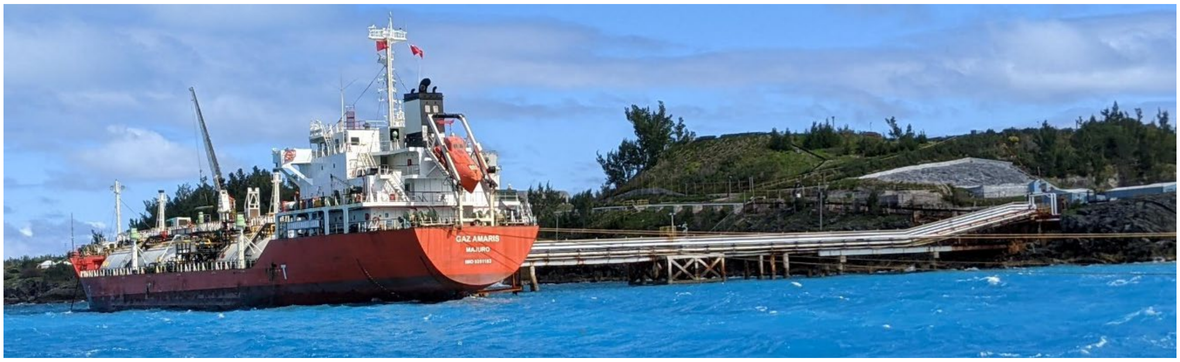


Figure 9.32 Oil Docks Pier

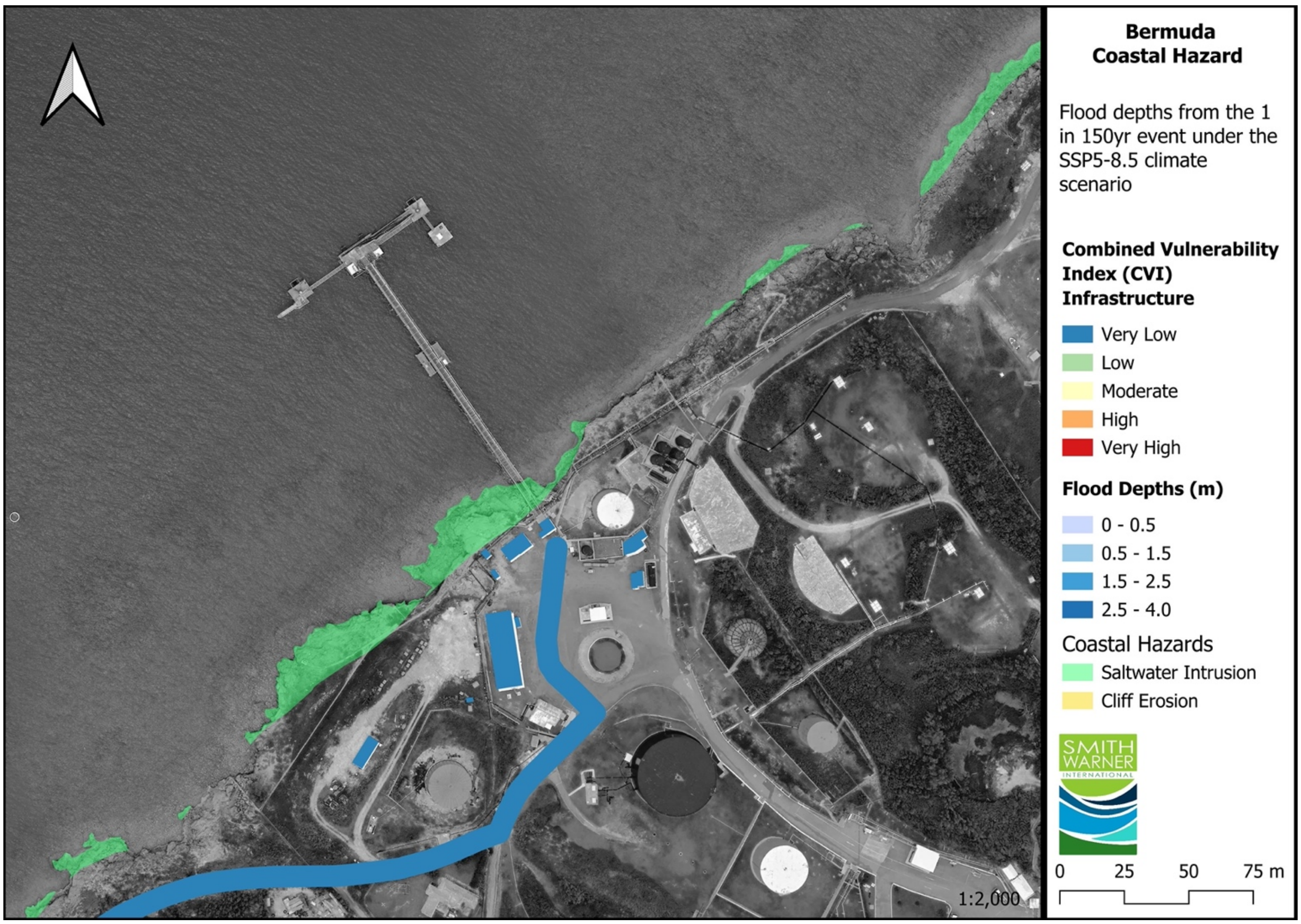


Figure 9.33 Flooding and Saltwater Intrusion along a small coastal strip around the Oil Docks Pier and surrounds (SSP5-8.5 100yr scenario)

Figure 9.34 Potential for Cliff Retreat around the Oil Docks Pier and surrounds (SSP5-8.5 100yr scenario)

9.4 Bermuda Electric Light Company (BELCO)

9.4.1 Central BELCO Power Station and North Power Plant:

The Bermuda Electric Light Company (BELCO) provides Bermuda's electricity needs. BELCO's central power station is located on Serpentine Road, directly adjacent to the often-flooded Mill Creek/Pembroke Canal. BELCO proximity to this waterway and its location in relatively low-lying terrain makes it particularly susceptible to flooding, in particular to the south of the canal. Flooding is predicted to occur for the milder SSP2-4.5 50yr event (Figure 9.35), and this is increased for the SSP5-8.5 100yr event. Given the investment and cost of replacement of such a vital infrastructure, immediate consideration should be given to protect the power plant from flood related events.

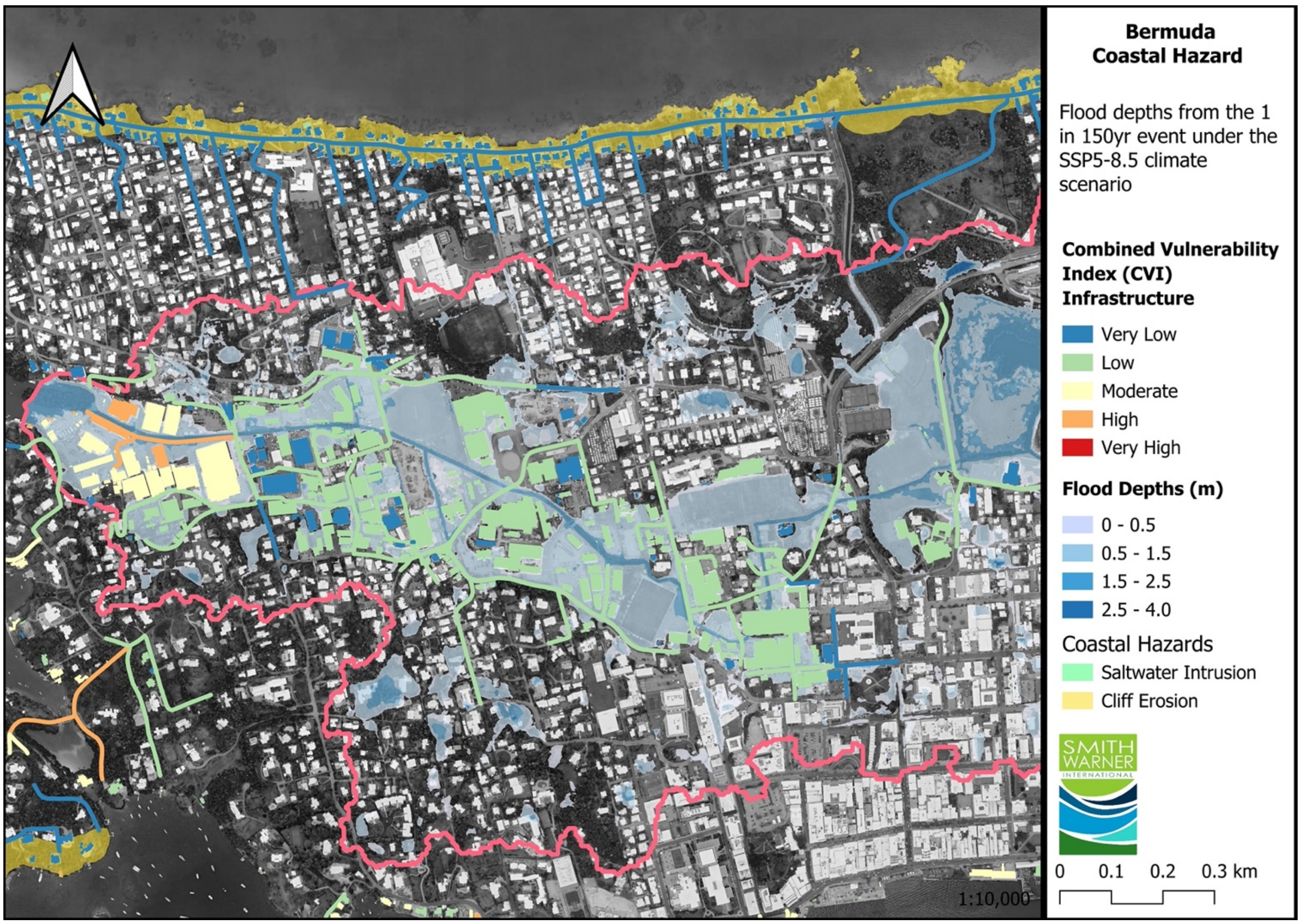


Figure 9.35 Flooding of the vicinity of BELCO's central power plant, showing impacted buildings, during the SSP2-4.5 50yr scenario

9.4.2 BELCO Solar Installation

In 2021, BELCO incorporated a solar photovoltaic (PV) installation at the southern end of the L.F. Wade International Airport. The solar installation provides 6MW peak output to fulfil approximately 8.5% of the island's electricity.

This installation is not impacted by the 50yr SSP5.5 event but shows that both flooding and saltwater inundation will encroach on the PV cells area for the 100yr SSP8.5 event (Figure 9.36), with wave heights less than 0.5 m high (Modelling Report, Figure 5.10).

Based on this modelling, we do not expect that there is any threat to these cells within the next 50 years. Given the typical lifetime of an industrial PV cell is estimated to be around 30-35 years, it is suggested that the elevation of these cells be raised when they are in need of replacement.

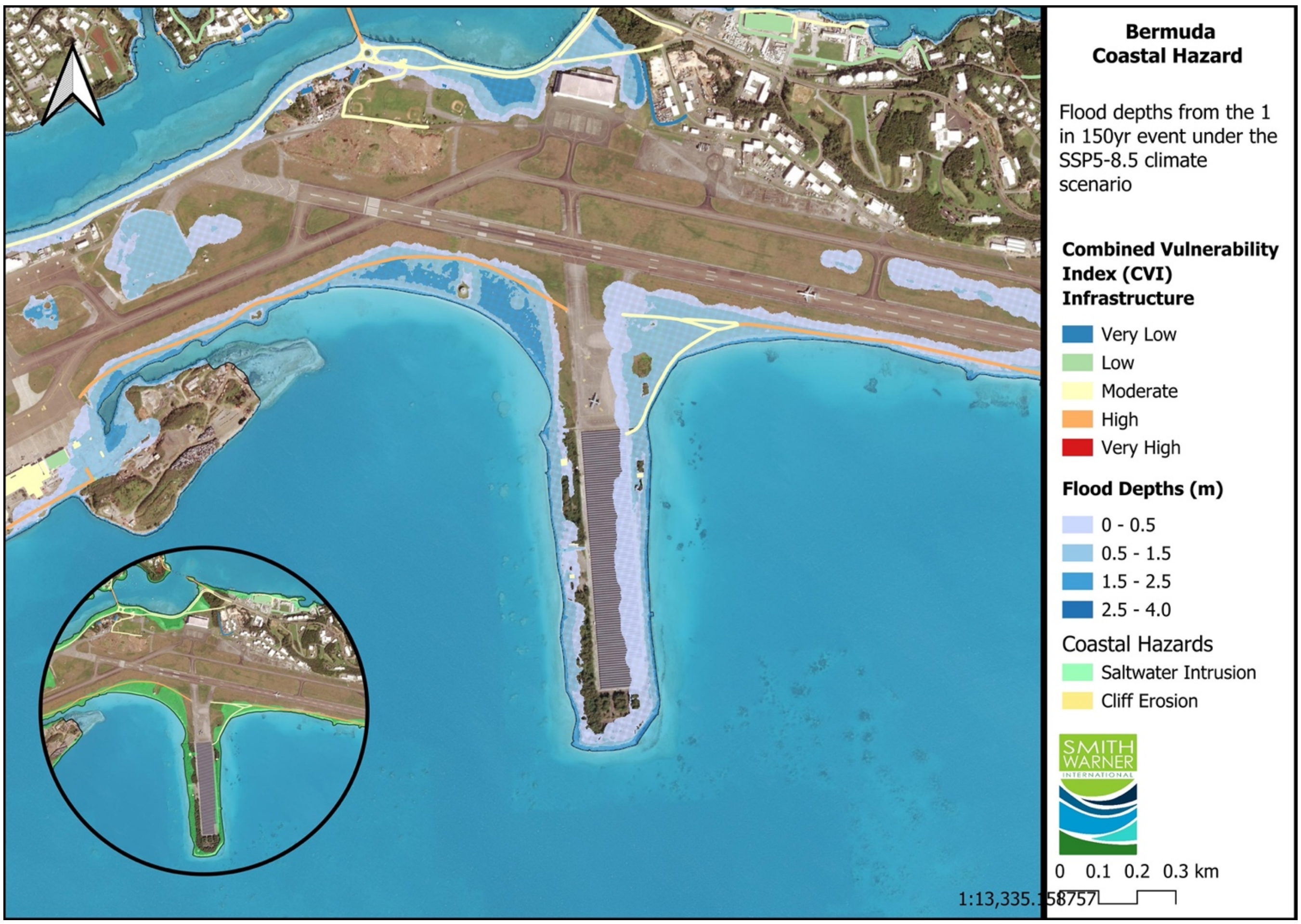


Figure 9.36 BELCO solar installation affected by saltwater intrusion and flooding for the SSP5-8.5 100yr scenario

9.5 King Edward VII Memorial Hospital Bermuda

King Edward VII Memorial Hospital (KEMH), established in 1920, serves as the sole full-service hospital in Bermuda. KEMH is not affected by either the SSP2-4.5 50yr or the SSP5-8.5 100yr events given its elevated position in Paget Parish. The immediate access roads are also not affected. Some roads in the general vicinity, such as areas of Crow Lane and South Road, show minor risk to flooding and saltwater inundation (Figure 9.37).

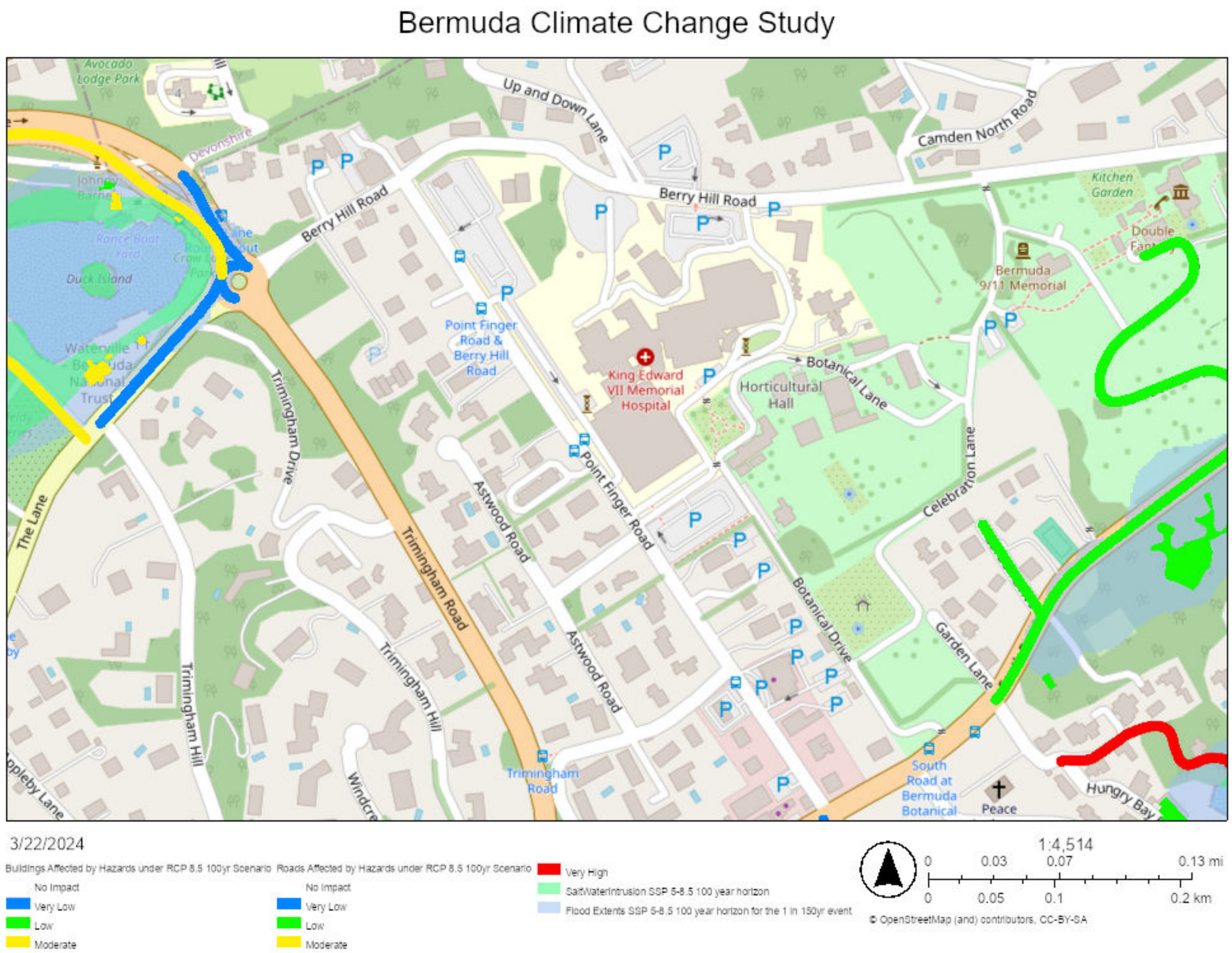


Figure 9.37 Hazards in proximity to King Edward VII Memorial Hospital (SSP5-8.5 100yr scenario)

9.6 Tynes Bay Waste to Energy Facility

The Tynes Bay Waste-to-Energy Facility, located on Palmetto Road in Bermuda's Devonshire Parish, is the island's sole means of municipal solid waste disposal. Opened in the late 1980s, it replaced overflowing landfills and revolutionized Bermuda's waste management strategy.

From a coastal risk perspective, the Tynes Bay plant is sufficiently elevated to avoid risks of surge inundation or saltwater intrusion in the main plant, although flooding is expected to occur over the North Shore Road in the SSP5-8.5 100yr event (Figure 9.38). The shoreline in this area drops steeply to the sea, and cliff erosion will likely be a threat in the longer term. The shoreline should be monitored over the next few decades to observe signs of erosion from waves and cliff toe protection added as necessary; rock (boulder) protection is likely the most cost-effective mechanism in this location. Wave heights are expected to be 1.0-2.0m high at the cliff face for the SSP5-8.5 100yr event (Modelling Report, Figure 5.10).

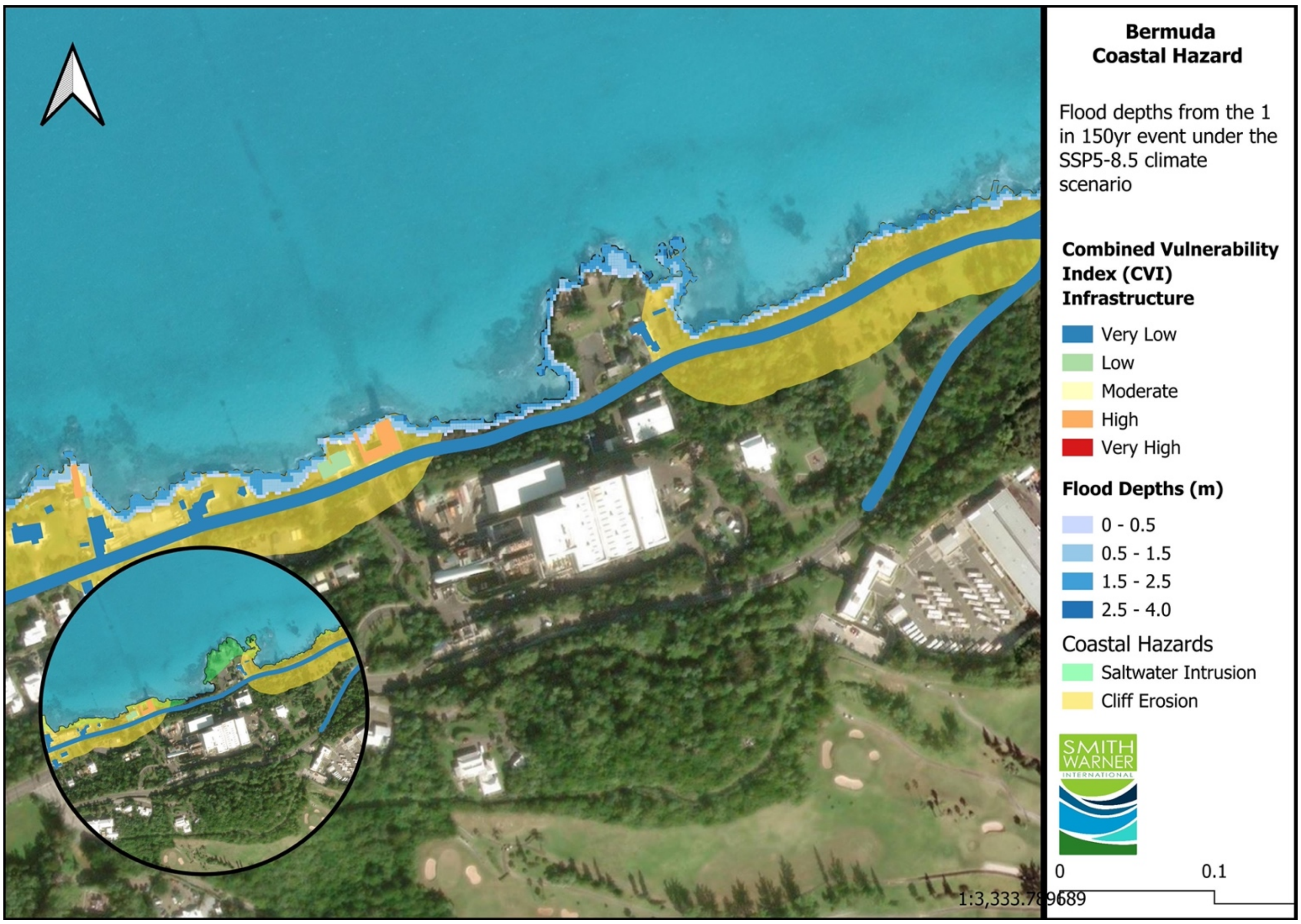


Figure 9.38 Flooding extents, cliff erosion and saltwater intrusion expected in the vicinity of the Tyne's Bay plant for the SSP5-8.5 100yr event

9.7 Watlington Waterworks

Established in 1932 by Sir Harry Watlington, Watlington Waterworks is a Bermudian company that plays a key role in the island's water supply. Through its subsidiary, Bermuda Waterworks Limited, they use both reverse osmosis desalination of seawater and electrodialysis reversal of groundwater to produce high-quality drinking water. Their main desalination plant is situated on the North Shore, within the parish of Devonshire.

The Watlington Waterworks main desalination plant is sufficiently elevated to avoid risks of surge inundation or saltwater intrusion in the main plant. However, cliff erosion will likely be a threat in the longer term. The shoreline should be monitored over the next few decades to observe signs of erosion from waves and cliff toe protection added as necessary; rock (boulder) protection is likely the most cost-effective mechanism in this location. Wave heights are expected to be 1.0-2.0m high at the cliff face for the SSP5-8.5 100yr event (Modelling Report, Figure 5.10).

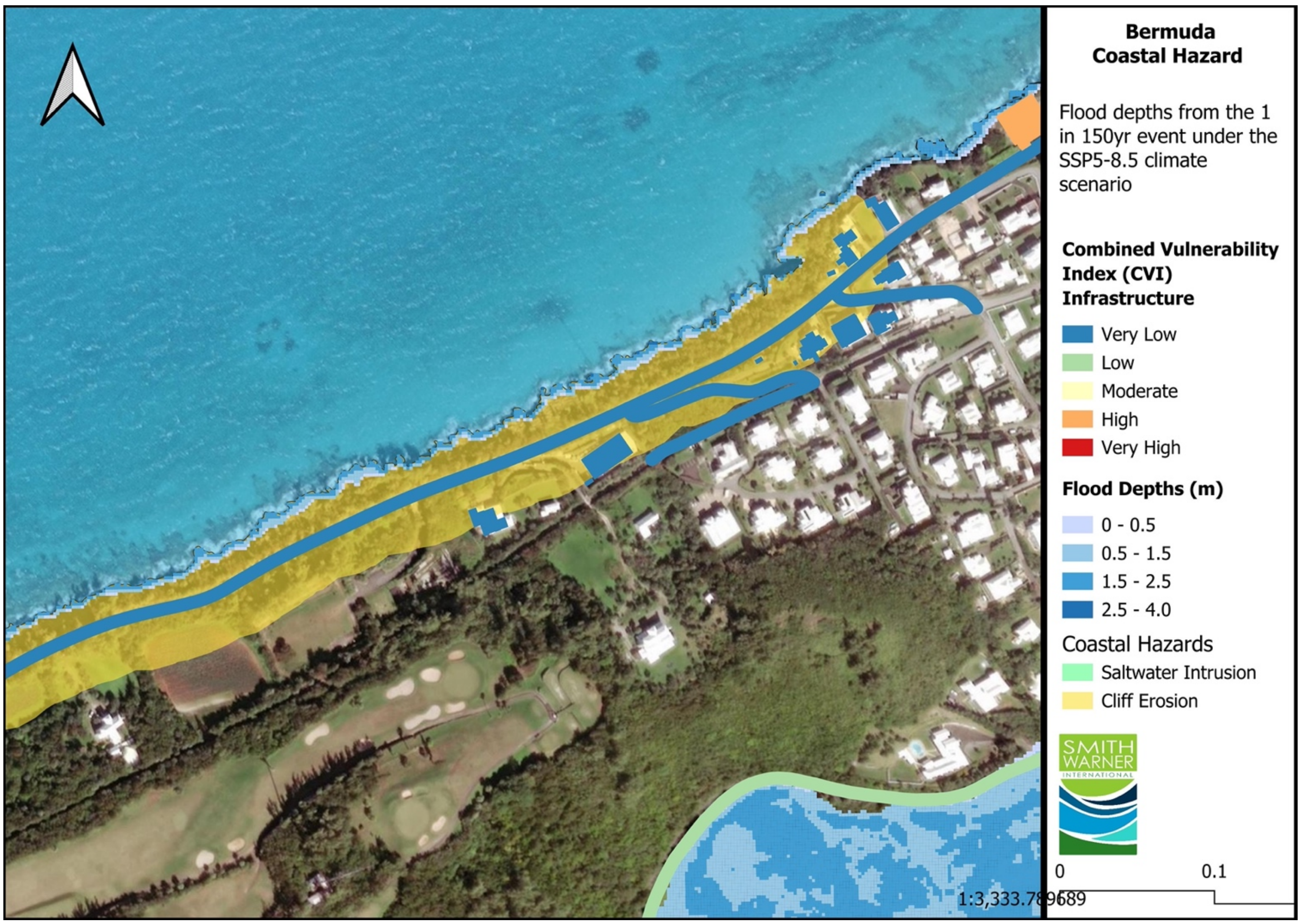


Figure 9.39 Flooding extents, cliff erosion and saltwater intrusion expected in the vicinity of the Watlington Waterworks plant for the SSP5-8.5 100yr event

9.8 Prioritization of Key Infrastructure

Based on the modelling and assessment herein, and our understanding of Bermuda's key infrastructure, the following prioritization is suggested based on vulnerability to the climate change hazards described in this report:

Short Term (0-20 years)		Medium Term (20-50 years)		Long Term (50+ years)	
Asset	**Suggested Approach**	**Asset**	**Suggested Approach**	**Asset**	**Suggested Approach**
Airport Parking lots	Elevate	Airport Runway	Elevate	Sol Fuel Storage	Elevate
Causeway	Rebuild	Airport Perimeter Roads	Elevate	King Edward VII Memorial Hospital	Protect
Somerset Bridge	Rebuild	Longbird Bridge	Rebuild		
St George's Harbour	Elevate (short term)	Flatts Bridge	Rebuild		
Dockyard	Elevate (short term)	Coney Island Bridge	Rebuild		
Oil Docks Terminal	Cliff protection, Rebuild for storm conditions	Swing Bridge	Rebuild		
BELCO Power Station	Elevate, Protect	Hamilton Harbour Ferry Terminal	Elevate		
Tyne's Bay Plant	Cliff protection	Hamilton Harbour Container Docks	Elevate		
Watlington Waterworks	Cliff protection	St George's Harbour	Strategic Retreat		
		Dockyard	Strategic Retreat		
		BELCO Solar Installation	Rebuild, elevate		

10 Recommendations for Further Work

The approach developed herein is a simple, transparent mechanism to represent risk that is readily understood by the range of stakeholders.

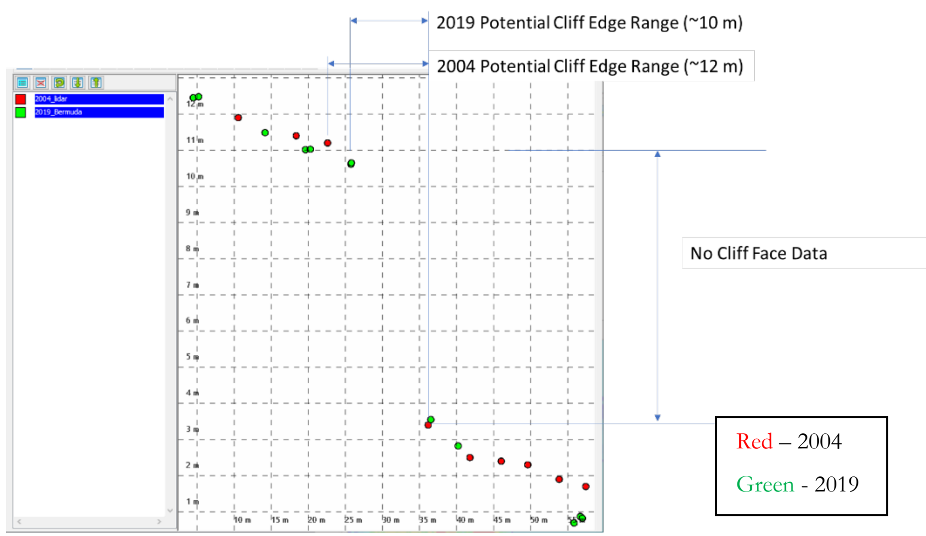
Unfortunately consistent, complete datasets were not available for many of the key features required to be defined for the full CVI analyses. Table 10-1 identifies the key data gaps and recommendations to inform future application of the risk assessment and CVI in Bermuda.

Table 10-1 Recommended data collection to support future conservation efforts

<table>
<tr><th colspan="2">Data Category</th><th>Datasets description</th></tr>
<tr><td>MetOcean data</td><td>Wave Data</td><td>Consider deployment of permanent wave buoys to collect continuous wave data throughout the year. Real time reporting could also provide for operational use by ports, marine facilities, coastal construction performance, environmental applications, etc.

Recommend that data recorders are sited to capture conditions along the various coastal orientations in Bermuda. As Bermuda is largely oriented SW-NE, two wave data buoys (one of each located offshore the north and south shore) should be sufficient to capture the coastal conditions faced.</td></tr>
<tr><td>Physical Characteristics</td><td>Topography</td><td>High quality LiDAR was collected in 2019 by the UKHO. As with bathymetry, it is recommended that new datasets are collected every 5 years to update the records and understand topographic and land use changes.

For comparison purposes, the Government of Bermuda also provided LiDAR from 2004. This was intended for use in the cliff erosion modelling exercise. However, the LiDAR datasets proved to be insufficient in resolution, especially at the most critical region: within the cliff face itself. The figure below demonstrates this through a comparison of the 2004 and 2019 datasets along a typical cliff face transect.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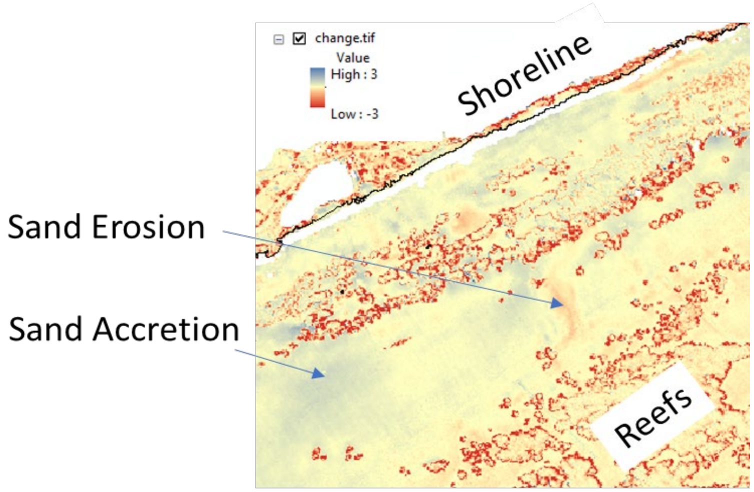
		This lack of data constrains the elevation models in cliff areas. This makes cliff erosion hard to validate unless the cliff retreat was very large. The recommendation is that specific cliff surveys are completed before and after cliff failures to accurately document the extent of the cliff erosion. In addition, it is suggested that repeat lidar surveys be conducted at least every 5 years of the whole coast, and more frequent surveys in areas of concern. LiDAR should be collected within 2 hours of low tide and meet USGS lidar standards QL1 or better (https://www.usgs.gov/media/files/lidar-base-specification-2022-rev-a). LiDAR should specifically target the cliff face, which is often missed during aerial campaigns. High resolution oblique and/or orthorectified nadir photos could also help.
	Bathymetry	The 2019 bathymetric survey conducted by the UKHO greatly improved the aged and obsolete survey preceding it, e.g., some areas which were recorded as lead line surveys dating back to 1919! This survey was flown using airborne bathymetric LiDAR technology and thus was depth-limited to ~25m. Additional surveys may be required in deeper waters. Bermuda's seabed is dynamic and prone to vary (especially following frequent storm events). The figure below demonstrates seabed change between the 2004 and 2019 LiDAR database, showing areas of erosion (shaded red) and accretion (shaded blue) over the 15-year period. Hence it is recommended that a bathymetric survey is repeated every 10 years to best represent the present-day bathymetry and better understand bathymetric change in the nearshore waters. 

	Beach profiles	Implement a beach profile survey programme to include: twice yearly surveys (winter and summer profiles) to capture typical beach change data pre- and post-storm surveys as appropriate to capture extreme event changes surveys should extend landward to end of active profile and seaward to below MLLW surveys every 100m alongshore Ensure collected profiles are quality checked and stored in a Geodatabase with previous profiles.
	Shore Protection Structures	Develop complete mapping of the location of shore protection and flood defence structures. Include details such as structure form, height, design standard of protection and condition. A status report on the 'structural integrity' of these engineering works should be carried out with some agreed regularity, e.g. every five years. This would essentially provide a basis for mandating the owner of the structure (whether the Crown or an individual) to undertake any necessary maintenance that may be required.
	Aerial Photography	Collection of continuous aerial imagery, at lower low water, would enable checking of all other terrestrial datasets, including intertidal characteristics. These could be done at times of LiDAR surveys, i.e., every 5 years.
Receptors	Property Data	Update existing building datasets to include all properties, with addition of type/use classification. Check against recent aerial imagery (plus field verification) to ensure complete coverage and accuracy.
	Infrastructure Data	Develop complete mapping of all infrastructure classes, including water, transportation, telecommunication and energy related infrastructure, both linear and area assets. Include details such as road classes, etc. Create GIS layers with full feature attribution.
	Agricultural Land and other open spaces	Develop comprehensive GIS mapping of agricultural areas and other open space type land uses, including data layer attribution.
Environmental Characteristics	Environmental Mapping	Conduct aerial or satellite surveys of critical habitat areas, specifically mangroves, seagrasses and coral reefs to assess larger scale changes that may be related to climate change effects. Correlate this mapping with more detailed environmental monitoring specific to each habitat (e.g., water quality monitoring) to be able to differentiate macro-scale climate change impacts from potential local impacts.

Hydrogeology	General	Over the life of the project there have been extensive discussions between Government of Bermuda hydrogeologist, Dr. Shaun Lavis, and SWI hydrogeologist, David Ruttan. These conclusions and recommendations are substantially the result of those discussions in addition to an extensive literature search on the geology and hydrogeology of the groundwater lenses in Bermuda. Much of the original investigations into the Bermudian freshwater lenses was completed nearly four decades ago during the mid-1980's using what is now outdated equipment and very labour intensive methods. For example, much of the tidally induced water table studies recorded analogue data that could not be analysed quantitatively. Also, tidal influences on water table elevation required a technician to undertake multiple measurements, using what by modern standards is inaccurate equipment, at several boreholes each day so that the changes could be quantified. Such limitations in the quality and frequency of data collection has resulted in numerous questions being either partially or completely unanswered. For example, the tidal and barometric influences on water table elevation and lens thickness remains poorly understood such that recharge events, even heavy rainfall, cannot be clearly detected in groundwater data. This has resulted in a poorly constrained water budget, with obvious consequences for setting sustainable abstraction rates. Furthermore, poor understanding of the responses of the water table and lenses to tidal and barometric changes limited the application and verification of quantitative groundwater models. These models could be used to predict climate-induced changes, as well as "stress test" different abstraction configurations, which could enable better identification of the most efficient, sustainable abstraction strategy as well as inform regulators on how to best respond to changes in rainfall patterns (e.g. extended dry spells). Unfortunately, since the mid 1980's numerous monitoring wells have partially or even fully collapsed or have been lost during development. Loss of these wells has reduced the capacity to fully characterise spatial and temporal changes in freshwater lenses as they respond to changes in recharge, abstraction, tides, weather and sea level rise. Over the 40 years since the last phase of significant hydrogeological investigations, there have been vast improvements in hydrogeological instrumentation, data collection, data analysis and computer modelling. The minimum distance between the base of proposed cesspits and the water table is currently 4 ft (1.22 m). Where the land surface remains approximately 5 m above the water table's maximum height this criteria can be maintained. No new cesspits should be installed where the water table maximum rise will be 3 m or less below the land surface. For the zone in between these two areas, the location of new cesspits will depend on assessments of the land elevation and the water table maximum elevation projected for 100 years in the future.

	Record Retrieval	Find and organize existing data on water table elevations, pumping tests, chemical analyses of groundwater etc. in order to allow easy access to data that was not available for this study. Assess the data and data gaps. If additional data from the 1970s and before 2020s can be found, it will help assess the rate of sea level rise to the present. 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. In order for mitigation and adaptation to be carried out, the characteristics and geometry of the freshwater lenses must be monitored through time. This data, which may exist from the early 1970s to the present (2022), was only minimally available for this study. Having this data available would have allowed a more accurate representation of the lenses to be delineated and compared to the interpretation of Vacher, 1974. Although, as indicated above, questions regarding the accuracy of the previously corrected data and the ease of analysing it remain. Sea level rise from the 1970s would have raised both the water table and the interface zones of the lenses. For this study the water table rise of the Central Lens was estimated and, with the tidal, local steric anomaly and meso scale effects added, the groundwater rise at the coasts and for a limited distance inland was estimated for the entire Bermuda land mass. In the future, the monitoring, analysis and systematic archiving of the data is essential, with updates to the estimates in this study repeated periodically. Locate the 1989 Thomson groundwater model and supporting data and examine the assumptions and expand on the model or adapt it to new modelling software. A long-term form of the model or a new steady-state model would be the optimum way of simulating the rate of change of the freshwater lenses and sea level rise. Since modelling of this nature is a complex undertaking, sufficient high quality data over years to decades is required for completion of a representative model. Significant data collection and correlation has to take place before undertaking an updated groundwater modelling exercise. Furthermore, poor understanding of the responses of the water table and lenses to tidal and barometric changes limited the application and verification of quantitative groundwater models. These models could be used to predict climate-induced changes, as well as "stress test" different abstraction configurations, which could enable better identification of the most efficient, sustainable abstraction strategy as well as inform regulators on how to best respond to changes in rainfall patterns (e.g. extended dry spells).

	Monitoring	Locate areas where mangrove forests yield to buttonwood trees (Conocarpus erectus) (perhaps at Hungry Bay). This indicates a change from saline conditions to non-saline conditions in the soil. Install piezometers to monitor daily water level fluctuations using data loggers. Install instruments to monitor electrical conductivity in soil profiles. This may involve hand auguring boreholes or possibly drilling. Install tensiometers and electrical conductivity sensors to monitor the vadose zone as salinity can increase in this zone by capillary rise and diffusion of saline contaminants upward. Chloride can be accurately determined using field equipment, either wet chemical methods or selective ion electrodes. Conduct a study on nutrient (nitrogen and phosphorous) release to groundwater in soils and phosphate in the carbonate aquifer as salinification increases. The change in salinity may release phosphate in the soils and carbonate aquifer which will be mobilised and flow to the sea and likely cause algal blooms along the coast. This could be carried out at the mangrove monitoring site but should also be done on an agricultural area where fertilizers are applied as well as high density residential unit areas with cesspits. As sea levels and the interface zone between saline and freshwater rise, upconing of saline water in some freshwater pumping wells will increase. It is important to monitor in which wells this is occurring and modify their pumping rates. Continue monitoring the interface zones in the four groundwater lenses especially near the coasts. The data available for this study included an annual listing of the average thickness of the water table to 3% sea water/97% fresh water interface zone for approximately 20 years. Given the fluctuations of local sea level from various influences, monitoring of the interface zone should occur much more frequently with several data loggers in each fresh water lens. Monitoring of water levels and salinity in the internal fresh and saline ponds on a regular basis is recommended. Monitoring of the discharge at Foot of the Lane and at Mill Creek/Pembroke Canal would help to determine if the discharge represents a drain for the Central Lens or not and whether this discharge is increasing with sea level rise. As the Central Lens rises, these areas may see an increase in discharge with the possible increase in horizontal hydraulic gradients. Monitoring of the water table and its fluctuations plus salinity levels in the vicinity of agricultural areas, infrastructure and built heritage areas will determine which of those areas will require mitigation (lowering of the water table, infiltration of rainwater) in the short term and which will require mitigation in the medium and long term. Some highly impacted areas nearest the coast may undergo a change in function. For example, agricultural areas may be abandoned to allow mangrove forests to retreat inland. In areas other than agricultural areas, and where possible, mangroves should be encouraged to develop and advance inland. This will involve an assessment of possible areas where this could happen and a program of land acquisition by the government. Watersheds should be delineated across the islands with a study of the potential to use runoff from precipitation to flush salt from impacted soils and for the installation of infiltration galleries to maintain the lens margins at the coasts. Monitor PFASs and PFOAs as well as other persistent organic chemicals (PCBs etc.) in the groundwater lenses in selected wells. It is likely that these chemicals are removed during the RO process, however, they may be accumulating in the lenses and since the groundwater in the lenses slowly discharges into the sea, these chemicals may be a long term threat to the reef organisms. There are no safe concentrations of these chemicals for organic life. It is unknown if these chemicals are adsorbed onto the limestone.

		Monitoring wells should be equipped with TCD (temperature, conductivity pressure) transducers to monitor changes to the lenses at sufficient resolution to resolve sub-diurnal changes in tides, recharge etc. Multiple transducers could be used in select wells. Data can be transmitted via the cellular network to decrease labour time. Abstraction wells should be equipped with flow rate meters and the data made available to the regulator so that responses of the lenses to pumping can be accurately characterised. Additionally, it should be pointed out that since Bermuda is sinking at a rate of 0.9 mm/yr, and OD was set at Mean Sea Level in 1963, then the land mass has sunk 53 mm since 1963 assuming the rate of subsidence is constant. This means that the ordnance datum location has sunk 53 mm since 1963. The wells which Vacher used in his 1974 report were surveyed for elevation of a measuring point in order to relate groundwater levels to OD. Given that measurement of water table elevations are a challenge due to the various oscillations that occur, and if the well measuring points have dropped 5 cm (approximately), comparing data from 2022 to that in the 1974 will present an additional challenge. It will be necessary to resurvey to sub-centimetre accuracy the location and elevations of all existing wells and infiltration galleries.

	Modelling and Mapping	Map lichen species near the seashore. Some species are tolerant to salt and others are not (Rose, Ian, 2023) and establishing sites to observe the change in lichen species will help understand the increasing salt water intrusion and salt water spray. 3D geological mapping: the currently un-cased monitoring wells are well suited to downhole geological logging using downhole cameras and equipment to detect the saline water gradient. Better understanding of the 3D distribution of the Brighton and Langton aquifers will enable better understanding of the behaviour of the lens on micro and macro scales. Rehabilitation of monitoring wells: after downhole logging, existing monitoring wells of sufficient depth should be completed with appropriate casing to preserve them for the long-term. Partially collapsed wells should be re-drilled to penetrate the lens and be completed with the appropriate casing. Expansion of monitoring well network: monitoring wells that have collapsed or have been lost should be replaced and completed with appropriate casing. Additional geological modelling should also be carried out for each new well. The hydraulic connection between the marshes and aquifers should be investigated and the results used to better constrain the water balance and hydrogeological model (see below). 3D geological modelling: results from surface and downhole geological modelling should be used to create a 3D geological model, showing the locations of potential confining layers (e.g. paleosols, base of marshes etc) as well as the aquifers. Re-appraisal of groundwater recharge should be carried out using the results of new data collected from high quality monitoring wells and modern GIS techniques. The information from the above recommendations should be used to create a hydrogeological model, using modern software that can be used to manage abstraction from the lenses and respond to the changes in weather patterns and steady increase in sea levels expected over the next few decades. The model can also be used to investigate hydrogeologic controls on salinization due to the long timescale over which changes in climate and sea level occur. Computer modelling in other jurisdictions has been employed in several studies to investigate this and provide a resource for methods that would be useful.
CVI		The CVI herein is focussed on sea level rise and associated storm conditions for various climate scenarios. As part of a wider initiative, there are a number of considerations for possible expansion or adaptation of the approach set out here. These include the following. Expansion and inclusion of quantifiable impact on environmental assets in the risk and vulnerability analyses. 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. Incorporation of other variables that may be affected by climate change, such as temperature, rainfall and sea surface temperature (SST). Sea level rise and storm surges are probably the greatest single impact of climate change for Bermuda; however, the addition of other climate change variables would provide for a more comprehensive impacts analysis. The benefits of this addition would need to be balanced against the additional analysis and uncertainties that these further variables would generate.

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Appendix A ArcGIS Step-by-step Guide

Bermuda Climate Change Report | Guide to ArcGIS WebApp

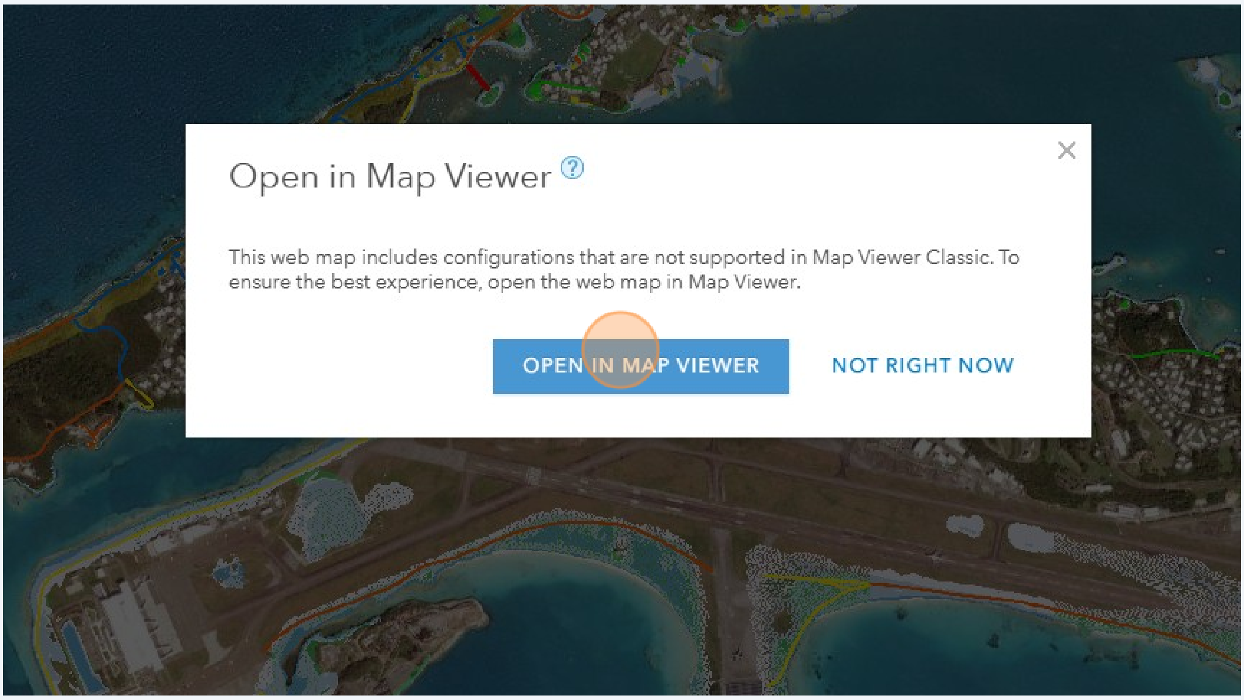
Smith Warner International Limited (SWIL) is currently using the ArcGIS Web Application for the Bermuda Climate Change Study 2022. This powerful and user-friendly tool facilitates the sharing and analysis of geographic data related to climate change impacts in Bermuda, allowing SWIL to present their findings and insights in an accessible manner to a wide range of stakeholders, decision-makers, and the general public.

A step-by-step guide for accessing and displaying the data is given below.

Assessing the ArcGIS Web App

1. Navigate to https://arcg.is/0yTniT

2. The platform will prompt you to switch from Map Classic to Map Viewer automatically. Please choose "Open in Map Viewer" when prompted.



Currently, there are six layer groups available on the platform, each containing various data files with different information

1. Assets in Pembroke Catchment Affected, SSP-2, 4.5, 50-Year Horizon:

    • Buildings Affected by Hazards under the RCP 4.5 in the 50-year scenario

    • Roads Affected by Hazards under RCP 4.5 in the 50-year scenario

2. Coastal Hazards Affected by the SSP-2, 4.5, 50-Year Scenario:

    • Buildings Affected by Hazards under RCP 4.5, 50-Year Scenario

    • Roads Affected by Hazards under RCP 4.5, 50-Year Scenario

    • Bridges Affected by Hazards under the RCP 4.5, 50-Year Scenario

3. All hazards assessed under the SSP-2, 4.5, 50-Year Horizon:

    • Effects of Compound Flooding (rainfall and storm surge under RCP 4.5, 50-Year Scenario in the Pembroke Catchment)

    • Flood Depths under RCP 4.5, 50-Year Horizons for the 1-in-100-Year Event

    • Saltwater Intrusion, SSP-2, 4.5, 50-Year Scenario

    • Saltwater Shoreline Retreat under SSP-2, 4.5, 50-Year Scenario

    • Cliff Retreat under SSP-2, 4.5, 50-Year Scenario

    • Significant Wave Heights for the RCP 4.5, 50-Year Horizon 1-in-150-Year Return Period

4. Assets in Pembroke Catchment Affected, SSP-5, 8.5, 100-Year Horizons:

    • Buildings Affected by Hazards under the RCP 8.5 in the 100-year scenario

    • Roads Affected by Hazards under RCP 8.5 in the 100-year scenario

5. Coastal Hazards Affected by the SSP-5, 8.5, 100-Year Scenario:

    • Buildings Affected by Hazards under RCP 8.5, 100-Year Scenario

    • Roads Affected by Hazards under RCP 8.5, 100-Year Scenario

    • Bridges Affected by Hazards under the RCP 8.5, 100-Year Scenario

6. All hazards assessed under the SSP-5, 8.5, 100-Year Horizons:

    • Effects of Compound Flooding (rainfall and storm surge under RCP 8.5, 100-Year Scenario in the Pembroke Catchment)

    • Flood Depths under RCP 8.5, 100-Year Horizons for the 1-in-100-Year Event

    • Saltwater Intrusion, SSP-5, 8.5, 100-Year Scenario

    • Saltwater Shoreline Retreat under SSP-5, 8.5, 100-Year Scenario

    • Cliff Retreat under SSP-5, 8.5, 100-Year Scenario

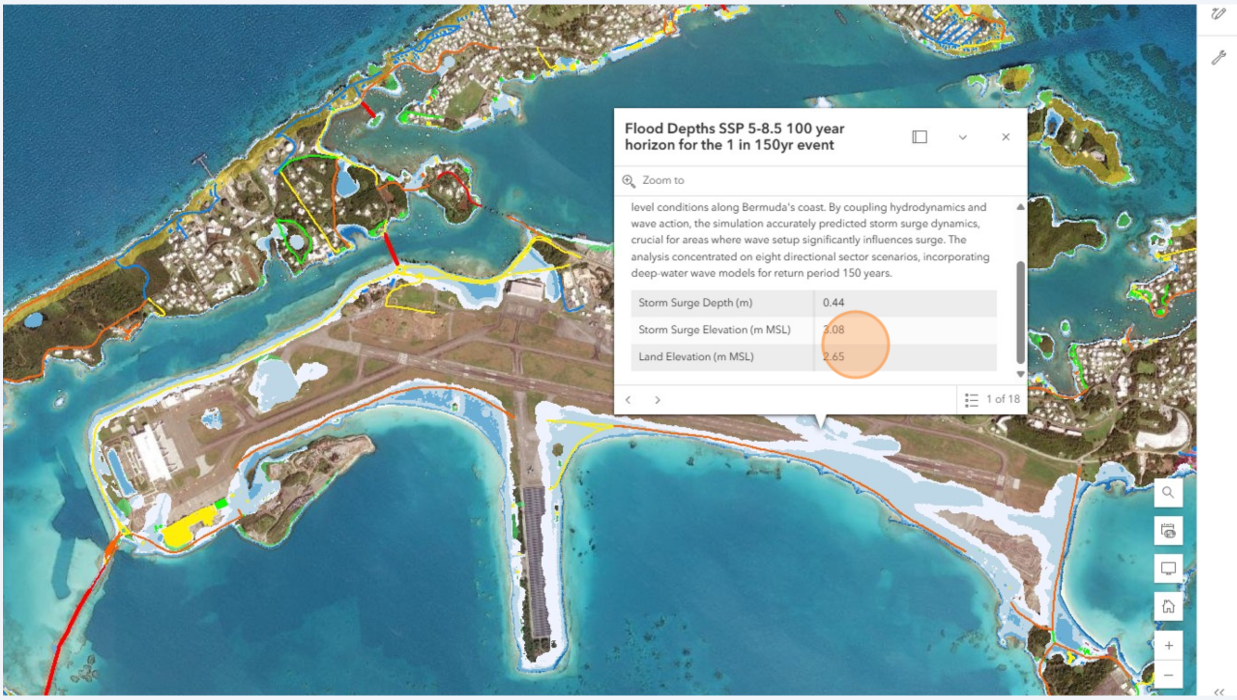
    • Significant Wave Heights for the RCP 8.5, 100-Year Horizon 1-in-150-Year Return Period

Exploring the Web-App

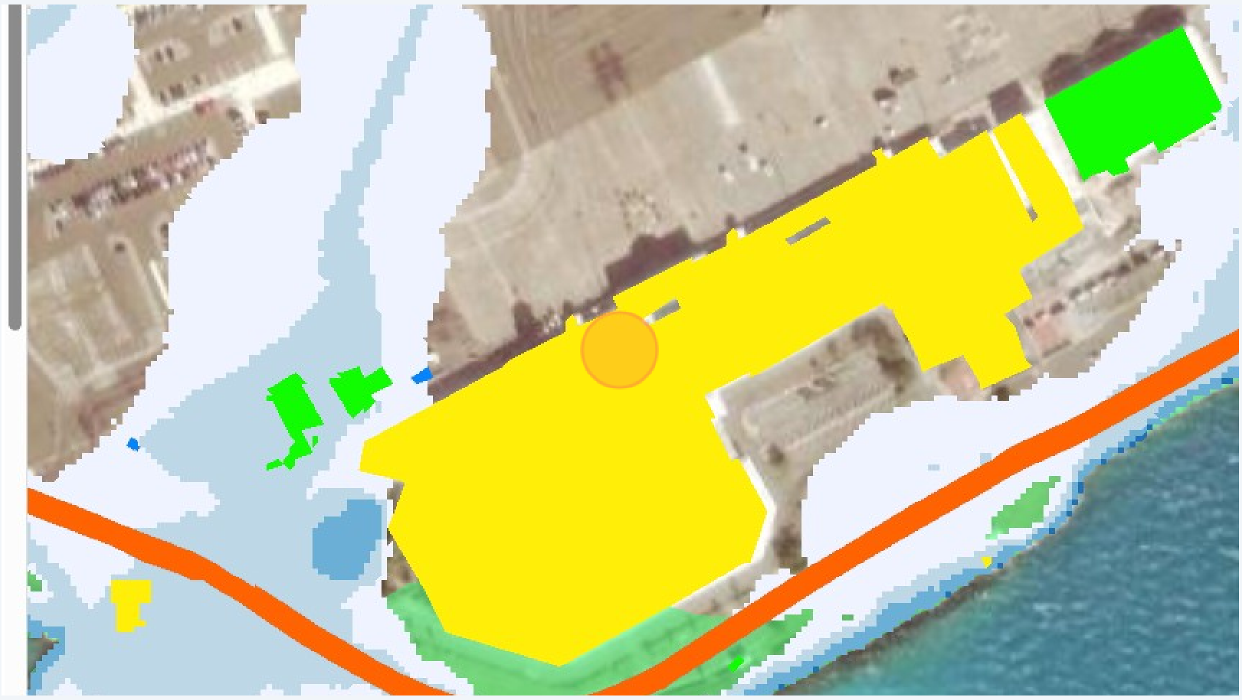
3 The web app will launch to the last saved window or display set by Smith Warner. On the left side, you'll find a legend showcasing all items currently visible on the active map window. Additionally, there's a legend displaying the combined vulnerability index (CVI) of infrastructure also well as legends for the various hazards depicted on the screen. This serves as the home screen of the web app, allowing users to freely pan, click, and explore different features of interest.

4

We've configured the platform to enable users to access further information about displayed data with a simple click. For example, in the image provided, if you're curious about flood depths, you can click to view details such as storm surge depth, elevation, and land elevation expected at the airport during the RCP 8.5 1-in-100-year event. You can explore by panning around and clicking on various buildings and roads uploaded to the platform for review. Each hazard comes with a distinct description outlining how the results were derived and the methodology involved. Once you're finishing with this pop up you can close and move on.



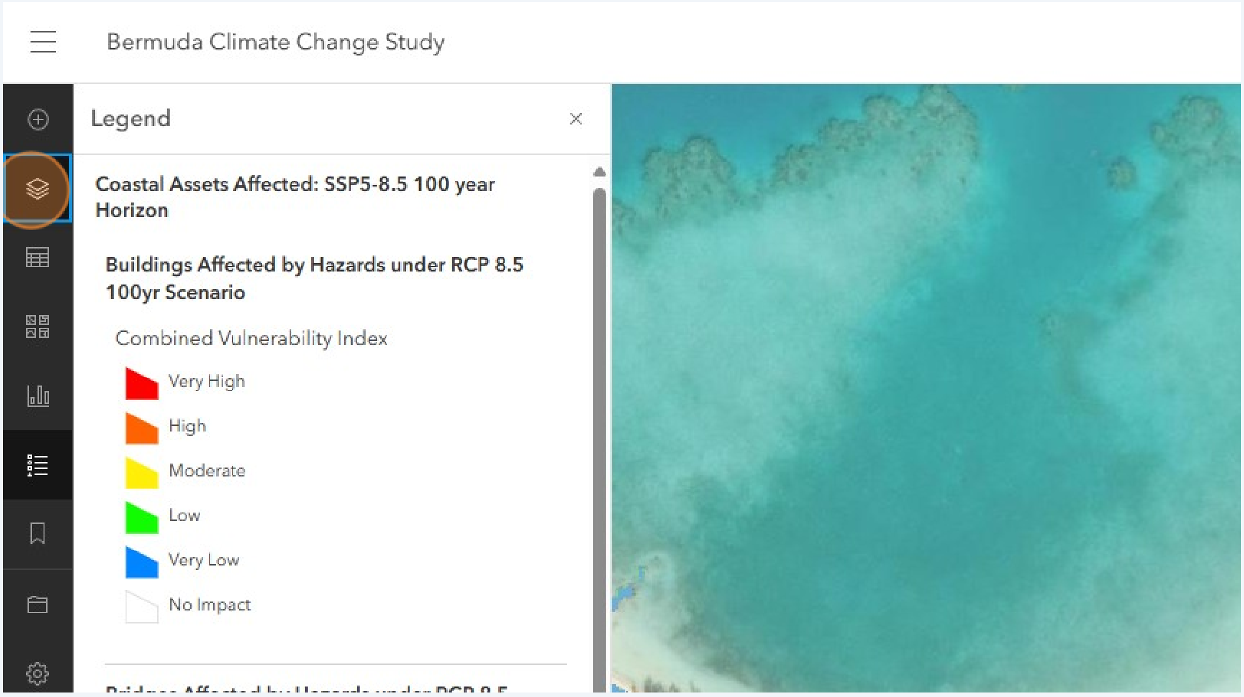
5 Click on the buildings and roads.



6 This will give more information on the asset.

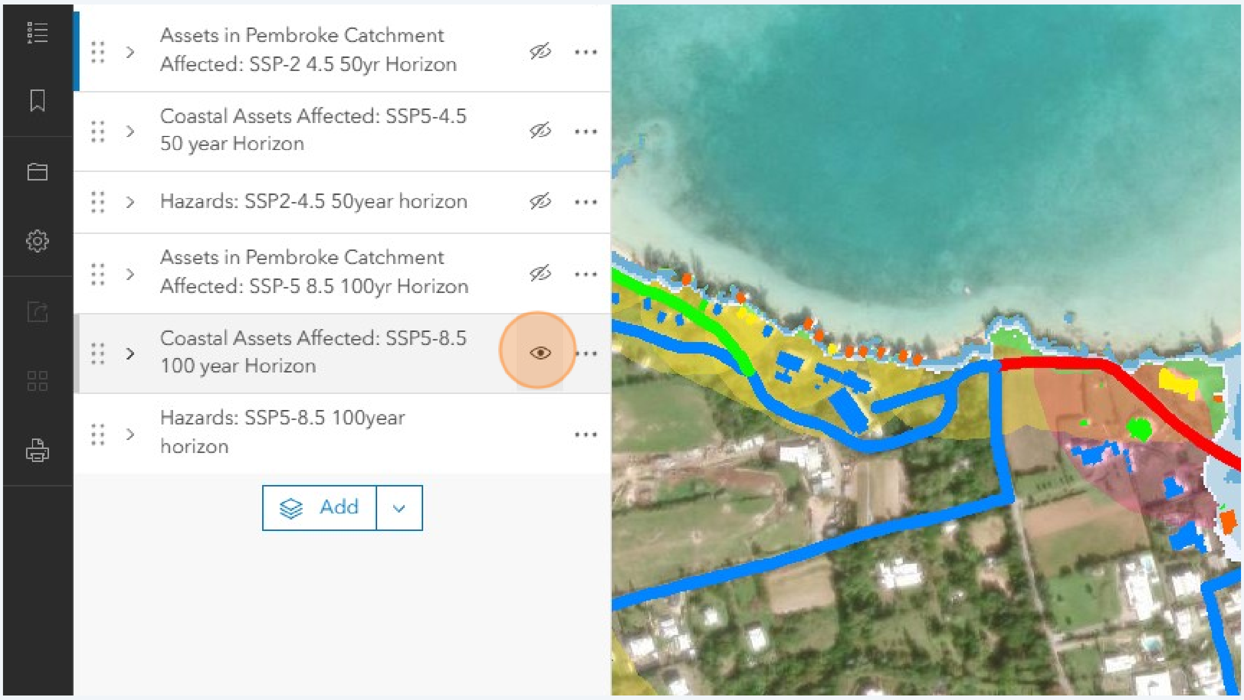
Exploring Layers

7 If you're interested in exploring different layers, you can click on the layers icon as depicted in the image below. From there, you'll have the option to toggle layers on and off using the eyeball icon. A slashed eyeball indicates that the layer is off and not displayed, while an unslashed eyeball signifies that the layer is currently displayed. You can customize your view by turning off all hazard-related layers for various return periods and scenarios, and then selectively turning on layers such as buildings to focus on specific features. Additionally, you can toggle off the buildings to exclusively view the extents of different hazards. Clicking on each feature will bring up a pop-up with more information for further exploration.

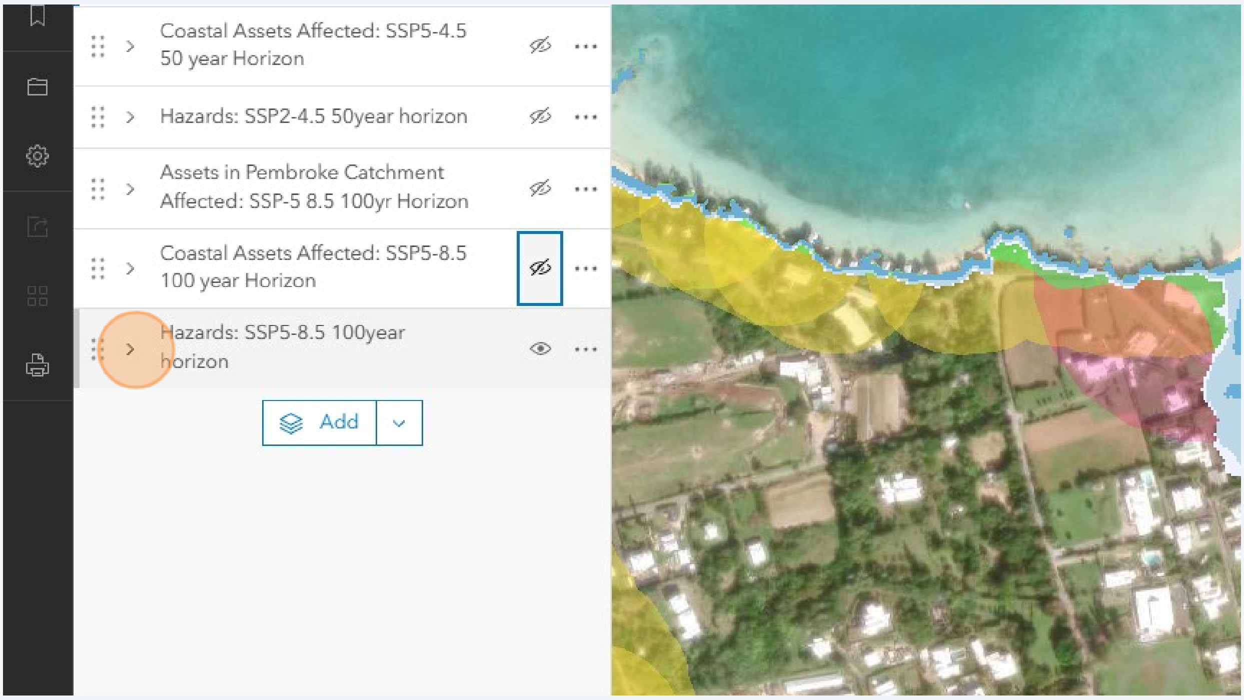


Please be aware that the flood depths layer was generated at an exceptionally high resolution to accurately represent the floods across the island, closely aligned with the LiDAR data available. This level of detail provides enhanced insight into the expected flood depths during storm surges. However, due to its high resolution, loading times may be prolonged. You may need to wait for up to about a minute for all flood depths to load fully. Additionally, rather than loading the entire island, it's advisable to zoom in to the specific location of interest to view the flood depths more efficiently.

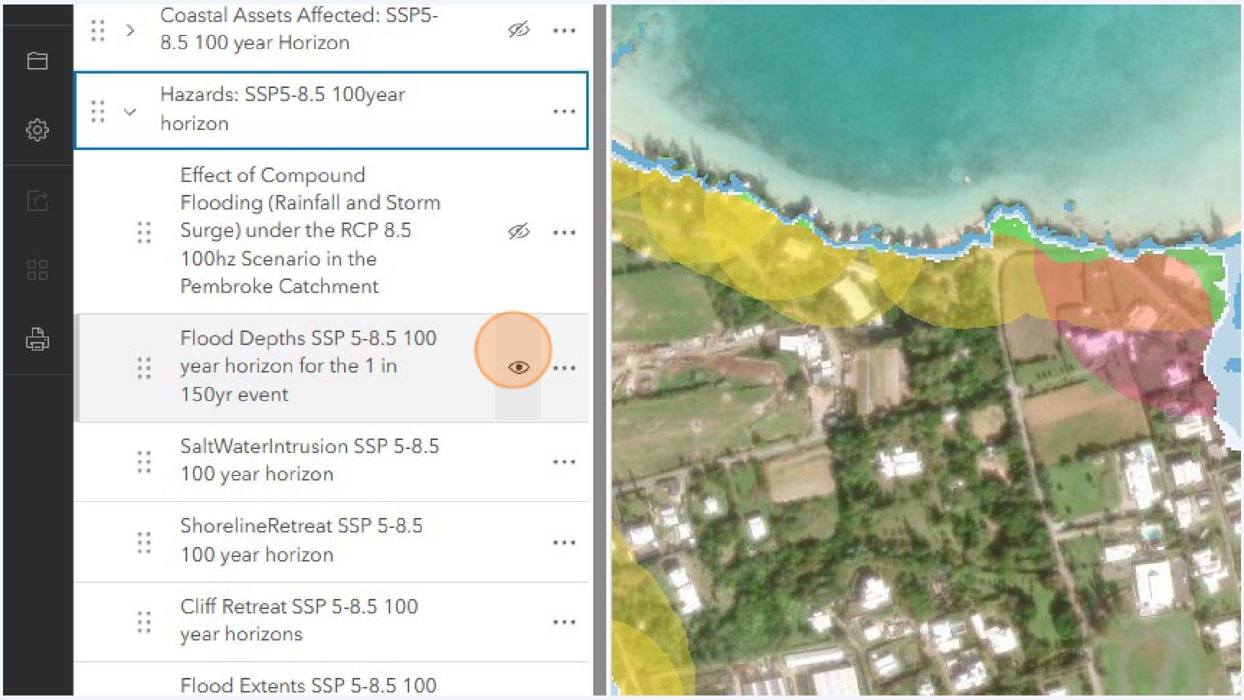
8 Click here.



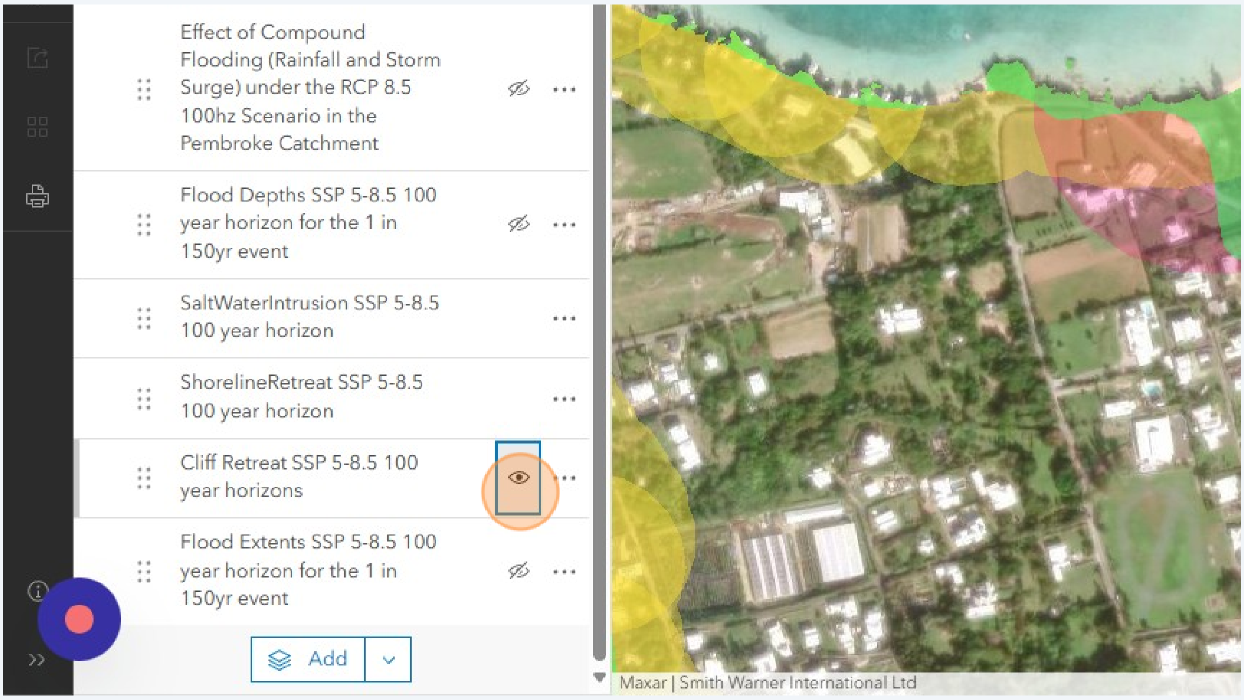
9 Click "Hazards: SSP5-8.5 100year horizon"



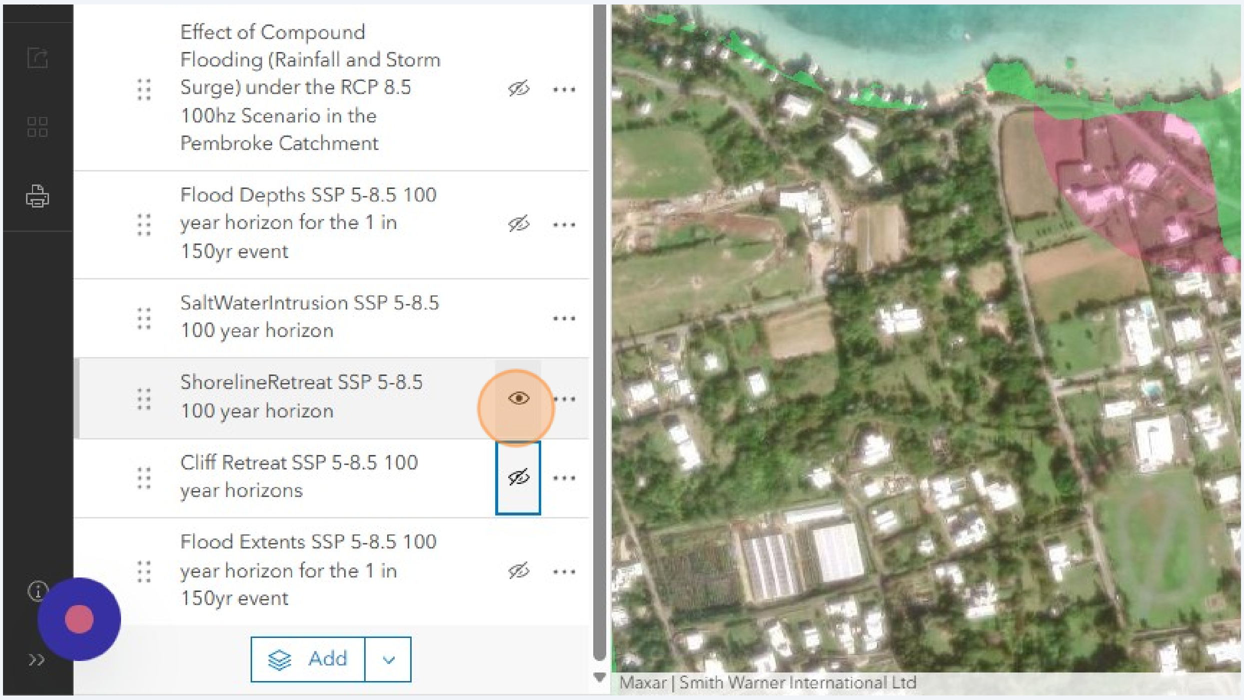
10 Click here.



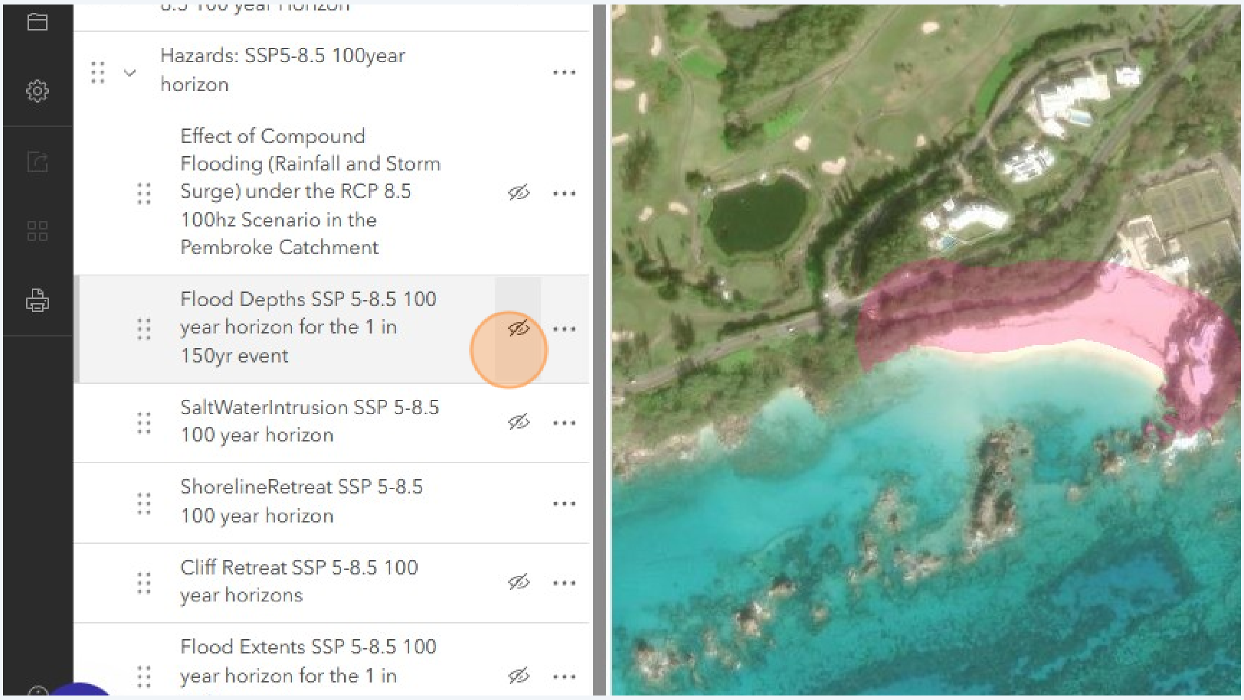
11 Click the eye icon to turn on and off layers.



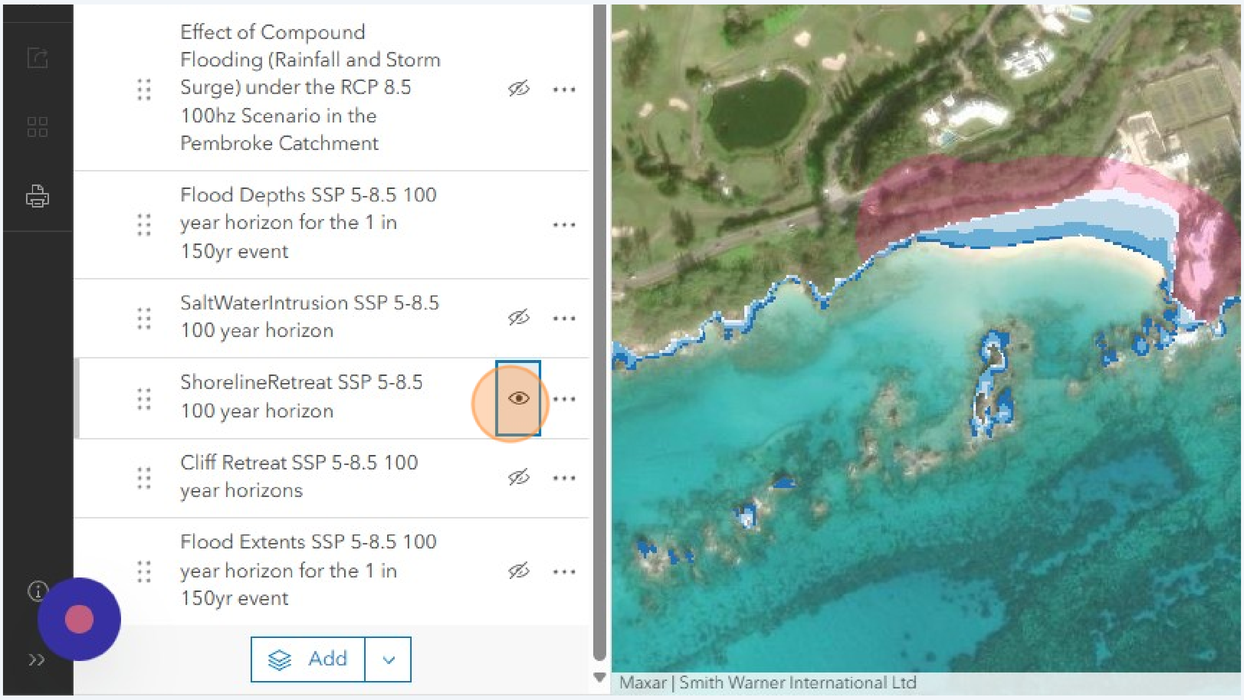
12 Click the eye icon to turn on and off layers.



13 Click the eye icon to turn on and off layers.

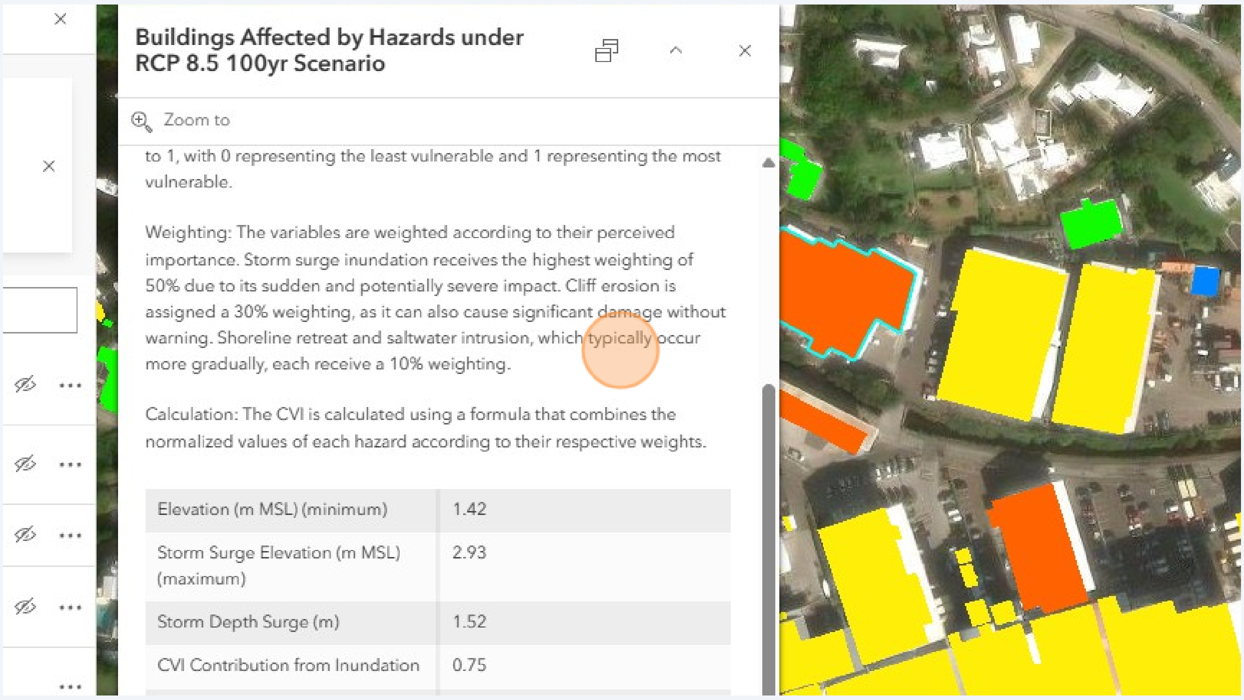


14 Now you can view the different layers.



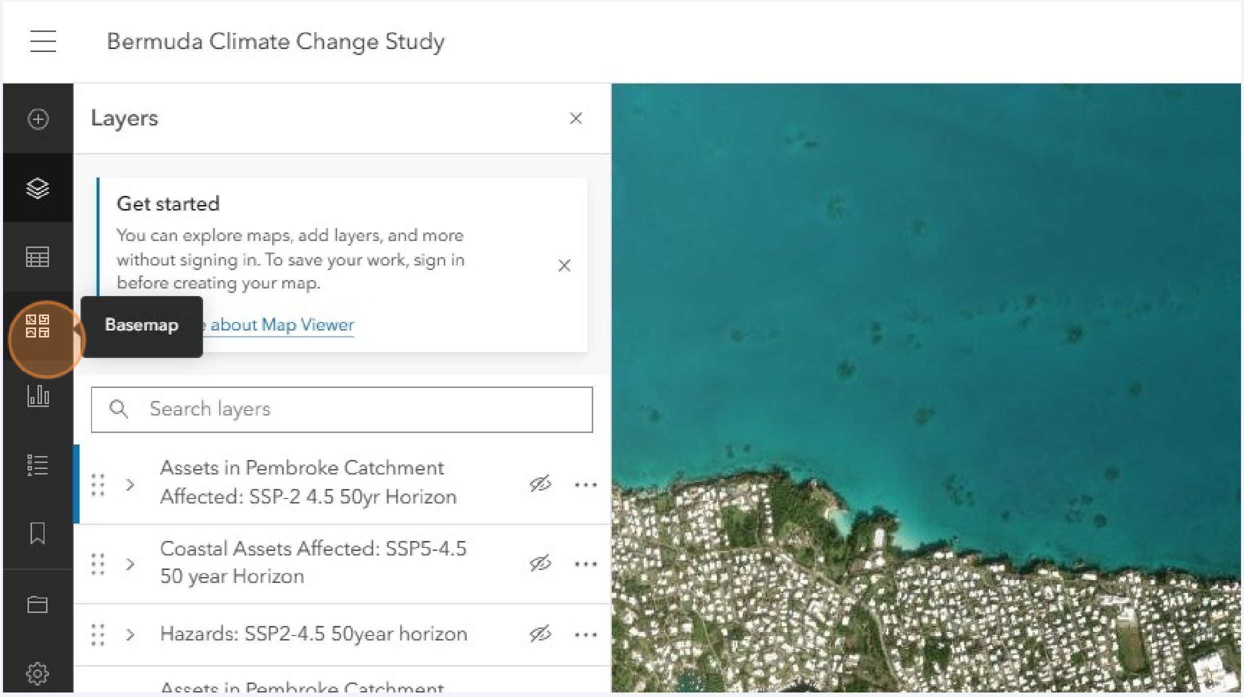
15 Click the eye icon to turn on and off layers.

16 Click the eye icon to turn on and off layers.

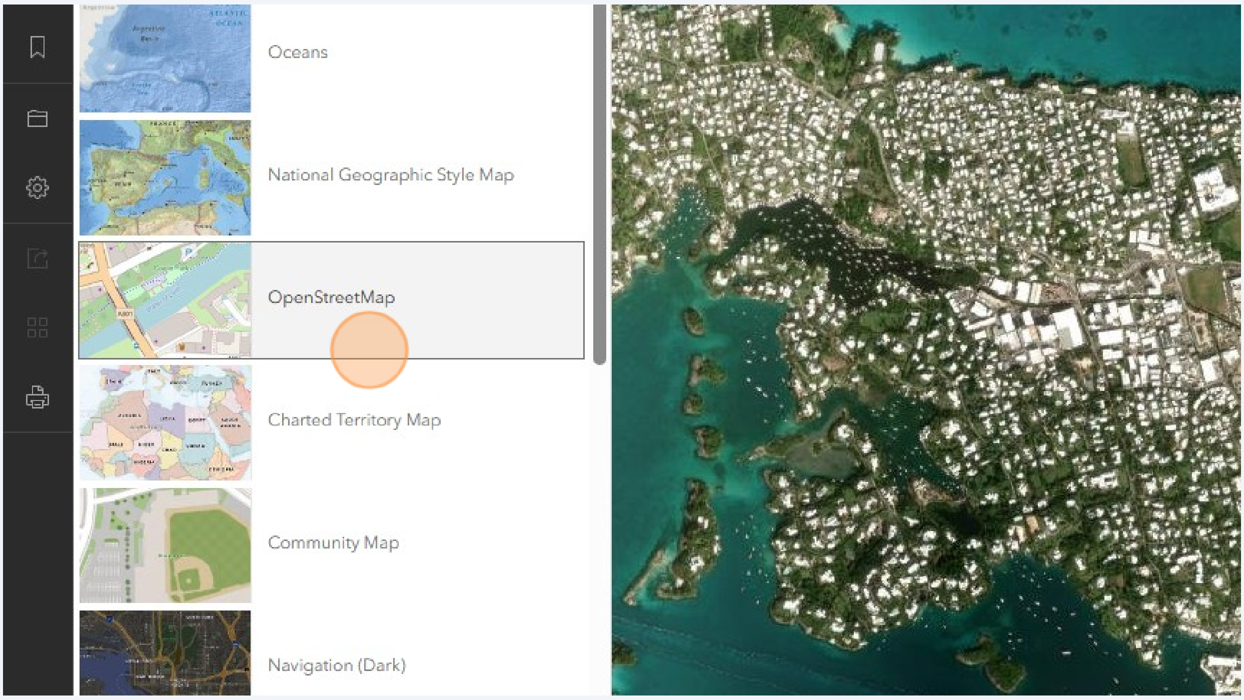


Changing Basemaps

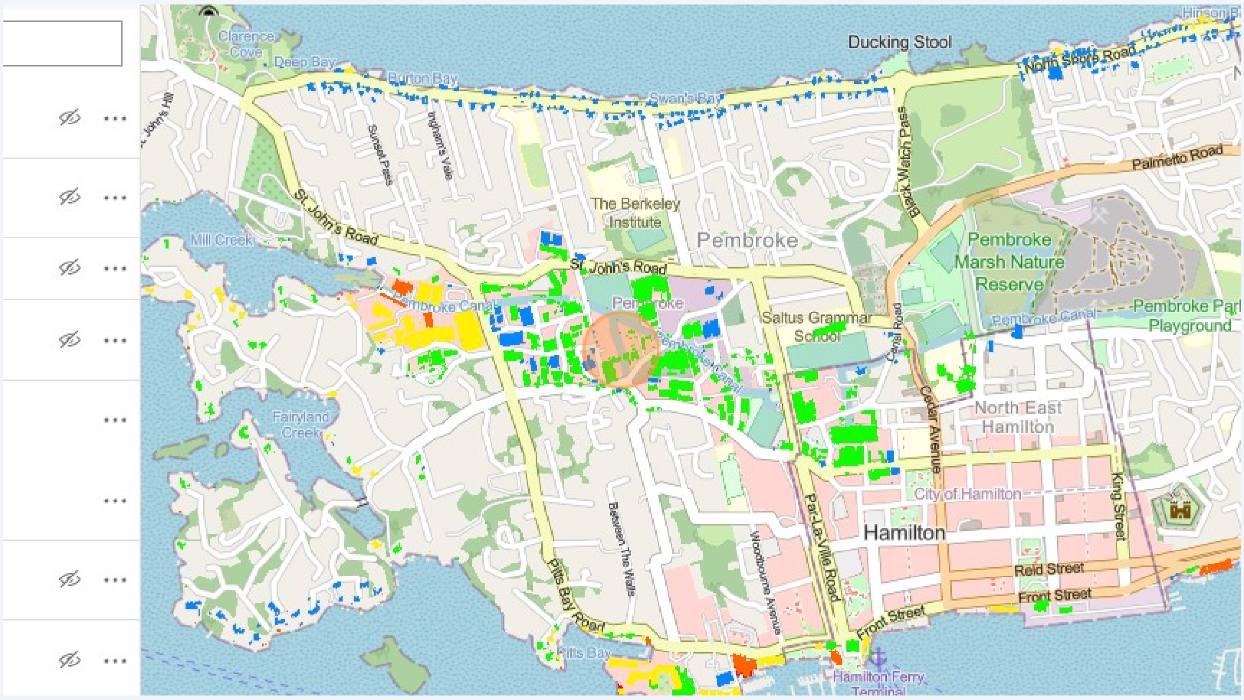
17 If you're interested in viewing with a different background, or encountering visibility issues with different layers, you may opt to adjust the base map layer. Within the base map options, you can select from various options provided by ArcGIS. These include grayscale maps, color-coded maps, and maps with detailed street and building labeling. Choosing a different base map can enhance the visibility and overall viewing experience on the platform. Follow the steps below to switch from, for instance, the satellite view to the open street map view detailed in the following steps.



18 Click "OpenStreetMap"



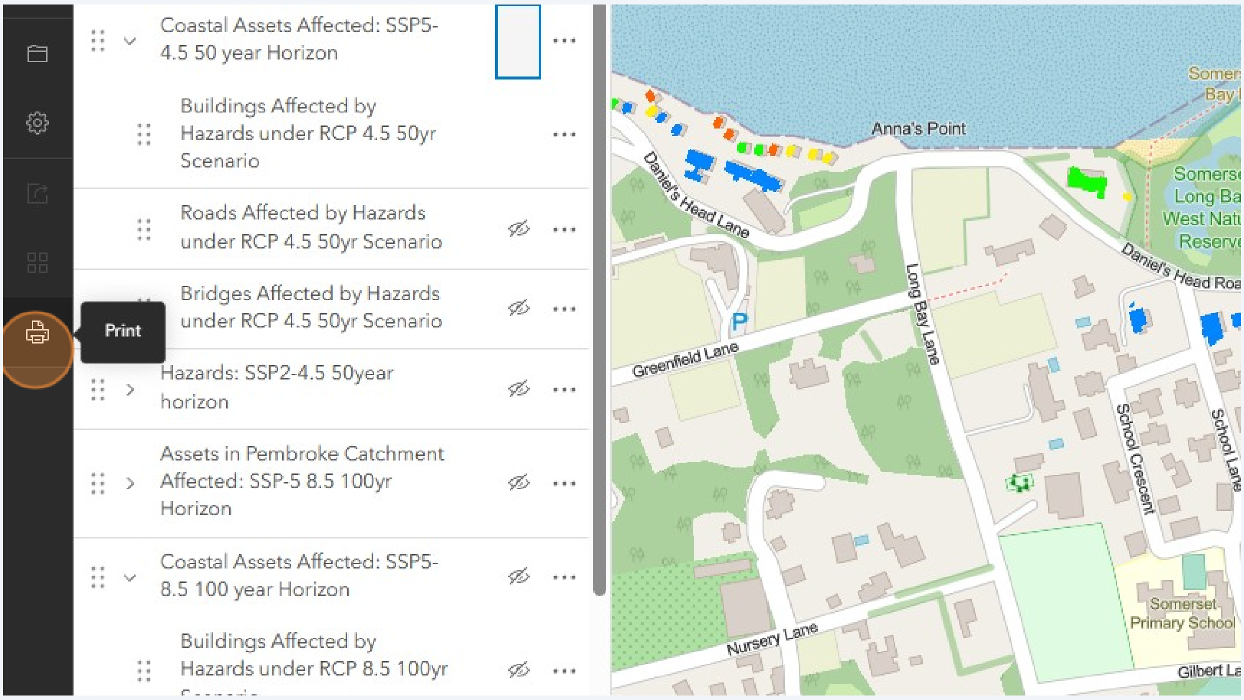
19 Pan around the island as before.



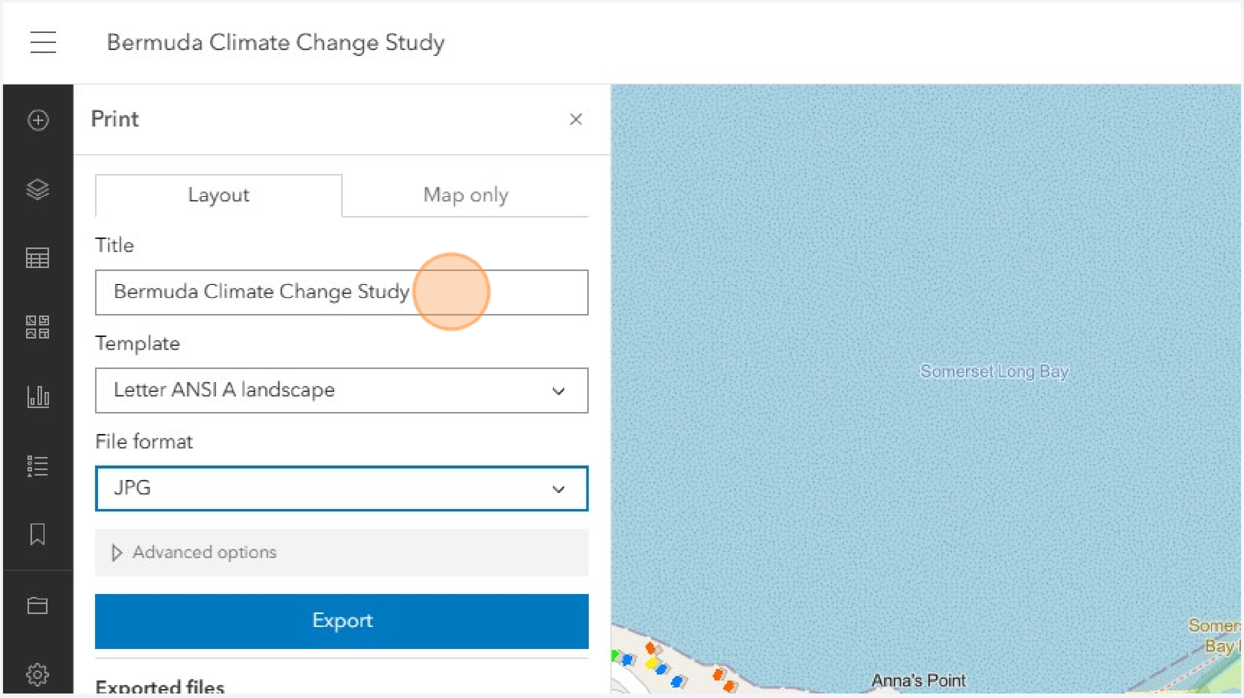
20 Pan around the island as before.

Exporting Maps

21 If you wish to print or export the maps displayed on the web-based app, it's entirely feasible. Simply click on the print icon, as indicated in the image below, and follow the subsequent steps outlined. You can then export your map as a JPEG or PDF, depending on your preference.

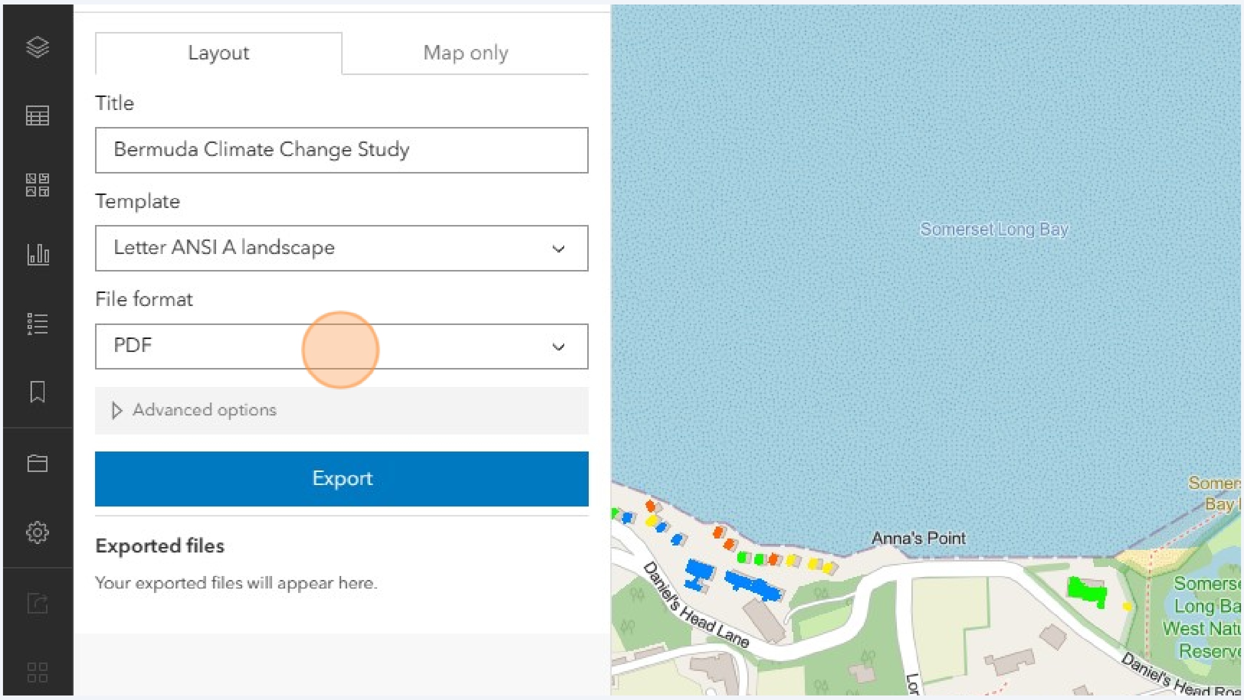


22 Click here.

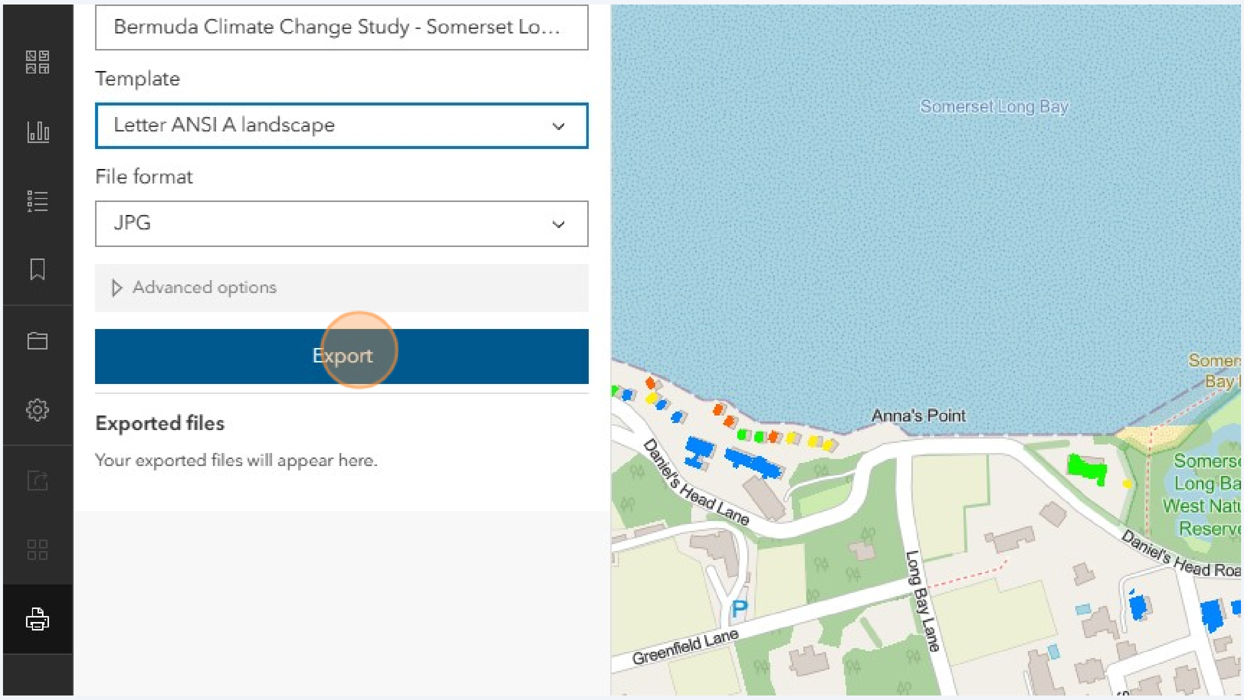


23 Type the map title "Bermuda Climate Study - Somerset Long Bay"

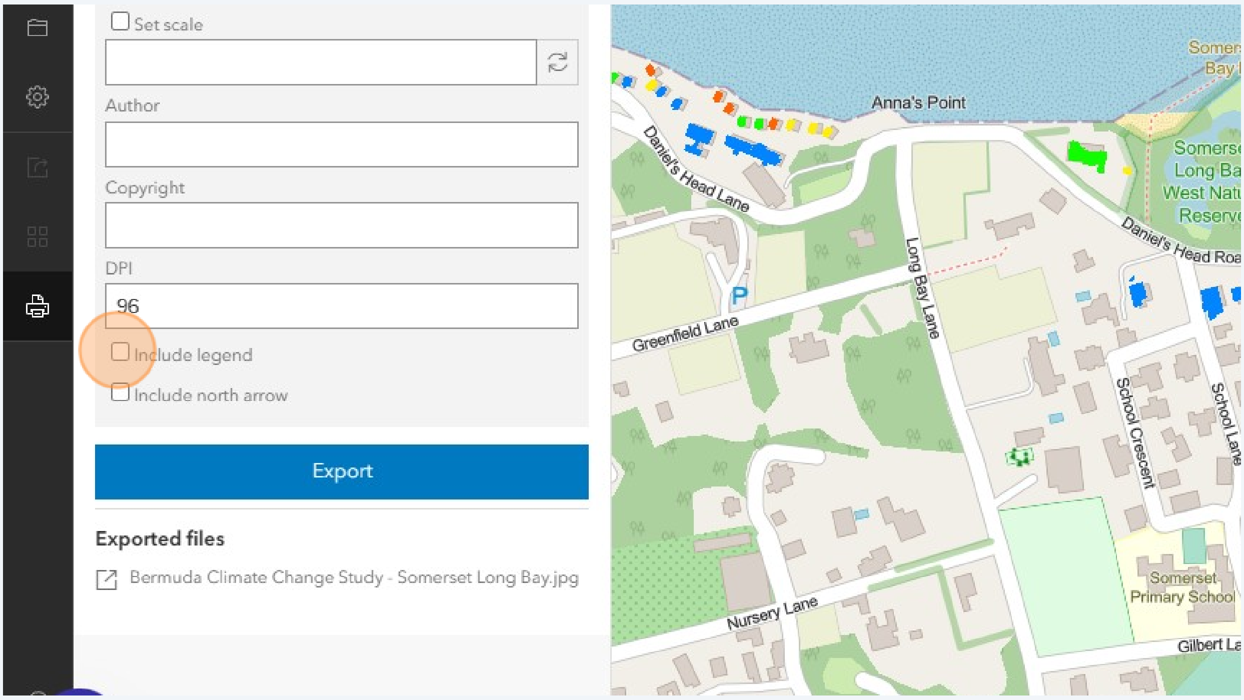
24 Click here.



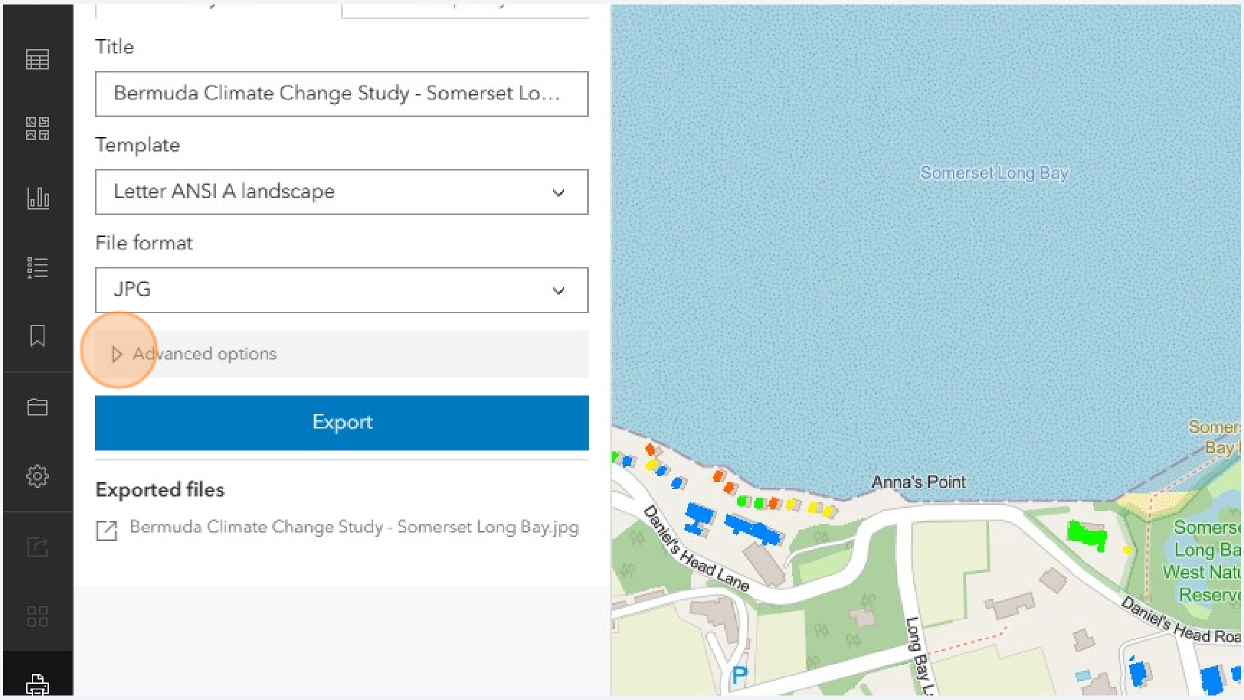
25 Click "Export"



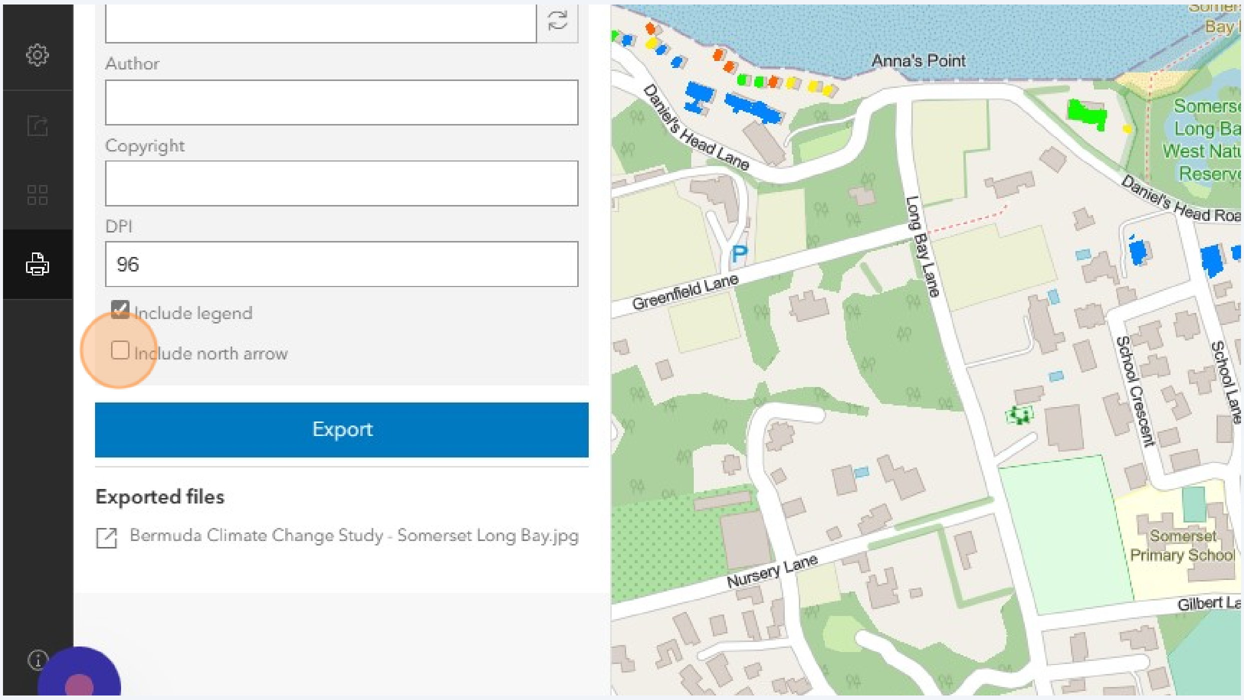
26 Click the "Include legend" field.



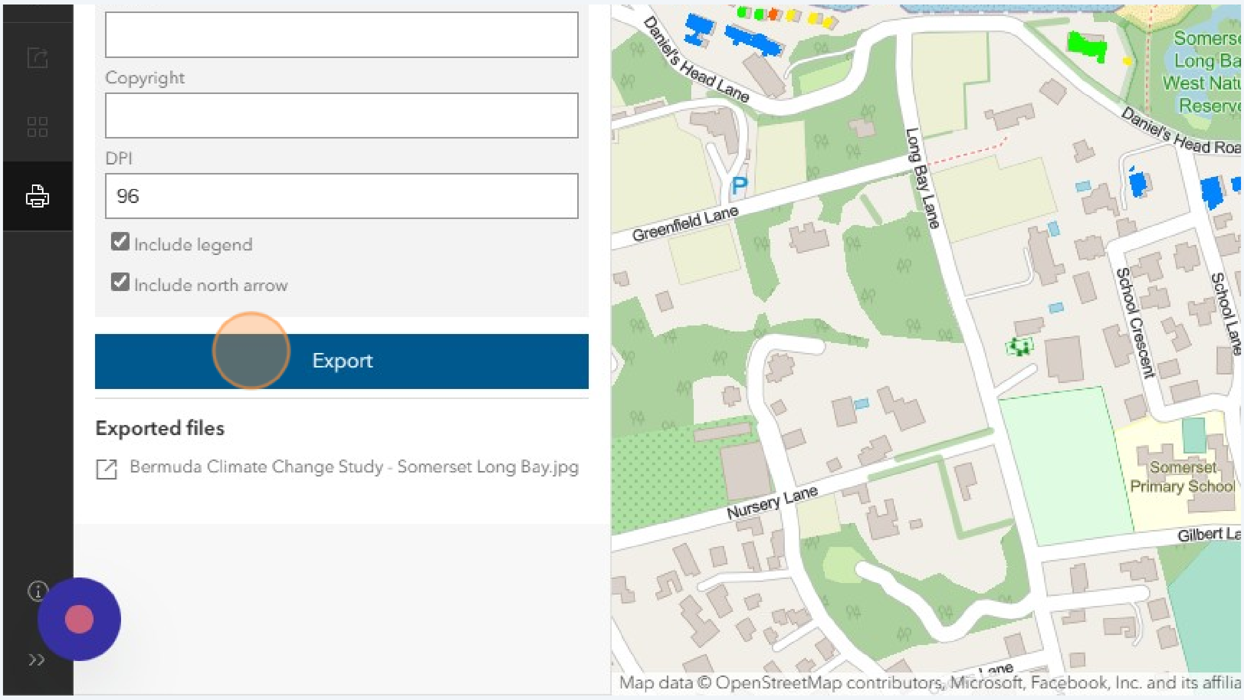
27 Click here.



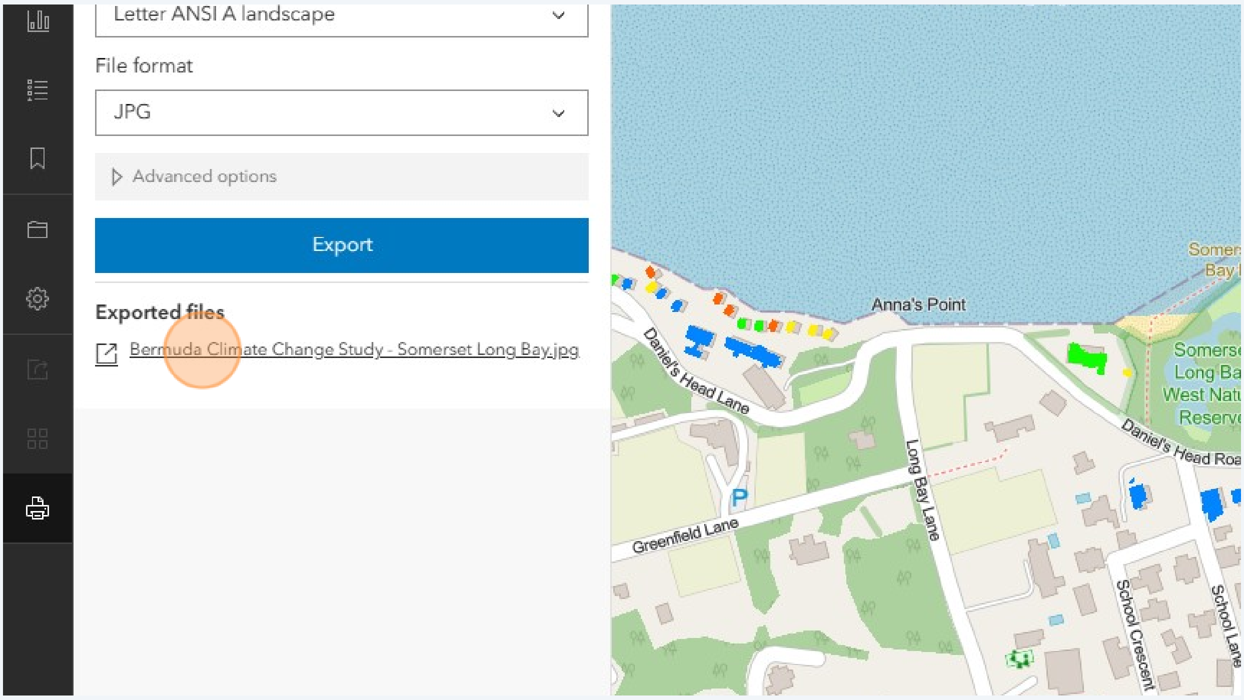
28 Click the "Include north arrow" field.



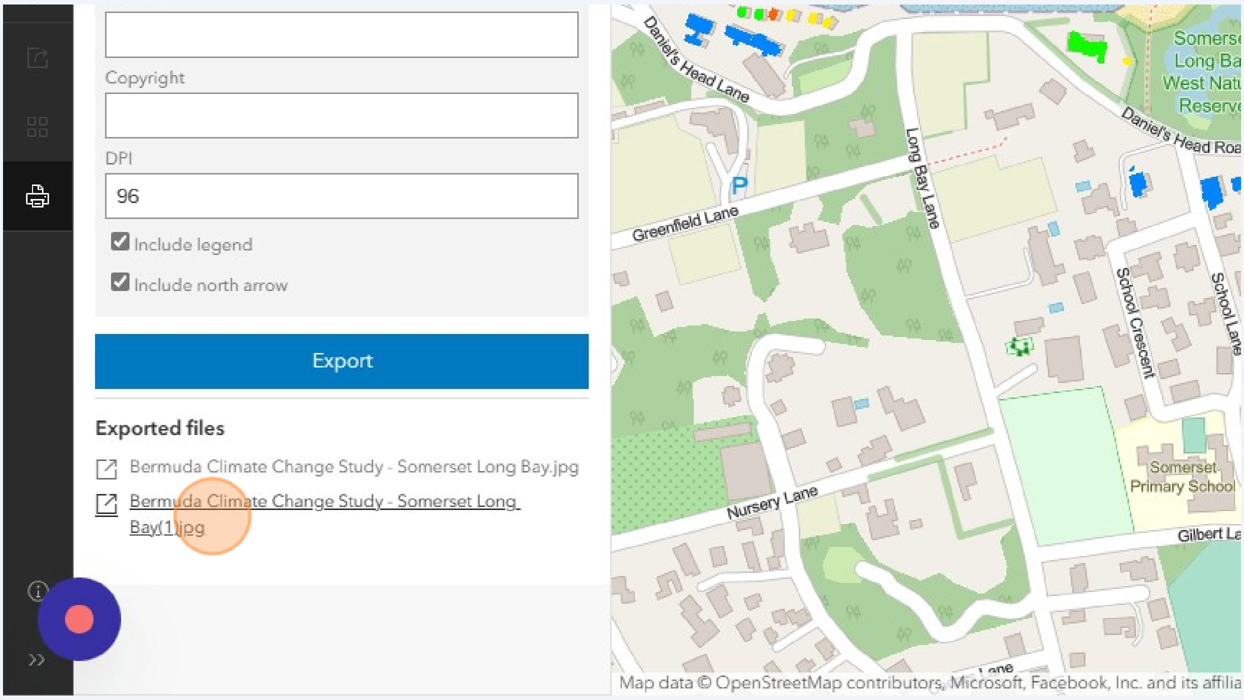
29 Click "Export"



30 Click "Bermuda Climate Change Study - Somerset Long Bay.jpg"



31 Click "Bermuda Climate Change Study - Somerset Long Bay(1)jpg"



32 This is your new map.