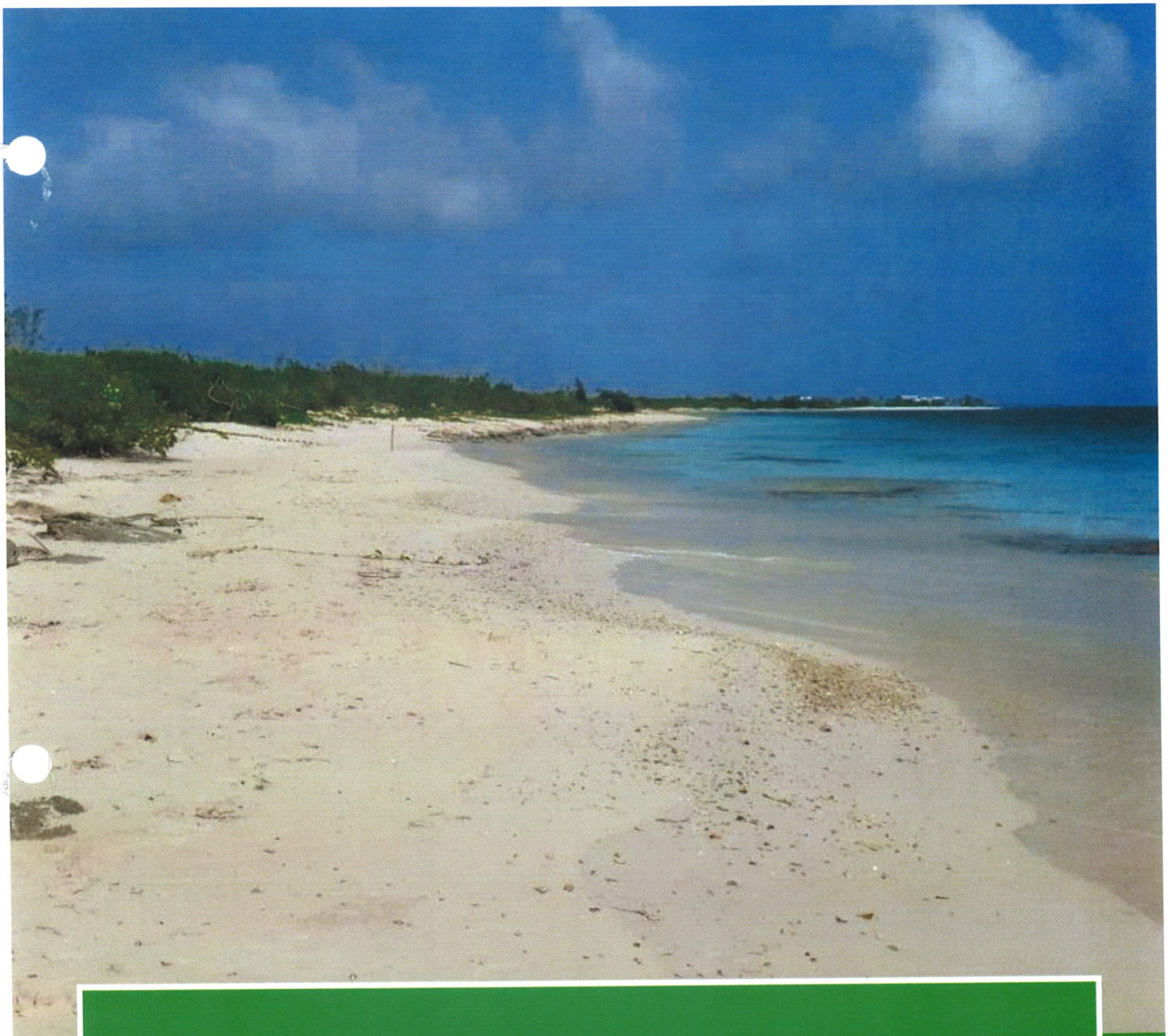

Escape To Barbuda

Coastal Conditions Assessment
FINAL REPORT

CBCL

201163.00 • February 2021

	Final Report	D. Kolijn	25/02/2021	A. Camarena A. Kaji
	Draft Report	D. Kolijn	14/01/2021	A. Camarena A. Kaji
Issue or Revision		**Reviewed By:**	**Date**	**Issued By:**

CBCL

Final Report 201163.00

February 25, 2021

Seamus Kelly
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Dear Mr. Seamus Kelly:

RE: Final – 'Escape To Barbuda' Coastal Conditions Assessment

As part of our work to support the design development of the 'Escape To Barbuda' coastal resort along the southwest coast of Barbuda, please find herein the final coastal conditions assessment report. In this report we present an executive technical summary, the project background, data analysis, numerical modelling, coastal hazard assessment and potential risk mitigation measures. These results are used to derive the design flood elevations and the development setback distance from the waterline.

Please do not hesitate to contact the undersigned with any questions or comments you may have with regards to the contents of this report.

Yours very truly,

CBCL Limited

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Project No.: 201163.00

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Appendices

Technical Executive Summary – 'Escape To Barbuda' Coastal Conditions Assessment

The coastal condition assessment was completed to investigate the main coastal hazards, and to provide setback distances and design flood elevations for the design of the 'Escape To Barbuda' development. The coastal development is located along the southwest coast of the island of Barbuda, and naturally protected from easterly swell waves. The project area is relatively flat with mild sloping sandy beaches (with rocky limestone and karst formations) and densely vegetated backshore areas.

Historical satellite images indicate limited shoreline change in the last couple of decades. The shoreline change at the site is mainly driven by extreme events like hurricanes. The normal daily wave conditions (i.e. calm conditions) have limited sediment transport capacity and are therefore not considered the main sources of coastal erosion.

Sea level is expected to rise 0.84 m (RCP8.5) by 2100, this will inevitably increase the risk of flooding and potentially coastal erosion. Natural coastal adaptation like sustaining or improving existing coral reef coverage and enhancing natural beach stability may be possible, but will depend on multiple factors, like water quality (for healthy coral growth), sediment availability (to allow for natural beach buildup), and broader impacts from climate change.

The most significant coastal hazard for the project site are hurricane events, leading to extreme surge, wave run-up and erosion. Barbuda has experienced the devastation of hurricanes in recent history, first with hurricane Luis in 1995 and more recently hurricane Irma in 2017. An analysis of hurricane frequency was completed using all hurricanes on record (170 years of hurricane tracks dating back to 1851), which provided representative storm conditions that were used as input for the numerical modelling component of this project.

The numerical modelling included calculation of wave propagation, wave run-up and beach erosion. The nearshore wave conditions were derived using Delft3D-WAVE and served as input for the run-up and beach erosion simulations that were performed using XBeach. Setback distances and design flood elevations were defined based on the numerical modelling results for non-hurricane wave conditions and three different hurricanes Categories (1, 3 and 5). The impacts of a Category 4 or 5 hurricane are likely too severe and catastrophic to accommodate in a reasonable setback design allowance, and are therefore not practical for land planning purposes. Major redevelopment actions are expected after these extreme events make landfall. Therefore, for the scale of the 'Escape To Barbuda' development we recommend the use of results from the Category 3 hurricane as the minimum setback distance and design flood elevation for infrastructure prone to damage caused by temporary flooding or erosion. Ultimately the level of risk tolerated at the site should be selected by the developer, considering the likelihood of a certain event occurring, the impacts it will have, and the resources available to manage that risk during the design stage of the project or in the future once it occurs.

Summary of Design Flood Elevation and Setback Distance

Extreme Event	Design Flood Elevation (MSL)	Design Flood Elevation Including	Erosion Setback Distance from the
Extreme non-Hurricane Wave Conditions	1.0 m (3.3 ft)	1.8 m (5.9 ft)	7 m (23 ft)
Hurricane – Category 1	2.3 m (7.5 ft)	3.1 m (10.2 ft)	15 m (49 ft)
Hurricane – Category 3	3.8 m (12.5 ft)	4.6 m (15.1 ft)	35 m (115 ft)
Hurricane – Category 5	5.8 m (19 ft)	6.6 m (21.7 ft)	80 m (262 ft)

The proposed risk mitigation measures proposed by CBCL include:

- Elevating the ground floor of critical infrastructure to at least 3.8 m (12.5 ft).
- Maintaining a healthy beach environment, including maintaining the beach well-nourished and protecting the coral reefs and vegetation.
- Avoid any type of infrastructure near the high water line.
- Disturb the natural beach profile as little as possible
- No cabanas or other temporary structures should be placed on the dune or the beach.
- Developing post-storm contingency beach nourishment plans, including the regular monitoring of beach profiles.
- Maintain or enhance local vegetation on the dune, and further inland, as it both stabilizes the dune and acts as a natural wave energy dissipation mechanism during storm surge events.
- Monitor and protect the existing coral reef system near the property.

Recommendations

Subsequent design of the proposed elements of the 'Escape To Barbuda' coastal development should be informed with the outcome and recommendations from this study. Long-term plans for the area must account for the ever-growing risks of coastal flooding due to accelerating sea level rise, combined with storm surge and wave run-up. Finally, it is recommended to further develop long-term coastal monitoring tools. Monitoring will provide a record of coastal processes, future long-term changes and impacts from extreme future storm events. Recommended information to formally document includes monitoring and surveying of pre-determined beach profiles, flood level measurements, limits of wave run-up, and reports of wave damage. The information would serve as a validation of assumptions and models used for this study, and for future update of plans and models for mitigation of local coastal risks.

[1] Based on the average beach slope derived from the topo-bathymetric transect measurements and DTM.

Chapter 1 Introduction

Kelly Construction Inc. is in the processes of developing a new hospitality offering on the island of Barbuda, along the southwest coast, known as the **'Escape To Barbuda'** resort. As part of the work to support the design development of the **'Escape To Barbuda'** coastal resort, CBCL has completed a coastal conditions assessment to characterize the coastal and metocean environment in the area. The objectives, methodology and findings of the study are described in detail in this report.

1.1 Study Objectives

To support the design development of the Escape to Barbuda project, CBCL Limited (CBCL) has completed a coastal conditions study. The objectives of this study are to:

- Analyze coastal and metocean conditions to schematize storm conditions at the site.
- Identify coastal hazards and risks to the proposed development. Including storm surge associated with hurricanes, shoreline erosion, and future climate change impacts such as sea level rise.
- Simulate the impact of extreme storm conditions (nearshore waves, wave run-up and beach erosion).
- Recommend setback distances and design flood elevations for the proposed infrastructure at the site based on a range of representative storm conditions.
- Propose risk mitigation approaches, as they pertain to coastal infrastructure exposure, specific to the project site.

1.2 Site Description

Barbuda is located in the eastern Caribbean forming part of the sovereign Commonwealth nation of Antigua and Barbuda. It is located north of Antigua Island and is part of the Leeward Islands of the West Indies.

Historically, most of Barbuda's 1,634 residents have lived in the town of Codrington. However, in September 2017, Hurricane Irma damaged or destroyed 95% of the island's buildings and infrastructure and, as a result, all the island's inhabitants were evacuated to Antigua, leaving Barbuda empty for the first time in modern history.[2]

The proposed site is 30.11 acres in size, and it is located on the southwestern coastline of Barbuda, less than 4 miles south of its capital Codrington. It is bounded on the north by Coco Point Road, and on the south by the Caribbean Sea. Barbuda Express Ferry terminal is located less than a mile west of the proposed site. The project site is relatively flat with small sand dunes and vegetated coastal areas. The site is currently undeveloped and consists only of native flora and fauna.

Barbuda has been devastated by two major hurricane events in recent history, first by Hurricane Luis (Category 4) in 1995, more recently in 2017, Hurricane Irma (Category 5 – one of the largest hurricanes on record in Caribbean history) caused catastrophic damage when it made landfall on the island on 6 of September 2017.

Figure 1 depicts the location of the island and the proposed coastal development site. Figure 2 presents four photos of the proposed development site. The area is composed by mostly sandy beaches, with vegetation along the backshore. In some areas the karst rocky under layer is exposed (see panel B).

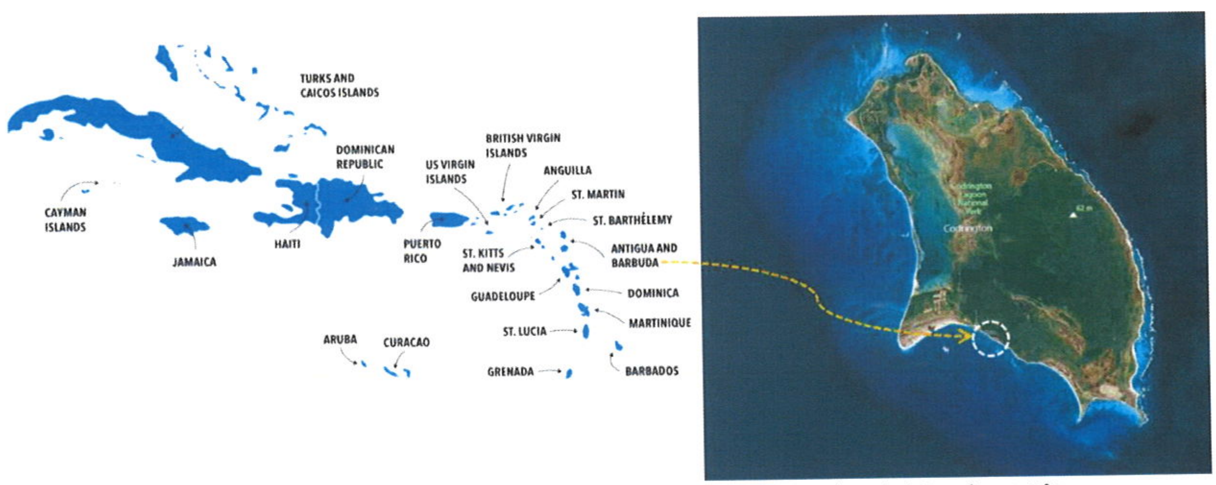

Figure 1: Location Overview of 'Escape To Barbuda' Project Site

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[2]Source: https://www.wnyc.org/story/us-virgin-islands-begin-clean-after-irma/

Figure 2: Site Photos – Mild Beaches with Visible Rock Cover along some Segments of the Proposed Development

1.3 Scope of Work

To characterize coastal processes at the site and to provide coastal set-back and risk reduction recommendations, the scope of the consultancy includes the following items.

- Review the project site, topography and bathymetric information.
- Assess historical hurricane data and analyze offshore extreme wave climate using a global wave and wind hindcast.
- Determine range of water levels such as tides, storm surge and sea level rise.
- Use an archive of historical satellite imagery to determine historical coastline evolution trends at the project site.
- Derive nearshore wave conditions based on ocean swell and hurricane events.
- Determine potential cross-shore erosion and wave run-up during extreme storms, using a 1D XBeach numerical model to study beach profile evolution.
- Give recommendations on coastal set-backs including both vertical (design flood elevation), and horizontal set-backs (from the water line).
- Based on the findings from the site and data analysis of water levels, waves, hurricanes, coastal evolution and potential flooding, provide a summary of project risks, as they pertain to coastal processes at the site.
- Provide preliminary recommendations to mitigate coastal risks.

Chapter 2 Data Analysis

2.1 Bathymetry and Topography

The island of Barbuda is relatively flat, where the highest point on the island is in the "highlands" on the eastern side of the island, and has a maximum elevation of 47 meters. The proposed development site goes from the water line to about 4-5 m above mean sea level (MSL).

The bathymetry around the island is relatively uniform and shallow, with a variety of complex fringing reef structures, for the first 3-4 km from the coastline, and then it drops to depths of about 20 m below MSL and rapidly changes to very large depths of over 100 m below MSL. The southwestern side of the island has a wide shallow island shelf in comparison to the east side of the island. The area in front of the proposed development has some scatter coral reefs, this serve as natural coastal protection structures, by dissipating wave energy. Figure 3 illustrates the regional bathymetry, which was derived from satellite imagery using remote sensing methods in late 2017, post hurricane Irma. This bathymetric data is used as input for the wave modelling described in Section 3.1.1. The depths presented on the figure are referenced to mean sea level (MSL), and the units are in meters. The deeper areas included in the satellite derived bathymetry reach depths of up to 35 m, and cover depths of to the waterline at the coastline. It should be noted that a degree of error is associated with satellite derived bathymetry. Satellite derived depths are most accurate in intermediate water depths (i.e. 2-10m below MSL), and become less accurate in very shallow (i.e. < 1-2m) and very deep (i.e. > 15m) of water depth, where associated error increases as a function of depth. The satellite derived water depths provide a reasonable and very comprehensive interpretation of the nearshore bathymetry around Barbuda and are suitable for numerical modelling purposes to characterize the nearshore at a preliminary planning level.

In addition to the high resolution bathymetric data, beach transects were measured to represent the transition area from areas below low tide to the vegetated backshore of the beach. These beach transects were provided by Kelly Construction, one of the beach transects is presented in Figure 4. In total ten (10) transects were measured to obtain an overview of the elevation changes from north to south across the proposal coastal development. The overview of the measured transects is presented in Figure 5.

Both the bathymetric and topographic data was combined and processed to use as input in the numerical modelling tasks of this project described in Chapter 3 .

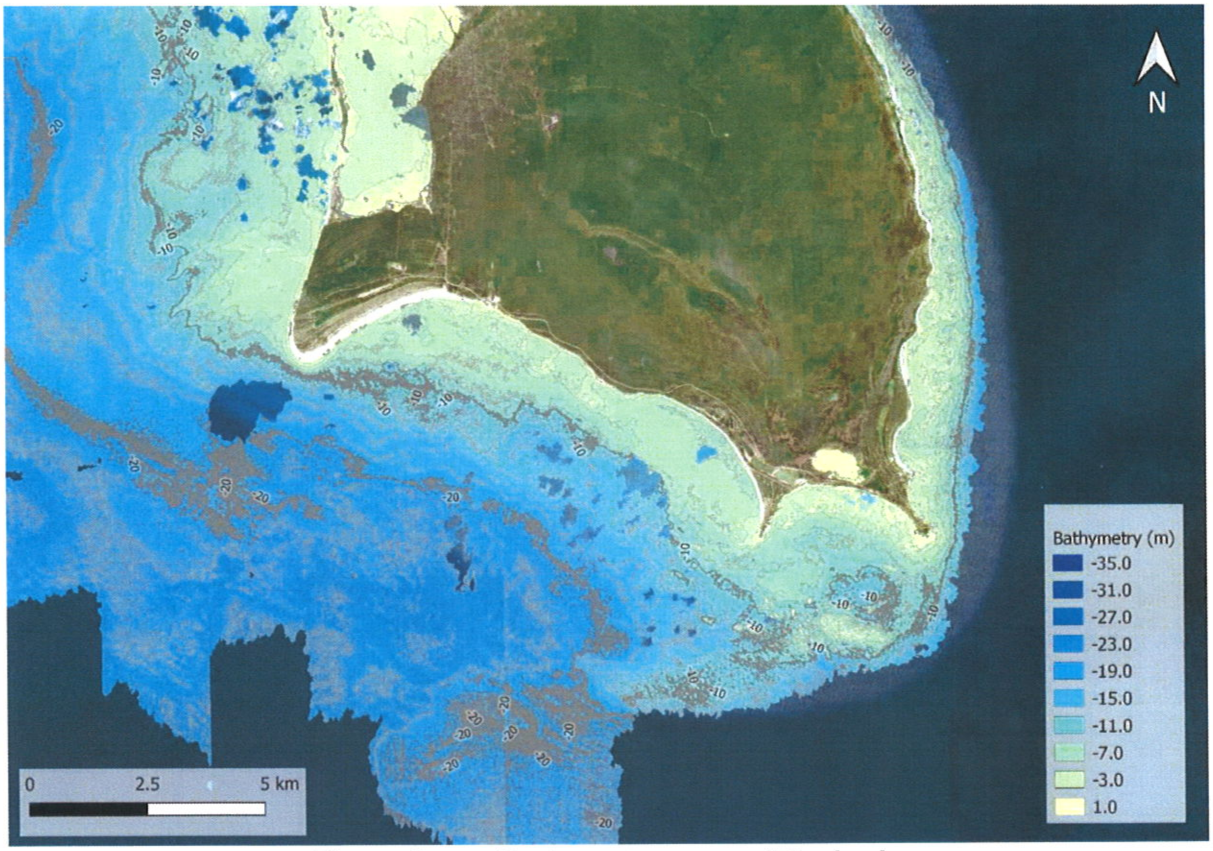

Figure 3: Bathymetry around Barbuda

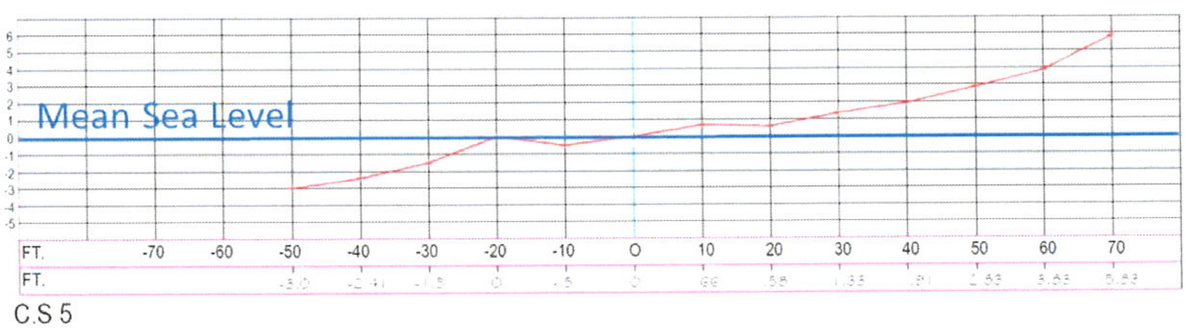

Figure 4: Example of Measured Beach Transect[3]

[3] Topo-bathymetric transect measurements provided by Kelly Construction Inc.

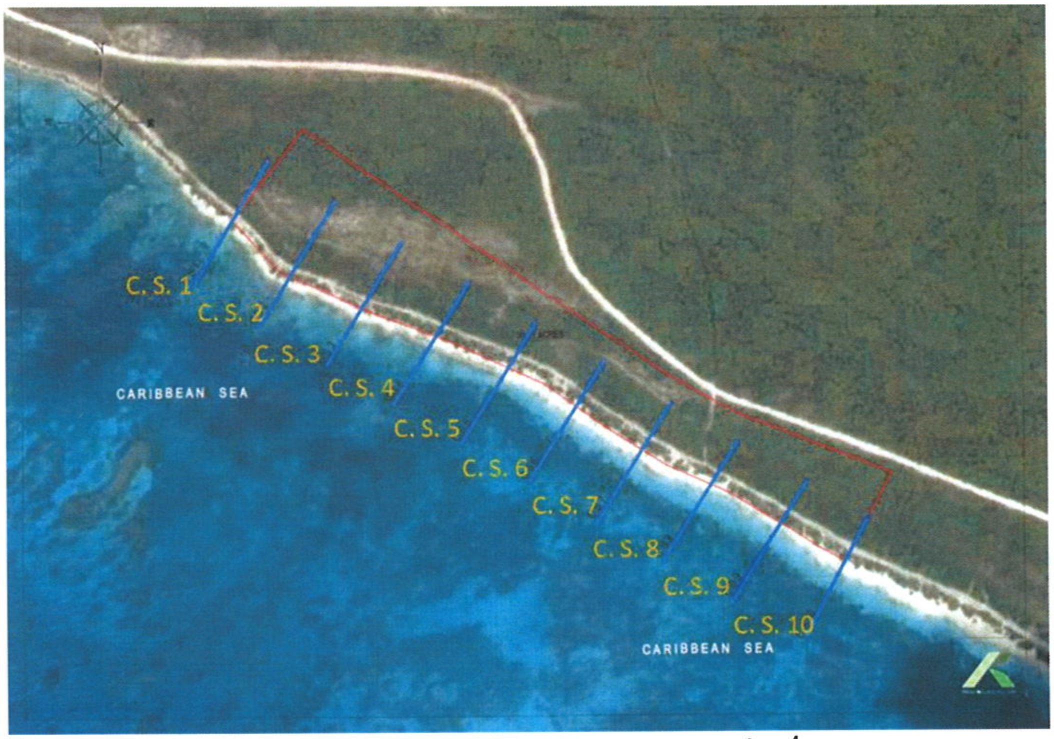

Figure 5: Beach Transect Location[4]

2.2 Historical Shoreline Evolution

Historical erosion and deposition trends at the proposed development site, and surrounding shoreline are important in understanding potential sources of sediment and future changes which can be expected within the region. These historical changes were assessed by comparing historical satellite photos and imagery of Barbuda spanning 15-years from 2005 to 2020.

The satellite imagery was georeferenced to an orthorectified base map in the QGIS Geographic Information System (GIS) mapping application. The following technical criteria were assessed in georeferencing imagery:

- There should be adequate land based features which can be used to establish ground control reference points to the ortho-rectified base map in QGIS.
- The coastal zone (area of interest) should not be located directly on, or too close to the edge of the photograph (this is where the most distortion occurs).
- The visual aspect of the photograph should be of high quality (a clear and crisp image as opposed to a high reflectance or a low contrast image).

[4] Source: Kelly Construction Inc.

It should be noted that shoreline change analysis is approximate and includes a considerable margin of error due to image resolution, georeferencing techniques, lack of common artifacts in the imagery to georeferenced each image, and differences between subsequent imagery.

In conclusion, from the 15 years of available satellite imagery we observed that the shoreline change along the southwestern coast was typically limited, and potentially more affected by seasonal changes. No clear long-term morphological evolution could be derived from the images. Images indicate marginal shoreline change, and mobility of regional sediment at the proposed development site. The associated low-energy wave climate (described in Section 2.7 this report), supports the conclusion that morphological changes due to longshore sediment transport at the 'Escape To Barbuda' project site are limited. However, extreme events like hurricanes can lead to coastal retreat and loss of sediments. Detailed event-driven (hurricanes) coastal erosion is described in Section 3.3.3.

The five (5) images selected for this analysis are shown in Appendix A. Figure 6 illustrates the results of the analysis and the coastline position for each of analyzed images.

An assessment of beach erosion hazards in Antigua and Barbuda[5] was completed in 2001 by the Organization of American States, Unit for Sustainable Development and Environment for USAID-Jamaica/Caribbean Regional Program. Their work concludes that the beach erosion depends on several factors, including:

- Location on island.
- The degree of shelter.
- The extent of coral reefs in the nearshore.
- Human related activities, especially sand mining.

The 'Escape To Barbuda' proposed development is in the sheltered side of the island (not exposed to the regular swell driven storms), it is not fully protected by coral reefs, but scattered reef outcrops are present. To CBCL's knowledge there are no localized human related activities directly affecting the area.

2.3 Earthquakes and Tsunamis

The Lesser Antilles is located at the eastern edge of the Caribbean plate where it borders with the North American plate. A moderate level of inter-plate activity is generated along these boundaries. Along the northern margin, including areas in the vicinities of Jamaica and the Virgin Islands, moderate earthquakes of shallow depth are generated.

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[5] Source: http://www.oas.org/pgdm/hazmap/cstlersn/ant_bar/cersn_nt.htm

The North American Plate is being subducted beneath the less-dense Caribbean Plate at a speed of approximately 2 cm every year and the islands within the arc have been formed from magma derived from the melting of the North American Plate.

According to the National Office of Disaster Services of Antigua and Barbuda, three major earthquake events happened in the recent history:

- October 8th, 1974, 5:51am – Antigua & Barbuda experienced a very significant quake. Larger un-reinforced buildings such as churches, public buildings and the West Indies Oil refinery took the brunt of the damage. Land slippage was evident in some areas like Deep Water Harbour. Damage was estimated at approximately 10 – 15 EC dollars.
- August 27th, 1990, 3:15am – A tremor of 4.9 on the Richter Scale was felt. At the same time, a hurricane also approached.
- November 29th, 2007, 3:00pm – A 7.4 tremor hit Antigua and other eastern Caribbean islands. No injuries were reported.
- April 16th and 17th 2017 – A series of earthquakes hit Antigua and Barbuda, with maximum magnitude of 5.8. There were no reports of damage or injuries.

According to the National Office of Disaster Services of Antigua and Barbuda, the trigger for a tsunami is usually an earthquake at a depth of 100 kilometers or less and at a magnitude of 6 and above on the Richter Scale. Research shows that since 1530, Antigua and Barbuda have been affected by 24 tsunamis[6].

Earthquakes are seen as the most common causes of tsunamis in the Caribbean region. Notwithstanding, severe earthquake and tsunami disasters in the Caribbean are very rare events and they are difficult to predict when based on empirical data that cover only a few hundred years (Harbitz *et al.*, 2012). According to the same authors, a significant extreme earthquake-tsunami event (M_w8) has a return period in the order of 500 years, whereas a landslide-tsunami event has an even larger return period (> 1000 years).

Historical tsunami records[7] indicate that for the 1867 Virgin Islands tsunami (associated with a 7.5 magnitude earthquake) led to tsunami run-up height of about 3 m in St. John (Antigua), 1.4 m in the west coast of Barbuda and 0.6 m at English Harbour (Antigua) according to eyewitness's observations.

In the context and scale of this project tsunamis have not been considered as a significant coastal hazard because the tsunami run-up levels in the area are likely smaller than the surge and wave run-up associated to hurricanes, which occur much more frequently.

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[6] Press Release from the National Office of Disaster Services of Antigua and Barbuda 18th April 2017 ("Six earthquakes affected Antigua and Barbuda Sunday and Monday")

[7] NCEI Hazard Runup Results https://www.ngdc.noaa.gov/hazel/view/hazards/tsunami/runup-data?country=ANTIGUA%20AND%20BARBUDA

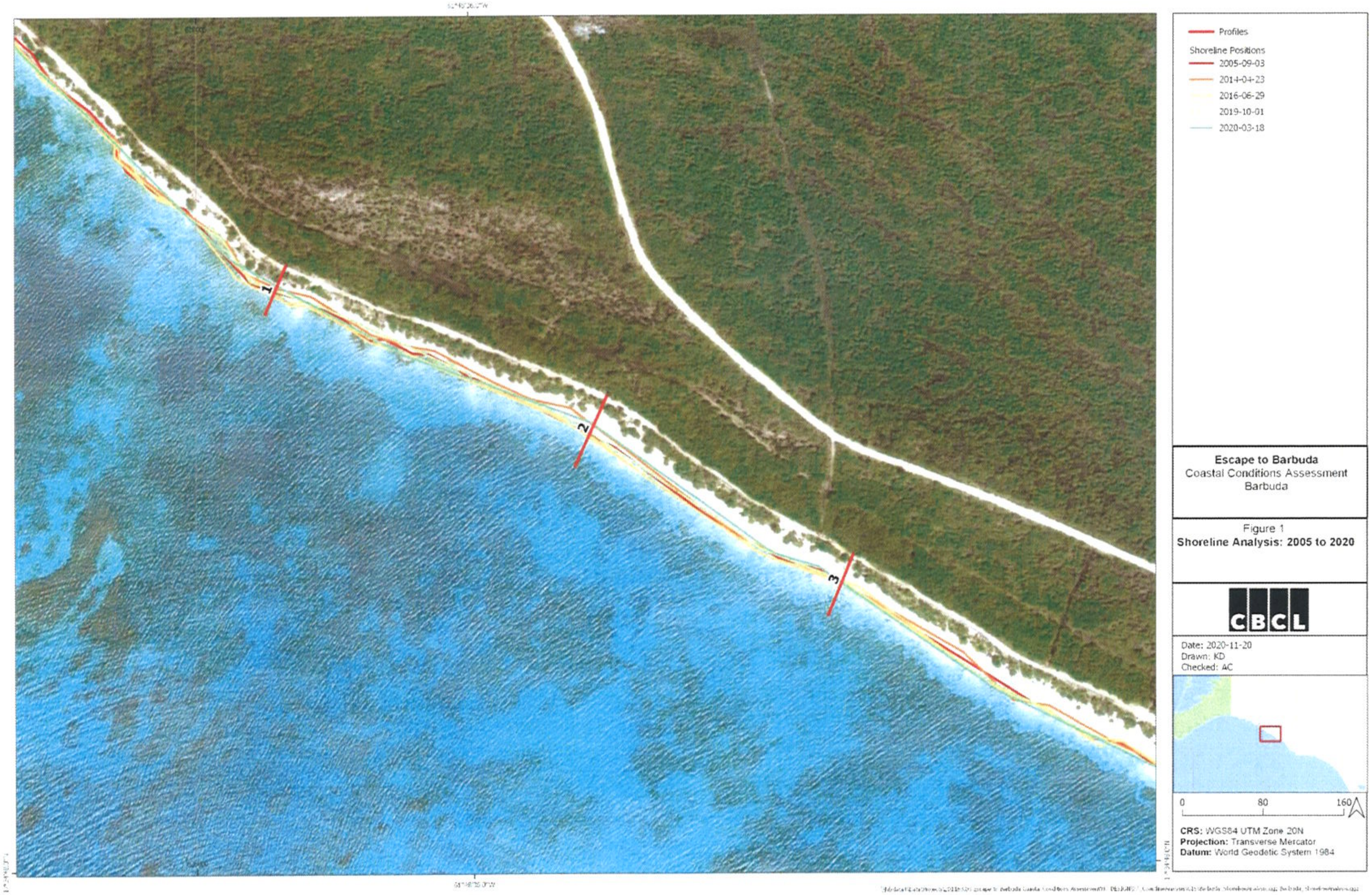

Figure 6: Recent History Coastline Evolution

2.4 Hurricanes

Barbuda is located in an area extremely prone to tropical storms and hurricanes. A hurricane is defined as a severe tropical, cyclonic storm that results in rising water levels (or storm surge) and the development of large storm waves, strong winds and extreme rainfall that can cause severe damage to coastal communities.

Hurricanes typically develop north of the equator in the tropical and subtropical latitudes of the Atlantic Ocean. Characteristics of hurricanes include low barometric pressure, high winds over 64 knots (74 mph), heavy rainfall, large waves, and storm surges. The hurricane season in the Caribbean typically extends from June to late October. The hurricane paths are generally unpredictable and can range from due westward to a gradual curvature northward, thereby impacting the Caribbean Islands and the east coast of Mexico and the U.S.

Hurricanes can be especially devastating when they make landfall, as was the case in Barbuda during Hurricane Irma in 2017 and Hurricane Luis in 1995.

Since 1852, Barbuda has experienced 51 tropical storm events[8], of which one was a Category 5 hurricane (Irma, 2017) and two were hurricanes with Category 4 (Luis, 1995 and Dog, 1950). Storms passing farther away from the island might still have an important impact by generating large waves that propagate towards the coast. Figure 7 shows the historical tracks of tropical storms and hurricanes around Barbuda. Time series of offshore significant wave height and wind speeds from the ECMWF-ERA5 reanalysis[9] and associated storm events are shown in Figure 8. Metocean parameters like waves, wind speeds, are variables that are strongly depend on the category of the hurricane, the direction of propagation (track), and the rapidly changing atmospheric parameters. Table 1 presents the estimated return periods based on historical hurricanes passing at a maximum distance of 50 kilometers from Barbuda and the same analysis using the tropical storms and hurricanes that made landfall.

Table 1: Frequency of Occurrence of Tropical Storms

Distance from Barbuda	Tropical Storm	Category 1	Category 2	Category 3	Category 4	Category 5
50 Km	3 years	8 years	11 years	19 years	57 years	170 years
Landfall	12 years	21 years	34 years	42 years	85 years	170 years

[8] Considering storms passing at a maximum 50 kilometers radius around Barbuda.
[9] Details on this data source are shown in Section 2.6.

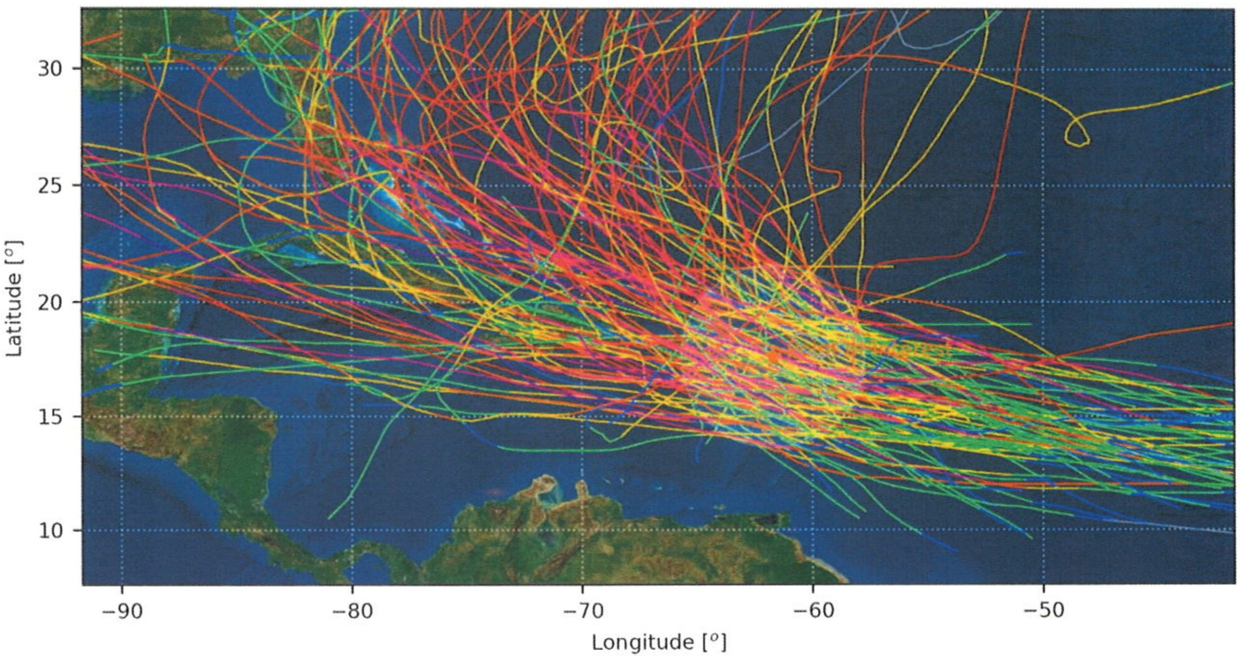

Figure 7: Tracks of Tropical Storms and Hurricanes around Barbuda[10]

Figure 8 illustrates that hurricane events are a frequent natural phenomenon to which Barbuda is exposed. Wave heights form the ECMWF – ERA5 hindcast shows that wave exceeding 5 meters (offshore) occurred six times in the last 40 years, each of these events was driven by a hurricane of Category 4/5 (shown in pink and purple in the figure). The biggest difference between hurricane Luis and Irma in comparison to other Category 4/5 hurricanes that generated large waves, is that both Luis and Irma made landfall on the island, as a consequence the damage caused by the waves and the sustained winds during the storm was considerably more catastrophic.

[10] Based on historical hurricane tracks from NOAA

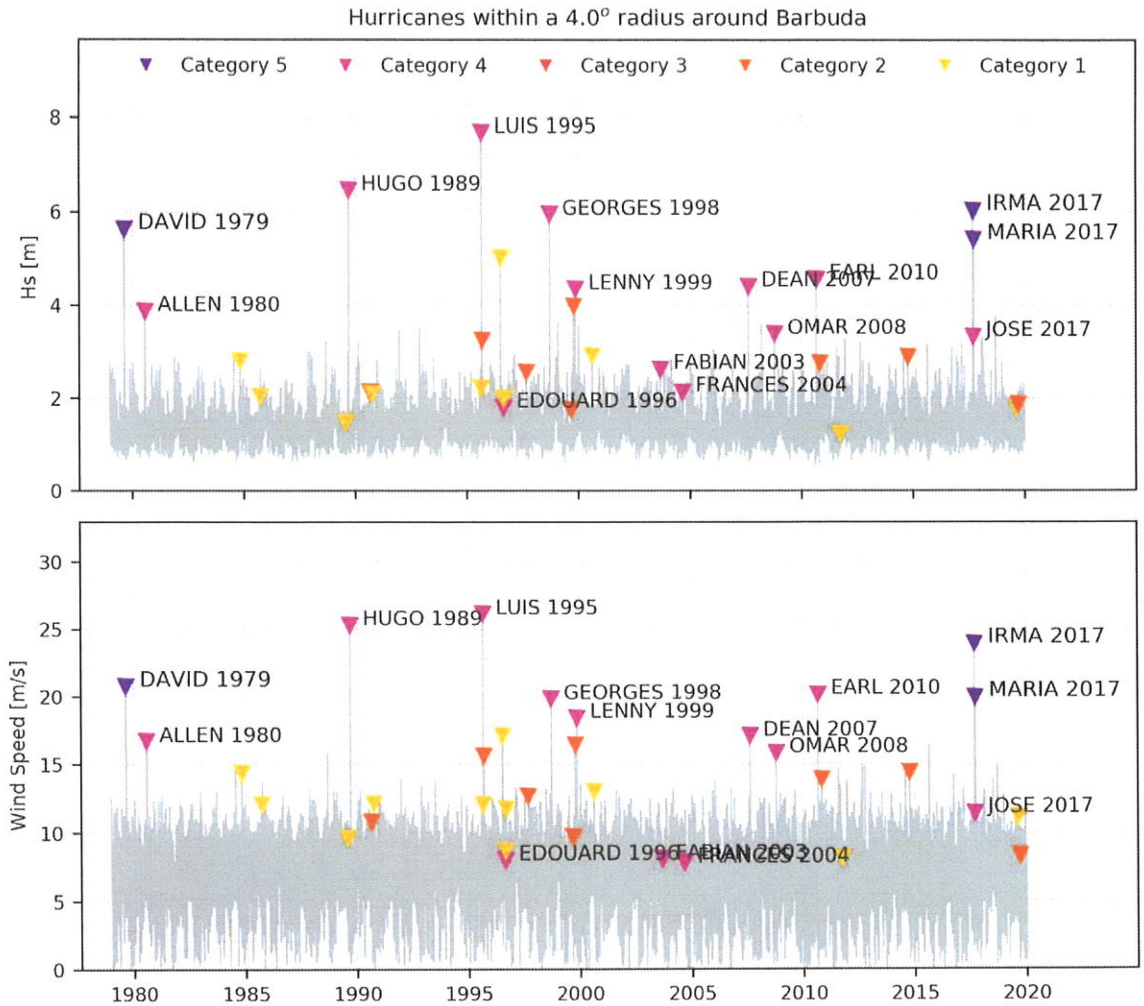

Figure 8: **Time Series of Offshore Significant Wave Height and Wind Speeds (ERA5) and Associated Storm Events**

Figure 9 shows the storm characteristics at different distances[11] from Barbuda based on the historical hurricane tracks. This analysis served as basis for the definition of "design storms". The storm surge and offshore wave conditions associated to those storms are discussed in the corresponding sections of the report (Sections 2.5.2 and 2.7). A summary of the extreme conditions associated with each design storm is shown in Section 2.8.

In this study we analyzed the effect of hurricanes solely on the coastal processes, including the generation of extreme storm surges and waves, and their impact in determining flood levels, coastal erosion and set-back distances. Hurricane hazards associated with extreme wind speeds and rainfall are outside the scope of this study but should be taken into consideration when analyzing the overall hazards and risks to the development.

[11] Distances are measured in degrees. At this latitude 1 degree corresponds to approximately 111 km or 69 miles.

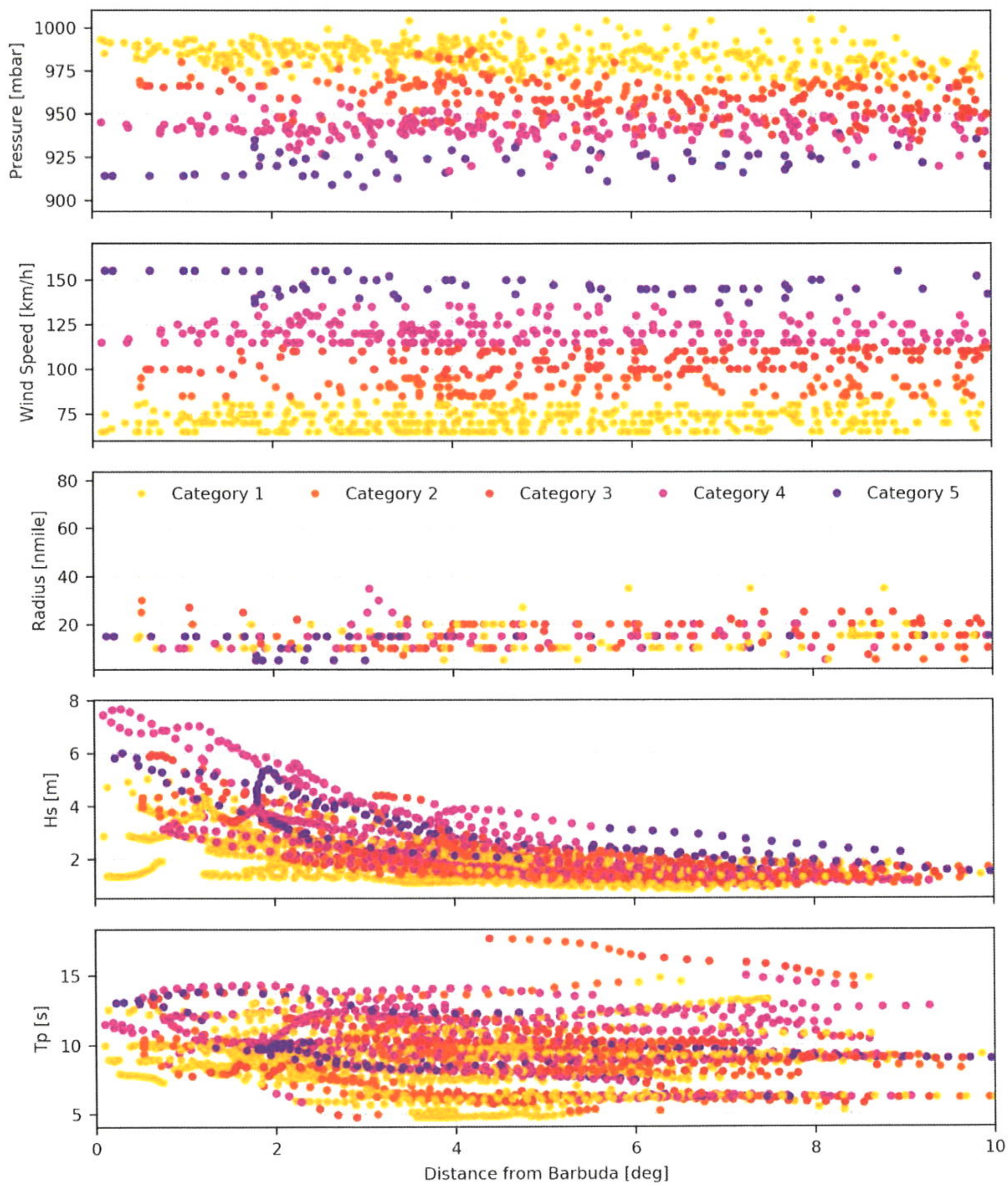

Figure 9: Storm Characteristics Based on the Distance from Barbuda

2.5 Water Levels

Water levels are an important aspect in both design and assessment of nearshore hydrodynamic conditions. Daily tidal variations influence the direction of flows at the beach; storm surge can introduce hazards during storm events; and sea level rise poses long-term risks to the development. Design water levels at the area of interest require understanding of local tides, storm surge, and future sea-level rise.

Coastal still water levels include contributions from the following parameters:

- **Tide –** The Highest Astronomical Tide (HAT) is a common parameter for representing high tide. It represents the average of the annual maxima from a 19-year tidal prediction cycle; At Barbuda, the tidal amplitude is very small (about 20 cm).
- **Storm Surge –** Storm surges are created by meteorological effects on sea level, such as wind set-up[12] and low atmospheric pressure, and can be defined as the difference between the observed water level during a storm and the predicted astronomical tide. Extreme storm surges typically occur during tropical hurricane events due to their low pressure and high wind speeds.
- **Sea-Level Rise (SLR) –** Global Mean SLR will likely accelerate due to climate change, causing increased risks of coastal erosion and flooding.

The following section outlines the tidal, storm surge and sea level rise data used in this study.

2.5.1 Tides

Barbuda's water level monitoring station (*Barbuda, Antigua and Barbuda – Station ID: 9761115*[13]) installed from July 2011 to June 2012 provides a baseline for tidal constituents and levels. Barbuda experiences mixed semi-diurnal tides. A mixed semi-diurnal tidal cycle is a cycle with two high and low tides with different sizes each lunar day. The difference in height between successive high (or low) tides is called the diurnal inequality, over a microtidal range (less than 2m in tidal range) with a mean tidal range of 0.2 metres (0.6 feet). The tidal levels derived by the National Oceanic & Atmospheric Administration (NOAA), are summarized in Table 2.

Table 2: Astronomical Tidal Levels. Source: NOAA Tides and Currents

Tidal Level	Tidal Elevation (m +MSL)
HAT (Highest Astronomical Tide)	0.15
MHHW (Mean Higher High Water)	0.09
MHW (Mean High Water)	0.09
MSL (Mean Sea Level)	0.00
MLW (Mean Low Water)	-0.01
MLLW (Mean Lower Low Water)	-0.13
LAT (Lowest Astronomical Tide)	-0.26

[12] Wind set-up refers to the increase in mean water level along the coast due to shoreward wind stresses on the water surface.

[13] Details of the measuring station are described at https://tidesandcurrents.noaa.gov/stationhome.html?id=9761115

2.5.2 Storm Surges

Storm surges are anomalies in the sea level during a storm, measured as the height of the water above the normal predicted astronomical tide. In Barbuda, storm surges are most frequently associated with tropical hurricane events. Details on the hurricane climate of the area is described in Section 2.4. Characteristics of hurricanes include very low barometric pressure and extreme wind speeds, both of which lead to extreme storm surges.

Storm surges are complex events to model numerically. The data are most reliable if measured locally, and so therefore we have assumed storm surges based on a combination of analyzing nearby historical hurricanes, and historical measured water level evidence during storms. For the scope of this study it is sufficient, but it is recognized that there are significant limitations to this approach and a more sophisticated analysis is recommended for detailed design.

For the purpose of this study, we make reference to a study that analyzed surge levels for different return periods based on the findings from the Global Assessment Risk (2015, Table 3).

Table 3: Surge Levels at Barbuda Based on the Global Assessment Risk (2015) Source: Deborah Brosnan & Associates (2020)

Storm Surge (Relative to Mean Water Level)		
Return Period	**Surge (m)**	**Surge (ft)**
10	1.1	3.6
25	1.7	5.4
50	2.2	7.2
100	2.3	7.5

To derive the storm surge associated with different hurricane categories, the different storm characteristics (atmospheric pressure and wind speeds) were analyzed. A baseline Category 5 storm event was defined based on the surge levels observed during Hurricane Irma 2017 and the associated atmospheric pressure and wind speeds. Then, those surge levels were pro-rated to other hurricane categories based on the relative contribution of atmospheric pressure and wind speeds. For example, Category 3 hurricanes present typically 50% less difference in pressure and 40% lower wind speeds than a Category 5 hurricanes, therefore we assumed that the surge levels are approximately 45% lower than the observed for Hurricane Irma. The derived surge levels are in line with previous studies (Table 3).

Table 4: Storm Characteristics and Pro-rated Surge Levels at Barbuda

Hurricane	Atmospheric Pressure (mbar)	Wind Speed (m/s)	Surge + Tide (m MSL)
Category 1	990	20.0	0.7
Category 3	965	28.0	1.3
Category 5	915	42.0	2.3

2.5.3 Sea Level Rise

As described by the latest Intergovernmental Panel on Climate Change (IPCC), Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities report (Oppenheimer *et al.* 2019), human communities in close connection with coastal environments, small islands (including Small Island Developing States, SIDS) are particularly exposed to ocean changes, such as sea level rise. The low-lying coastal zone is currently home to around 680 million people (nearly 10% of the 2010 global population), projected to reach more than one billion by 2050. SIDS are home to 65 million people.

Global mean sea level (GMSL) is rising and accelerating The sum of glacier and ice sheet contributions is now the dominant source of GMSL rise. GMSL from tide gauges and altimetry observations increased from 1.4 mm/yr over the period 1901–1990 to 2.1 mm/yr over the period 1970–2015 to 3.2 mm/yr over the period 1993–2015 to 3.6 mm/yr over the period 2006–2015.

Future rise in GMSL caused by thermal expansion, melting of glaciers and ice sheets and land water storage changes, is strongly dependent on which Representative Concentration Pathway (RCP) emission scenario is followed. SLR at the end of the century is projected to be faster under all scenarios, including those compatible with achieving the long-term temperature goal set out in the Paris Agreement. GMSL will rise between 0.43 m (0.29–0.59 m, likely range; RCP2.614) and 0.84 m (0.61–1.10 m, likely range; RCP8.515) by 2100 (medium confidence) relative to 1986–2005. The expected sea level rise for 2060 and 2100 are summarized in Table 5.

Table 5: Sea Level Rise Projections[16]

Scenario/Sea Level Rise Horizon	2060 (m)	2100 (m)
RCP2.6 (low CC scenario)	0.30	0.43
RCP8.5 (high CC scenario)	0.36	0.84

The combination of gradual change of mean sea level with Extreme Sea Levels (ESL) events such as tides, surges and waves causes coastal impacts. ESL events at the coast that are rare today will become more frequent in the future, which means that for many locations, the main starting point for coastal planning and decision making is information on current and future ESL events.

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[14] RCP 2.6 is a "very stringent" pathway. According to the IPCC, RCP 2.6 requires that carbon dioxide (CO2) emissions start declining by 2020 and go to zero by 2100.

[15] This is a high climate change scenario in which the atmospheric carbon dioxide concentration will reach a peak of 1370 parts per million by 2100 and will continue increasing after that.

[16] Intergovernmental Panel on Climate Change (IPCC), Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities report (Oppenheimer et al. 2019)

Finally, the science of SLR will keep evolving with updated observations and improving model predictions. Implications for infrastructure and coastal flooding will need to be re-evaluated with periodic updates in SLR projections.

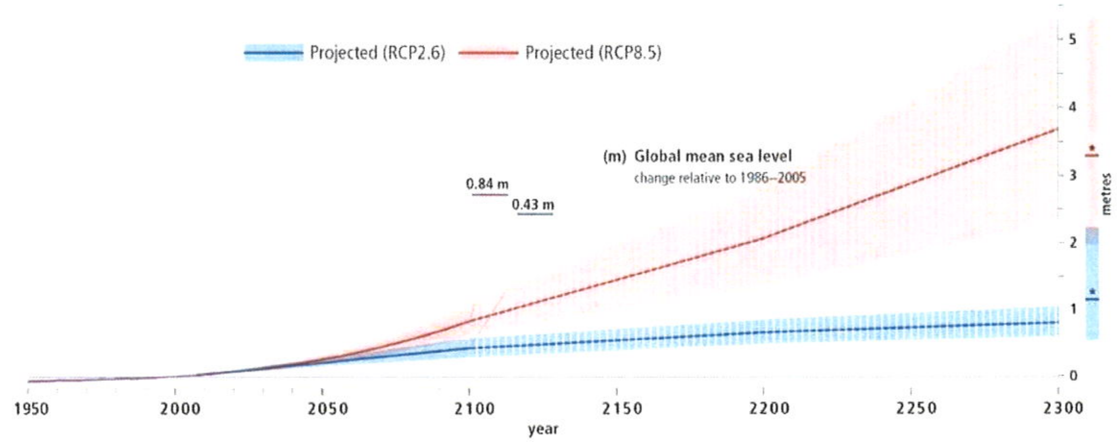

Figure 10: Global Mean Sea Level Rise Projections (RCP 2.6 and RCP8.5)

2.6 Wind

Wind speeds along the coast of Barbuda were obtained from the European Centre for Medium-Range Weather (ECMWF) ERA5 reanalysis. ERA5 is a global reanalysis dataset covering the Earth on a 30km grid and resolving the atmosphere using 137 levels from the surface up to a height of 80km. ERA5 combines vast amounts of historical observations into global estimates using advanced modelling and data assimilation systems.

For this analysis, hourly wind speeds at 10 m height were obtained for the period 1979-2019 at a location offshore of Barbuda (Lon -62.05°, Lat 17.25°). The wind climate in the area is controlled by the easterly trade winds. Typical wind speeds range from 5 to 9 m/s. During hurricane events hourly-averaged wind speeds up to 26 m/s can occur, with maximum sustained wind speeds of 45 m/s and wind gusts up to 80 m/s[17] (for Category 5 storms).

[17] According to the National Hurricane Center Report https://www.nhc.noaa.gov/data/tcr/AL112017_Irma.pdf

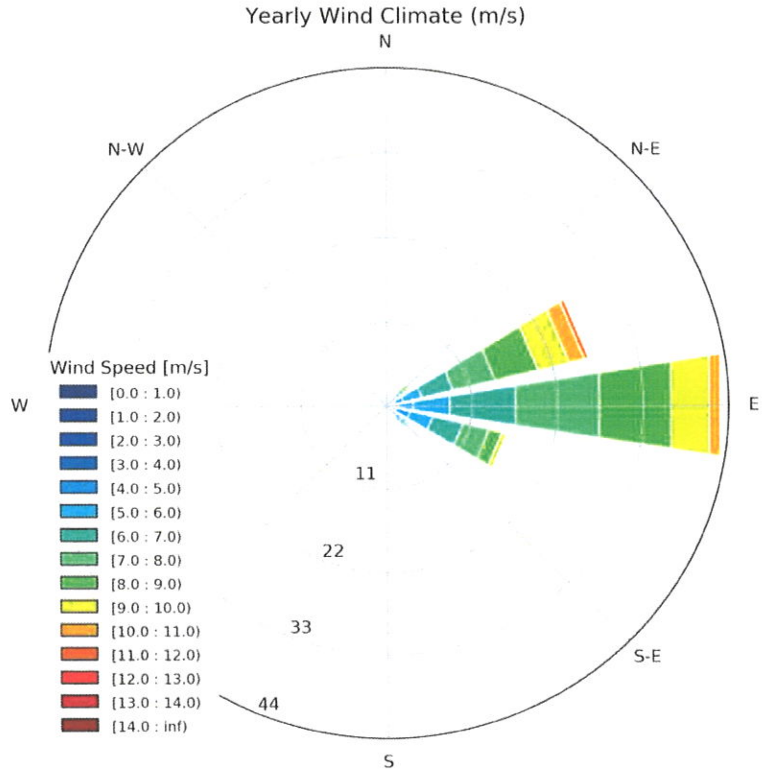

Figure 11: Wind Climate Schematization – Annual Wind Rose The Circles Indicate the Cumulative Percentage of Occurrence

2.7 Offshore Waves

Offshore wave conditions were also obtained from the European Centre for Medium-Range Weather (ECMWF) ERA5 reanalysis. Following the wind climate, most of the waves in the area come from Easterly directions. Wave heights are typically below 2 m but larger waves occur during hurricane events. Hurricane-generated waves also come from a wide range of directions, due to the rotational nature of the storm.

Peak wave periods show a large range, indicating two components of the wave climate: locally-generated wind-sea with periods up to 10 s and long swell coming from the North Atlantic with periods up to 18 s (Figure 13).

Very rare events come from the southerly directions (SE-SW) which are the directions dominant for design. Those waves are typically smaller and have shorter periods than East/Northeast events.

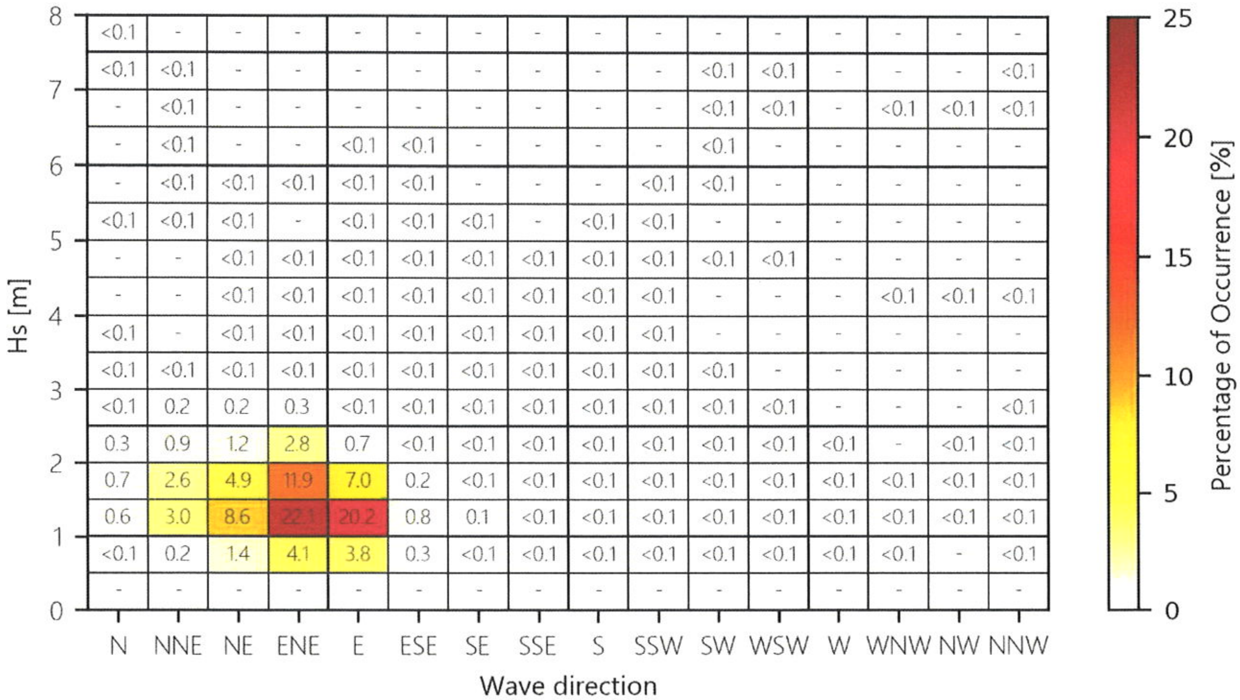

Figure 12: Joint Occurrence of Offshore Mean Wave Direction and Significant Wave Height

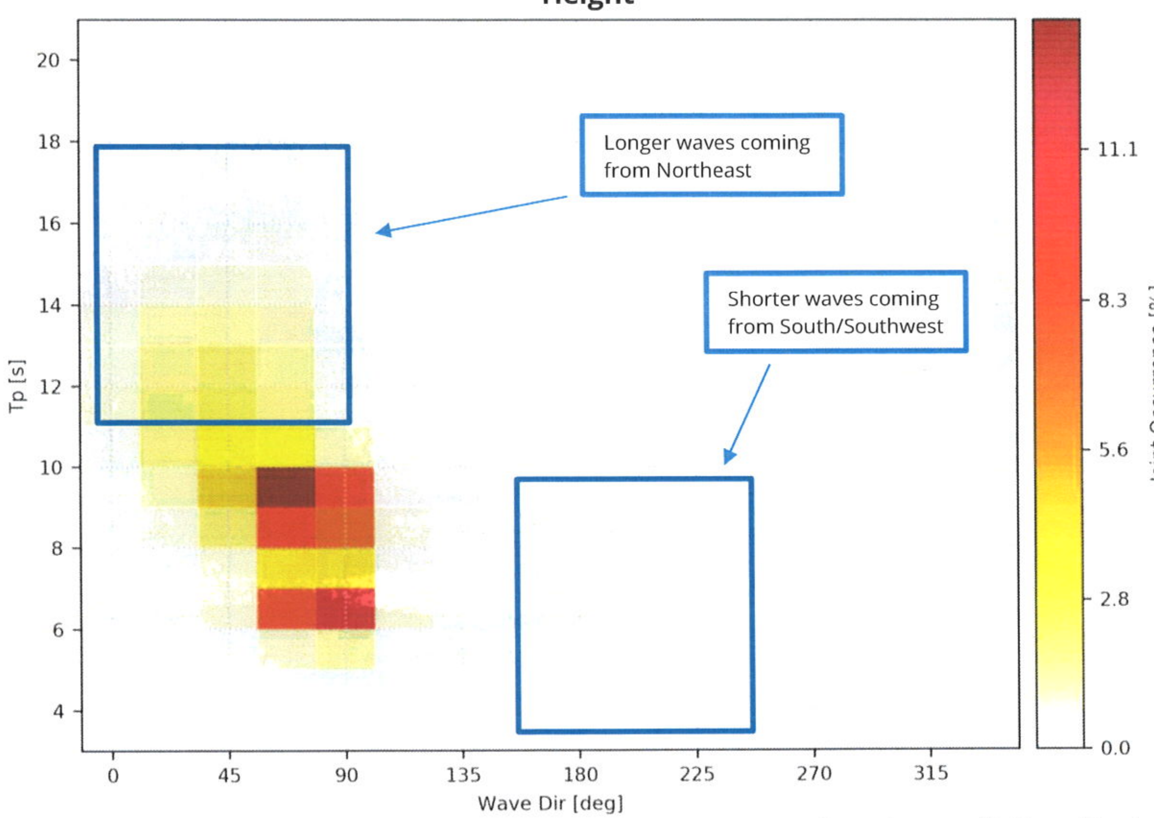

Figure 13: Joint Occurrence of Offshore Mean Wave Direction and Wave Peak Period

2.7.1 Extreme Value Analysis of "Normal" (Non-hurricane) Conditions

For the analysis of the ("**normal**") non-hurricane wave conditions, the hurricane events were removed from the time series and a directional extreme value analysis was performed on ocean waves only (including swell and wind-generated waves only). Wave conditions were divided into 8 directional bins (45°) and the peaks over certain thresholds were fitted into a Generalized Pareto Distribution curve for each directional bin.

For most directional bins S, SW, W, NW, N and NE there were not enough peaks for an accurate calculation of Generalized Pareto Distribution curve. Therefore those estimates should be used with care. For this analysis the return period of 50 years was selected because those estimates are close to the total duration of the input time series (41 years) and therefore are considered a bit more reliable. For southwest waves only 2 peaks have been observed during this period, indicating that the minimum return period for this direction is 20 years. Four conditions were selected for further analysis and model simulations (Table 6).

Associated peak wave periods have been defined based on the Hs/Tp relationship of the peaks. Two methods are considered:

1. Most common wave steepness.
2. Logarithmic fit.

The associated Tp is calculated for both methods and the largest value is selected (conservative approach). The associated wind speed was calculated based on a linear fit between Hs and wind speed.

Table 6: Selected Extreme Offshore Wind/Wave Conditions for Non-hurricane Events

Directional Bin	RP [years][18]	Direction [deg]	Hs [m]	Tp [s]	WS [m/s]
E	50	90	3.6	10.5	15.8
SE	50	110	3.6	11.6	15.7
S	50	180	2.7	7.3	13.2
SW	50	225	2.1	6.4	11.5

2.7.2 Hurricane-generated Waves

To derive wave conditions associated with different hurricane categories, the hurricane tracks were matched with the ECMWF-ERA5 offshore wave conditions. The wave height and peak period for different hurricane categories and distance of the hurricane center are shown in Figure 9. The typical significant wave height (Hs), peak wave period (Tp) and wind

[18] Return period of offshore conditions associated with non-hurricane events.

speeds per hurricane category were defined based on the average values associated to storms at distances smaller than 1 deg.

For the model simulations it was assumed that waves approach perpendicular to the coastal orientation (waves/wind coming from direction = 210º). This is because hurricane-generated waves come from a wide range of directions, due to the rotational nature of the storm. As summary of the conditions per storm event is shown in Table 7.

2.8 Summary of Extreme Conditions

To determine extreme storm conditions for the coastal hazard assessment the following metocean parameters were analyzed:

- Offshore Waves (40+ years of data coverage).
- Offshore Winds (40+ years of data coverage).
- Hurricanes (100+ years of data coverage).
- Tides from local station.
- Surge levels (including measured extreme events like Irma 2017).
- Sea Level Rise projections (IPCC).

Table 7 shows the summary of the selected extreme conditions that were used as input for the numerical modelling of wave propagation, wave run-up and erosion.

Table 7: Summary of Representative (Offshore) Extreme Storm Conditions

	Storm Event	H_s (m)	T_p (s)	Wind Speed (m/s)	Surge + Tide (m MSL)
Non-hurricane Wave Conditions		2.1	6.4	11.5	0.1
Hurricanes	Category 1	3.0	9.0	20.0	0.7
	Category 3	5.5	11.0	28.0	1.3
	Category 5	8.4	15.3	42.0	2.3

Chapter 3 Modelling of Extreme Conditions

3.1 Modelling Methodology

Two different models were used in this study: Delft3D-WAVE for wave propagation from offshore to nearshore and XBeach for wave propagation until the coastline and beach morphological development.

Table 8: Summary of Models Applied in the Present Study

Area of Application	Model	Objective	Inputs	Outputs
Regional wave transformation, wind wave growth.	Delft3D-WAVE	Nearshore transformation and wind wave growth up to 10 m water depth.	ECWMF-ERA5 extreme wave/wind conditions; Hurricane characteristics.	Offshore wave conditions at 10 m water depth.
Run-up and Morphology	XBeach	Flood levels and erosion distances for set-back definition.	Wave conditions at 10 m water depth from Delft3D-WAVE.	Wave run-up and maximum erosion distance

3.1.1 Wave Modelling (Delft3D – WAVE)

Delft3D-WAVE is based on the SWAN model (Simulating Waves Nearshore). The model computes the evolution of random, short-crested waves in coastal regions with deep, intermediate and shallow water and ambient currents. The SWAN model accounts for (refractive) propagation due to current and depth and represents the processes of wave generation by wind, dissipation due to whitecapping, bottom friction and depth-induced wave breaking and non-linear wave-wave interactions (both quadruplets and triads) explicitly with state-of-the-art formulations.

A curvilinear grid was developed, with resolution of computational grid cells varying from about 100 m near the study area to 300 m near the boundaries (Figure 14). The bathymetry was based on the nearshore bathymetric measurements (described in Section 2.1) and the

General Bathymetric Chart of the Oceans (GEBCO)[19] for the offshore areas. Bathymetry was smoothed to avoid model instabilities.

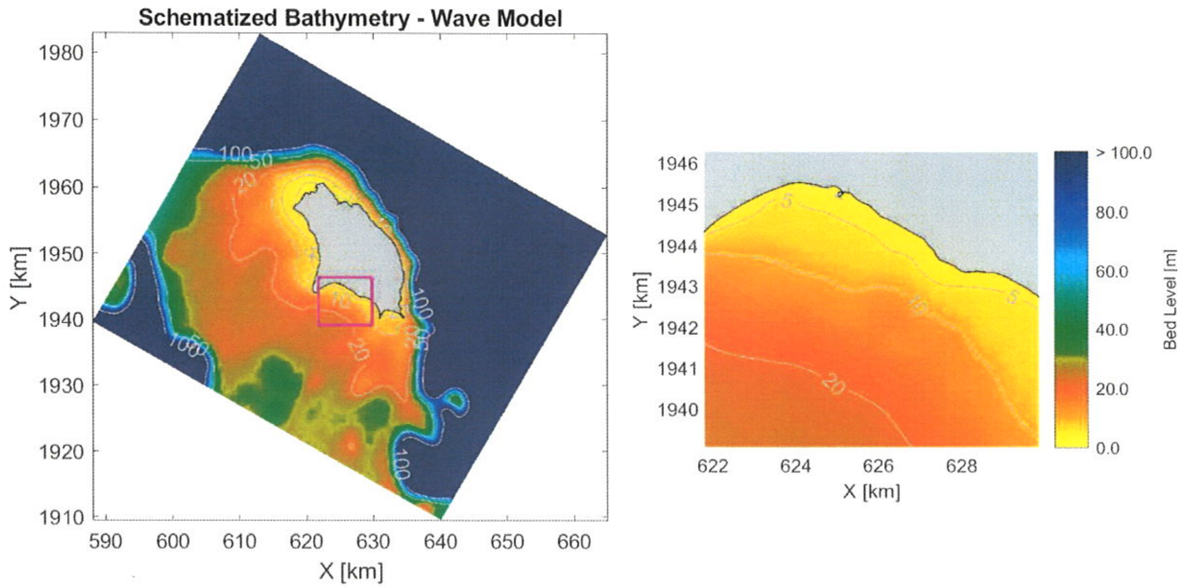

Figure 14: Computational Grid and Bathymetry

Two obstacles were defined to represent some coastal features that are not properly represented with the bathymetry. The model uses (mostly) default settings from Delft3D-WAVE (main changes include increasing the directional resolution to 72, increasing the frequency resolution to 48 and changing whitecapping formulation to Westhuysen).

3.1.2 Run-up and Morphology Modelling (XBeach)

To determine setback distances and flood levels during extreme events, wave run-up and beach erosion were calculated using the XBeach model.

XBeach is an open-source numerical model which is originally developed to simulate hydrodynamic and morphodynamic processes[20] and impacts on sandy coasts with a domain size of kilometers and on the time scale of storms. Since then, the model has been applied to other types of coasts and purposes.

The model includes the hydrodynamic processes of short wave transformation (refraction, shoaling and breaking), long wave (infragravity wave[21]) transformation (generation,

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[19] GEBCO – The General Bathymetric Chart of the Oceans https://www.gebco.net/

[20] Morphodynamics is the process by which morphology affects hydrodynamics in such a way as to influence the further evolution of the morphology itself.

[21] Infragravity waves are ocean surface waves with a typical period of 25-250s (frequency of 0.004-0.04 Hz). They are indirectly formed by the wind because they receive their energy from the short sea- and swell waves, which have typical periods of 2-20s. While infragravity waves are generally small on the open ocean, close to the coast they can be up to a few meters in height and thus dominate the water motion, in particular during storms.

propagation and dissipation), wave-induced setup and unsteady currents, as well as overwash and inundation. The morphodynamic processes include bed load and suspended sediment transport, dune face avalanching, bed update and breaching. The overall model development has been validated with a series of analytical, laboratory and field test cases using a standard set of parameter settings which serve as recommendations for the application of the model for sites like the proposed development ('Escape To Barbuda').

XBeach is used to simulate storm events and estimate beach retreat during those events. The accuracy of the model is mainly driven by the input conditions such as waves, tide, surge and sediment properties. Additionally, physical and numerical settings[22] can be changed to calibrate the model and to carry out a detailed and project-specific investigations.

As most numerical models, grid resolution (in this case 1D grid spacing), is key to properly propagate wave energy along the modeling domain. One key limitation of a 1D cross-shore model is that it does not take into account longshore sediment transport. In this study, based on the analysis of the wave climate and the historical shoreline evolution, we have concluded that morphological changes due to longshore sediment transport is minor, therefore this is an ideal application of the 1D XBeach model.

Two different sets of runs were performed using the XBeach model:

- Surfbeat mode, where the short wave variations on the wave group scale (short wave envelope) and the long waves associated with them are resolved. This setting was used to analyse beach erosion.
- Non-hydrostatic mode (wave-resolving), where a combination of the non-linear shallow water equations with a pressure correction term is applied, allowing to model the propagation and decay of individual waves. This setting was used to analyse wave run-up and maximum flood levels.

Simulations were performed for five (5) representative cross-shore profiles23 along the beach of the proposed development. The grid was setup to cover a varying length per profile from a depth of 10m to the upper beach section, where 0.0m indicates the mean water line. The depth assigned to the grid was derived based on the merged nearshore bathymetric survey data and the beach profile topographic survey (described in Section 2.1), and interpolated accordingly to the required grid resolution. When necessary, the profile was extended inland using the average beach slope. An example of one model bathymetry is shown in Figure 15.

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[22] For more details on model physical and numerical settings see the official Xbeach website: https://xbeach.readthedocs.io/en/latest/index.html

[23] Profiles 1,3,5,7 and 9 from Figure 5 were used as representative profiles.

For the sediment characteristics we considered a mean grain size (D_{50}) of 0.2 mm (medium sand) and porosity of 40%. This was assumed based on typical sediment characteristics for Caribbean islands.

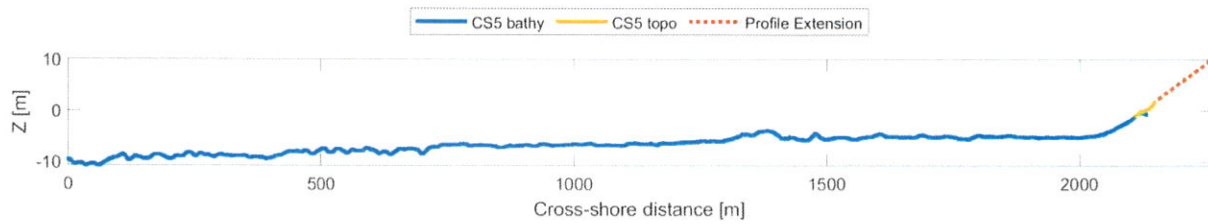

Figure 15: Example of Cross-shore Profile used in the XBeach Model[24].

3.2 Nearshore Wave Conditions

3.2.1 Boundary Conditions

The Delft3D-WAVE model was forced with extreme wave conditions (Hs, Tp, Direction) at the model boundaries and a uniform wind field over the entire domain. Simulations were performed for both "normal" (non-hurricane) wave condition and hurricane events. A summary of those events is shown in Table 7.

3.2.2 Numerical Modelling Results

Figures 16 to 18 depict the wave propagation and transformation nearshore for different offshore wind/wave scenarios. Note that different color scales were used in the figures for hurricane and non-hurricane conditions.

The area of the development is relatively protected from the most common wave direction (from the East). Extreme East waves are reduced from 3.6 m offshore in deep water, to 1.3 m at a 5 m depth (Figure 16), whereas waves coming from the Southwest, although smaller offshore, have very little reduction towards the coast (Hs reduces from 2.1 m offshore in deeper water to 1.7 m at 5 m depth, Figure 17).

Hurricane events can generate waves in a wide range of directions due to the rotational nature of the storm. For this analysis it was assumed hurricane-generated waves come from the Southwest (which is the most critical wave direction). Those waves are depth-limited (due to wave breaking) with significant wave height reducing towards the coast (Figure 18). Table 9 shows a summary of the wave conditions at the 10 m depth contour which are used as the boundary condition of the XBeach model (Section 3.3).

[24] The profile is shown with a vertical exaggeration factor 10.

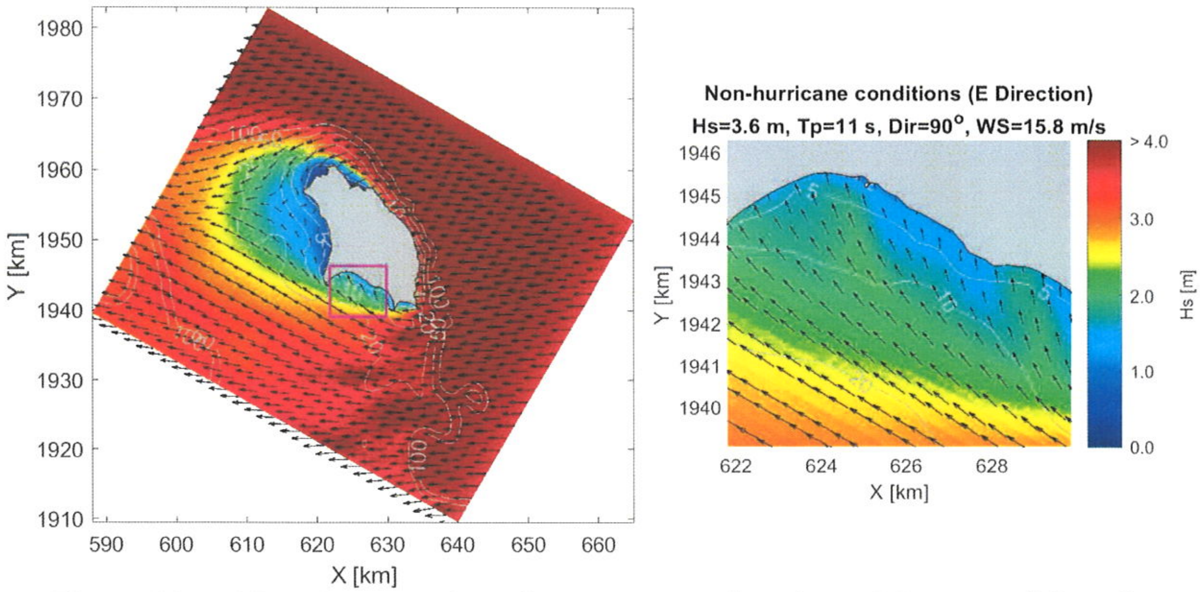

Figure 16: Wave Propagation of Extreme Non-hurricane Wave Conditions for Waves coming from the East (the Most Common Offshore Wave Direction)

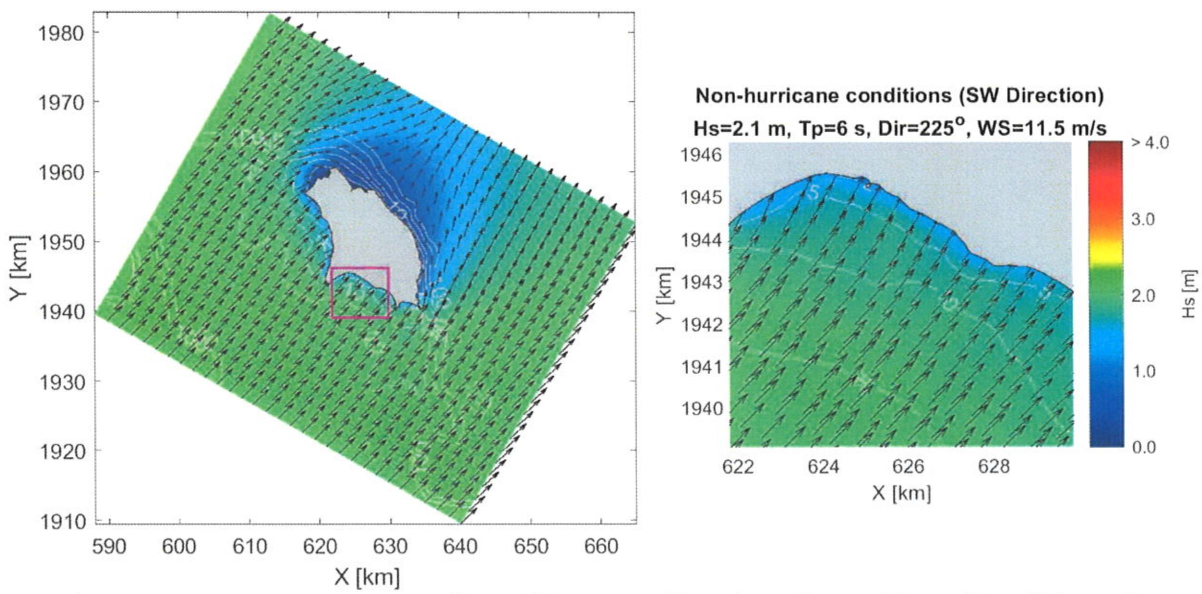

Figure 17: Wave Propagation of Extreme Non-hurricane Wave Conditions for Waves coming from the Southwest (Directly Incident at the Project Site)

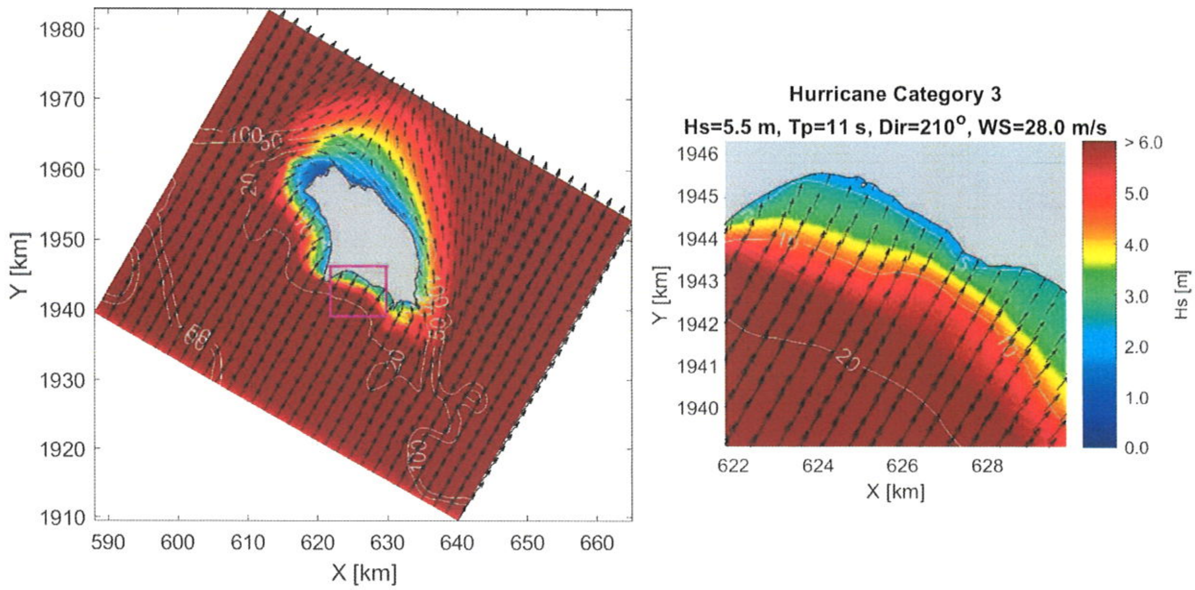

Figure 18: Wave Propagation of Offshore Waves Generated by a Hurricane Category 3

Table 9: Wave Conditions at 10 m Depth Contour in Front of 'Escape To Barbuda' Development Area Based on the Delft3D-WAVE Model. Those Conditions are used as the XBeach Model Boundaries

Scenario	Wind Speed [m/s]	Hs [m]	Tp [s]	Mean Direction [deg]
Extreme East Waves	15.8	2.1	10.6	146
Extreme Southwest Waves	11.5	1.9	6.5	220
Hurricane Category 1	20.0	3.8	8.9	206
Hurricane Category 3	28.0	4.3	11.0	205
Hurricane Category 5	42.0	4.6	15.3	202

3.3 Wave Run-up and Beach Morphology

The XBeach model was used to calculate wave run-up and beach morphological development during storm events.

3.3.1 XBeach Boundary Conditions

The XBeach model inputs can be summarized as:

- **Waves –** The model is forced with a Jonswap wave spectrum defined by the significant wave height and peak wave derived from the Delft3D-WAVE model results (Table 9).
- **Tide and surge –** A time-varying water level signal is applied at the model boundaries. A storm with sinusoidal shape is generated using the total water level derived from the hurricane surge analysis.

Table 10 presents the summary of the input conditions that were used for the XBeach simulations. An artificial input time series was created with a duration of 6 hours with a sinusoidal shape, where the peak of the storm has the values shown in Table 10 .Example of XBeach boundary conditions for a Category 1 hurricane event is shown in Figure 19.

Table 10: Input Wave Conditions for 1D XBeach Simulations

	Hs [m]	Tp [s]	Maximum Water Level [m]
Extreme non-Hurricane Wave Conditions	1.9	6.5	0.1
Hurricane Category 1	2.8	9.0	0.7
Hurricane Category 3	4.3	11.0	1.3
Hurricane Category 5	4.6	15.3	2.3

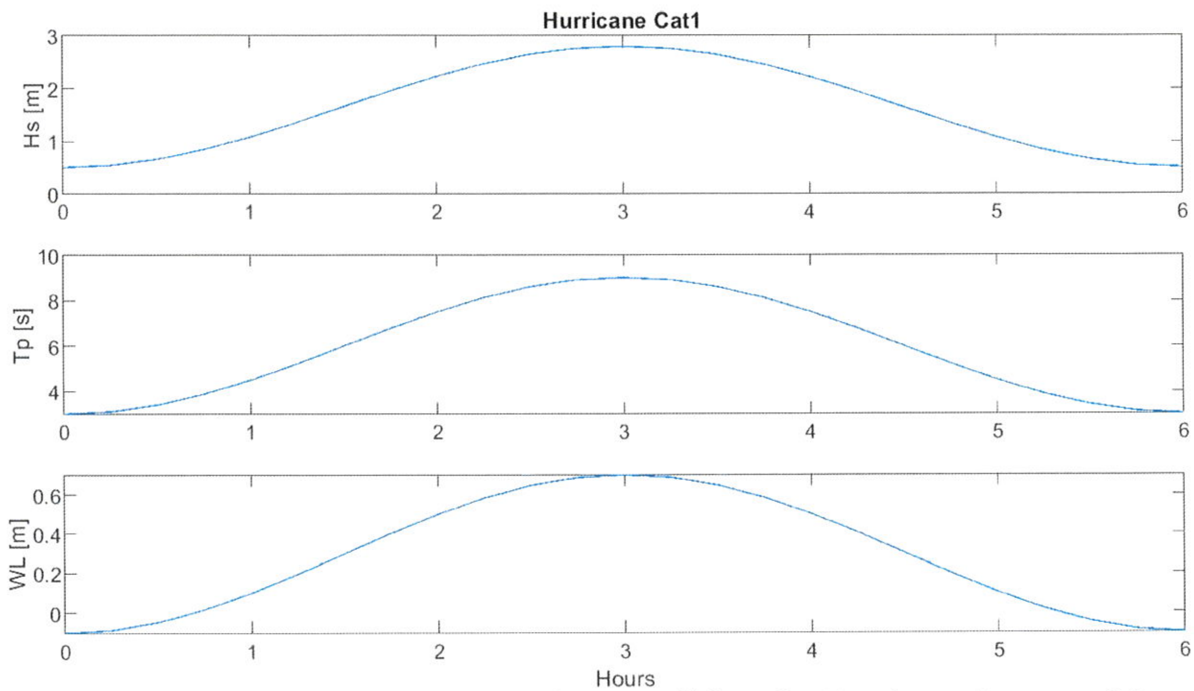

Figure 19: Example of XBeach Boundary Conditions for Hurricane Category 1 Event

3.3.2 Numerical Modelling Results (XBeach) – Wave Run-up

Figure 20 depicts the wave run-up calculated using the XBeach model for a selection of scenarios. Overall, the run-up and flood levels are relatively similar along the different profiles. Maximum flood levels ranged from 0.8 and 1.0 m during normal wave conditions and 3.5 to 4.4 m during hurricane Category 3 events. For extreme events, the maximum flood levels are mostly influenced by the peak water levels and wave period. Longer waves lead to more wave run-up and higher water levels increase the flood levels. For those events nearshore wave height are similar due to a number of factors like depth induced wave breaking and wave transformation due to bottom roughness.

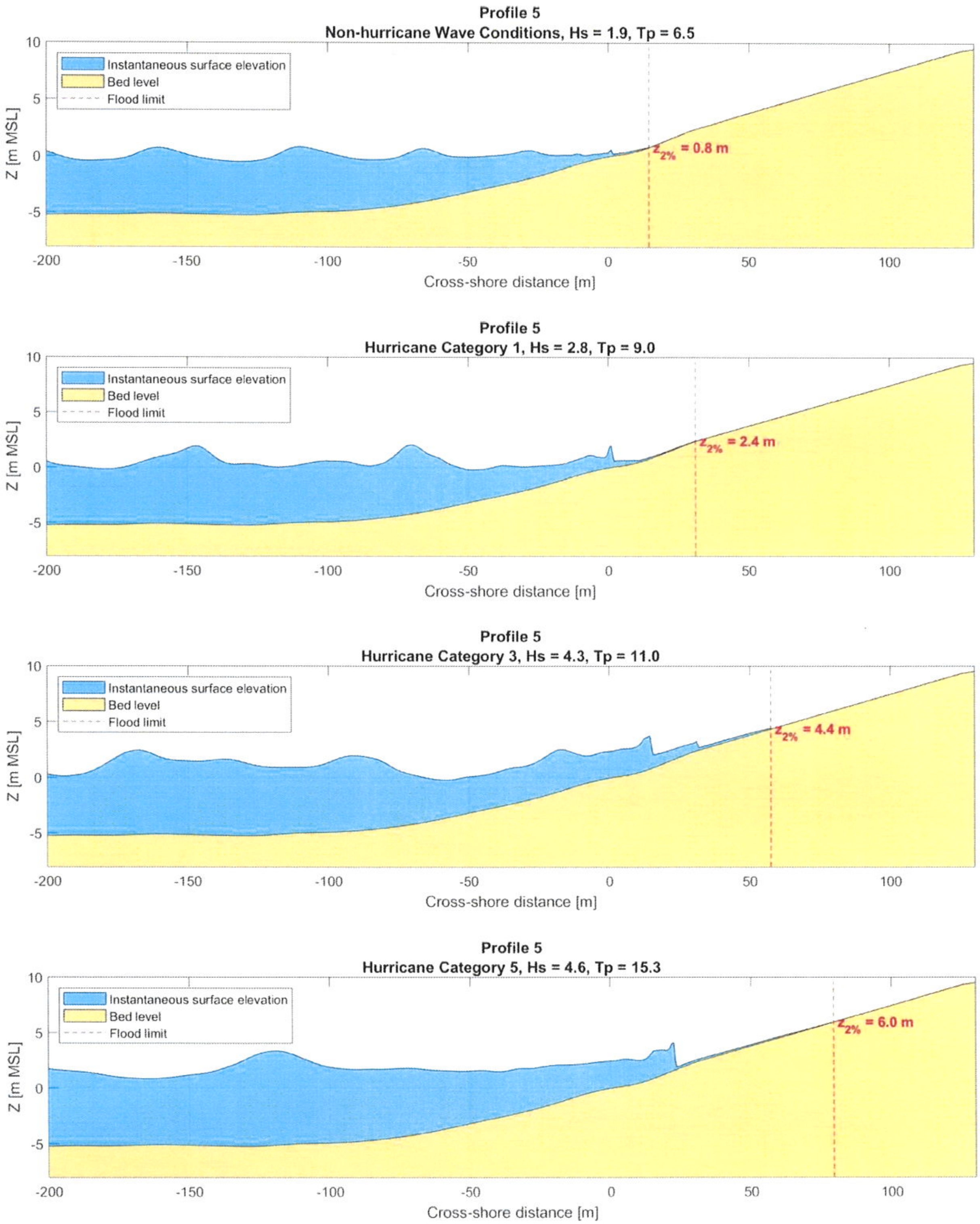

Figure 20: Instantaneous Surface Elevations at the Peak of the Storm and Wave Run-up for Profile 5 for Different Scenarios[25]

[25] The profiles are shown with a vertical exaggeration factor 4.

3.3.3 Numerical Modelling Results (XBeach) – Beach Erosion

The potential for beach erosion during storm events was calculated using the XBeach model. Figure 21 shows the beach development at different times during the storm for Profile 5 (see location in Figure 5). The model indicates that the beach could temporarily retreat about 35 m during extreme events (Category 3 hurricanes) in areas where no vegetation and/or other natural protection features are present. The beach retreat caused by non-hurricane events is less than 10 m.

During calm weather (mild ocean waves) it is expected that a partial beach recovery will occur, however, if an event of this magnitude (Category 3 or higher) makes landfall it is recommended to enhance the natural recovery with beach nourishment.

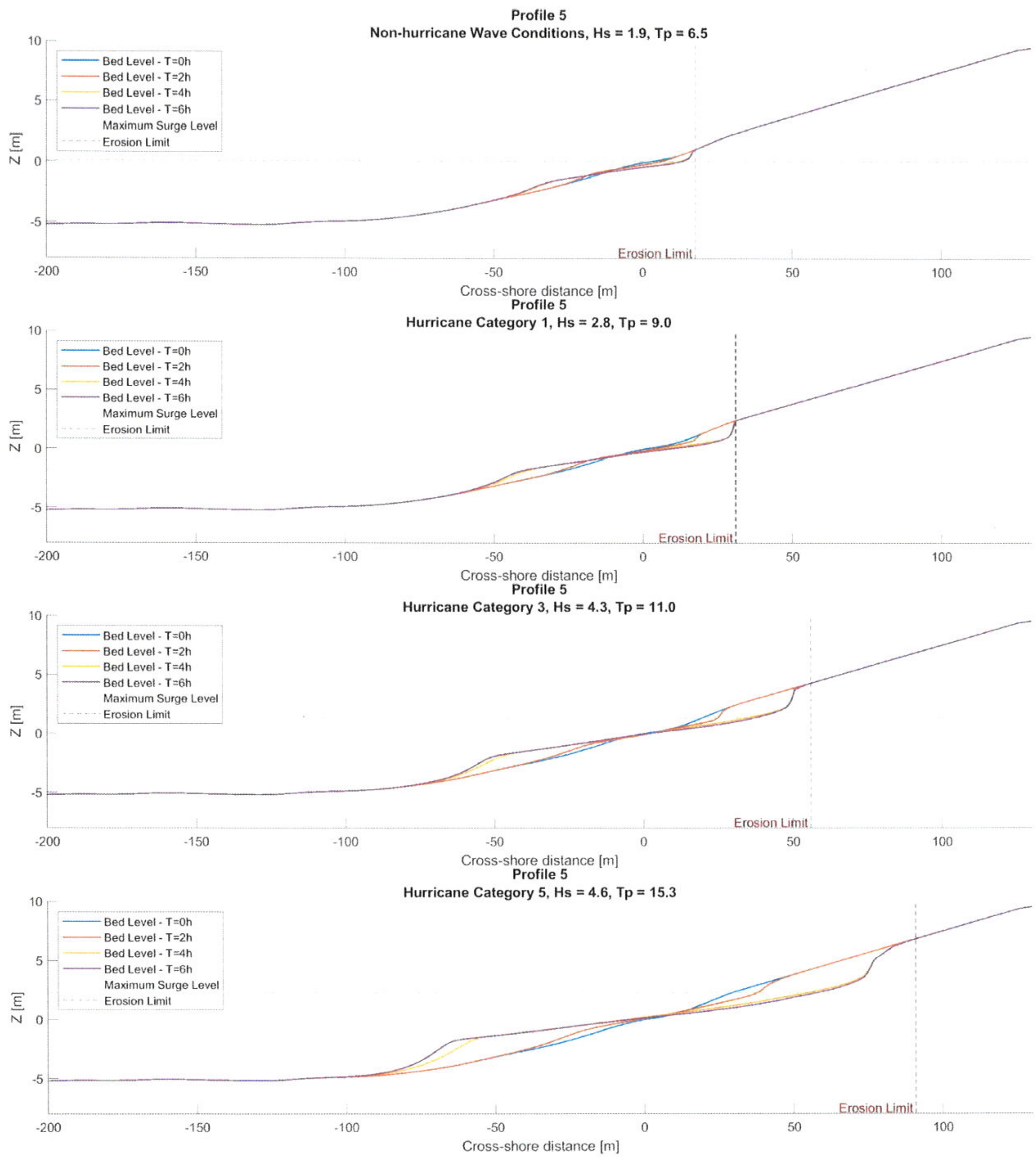

Figure 21: Beach Morphological Development for Profile 5 for Different Storm Events[26]

[26] The profiles are shown with a vertical exaggeration factor 4.

3.4 Modelling Conclusions

The area is naturally protected from the dominant wave direction (East/Northeast); therefore, the largest waves in the area are generated by occasional tropical storms. Typically, hurricane-generated waves are depth-limited but might have long periods which can lead to significant wave run-up and erosion.

Abrupt changes in the coastal morphology brought about by storms can be considered reversible if the system can repair itself during normal conditions (i.e. sufficient accessible sediment supply). The changes are irreversible when the new morphology changes hydrodynamic and sediment regimes to such an extent that recovery of the feature back to its former profile is impossible, at least within an immediate (less than decadal) timeframe and/or when significant amount of sediment is lost to deep water, especially in areas where constant sediment supply from rivers is non-existent.

Growth and recovery of coastal dune systems are driven primarily by wind action and the sandy sediment supply of the beach (Jackson & Short, 2020). The transport processes of sand grains by wind forcing have similar fundamentals as transport by currents; a threshold shear force must be reached on individual grains to initiate movement. The amount of sand mobilized on a beach is controlled by several factors that interact together in a complex mechanism that in turn drives dune morphodynamics, including wind, beach width, moisture content, sediment properties, topography, and roughness elements including vegetation, debris, or other anthropogenic factors. In addition to wave and hydrodynamic beach dynamics, the following processes are also important:

- **Wind forcing and climate** – Magnitude and direction play key roles in the movement of sediment. Changes to wind climate could result in changes to the migration of beach/dune systems. However, there is not enough evidence in the climate projections for the area so far pointing to significant changes in the future wind climate.
- **Beach width** – A wider sandy beach provides a larger area and more sediment to be mobilized to input to dune systems. Increased water levels due to SLR will result in adapted beach profiles, which could in turn change the amount of exposed sandy foreshore that can provide sediment input to dunes.
- **Moisture content –** Increases capillary and cohesive forces to resist movement by wind forcing. Increases to precipitation frequency and intensity would result in higher moisture content, which could result in less sediment supply able to be mobilized by wind forcing also referred to as aeolian transport.

The XBeach modelling illustrates the importance of modelling shoreline erosion in the cross-shore direction which includes both water level processes such as storm surge and tide, and sediment characteristics, local bathymetry, as well as wave processes such as wave set-up and breaking. Combining these processes give an accurate representation of the processing occurring at the **'Escape To Barbuda'** nearshore. Conclusions from the modelling are:

- The combination of high surge water levels and long waves is the dominant driver of cross-shore erosion.
- Given the small tidal amplitude, tidal currents are not expected to play a significant role in facilitating beach erosion or sediment transport in general.
- The erosion rates give an estimation of the expected impact of a single storm event. It is expected that the beach will likely recover naturally after a period of calm conditions, given that ample natural sediment is available in the system.
- Coarser sand or sections with rocky outcrops offer a steeper profile and withstand greater wave action, which results in less erosion.
- The shallow foreshore works as a dissipative nearshore platform that reduces wave energy considerably.

Chapter 4 Coastal Hazard Analysis

4.1 Project Risks

The main coastal hazards at the proposed development are coastal flooding and erosion, which are governed by the combination of:

- **Still water levels** from tide, storm surge and sea level rise as defined in the previous sections of this report.
- **Wave impacts**, including wave run up and overtopping components for areas exposed to ocean swell and hurricane generated waves

Coastal areas are already impacted by the combination of sea level rise (SLR), other climate-related ocean changes, and adverse effects from human activities on ocean and land. Risk related to SLR (including erosion and flooding) is expected to significantly increase by the end of this century along all low-lying coasts throughout the world, and especially in the Caribbean (incl. Barbuda), in the absence of major additional adaptation efforts.

Figure 22 presents the risk classifications related to sea level rise, taking into account scenarios of no-to-moderate response and a maximum potential response. The darker purple colors represent "Very high" risk, while the lighter yellow colors represent "Undetectable" to "Moderate" risk. The figure illustrates that if we consider RCP 8.5 SLR by 2100, islands will be at High to Very High risks regardless of the mitigation measures that are done in the short term. When considering RCP 2.5 SLR scenario the risks range from Moderate to High. For resource-rich coastal areas the expected risks are lower due to the ability to invest very significant resources to mitigate coastal risks as well as other factors such as; understanding of coastal change using data from long-term monitoring campaigns, and the implementation of gradual and planned adaptation measures.

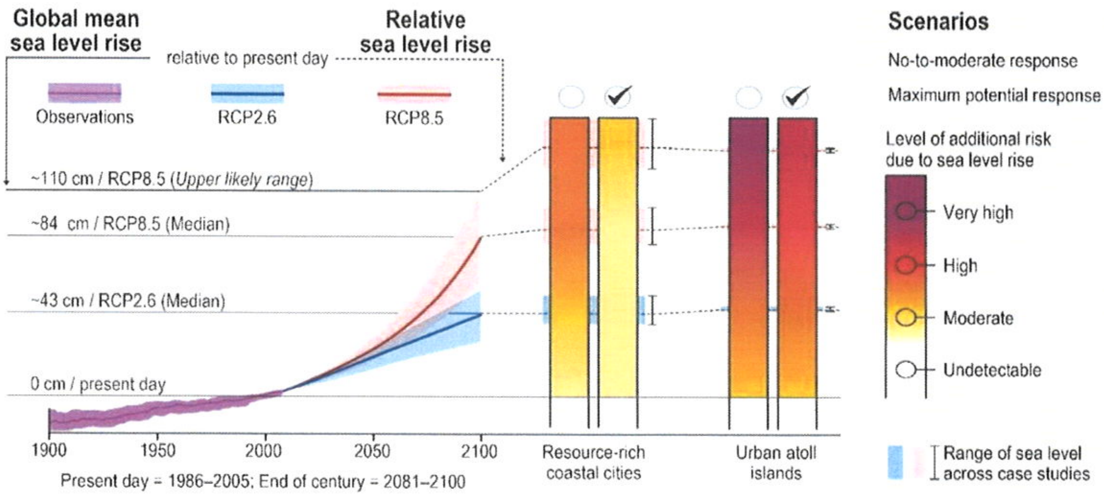

Figure 22: Risk to Coastal Areas and Urban Atoll islands. Source: Oppenheimer *et al.* (2019)

In addition to projected sea level rise, the main coastal risks for the proposed coastal development ('Escape To Barbuda') are related to hurricane events. As it was explained throughout the previous sections of this report, hurricanes lead to exceptionally high water levels, extreme wave heights and extreme wind speeds, which when occurring in parallel cause severe coastal flooding and erosion.

In addition to the above, hurricane hazards associated with extreme wind speeds and rainfall should be taken into consideration when analyzing the overall hazards and risks to the development. These are outside the scope of the present study.

Tsunamis are also a potential hazard along the coast of Barbuda. However, those events have been historically very rare and do not pose additional risk to the development since the tsunami run-up levels in the area are likely smaller than the surge and wave run-up associated to hurricanes, which have a much more frequent occurrence.

Although rare, earthquakes might have a devastating impact in the development, potentially leading to severe damage of buildings. This is outside of the scope of the present study, however it is recommended that design should follow building standards for earthquake-prone areas.

4.2 Setback & Design Flood Elevation

The results of the numerical models were used to determine the setback distance and the design flood elevation for the proposed infrastructure on the project site.

The 'setback' distance provides a buffer zone that allows room for the average high water mark to naturally move inland while taking into consideration sea level rise, coastal storms, hurricanes and other processes that might affect the property during its economic lifetime. Setbacks provide protection to properties against coastal flooding and erosion by ensuring that buildings are not located in an area susceptible to coastal hazards. Figure 23 depicts a schematization of the parameters that are used to determine the setback and design flood elevation, which include tides, storm surge, wave effects, and long-term sea level rise projections.

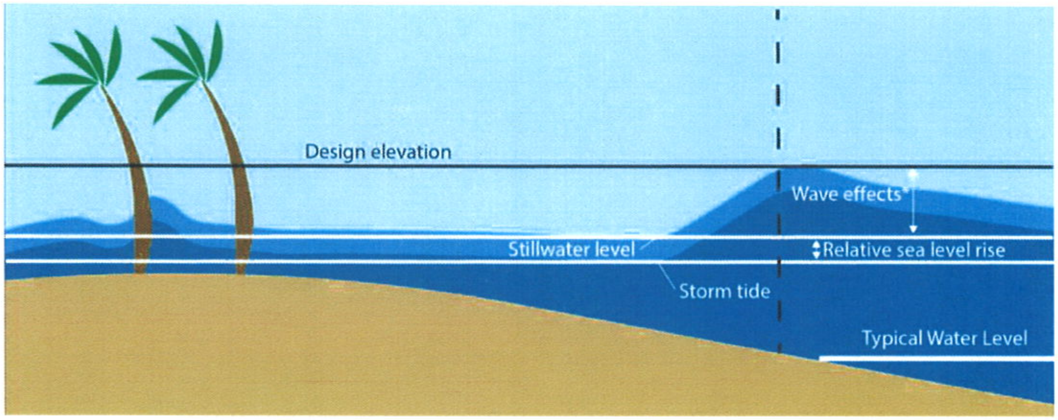

Figure 23: Schematization of Metocean Parameters that Define the Setback and Design Flood Elevation

Error! Reference source not found. presents the summary of the setbacks and design lood elevation for four (4) different storms. Figure 24 show a schematization of the different components contributing to the design flood elevation for a hurricane Category 3.

The extreme non-hurricane event illustrates the type of erosion caused by waves on the existing coastline with a present day climate (excluding sea level rise). Due to the orientation of the coastline, the area is typically protected from the "normal" (non-hurricane) swell waves (coming from the East); and therefore, hurricane events are dominant for the design conditions at the area. As a result, the methodology was focused on extreme conditions generated by hurricanes. Three (3) representative hurricane categories were simulated to determine setback distance and design flood elevations, these results provide a range (Category 1-5) to define the development design and footprint. Table 11 gives a summary of the design flood elevations and setback distance from the water line.

The setback distance varies along the coastline due to changes in: coastal orientation, bathymetric features, presence of vegetation and beach profile slope. All these factors influence the extent of the run-up. Especially for the hurricane – Category 5 flooding simulations and mapping of the setback distance could vary ±20 meters due to the abovementioned factors.

Erosion setback distances are calculated considering the potential for erosion of the beach with the present sea level. Although it is expected that sea level rise will potentially lead to more beach erosion this has not been quantified in this study. Due to the longer time scale of sea level rise (compared to a storm event) it is difficult to quantify its influence in beach erosion with typical (storm-driven, short-term) numerical models, such as the ones used in this study. In this sense, the erosion setback distances shown in Table 11 should always be viewed as relative to the water line at the time (which might recede due to SLR).

The main factors for uncertainty arise from the detail of the available data in the area.

- Bathymetric representation is relatively coarse to integrate all coastal features in the modelling approach.
- Topographic elevations from the survey, Digital Terrain Models (DTM) and Digital Surface model (DSM) show discrepancies in the elevation of the area.
- The measured profiles in combination with the satellite derived bathymetry were used as a baseline for the modelling approach and the definition of the setback distance and design flood elevations.
- The density variation of the local vegetation is not resolved in the modelling approach.

Uncertainty could be reduced by confirming the land elevations measured by the survey, acquiring more information on the location of rocky outcrops and vegetation with respect to the design of the development (i.e. if the location of the cottages and other infrastructure is protected by natural features), and by performing a more detailed modeling of the area (i.e. by considering a 2D model and vegetation).
Sea level rise is an additional component that needs to be taken into account. In the next 40 years it is expected that the sea level in Barbuda will rise between 0.30 (RCP2.6) to 0.43 (RCP8.5) meters, and a total of 0.36 (RCP2.6) to 0.84 (RCP8.5) meters in the next 80 years (by year 2100). It is recommended and standard practice throughout the region, and globally, to incorporate the RCP8.5 sea level rise estimates into the design flood elevation. To account for sea level rise under the RCP8.5 scenario, structures can be modified by raising the ground level, introducing localized barriers, accounting for sacrificial infrastructure or infrastructure which is designed to withstand occasional inundation, or by increasing set-back distances. Although increasing the setback distance presents a potential solution, the resulting setback distance would cover a large percentage of the available land, thereby reducing the value and functionality of the proposed development.

Table 11: Summary of Design Flood Elevation and Setback Distance

Extreme Event	Design Flood Elevation (MSL)	Design Flood Elevation Including SLR 2100 (MSL)	Erosion Setback Distance from the Water Line (MSL)[27]
Extreme non-Hurricane Wave Conditions	1.0 m (3.3 ft)	1.8 m (5.9 ft)	7 m (23 ft)
Hurricane – Category 1	2.3 m (7.5 ft)	3.1 m (10.2 ft)	15 m (49 ft)
Hurricane – Category 3	3.8 m (12.5 ft)	4.6 m (15.1 ft)	35 m (115 ft)
Hurricane – Category 5	5.8 m (19 ft)	6.6 m (21.7 ft)	80 m (262 ft)

The bottom panel of Figure 24 illustrates a schematized version of the results for the Category 3 hurricane simulations (including the effect of sea level rise). MSL, MHHW, surge and sea level rise are considered 'still water levels', while the wave run-up component is a cyclical water movement that depends on wave height and period, long waves (infragravity component), and is influenced by presence of coral reefs, vegetation and bed roughness. The top panel of Figure 24 depicts the results for present clime (not including sea level rise).

[27] Based on the average beach slope derived from the topo-bathymetric transect measurements and DTM.

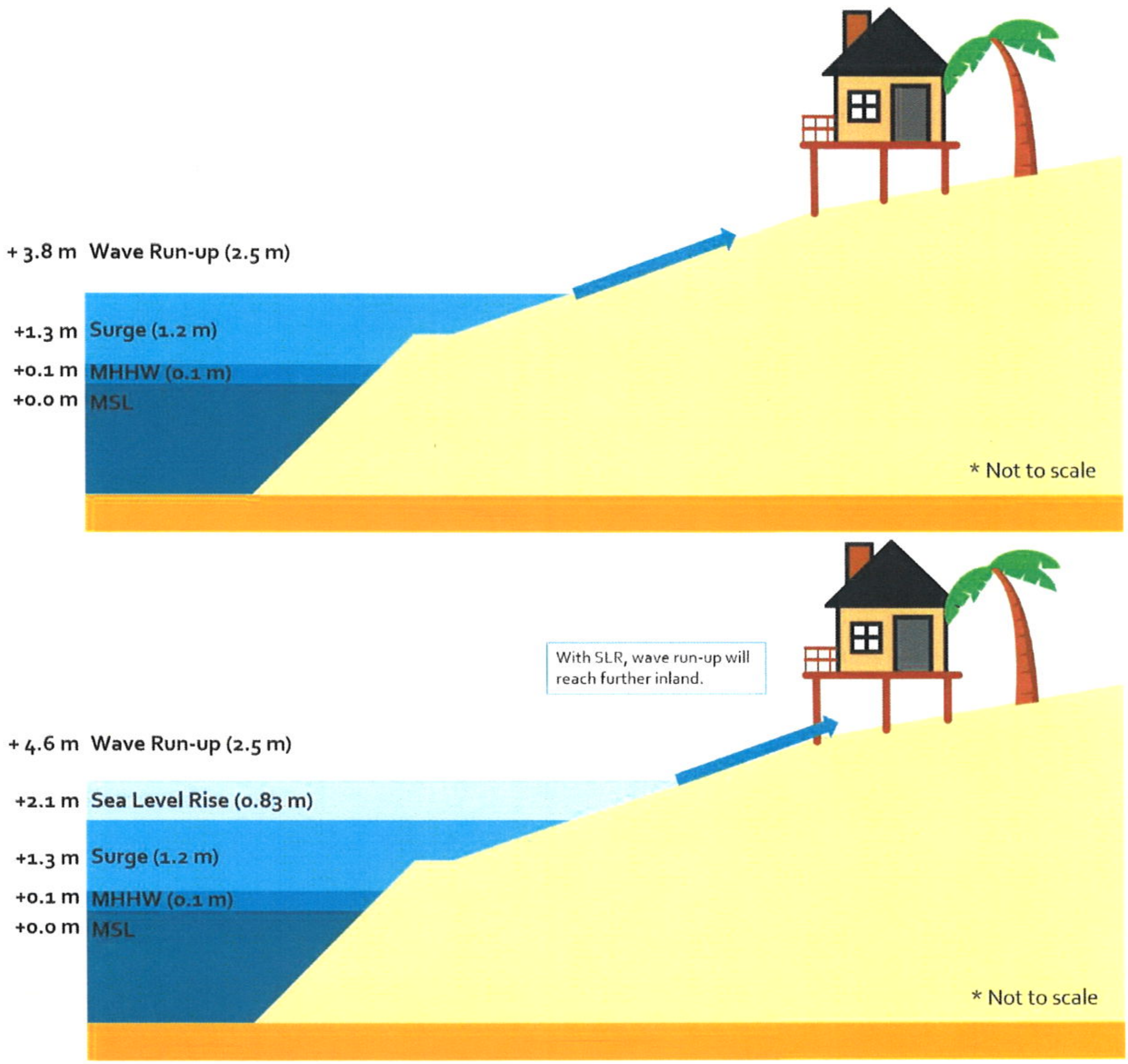

Figure 24: Schematized Design Flood Elevation for Hurricane Category 3

Figure 25 depicts the approximate delineation of the setback line along the coastline (based on the Digital Terrain Model elevations). The blue line represents the waterline (Mean Sea Level – MSL); green line represents the estimated setback for a non-hurricane extreme event; yellow the Category 1 hurricane setback; orange the Category 3 hurricane setback; and red the Category 5 hurricane setback, the solid lines show the estimated setback lines for the present scenario, while the dashed lines show the future setback lines including SLR. In the future, due to sea level rise, the entire area of the development and large parts of the island will likely be prone to flooding during stronger hurricane events (Category 3 or higher).

Figure 25: Setback Delineation[28] for Representative Extreme Events[29]. Dashed Black Line Indicates the Development Boundary

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[28] Based on the elevations from the DTM

[29] For hurricane Category 5, most of the area is flooded with exception of some pockets indicated by the dashed red lines.

4.3 Risk Mitigation

A description of general approaches for mitigating coastal hazards and coastal management strategies are shown in Table 12, including the potential application of different solutions to the 'Escape To Barbuda' development.

Table 12: Approaches for Risk Mitigation and Coastal Development Management

Approach	Description	Potential Application to 'Escape To Barbuda' Coastal Development
Hazard Reduction Approaches		
Protect i.e. 'Advance' or 'hold the line'	▸ Historically the most common form of coastal adaptation in locations where infrastructure is already present. ▸ Expensive over the long-term, especially with the expected increase in the rate of sea-level rise. ▸ Would require large investments to protect the coastline against hurricanes.	▸ Since the footprint of the development has not yet been defined, we do not recommend this approach, as it is likely too costly, and introduces unnecessary risk to structures.
Consequence Reduction Approaches		
Accommodate	▸ Allows for continued use of coastal land. ▸ Changes the current use of coastal land or infrastructure to become water dependent or tolerating.	▸ Prepare a post-storm cleanup and repair management plan. ▸ Introduces some sacrificial structures or components which can be easily and cheaply replaced after a hurricane. ▸ Emergency sandbag placement. ▸ Build beach access structures (e.g. timber stairs and boardwalk) with removable structures, such as beach access mats that can be rolled out and removed before forecasted storms.
Managed Retreat	▸ Relocate people / infrastructure away from coastal hazard.	▸ Since the footprint of the development has not yet been defined, this is not