Public Investment Profile for Disaster Risk Reduction

Beach Erosion and Risk Mitigation Model for Barbados

Inter-American Development Bank

Environment, Rural Development and Risk Management Division

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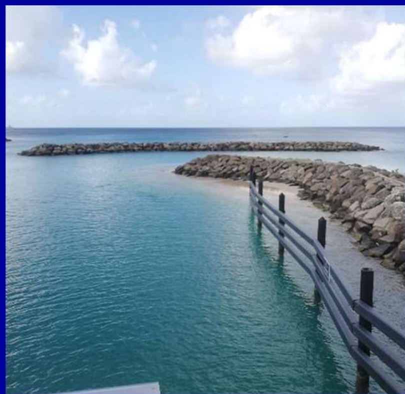

GOVERNMENT OF BARBADOS

PUBLIC INVESTMENT PROFILE FOR DISASTER RISK REDUCTION:

BEACH EROSION AND RISK MITIGATION MODEL FOR BARBADOS

January 2022

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LIST OF ACRONYMS

- **BCR:** Benefit Cost Ratio
- **CAPRA:** Comprehensive Approach Probabilistic Risk Assessment
- **CZMU:** Coastal Zone Management Unit
- **CC:** Climate Change
- **DRM:** Disaster Risk Management
- **EAL:** Expected Annual Loss
- **EN:** Engineering Nourishment
- **GDP:** Gross Domestic Product
- **NPV:** Net Present Value
- **NN:** Natural Nourishment
- **PML:** Probable Maximum Loss
- **SLR:** Sea Level Rise
- **TBR:** Total Beach Revenue
- **TBRC:** Total Beach Recovery Cost

CHAPTER

1

GENERALITIES

1.1 INTRODUCTION

Risk assessment associated with extreme natural events is one of the key strategic activities of disaster risk management (DRM) that is useful at a national and a regional level. Disaster risk assessment requires the use of reliable methodologies that allow to adequately estimate and quantify the potential losses at a given time. To this end, probabilistic risk assessment methods are typically used (Yamin, Ghesquiere, Cardona, & Ordaz, 2013).

This report presents a probabilistic disaster risk assessment model for Barbados, focusing on beach erosions caused by episodic cyclonic hazard events and chronic effects associated with maritime climate. The probabilistic risk is expressed in terms of direct and indirect economic losses due to expected repair costs and downtimes, and income losses due to declines in tourism visitation and touristic usage in affected beach areas. The Comprehensive Approach for Probabilistic Risk Assessment (CAPRA) platform serves as a methodological model for conducting this study. CAPRA is an open architecture platform that was developed with the support of the Inter-American Development Bank (IDB), the World Bank and the United Nations International Strategy for Disaster Reduction (see www.ecapra.org).

This report states all methodologies, procedures and outcomes of the study developed for a consistent risk assessment at a country level. Chapter 2 presents a general background of the study area; Chapter 3 summarizes the methodological approach; Chapter 4 introduces the hurricane hazard model in relation to beach erosion processes; Chapter 5 presents the national exposure model, including the geographical distribution of the most representative beach types and their economic valuation based on tourism revenue; Chapter 6 presents the erosion vulnerability model; In Chapter 7 the corresponding risk assessment results are reported including the proposed retrofitting alternatives; and ultimately, Chapter 8 presents the conclusions and recommendations of the study.

1.2 OBJECTIVE

The main objective of this study is to develop a probabilistic risk assessment model that deals with economic impact of beach erosion issues on Barbados.

The final output of this study is the simplified probable beach loss exceedance curve for critical coastal areas in Barbados, with and without the climate change scenarios constructed by the Intergovernmental Panel on Climate Change (IPCC). In addition, the study assesses indicative possible mitigation options to dimension their benefit cost ratios (BCR) and assess their technical and economic viability.

The study includes:

- A probabilistic hazard model considering the wave intensity under normal daily conditions and extreme storm surge events.

- Potential climate change effects in the hazard model, such as a possible sea-level rise for different time periods in the future, increased frequency or intensity of extreme events, and a corresponding sensitivity analysis.

- An exposure model accounting for exposed assets, infrastructure, and economic flows, such as tourism-related economic activity.

- A vulnerability model that establishes the relationship between different intensity parameters (beach erosion, wave intensity, flood depth or sea level) with their direct impact in terms of erosion volumes that will affect the country's main economic activity: tourism, and therefore generate direct and indirect economic losses due to beach area reduction, downtime during recovery periods, and other significant direct and indirect losses.

- A probabilistic risk assessment model for critical areas and relevant tourist beach zones. The model generates a simplified probable loss exceedance curve including direct and indirect impacts.

- Risk assessment considering climate change scenarios and their possible impacts, such as, expected sea-level rise for different future time periods and increase in the frequency or intensity of extreme events, with a corresponding sensitivity analysis.

- Recommendations regarding possible mitigation measures/works against beach loss/erosion to be adopted in future studies. Both conventional hard structural options and nature-based solutions as alternatives will be presented and discussed for future interventions. The main goal of the possible mitigation measures presented is to provide alternatives that increase the resilience of each site in the face of extreme events, chronic processes, and climate change.

1.3 SCOPE

The study focuses on the south and west coasts of Barbados, areas that are most frequently used for recreational beach tourism but are experiencing increasing erosions/beach losses due to chronic events and climate impacts. In addition, beaches on the north and east coasts experiencing erosion have been included in the analysis, even though they are not commonly used for recreational tourism. Schematically, these results may be included in a graphical form as shown in Figure 1-1, where the comparison of Probable Maximum Loss (PML) curves summarizes the risk conditions of the current status (without interventions) with respect to a proposed set of measures to reduce risk, with and without climate change scenarios.

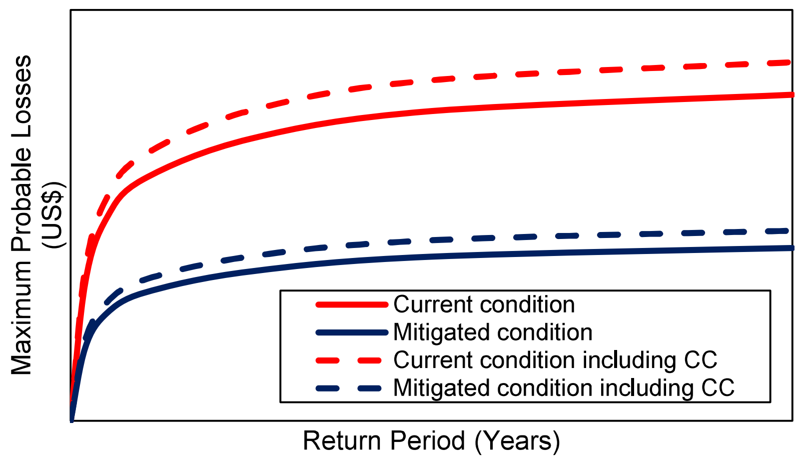


Figure 1-1. Probable maximum loss representation (for illustrative purposes)

This study includes:

- Disaster risk assessment based on existing information provided by the Barbados Government, and on some additional field data collected and processed by the study team.
- Disaster risk results that could help establish overall risk metrics for defining detailed risk mitigation options related to beach erosion.

It is important to note that all estimates were based on a non-COVID-19 scenario, based on information collected from 2018 and 2019 reports.

CHAPTER

2

COUNTRY BACKGROUND

2.1 INTRODUCTION

Barbados is a part of the Lesser Antilles and is the easternmost Caribbean island, near the islands of Saint Lucia and St. Vincent and the Grenadines. The country has 294,560 inhabitants as of 2020 (CIA, 2020), is divided into 11 parishes, and its capital is Bridgetown. Historically, the economy relied on sugarcane crops, but since its independence from the UK in 1966, the economy has expanded into different activities. Tourism became one of the most important economic activities. The main characteristics of the country are presented in Table 2-1.

Table 2-1. Barbados characteristics (BTI, 2020; CIA, 2020; World Bank, 2021)

Area (km^2)	430
Coastline (km)	97
Highest point (m.a.s.l.)	336
Capital	Bridgetown
Population 2019	294,560
Official language	English
Urban population 2019	31.2%
GDP 2018 (US$ billion)	5.1
GDP per capita 2018 (US$)	17,313
GDP 2019 (US$ billion)	5.2
GDP per capita 2019 (US$)	17,653
Tourism GDP 2019 (US$ billion)	1.7

Tourism is one of the main economic sources on the island, with around 500,000 visitors each year (BSS, 2016). The beaches and the cliffs around the coastline of the island are the main tourist attractions. The country has four main coasts: west, south, east and north as shown in Figure 2-1. The country's total coastline length is around 97 km, of which 33 km corresponds to recreational beaches, located mainly at the west and south coasts. The following sections describe each coast and include pictures taken during the field work of this study.

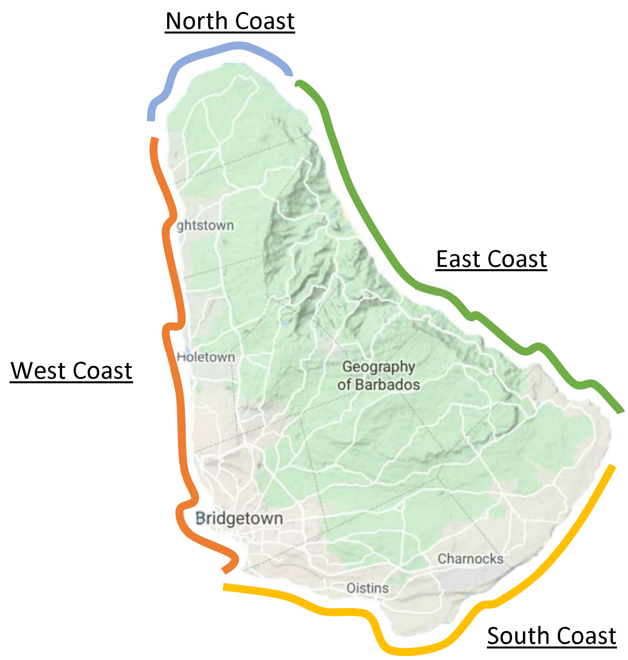


Figure 2-1. Main coasts in Barbados

2.1.1 West coast

The west coast is one of the most important regions in the country since it has three main cities: Bridgetown (the capital), Holetown, and Speightstown. It is mainly composed of sandy beaches used for tourist-related activities and hosts the summer houses of some of the wealthiest inhabitants. Some pictures of this coast are presented in Figure 2-2.

Figure 2-2. West coast (source: ITEC)

2.1.2 South coast

The south coast is the most touristic coast, hosting the most luxurious hotels in the country. The coast is composed of sandy beaches and cliffs. Some pictures of this coast are presented in Figure 2-3.

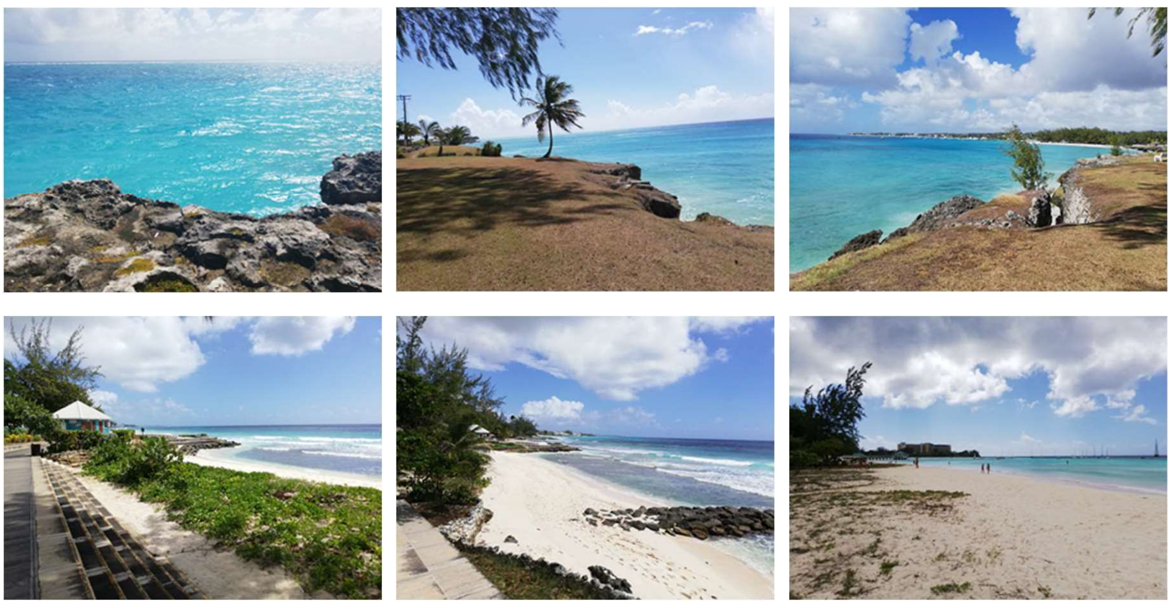


Figure 2-3. South coast (source: ITEC)

2.1.3 East coast

The east coast does not have many tourist spots and is mainly occupied by some recreational resorts. Waves have more high energy in this area than those in the west and south coasts, rendering the region relatively unsafe for recreational swimming. The coast is composed of localized sandy beaches and cliffs. Some pictures of this coast are presented in Figure 2-4.

Figure 2-4. East coast (source: ITEC)

2.1.4 North coast

The north coast is mainly composed of large cliffs that are visited by tourists throughout the day. It is uncommon to find hotels or restaurants on this coast. Some pictures of the north cost are presented in Figure 2-5.

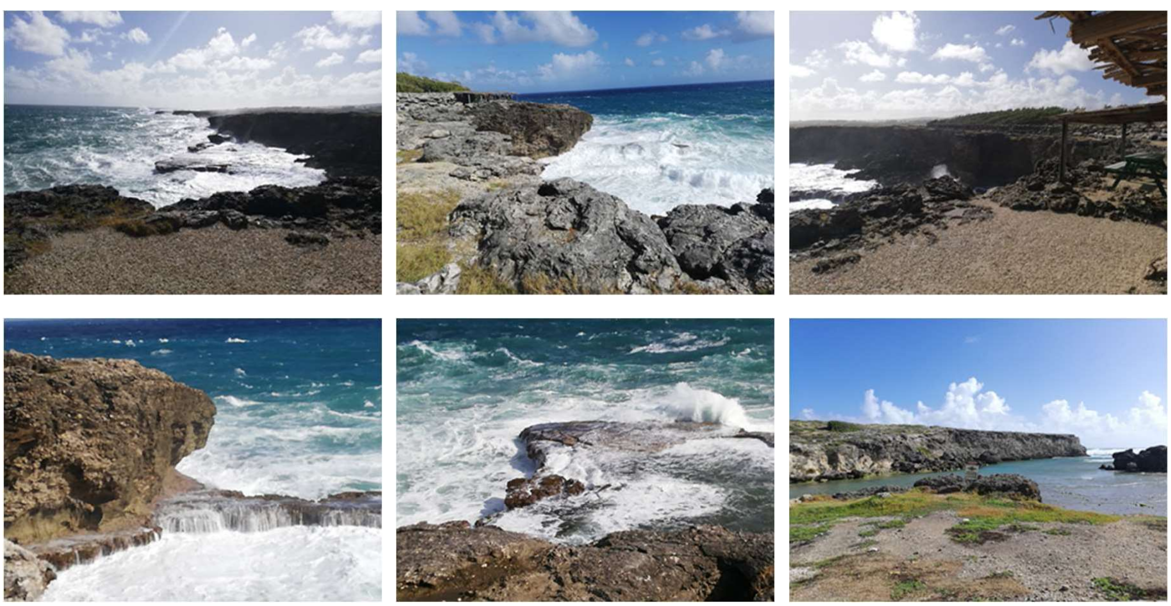


Figure 2-5. North coast (source: ITEC)

2.2 ENVIRONMENTAL BASELINE AND CURRENT CONDITIONS

In the preparation of this study, the study team collected an adequate amount of baseline environmental information with the support of the Coastal Zone Management Unit (CZMU), as presented in 3.6.2. The following figures present the most relevant information collected.

Figure 2-6 presents beach classification developed by Baird (Baird, 2015) in a previous study. In this classification, the entire Barbados coast was divided into nine categories according to the dynamics of erosion, or accretion, and the beach type (natural, artificial, engineered or cliff). In this study the focus will be on the coasts classified as natural or artificial, while the segments classified as cliffs are out of the scope of the project.

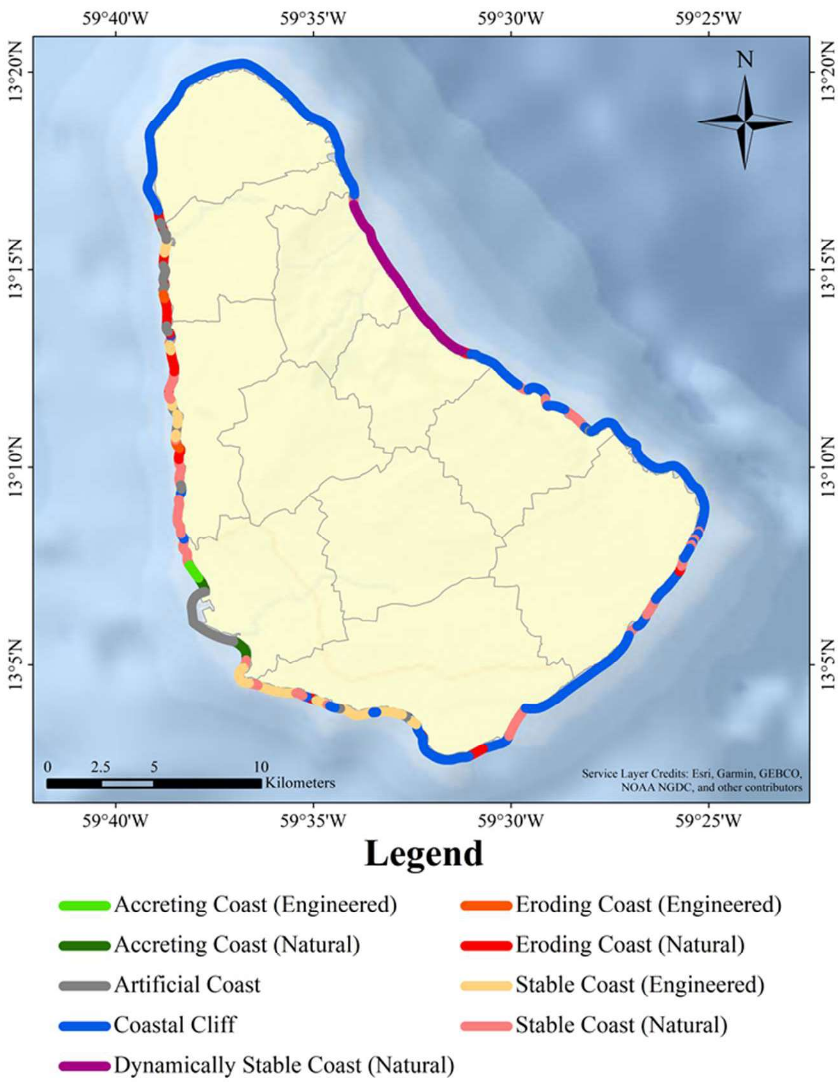


Figure 2-6. Beach classification by Baird (Baird, 2015)

Figure 2-7 and Figure 2-8 present information regarding land use and land cover, from which this study identified the most relevant areas of the country.

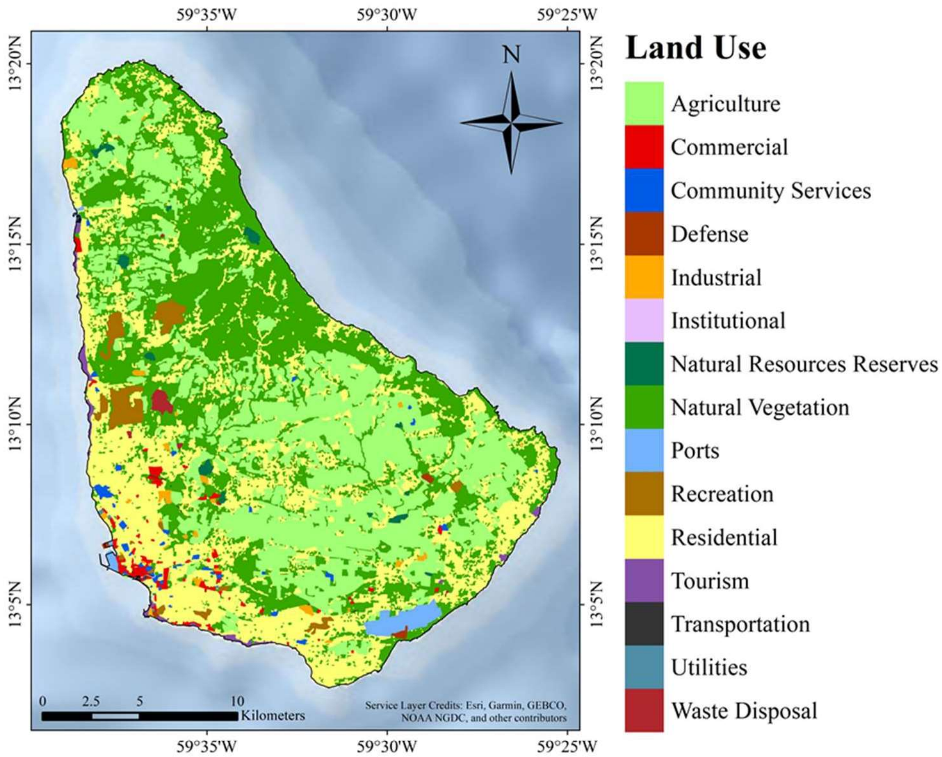


Figure 2-7. Land use (adapted from CZMU information)

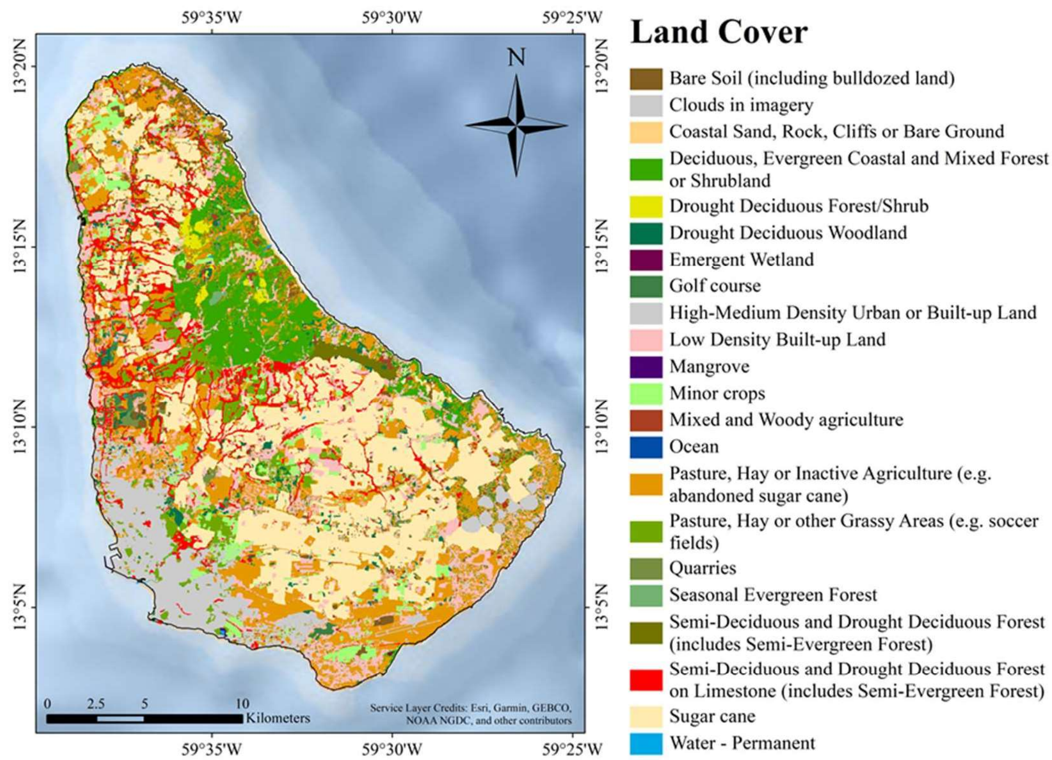


Figure 2-8. Land cover (Adapted from CZMU information)

Figure 2-9 presents the locations of mangroves, wetlands, and sand dunes along the coast of the country.

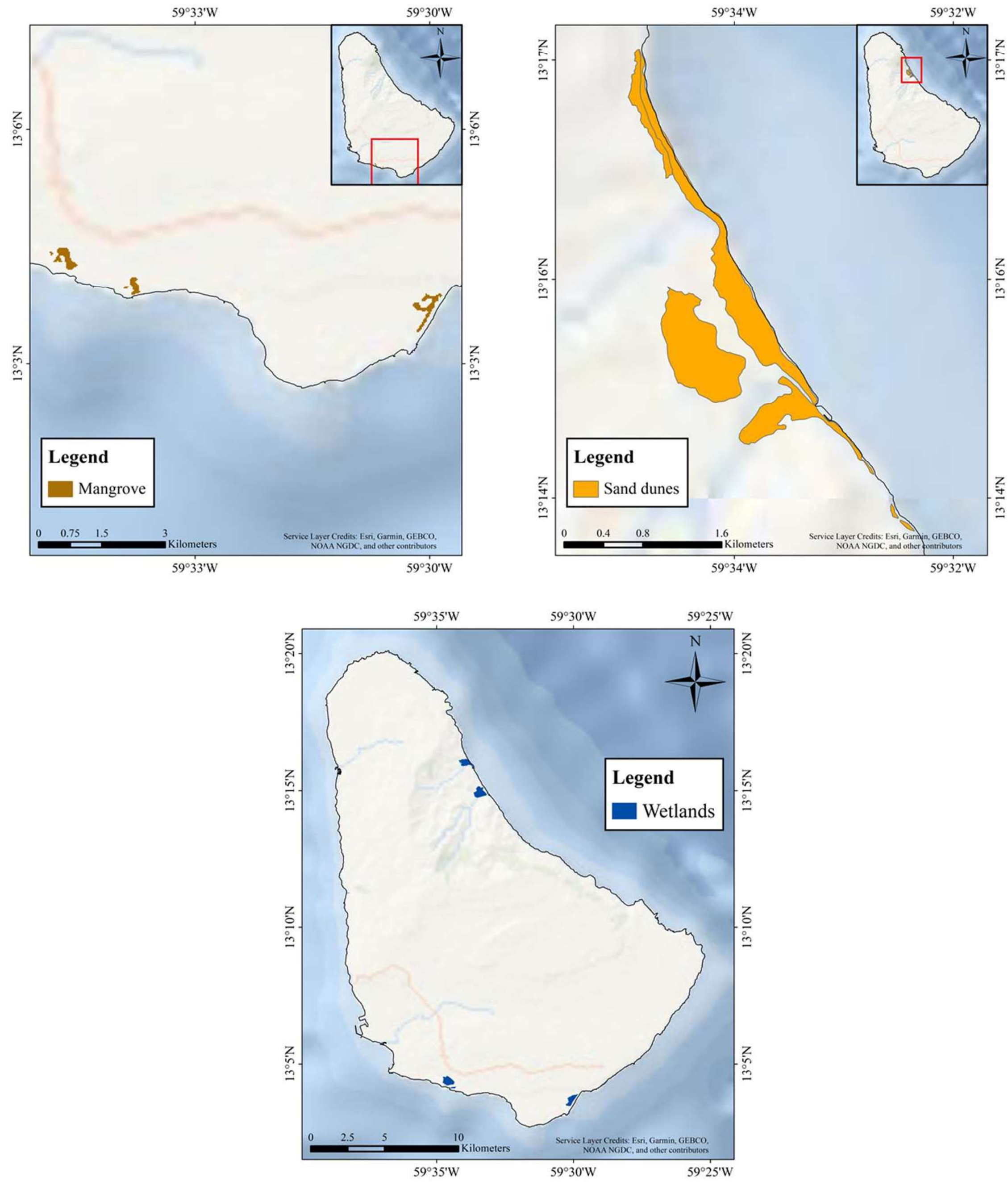


Figure 2-9. Mangroves, sand dunes and wetlands (Adapted from CZMU information)

Figure 2-10 demonstrates the main watercourses and gullies of the country that can affect the sediment balance in the beaches and generate erosion events.

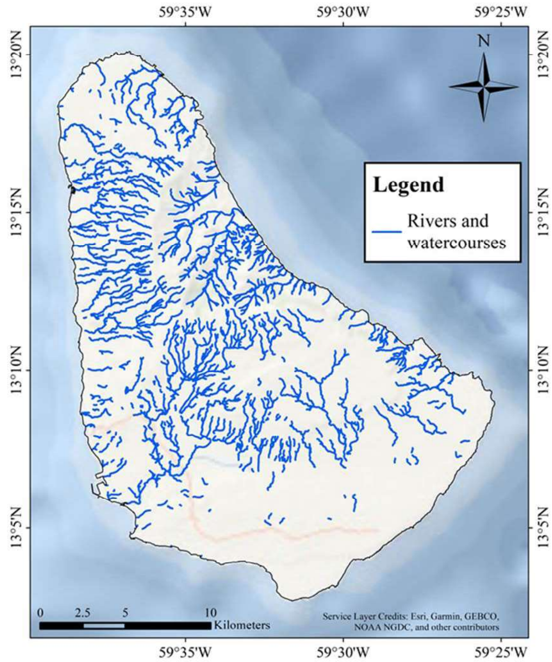


Figure 2-10. Watercourse and gullies (Adapted from CZMU information)

Figure 2-11 shows the location of the benthic habitat along the coast of the country, associated with the occurrence of particular species.

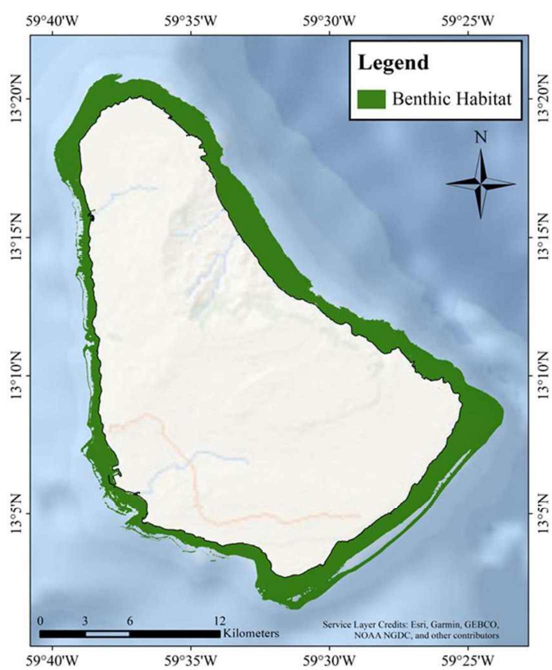


Figure 2-11. Benthic habitat on Barbados coast (Adapted from CZMU information)

Figure 2-12 presents the locations of coastal structures divided into three categories: gray structures (traditional concrete structures such as breakwaters), green structures (nature based solutions such as coral reefs and mangroves), and hybrid structures that combine these. It is important to note that not all these structures correspond to civil protection infrastructure; there are also beach improvement elements and measures for tourist and landscaping purposes.

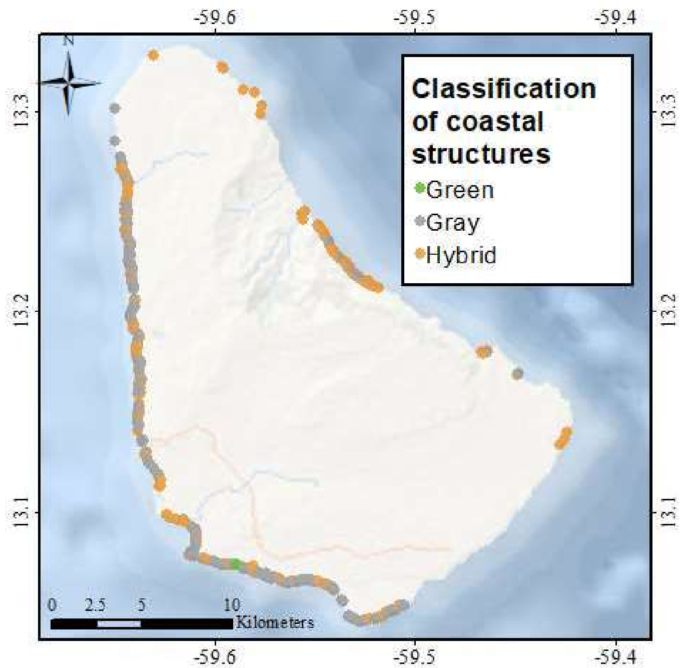


Figure 2-12. Location of coastal structures (Adapted from CZMU information)

CHAPTER

3

METHODOLOGICAL FRAMEWORK

3.1 PROBABILISTIC RISK ASSESSMENT GENERALITIES

Probabilistic risk assessment anticipates events that might occur in the future based on historical information and additional available/complementary data. Daily wave data, beach profiles, available periodical satellite images, economic values and flows (especially in tourism-related activities in case of Barbados), historical intensive hazard events, topography and digital bathymetry data are the main inputs that need to be considered for a reliable risk assessment. The probabilistic risk assessment requires three submodules including: hazard, exposure, and vulnerability. The probabilistic risk model conceptual framework is illustrated in Figure 3-1.

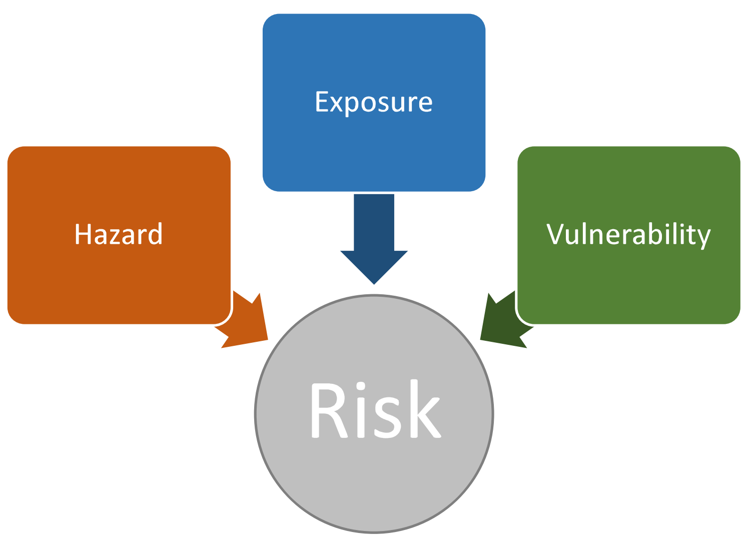


Figure 3-1. General scheme of the probabilistic risk analysis

The hazard assessment is depicted in a scenario-based model representing the severity and frequency occurrence of intense events. The hazard intensity considers an established relation between wave events and beach erosion/sedimentation processes. The hazard in this study is assessed through a collection of representative stochastic scenarios consistent with historic past events reported in international databases. For each scenario, an intensity measure is selected (maximum wind speed, maximum storm surge, etc.) and its distribution is estimated in the area of interest. The relative occurrence rate of each scenario is estimated based on historic information. Climate change scenarios are introduced in the hazard model by modifying the event frequency and/or intensity and considering sea level rise in the long term.

In this study, the exposure model represents coastal areas that can be affected by hazard events. The exposed value at risk of the coastal areas is based on the capacity of the beach to attract tourism and the susceptibility to erosion. Specific characterization of each sector of the beach is conducted in terms of erosion susceptibility, representative repair cost, downtime costs, and direct and indirect revenue. Property value of existing tourism assets/buildings, such as hotels are not included in the model since erosion hazard is limited to the beach recreational areas.

A vulnerability model establishes the relation between the hazard intensities and the expected economic losses. The vulnerability of each sector is assessed by estimating the damages which depend on the erosion volumes of sand for different hazard intensities. An analysis is performed for the present conditions or after considering protective measures in critical zones. It is important to note that a beach is a consequence between agents (natural and anthropogenic) and the environment and that any variation in the agents could generate a new condition for the beach. In this way, the approach of the present study relies on considering the erosion as a result of a new equilibrium, focusing on the causes and not the symptoms (Silva, et al., 2019).

The probabilistic risk in this study is expressed in terms of direct and indirect expected annual losses or the maximum probable losses, considering repair costs, downtimes, and direct and indirect revenue losses due to declined tourism activities in affected beach areas. Specific risk mitigation works are evaluated in terms of their implementation costs and their corresponding risk reduction. Benefit-cost analyses are then performed to select the best possible economic options and assess their viability. Details on the methodological approach for the probabilistic risk assessment have been published (CAPRA, n.d.; Yamin, Hurtado, Barbat , & Cardona, 2014; Yamin, Hurtado, Rincón, Dorado, & Reyes, 2017; Yamin, Ghesquiere, Cardona, & Ordaz, 2013).

3.2 SPECIFIC BEACH EROSION RISK ASSESSMENT

This study places focus on assessing beach erosion caused by episodic events, considering erosion can be caused different hazards. Chronic and episodic erosion events are analyzed as a result of maritime climate and cyclones, respectively. Sea levels rise due to climate change considerations are also included. These events are considered independently due to the lack of detailed information and the scope of this project. Direct and indirect losses due to declined tourism will be presented. The final risk metrics will be expressed in terms of the Probable Maximum Losses (PML) and the Expected Annual Losses (EAL), both expressed in US dollars. The general overview of estimating beach losses is presented in Figure 3-2.

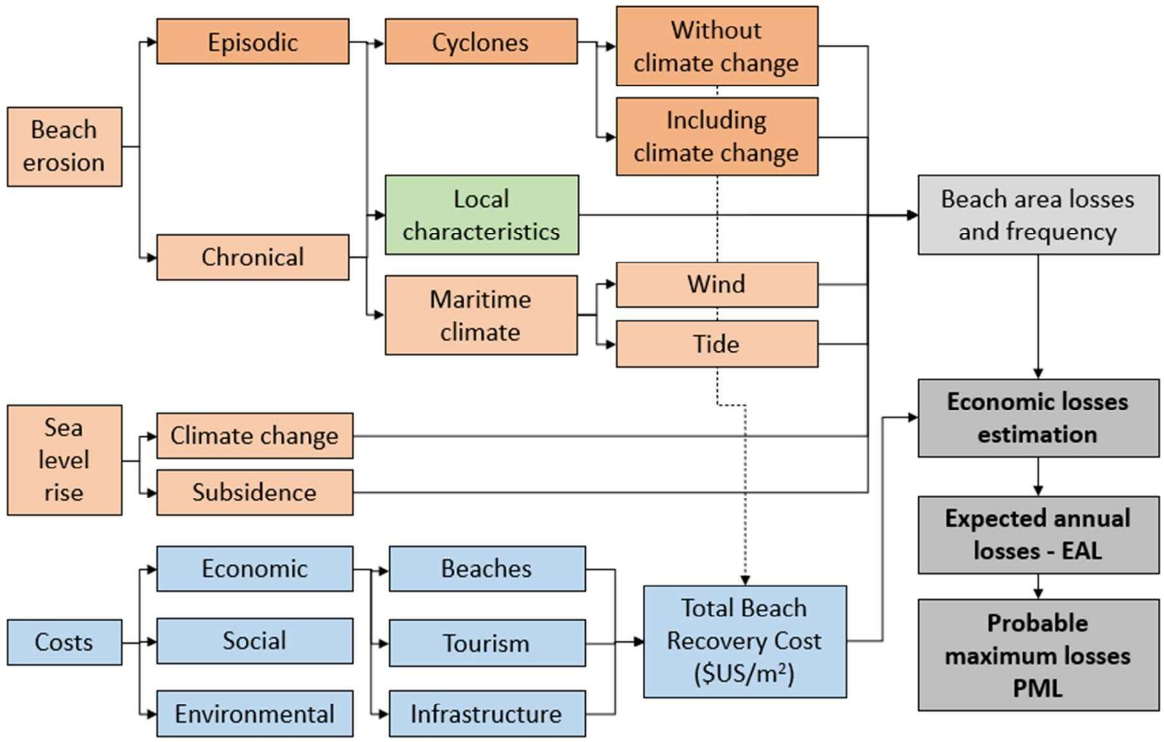


Figure 3-2. General overview of beach loss estimation

The above overview can be adapted and presented in the context of the probabilistic risk assessment that was previously explained. The different steps are included in three main modules: exposure, hazard, and vulnerability. The adapted general methodology is demonstrated in Figure 3-3.

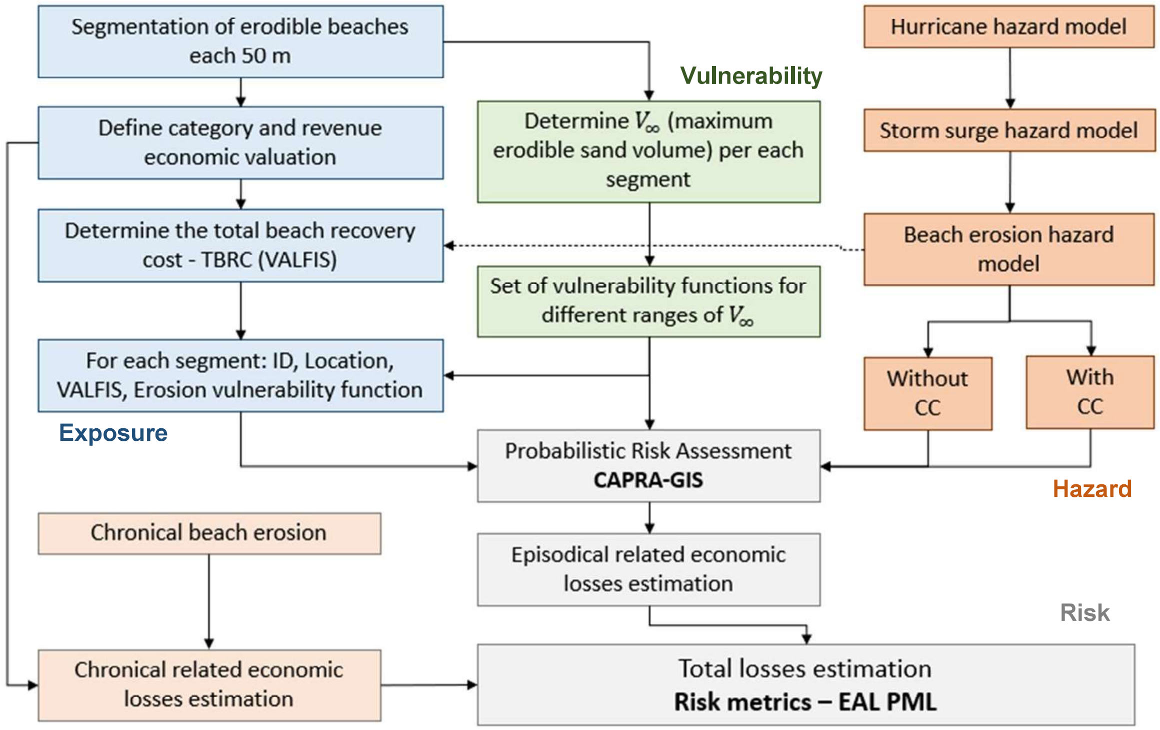


Figure 3-3. Beach erosion methodology

The methodological approach and the specific details of each module are presented in the following sections.

3.3 HAZARD MODEL METHODOLOGY

3.3.1 Episodic erosion

3.3.1.1 General model

From a hydrometeorological point of view, tropical cyclones typically lead to the worst possible consequences, as they generate high wind velocities, and intensive rainfall and coastal storm surges in the vicinities of the cyclone eye trajectory. Storm surge can lead to coastal erosion, ecosystem changes, loss of human life and property damage due to extreme flooding.

Despite the relatively high frequency of hurricane occurrences in the Caribbean region, the frequency of catastrophic events around Barbados remains relatively low. To represent this characteristic, this study used the CAPRA platform to assess the cyclonic risk, considering the occurrence frequency of intense hazard events and the associated uncertainty with its estimation. The tropical cyclone hazard model is constructed from identifying related events in the historical catalogue and cyclone trajectories, the digital bathymetry and terrain model for the study area, and modification factors to account the land uses and terrain roughness. Tropical cyclone hazard can be represented by a set of stochastic events that consider all possible cyclones in a specific area. Each event is defined by the eye trajectory and the distribution of an intensity measure, such as wind velocity, rainfall depth, or storm surge level. To consider the uncertain eye trajectory of the cyclone, ‘children’ stochastic scenarios are simulated from a ‘parent’ historical event with a known trajectory, through a random walk simulation. The occurrence frequency for the set or ‘family’ of stochastic scenarios is consistent with the historical frequency of the event listed in the catalogue.

The present study characterizes the hazard intensity using the following main parameters: the storm surge height along the coastline, the duration of each passing storm, and the corresponding beach erosion potential associated with each stochastic storm event. These intensity measures consider the variation of the hurricane eye location and the corresponding intensity in each location. In this way, a collection of maximum storm surge heights and eroded sand volumes is calculated for each stochastic scenario (cyclonic events). Each scenario has in turn a specific annual occurrence. The collection of scenarios, their corresponding intensity measures and the geographical distribution are stored in a single multi-layered file with the extension ‘AME’ (according to the CAPRA platform definitions).

The general methodology for the hurricane hazard assessment is summarized in Figure 3-4, while Figure 3-5 presents indicative results from previous studies.

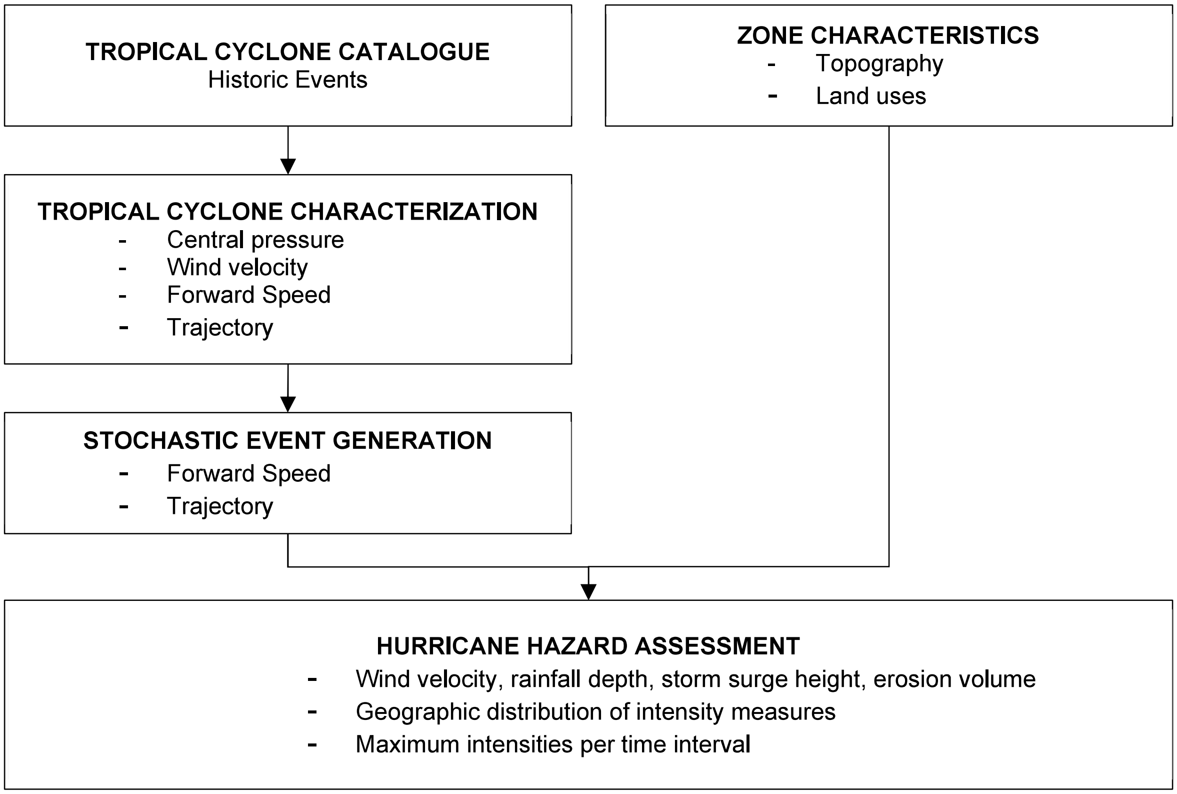


Figure 3-4. Hurricane hazard assessment methodology (CAPRA)

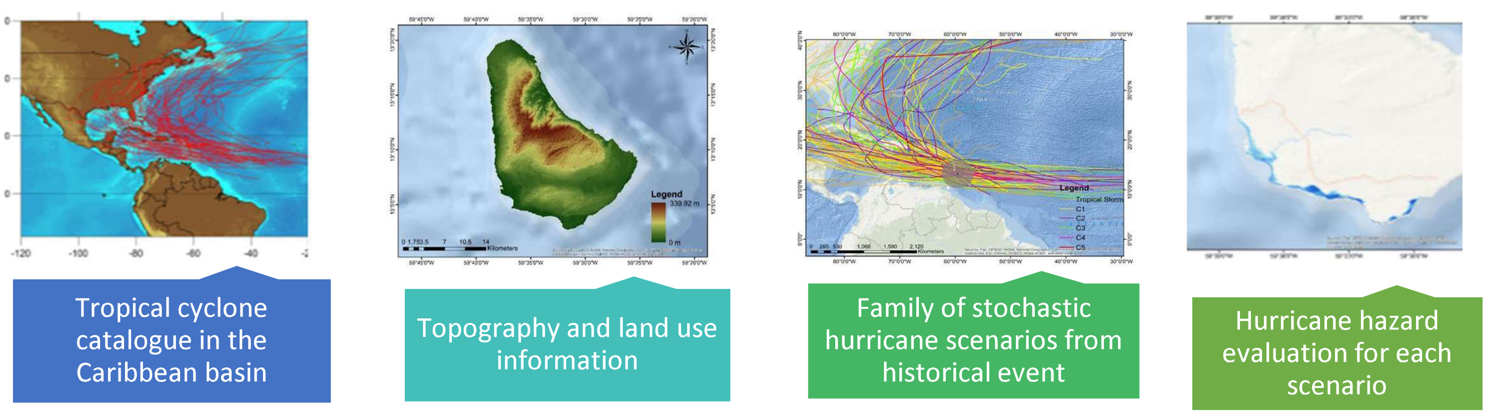


Figure 3-5. Indicative results of hurricane hazard assessment (CAPRA)

3.3.1.2 Climate change general considerations

The present study does not intend to perform a detailed climate change assessment. However, it makes simplified considerations based on previous studies and figures used in similar projects in the region to indicate possible beach erosion effects due to climate change. The objective is to assess possible worst-case scenarios in the medium term to ultimately estimate risk. The following points present considerations for implementing a simplified climate change model:

a) The observed variability in regional climate generally represents a complex convolution of natural and anthropogenic factors. The response of tropical cyclones to each factor is not yet well understood (IPCC, 2013).
b) Assessing changes in regional tropical cyclone frequency is still limited because projection reliability strongly depends on the simulation performance. Current climate models are still limited in simulating observed temporal and spatial variations in tropical cyclones (IPCC, 2013).
c) There is low confidence in projections of changes in tropical cyclone genesis, location, tracks, duration, or areas of impact (IPCC, 2012).
d) The projected results highly depend on the future scenario selected (Emission Scenarios for IPCC4 or Representative Concentration Pathways for IPCC5).
e) It is likely that the global frequency of tropical cyclones will either decrease or remain the same (IPCC, 2012). This means that the global or total frequency of tropical storms that affects a certain area will not change or will present a small change compared to the actual global frequency.
f) The available modeling studies project substantial increases in the frequency of the most intense cyclones. It is more likely that this increase will be larger than 10% in some basins (IPCC, 2013). This means that the annual frequency of hurricane categories 3, 4 and 5 will increase, but the global frequency (including tropical storms and hurricanes) will remain stable.
g) Under the Representative Concentration Pathway (RCP) 8.5 scenario, hurricanes of category 3, 4, and 5 are likely more common in the North Atlantic (NCAR, 2017).

3.3.1.3 Storm surge

The storm surge model is based on an implicit finite-difference two-dimensional model, in which there are three governing equations (two vertically averaged momentum equations, and the continuity equation). These equations are known in the literature as Shallow Water Equations or Saint-Venant Equations (Bautista Godínez, Silva Casarin, & Salles A. de Almeida, 2003). In CAPRA, the sea level increase in each specific region under analysis is calculated for each location of the eye storm considering the mean slope, bathymetrical and topographical information. The uncertain eye trajectory and intensity of the hurricane are considered in the analysis of the complete stochastic events of the hazard model. The maximum storm surge level in each location is selected as the maximum water depth obtained in each cyclone simulation. The following basic equation is used, which corresponds to a simplification of the basic two-dimensional solution.

$$\eta = \frac{P_a}{100} + \frac{K * w^2 * x}{g * (h - \eta)} * \ln\left(\frac{h}{\eta}\right)$$

Where Pa [mb] is the atmospheric pressure gradient in each location along the coast with respect to the standard pressure, x [km] is the distance between the hurricane eye and the site of analysis on the beach, w [m/s] is the normal component of the wind velocity in the coast line m/s, g [m/s2] is the acceleration of gravity, h [m] is the water depth in the sea in the location of the each hurricane eye and K is the dragging coefficient of air, which in turn can be calculated using the following equation:

$$K = \frac{\rho_{air}}{\rho_{water}} * C_D$$

Where ρ_{air} y ρ_{water} are the specific weights for air and water, respectively, and C_D is a coefficient that varies between $2x10^{-6}$ a $9x10^{-6}$ (for hurricane cases, a value of $9x10^{-6}$ is usually employed). The maximum storm surge height in each beach segment is calculated for each cyclonic event in the entire analysis region and the maximum intensities are then collected into a hazard '.AME' file.

3.3.1.4 Beach erosion

Coastal erosion can be caused by natural phenomena and/or anthropogenic activities. This study emphasizes the main role of natural phenomena in coastal erosion. These events are related to changes in the hydro-sedimentary balance, changes in the angle of incidence of waves, the occurrence of extreme events, land subsidence, sea level rise, ecosystem degradation, land-use changes, and construction of coastal infrastructure. Different cases of coastal erosion have been documented in Latin America and the Caribbean. Figure 3-6 presents an example of extreme beach erosion in Cancun (left image), compared to the original natural state (center) and the result of artificial recovery (right).

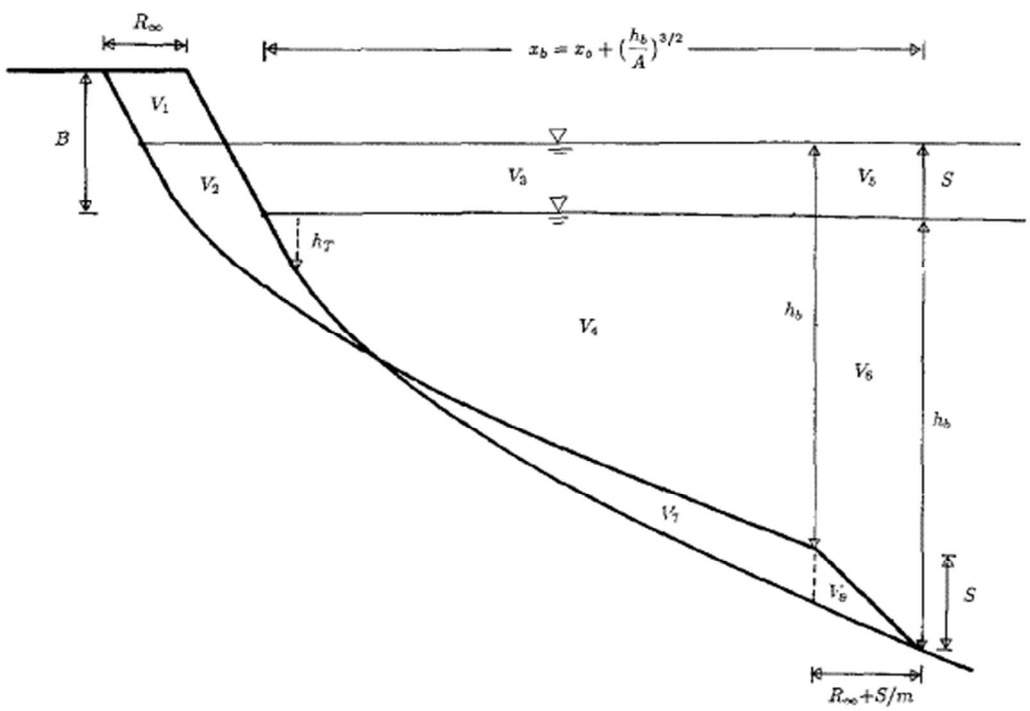
Figure 3-6. Beach erosion in Cancun before and after hurricane Wilma (Silva, et al., 2012)

This study focuses on waves caused by extreme events including storm surge from hurricanes and inducing currents that transport the sediment alongshore and generate coastal erosion. The mathematical model used to correlate storm surges to the coastal erosion volume is the convolution method, described in Kriebel (1993) and recommended by FEMA (2005). This method has demonstrated good correlation between real eroded volumes with the method developed by Ranasinghe, Callaghan and Roelvink (2013).

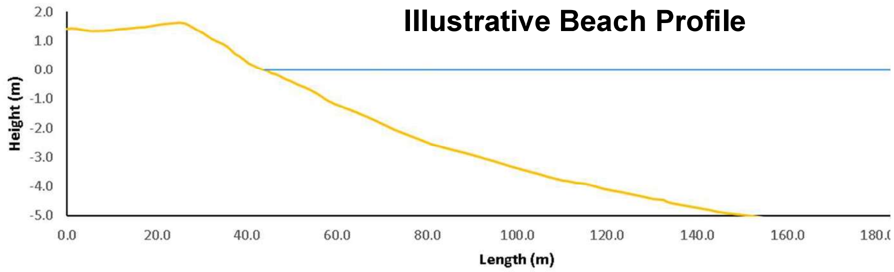
The convolution method calculates the eroded volume caused by a storm surge using some geometric parameters of the representative beach profile for a given segment. It is important to state that this method relates the profile characteristics of a particular beach and the storm surge to obtain the eroded volume. It also approximates shore proximal bathymetry by an exponential factor, and indirectly correlates wave energy with storm duration. The actual erosion potential is calculated as a percentage of its theoretical erosion potential.

Although the methodology does not consider tidal or long-term sea-level variations, it is deemed sufficient for the level of detail required for studying the erosion potential of beaches in this study. The limitations inherent to this methodology can be overcome by calibrating some of its parameters using state-of-the-art bathymetry, wave energy, climate change, tidal models, etc.

Figure 3-7 demonstrates an example of the theoretical profiles described by the method, together with a typical real beach profile found in Barbados.



(a) Theoretical profile: Type 2



(b) Typical beach profile in Barbados classified as type 2

Figure 3-7. Type 2 beach profile according to (FEMA, 2005). For more information on Theoretical profiles 1, 3 & 4 please refer to (Kriebel & Dean, 1993).

For this profile type, the potential eroded volume V_∞ by a given storm surge of height S can be calculated as follows:

$$R_\infty = \frac{S\left(x_b - \frac{h_b}{m}\right)}{B + h_b - \frac{S}{2}}$$

$$V_\infty = R_\infty B + \frac{S^2}{2m} - \frac{2S^{\frac{5}{2}}}{5A^{\frac{3}{2}}}$$

The real eroded volume (V_e) for a given storm (H_i) can be calculated as a percentage of V_∞. This percentage is correlated with the storm duration by a parameter known as the time scale of the profile (T_s). Other variables are shown in Figure 3-7. For a detailed explanation on this method, see Kriebel & Dean (1993).

It is important to note that the total eroded volume of sand in each beach segment depends on both the maximum storm surge height and the total storm duration.

3.3.2 Chronic erosion

Chronic coastal erosion describes the removal of material because of wind currents, wave action, tidal currents, geology and geomorphology of the coast and nature of the sediment balance. Chronic erosion is a very complex process that requires paying attention to morphodynamics, maritime climate, soil properties, and other parameters. The detailed assessment of the chronic erosion in locations other than Barbados is outside the scope of this study. The main parameters to assess chronic erosion are the following:

Maritime Climate:

Maritime climate depends on the location characteristics and the location itself. Barbados lies within the belt of northeast trade winds and is characterized by a humid to sub-humid tropical maritime climate. The eastern, windward side of the island experiences high-energy wave action, with Atlantic rollers crashing on eroding sea cliffs. The western, leeward side of the island faces the Caribbean Sea and experiences gentle waves lapping onto sandy beaches (Vacher & Quinn, 2004).

Wind:

Wind has relevant effect in coastal erosion processes. It moves exposed sand particles which can lead to the generation of dune blowouts or decreases in the amount of sand available in a local system. Wind can also cause shoreline accretion when acting as a barrier for the sediment transportation (Sea Grant, 2015).

Figure 3-8 presents a bar graph of multiannual average wind speed in Barbados obtained from the WAVEWATCH III Model developed at NOAA/NCEP (National Oceanic and Atmospheric Administration, 2020) using data from 2005 to 2016.

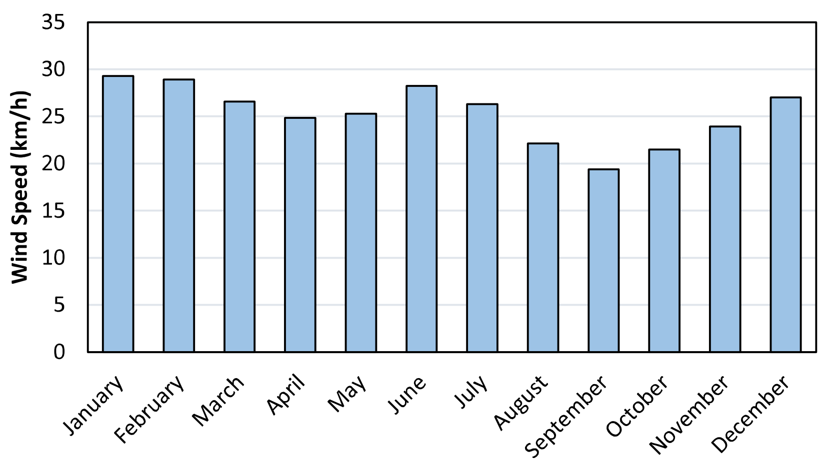


Figure 3-8. Multiannual average wind speed in Barbados (National Oceanic and Atmospheric Administration, 2020)

Waves and Tidal Range:

Waves are a main cause of coastal erosion. The wave energy is the result of different factors, including the wind speed over the sea surface, the fetch length and the time that the wind has been blowing. The higher the wave energy, the higher the erosion rate (Nehra, 2016). The wave normal conditions also influences the tidal range, which is another variable that influences the chronic erosion Wave regime and tidal range were evaluated based on information available from the Coastal Zone Management Unit and the WAVEWATCH III Model (National Oceanic and Atmospheric Administration, 2020). Figure 3-9 presents the multiannual average wave height in Barbados (using data from 2005 to 2016).

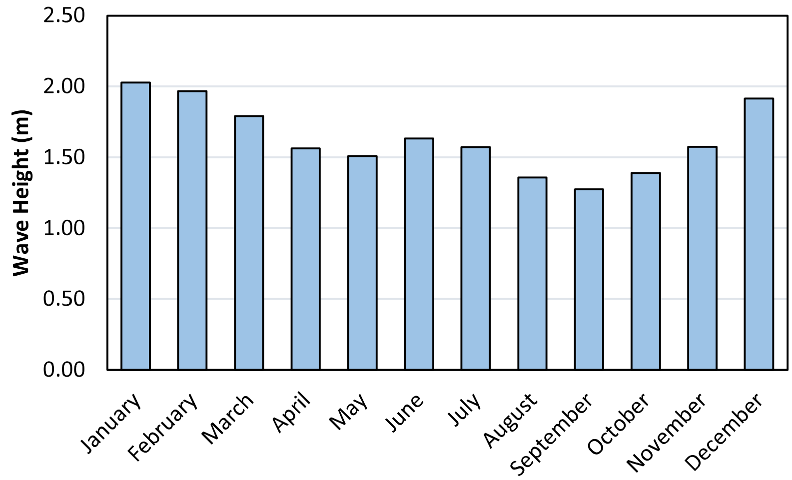


Figure 3-9. Multiannual average wave height in Barbados (National Oceanic and Atmospheric Administration, 2020)

Geology:

The geology of the coastline affects the beach erosion rates. In Barbados, geology renders coasts more prone to erosion because approximately 86% of the island is coral limestone that erodes easily than any other type of soil (Mycoo & Chadwick, 2012).

Sediment Balance:

The sediment transport processes supplying the beaches, is a principal variable that affects coastal erosion. As mentioned before, the proposed model takes into account the changes generated by cyclonic events in the sediment balance, while Baird erosion rates (Baird, 2015) consider the sediment balance for chronic erosion.

3.3.3 Sea level rise consideration

The present study does not directly include sea level rise (SLR) and the associated erosion rates in the probabilistic risk assessment analysis. They are only considered in a simplified way to understand its relative importance in chronic or episodic events. In addition, SLR requires a different approach when it comes to identifying mitigation strategies. SLR is a long-term effect and standard interventions options to reduce the risk associated with chronic or episodic events may not have an important effect.

3.4 EXPOSURE MODEL METHODOLOGY

The exposure model main objective is to define what would be the maximum recovery cost of the beach in Barbados. This recovery cost depends on several factors, such as the tourism revenue, the area prone to erosion and the recovery strategy. Therefore, the following concepts are defined:

- **Total beach revenue (TBR):** defined as the yearly revenue valuation derived from the tourism. This value is obtained as a percentage of the Gross Domestic Product (GDP) and is distributed in the country beach area based on the importance of each beach segment. The unit of this value is in US dollars per square meter per year (US$/m2/year).
- **Total beach recovery cost (TBRC):** the cost of recovering the beach after an erosion event. Since there are several strategies to recover the beach, such as engineered nourishment or natural recovery, this cost will be estimated for different scenarios. This value is estimated for each beach and each strategy from the TEBR, considering the maximum possible erosion potential. The unit is in US dollars per square meter (US$/m2) -it is important to note, that unlike the TBR and TEBR, the TBRC is not a yearly valuation.

The graphical representation of the above-mentioned concepts is presented in Figure 3-10. It is important to note that the TBR is considered as a fixed value in the prospective analysis as a conservative estimation. It is also out of the scope of this study to do a macro economic analysis of these variables.

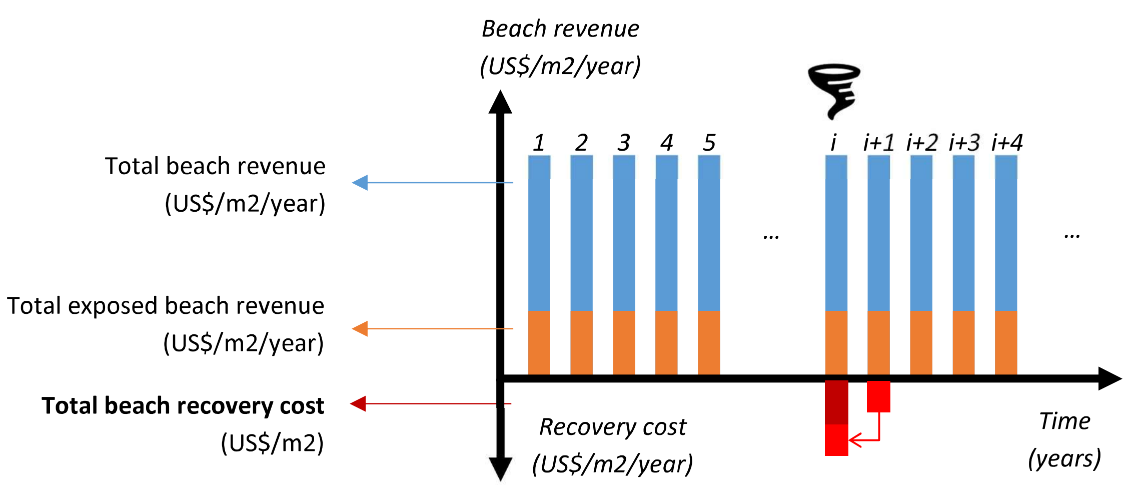


Figure 3-10. Exposure model concepts

Based on the concepts defined, the methodology to develop the exposure model is presented in Figure 3-11. The first step is to identify the total beach revenue at national level, and the distributed in each beach segment based on its tourism-related characteristics. Next, the potentially erodible area for each beach is identified and with this information, engineered nourishment and natural nourishment recovery strategies are identified and the recovery cost for each is assessed. The following sections present the detailed methodology for each step.

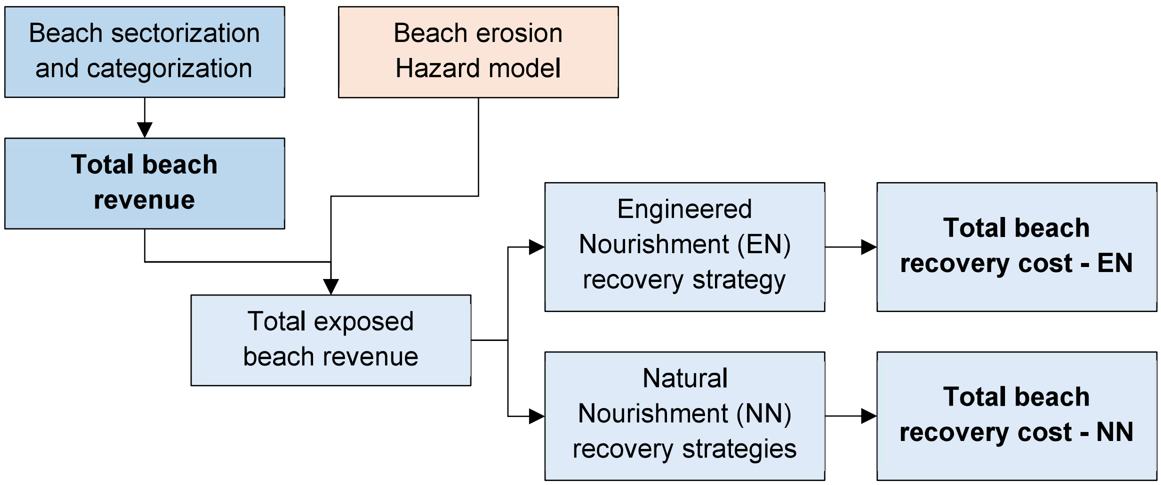


Figure 3-11. Exposure model general methodology

3.4.1 Total beach revenue (TBR)

The total beach revenue valuation corresponds to the yearly revenue valuation derived from tourism. Traditional asset valuation uses commercial, market, land, and replacement indicators for assigning a total valuation or valuation per occupied area to a specific good (e.g., 500 US$/m2 for residential buildings). Nevertheless, the traditional value is related to assets and more specifically to goods that can be traded in the market. Beaches cannot be valuated this way since they are natural public resources and cannot therefore be commercially traded.

There is extensive literature regarding a wide variety of proposed methodologies for assigning economic and revenue valuations to coastal areas and to natural resources in general (Gopalakrishnan, Smith, Slott, & Murray, 2011; Alexandrakis, Manasakis, & Kampanis, 2015; Baird, 2017; Castaño-Isaza, Newball, Roach, & Lau, 2015; Pendleton, Mohn, Vaughn, King , & Zoulas, 2012; Rosen, 1974; Schuhmann, Bass, Casey, & Gill, 2016). A broadly accepted economic approach is the hedonic price methodology, according to Rosen (1974). The concept of the hedonic price method relies on calculating the intrinsic valuation of a non-market asset based on related assets that are market valuated. For example, the value of a city park relates to the value of the buildings around it, the infrastructure quality, the economic activities in the surrounding area, etc. This methodology allows to define a set of characteristics of a specific area to determine the value of a non-market asset, such as a beach.

Surveys are another type of widely used approaches in economic studies to determine the willingness of people to pay, and specifically of tourists (Schuhmann, Bass, Casey, & Gill, 2016). The advantage of identifying the willingness to pay is to find a value potentially related to the real valuation of a non-market asset. For example, several surveys try to estimate the value of a city park by asking people how much they would be willing to pay to retain the park as is. Additionally, considering that the survey is properly carried out, there are two more indicators that would allow evaluating the non-market asset: 1) value at risk or revenue losses, and 2) people's preference for certain characteristics or states in the particular asset. The first step is to obtain from a questionnaire information of whether people would return to a particular place if a certain characteristic change. For example, this is very clear in the case of coral reefs if one considers a reduction in the fish concentration or in the total reef area (for example, by half). The number of visitors that would not return to the coral reef represents the revenue at risk, using the relationship between visitor and revenue (Castaño-Isaza, Newball, Roach, & Lau, 2015). The second aspect related to peoples' preferences is derived by questions on the perceived value (Gopalakrishnan, Smith, Slott, & Murray, 2011; Schuhmann, Bass, Casey, & Gill, 2016). For example, this applies to the quality of the sand of a particular beach or the allowable amount of litter. A possible indicator could be the concentration of litter pieces (e.g., 10 pieces per 25 meters).

Several methodologies, approaches, and results have been published regarding beach valuation purposes (Alexandrakis, Manasakis, & Kampanis, 2015; Baird, 2017; Pendleton, Mohn, Vaughn, King , & Zoulas, 2012). Nevertheless, in one way or another they are all based on the above-stated framework: the hedonic pricing from the physical characteristics and the willingness to pay. An equivalent approach is adopted to assess the beach valuation in different zones of Barbados.

In general terms, the proposed methodology leverages insights from different studies that use 'willingness to pay' surveys and information related to beach valuation, beach characteristics preferences, and value at risk for eroded beaches in Barbados and the Caribbean. This insight is used to determine the total proportion of the tourism GDP revenue that is at risk and could be lost due to beach erosion, loss of land, or beach closure. Once the revenue at risk is estimated based on hedonic price methods, the physical, economic, commercial and tourism characteristics of the beaches allow a proper geographical distribution of the revenue. The general methodology for the beach revenue valuation is presented in Figure 3-12.

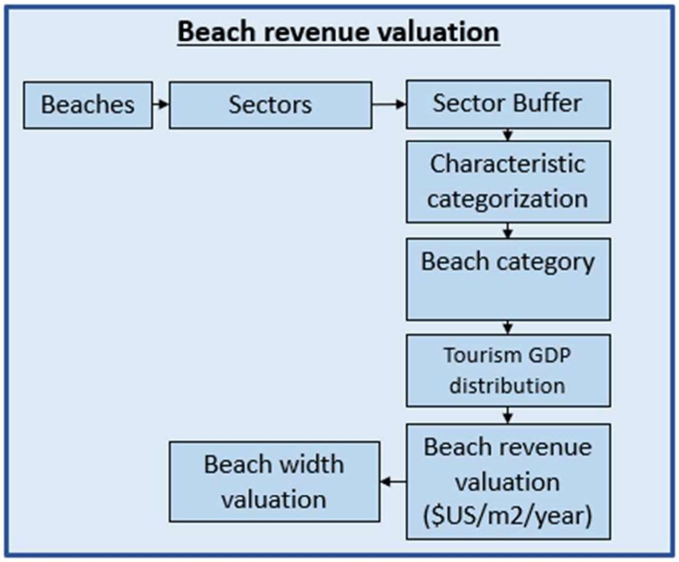


Figure 3-12. Beach revenue valuation methodology

Finally, the methodology shown above is based on the direct contribution of tourism to the GDP. However, tourism has a wider economic impact on the national GDP, as shown in Figure 3-13 developed by the World Travel and Tourism Council and Oxford Economics (2020) that should be considered to increase the final coastal valuation. In this study, the wider economy multiplier is included as a factor to increase the direct contribution of tourism in GDP. This estimation is presented in section 5.2.4.

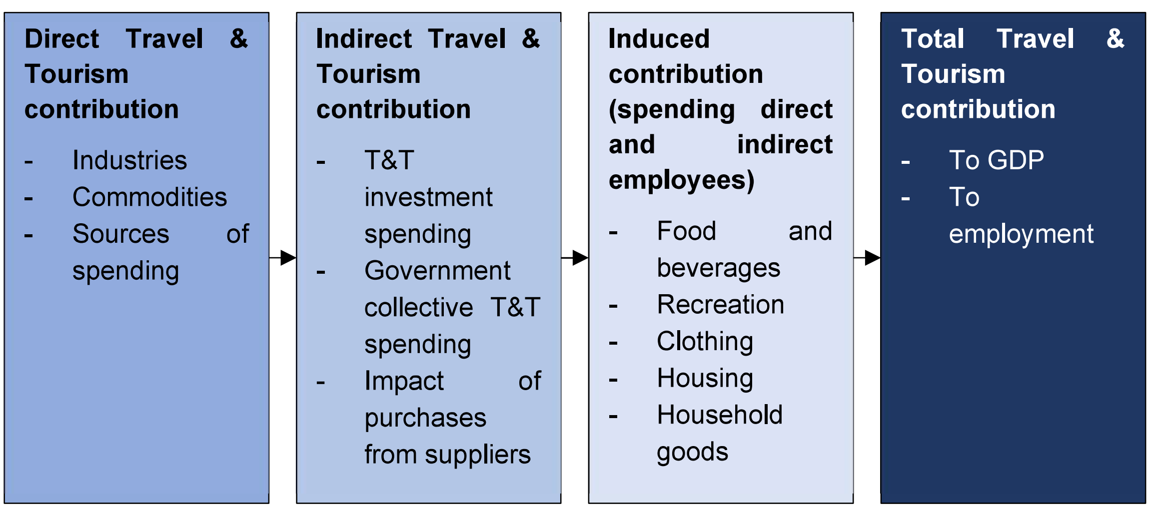


Figure 3-13. Total travel and tourism (T&T) contribution to GDP. Adapted from WTTC & Oxford Economics (2020)

3.4.2 Total beach recovery cost (TBRC)

As expressed above, there are differences between the revenue value and the total value that can be lost from erosion. Therefore, this study defines the Total Beach Recovery Cost (TBRC) as the replacement cost due to erosion caused by cyclonic events. Similarly, this value can be defined as the maximum economic loss for the worst-case scenario of erosion.

For the present study, the potential erosion that occurs on a beach segment after a hazard event is handled in two different ways:

a) **Engineered Nourishment**: Restoration/repair by nourishing the eroded sand with grain sizes that match those that previously existed in the beach.
b) **Natural Nourishment**: Recuperation by a natural sedimentation process.

The first option would be to recover the sand lost by erosion through a work contractor who will consider the location of the potential source of sand, and material transportation and placement on the selected beach. This process will have a cost estimate and would require a particular period of time, which would be in general much shorter than the time needed for a natural sedimentation recuperation process. This option minimizes interruption time for intervened beach sectors.

The second option is the natural nourishment which applies to beaches with high sediment budgets. According to Kobayashi (2012), the Rehoboth Beach located in Delaware (US) took about seven months to recuperate after an event in 1992 which generated an erosion volume from 42 to 91 m^3/m (cubic meters eroded each meter of width). In that case, the main impact of the erosion would be the reduction of tourist activities during the recuperation phase, which as previously mentioned, can take several years in certain cases.

3.5 EROSION VULNERABILITY - DEFINITION

3.5.1 Vulnerability definition

In the context of this study, vulnerability is defined as the susceptibility of each beach segment to erosion caused by a particular storm. The erosion vulnerability indicates the relation between the hazard intensity parameter and the expected loss for each beach segment.

The hazard intensity parameters considered are the maximum storm surge height and the maximum duration of the storm. The correlation between the two parameters is implicitly considered in the stochastic hazard catalog. The hazard model generates a unique integrated intensity parameter for each storm. This parameter corresponds to the total volume of eroded sand, normalized by the horizontal area of each beach segment. This parameter can be interpreted as the mean equivalent vertical erosion depth in the complete exposed area of each beach segment.

The exposed value for each segment is defined as the maximum economic loss for the worst-case erosion scenario. As previously explained, this value corresponds to the parameter V_{∞}, calculated by the sum of the direct and indirect costs corresponding to the maximum volume that could be eroded, considering the geomorphology of the section as explained in Chapter 3.3.1.4. The total direct costs correspond to the total replacement costs of the maximum erodible volume of sand, whereas the indirect costs correspond to the maximum time frame that the beach could be closed under those critical conditions.

Considering the characteristics of each beach segment, each segment is assigned a particular vulnerability curve. This vulnerability curve relates the hazard intensity parameter to the expected loss in percentage of the maximum economic loss in each segment. With this information for each storm scenario, the intensity parameter (equivalent depth of erosion in each beach segment) is calculated from the hazard model. Then, the expected loss is estimated using the corresponding vulnerability curve assigned. Before assigning specific vulnerability functions, a general susceptibility index is first estimated for each beach segment.

3.5.2 Erosion susceptibility

A susceptibility index is calculated to assign a characteristic erosion vulnerability function to each beach segment. Several beach erosion susceptibility indices have been proposed in the literature (Evelpidou, Karkani, Polidorou, & Kotinas, 2018; Rangel-Buitrago & Anfuso, 2015; Narra, Coelho, & Sancho, 2019; Fitton, Hansom, & Rennie, 2016). In the present assessment, the Coastal Vulnerability Index proposed by Evelpidou et al. (2018) is used since it includes coastal morphology and maritime climate variables. It requires the following parameters in the current condition:

- Morphology of the coast
- Shoreline change (m/y)
- Coastal slope (%)
- Sea level change (mm/y)
- Wave height (m)
- Tidal range (m)

A variation was proposed to the Coastal Susceptibility Index to consider protection structures on the coasts. This variation relies on the use of a K factor that represents the existence of structures, which according to their type and quantity, they decrease the beach susceptibility to erosion. Figure 3-14 presents the structure of the adapted index.

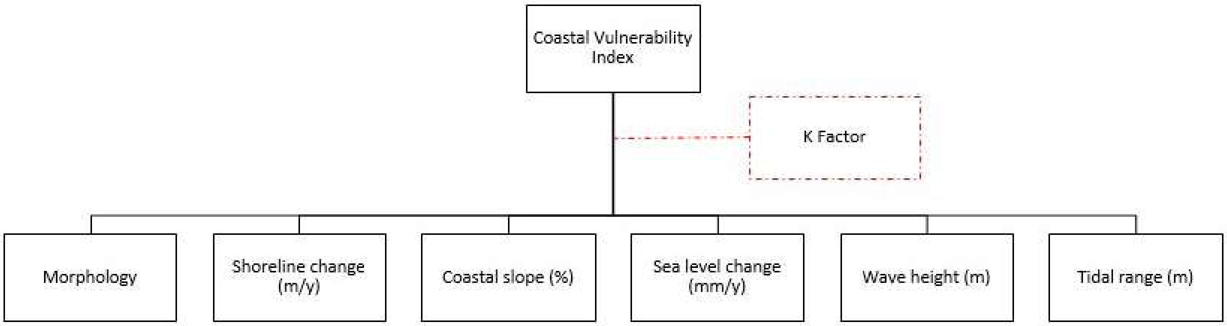


Figure 3-14. Modified Coastal Susceptibility Index. Adapted from. Adapted from Evelpidou, Karkani, Polidorou & Kotinas (2018)

To calculate the index, a value from 1 to 5 should be assigned for each parameter, as presented in Table 3-1. The final index per beach segment is obtained as the mean value for all the parameters included in the index.

Table 3-1. Parameters ranges for the Modified Coastal Susceptibility Index. Adapted from Evelpidou, Karkani, Polidorou & Kotinas (2018)

	Very low (1)	Low (2)	Middle (3)	High (4)	Very high (5)
Morphology	Rocky shores, high cliffs	Cliffs of average height	Low cliffs, alluvial plains	Shores with pebbles, lagoons	Barrier islands, deltas, sandy shores
Shoreline change (m/a)	>2.0	1.0 – 2.0	-1.0 – 1.0	-1	<-2.0
Coastal slope (%)	>1.20	1.20 – 0.90	0.90 – 0.60	0.60 – 0.30	<0.30
Sea level change (mm/a)	<1,8	1.8 – 2.5	2.5 – 3.0	3.0 – 3.4	>3.4
Wave height (m)	<0.55	0.55 – 0.85	0.85 – 1.05	1.05 – 1.25	>1.25
Tidal range (m)	>6.0	4.0 – 6.0	2.0 – 4.0	1.0 – 2.0	<1.0
K factor	Existing protection structures	-	-	-	Without any protection structure

3.5.3 Vulnerability functions derivation

To assign a vulnerability function to a specific beach segment, it is necessary to obtain its cross-section profile and main characteristics. With this information, along with the methodology explained in section 3.3, it is possible to establish the maximum erodible sand volume for each segment. This volume can then be normalized by the segment area to obtain an equivalent height of erosion. Once these parameters are calculated, it is possible to define the vulnerability function for each beach segment. The methodology used for developing the vulnerability functions is summarized in Figure 3-15.

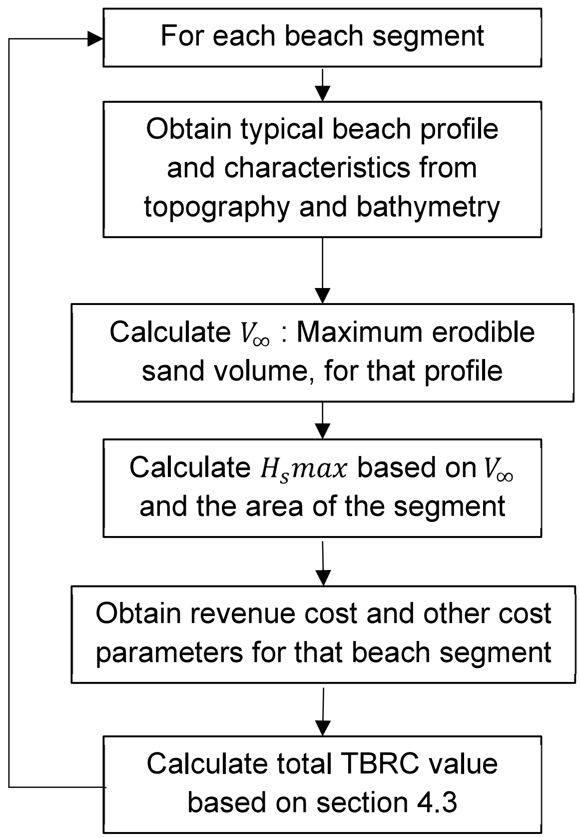


Figure 3-15. Vulnerability function assignment methodology

Additionally, the vulnerability functions assume the following two conditions:

a) **No-damage intensity:** defined as events that cause small amounts of erosion, an erosion that is likely to regenerate itself after a relatively short period of time, thus generating no significant economic losses. This no-damage intensity will be assigned following the susceptibility classification presented in section 6.1.
b) **Minimum damage**: a minimum damage is defined for the engineered nourishment case as one that requires a minimum of two months to include all the administrative procedures before starting the artificial nourishment works. The minimum damage is established in all beach segments as 30% of the total TBRC for the engineered nourishment condition and 0% in the natural nourishment condition.

Figure 3-16 presents an illustrative example of an erosion vulnerability function for$H_s \max = 1.00\, m$, a no-damage intensity of 5%$H_s max$ and a minimum damage of 30%

TBRC. Both the mean damage ratio and the estimated variance (Var) are presented in the same figure.

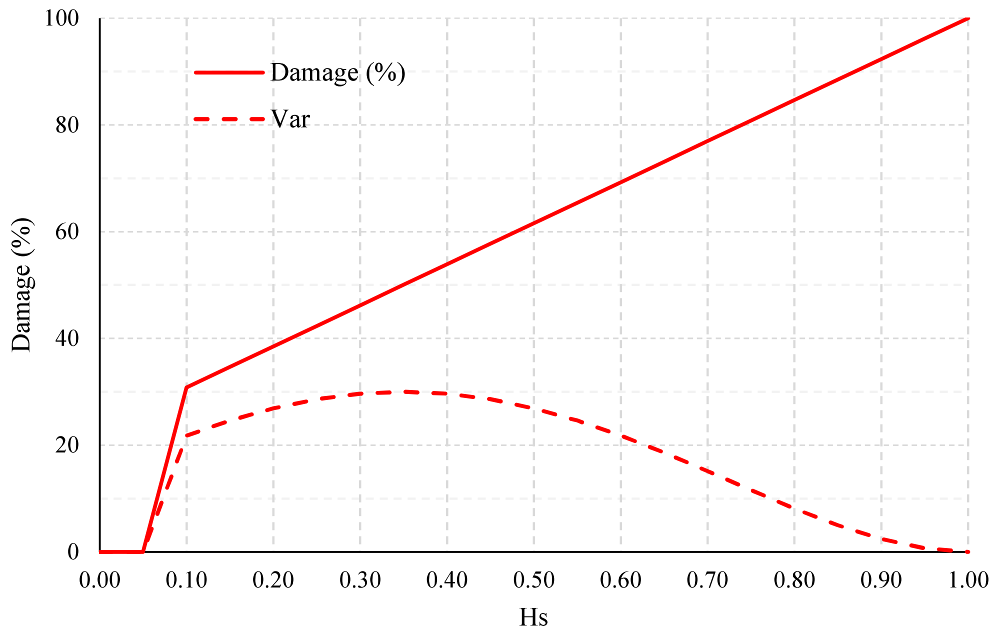


Figure 3-16. Vulnerability function example

To ensure consistency in risk assessment, this study defined the Average Erosion Height, H_s as the maximum erodible sand volume normalized by the total plan area of each beach segment. This parameter is graphically explained in Figure 3-17.

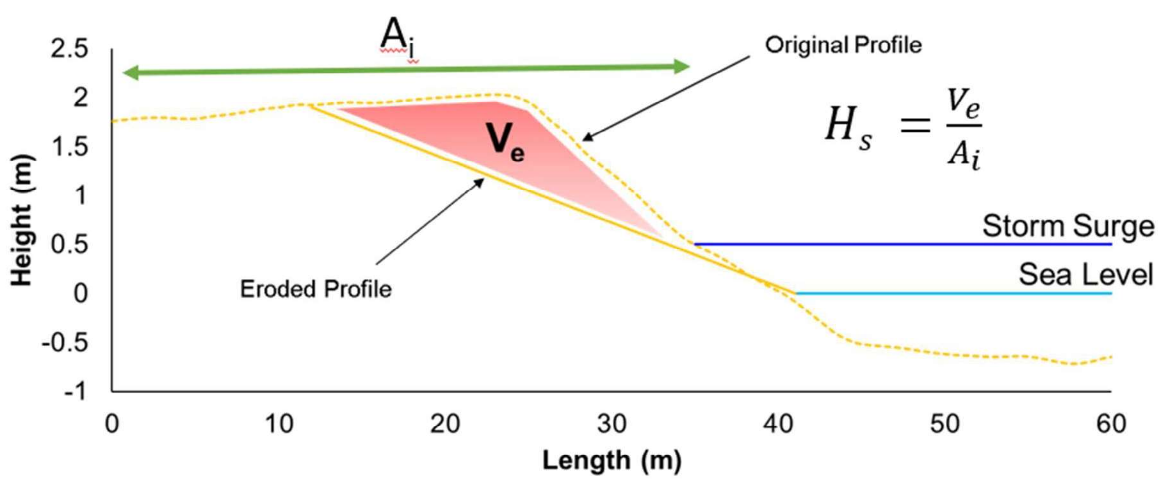


Figure 3-17. Average erosion height H_s Source: original.

In this study, the parameter H_s is used as the main intensity parameter from the hazard model. The erosion vulnerability functions will establish the relationship between the hazard intensity parameter and the expected loss for each beach segment.

3.6 DISASTER RISK REDUCTION ALTERNATIVES

3.6.1 Erosion mitigation strategies

Erosion mitigation alternatives depend on multiple factors, ranging from the beaches' geomorphological conditions to maritime climate, sediment dynamics, and existing natural protection structures. Several studies in the literature have addressed the mitigation strategies that should be performed to reduce beach susceptibility to erosion. The mitigation alternatives should include nature-based solutions as shown in Figure 3-18. The main goal will be to provide alternatives that increase the resilience of each site in the face of extreme events and climate change.

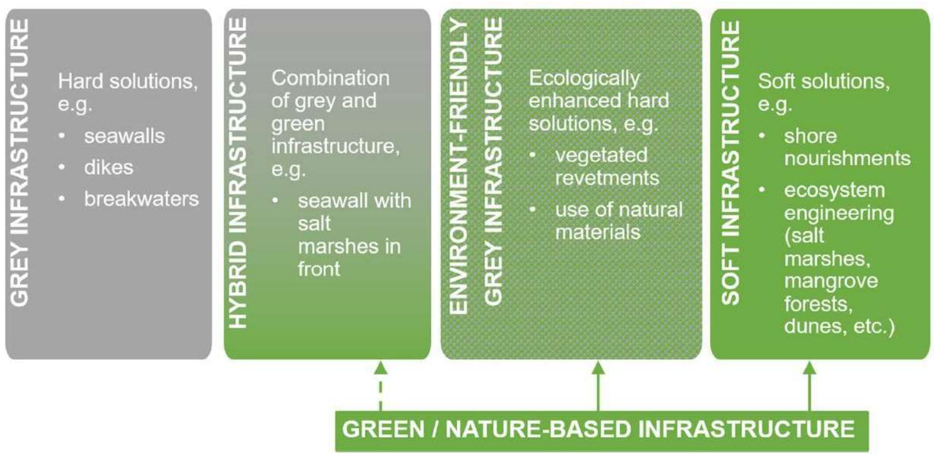


Figure 3-18. Risk mitigation measures description (Schoonees, et al., 2019)

In this study, a particular intervention strategy for each beach segment will be selected based on the probabilistic risk assessment results. The general methodology for formulating the risk mitigation strategy is presented in Figure 3-19.

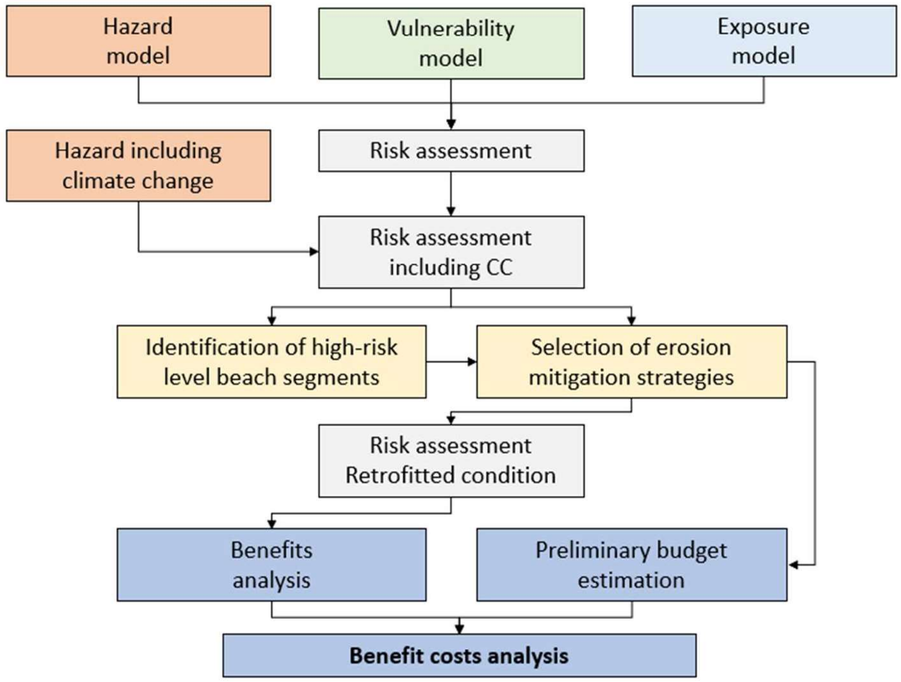


Figure 3-19. Risk mitigation strategy methodology

3.6.2 Available data and information

In this study, data and information were collected in January 2020. This process was carried out with the support of the Coastal Zone Management Unit (CZMU). Table 3-2 summarizes the main sources of information used.

Table 3-2. Main sources of information

Description	Type	Development date	Institution
Bathymetric data in contour shapefile and raster grid formats (LiDAR Study)	GIS	2015	CZMU - Baird
Topography data in contour shapefile and raster grid formats (LiDAR Study)	GIS	2015	CZMU - Baird
Census data in shapefile and table formats (2010 census)	GIS	2015	CZMU - Baird
Land cover in shapefile format (LiDAR Study)	GIS	2015	CZMU - Baird
Land use in shapefile format (LiDAR Study)	GIS	2015	CZMU - Baird
Building footprints in shapefile format (LiDAR Study)	GIS	2015	CZMU - Baird
Building type in shapefile format (Land Tax parcels)	GIS	2015	CZMU
Country Limits	GIS	2015	CZMU
Urban Centers and internal political divisions	GIS	2015	CZMU
Urban perimeter of Bridgetown	GIS	2015	CZMU
Distribution of coastal ecosystems	GIS	2015	CZMU
Rivers	GIS	2015	CZMU

Description	Type	Development date	Institution
Database of historic flood hazard events and events which impacted infrastructure (DesInventar database)	xls	2019	Desinventar
Time series of oceanographic data (Nearshore Wave Study)	Web	2015	CZMU - Baird
SCS–Shoreline Change Study	PDF, xlsx, shp	2015	CZMU - Baird
Ecosystem based adaptation pilot project	PDF	2017	Baird
National Coastal Risk Information & Planning Platform Draft Vulnerability Report	PDF	2017	Baird
National Coastal Risk Information & Planning Platform Climate Change Report	PDF	2017	Baird
National Coastal Risk Information and Planning Platform Final Hazard Report	PDF	2017	Baird
National Coastal Risk Information & Planning Platform Revised Draft Risk Report	PDF	2018	Baird
Institutional Stability for Integrated Coastal Risk Management for the Coastal Zone Management Unit: Proposal for Cost Recovery Mechanisms for Coastal Infrastructure	PDF	2018	Peter W. Schuhmann
The Impact of Coastal Infrastructure Improvements on Economic Growth	PDF	2016	IDB

CHAPTER

4

HURRICANE HAZARD–BEACH EROSION ANALYSIS

4.1 GENERALITIES

The first step is to establish the potential coastline that could be affected by extreme events. This study considered only the most important touristic areas as the critical components for the assessment. Figure 4-1 illustrates the coastline areas that are susceptible to potential impacts by extreme events. In total, 33.0 km were identified as beach segments that could suffer damage related to tourism activities from a total of 97 km of coastline. A total of 659 beach segments of 50 m wide, and total area of 639,190 m^2 were identified for the susceptible coastline.

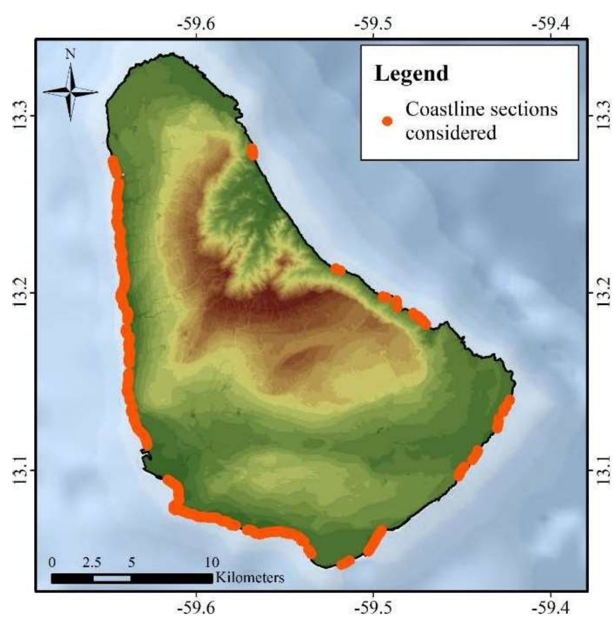


Figure 4-1. Coastline sections susceptible to potential impacts by extreme events (Source: original)

The hazard model in this study was divided into three components, as presented in section 3.3: erosion events generated by cyclonic events; chronic erosion events; and events caused by the expected sea level rise (SLR).

Based on a stochastic scenarios collection, the cyclonic hazard model generates storm surge events that help estimate the entire beach erosion catalogue. The chronic erosion module was developed using annual erosion rates determined by Baird (Baird, 2015) in previous risk studies for the entire Barbados coasts. The hazard related to sea level rise was determined using projected IPCC scenarios until 2100. The methodological approach is presented in section 3.3. The following sections describe each component of the hazard model. In each case, specific focus is placed on the time and frequency of events to assess, when possible, their consequences and impacts.

4.2 EPISODIC EROSION HAZARD MODEL

4.2.1 Input data

The cyclonic hazard model was developed across the nation for the purpose of the present assignment. The main sources of information to conform the hazard model are the following:

- National Oceanic and Atmospheric Administration of the U.S. department of Commerce (NOAA, 2019).
- Shuttle Radar Topography Mission Data (NASA, 2014).
- European Commission’s Science and Knowledge Service (EU Science Hub, 2019).
- Barbados Coastal Zone Management Unit

The information required to build the hazard model includes the historical information of tropical cyclones, the digital elevation model, the wind exposure factors, the land use and roughness factors, the tidal grid, the bathymetry, and the erosion shape.

For constructing the historical catalogue, we revised all available information about historical hurricane tracks, passing through the Caribbean. Figure 4-2 illustrates the distribution of tropical storms and all hurricanes from 1851 to 2019, according to the Saffir-Simpson scale. In this period, a total of 1,635 events were included in the database of historical information.

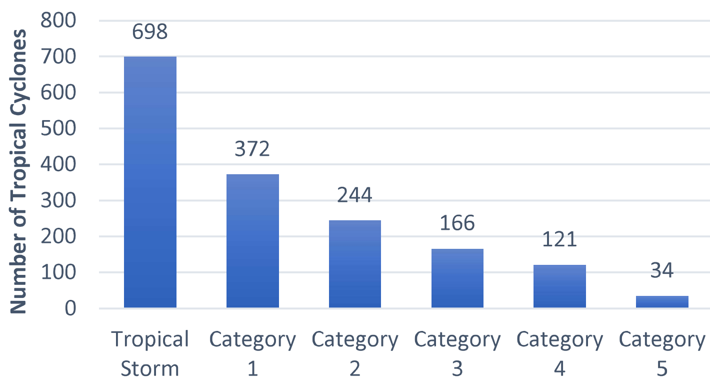


Figure 4-2. Historical hurricanes between 1851 and 2019 per category in the Atlantic Basin

Among this number of events, only the hurricanes whose eye passed within 300 km of the Barbados coastline were selected for the model. These events make a set of 145 hurricanes shown in Table 4-1. The storm paths of the selected events are presented in Figure 4-3 with each corresponding maximum category. Using this event catalogue and the hazard model, a total of 1,450 stochastic scenarios were generated.

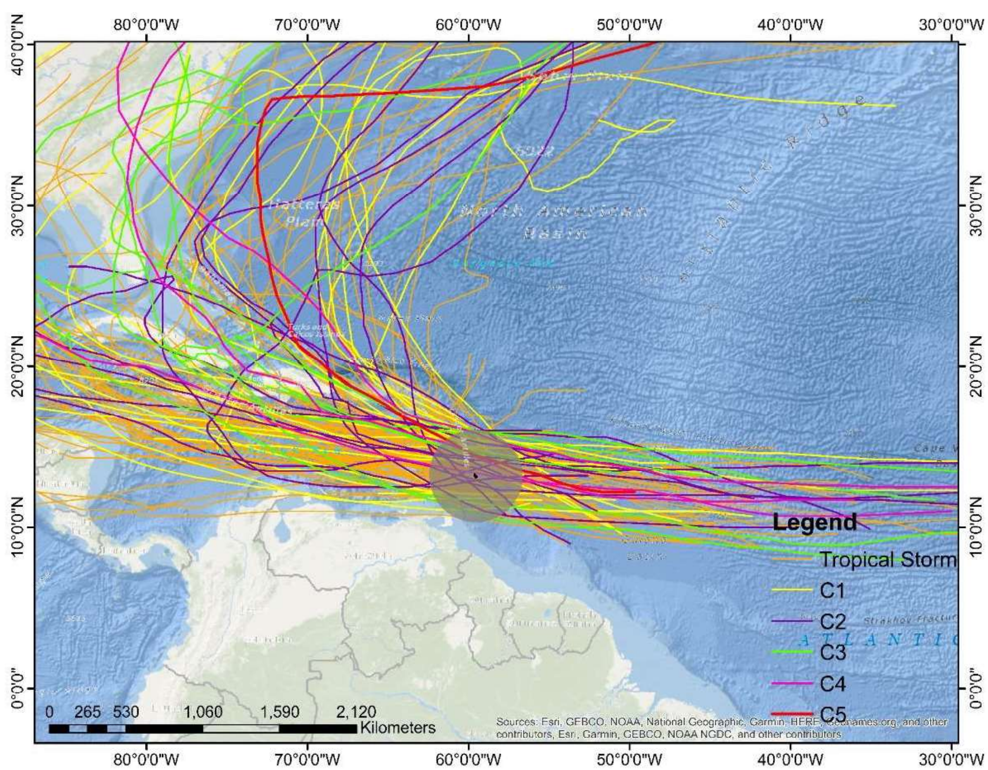


Figure 4-3. Hurricanes and storms recorded in the Atlantic Basin from 1851 to 2019 near Barbados

Table 4-1. Cyclones categories and frequency

Category	Number	Frequency
Tropical storms	100	69%
C1	20	14%
C2	14	10%
C3	7	5%
C4	3	2%
C5	1	1%

The additional information required for the hazard assessment is presented from Figure 4-4 to Figure 4-8.

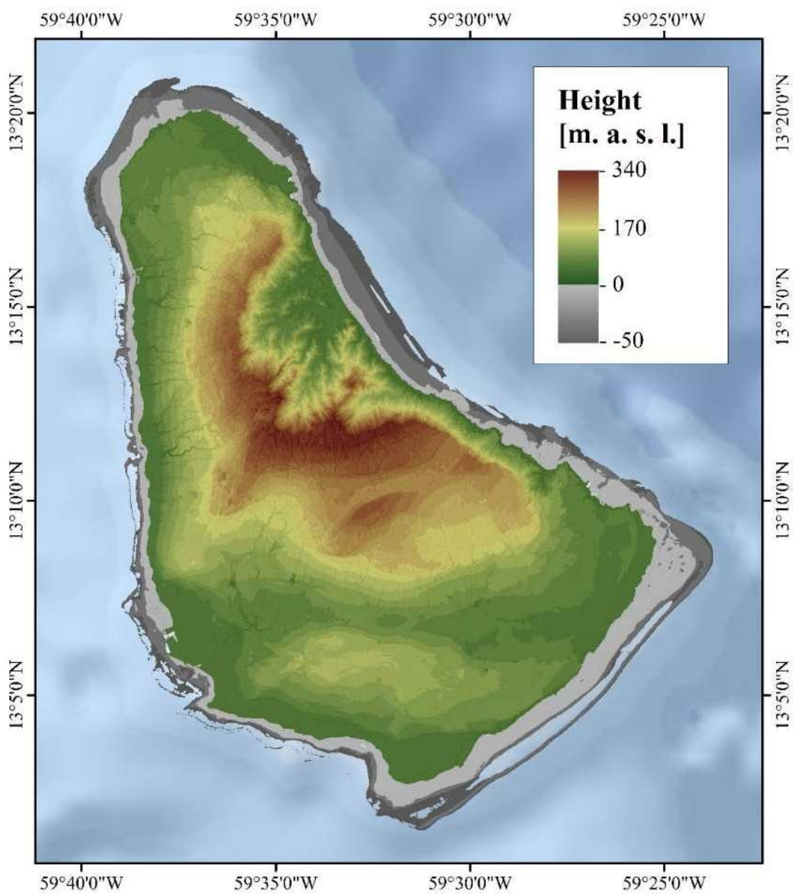


Figure 4-4. Digital Elevation Model for Barbados (LiDAR data given by CZMU)

For this model, a 1m x 1m resolution digital elevation model is used. This LiDAR data was provided by the Coastal Zone Management Unit in Barbados.

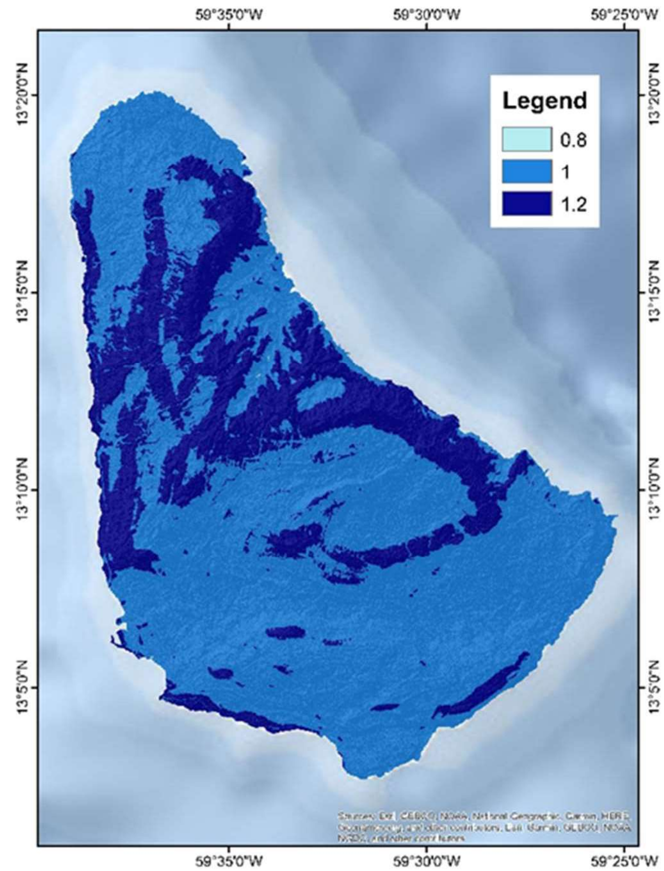


Figure 4-5. Wind Factors (generated by the consultant based on the DEM)

Wind exposure factors data considers whether a respective area is exposed or protected depending on the topographic elevation adapted from ASCE 7-16 (2016).

Table 4-2. Wind exposure factors

Site	Topography	Factor
Protected	Closed Valley	0.8
Flat	Flat terrain, open field, lack of important orographic structures, slope lower than 5%	1
Exposed	Hill or mountains, terrain with slope higher than 5%	1.2

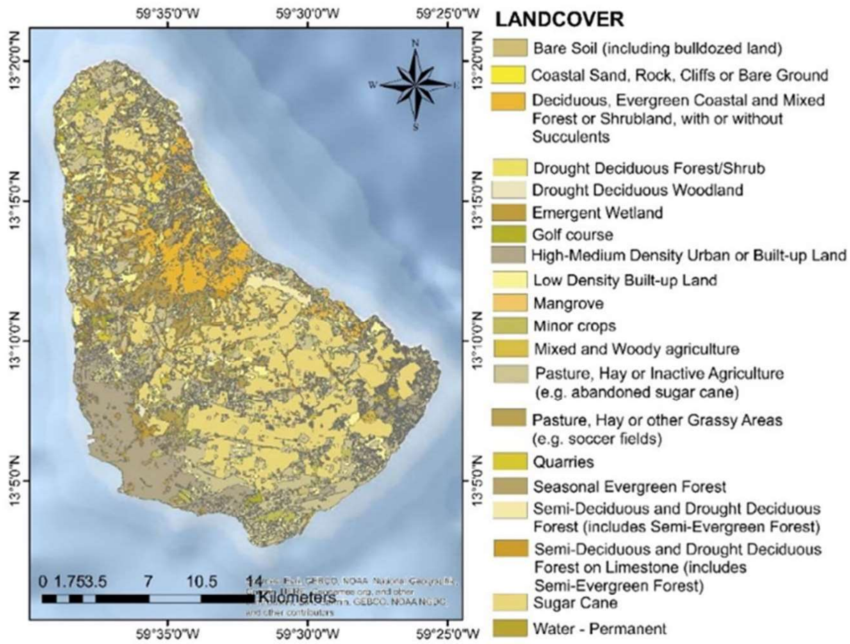


Figure 4-6. Land cover (data given by CZMU)

The roughness factors are determined by the type of land cover. Each type must be assigned a value between 1 and 4 depending on the description given in Table 4-3 adapted from ASCE 7-16 (2016).

Table 4-3. Roughness factors description

Type	Categories	Description
1	Flat open ground	Open ground, almost flat without obstructions, for example, flat coastal strips, swampland, pasture, and crops not surrounded by enclosures.
2	Trees or standard construction	Crops or farms with two obstructions, such as enclosures, trees, and scattered constructions.
3	Trees, residential district	Land covered by closely spaced obstructions, for example, urban areas, suburbs, woodland. The size of constructions corresponds to housing.
4	Many obstructions, city center	Land with large high buildings, closely spaced, such as in the center of major cities and developed industrial complexes.

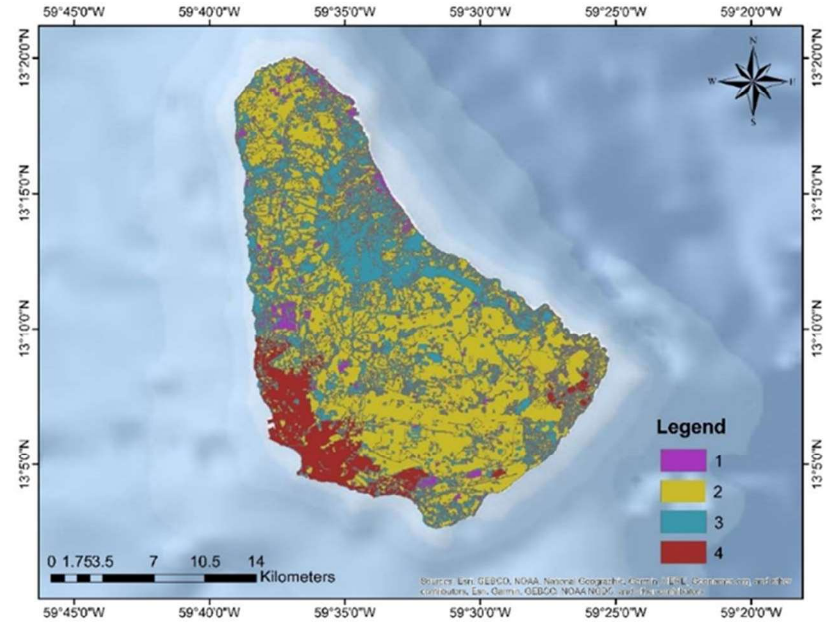


Figure 4-7. Roughness factors (generated by the project team based on land cover information)

Tidal grid defines the points at 0 m above sea level (m.a.s.l.) and points at 15 m above sea level where the possible impact from storm surges should be negligible.

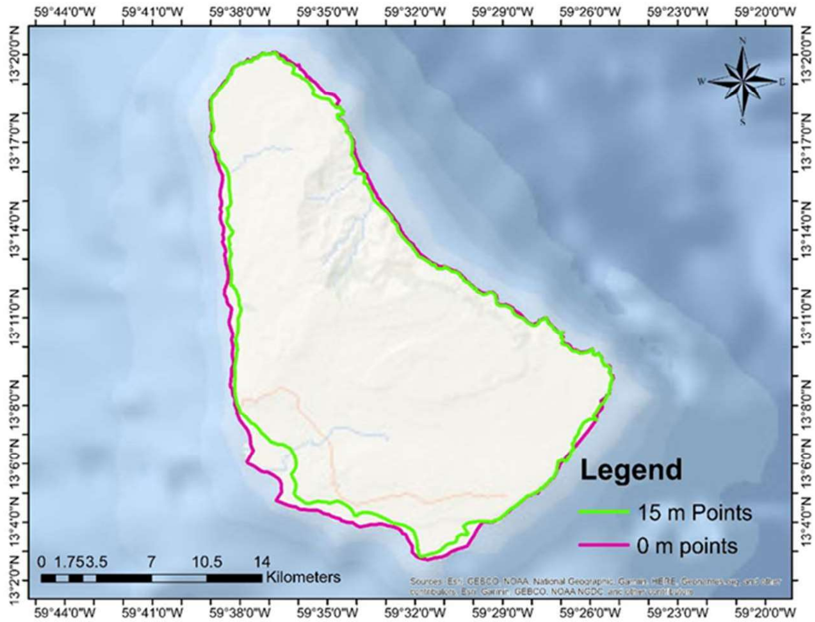


Figure 4-8. Tidal grid each 50m (generated by the project team based on the DEM)

The definition of erosion points serves as the final input for the model. These points correspond to the beach segments in which erosion has been observed in the past (section 2.2) and will therefore be included in the assessment. Cliffs are not included in the analysis. Each point has the information associated with the erosion model that is explained in section 4.2.3.2.

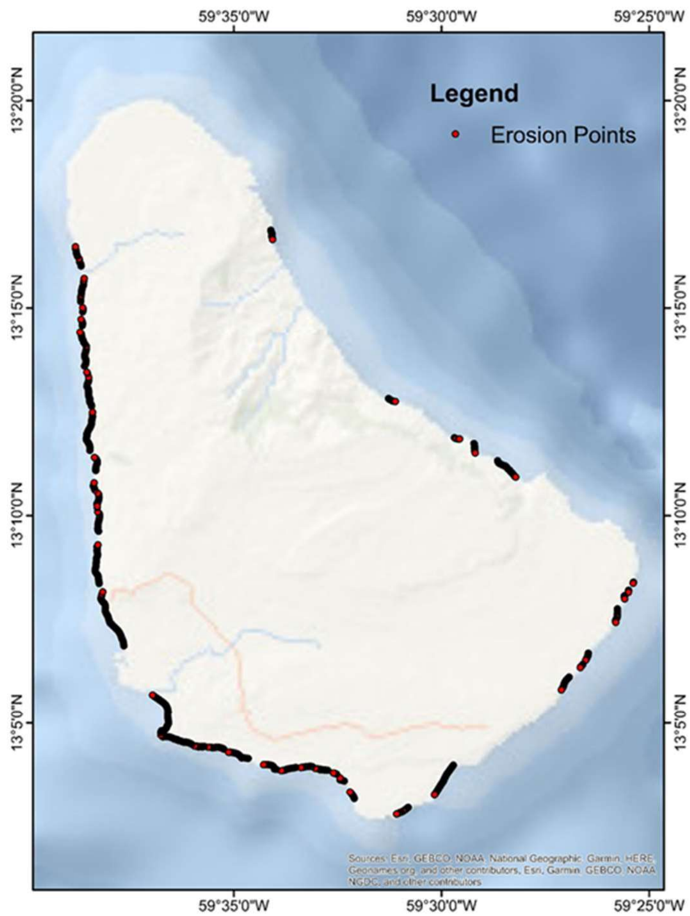


Figure 4-9. Erosion shape (generated by the project team based on Kriebel (1993))

4.2.2 Climate change scenario

A climate change scenario is proposed in the present assessment that factors in an increase in the annual frequency of the occurrence of category 3 hurricanes or higher, as shown in Figure 4-10.

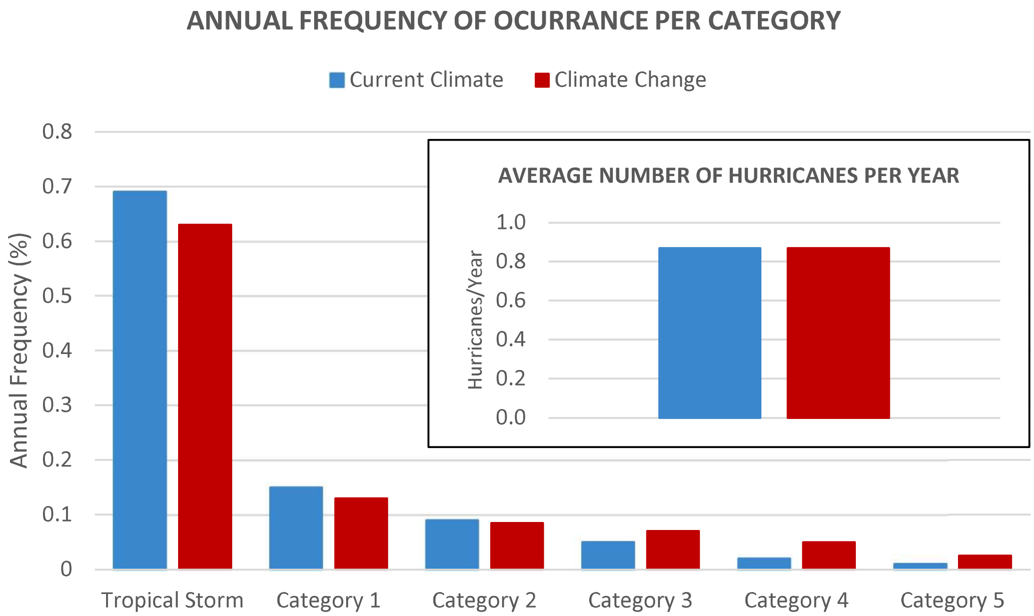
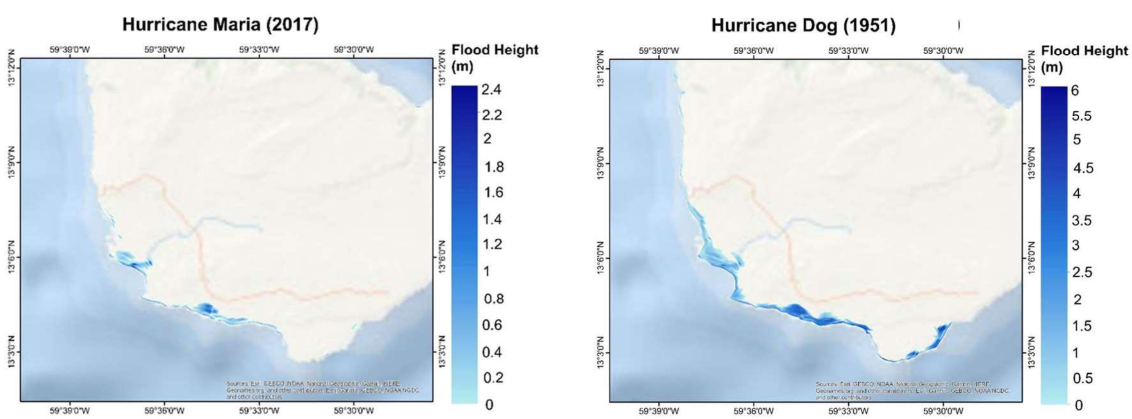


Figure 4-10. Annual frequency of hurricane occurrence in current and climate change (generated by the project team based on IPCC (2013))

4.2.3 Episodic model results

4.2.3.1 Strom surge

Figure 4-11 presents three representative storm surge hazard maps in terms of water height along the coastline of Barbados during the three modelled historic scenarios.



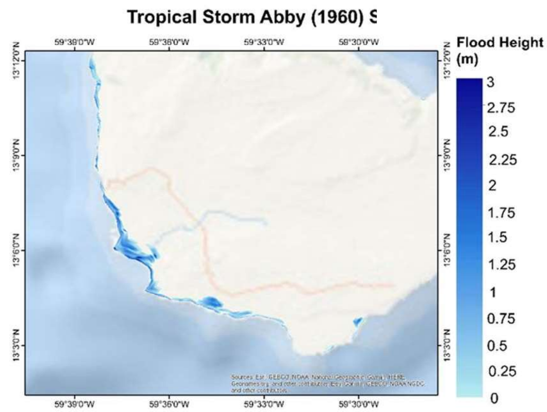


Figure 4-11. Storm surge modelled scenarios (generated by the project team)

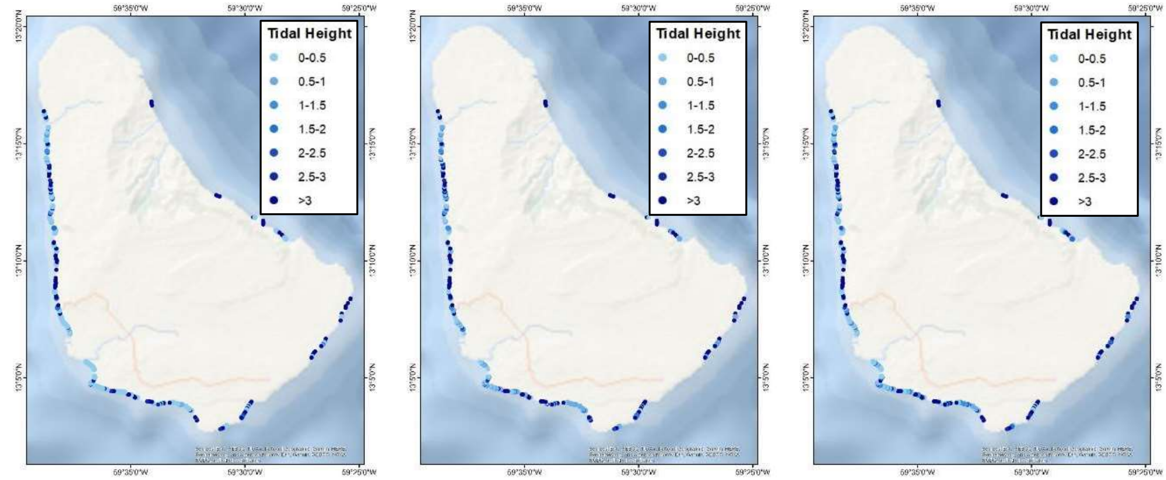
4.2.3.2 Beach erosion

Based on the methodology presented in chapter 3.3.1.4, the maximum erosion volume, which correspond to the sum of the potential maximum beach erosion per each beach segment, is estimated in 519,810 m^3. The mean averaged erodible height $H_{s,mean}$ is estimated in 0.81m and the range of H_s for all beach segments is between 0.19 and 3.61 m.

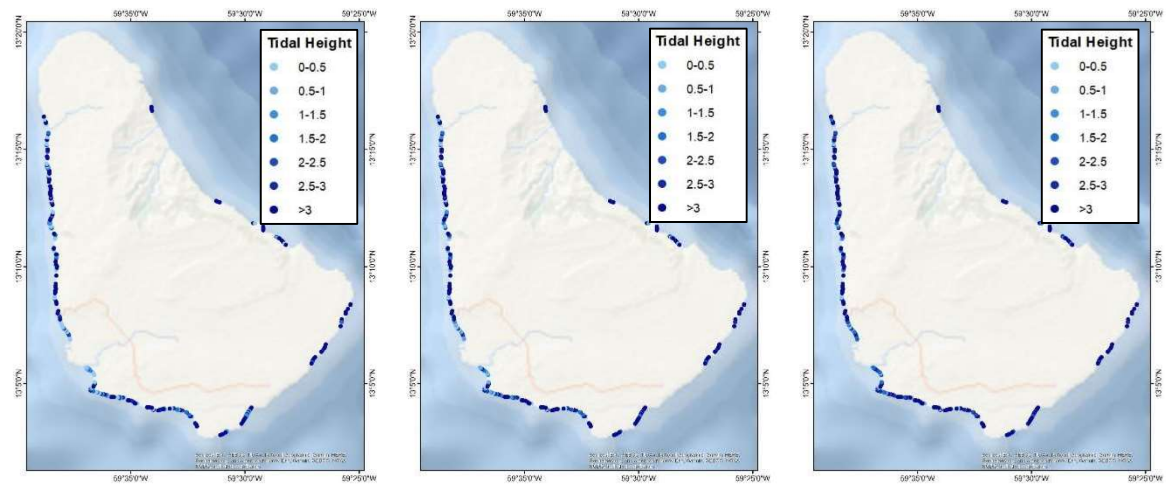
Figure 4-12 shows different scenario simulations affecting the south coast to illustrate the stochastic erosion catalogue. Each scenario is characterized with its magnitude, in terms of eroded volume in each beach segment and with an annual frequency (same frequency of the cyclone generating the storm surge). This stochastic catalogue is used in the risk model to estimate the losses in terms of the EAL and the PML for different return periods.

Figure 4-12. Stochastic erosion scenarios (illustrative by the project team)

From the stochastic catalogue presented above it is possible to obtain the probabilistic maps for different return period in terms of the tidal height (Figure 4-13) and in terms of eroded volume (Figure 4-14).

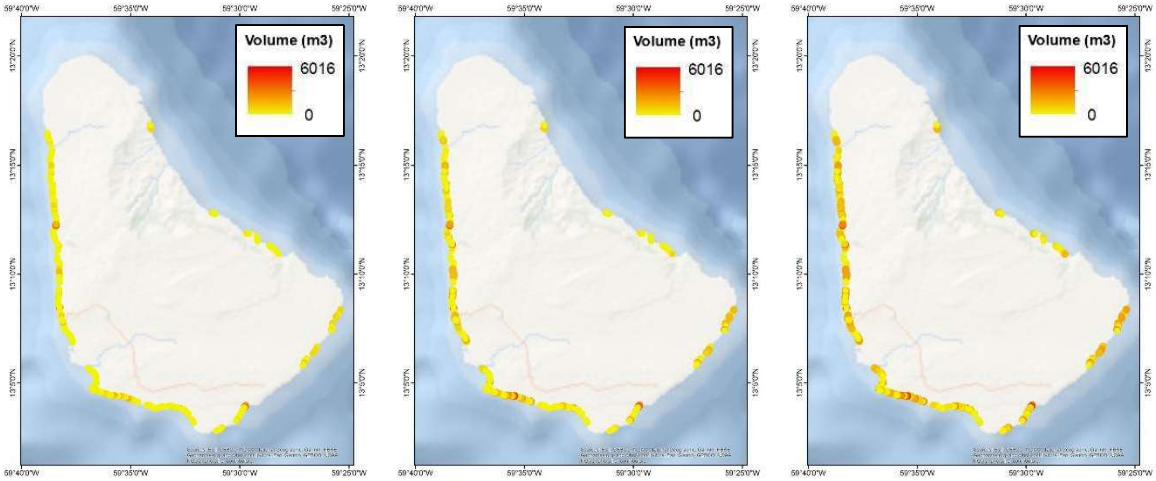


a) TR = 2 years b) TR = 5 years c) TR = 10 years

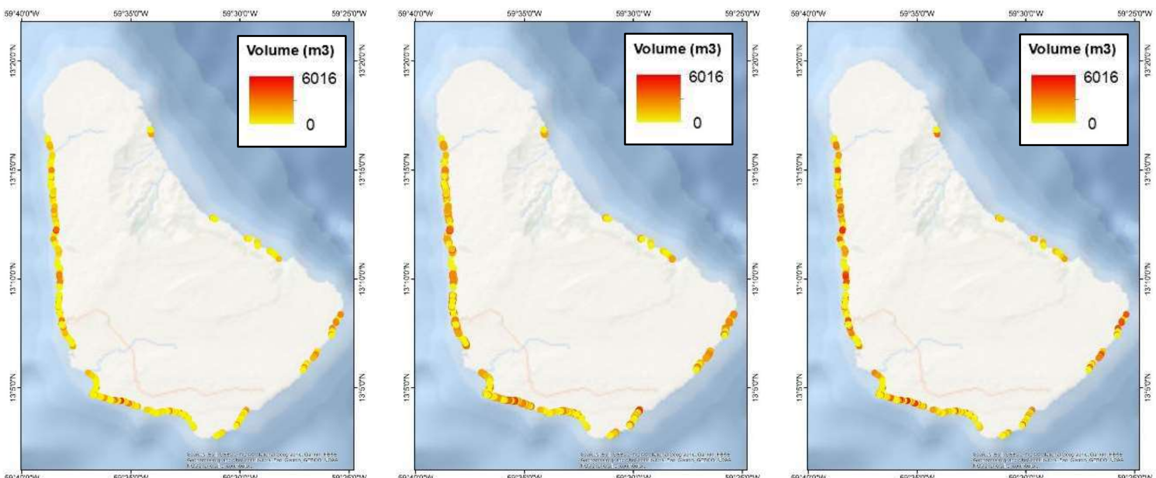


d) RP = 25 years e) RP = 50 years f) RP = 100 years

Figure 4-13. Probabilistic results for tidal height (m) at national level



a) TR = 2 years b) TR = 5 years c) TR = 10 years



d) RP = 25 years e) RP = 50 years f) RP = 100 years

Figure 4-14. Probabilistic results for beach erosion (m^3) at national level

In addition, form the probabilistic results, it is possible to identify the corresponding area affected by the estimated erosion for each return period. Table 4-4 presents the results in terms of affected areas for different years of return period.

Table 4-4. Beach erosion probabilistic results

		Current	
Total Beach Area	**M²**	639,190	
Probable Maximum Area Losses			
Return Period		**M²**	**% from total beach area**
10		71,968	11.3
20		86,334	13.5
50		94,837	14.8
80		99,656	15.6
100		102,536	16.0
250		118,634	18.6
500		124,606	19.5
1000		129,948	20.3

4.3 CHRONIC EROSION

The detailed assessment of the chronic erosion at different locations from Barbados is outside the scope of this study. However, to account for this type of erosion in the hazard model, this study used the coastline change study conducted by Baird (Baird, 2015). The summary of the main parameters to assess the chronic erosion was presented in section 3.3.2. The following sections present results of historical annual erosion rates.

4.3.1 Historical annual erosion rates

The historical annual erosion rates were determined by Baird (2015). In that study, satellite images were collected over a period of 65 years between 1950 and 2015. Digitizing the dividing line between the sea and the coast enabled to estimate trends in growth (accretion), regression (erosion) or invariance of the coasts through time. The obtained rates of this analysis have been adapted to the study area of this report and are seen in Figure 4-15. Negative values indicate accretion trends, while positive values indicate erosion predominance. From these results, is possible to estimate that in total, 8.15 km of beach in Barbados are presenting historical rates of erosion, only 3 km are presenting accretion and 21.8 are considered stable beaches (no accretion or erosion).

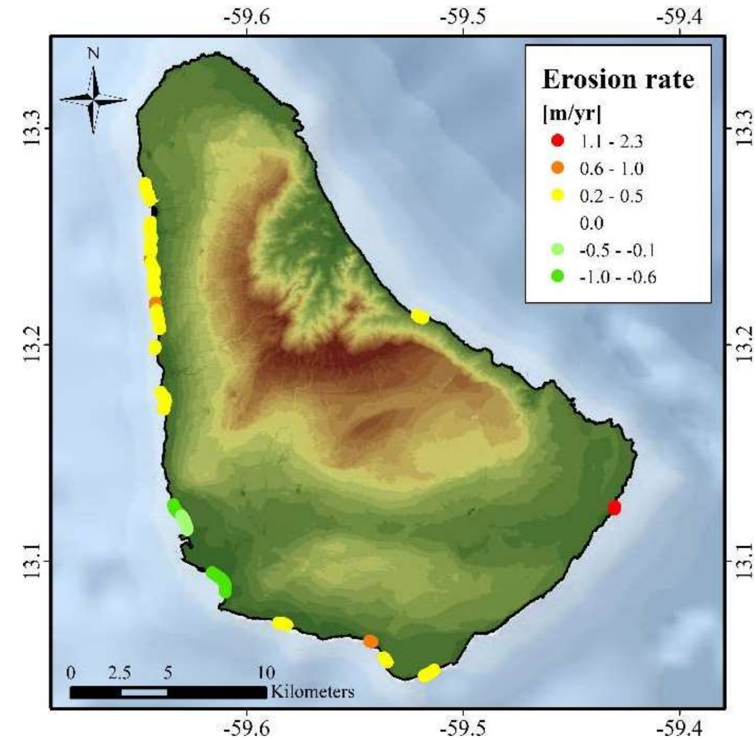


Figure 4-15. Historic annual erosion rates (1950–2015).
Adapted from Baird (Baird, 2015)

The chronic erosion rates will be treated independently from the episodic erosion assessment. This means that historical rates will be included in the risk assessment as an additional element with its own associated losses, besides episodic erosion generated by cyclonic events using CAPRA.

4.4 SEA LEVEL RISE

The erosion generated by SLR was estimated using different studies and projections. The following tables list the projection results at a global level and at the Caribbean level by 2100 according to Baird (Baird, 2015).

Table 4-5. Projected sea level rise by 2100 (Baird, 2015)

Scenario	Global mean sea level rise (m)	Caribbean mean sea level rise (m)
IPCC B1	0.18–0.38	0.13–0.43
IPCC A1B	0.21–0.48	0.16–0.53
IPCC A2	0.23–0.51	0.18–0.56
Rahmstorf (2007)	Up to 1.4	Up to 1.45
Perrette et al. (2013)		Up to 1.5

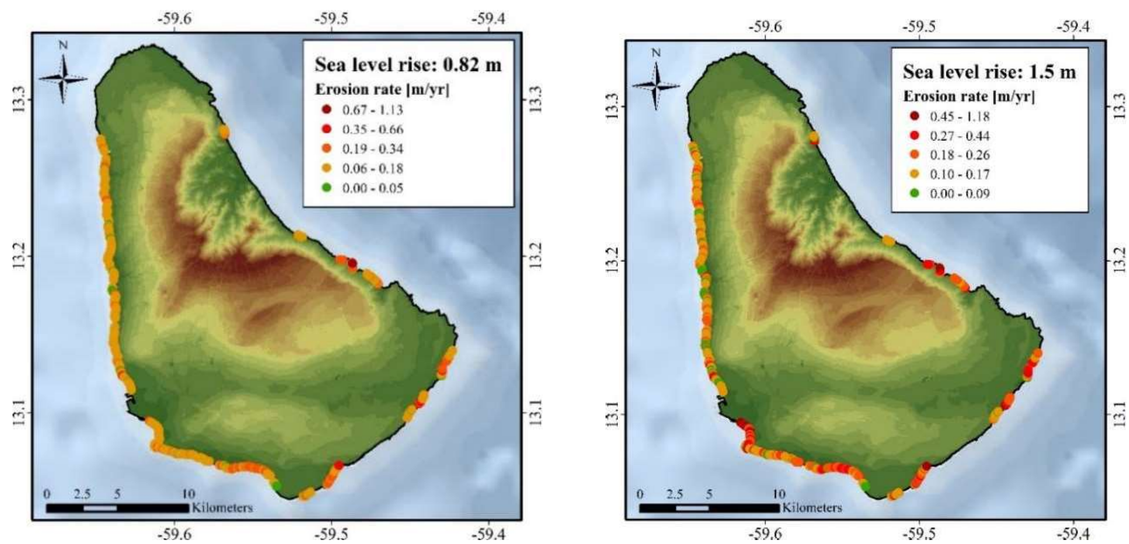
Table 4-6. Projected sea level rise from (IPCC, 2013)

Sea level rise by 1981–2100 (m)	
RCP 2.6	0.26–0.55
RCP 4.5	0.32–0.63
RCP 6	0.33–0.63
RCP 8.5	0.45–0.82

Due to estimation variability, the most critical scenarios were considered (Baird, 2015). The first projection is of 0.82 m SLR made by the IPCC (SLR082), corresponding to the most critical projection under the RCP scenarios. The second one, with an SLR of 1.5 m (SLR150) for the Caribbean, was considered as a catastrophic scenario (Perrette, Laundered, Riva, Frieler, & Meinshausen, 2013). From these projections, a typical example of the SLR long-term effects on the shoreline retreat of Barbados beaches is seen in Figure 4-16.

Figure 4-16. Sea level rise projections in 2100

To incorporate the SLR into the hazard model, for each of the selected scenarios, an annual erosion rate was calculated based on the maximum retreat of the coastline, over a period of time of 85 years as presented in Figure 4-16. The annual erosion rates for each beach segment are presented in Figure 4-17. In the 0.82 mts SLR scenario, 0.05 km of beaches are presenting high rates of erosion (more than 0.8m/yr), 4.25 km are experiencing a medium rate of erosion (between 0.2 m/yr and 0.8m/yr) and 28.65 km can be catalogued with a low rate of erosion (lower than 0.2 m/yr). For the 1.5 mts SLR scenario, the length of beaches at high, medium, and low rate are 0.10 km, 11.5 km and 21.35 km correspondingly.



(a) (b)

Figure 4-17. Annual erosion rates due to sea level rise scenarios (2020–2100): (a) SLR082; (b) SLR150

The sea level rise rates, similarly, to chronic erosion rates, will be considered independently from the episodic erosion assessment. This means that sea level rise rates will be included in the risk metrics as an additional element with its own associated losses, besides episodic erosion losses generated by cyclonic events using CAPRA.

4.5 HAZARD RESULTS SUMMARY

Table 4-7 presents a summary of the most important features of the model. It is important to note that the total beach length analyzed corresponds to the beach segments under study that may experience erosion. This categorization will be explained later in section 5.1. All these segments were analyzed for episodic and chronic erosion and will be used to characterize the exposure and the vulnerability model.

Table 4-7. Hazard Erosion Model summary

Total number of 50-mts beach segments analyzed	659
Total area of beach segments analyzed (m^2)	639,190
Total beach length analyzed (km)	33.0
Episodic Erosion	
Maximum erodible volume (m^3)	519,810
Mean averaged erodible height $H_{s,mean}$ (m)	0.81
Range of values of Hs (m) for all beach segments analyzed	0.19–3.61
Maximum probable area loss for 10 years of return period (% total area)	11.3
Maximum probable area loss for a 50 years of return period (% total area)	14.8
Maximum probable area loss for a 100 years of return period (% total area)	16.0
Maximum probable area loss for a 500 years of return period (% total area)	19.5
Maximum probable area loss for a 1000 years of return period (% total area)	20.3
Chronic Erosion	
Total beach length presenting historical rates of erosion (km)	8.15
Total beach length presenting historical rates of accretion (km)	3
Total beach length presenting historical stable rates (km)	21.8
Sea Level Rise	
Total beach length with high rate of SLR082 erosion (greater than 0.8 m/yr) (km)	0.05
Total beach length with medium rate of SLR082 erosion (between 0.2 m/yr and 0.8 m/yr) (km)	4.25
Total beach length with low rate of SLR082 erosion (lower than 0.2 m/yr) (km)	28.65
Total beach length with high rate of SLR150 erosion (greater than 0.8 m/yr) (km)	0.10
Total beach length with medium rate of SLR150 erosion (between 0.2 m/yr and 0.8 m/yr) (km)	11.50
Total beach length with low rate of SLR150 erosion (lower than 0.2 m/yr) (km)	21.35

CHAPTER

5

EXPOSURE ANALYSIS

5.1 INTRODUCTION

This chapter presents the economic valuation for the coastal area, based on the methodology presented in chapter 3.4. The following sections presents the description of the exposure model steps for the case of Barbados.

5.2 TOTAL BEACH REVENUE (TBR)

5.2.1 Sectorization and characteristics

The first step to develop the exposure model is to find homogenous beach segments (Alexandrakis, Manasakis, & Kampanis, 2015; Thin, Thanh, Tuyen, & Hens, 2019). Each segment must be characterized to determine the qualities and characteristics that are common to a certain group of beaches. The classification was made for homogenous segments of beaches of 50 m in length (average) as shown in Figure 5-1. For consistency, this beach segmentation is the same used in the hazard and vulnerability assessment. This approach offers two advantages: first, homogenous segments can be selected according to geographical variations and socio-economic information; and second, sectors can be uniformly classified in terms of vulnerability, allowing to define different degrees of potential impacts (for example, fine sand beaches, steep cliffs or non-susceptible zones).

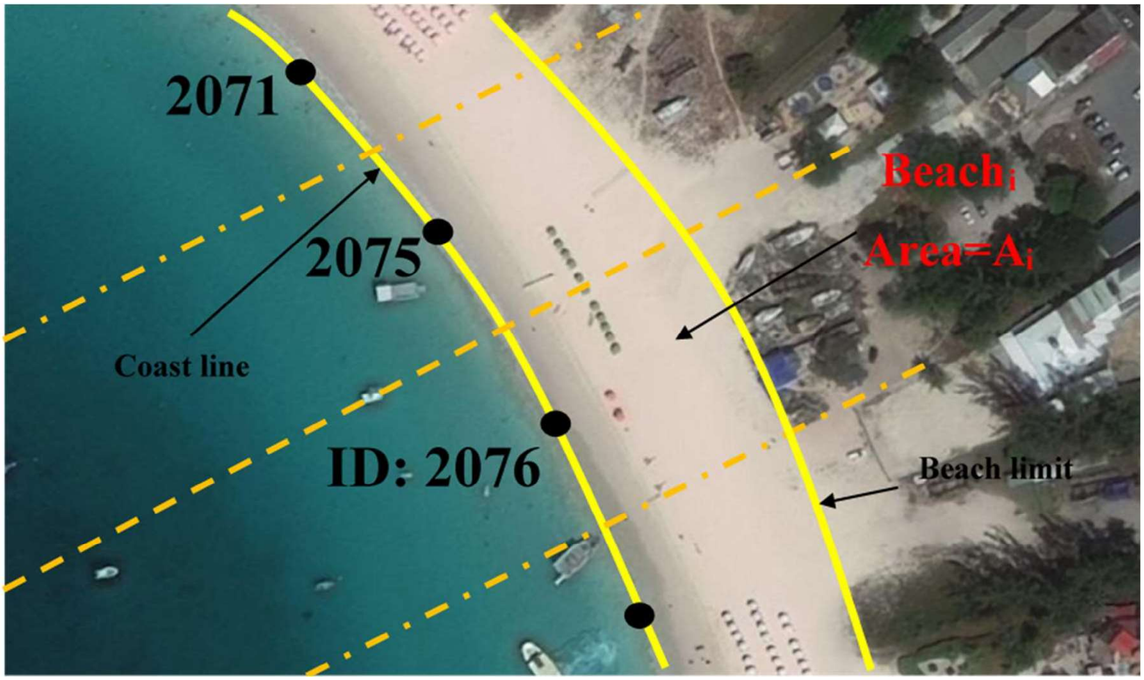


Figure 5-1. Example of beach segment (50m each)

It is necessary to characterize each of the sections defined above according to the following parameters:

- Physical characteristics: mean beach width.
- Area of influence.
- Commercial and tourism characteristics: Commercial sector, number of hotels, average price of hotels, hotel guestrooms, and hotel star category.

The stated information was collected for an influence area of each beach segment (buffer of 500m radius) illustrated in Figure 5-2. The methodology for collecting the information is summarized in Table 5-1.

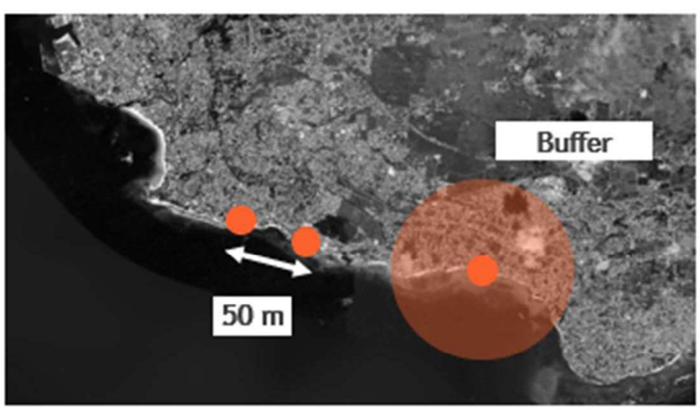


Figure 5-2. Beach segmentation buffers for beach valuation

Table 5-1. Data collection methodology

Information	Methodology and source
Commercial sector	The total number of commercial spots was determined using Google Maps.
Number of hotels	The number of hotels and their characteristics were determined using tourist and travel websites. The information available on the websites is: room price for a specific and set date, number of stars, and localization.
Hotel size and guestrooms	The area footprint of each building is available in the shapefiles. Therefore, there is a necessary process to relate the hotel location to an existing building. The shapefile contains the total floors of each building. Using the estimated total area and the total room information available in the hotel's website for validation, it was possible to calculate the expected number of guestrooms based upon the hotel category.

5.2.2 Beach valuation

To classify the different beach segments, a beach category is used. The category is based on different socio-economic characteristics, each one classified initially in a range from 0 to 5 using central tendency measures, common values, and value limits from literature (Baird, 2017; Schuhmann, Bass, Casey, & Gill, 2016) as illustrated in Figure 5-3. Based on the hedonic price methodology, the final beach category depends on the aggregation of the categorical characteristics. Two methods were applied to find the final beach category: multi-attribute aggregation and sum categorization. The first one assigns a relative weight to each characteristic to aggregate them into one final value, and the second one categorizes the total sum of the individual scores from the categorical characteristics. The final distribution of beach segment categories in Barbados is illustrated in Figure 5-4 and in Table 5-2.

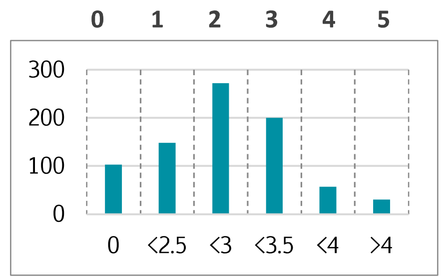
Categories

0–5 scale

The following graphs are histograms for each category. The Y axes represent quantity of beaches and the X axes the different values for each category.

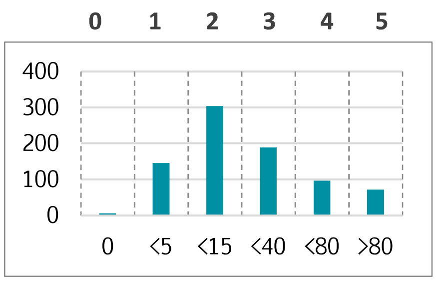
Mean hotel stars

Units



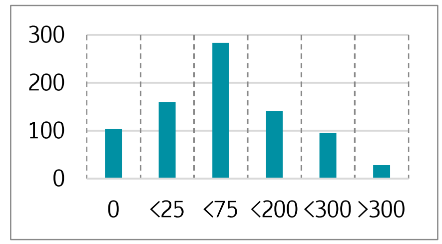
Commerce

Units



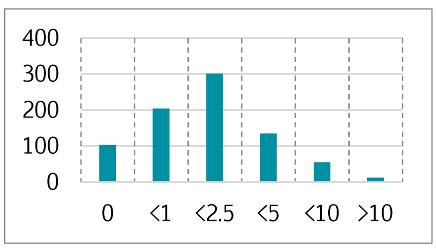
Estimated Hotel rooms

Units



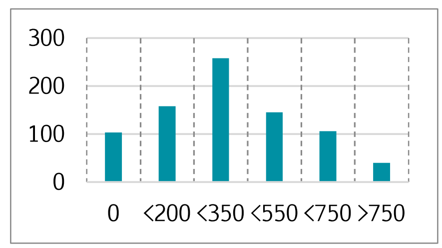
Hotel Total Area

Thousands of m^2



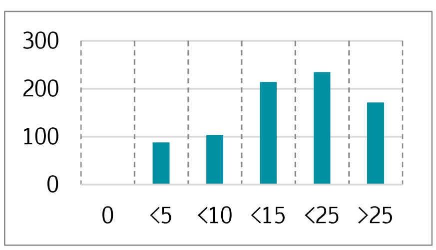
Mean room price

US$



Beach width

Meters



Total revenue

Rooms x Price

Thousands of US$

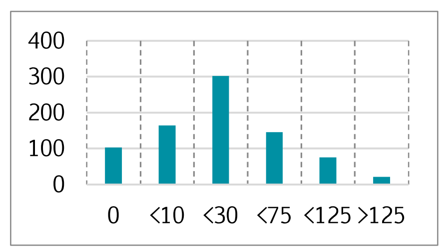


Figure 5-3. Characteristic category histograms

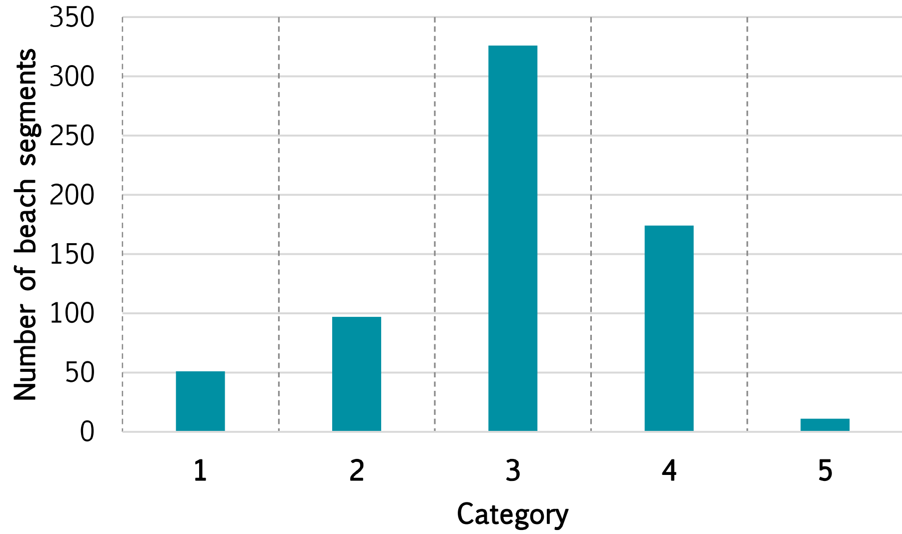


Figure 5-4. Final distribution of beach segment categories in Barbados

Table 5-2. Summary of beach categories in Barbados

Category	Number of segments	Total Length (km)	Percentage (%)
1	51	2.55	7.7%
2	97	4.85	14.7%
3	326	16.3	49.5%
4	174	8.7	26.4%
5	11	0.55	1.7%
Total	**659**	**32.95**	**100%**

The next step was to distribute the revenue at risk to all beaches using the defined categories. This process was based on the GDP distribution that corresponds to tourism and the 'willingness to pay' surveys available in literature for the Caribbean region, and specifically for Barbados. The following assumptions were made:

1. The tourism GDP is affected by the tourist attractions and number of tourists. If the conditions of the beaches change, (loss of beach due to erosion) the tourists are not going to visit the country nor spend in commercial establishments and hotels.
2. The tourism that is related exclusively to the beaches in Barbados corresponds to the Sun & Bath tourism, which according to the Barbados Statistical Systems represents up to 80% of total tourism GDP from 2010 to 2015 (BSS, 2016).
3. From the tourism that is exclusively related to beaches, the 'willingness to pay' studies conclude that up to 70% of the Sun & Bath tourists will not travel or return if the physical condition of beaches are changed in a negative way (erosion, loss land or beach width, or beach closure) (Castaño-Isaza, Newball, Roach, & Lau, 2015).
4. The remaining annual revenue (Percent of GDP) will be distributed to the identified beach according to the category and represents the annual beach revenue valuation.

Table 5-3 summarizes the revenue at risk to be distributed.

Table 5-3. Beach revenue valuation

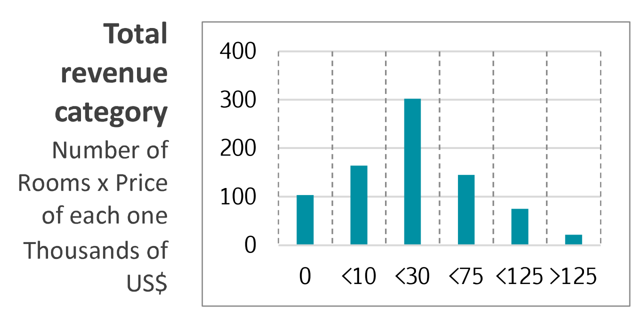
Parameter	Source	Value	Units
GDP 2018	(CIA, 2020)	5100	US$ millions
Tourism GDP	(BTI, 2020)	1100 (21.6%)	US$ millions
Sun & Bath tourism	(BSS, 2016)	80%	-
		880	US$ millions
Annual Beach Revenue at risk	(Castaño-Isaza, Newball, Roach, & Lau, 2015; Uyarra, et al., 2005)	70%	-
Total Beach annual revenue valuation	-	616	US$ millions

The annual revenue for distribution uses the relative ratio between the categories from the ‘Total Revenue’ category. Using these relative differences in revenue between categories, the final valuation of annual revenue per unit area is illustrated in Table 5-4. The total aggregation of these values using each beach category and total area gives the total annual revenue of US$ 616 million.

Table 5-4. Beach category final valuation of annual revenue per area unit

Category	Estimated length (Km)	Annual Revenue US$/$m^2$
1	2.55	32.0
2	4.85	217.5
3	16.3	641.4
4	8.7	1596.0
5	0.55	3241.0

Total revenue category from Figure 5-3



Using the stated values, the total distribution of beach segments according to the mean annual revenue is illustrated in Figure 5-5. The graph shows that most of the annual revenue of beach segments is below US$1 million and half of it is below US$ 500,000. The most expensive beach segments generate up to US$ 7.5 million per year and correspond to those located near the bigger and more exclusive resorts.

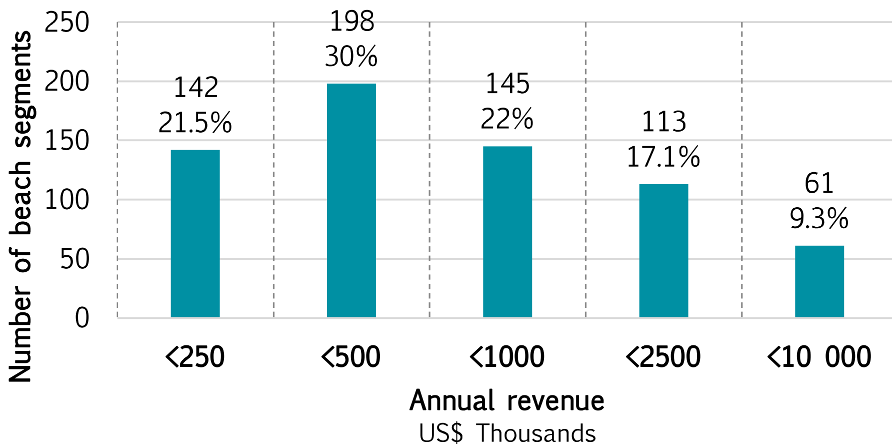
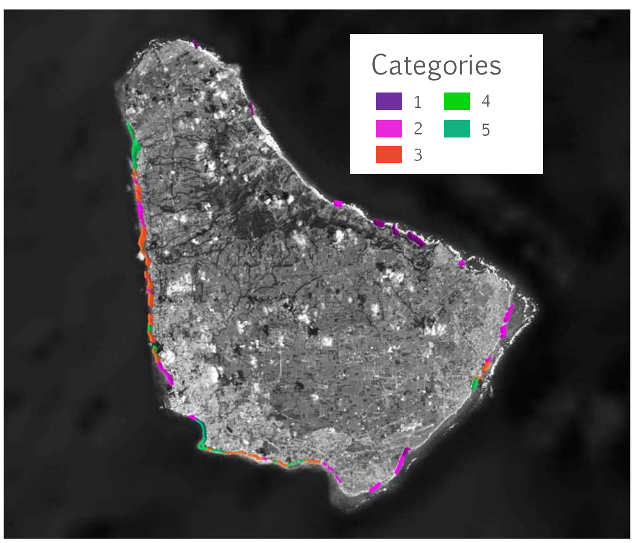


Figure 5-5. Beach annual revenue histogram

Figure 5-6a illustrates the final category distribution, whereas Figure 5-6b represents the annual revenue of beach segments through bar heights. The higher the bar, the higher the annual revenue of the beach segment. Both images illustrate the expected behaviour of Barbados tourists. Higher-level tourism visits the west coast, particularly the south-west (Bridgetown and surroundings). There is another tourist hotspot in the north-west segments. As expected, the east coast represents the lower expected revenues in terms of tourism.



(a) (b)

Figure 5-6. (a) Beach categories distribution, and (b) beach segment annual revenue representation

5.2.3 Comparison with similar studies

A validation of the previous results is performed by comparing the final revenue values with those of accepted and recognized similar studies. The validation is based on economic valuations and economic loss estimations from previous projects. The following list contains the main references used for value comparisons:

1. The study 2017 study conducted by Baird concludes that different losses could occur in Barbados according to the original width of the beach. In a particular example for an 8-meter wide and 1-kilometer-long beach that loses 5 meters, the study totalled the annual losses at US$9 million. In the present study, for the same beach loss conditions, there would be an annual average expected loss of US$ 5.7 million. Nevertheless, the Baird study does not categorize beaches. Under the same conditions, the equivalent annual average expected revenue loss in a beach category 4 would be US$ 9.9 million.

2. The CARICOM/UNDP study of Sea Level Rise Assessment (Haites, 2002) concludes that for 2000, if there is a 15% loss in the width of a 12-meter beach, (assuming that the whole country's beach coast has a 12-meter-wide beach), a revenue loss of US$36.4 million is expected within one year. For the GDP growth rate is equivalent to US$ 73 million in 2020. They also calculated that if there is 80% loss in the width of an 18-meter beach (assuming that the whole country beach coast has an 18-meter-wide beach), a revenue loss of US$ 195 million is expected within a year. For the GDP growth rate of the study, it is equivalent to US$390 million in 2020. For the same beach loss condition, in the present study the equivalent economic losses for both scenarios are US$ 49 million and US$ 393 million, respectively.

3. The general study conducted by CARICOM/UNDP (Simpson, et al., 2010) reports two findings related to the beach valuation. First, the ratio between land valuation (cadastral) and annual revenue is around 1:8 to 1:10. Using this ratio, the land valuation would be on average US$ 1 million per hectare. The equivalent valuation made in the present study varies from US$ 0.4 to US$ 1 million per hectare. Secondly, considering critical estimation for sea level rise, there would be catastrophic consequences resulting on annual losses around 10 to 20% of GDP. In the framework of the present study, for a catastrophic scenario (a majority of beaches close) there would be an equivalent loss of 12% of GDP (total beach losses). Given that the CARICOM/UNDP study considers other secondary components for estimating the total annual loss, the proportions are comparable.

4. Based on two studies conducted on different touristic beaches (Greece (Alexandrakis, Manasakis, & Kampanis, 2015) and Vietnam (Thin, Thanh, Tuyen, & Hens, 2019)), comparisons were made for average revenue per coastline length, daily revenue, and category valuation. First, the Greek beach is a 4-5 category equivalent to luxury tourist beaches. The average revenue per coastline meter is US$ 76,000 per year. In the present study, the equivalent value varies from US$ 45,000 to US$ 110,000 for categories 4 and 5. Second, for the Greek beaches, the average daily 150-day season revenue was US$ 18.50 per square meter. In the

present study, the equivalent revenue for categories 4 and 5 is US$ 10.48 and considering only category 5 it is US$ 22 per square meter. Finally, using the study on Vietnam with different characteristics in the analyzed segments, equivalent categories were found and similar annual revenue per unit of area. In comparison, the annual revenues per unit of area (m^2) are US$ 621, US$ 2,057, and US$ 3,819 for categories 3, 4, and 5, respectively. The equivalent annual revenues developed in the present study are US$ 593, US$ 1,476, and US$ 2,998 proposed for the present study.

Table 5-5 summarizes the validations and the mentioned comparisons.

Table 5-5. Methodology and results validations

<table>
<tr><th>Location</th><th>Source</th><th>Parameter</th><th>Source Value</th><th>Comparison</th><th>Present Report Value</th><th>Unit</th></tr>
<tr><td rowspan="2">Barbados</td><td rowspan="2">Baird (2017)</td><td rowspan="2">Loss of revenue
8m to 3m beach of 1km</td><td rowspan="2">9</td><td>Average</td><td>5.7</td><td>US$M/year</td></tr>
<tr><td>Category 4</td><td>9.9</td><td>US$M/year</td></tr>
<tr><td rowspan="2">Barbados</td><td rowspan="2">MARGAREE consultants (Haites, 2002)</td><td>Total revenue impact 15% Loss of 12 m width beach</td><td>36 (2000)
73 (2020)</td><td rowspan="2">Equivalent loss</td><td>49</td><td>US$M/year</td></tr>
<tr><td>80% Loss of 18 m width beach</td><td>195 (2000)
390 (2020)</td><td>393</td><td>US$M/year</td></tr>
<tr><td rowspan="3">Barbados</td><td rowspan="3">CARICOM UNDP (Simpson, et al., 2010)</td><td>Value of land</td><td>0.40 - 1</td><td>Land value*</td><td>1</td><td>US$M/ha</td></tr>
<tr><td rowspan="2">2050–2080 Beach revenue loss catastrophic SLR scenarios</td><td>10.8–20 (2050)</td><td rowspan="2">Total Loss</td><td rowspan="2">12</td><td rowspan="2">% GDP</td></tr>
<tr><td>15.5 - 22.2 (2080)</td></tr>
<tr><td rowspan="8">Greece</td><td rowspan="8">(Alexandrakis, Manasakis, & Kampanis, 2015)</td><td rowspan="4">Average Revenue per length (coastline)</td><td rowspan="4">76,082</td><td>All beaches</td><td>20,000</td><td rowspan="4">US$/m/year</td></tr>
<tr><td>Category 3–5</td><td>23,231</td></tr>
<tr><td>Category 4–5</td><td>46,993</td></tr>
<tr><td>Category 5</td><td>109,723</td></tr>
<tr><td rowspan="4">High season daily revenue average</td><td rowspan="4">18.5</td><td>All beaches</td><td>5.48</td><td rowspan="4">US$/m²/day</td></tr>
<tr><td>Category 3–5</td><td>6.77</td></tr>
<tr><td>Category 4–5</td><td>11.45</td></tr>
<tr><td>Category 5</td><td>21.72</td></tr>
<tr><td rowspan="3">Vietnam</td><td rowspan="3">(Thin, Thanh, Tuyen, & Hens, 2019)</td><td rowspan="3">Equivalent beach area valuation by equivalent category</td><td>621 (C3)</td><td>Category 3</td><td>641</td><td>US$/m²/year</td></tr>
<tr><td>2057 (C4)</td><td>Category 4</td><td>1,596</td><td>US$/m²/year</td></tr>
<tr><td>3819 (C5)</td><td>Category 5</td><td>3,241</td><td>US$/m²/year</td></tr>
</table>

5.2.4 Wider economic indirect multiplier

The results shown above are based on the direct contribution of the tourism sector to the GDP based on the Barbados Tourism Investment Inc. (2020). To include the wider economic impact on the national GDP, it is important to identify the indirect contributions of travel and tourism. For Barbados, this contribution in 2019 is estimated to be 34.9% of the total economy (WTTC & Oxford Economics, 2020). Taking this into account, the relation between direct and indirect contribution to GDP can be estimated to be 1.62:

$$\frac{Indirect}{Direct} = \frac{34.9\%}{21.6\%} = 1.62$$

To include this effect in the loss assessment, the revenue costs will be increased by the indirect-direct ratio. The summary of the final valuation considered in this study is presented in Table 5-6.

Table 5-6. Total beach revenue valuation in this study for Barbados

Direct revenue valuation (US$ million/year)	616
Indirect-direct ratio	1.62
Indirect revenue valuation (US$ million/year)	384
Total beach revenue (US$ million/year)	**1,000**
Total beach revenue per unit area (US$/m^2/year)	1,561
Total beach revenue per unit length (US$ million/km/year)	30.3

5.3 TOTAL BEACH RECOVERY COST (TBRC)

5.3.1 TBRC for Engineered Nourishment (EN)

The total beach recovery cost (TBRC–see section 3.4.2) associated with engineered nourishment is calculated by the sum of the direct and indirect costs corresponding to the maximum volume that could be eroded, considering the geomorphology of the section as presented in Chapter 4 (corresponds to the parameter V_{∞}). The considered costs are the following:

a) Direct repair costs depending on the erodible volume.
b) Total revenue costs during expected downtime
    a. Direct revenue valuation as explained in section 5.2.2
    b. Indirect revenue valuation as explained in section 5.2.4

The following equation is used:

$$TBRC_{Engineered\ Nourishment} = [DC + IC]\ (\$/m^3)\ x\ Maximum\ Eroded\ Volume\ (m^3)$$

Where:

- $TBRC_{Engineered\ Norushment}$: total beach recovery cost of each beach segment for the engineered nourishment case in US$
- DC: Direct Costs ($\$/m^3$) = Materials, Labor, Transportation (Costs of sand reposition)

- $Maximum\ Eroded\ Volume\ (m^3)$ based on results presented in section 4.2
- IC: Indirect Costs $(\$/\mathrm{m}^3)$ = Total Revenue Cost $(\$/\mathrm{m}^2/\mathrm{day})$ * Area (m^2) $*t_u(\mathrm{days}/\mathrm{m}^3)$ (costs associated with tourism interruption due to closing of the beach segment)

To assess the direct costs associated with a particular erosion case, the following considerations are made:

a) The total eroded volume in one event would be replaced by the equivalent amount of sand in a framework of a typical construction project. For this, the costs of a unit volume of compacted sand are estimated from past experiences indicated in Table 5-7. As shown, there is a large variability in the costs, they depend on the availability of material, construction capacities and personnel. Taking this into account, an average value of US$ 30 for each m3 is considered in the present calculations.

Table 5-7. Unit cost assessment for beach nourishment

Project	Country	Author	Unitary Cost (US$/m3)
National Beach Nourishment Database	USA -	NOAA	Minimum = 1.2 Maximum = 54.5
Historical beach nourishment construction costs	Panama	Parkinson & Ogurcak (2018)	Minimum = 2.82 Maximum = 23.17
Sand nourishment strategies to mitigate coastal erosion and sea level rise at the coasts of Holland (The Netherlands) and Aveiro (Portugal) in the 21st century	Netherlands and Portugal	Stronkhorst et al (2017)	5–11
NCRIPP	Barbados	Baird (2017)	35
Present Study			**30**

b) The total time required to accomplish the beach nourishment project is estimated considering the use of heavy machinery, unit performance times per volume of compacted sand and dead times required for administrative activities, organization, and completion of the work. For the present study, a reference unit value of 0.04 days/m3 of compacted sand is adopted, based on typical performance times in equivalent projects. A minimum period of two months is considered in a beach closed for repairs for events with medium impacts. For intense events, the total time would additionally include the time required for placing the equivalent amount of sand. For example, to repair a particular segment of 100 m of length which has suffered an erosion of 5 m width (considering a mean value of 2 m depth), a total of 40 effective days will be required for completing the works. In addition, considering the minimum of two months dead period, the total period for repairs would be around 4 months.

The total costs associated with the time that the beach segment remains closed is assessed using the beach revenue valuation presented above.

5.3.2 TBRC for Natural Nourishment (NN)

The TBRC associated with natural nourishment is calculated as the total costs corresponding to the maximum area that can be lost from erosion and, the time that the beach takes to recover. The area is calculated considering the geomorphology of the section as explained in Chapter 3. The considered costs include the total direct and indirect revenue costs during expected downtime as explained in sections 5.2.2 and 5.2.4.

The maximum recovery time for each beach should be estimated based on the sand budgets, the geomorphology, the maritime and climate conditions, and dynamics of the analyzed segment. This is a time-consuming task and detailed information is needed to estimate the recovery time. However, according to the available information, the recovery time for typical beach areas in Barbados can range from a few months to several years. Taking this into account, three general scenarios are considered in the present study for illustrative purposes:

a) **Scenario 1:** maximum recovery time of one year for all beach segments considered in the analysis.
b) **Scenario 2:** maximum recovery time of six months for south coast segments and two years for the rest of the segments.
c) **Scenario 3:** maximum recovery time of two years for all beach segments considered in the analysis. This scenario is considered as the most critical.

To estimate the TBRC in those cases, the following equation is used:

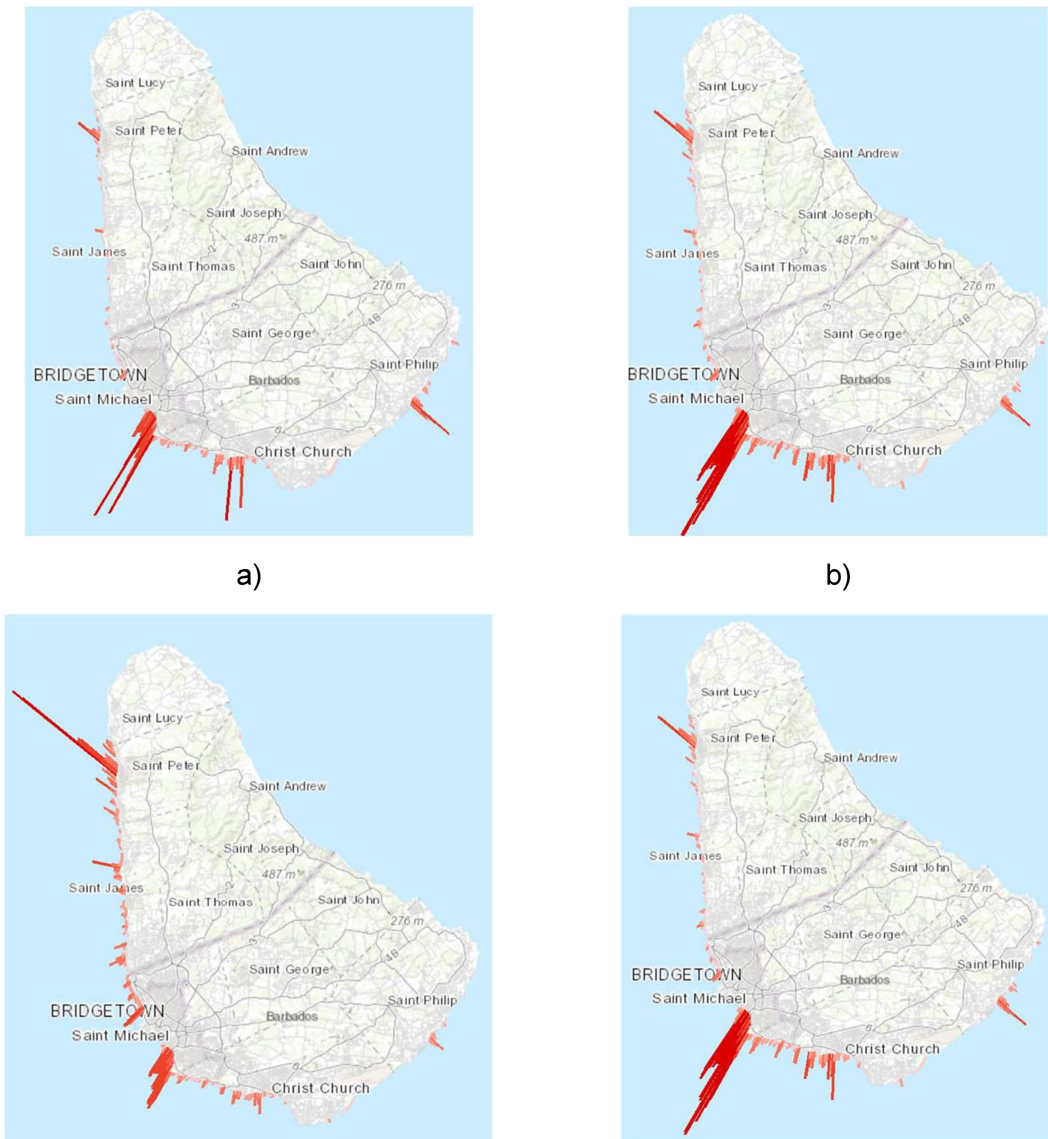
$$TBRC_{Natural\ Nourishment} = [IC]\ x\ Max\ Eroded\ Area\ *\ Max\ Considered\ Time$$

Where:

- $TBRC_{Natural\ Norushment}$: total beach recovery cost of each beach segment for the natural nourishment case in US$/m^2/year.
- IC: Indirect Costs ($\$/\mathrm{m}^3$) = Total Revenue Cost ($\$/\mathrm{m}^2/\mathrm{day}$) (costs associated with tourism interruption due to closing of the beach segment during a year).
- $Maximum\ Eroded\ Area\ (m^2)$ area that can be lost associated with the maximum erodible volume. The area varies in each beach segment from 20% to 50% of total beach area.
- $Maximum\ considered\ Time\ (\%year)$ is the maximum recovery (depending on the scenario).

5.3.3 Results summary

The TBRC for engineered (EN) and natural nourishment (NN) is calculated for each beach segment considered in the model. Figure 5-7 shows the distributions of the TBRC for each recovery strategy.



a) b) c) d)

Figure 5-7. Total Beach Recovery Cost per beach segment–a) Engineered Nourishment, b) Natural nourishment Scenario 1, c) Natural nourishment Scenario 2 and d) Natural nourishment Scenario 3

The summary of the most important values related to the TBRC for each scenario is presented in Table 5-8. It is important to note that the TBRC is not a yearly valuation. The

TBRC represents the maximum recovery cost if the maximum erosion is presented at the same time in all the coastline. It can also be understood as the maximum potential losses for beach erosion at the country-level.

Table 5-8. TBRC valuation

Recovery Strategy	Total TBRC (US$ million)	TBRC per unit area (US$/m^2)	TBRC per unit length (US$ million/km)
Engineered Nourishment (EN)	253.9	369.1	7.16
Natural Nourishment (NN) – Scenario 1	360.0	563.2	11.88
Natural Nourishment (NN) – Scenario 2	325.6	509.4	9.88
Natural Nourishment (NN) – Scenario 3	720.0	1,126.4	23.76

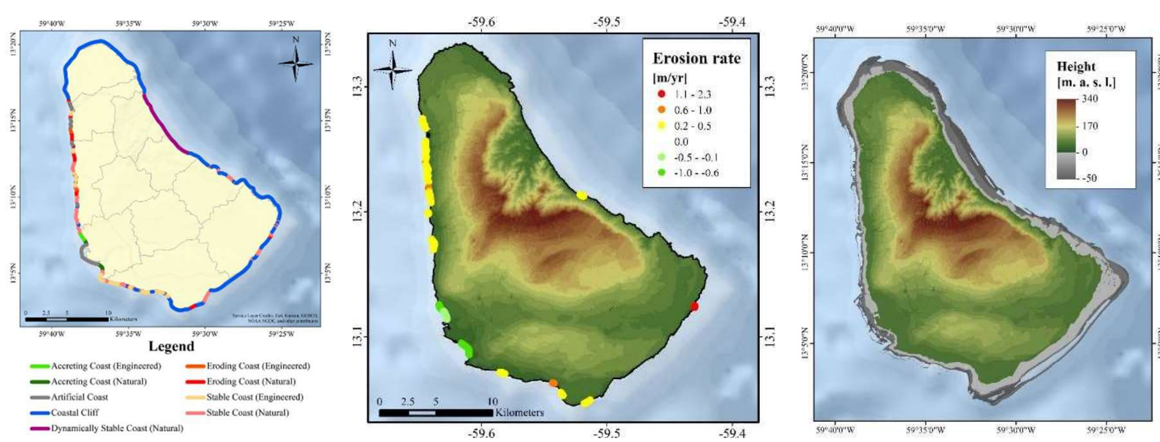
To conclude, this chapter has calculated TBR and TBRC as the exposure analysis. Firstly, TBR is the total annual revenue valuation from tourism, which was found to be US$1,000 million/year. This value can be divided into two parts: the part exposed to erosion and the part that is not. In this study, the former is defined as TBRC. In other words, TBRC can also be defined as the economic value of the tourism sector that is exposed to coastal erosion. This value yields different amounts in different ways, such as Engineered Nourishment and Natural Nourishment. The result of this valuation is shown in Table 5-8.

CHAPTER
6

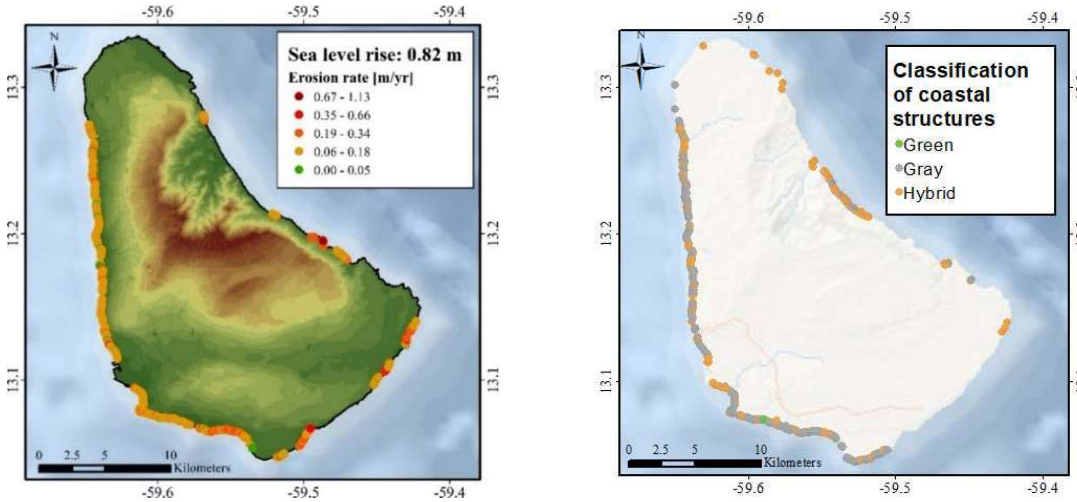
EROSION VULNERABILITY ANALYSIS

6.1 BEACH EROSION SUSCEPTIBILITY INDEX

The assessment of the susceptibility to erosion was performed as explained in section 3.5.2, identifying each beach segment's susceptibility level (low, medium, or high). This is a country-relative scale of erosion susceptibility level at each segment, including the following characteristics: morphology of the coast (Figure 6-1 a), historical shoreline change (Figure 6-1 b), coastal slope (Figure 6-1 c), sea-level change (Figure 6-1 d, see section 4.4), wave height and tidal range (section 3.3.2), and the existence of protection structures (Figure 6-1 e).



a) Morphology of coasts b) Shoreline change c) Coastal slope (DEM)



d) Sea level rise

e) Existing protection structures

Figure 6-1. Inputs for susceptibility index

Using the information presented above, Figure 6-2 presents the results from this analysis of the susceptibility index for all beach segments included in the study.

Figure 6-2. Susceptibility classification

Figure 6-3 presents the susceptibility classification considering the existing protection structures and a comparison with the classification performed by Baird (2015).

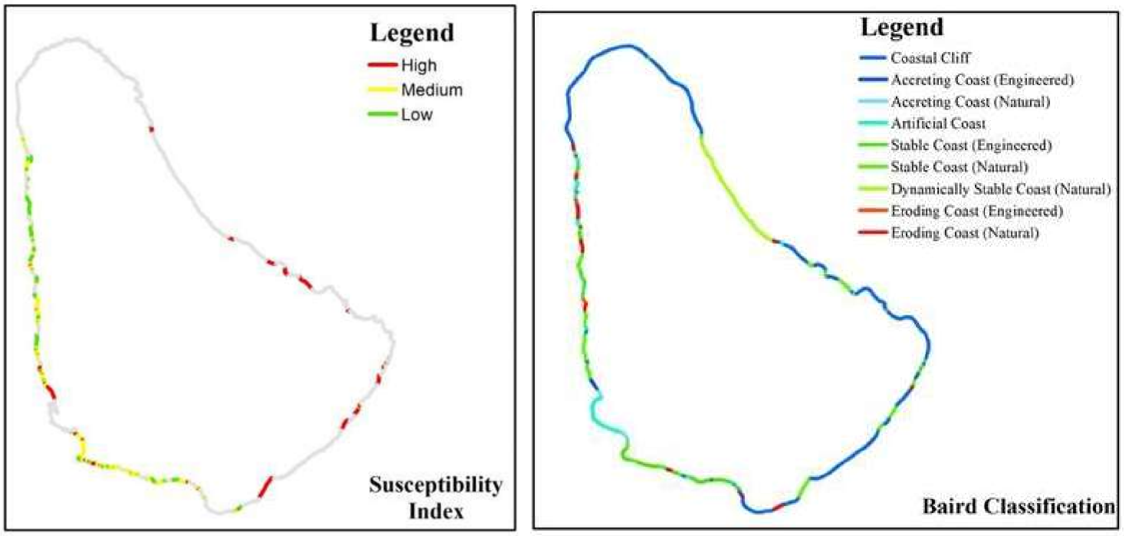


Figure 6-3. Beach susceptibility classification considering existing protection structures

As seen in Figure 6-3, the beaches that were not deemed susceptible to erosion correspond to coastal cliffs, artificial coasts, and dynamically stable coasts according to Baird; while all the accreting, eroding and stable coasts were considered in the risk assessment in this study.

Based on this susceptibility classification, the vulnerability functions were assigned to each beach segment to develop the risk assessment analysis. The summary of the number of segments and the total length assigned to each susceptibility level is presented in Table 6-1.

Table 6-1. Erosion susceptibility summary

Erosion Susceptibility Level	Number of segments	Total erodible volume (m3)	Total Length (km)	Percentage (%)
High	196	167,964	9.8	29.7%
Medium	273	227,976	13.65	41.4%
Low	190	123,870	9.5	28.8%
Total	**659**	**519,810**	**32.95**	**100.0%**

6.2 VULNERABILITY FUNCTIONS FOR CURRENT CONDITION

6.2.1 Beach segment parameters

A beach segment database is constructed including all of the previous information. The main fields of the data base are:

- Beach ID
- Segment ID

- Geographical coordinates
- Susceptibility index (see section 6.1)
- Profile type (1, 2, 3 or 4) (see section 3.3.1.4)
- Beach width
- Beach segment area
- Material properties (D50, Average slope, Shoreline, etc.)
- Maximum erodible volume
- Maximum *Hs*
- Maximum repair time
- TBRC (see section 5.3)
- Assigned vulnerability function

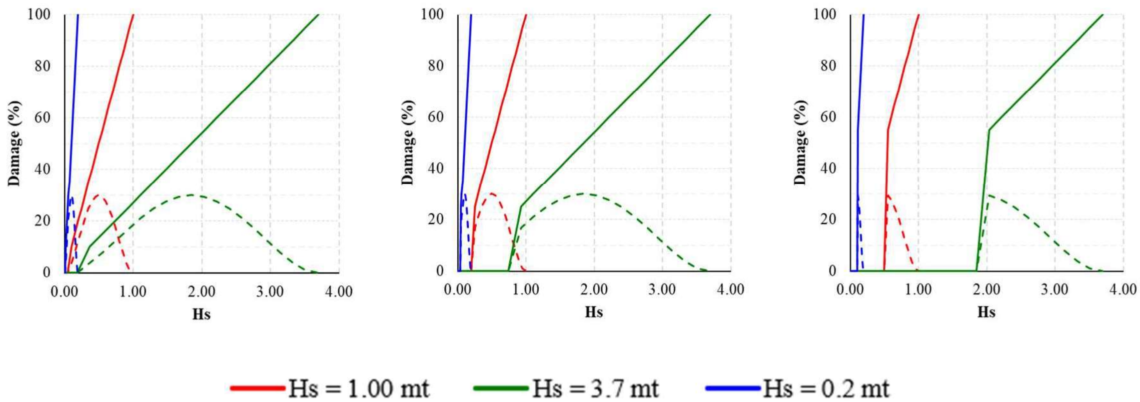
6.2.2 Vulnerability functions catalogue

The vulnerability functions catalogue is created for different H_s intervals and for each susceptibility level identified in section 6.1. The H_s intervals are considered between the maximum and the minimum $H_s max$ with intervals of 0.1, calculated for all the segments profiles in the exposure model, as defined in section 3.5. The no-damage intensity is assigned based on the susceptibility classification. Table 6-2 presents the values for the no-damage intensity for each susceptibility level, based on the relations between erosion shoreline changes expected at the index developed by Evelpidou et al. (2018).

Table 6-2. No-damage intensities

Susceptibility classification	No-damage intensity (% of $H_s max$)
High	5
Medium	20
Low	50

Some illustrative examples of functions within the catalogue are shown in Figure 6-4. The total catalogue of vulnerability functions includes 72 different functions for $H_s Max$ from 20 cm to 370 cm and for each susceptibility level. These functions are assigned to each coastal segment based on the maximum erosion capacity following section 4.2.3.2 and the susceptibility classification presented in section 6.1. The summary of the number of segments, erodible volumes and length assigned to each category is presented in Table 6-1.



a) High Susceptibility $H_{smin} = 5\%$

b) Medium Susceptibility $H_{smin} = 20\%$

c) Low Susceptibility $H_{smin} = 50\%$

Figure 6-4. Vulnerability functions examples for different Hs

CHAPTER

7

RISK ASSESSMENT

7.1 EPISODIC RISK RESULTS

This chapter presents the main results from the probabilistic risk assessment analysis. The methodological approach used in the present study was explained in Chapter 1. For the risk assessment analysis, the CAPRA-GIS V 2.4 was used.

The results include the following risk metrics:

- Expected Annual Losses (EAL) in absolute and relative values with respect to the Total Beach Recovery Cost (TBRC).
- Probable Maximum Loss (PML) curve for different return periods for the island in absolute and relative values with respect to Total Beach Recovery Cost (TBRC).

7.1.1 Current conditions–Engineered Nourishment

The probabilistic risk is estimated for the current condition considering an engineered nourishment strategy after each erosion event as explained before. Table 7-1 presents the most relevant results for the total exposed values, the expected annual losses (EAL) and the probable maximum losses (PML) for different return periods.

Table 7-1. Beach erosion risk - current condition, engineering nourishment - EAL and PML, total

Total Beach Revenue – TBR	**US$/year**	$ 1,000,000,000
Total Beach Recovery Cost – TBRC - EN	**US$**	$ 254,000,000
Expected Annual Loss - EAL	**US$**	$ 30,383,985
	% of TBR	3.0
	% of TBRC - EN	12.0
Probable Maximum Losses, PML		
Return period, RP	**US$**	**% of TBRC - EN**
10	$ 94,295,777	37.1
20	$ 113,181,155	44.6
50	$ 120,183,385	47.3
80	$ 123,765,292	48.7
100	$ 127,486,563	50.2
250	$ 143,396,094	56.5
500	$ 153,911,979	60.6
1000	$ 158,800,000	62.5

In addition, Figure 7-1 presents the PML curve at the national level.

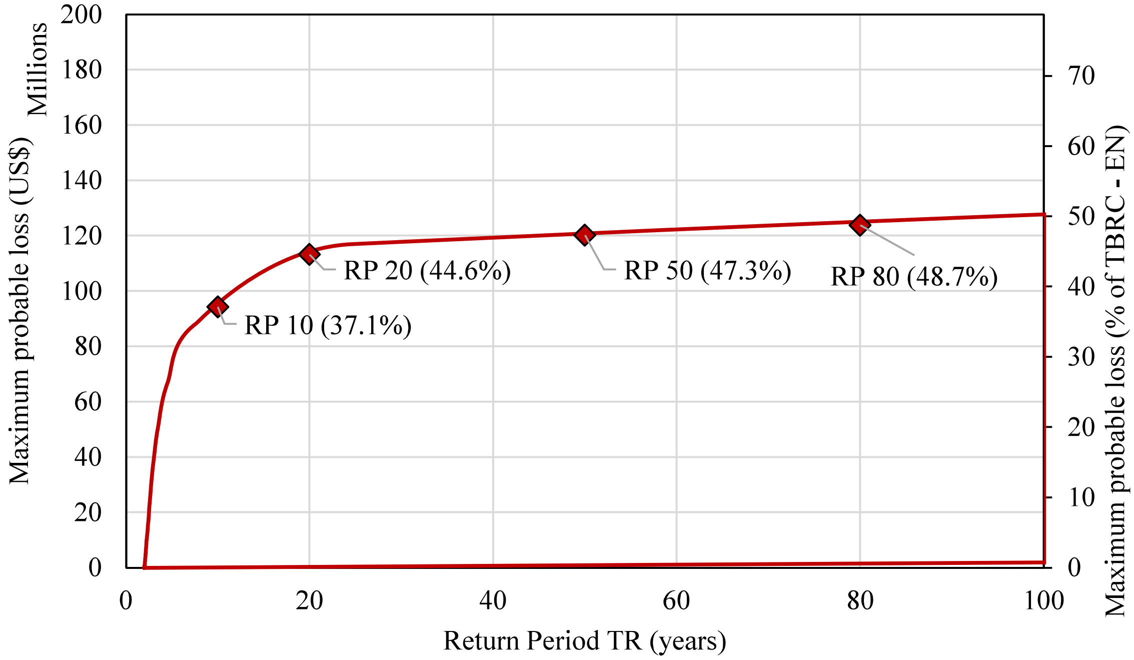


Figure 7-1. Beach erosion risk, current condition - engineering nourishment - PML

7.1.2 Current conditions including climate change – engineered and natural nourishment

This chapter presents the risk results considering climate change for the four scenarios considered: engineered nourishment, natural nourishment scenario 1, natural nourishment scenario 2 and natural nourishment scenario 3.

As explained before, to assess the possibility of considering natural beach nourishment as an option for a 'do-nothing' action, an additional assessment is performed under the following considerations:

a) All previous parameters are maintained unchanged except as indicated.
b) The economic valuation of each beach segment is done for two scenarios considering only total revenue value (direct and indirect) as indicated in section 5.3.2.
    a. **Scenario 1:** maximum recovery time of one year for all beach segments considered.
    b. **Scenario 2:** maximum recovery time of six months for south coast segments and two years for the rest of the segments.
    c. **Scenario 3:** maximum recovery time of one year for all beach segments considered.

c) The mean time for recovery of each beach segment is estimated for each individual storm in proportion to the modelled eroded volume.
d) Vulnerability functions for each beach segment are maintained, but minimum damage is not considered, and the assignment depends on the erosion susceptibility level in each segment as specified in section 6.1.

Of course, the losses associated with the natural beach nourishments will depend on the expected nourishment rates in each beach segment. Considering this a first indicative assessment, more reliable results can be obtained if such rates can be estimated from historic information or additional studies. The results for the four scenarios are summarized in Table 7-2 and Figure 7-3.

Table 7-2. Beach erosion risk - current conditions including climate change - natural nourishment, EAL and PML

		Engineered nourishment	Natural nourishment		
			Scenario 1	Scenario 2	Scenario 3
Total Beach Revenue - TBR	**US$ Million/year**	$ 1,000	$ 1,000	$ 1,000	$ 1,000
Total Beach Recovery Cost - TBRC	**US$ Million**	$ 254.0	$ 360.0	$ 325.0	$ 720.0
Expected Annual Loss - EAL	**US$ Million**	$ 31.7	$ 36.5	$ 35.2	$ 73.0
	% of TBR	3.2	3.6	3.5	7.3
	% of TBRC	12.5	10.1	10.8	10.1
PML					
TR		**US$ Million**	**US$ Million**	**US$ Million**	**US$ Million**
10		$ 96.9	$ 115.9	$ 107.9	$ 231.8
20		$ 115.7	$ 140.9	$ 128.3	$ 281.8
50		$ 123.8	$ 165.8	$ 149.7	$ 331.7
80		$ 128.9	$ 169.0	$ 152.6	$ 338.0
100		$ 135.6	$ 175.1	$ 158.5	$ 350.3
250		$ 152.9	$ 194.1	$ 175.8	$ 388.2
500		$ 156.7	$ 216.7	$ 195.6	$ 433.4
1000		$ 165.3	$ 231.3	$ 209.3	$ 462.6

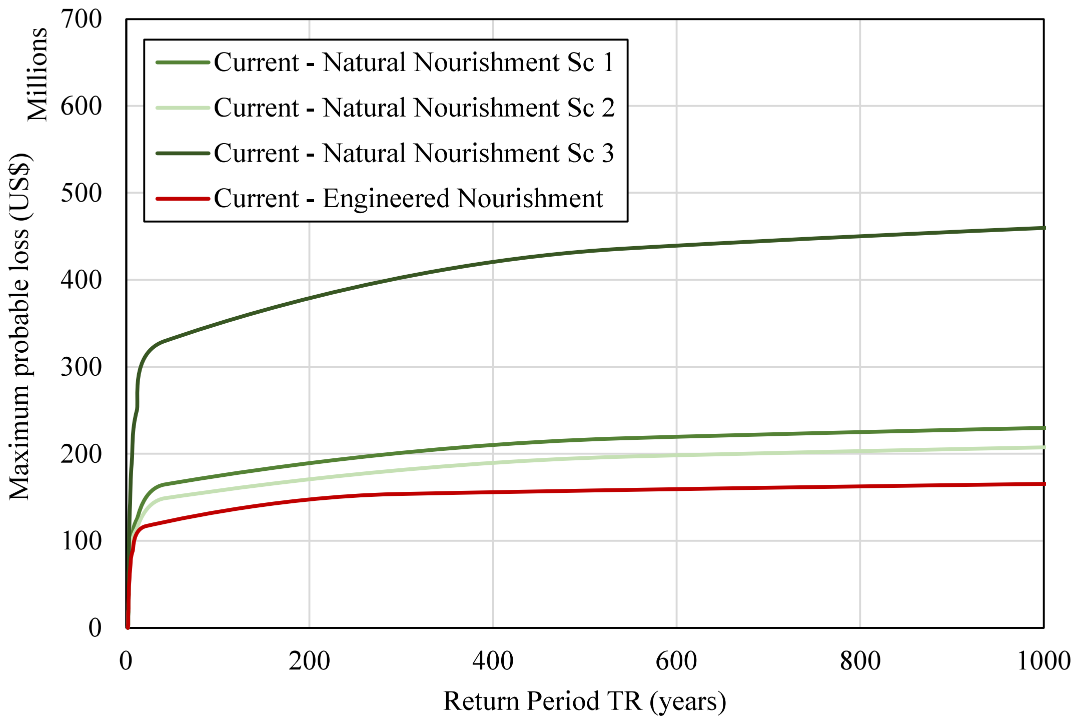


Figure 7-2. Beach erosion risk including climate change, PML comparison

7.1.3 Retrofitted conditions, engineering nourishment including climate change

7.1.3.1 Erosion mitigation alternatives

Throughout the years, the CZMU has been intervening in different beaches with the aim to reduce erosion and enhance functionality. Since 2003, the CZMU have been working on two different programs, the Coastal Infrastructure Program (CIP) and the Coastal Risk Assessment and Management Program (CRMP). Table 7-3 shows the most common interventions and some pictures of them in Barbados.

Table 7-3. Erosion mitigation measures

Intervention type	Category	Description	Photo
Breakwater (submerged)	Foreshore	Usually built parallel to the shoreline with the objective of improving recreational conditions behind reducing beach erosion (Schoonees, et al., 2019).	
Groyne	Foreshore	Structures usually built perpendicular to the shoreline, can be built of timber, rocks or concrete. Groynes prevent (or slow down) longshore sediment transport (Schoonees, et al., 2019).	
Artificial coral reef (submerged)	Foreshore	Usually built parallel to the shoreline with the objective of improving recreational conditions and improving natural ecosystem (Silva, Mendoza, Mariño-Tapia, Martínez, & Escalante, 2016).	 (Silva, Mendoza, Mariño-Tapia, Martínez, & Escalante, 2016)
Revetment	Onshore	Structures built onshore and parallel to the shoreline to prevent landward retreat. Can be permeable (rocks as in the picture) or impermeable (concrete). Usually built on low width beaches with a sidewalk. (Schoonees, et al., 2019).	 

Table 7-4 presents some of the mitigation programs and their associated costs. These interventions show that the unit costs vary from US$ 0.6 million to around US$ 10 million per km. The more extreme interventions have a mean cost of around US$ 8 million and minor interventions with a mean of approximately US$ 2 million.

Table 7-4. Mitigation projects performed in Barbados (provided by CZMU)

Program	Beach	Description	Construction cost (US$ million)	Length (km)	Unitary cost (US$ million/km)
CRMP (2012 - 2020)	Sand Street	Breakwaters (submerged) Groynes Revetments Sidewalks	3.04	0.38	8.00
	Clinketts	Breakwaters (submerged) Groynes Revetments Sidewalks	4.16	0.43	9.67
	St. Peters bay to Mullins	Breakwaters (submerged) Groynes Revetments Sidewalks Beach fill	6.00	0.73*	8.22
	Oistins	Breakwaters (submerged) Groynes Revetments Sidewalks Beach widening Increase road level	5.34	0.50*	10.68
	Rockley to ST. Lawrence	Groynes Revetments Sidewalks	17.90	1.91	9.37
CIP (2003–2010)	Holetown	Revetment Sidewalks	3.10	5.03	0.62
	Welches	Revetment Sidewalks Groyne reconstruction	1.40	0.45	3.11
	Rockley to Drill Hall	Revetment Sidewalks Groynes (low density) Breakwaters (1, submerged)	9.10	1.60	5.69

*lengths estimated using google earth

7.1.3.2 Vulnerability functions for mitigated condition

All beaches with high and medium susceptibility to erosion will move to a low vulnerability condition with the above-stated mitigation alternatives. As stated in the previous chapter, beaches with high susceptibility to erosion will need more invasive, and therefore more costly, intervention than a beach with medium susceptibility to erosion. The set of vulnerability functions for the mitigated scenario will be the ones corresponding to beaches with low susceptibility to erosion as shown in Figure 6-4.

Based on the type of alternatives and the unitary costs presented in section 7.1.3.1, Table 7-5 lists the estimated costs for each intervention type and the total costs of the projected interventions. Note that the beaches classified as having low susceptibility levels would not require mitigation alternatives and are not included in the mitigation strategy. The mitigation strategy included in the table serves as an example for estimating the unitary costs. However, in each specific beach, further analysis should be made to make the interventions. Priority should be given to hybrid, environmentally friendly and soft infrastructure to maintain a nature-based solutions approach.

Table 7-5. Erosion mitigation alternatives costs

Beach Current susceptibility	Beach mitigated susceptibility	Mitigation strategy*	Length (Km)	Unitary cost (US$ million/km)**	Total estimated cost (US$ million/km)
High	Low	Ecologically enhanced hard solution (breakwaters, groynes, revetments, sidewalks) and/or NbS like artificial coral reefs	9.8	9	88.2
Medium	Low	Ecologically enhanced hard solution (small groynes, revetments, sidewalks)	13.65	2	27.3
Total					**115.5**

*Mitigation strategies should be designed for each specific beach segment and whenever possible nature-based solutions should be prioritized.
**based on past mitigation measures built and designed in the country.

The estimated costs in the present study have the following limitations:

- No design or pre-design cost is included.
- They are based on previous mitigation strategies built on the island.
- Cost estimations are indicative to established overall risk metrics for defining risk mitigation programs in relation to beach erosion processes.
- The interventions proposed in this report are indicative; therefore, an exhaustive analysis including field data collection before defining any specific mitigation measure is required.
- Considerations in each beach segment should be validated in field before approving any type of mitigation intervention.

- All interventions should be considered with an integrated approach including the possible effect on nearby beaches or other possible downstream effects, such as social and environmental issues that are outside the scope of this study.

7.1.3.3 Risk results in retrofitted condition

Based on the mitigation alternatives presented above, the assessed risk for the retrofitted condition is estimated using engineered nourishment. Table 7-6 present the expected annual losses (EAL) and the probable maximum losses (PML) for different return periods, including as current condition the engineered nourishment and the scenario 1 for natural nourishment which is considered as an intermediate scenario. Table 7-7 presents the avoidable loss from episodic cyclonic erosion, considering the engineered nourishment as the base condition.

Table 7-6. Beach erosion risk, engineering nourishment - current and retrofitted condition including climate change, EAL and PML, total

		Current Condition		Retrofitted Scenario
		Engineered nourishment	Natural nourishment (Scenario 1)	
Total Beach Revenue - TBR	US$ Million/year	$ 1,000	$ 1,000	$ 1,000
Total Beach Recovery Cost - TBRC	US$ Million	$ 254.0	$ 360.0	$ 254.0
Expected Annual Loss - EAL	US$ Million	$ 31.7	$ 36.5	$ 2.4
	% of TBR	3.17	3.65	0.24
	% of TBRC	12.5	10.1	0.9
Probable Maximum Losses, PML				
TR		US$ Million	US$ Million	US$ Million
10		$ 96.9	$ 115.9	$ 7.4
50		$ 123.8	$ 165.8	$ 12.0
80		$ 128.9	$ 169.0	$ 13.0
100		$ 135.6	$ 175.1	$ 13.7
500		$ 156.7	$ 216.7	$ 21.2
1000		$ 165.3	$ 231.3	$ 26.4

Table 7-7. Beach erosion risk, engineering nourishment – economic benefits from episodic cyclonic erosion

Expected Annual Benefit - EAB	US$ Million	$ 29.3
Probable Maximum Losses Reduction		
Return Period, RP		US$ Million
10		$ 89.5
50		$ 111.9
80		$ 115.9
100		$ 121.9
500		$ 135.5
1000		$ 138.9

In addition, Figure 7-3 shows the PML at the national level for the current and the mitigated conditions presented above.

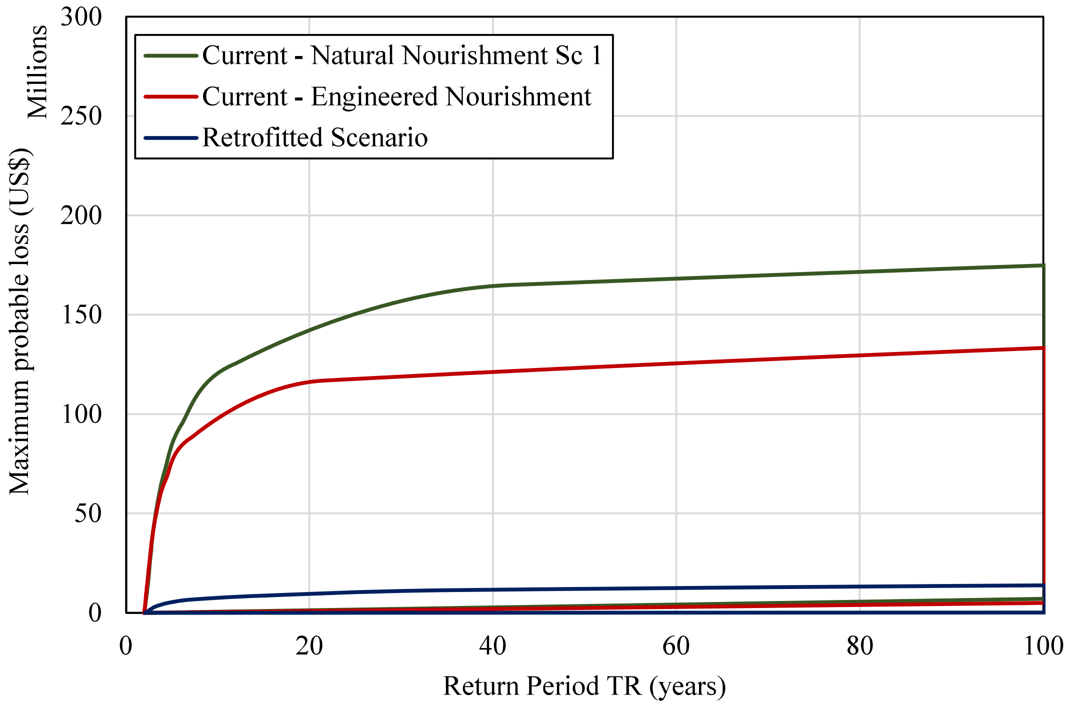


Figure 7-3. Beach erosion risk - current and retrofitted condition including climate change, total PML

As seen above, the PML values for 100-year return period events are about US$ 136 million if immediate repair strategy is implemented, about US$ 14 million for an integral retrofitted scheme (with investments of about US$ 120 million) and about US$ 175 million for a natural nourishment strategy, assuming Scenario 1 as explained above.

In summary, three response strategies were evaluated for the case of intensive episodic erosion:

(i) Immediate mechanical nourishment after critical events. This strategy would require allocating funds of about US$ 30 million per year and a PML provision of about US$ 130 million for a 100-year return period.

(ii) Natural beach nourishment. This strategy would require allocating funds of about US$ 37 million per year and a PML provision of about US$ 175 million for a 100-year return period.

(iii) Integral and immediate implementation of combined gray-green mitigation options to reduce beaches' susceptibility to erosion (prevention strategy). This strategy would require allocating funds of about US$ 2.4 million per year and a PML provision of about US$ 30 million for a 100-year return period. It will require, however, an estimated immediate investment of about US$ 120 million in mitigation works and programs.

7.2 CHRONIC INDICATIVE RISK RESULTS

For chronic event risk assessment, an indicative average annual loss is estimated using the historical erosion rates (HER) presented in section 4.3 and the sea level rise erosion rates presented in section 4.4 (SLR083 and SLR150). The expected annual loss is calculated from the erosion rates using the following equation:

$$EAL_i = \sum_{j=1}^{j=660} w_{segment-} * ER_i * RV_{segment-j}$$

Where $w_{segment-j}$ is the width of each segment (50m), ER_i is the annual erosion rate and $RV_{segment-j}$ is the revenue valuation of each segment calculated in section 5.2.

The EAL calculated for each chronic erosion type is presented in Figure 7-4. It is important to mention that the Historic Erosion Rates (HER) are calculated only in eroding beaches, without considering the possible gain of land in accreting beaches.

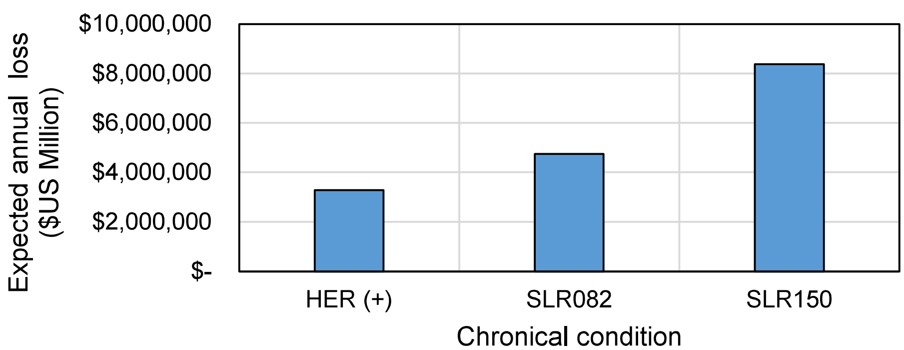


Figure 7-4. Chronic estimated expected annual losses

The mitigation options considered in section 7.1.3.1 will have a significant impact on the reduction of mean erosion rates. For the present assessment, the erosion rates in the mitigated scenario are the corresponding to low susceptibility in all segments, according to section 6.1. However, no impact is considered in the reduction for the SLR082 and SLR150 conditions since mitigation options do not tend to increase the height of the profiles in each segment, and therefore, they will not reduce the expected erosion due to SLR. Table 7-8 summarizes the EAL for the current conditions and the estimated EAL in a mitigated scenario condition.

Table 7-8. Chronic erosion expected annual losses and benefits

Type	Mean erosion rate	Current condition EAL	Mitigated condition EAL
HER (+)	0.105	$ 3,276,547	$ 1,378,555
SLR082	0.127	$ 4,742,174	$ 4,742,174
SLR150	0.193	$ 8,375,370	$ 8,375,370

7.3 INTEGRATED RISK RESULTS

Although both chronic and episodic losses usually interact with each other over time, they are treated independently in this assessment as a simplification. Based on this, the integrated risk results consider the episodic EAL plus the chronic EAL specified in the previous section. Table 7-9 shows the integrated results for the current and the mitigated conditions considering the episodic losses estimated with engineered nourishment.

Table 7-9. Integrated episodic and chronic risk results for current and mitigated conditions

Condition	Type	Current condition EAL (US$)	Mitigated condition EAL (US$)	Annual benefits (US$)
Episodic	Cyclonic model including CC	$ 31,696,726	$ 2,430,016	$ 29,266,710
Chronic	HER (+)	$ 3,276,547	$ 1,378,555	$ 1,897,992
Total		**$ 48,090,818**	**$ 3,808,571**	**$ 31,164,702**

The previous results are also shown graphically in Figure 7-5. The resulting numbers allow to conclude that the episodic risk for Barbados beaches is much more important than the chronic risk. This indicates how important is to adopt a risk mitigation plan mainly oriented to chronic impacts.

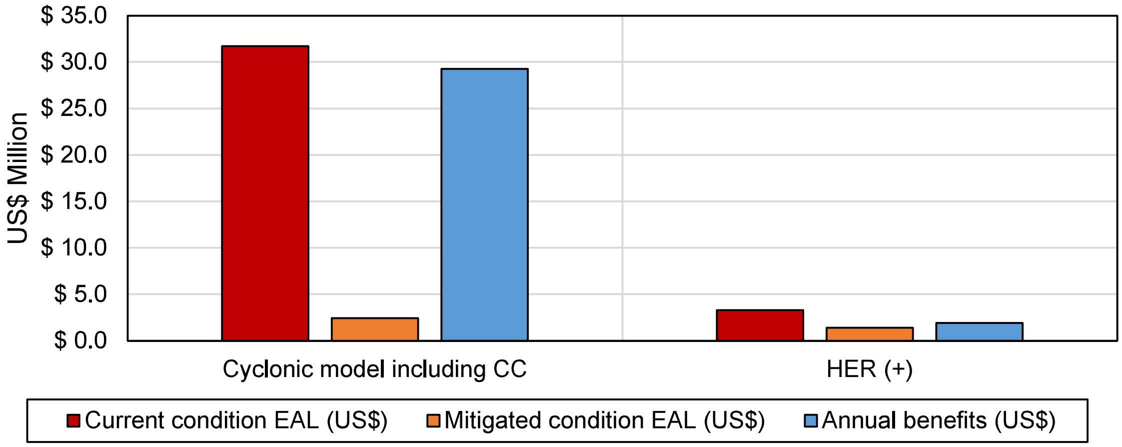


Figure 7-5. Episodic and chronic integrated risk results

7.4 EXPECTED ANNUAL LOSSES AND BENEFITS IN MAIN BEACH AREAS

The expected annual losses are used as a relative risk indicator to prioritize areas for interventions. They can be grouped by the main beach areas in the island. Figure 7-6 presents the geographical distribution of results in terms of total EAL in each beach segment considered in the analysis. Table 7-10 presents the EAL grouped for each one of the five categories defined for the revenue valuation in section 5.2.1.

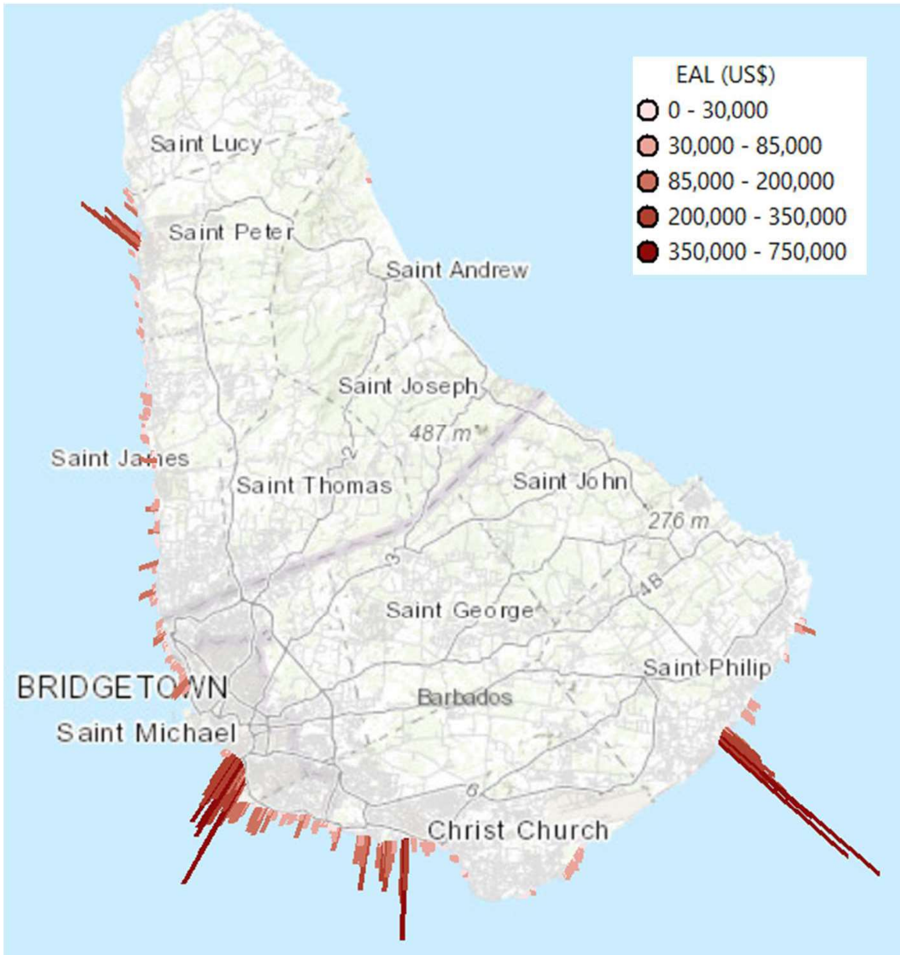


Figure 7-6. Expected annual losses as a relative risk indicator for all beach segments

Table 7-10. Expected annual losses per beach revenue valuation categories

Beach Valuation Category	EAL–Current condition including CC–engineered nourishment (US$)	EAL–Retrofitted condition including CC–engineered nourishment (US$)
1	$ 133,611	$ 0
2	$ 1,892,679	$ 36,208
3	$ 7,932,627	$ 1,413,687
4	$ 19,581,313	$ 980,121
5	$ 2,156,496	$ 0
Total	**$ 31,696,726**	**$ 2,430,016**

Results can also be grouped by the most important beaches in the country (Figure 7-7) as shown in Figure 7-8. These values can be used as a basis to prioritize interventions in the most critical areas and protect tourism revenues as much as possible. These results form the basis for more detailed risk assessments, looking forward to the design of a risk mitigation plan at a country level.

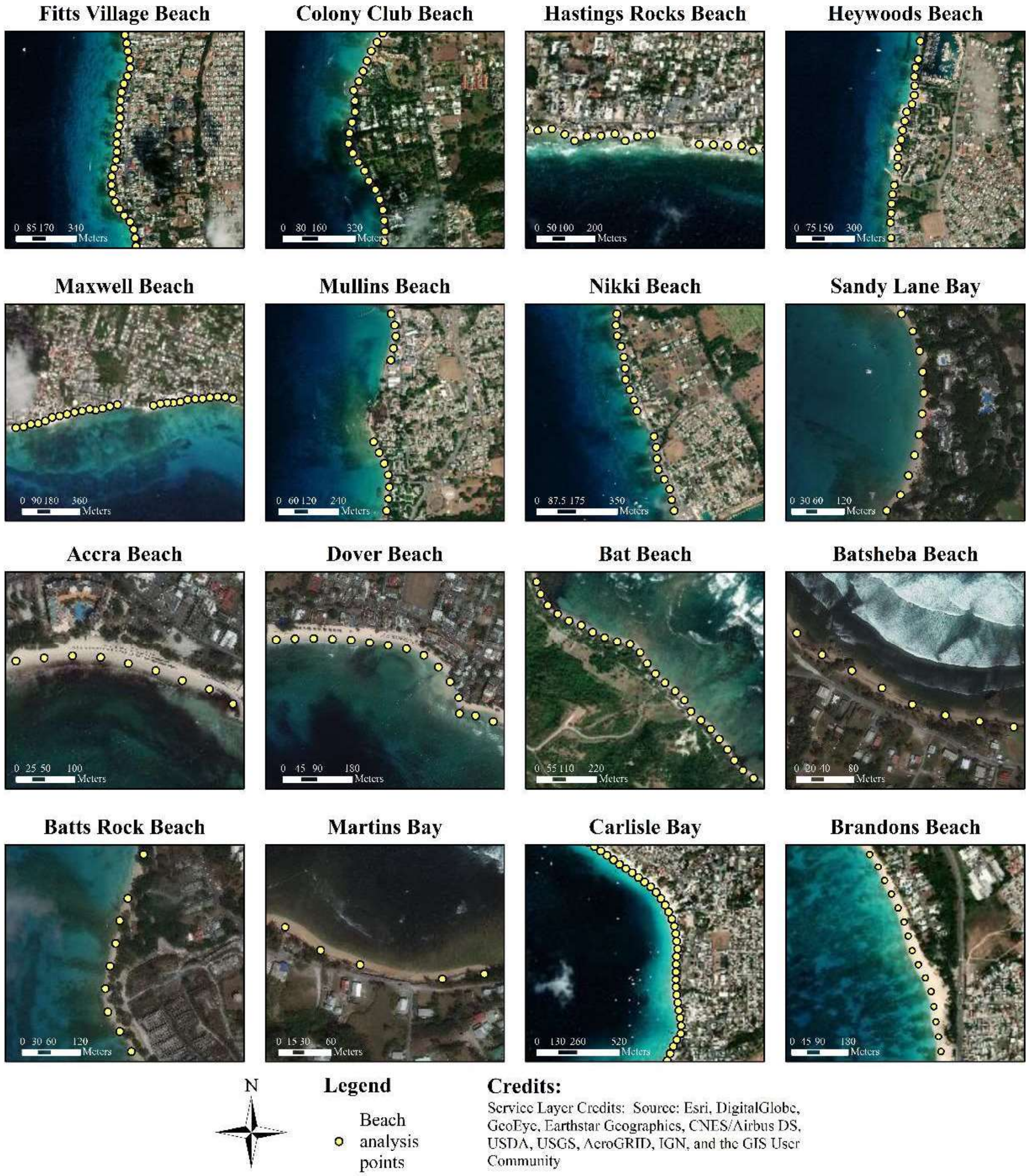


Figure 7-7. Main beaches in the country with analyzed beach segments

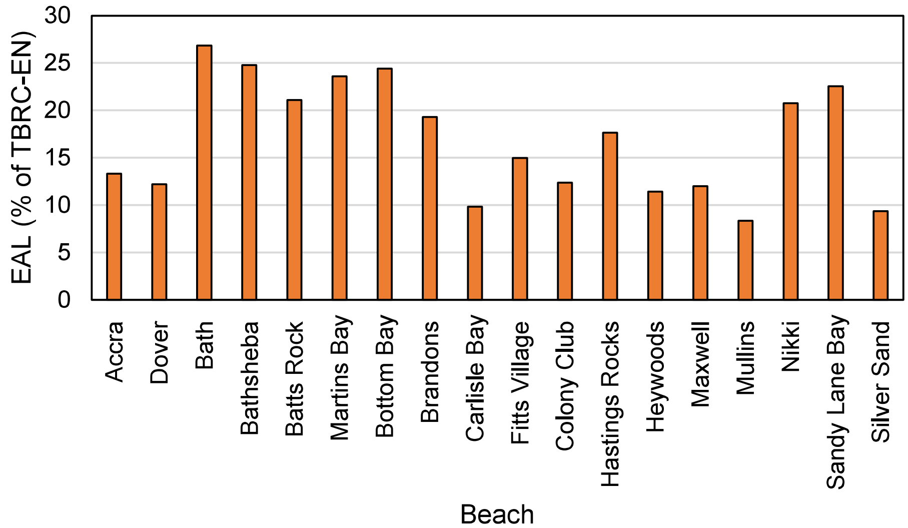


Figure 7-8. Expected annual losses per beach

Table 7-11 presents the estimated integrated benefits for high susceptibility beach segments.

Table 7-11. Episodical and chronical benefits for high susceptibility erosion beach segments

ID	Latitud	Longitud	TBRC Engineered Nourishment	TBRC Natural Nourishment Sc1	TBRC Natural Nourishment Sc2	Annual Benefits Episodic Erosion	Annual Benefits Chronic Erosion
65	13.19573	-59.64169	$ 39,075	$ 71,663	$ 143,327	$ 8,252	$ -
66	13.19613	-59.64187	$ 38,605	$ 71,664	$ 143,329	$ 10,971	$ -
94	13.20767	-59.64003	$ 228,439	$ 182,294	$ 364,587	$ 85,135	$ 19,246
95	13.20810	-59.63999	$ 206,190	$ 182,293	$ 364,586	$ 73,749	$ 19,246
782	13.28110	-59.56846	$ 16,227	$ 7,807	$ 15,615	$ 3,118	$ -
783	13.28067	-59.56839	$ 13,459	$ 5,408	$ 10,816	$ 3,888	$ -
784	13.28027	-59.56821	$ 14,631	$ 6,152	$ 12,304	$ 4,355	$ -
785	13.27987	-59.56803	$ 13,128	$ 6,152	$ 12,304	$ 2,715	$ -
786	13.27945	-59.56794	$ 45,953	$ 40,058	$ 80,115	$ 7,301	$ -
787	13.27904	-59.56809	$ 14,747	$ 6,782	$ 13,564	$ 2,648	$ -
788	13.27860	-59.56811	$ 27,785	$ 13,272	$ 26,545	$ 5,795	$ -
789	13.27821	-59.56791	$ 52,793	$ 42,445	$ 84,890	$ 9,815	$ -
790	13.27781	-59.56783	$ 88,750	$ 92,051	$ 184,103	$ 18,691	$ -
791	13.27738	-59.56777	$ 131,392	$ 112,282	$ 224,565	$ 31,652	$ -
981	13.21357	-59.52124	$ 38,866	$ 46,472	$ 92,944	$ 10,252	$ 4,909
982	13.21329	-59.52092	$ 39,756	$ 49,482	$ 98,965	$ 7,699	$ 4,909
983	13.21309	-59.52054	$ 44,319	$ 50,439	$ 100,877	$ 11,933	$ 4,909
984	13.21287	-59.52016	$ 40,972	$ 50,439	$ 100,878	$ 8,966	$ 4,909
985	13.21266	-59.51978	$ 30,334	$ 38,998	$ 77,996	$ 11,811	$ 4,909
986	13.21253	-59.51936	$ 33,906	$ 38,998	$ 77,996	$ 8,881	$ 4,909
987	13.21245	-59.51893	$ 35,568	$ 40,663	$ 81,326	$ 7,994	$ 4,909
988	13.21238	-59.51849	$ 39,327	$ 40,663	$ 81,325	$ 7,529	$ 4,909
1060	13.19786	-59.49478	$ 13,902	$ 6,787	$ 13,574	$ 2,142	$ -
1061	13.19762	-59.49442	$ 8,310	$ 4,814	$ 9,629	$ 2,535	$ -
1062	13.19747	-59.49401	$ 9,764	$ 4,814	$ 9,629	$ 1,572	$ -

ID	Latitud	Longitud	TBRC Engineered Nourishment	TBRC Natural Nourishment Sc1	TBRC Natural Nourishment Sc2	Annual Benefits Episodic Erosion	Annual Benefits Chronic Erosion
1064	13.19733	-59.49315	$ 11,854	$ 4,965	$ 9,931	$ 2,831	$ -
1065	13.19738	-59.49272	$ 10,966	$ 4,945	$ 9,889	$ 3,847	$ -
1083	13.19557	-59.48696	$ 19,524	$ 4,211	$ 8,421	$ 2,341	$ -
1084	13.19517	-59.48676	$ 6,325	$ 4,211	$ 8,421	$ 2,130	$ -
1085	13.19474	-59.48675	$ 4,638	$ 2,743	$ 5,486	$ 1,248	$ -
1086	13.19430	-59.48669	$ 7,951	$ 2,743	$ 5,486	$ 2,243	$ -
1087	13.19387	-59.48674	$ 11,249	$ 2,602	$ 5,205	$ 3,509	$ -
1088	13.19343	-59.48670	$ 10,049	$ 2,998	$ 5,996	$ 2,695	$ -
1089	13.19300	-59.48662	$ 5,742	$ 2,998	$ 5,996	$ 1,251	$ -
1090	13.19256	-59.48669	$ 5,754	$ 3,846	$ 7,693	$ 1,302	$ -
1091	13.19216	-59.48656	$ 7,060	$ 3,846	$ 7,693	$ 1,822	$ -
1092	13.19174	-59.48644	$ 15,239	$ 6,142	$ 12,283	$ 4,718	$ -
1118	13.18865	-59.47746	$ 3,345	$ 2,602	$ 5,205	$ 772	$ -
1119	13.18823	-59.47732	$ 5,160	$ 2,602	$ 5,205	$ 1,131	$ -
1120	13.18786	-59.47708	$ 6,557	$ 5,205	$ 10,410	$ 1,329	$ -
1121	13.18757	-59.47675	$ 5,678	$ 3,399	$ 6,798	$ 1,317	$ -
1122	13.18734	-59.47638	$ 5,599	$ 3,399	$ 6,797	$ 1,475	$ -
1123	13.18720	-59.47596	$ 19,772	$ 13,272	$ 26,545	$ 5,520	$ -
1124	13.18697	-59.47559	$ 8,516	$ 4,971	$ 9,941	$ 1,946	$ -
1125	13.18679	-59.47519	$ 7,941	$ 4,971	$ 9,941	$ 2,971	$ -
1126	13.18665	-59.47477	$ 9,603	$ 5,288	$ 10,576	$ 2,819	$ -
1127	13.18657	-59.47434	$ 9,052	$ 6,064	$ 12,127	$ 2,844	$ -
1128	13.18628	-59.47401	$ 8,983	$ 6,064	$ 12,127	$ 2,269	$ -
1129	13.18592	-59.47376	$ 8,354	$ 5,475	$ 10,951	$ 2,392	$ -
1130	13.18557	-59.47349	$ 8,500	$ 5,476	$ 10,951	$ 2,841	$ -
1131	13.18528	-59.47317	$ 8,242	$ 5,278	$ 10,555	$ 2,425	$ -
1132	13.18500	-59.47283	$ 11,529	$ 6,527	$ 13,054	$ 2,889	$ -
1133	13.18469	-59.47252	$ 11,844	$ 6,527	$ 13,054	$ 2,827	$ -
1134	13.18431	-59.47230	$ 10,874	$ 4,997	$ 9,993	$ 2,986	$ -
1135	13.18402	-59.47197	$ 13,983	$ 4,710	$ 9,421	$ 4,227	$ -
1136	13.18372	-59.47164	$ 13,271	$ 4,710	$ 9,421	$ 3,965	$ -
1137	13.18339	-59.47136	$ 14,414	$ 7,058	$ 14,115	$ 3,456	$ -
1138	13.18305	-59.47108	$ 11,329	$ 6,522	$ 13,043	$ 2,644	$ -
1139	13.18268	-59.47085	$ 8,979	$ 5,632	$ 11,263	$ 2,694	$ -
1140	13.18235	-59.47056	$ 10,534	$ 5,632	$ 11,263	$ 2,552	$ -
1141	13.18208	-59.47021	$ 12,449	$ 5,632	$ 11,263	$ 2,646	$ -
1390	13.13990	-59.42298	$ 67,856	$ 62,305	$ 31,152	$ 4,302	$ -
1391	13.13947	-59.42306	$ 181,638	$ 196,584	$ 98,292	$ 4,612	$ -
1403	13.13666	-59.42494	$ 100,843	$ 78,208	$ 39,104	$ 25,627	$ -
1404	13.13623	-59.42496	$ 135,050	$ 108,033	$ 54,016	$ 33,696	$ -
1405	13.13579	-59.42500	$ 120,624	$ 96,627	$ 48,314	$ 27,602	$ -
1411	13.13448	-59.42659	$ 755,245	$ 448,070	$ 224,035	$ 107,311	$ -
1412	13.13404	-59.42659	$ 175,134	$ 161,163	$ 80,582	$ 41,305	$ -
1413	13.13362	-59.42658	$ 253,261	$ 232,004	$ 116,002	$ 55,657	$ -
1414	13.13319	-59.42652	$ 146,579	$ 125,743	$ 62,871	$ 38,970	$ -
1428	13.12924	-59.42941	$ 19,437	$ 27,486	$ 13,743	$ 2,937	$ -
1429	13.12881	-59.42935	$ 24,176	$ 27,486	$ 13,743	$ 3,739	$ -
1430	13.12838	-59.42935	$ 21,638	$ 27,486	$ 13,743	$ 7,404	$ -
1431	13.12794	-59.42938	$ 108,775	$ 52,919	$ 26,459	$ 21,569	$ -
1432	13.12750	-59.42940	$ 54,125	$ 52,918	$ 26,459	$ 10,695	$ -
1433	13.12707	-59.42946	$ 60,993	$ 59,896	$ 29,948	$ 15,453	$ -
1434	13.12663	-59.42945	$ 34,951	$ 42,859	$ 21,429	$ 8,862	$ -
1435	13.12619	-59.42945	$ 33,139	$ 42,859	$ 21,429	$ 10,097	$ -

ID	Latitud	Longitud	TBRC Engineered Nourishment	TBRC Natural Nourishment Sc1	TBRC Natural Nourishment Sc2	Annual Benefits Episodic Erosion	Annual Benefits Chronic Erosion
1436	13.12576	-59.42952	$ 39,403	$ 70,841	$ 35,421	$ 10,998	$ -
1438	13.12511	-59.42987	$ 138,868	$ 76,792	$ 38,396	$ 18,613	$ 37,633
1439	13.12472	-59.43007	$ 102,393	$ 90,322	$ 45,161	$ 32,110	$ 37,633
1440	13.12431	-59.43024	$ 112,828	$ 90,322	$ 45,161	$ 18,001	$ 37,633
1442	13.12378	-59.43007	$ 132,974	$ 84,478	$ 42,239	$ 28,537	$ 37,633
1490	13.11146	-59.44110	$ 12,671	$ 17,710	$ 8,855	$ 2,286	$ -
1491	13.11104	-59.44122	$ 12,012	$ 17,710	$ 8,855	$ 3,823	$ -
1494	13.11013	-59.44138	$ 381,046	$ 216,558	$ 108,279	$ 62,022	$ -
1495	13.10975	-59.44156	$ 200,389	$ 216,558	$ 108,279	$ 38,711	$ -
1496	13.10937	-59.44178	$ 162,683	$ 208,932	$ 104,466	$ 48,712	$ -
1497	13.10896	-59.44194	$ 229,351	$ 475,321	$ 237,660	$ 45,275	$ -
1498	13.10859	-59.44217	$ 212,493	$ 230,138	$ 115,069	$ 39,286	$ -
1503	13.10700	-59.44327	$ 458,265	$ 793,943	$ 396,971	$ 51,866	$ -
1504	13.10665	-59.44353	$ 407,576	$ 356,543	$ 178,271	$ 69,006	$ -
1505	13.10634	-59.44384	$ 416,493	$ 356,543	$ 178,271	$ 63,709	$ -
1506	13.10604	-59.44416	$ 598,761	$ 441,684	$ 220,842	$ 78,438	$ -
1507	13.10569	-59.44429	$ 621,450	$ 441,682	$ 220,841	$ 69,635	$ -
1528	13.10189	-59.44877	$ 64,849	$ 101,018	$ 50,509	$ 18,198	$ -
1529	13.10159	-59.44909	$ 80,047	$ 111,256	$ 55,628	$ 23,385	$ -
1530	13.10128	-59.44940	$ 684,922	$ 734,915	$ 367,457	$ 149,538	$ -
1531	13.10097	-59.44971	$ 746,343	$ 792,886	$ 396,443	$ 214,977	$ -
1532	13.10064	-59.45000	$ 153,985	$ 183,338	$ 91,669	$ 60,737	$ -
1533	13.10027	-59.45025	$ 1,170,747	$ 1,182,829	$ 591,415	$ 231,491	$ -
1534	13.09989	-59.45046	$ 981,748	$ 821,221	$ 410,610	$ 302,770	$ -
1535	13.09949	-59.45064	$ 833,996	$ 726,076	$ 363,038	$ 217,283	$ -
1536	13.09909	-59.45082	$ 1,103,080	$ 1,052,848	$ 526,424	$ 248,232	$ -
1537	13.09867	-59.45096	$ 1,238,218	$ 1,312,811	$ 656,405	$ 364,031	$ -
1538	13.09826	-59.45109	$ 3,844,737	$ 3,158,544	$ 1,579,272	$ 709,361	$ -
1539	13.09784	-59.45124	$ 2,631,250	$ 1,975,715	$ 987,858	$ 479,643	$ -
1540	13.09746	-59.45144	$ 1,196,950	$ 1,312,811	$ 656,405	$ 238,005	$ -
1541	13.09711	-59.45168	$ 1,237,206	$ 1,442,792	$ 721,396	$ 292,545	$ -
1542	13.09673	-59.45189	$ 1,953,435	$ 840,979	$ 420,489	$ 622,459	$ -
1701	13.06630	-59.49526	$ 31,078	$ 10,045	$ 5,023	$ 4,223	$ -
1702	13.06593	-59.49549	$ 9,572	$ 4,929	$ 2,464	$ 3,464	$ -
1703	13.06559	-59.49577	$ 9,304	$ 4,929	$ 2,464	$ 1,958	$ -
1704	13.06523	-59.49602	$ 5,153	$ 3,263	$ 1,632	$ 1,279	$ -
1705	13.06487	-59.49628	$ 5,555	$ 3,263	$ 1,632	$ 1,477	$ -
1706	13.06451	-59.49653	$ 10,296	$ 5,517	$ 2,759	$ 2,686	$ -
1707	13.06416	-59.49680	$ 58,105	$ 43,112	$ 21,556	$ 14,222	$ -
1708	13.06379	-59.49704	$ 48,060	$ 38,055	$ 19,027	$ 13,310	$ -
1709	13.06344	-59.49731	$ 47,764	$ 38,055	$ 19,027	$ 12,258	$ -
1710	13.06309	-59.49757	$ 53,408	$ 41,980	$ 20,990	$ 12,218	$ -
1711	13.06274	-59.49783	$ 110,861	$ 91,952	$ 45,976	$ 30,412	$ -
1712	13.06237	-59.49807	$ 113,054	$ 91,951	$ 45,976	$ 20,884	$ -
1713	13.06197	-59.49826	$ 122,050	$ 97,690	$ 48,845	$ 35,159	$ -
1714	13.06157	-59.49845	$ 136,568	$ 103,641	$ 51,820	$ 33,295	$ -
1715	13.06119	-59.49866	$ 135,051	$ 103,641	$ 51,820	$ 38,510	$ -
1716	13.06080	-59.49887	$ 252,825	$ 214,294	$ 107,147	$ 39,745	$ -
1717	13.06041	-59.49905	$ 181,590	$ 121,634	$ 60,817	$ 44,939	$ -
1718	13.05999	-59.49915	$ 124,654	$ 102,224	$ 51,112	$ 34,983	$ -
1719	13.05965	-59.49942	$ 126,683	$ 93,369	$ 46,684	$ 22,115	$ -
1720	13.05927	-59.49965	$ 120,198	$ 93,368	$ 46,684	$ 22,183	$ -
1721	13.05891	-59.49990	$ 158,389	$ 109,201	$ 54,601	$ 34,121	$ -

ID	Latitud	Longitud	TBRC Engineered Nourishment	TBRC Natural Nourishment Sc1	TBRC Natural Nourishment Sc2	Annual Benefits Episodic Erosion	Annual Benefits Chronic Erosion
1722	13.05854	-59.50014	$ 252,858	$ 251,486	$ 125,743	$ 51,610	$ -
1723	13.05817	-59.50038	$ 155,816	$ 119,757	$ 59,878	$ 33,002	$ -
1724	13.05779	-59.50061	$ 154,847	$ 117,738	$ 58,869	$ 31,341	$ -
1725	13.05743	-59.50085	$ 166,824	$ 122,944	$ 61,472	$ 30,495	$ -
1726	13.05705	-59.50108	$ 192,065	$ 178,874	$ 89,437	$ 31,947	$ -
1727	13.05666	-59.50129	$ 154,603	$ 125,743	$ 62,871	$ 31,409	$ -
1728	13.05630	-59.50153	$ 166,808	$ 143,453	$ 71,727	$ 30,437	$ -
1729	13.05594	-59.50179	$ 182,828	$ 178,874	$ 89,437	$ 34,340	$ -
1730	13.05556	-59.50201	$ 163,430	$ 127,230	$ 63,615	$ 34,707	$ -
1731	13.05519	-59.50226	$ 163,189	$ 127,231	$ 63,615	$ 37,172	$ -
1732	13.05484	-59.50252	$ 133,387	$ 115,648	$ 57,824	$ 25,614	$ -
1733	13.05448	-59.50277	$ 135,147	$ 110,583	$ 55,291	$ 36,788	$ -
1768	13.04858	-59.51438	$ 41,040	$ 52,741	$ 26,371	$ 8,090	$ 8,181
1769	13.04831	-59.51473	$ 41,209	$ 52,741	$ 26,371	$ 9,695	$ 8,181
1777	13.04690	-59.51762	$ 65,871	$ 62,871	$ 31,436	$ 13,324	$ 8,181
1778	13.04675	-59.51803	$ 26,478	$ 36,200	$ 18,100	$ 6,654	$ 8,181
1849	13.05996	-59.53899	$ 157,495	$ 155,627	$ 77,814	$ 37,335	$ -
1850	13.06010	-59.53941	$ 132,663	$ 212,758	$ 106,379	$ 32,590	$ -
1869	13.06422	-59.54566	$ 79,391	$ 133,507	$ 66,754	$ 15,627	$ -
1870	13.06427	-59.54610	$ 84,122	$ 133,508	$ 66,754	$ 14,274	$ -
2016	13.07546	-59.60206	$ 522,393	$ 690,460	$ 345,230	$ 155,844	$ -
2017	13.07552	-59.60250	$ 401,772	$ 1,052,848	$ 526,424	$ 91,133	$ -
2018	13.07553	-59.60294	$ 363,244	$ 792,886	$ 396,443	$ 82,103	$ -
2019	13.07552	-59.60338	$ 724,313	$ 1,572,773	$ 786,387	$ 139,744	$ -
2020	13.07558	-59.60381	$ 569,941	$ 1,052,848	$ 526,424	$ 108,788	$ -
2031	13.07725	-59.60806	$ 328,561	$ 662,904	$ 331,452	$ 89,728	$ -
2032	13.07736	-59.60848	$ 286,819	$ 436,218	$ 218,109	$ 84,269	$ -
2050	13.08014	-59.61143	$ 172,857	$ 303,897	$ 151,948	$ 29,414	$ -
2051	13.08038	-59.61106	$ 259,363	$ 1,182,829	$ 591,415	$ 67,106	$ -
2073	13.08953	-59.61003	$ 4,959,445	$ 1,570,713	$ 785,357	$ 289,991	$ -
2074	13.08993	-59.61020	$ 2,441,925	$ 5,189,677	$ 2,594,838	$ 419,939	$ -
2085	13.09316	-59.61373	$ 1,215,206	$ 1,361,943	$ 680,972	$ 196,213	$ -
2086	13.09342	-59.61409	$ 241,510	$ 430,359	$ 215,180	$ 35,851	$ -
2087	13.09366	-59.61445	$ 197,125	$ 127,691	$ 63,846	$ 29,631	$ -
2088	13.09391	-59.61482	$ 387,464	$ 680,074	$ 340,037	$ 45,082	$ -
2234	13.11485	-59.62750	$ 219,540	$ 232,081	$ 464,162	$ 43,666	$ -
2235	13.11529	-59.62758	$ 865,993	$ 1,339,331	$ 2,678,663	$ 126,955	$ -
2236	13.11572	-59.62763	$ 468,923	$ 387,150	$ 774,301	$ 94,873	$ -
2237	13.11616	-59.62771	$ 971,562	$ 1,409,088	$ 2,818,176	$ 145,003	$ -
2238	13.11656	-59.62788	$ 520,308	$ 1,161,451	$ 2,322,903	$ 116,069	$ -
2239	13.11695	-59.62809	$ 440,303	$ 847,546	$ 1,695,091	$ 108,774	$ -
2240	13.11735	-59.62827	$ 292,400	$ 530,152	$ 1,060,304	$ 71,794	$ -
2241	13.11777	-59.62838	$ 158,901	$ 185,832	$ 371,663	$ 33,567	$ -
2242	13.11819	-59.62850	$ 128,622	$ 156,744	$ 313,488	$ 35,486	$ -
2243	13.11860	-59.62868	$ 182,211	$ 282,515	$ 565,030	$ 56,638	$ -
2244	13.11899	-59.62887	$ 115,863	$ 142,025	$ 284,050	$ 25,719	$ -
2245	13.11938	-59.62907	$ 113,210	$ 177,880	$ 355,760	$ 30,528	$ -
2246	13.11978	-59.62925	$ 118,176	$ 177,880	$ 355,760	$ 35,532	$ -
2247	13.12015	-59.62950	$ 81,457	$ 108,541	$ 217,082	$ 30,531	$ -
2248	13.12049	-59.62977	$ 177,061	$ 247,637	$ 495,274	$ 35,326	$ -
2249	13.12080	-59.63008	$ 145,234	$ 177,880	$ 355,760	$ 42,870	$ -
2250	13.12109	-59.63041	$ 183,500	$ 282,515	$ 565,030	$ 34,605	$ -
2251	13.12139	-59.63073	$ 180,939	$ 282,515	$ 565,030	$ 47,411	$ -

ID	Latitud	Longitud	TBRC Engineered Nourishment	TBRC Natural Nourishment Sc1	TBRC Natural Nourishment Sc2	Annual Benefits Episodic Erosion	Annual Benefits Chronic Erosion
2252	13.12171	-59.63103	$ 173,597	$ 194,970	$ 389,941	$ 46,185	$ -
2253	13.12201	-59.63135	$ 182,282	$ 211,014	$ 422,028	$ 27,924	$ -
2254	13.12232	-59.63167	$ 196,883	$ 211,015	$ 422,029	$ 50,884	$ -
2259	13.12394	-59.63307	$ 223,313	$ 456,907	$ 913,815	$ 43,428	$ -
2260	13.12433	-59.63327	$ 223,313	$ 456,907	$ 913,815	$ 52,181	$ -
2277	13.13138	-59.63524	$ 341,668	$ 510,567	$ 1,021,134	$ 70,369	$ -
2278	13.13170	-59.63553	$ 372,229	$ 510,565	$ 1,021,129	$ 91,993	$ -
2281	13.13267	-59.63634	$ 140,223	$ 190,651	$ 381,302	$ 40,088	$ -
2282	13.13303	-59.63656	$ 98,549	$ 157,849	$ 315,698	$ 23,502	$ -
2283	13.13346	-59.63661	$ 105,756	$ 157,848	$ 315,696	$ 21,795	$ -
2284	13.13389	-59.63653	$ 58,117	$ 101,959	$ 203,917	$ 16,794	$ -
2285	13.13431	-59.63642	$ 56,915	$ 101,959	$ 203,919	$ 17,176	$ -

7.5 SIMPLIFIED BENEFIT COST ANALYSIS

The previous information allows a simplified benefit cost assessment for an eventual risk mitigation plan based on the mitigation options indicated in section 7.1.3.1. Assuming the implementation of an integrated mitigation strategy in beaches that demonstrate medium and high susceptibility to erosion in the country, the corresponding benefits of such an initiative can be estimated from the reduced expected annual losses from both episodic cyclonic risk and chronic risk. The Benefit Cost Ratio (BCR) is evaluated using the following equation:

$$BCR = \frac{Benefits_{NPV}}{Costs}$$

Where the costs are obtained from the mean value of retrofitting alternatives presented in section 7.1.3.1 and the net present value of the benefits is calculated as follows:

$$Benefits_{NPV} = \frac{Annual\ benefits}{i} * \left(1 - \frac{1}{(1+i)^T}\right)$$

In which i corresponds to the interest rate and T to the time horizon. Considering that the benefits are constant at perpetuity ($T \rightarrow \propto$) the equation simplifies as follows:

$$Benefits_{NPV} = \frac{Annual\ benefits}{i}$$

Table 7-12 summarizes the results for the total portfolio, considering an interest rate i of 12%. The results show a BCR of 2.2, which indicates a very attractive investment return in the long term.

Table 7-12. Simplified benefit cost analysis for the intervention of the beach portfolio

Annual Episodic risk reduction	$ 29,266,710
Annual Chronic risk reduction	$ 1,378,555
Total annual benefits	$ 30,645,265
Benefits NPV (*i*=12%)	**$ 255,377,210**
Total estimated mitigation cost	$ 115,500,000
BCR	**2.2**

The graphical representation of the BCR in time is presented in Figure 7-9. As the figure shows, the BCR becomes greater than one after a time period of about six years, meaning a short- to medium-term return of the initial investment.

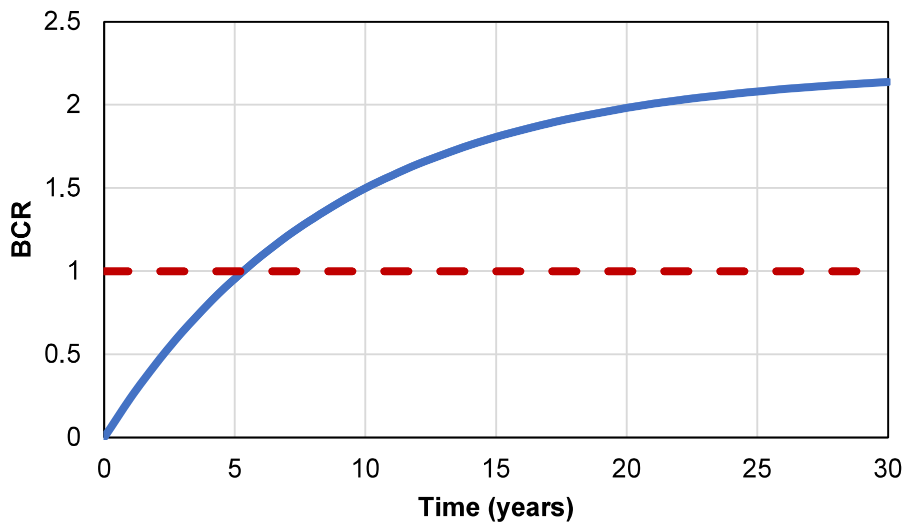


Figure 7-9. Benefit cost ratio in time

CAPITULO

8

CONCLUSIONS AND RECOMMENDATIONS

8.1 CONCLUSIONS

The most important findings of this study are the following*:

a) Historic information indicates that Barbados shoreline has directly or indirectly experienced the effects of about 45 hurricanes over the last 168 years, 4 of which have reached category 4 and 5 at certain point in their trajectory. This natural threat could generate a great impact on the total tourism revenue in the future.

b) The total beach revenue (TBR) associated with direct and indirect revenue in the tourism sector in Barbados is estimated to be about US$ 1,000 million per year. The Total Beach Recovery Cost (TBCR) associated with erosion beach susceptibility in Barbados is estimated for a engineered nourishment strategy to be about US$ 253 million and includes direct and indirect losses due to downtimes, and indirect revenue losses due to tourism-related business interruption activities.

c) A simplified probabilistic hurricane risk model was developed based on the historic information and the beach erosion risk model developed in this study. To estimate expected losses and define optimal mitigation strategies, three different response strategies were analyzed: (i) Immediate mechanical nourishment of any affected beach segment after critical events; (ii) natural nourishment of beaches; (iii) integral and immediate implementation of gray and combined gray-green mitigation options to reduce beach erosion susceptibility (prevention strategy).

d) If no risk reduction measures are taken and with an <u>immediate mechanical nourishment strategy</u>, the country would have to expect a loss of about US$30 million per year in the long term and would require a PML provision of about US$ 130 million for a 100-year return period event.

e) If no risk reduction measures are taken, and with a <u>natural nourishment of beaches strategy for a scenario of 1 year uniform expected time for recuperation (scenario 1),</u>

the country would have to expect a loss of about US$ 37 million per year in the long term and a would require a PML provision of about US$ 175 million for a 100-year return period event. This represents an increase of about 34% with respect to the previous option.

f) The integral and immediate implementation of gray and combined gray-green mitigation options to reduce beach erosion susceptibility (prevention strategy) will require an estimated immediate investment of around US$ 120 million in mitigation works and programs in the short-term period. These interventions will reduce the required annual availability of funds in the long term to about US$ 2.4 million per year, and a PML provision to about US$ 30 million for a 100-year return period event.

g) Study results also show that periodical coastal erosions due to chronic events are currently causing economic losses, associated mainly with the expected effective retreat in coastal lines in the long term. According to this study, in the long term the country could lose an approximate US$3.2 million every year from eventual direct and indirect tourism revenue losses. Climate change scenarios would increase these losses in the near future.

h) Beach erosion catastrophic risk and its impact on the tourism revenues in Barbados are controlled by episodic critical events that will occur in the future. Climate change will increase the expected frequency of catastrophic events (hurricanes category 4 and 5). Considering its high participation in the total country GDP, the protection of the tourism sector revenues against episodic critical events should be a priority.

i) Considering the expected high impact of catastrophic events, the optimal strategy corresponds to a prevention strategy which shall include an integral and immediate implementation of naturally enhanced gray and combined gray-green mitigation options to reduce beach erosion susceptibility.

j) Risk mitigation/prevention options will significantly reduce both episodic and chronic erosion susceptibility and risk. They will reduce both the expected annual losses in the long term and the maximum probable losses for critical catastrophic scenarios. Considering recent historic intervention projects and experience in Barbados, the estimated total intervention costs to reduce the susceptibility of beaches from high and medium to low susceptibility is estimated at about US$120 million. For a long-term assessment, simplified benefit cost analysis indicates returns of about 2.2 times the investment amounts in mitigation.

k) Therefore, disaster risk management and risk mitigation investments related to beach erosion under episodic critical events should be a priority of the government to protect direct and indirect tourism revenues in the long term.

*It is important to note that all estimates were based on a non-COVID-19 scenario.

8.2 RECOMMENDATIONS

To reduce and control the risk associated with beach erosion and tourism revenue losses, a risk mitigation plan shall be established and implemented. The mitigation plan should include the following main dimensions:

a) Risk assessment and reconnaissance: The present report and previous ones are the first step for the disaster risk management. More detailed assessments are required to construct a comprehensive disaster risk management information database.

b) Risk prevention and mitigation plan: This plan should consider technical, social, environmental and economic aspects. It should include different intervention options according to the particular conditions in each beach segment. Prioritization strategies can be defined based on the risk results presented in this report and a further benefit cost ratio (BCR) analysis for different options.

c) Financial protection: Independently of the risk mitigation plans adopted, a financial protection strategy should be considered as a following step for being designed and implemented. It should include a risk retention and transfer strategy, insurance programs, emergency funds, contingency loans, and available financial options. The particular design of the financial protection plan is recommended to be in accordance with the risk figures presented in this report and adjusted according to the main response strategy adopted by the CZMU as part of an integrated risk management program.

d) Emergency response and recovery: This strategy should include an emergency response plan for critical events, a series of contingency plans for selected representative events and a reconstruction and recuperation program in case a disaster occurs.

The optimal intervention strategy to reduce risk corresponds to a prevention strategy. This involves implementing complete and immediate mitigation strategies to reduce beaches' susceptibility to erosion. Based on this strategy, the Integrated Coastal Zone Management (ICZM) plan for Barbados should be integrated with Disaster Risk Reduction strategies to ensure a comprehensive approach to making coastlines more resilient.

More detailed information about episodic or chronic beach erosion should also be a priority of the government. This information will be extremely important to validating and calibrating the available exposure, vulnerability, and risk models. With more specific risk and reliable assessments for individual beach areas, the catastrophic model can be subjected to further validation, considering the particular and unique conditions of Barbados in the Caribbean region. The DRM plan can therefore be adapted and optimized accordingly.

REFERENCES

Alexandrakis, G., Manasakis, C., & Kampanis. (2015). Valuating the effects of beach erosion to tourism revenue. A management perspective. *Ocean and Coastal Managment*, 1-11.

American Society of Civil Engineers. (2016). *Minimum design loads for buildings and other structures - ASCE/SEI 7-16.*

Baird. (2015). *Coastal Risk Assessment and Management Program - CRMP Shoreline Change Strudy.*

Baird. (2017). *National Coastal Risk Information and Planning Platform NCRIPP Final Hazard Report .*

Bautista Godínez, E. G., Silva Casarin, R., & Salles A. de Almeida, P. (2003). Predicción de marea de tormenta generada por ciclones tropicales. *Ingeniería hidráulica en México*, 5-19.

BSS, B. S. (2016). *Annual Stay-Over Arrivals by Purpose of Visit.*

BTI, B. T. (2020). *Tourism Profile*. Retrieved from Barbados Tourism Investment INC.: https://www.barbadostourisminvestment.com/tourism-profile/

CAPRA. (n.d.). *CAPRA*. Retrieved from Probabilistic Risk Assessment: www.ecapra.org

Castaño-Isaza, J., Newball, R., Roach, B., & Lau, W. (2015). Valuing beaches to develop payment for ecosystem services schemes in Colombia's Seaflower marine protected area. *Ecosystem services*, 22-31.

CIA. (2020). *The World Factbook*. Retrieved from Barbados: https://www.cia.gov/library/publications/the-world-factbook/geos/bb.html

EU Science Hub. (2019). *European Commission’s Science and Knowledge Service*. Retrieved from https://ec.europa.eu/jrc/en

Evelpidou, N., Karkani, A., Polidorou, M., & Kotinas, V. (2018). *Coastal Erosion.*

FEMA. (2005). *Coastal Flood Hazard Analysis and Mapping for the Pacific Coast of the United States.* Oakland.

Fitton, J., Hansom, J., & Rennie, A. (2016). *A national coastal erosion susceptibility model for Scotland.*

Gopalakrishnan, S., Smith, M. D., Slott, J. M., & Murray, A. B. (2011). The vlaue of dissappearing beaches: A hecodin pricing model with endogenous beach width. *Journal of Environmental Economics and Managment*, 297-310.

Haites, E. (2002). *Assessment of the Economic Impact of Climate Change in CARICOM Countries.*

IPCC. (2012). *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change.* Cambridge: Cambridge University Press.

IPCC. (2013). *IPCC Fifth Assessment Report.* Noruega: Cambridge University Press.

Kobayashi, N., & Hooyoung, J. (2012). Beach erosion and recovery. *Journal of Waterway, Port, Coastal and Ocean Engineering*, 473-483.

Kriebel, D., & Dean, R. (1993). *Convolution Method for Time-Dependent Beach-Profile Response.* ASCE.

Mycoo, M., & Chadwick, A. (2012). *Adaptation to climate change: the coastal zone of Barbados.* Institution of Civil Engineers Publishing.

Narra, P., Coelho, C., & Sancho, F. (2019). *Multicriteria GIS-based estimation of coastal erosion risk: Implementation to Aveiro sandy coast, Portugal.*

NASA. (2014). *Shuttle Radar Topogtaphy Mission Data*. Retrieved from https://www2.jpl.nasa.gov/srtm/

National Oceanic and Atmospheric Administration. (2020). *WAVEWATCH III Model*. Retrieved from National Weather Service, Environmental Modeling Center: https://polar.ncep.noaa.gov/waves/wavewatch/

NCAR. (2017). *Impact of Climate Change on Gulf of Mexico Hurricanes.* Boulder: NCAR.

Nehra, V. (2016). *A Study of CoastalErosion& Its Causes, Effectsand Control Strategies.* International Journal of Research and Scientific Innovation.

NOAA. (2019, Febrero). *National Oceanic Atmospheric Administration of the U.S Department of Commerce*. Retrieved from https://www.noaa.gov/

Parkinson, R., & Ogurcak, D. (2018). *Beach nourishment is not a sustainable strategy to mitigate climate change.* Miami.

Pendleton, L., Mohn, C., Vaughn, R. K., King , P., & Zoulas, J. G. (2012). Size matters: The economic value of beach Erosion and Nourishment in Southern California. *Contemporary Economic Policy*, 223-237.

Perrette, M., Laundered, F., Riva, R., Frieler, K., & Meinshausen, M. (2013). A scaling approach to project regional sea level rise and its uncertainties. *Earth Syst. Dynam.*, 4: 11-29.

Ranasinghe, R., Callaghan, D., & Roelvink, D. (2013). DOES A MORE SOPHISTICATED STORM EROSION MODEL IMPROVE PROBABILISTIC? *Coastal Dynamics*.

Rangel-Buitrago, N., & Anfuso, G. (2015). *Risk assessment of storm in coastal zones: Case studies from Cartagena (Colombia) and Cadiz (Spain).*

Rosen, S. (1974). Hedonic Prices and Implicit Markets: Product differentiation un pure competition. *The University of Chicago Press Table*, 34-55.

Schoonees, T., Gijón Mancheño, A., Scheres, B., Bouma, T. J., Silva, R., Schurlmann, T., & Schuttrumpf, H. (2019). Hard structures for Coastal Protection, Towards Greener Designs. *Jorunal of the Coastal and Estuarine Research Federation*.

Schuhmann, P. W., Bass, B. E., Casey, J. F., & Gill, D. A. (2016). Visitor preferences and willingness to pay for coastal attributes in Barbados. *Ocean and Coastal Managment*, 34-55.

Sea Grant. (2015). *Coastal Processes and Causes of Shoreline Erosion and Accretion.* Newark: Sea Grant.

Silva, R., Chávez, V., Boum, T. J., van Tussenbroek, B., Arkema, K. K., Martínez, M. L., . . . Pereira, P. (2019). The Incorporation of Biophysical and Social Components in Coastal Management. *Estuaries and Coasts.*, 1695-1708.

Silva, R., Mendoza, E., Mariño-Tapia, I., Martínez, M. L., & Escalante, E. (2016). An artificial reef improves coastal protection and provides a base. *Journal of Coastal Research*.

Silva, R., Ruis, G., Mariño-Tapia, I., Posada, G., Mendoza, E., & Escalante, E. (2012). Manmade Vulnerability of the Cancun Beach System: The Case of Hurricane Wima. *CLEAN - Soil, Air & Water*.

Simpson, M. C., Scott, D., Harrison, M., Sim, R., Silver, N., O'Keeffe, E., & McSharry, P. (2010). *Quantification and magnitude of losses and damages resulting from the impacts of climate change: modelling the transformationl impacts and costs of sea level rise in the Caribbean.* Barbados.

Stronkhorst, J., Huisman, B., Giardino, A., Santinelli, G., & Duarte, F. (2017). Sand nourishment strategies to mitigate coastal erosion and sea level rise at the coasts of Holland (The Netherlands) and Aveiro (Portugal) in the 21st century. *Ocean and Coastal Managment*.

Thin, N., Thanh, N., Tuyen, L. T., & Hens, L. (2019). Torusim and beach erosion: valuing the damage of beach erosion for tourism in the Hoi An World Heritage site, Vietnam. *Environment, Development and Sustainability*, 2113-2124.

Uyarra, M. C., Cote, I. M., Gill, J. A., Tinch, R., Viner , D., & Watkinson, A. R. (2005). Island-specific preferences of tourists for environmental features: Implications of climate change for tourism-dependent states. *Environmental Conservation*, 11-19.

Vacher, L., & Quinn, T. (2004). *Geology and hydrogeology of carbonate islands.* Tampa : Elsevier.

World Bank. (2021, June). *GDP (US$ to current prices) - Barbados*. Retrieved from https://datos.bancomundial.org/indicador/NY.GDP.MKTP.CD?locations=BB

WTTC & Oxford Economics. (2020). *Travel & Tourism Economic Impact Research.*

Yamin, L. E., Hurtado, A. I., Barbat , A. H., & Cardona, O. D. (2014). Seismic and wind vulnerability assessment for the GAR-13 global risk assessment. *International Journal of Disaster Risk Reduction*, 452-460.

Yamin, L. E., Hurtado, A. I., Rincón, R., Dorado, J. F., & Reyes, J. C. (2017). Probabilistic seismic vulnerability assessment of buildings in terms of economic losses. *Engineering Structures*, 308-323.

Yamin, L., Ghesquiere, F., Cardona, O. D., & Ordaz, M. (2013). *Modelación probabilista para la gestión del riesgo de desastres.* Bogotá: Banco Mundial.