Disaster Risk Profile for The Bahamas

Environment, Rural Development and Disaster Risk Management

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* This public report does not include Annexes; please contact the IDB project members if further information is needed.

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EXECUTIVE SUMMARY

The Country Disaster Risk Profile for The Bahamas presents three study modules: the Probabilistic Hazard Assessment, the Exposure and Vulnerability Assessment, and the Disaster Risk Assessment for the country.

Probabilistic Hazard Assessment

The Probabilistic Hazard Assessment aims to quantify the magnitude of key target hazards in terms of the following return periods: 10, 50, 100, and 500 years at two spatial scales: national and local (at three local sites). Additionally, the impacts of climate change on the target hazards have been analyzed.

The selected hazards for this study in The Bahamas are:

- Tropical Cyclone (TC), including the effects of wind, precipitation, and storm surge at the national scale (the whole territory of The Bahamas).
- Coastal floods and coastal erosion in three local study areas: 1) the south coast of Grand Bahama, 2) the east coast of Andros and 3) a 17 km stretch along the east coast of Long Island (from Gray's settlement to Scrub Hill).

In this study, of all the meteorological, atmospheric, and oceanic phenomena (wind, waves, and changes in atmospheric pressure, storm surge, precipitation, flooding and coastal erosion) only **wind**, **coastal flooding and erosion** are considered as the focus of the hazards that have the potential to cause some negative socioeconomic impact. Particularly, storm surge and rainfall are considered drivers of coastal flooding and storm surges and waves are drivers of coastal erosion.

Even in The Bahamas, although Tropical Cyclones (TC) are prone to country, the number of TC events in the available historical records is limited, to consistently estimate an accurate return period of probable hazard variables. Therefore, the first step in the proposed methodology is developing of a **synthetic TC database** populated with thousands of events. This database comprises 115 events from the 125- year historical record of The Bahamas and 3,500 synthetic events in 5,000 simulated years (including TCs of category 2 and higher).

For each tropical cyclone in the database developed, representative variables for atmospheric and marine dynamics were numerically simulated, including **sea level pressure (SLP), wind**

fields, rain, waves, and storm surges. These dynamics were then used as inputs for the flood and erosion models to estimate **coastal flooding and erosion.**

This model, supported with a large number of events, finally enabled the development of a probabilistic hazard assessment (expressed as maps) as follows:

- **Hurricane winds in The Bahamas (national scale).** The results show that the northern (e.g., Abaco Island and Grand Bahama) and southern (e.g., Crooked Island) islands of The Bahamas would experience more intense winds than the central islands. At the same time, western central islands (e.g., Andros, Exuma), located on the archipelago's leeward side, would receive winds with lower speeds. Averaged one in 10-year wind speeds would range from 50 km/h to 100 km/h, whereas with one in 500-year winds, average wind speeds would range from 180 km/h to 280 km/h.
- **Coastal flooding in The Bahamas (national scale) and additional detailed analysis in Grand Bahama, Andros, and Long Island.** The results in **Grand Bahama** show more intense floods on the northern coast. On the southern coast, and the central part of the island is less affected than the rest. On the southern coast of Grand Bahama (local study site), some areas (i.e., around the city of Freeport) would not be flooded at all, even with a one in 500-year return period. In **Andros**, more serious coastal floods occur on the west side of the island. On the eastern coast (local study site) only scattered locations in Central Andros and along the southern boundary of South Andros are expected to be flooded in a one in 10-year return period. Large areas of the eastern coast would not be flooded even with a one in 500-year return period, except for some specific areas. Coastal flooding would be infrequent in the study area of **Long Island** (17 km from Gray's settlement to Scrub Hill), even for a one in 500-year return period, except for some minor flooding. On the contrary, a considerable extension of the western coast of Long Island is expected to be flooded at least once with a one in 10-year return period.
- **Coastal Erosion in Grand Bahama, Andros, and Long Island.** In **Grand Bahama**, the results show higher erosions in the central part of the island, reaching shoreline recessions of less than 10 m with a one in 10-year return period, but more than 20 m with a one in 100-year return period at three hotspots between the Fortune and Gold Rock Beaches. According to the 500-year erosion assessment, a recession over 15m would be generalized in the central part of the island. In **Andros**, overall, erosion is less relevant than in Grand Bahama reaching shoreline recessions of less than 5m with a one in 10 year return period and less than 12m for a one in 500 year scenario. The results show

shoreline recessions would be seen up to 17m, once in a 500-year return period, only around Kemp's Bay in South Andros. In **Long Island**, the results show some coastal recession would be seen only on the northern boundary of this the coastal stretch under study because most of the study area is rocky.

- **Storms in Grand Bahama, Andros, and Long Island.** The result shows Grand Bahama, Andros, and Long Island would experience a significant major **collapse of vertical seawalls at the back of beaches, rip-rap revetments, groins, and jetties**. In **Grand Bahama**, the 10-year return period map shows the collapse of vertical seawalls in only one coastal area (or a cell in the map), whereas the 500-year return period map shows seawall collapse in several locations along with Freeport, the West end, and the eastern boundary of West Grand Bahama. The 10-year return period map shows the collapse of rip-rap revetments, groins, and jetties in several locations along Freeport, and the 500-year return period map shows a significant collapse of coastal structures along the coast of the central part of the island. In **Andros**, the 10-year return period map shows no collapse of structures, and the 500-year return period map shows the collapse of both seawalls and coastal structures in only two coastal cells. There are no coastal structures in the local study area of **Long Island**.

As for the impacts of **climate change** on tropical cyclone activity (intensity or frequency), according to the Intergovernmental Panel for Climate Change (IPCC), the evidence is not conclusive, and therefore wind hazard has been characterized only for the current situation. Nevertheless, coastal flooding and erosion maps have been obtained for the current situation and the 2050 horizon year under the most pessimistic and up-to-date scenario, which yields a projection for sea-level rise in The Bahamas of approximately 291 mm. As for the obtained results for the **impacts of climate change on coastal flooding**, Freeport shows the largest increase in flooded areas (in %), particularly for the 100-year return period. Notwithstanding, the total extent of flooding in Freeport is very limited with less than 3 km^2 of flooded areas experienced with a one in 500-year return period, including the impacts of climate change. The three study islands, Grand Bahama, Andros, and Long Island show increases of flooded areas for the 2050 horizon year that range between 3% and 15.8%, with higher values for the lower return periods. At the national scale, increases in the total flooded area for the horizon year range between 6% and 13.3%. The results show that **the impacts of climate change on the loss of dry beach area** are more severe for lower return periods. For example, in view of the results for the 10-year return period, Grand Bahama is the most affected of the three local study sites with an increase of total dry

beach area of more than 80% for the 2050 horizon year. West Grand Bahama is particularly affected by an overall increase of eroded dry beach area across the 2050 horizon year that doubles the current eroded dry beach area. On the other hand, results show that Andros is less affected by climate change with a less than 30% increase in the total dry beach area. Regarding the higher return periods, all three areas show similar increases of the eroded dry beach area with values ranging from 4.3% in Grand Bahama to 9.1% in Long Island and 5.1% in Andros. Finally, **impacts of climate change on coastal structures** reveal an overall net increase in the total length of potentially collapsed coastal structures between 400 and 4000 linear meters in the three study areas. At the district level, there are even negative values which correspond to the fact that scour in front of seawalls may be reduced due to the rise of mean sea level as the capacity of waves to mobilize sediment decreases due to deeper seafloors.

The accuracy of the obtained results is conditioned by the low resolution of the available Digital Elevation Model (DEM) used for this study (90m x 90m). Only major features are properly described in the modeling exercise, which affects the hydraulic connectivity in the flood model and leads to a stationary estimation of coastal flooding. Also, the extent of the local study sites (hundreds of kilometers) conditions the erosion assessment resolution based on study units (coastal cells) of circa 1 km of alongshore length. Finally, the scarcity of measurements for a proper quantitative model validation limits the obtained results' accuracy.

Exposure and Vulnerability Assessment

The spatial distribution of exposed assets and residents in The Bahamas was calculated by collating available information from existing sources and downscaling the data to the spatial definition required for the project. As a result, a three-level characterization of the country was obtained. First, a high concentration of physical elements and residents is observed in New Providence, where 70% of the population resides. Second, a low-density distribution of exposed elements and socioeconomic activities covering most of the islands can be observed, and finally, some areas were observed where no human activities exist. Therefore, the results obtained are heavily conditioned by the impact on Nassau and New Providence.

The exposure and vulnerability assessment was conducted first at the national scale; then, a detailed analysis was presented to identify the three study islands' exposure to different hazards.

The vulnerability functions were defined using existing collections from the available literature. These available vulnerability functions were finally calibrated for the specific characteristics of the project sites.

A set of representative vulnerability functions was then used in the risk assessment.

Disaster Risk Assessment

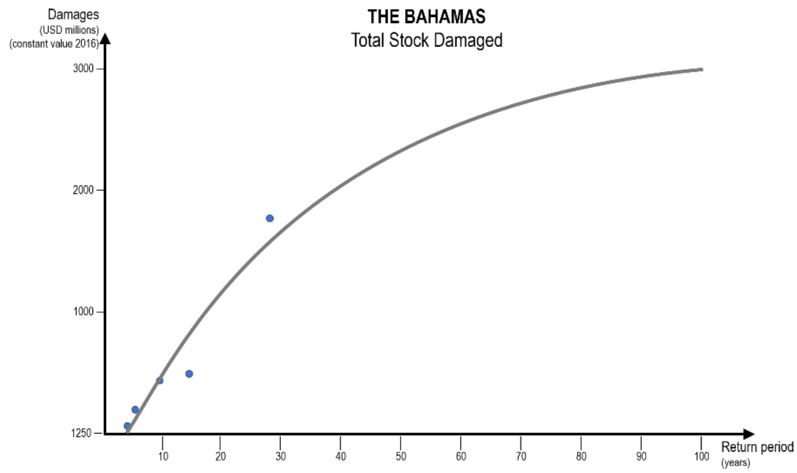
There is a long history of the hurricane and tropical storm (TC) activities in The Bahamas, and hence numerous and detailed series of historical losses assessments exist. However, the existing evidence is limited to develop a probabilistic risk assessment in the long term, considering the climate change negative effect. On the one hand, the existing damage and loss assessment are not sufficiently recorded per sector and island. The characteristics of the society (e.g., populations) has also changed in recent decades and will be changing in the future.

There are additional limitations of the existing damage and loss assessments in The Bahamas, including the influence of hurricanes at the local level, the lack of representative samples of events, and the short length of the series registered.

Under these limitations, the available information was filtered to extract the subset of data truly representative of the present risk level, focusing on recent experiences and detailed ex-post analyses of impacts. Additionally, the economic data was homogenized to avoid monetary disturbances. In this sense, this study incorporated the four past hurricane damage and loss assessments: Hurricane Matthew (2016), Hurricane Joaquin (2015), Hurricane Frances (2004), and Hurricane Andrew (1992).

The ex-ante probability of occurrence associated with each selected historical hurricane was estimated as the observed relative frequency of similar events in terms of both trajectories and intensities among dozens of historical data and thousands of synthetic TCs in the database developed by means of the Hazard Assessment. Combining the observed damages and the estimated return periods for the selected historical events generates the Historical Loss Exceedance Curve (Figure 1).

Figure 1. Historical Damage Exceedance Curve for Hurricanes in The Bahamas

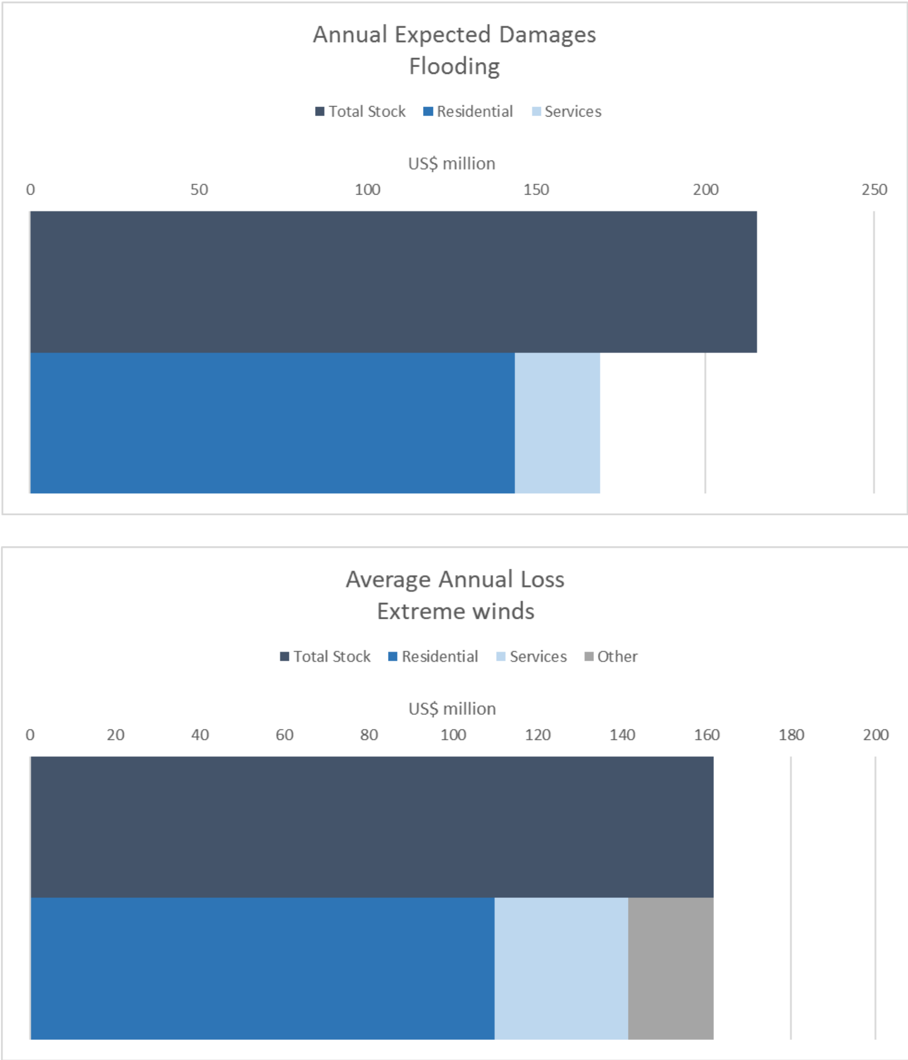


A probabilistic disaster risk estimation of the Bahamian society has been developed by combining different expected damage scenarios derived from coastal flooding and extreme winds events associated with different occurrence probabilities. These damage scenarios include the probable maximum losses (PML) and the average annual losses (AAL), both for population, capital stock, and road networks.

Estimated results show that more than 4,000 people are expected to be affected by coastal flooding every year. More than 9,000 are expected to be affected by extreme winds every year. These represent less than 3% of the total population of The Bahamas.

Regarding damages to stock, coastal flooding is expected to cause more than US$200 million in damages every year (less than 0.5% over total value), including US$140 million in residential stock and about US$25 million in services stock (Figure 2). Extreme winds are expected to damage more than US$160 million/year. About 250km of the road network (including all road categories and streets) with an estimated value of US$159 million have the potential to be damaged by coastal flood every year.

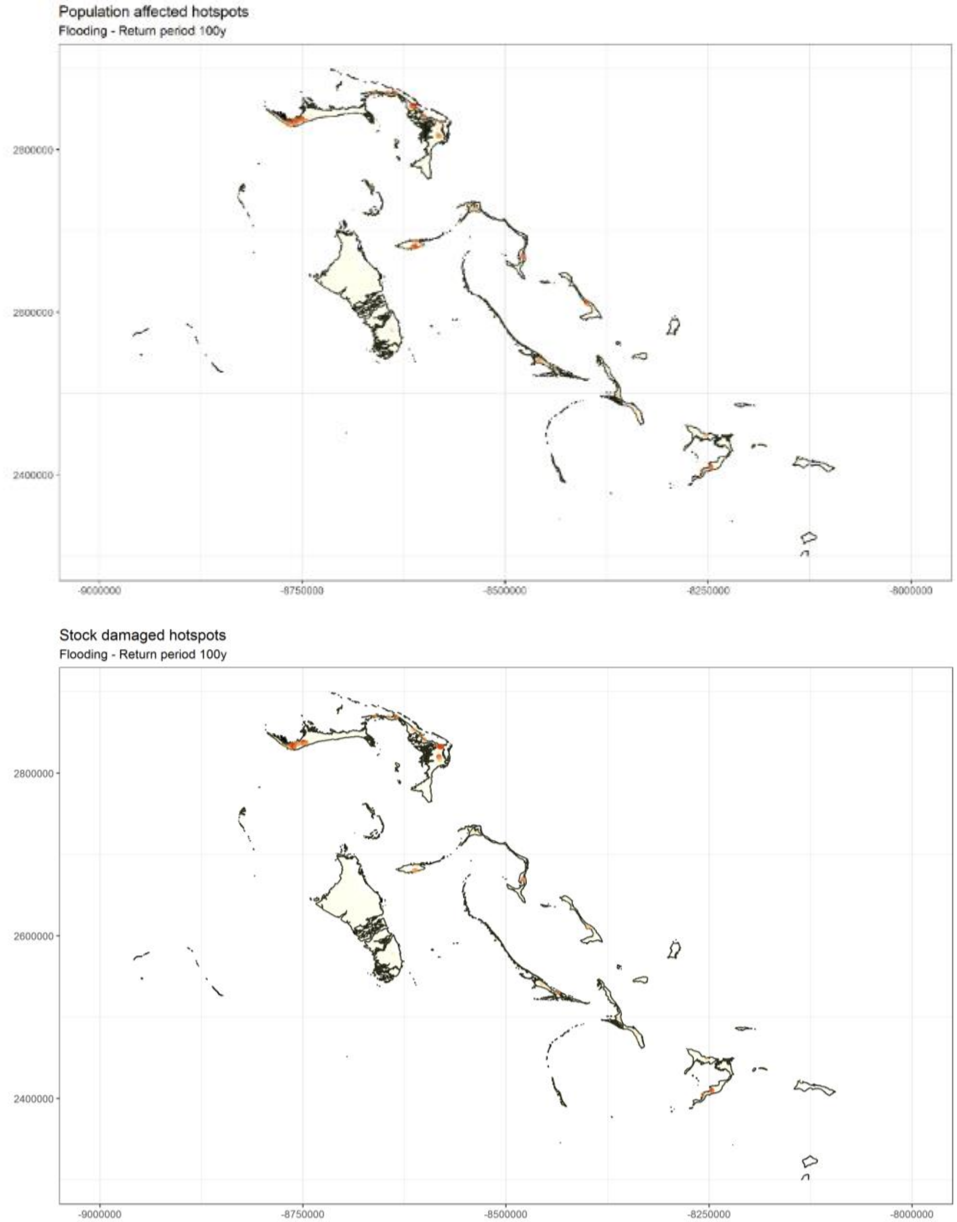
Figure 2. Average Annual Loss (Flooding and Extreme Wind)



Source: Self elaborated.

The most hazard exposed islands to be impacted by coastal flooding, are Central Abaco, West Grand Bahama, Long Island, Exuma, North Abaco and Acklins (Figure 3). New Providence is the most hazard exposed island to be impacted by hurricane winds, because of the concentration of assets and population on this island.

Figure 3. Affected Population and Stock Damage Hotspots

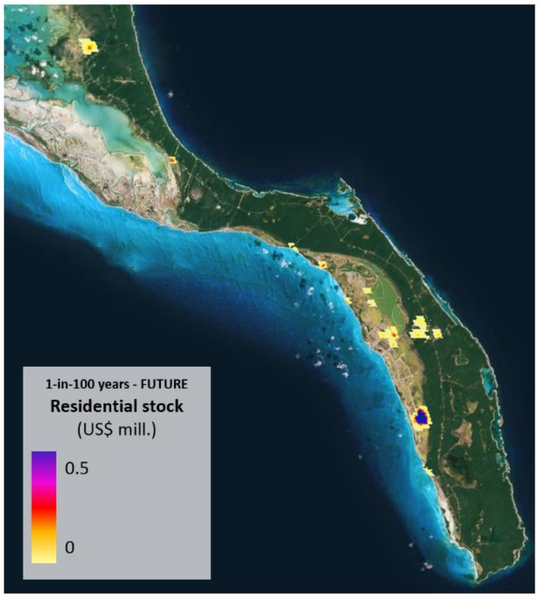


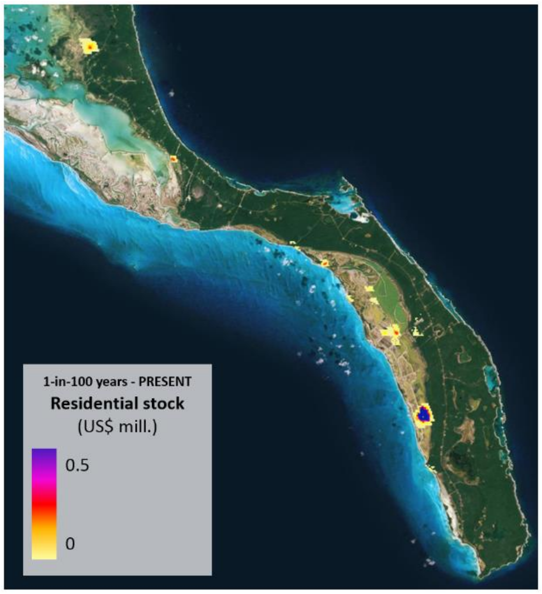
Source: Self elaborated. *The results show strong increase rates in the affected population (120%), capital stock (135%) and infrastructure (180%). The results at local sites show higher absolute increases in Grand Bahama (+US$15 million in damages on capital stock) and higher relative growth rates in Andros (449% growth in affected population) and with a lower level on Long Island (274 % growth in infrastructure).*

Climate change additional impact

The impact of climate change associated with a Representative Concentration Pathway (RCP) 8.5 projection has been examined in this study for a 2050 horizon year. The Sea Level Rise (SLR) considered according to IPCC predictions and downscaling in The Bahamas is 291mm. (Church et al., 2013). As an example, Figure 4 shows the comparison in damaged residential stock for Long Island.

Figure 4. Comparison of Damaged Residential Stock for Long Island





Source: Self elaborated.

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GLOSSARY[1]

Atmospheric Hazard Drivers: Atmospheric dynamics governing the occurrence of a natural hazard. In this study wind, sea level atmospheric pressure and precipitation under tropical cyclones.

Capital Stock: A category of elements available for a society that contribute to its wealth flows. Typically associated to physical capital (human built) include several subcategories as residential, industrial, services or infrastructures according with the characteristics of flows provided.

Coastal Recession: The horizontal loss or displacement of land, sediment and/or rocks along the coastline due to the action of waves, currents, tides, wind-driven water, or other impacts of storms.

Damage Function:

Economic assets: Any human made element contributing to economic activity. It is included in the general category of capital elements and frequently confronted with natural assets (non-built). As they are supposed to deserve an income, they can be accounted either through their build cost or the discounted sum of their contribution to income (rents).

Exposure: Magnitude used to characterize the elements of a society (human, assets or activities) that make them susceptible of being damaged by an event associated with a given probability. It is one of the basic components of risk and therefore one of the main sources of risk for a society.

Hazard: A process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption, or environmental degradation (UINSDR, 2016)[2].

Income: Retribution obtained by any agent participating in the economic activity as a reward for his contribution. It typically expresses the flow of economic wealth annually generated in a community as a whole or averaged per person.

Infrastructure: Set of elements include in the category of **Capital Stock** that provide the basic support for the activities of a community. The concept historically focused physical elements on basic supplies energy and transport elements (publicly supplied), but has expanded to include

[1] See https://www.undrr.org/terminology

[2] In this study wind, sea level atmospheric pressure and precipitation under tropical cyclones.

social support activities as health, education and social safeguard, and social structures that conform societies.

Losses: Economic negative consequences derived from the impact of an event on the society. It generally includes damages on assets to be recovered by repairing or substituting, and non-recovery losses due to activities disruption.

Met-Ocean Hazard Drivers: Marine and coastal dynamics governing the occurrence of a natural hazard. In this study storm surge and waves.

Probabilistic Hazard: Stochastic or non-deterministic hazard that is analyzed statistically by means of its probability distribution.

Return Period: The probability of an occurrence of a given hazard event. It gives the estimated time interval between events of a similar size or intensity. For example, if the return period of a flood is 100 years, his does not mean that this event only occurs every 100 years, it means that, in any given year, there is a 1% chance that an event of a similar intensity/size will happen. Conversely, events with lower return periods (e.g., 10 years), have a higher likelihood (i.e., 10%) of occurrence each year (or similar/size intensity). Please note that an event with an estimated with return period can still happen more than once in any given year and this statistical function only identifies the that the likelihood/probability of the said event occurring within a given timeframe.

Risk: Is a characteristic of the situation under which an individual or society develops its activities. It is quantified through a magnitude of the probability of a range of damages eventually suffered by a society due to the action of hazardous events of different probabilities. Three basic components of risk are used to give visibility to its basic sources: Hazard (summarizing the potential threatening events), Exposure (summarizing the elements at risk), and Vulnerability (summarizing the capacity of the threats to damage the elements),

Tropical cyclone track: Path followed by the center of a tropical cyclone.

Vulnerability: Characteristic of an element or set of elements, that express the expected affection derived from the action of a category of events, showing the range of variation of the effects on the element under different events intensities. It is typically formulated as a transfer function showing the degree of damage for each specific hazardous event intensity.

ACRONYMS

AAL	Average Annual Losses
ADCIRC	Advanced 3D Circulation Model
AN	Andros Island
D50	Mean sand grain size
DEM	Digital Elevation Model
DTM	Digital Terrain Model
ESA	European Space Agency
GB	Grand Bahama
GDP	Gross Domestic Product
GEBCO	The General Bathymetric Chart of the Oceans
GHCN	Global Historical Climatology Network
IBTrACS	Best Track Archive for Climate Stewardship
IDB	The Inter-American Development Bank
IHCantabria	The Environmental Hydraulic Institute "IH Cantabria"
IPCC	Intergovernmental Panel on Climate Change
LI	Long Island
MetOffice	Department of Meteorology of the Ministry of Environment and Housing - Government. of The Bahamas
MSL	Mean Sea Level
NOAA	National Ocean and Atmospheric Administration
PDI	Power Dissipation Index
POT	Peaks Over Threshold
RCP	Representative Concentration Pathway
RFSM-EDA	Rapid Flood Spreading Diffusion Method-wave Explicit with Acceleration term
RP	Return Period
SLP	Sea Level Pressure
SLR	Sea Level Rise
SST	Sea Surface Temperature
SWAN	Simulating Waves Nearshore Model
TC	Tropical Cyclone (TCs: plural)
TRMM	Tropical Rainfall Measuring Mission (NOAA)
TRR	Tropical Rainfall Rates
XBEACH	eXtreme Beach Behavior Model

INTRODUCTION

1.1. Background

The Bahamas has an area of approximately 0.5 million square miles with more than 700 islands and cays. Its location in the Atlantic between latitudes 20° and 28°N and longitudes 72° and 80°W (North of Cuba and Haiti and East of Florida) makes the country prone to be struck by hurricanes more frequently than any other area in the Caribbean. All Bahamian islands are low lying with ridges that rarely get over 15 to 20 m, which makes the archipelago particularly vulnerable to the impacts of hurricanes and tropical storms. Climate change, and specifically sea level rise, will exacerbate these impacts in the near future.

The general goal of this study is to obtain a better understanding of the risk that The Bahamas faces from the following natural hazards:

- **Hurricane hazards**, namely: wind, precipitation, and storm surge at national scale.
- **Coastal floods triggered by hurricanes,** and **coastal erosion** in three local study areas.

The study additionally includes the analysis of increasing hazardous risk due to climate change.

The specific objective of the study is the estimation of the magnitude of risk, understood as infrastructure damage, economic losses, and human/social impacts due to hazard events for several development sectors and geographic areas and for various return periods. To do this, the study focuses on the development of a hybrid losses exceedance curve which integrates to the risk profile i) an empirical risk analysis based on the Historical Disaster Loss Assessment and ii) an estimation of the potential risk based on the probabilistic risk assessment.

1.2. Study area

This study addresses two different geographical scopes - national scale and three local study areas:

National scale (whole country).

Figure 5. Location of the Three Target Islands at Local Scale

Source: Self-elaborated

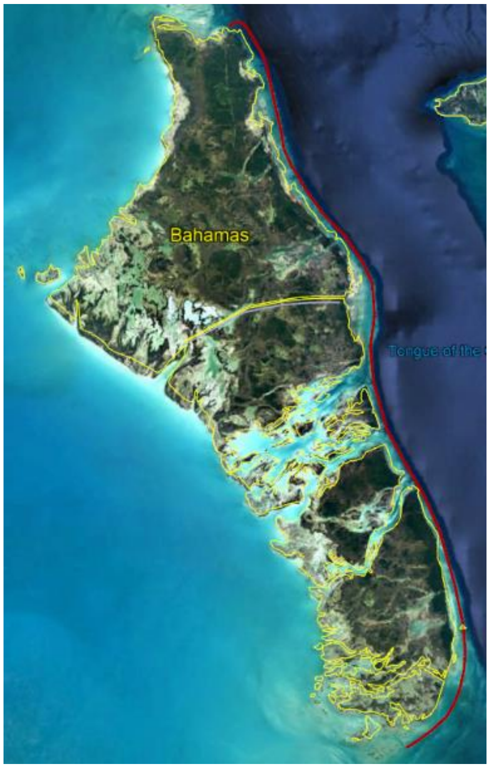
1. **Three local study areas** located in three different islands (see also Figure 5)
   - Study site 1: A coastal stretch of circa 133 Km along the south coast of **Grand Bahama**, including Freeport, from West End to the east end (red polygon in Figure 6).

Figure 6. Study Site 1 - East Grand Bahama

Source: Self-elaborated.

- Study site 2: A coastal stretch of circa 192 km along the east coast of **Andros** from Pleasant Harbor on the north to Jackfish Channel on the south (red polygon in Figure 7).

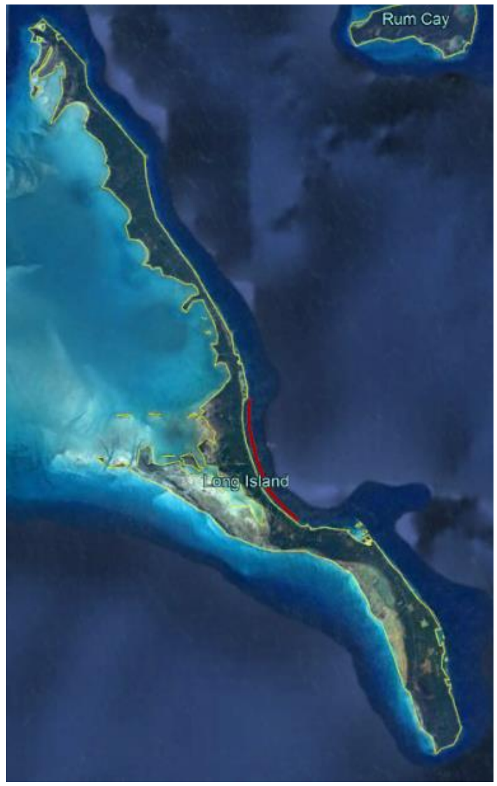
Figure 7. Study Site 2 - Andros



Source: Self-elaborated.

- Study site 3: A coastal stretch of circa 17 km along the east coast of **Long Island** from Gray's settlement to Scrub Hill (red polygon in Figure 8).

Figure 8. Study Site 3 - Central Long Island



Source: Self-elaborated.

1.3. Organization of the report

This study is organized into five chapters. The first chapter describes the background, project objectives, and the organization of this study. Chapter 2 clarifies the conceptual and methodological framework of the study. Chapter 3 focuses on the Hazard Assessment. It includes a description of the methodology used for the characterization of the selected hazards as the results of hurricanes (wind, rain and surge, flooding and erosion) associated with various return periods. Chapter 4 analyses Exposure and Vulnerability, and Chapter 5 focuses on Risk Assessment. Two annexes provide detailed information on the methodologies used for the characterization of the risk components, namely:

ANNEX 1: Probabilistic Hazard Assessment;

ANNEX 2: Historical Disaster Loss Assessment.

Note: This public report does not include these Annexes; please ask an IDB project member if necessary.

2. METHODOLOGY

2.1. Introduction

This chapter describes the conceptual framework for Risk Assessment. The global methodological approach for the entire study is presented including the workflow for risk estimation with an example.

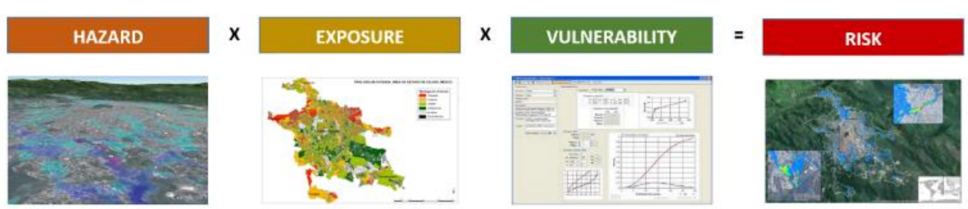
2.2. Conceptual framework

In this **Country Disaster Risk Profile for The Bahamas**, the term "disaster risk" refers to the infrastructure damage, economic losses, and human/social impacts due to hazard events. The magnitude of the risk is estimated for several development sectors and geographic areas for various return periods through the analysis of Probable Maximum Losses (PML), Average Annual Losses (AAL), and the development of a Hybrid Loss Exceedance Curve at the national level based on the methodology by UNISDR (2011), which integrates in the risk profile of i) an empirical constituent and ii) an analytical constituent.

The empirical constituent refers to the **Historical Disaster Loss Assessment** based on the collected experience of past catastrophic events in The Bahamas, whereas the analytical constituent is obtained from a **Probabilistic Risk Assessment** based on the concept of Risk as the combination of the probability of an eventual event and its negative consequences (UNISDR, 2009).

Specifically, in the probabilistic risk assessment approach, **Risk** is conceived as the probability of harmful consequences or expected losses resulting from a given hazard to a given element at risk over a specified period (Schneiderbauer et al., 2004). Therefore, **Probabilistic Risk is a function of probability of the occurrence of Hazard, Exposure of elements in study area, and their Vulnerability** (see Figure 9).

Figure 9. Conceptual Framework for the Probabilistic Risk



Source: Self-elaborated.

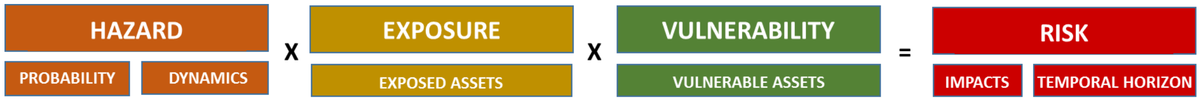
In this conceptual framework for the Probabilistic Risk Assessment, **Hazard** is defined as a process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption, or environmental degradation (UNISDR, 2016). A hazard is characterized by its location, intensity, frequency, probability of occurrence and duration. **Exposure** refers to people, property, systems, or other elements present in hazard zones that are thereby subject to potential losses (UNISDR, 2009). **Vulnerability** is related to the characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard (UNISDR, 2009). In probabilistic/quantitative risk assessments, the term vulnerability expresses the percentage of exposed elements that are likely to be damaged due to a specific hazard impact.

Further details regarding the conceptual framework for the Probabilistic Risk Assessment are given in the following section.

2.3. Extended Conceptual Framework for the Probabilistic Risk Assessment

In this section, several concepts related to the probabilistic hazard, exposure, and vulnerability as components of risk are described in detail, including their subcomponents (see Figure 10).

Figure 10. Extended Conceptual Framework of Probabilistic Risk



Source: Self-elaborated.

The **<u>Hazard</u>** Assessment includes the analysis of potentially damaging physical events under study, which will be based on their location, intensity, frequency and duration. To analyze these hazards, it is necessary to calculate the **dynamics** that originate from these damaging events and the associated **probability of occurrence**. The effect of climate change on these variables needs to be addressed, if applicable.

The **<u>Exposure</u>** Assessment includes the identification and characterization of the **exposed assets**. The most relevant variables related to exposure are population density, building classification by type of construction and critical infrastructures catalogue. To do this, an inventory of exposed assets is developed, based on official cadastral available information and observations of satellite imagery, as well as its interpretation. In the case of immovable properties,

the construction area, the value of the assets (buildings and estimated domestic contents) and their location are estimated.

The **Vulnerability** Assessment of the exposed elements includes the study of the degree of impacts that the hazard can generate in the exposed elements, being an intrinsic quality of the system and function of the natural characteristics of these elements. It also addresses the threshold from which the impact under study occurs. The vulnerability functions are based on various construction typologies or infrastructure identified of each target hazard, characterizing the ability of the building to withstand the considered event.

Finally, **Risk** estimation focusses on the negative consequences of the event, which are expressed in terms of potential human and economic **impacts** for a particular **temporal horizon** (current situation or a future scenario). These impacts will be based on the characteristics of the hazard and the vulnerability of the exposed elements.

2.4. Methodological approach

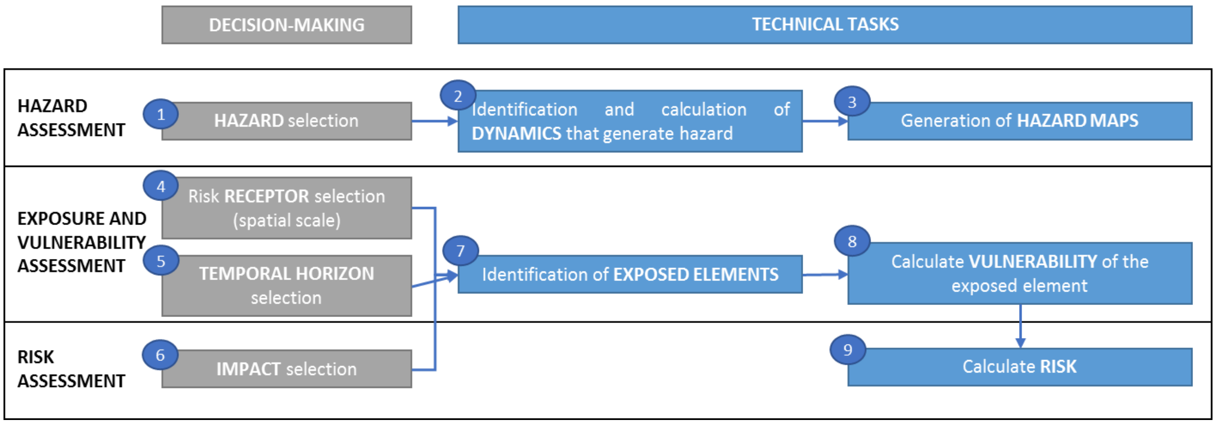
This section presents the methodology for the elaboration of the Probabilistic Hazard, Exposure and Vulnerability and Risk Assessment in The Bahamas. The workflow for risk calculation is described along with the list of the selected variables in this study related to risk components and subcomponents, according to the conceptual framework previously described. Finally, an example of risk calculation is included.

Given the number and complexity of the concepts defined in the previous section, it is necessary to raise a homogeneous way of expressing risk results. The specific question that this study aims to answer is as follows:

What is the RISK of an IMPACT by a HAZARD to a RECEPTOR in a TEMPORAL HORIZON for a RETURN PERIOD?

In order to calculate the risk of a particular impact due to a flooding (hazard) to a receptor in a temporal horizon for a given time period; Hazard, Exposure and Vulnerability information will be cross-checked, for that probability of occurrence and those conditions of location and time, taking into account the human and/or infrastructural dimensions. According to this question, the flowchart for risk assessment is shown in Figure 11.

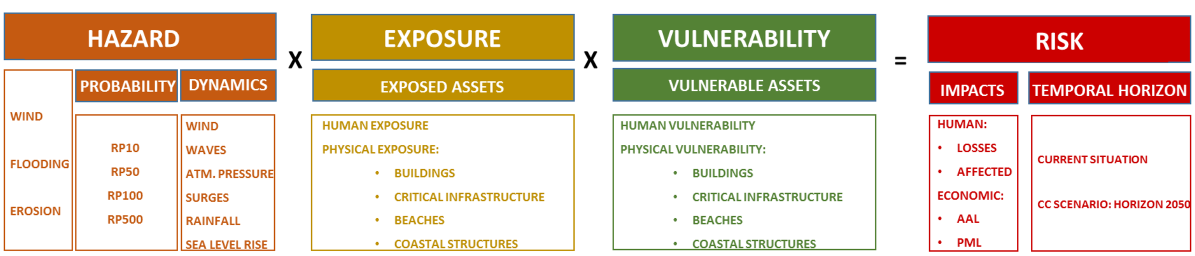
Figure 11. Risk Calculation Process



Source: Self-elaborated.

The selected hazards, dynamics and return periods for the Hazard Assessment, the Exposure and Vulnerability indicators and the selected impacts and temporal horizons for the Risk Assessment in this study, according to the presented conceptual framework, are schematized in Figure 12.

Figure 12. Risk Components and Sub-Components



Source: Self-elaborated.

The structure of the report corresponds directly with this workflow and further description of the methodological approaches for the calculation of each risk component and subcomponent are detailed in the following chapters of this report: Hazard Assessment in Chapter 3, Exposure and Vulnerability Assessment in Chapter 4, and Risk Assessment in Chapter 5.

2.4.1. Example of risk calculation

In this section, an example to illustrate the proposed methodological approach is described. The specific question raised in the previous section is described as an example:

Which is the PROBABLE MAXIMUM LOSS of SEAWALLS in Grand Bahama affected by COASTAL EROSION due to tropical cyclones under scenario RCP8.5 (AR5) for the horizon year 2050 and for a 500-YEAR RETURN PERIOD?

The following table shows each step of the workflow in 11 for this particular example.

Table 1. Risk Calculation Example

No.	STAGES	Example
1	**Hazard selection**	Coastal erosion
2	**Identification and calculation of dynamics that generate hazard**	Tropical cyclone (i.e., storm surge, waves), climate change projections for sea level rise, sediment transport modelling
3	**Generation of hazard maps**	Maps of 500-year return period scour
4	**Risk receptor selection (spatial scale)**	Grand Bahama (local scale)
5	**Temporal horizon selection**	2050
6	**Impact selection**	Economic impact
7	**Identification of exposed elements**	Exposed seawalls
8	**Calculation of vulnerability of the exposed element**	Scour threshold for failure of seawall foundation
9	**Risk estimation**	Probable maximum loss

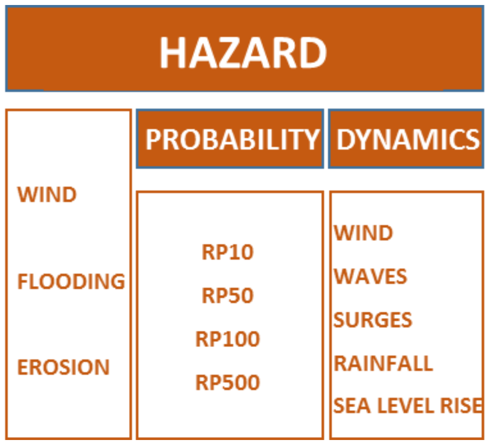
Source: Self-elaborated.

3. HAZARD ASSESSMENT

3.1. Introduction

Aligned with the conceptual framework described in Chapter 2, the aim of this chapter is to assess the probabilistic characterization (in terms of return periods: RPs) of the target hazards, i.e., wind, coastal flooding and erosion caused by hurricanes in The Bahamas, based on the characteristics of the corresponding dynamics of the hazard drivers (see Figure 13).

Figure 13. Hazard Selection and Return Periods for Hazard Assessment



Source: Self-elaborated.

This chapter is organized in 4 sections: an introduction, a brief description of all sources of information, the presentation of the methodology proposed for the hazard assessment and a summary of the obtained results, including a summary of the main findings. The chapter presents an overview of the analysis and modelling exercise undertaken for the Probabilistic Hazard Assessment, which is described in detail in Annex 1 (Hazard Assessment).

3.2. Sources of information

To obtain accurate results, the quality of the input data of the hazard assessment conditions was essential. These include collecting detailed information related to Tropical Cyclone (TC) tracks and physical characteristics of the area (topo-bathymetry, sediments, etc.). Furthermore, measured data was key for the calibration of the numerical models used in this study and validating of the final hazard profiles. Data were collected from August until December 2017 through the following activities:

- Gathering available information from global data sources such as space agencies, international organizations, and IDB and other archives;

- Gathering information from public sector stakeholders and other data providers in the Bahamas. In doing so, the first National Workshop (WS) was organized in Nassau on September 29, 2017. In this WS, stakeholders were consulted regarding data availability. After that, Met Office (as the Department of Meteorology of the Ministry of Environment and Housing - Government of The Bahamas), Waterkeepers (Non-Government Organization), and Overseas Marine Group LTD (private company) mainly provided the information necessary for the study (details on the information provided by each institution are detailed below in this very same section);
- A field survey was carried out from November 28 to December 1, 2017, along with West Grand Bahama's coast to collect additional data. The survey included the inspection of 20 sites where beach profiles were measured. Sediment size was estimated additionally, and evidence of coastal erosion and flooding were collected (see Annex 1. Hazard Assessment, for further details on this field survey).

Further details on the data collection activities can be found in Annex 1 (Hazard Assessment).

The collected data and information were used as input for this study summarized as follows:

- Information about historical tropical cyclones was obtained from the International **Best Track Archive for Climate Stewardship (IBTrACS)** v03r10 (Knapp et al., 2010) provided by NOAA. IBTrACS provides more than 400 events that have affected The Bahamas in the last 150 years, of which 115 have reached Category 2 or higher in the Saffir-Simpson hurricane scale.

Instrumental information available to assess, calibrate and validate the met-ocean hazard or hazard drivers to be addressed in this study (see Figure 14) was obtained as follows: meteorological records of wind speed and direction and rainfall were provided by the Met Office from six stations, rainfall records from the Global Historical Climatology Network (GHCN) provided by NOAA from six local stations in The Bahamas and NOAA wind and sea level records from a NOAA weather station and tide gauge at Settlement Point, West End, Grand Bahama.

Figure 14. Meteorological Stations (Data Collected for this Study)

Source: Self-elaborated.

- Several sources of information have been merged to obtain the best topo-bathymetry information possible that fully cover the national territory of The Bahamas, including the seabed surrounding all Bahamian islands: **The General Bathymetric Chart of the Oceans (GEBCO),** NOAA's digital **nautical charts** US2EC01M and US2EC02M, bathymetric data estimated from **satellite Sentinel-2A imagery**, the **SRTM MERIT Digital Elevation Model** (Yamazaki et al., 2017).

- **Measurements of beach profiles** from two different sources: monthly beach profiles from June 2017 to January 2018 in nine locations along the southern coast of Grand Bahama provided by Waterkeepers Bahamas and Save The Bays (field work and data assessment by Rashema Ingraham, Alec Nabb, Andurah Daxon and Richard Shepherd) and beach profiles in 15 locations along the coast of West Grand Bahama measured during a field survey from the 28th of November to the 1st of December 2017.

- **Shoreline evolution** based on rectified Google Earth Imagery, which has provided aerial views of several dates from the year 2000 until 2017. In addition, several satellite and conventional images have been collected including low resolution (30m) visible light satellite imagery from Landsat-5 and Sentinel-2 and historical pictures from the archives of Overseas marine group LTD and photographs from the field surveys conducted by the working team of this project.

- **Beach sediments** were analyzed through visual inspection of 10 beaches along with the Grand Bahama's southern coast, which allowed the estimation of the median diameter of the particle size distribution of beach sand (1 mm to 0.1 mm).

Further details on data collection campaigns and collected information can be found in Annex 1 (Hazard Assessment).

3.3. Methodology

3.3.1. Introduction

The probabilistic hazard analysis of this study aims to quantify the target hazards' potential magnitudes in terms of the following selected return periods: 10, 50, 100 and 500 years at two spatial scales: national and local (three local sites). In addition, the study analyzes the additional impacts of climate change on the target hazards.

In this section, a summary of the proposed methodology is described. First, the selection of hazards is presented, and the distinction between the hazard-derived risk and the dynamic risk that drive the current hazards is clarified. Next, the methodology for the probabilistic characterization of the atmospheric (including wind hazard) and marine dynamics associated to tropical cyclones along with the modelling of the consequent coastal flooding and erosion hazards is summarized.

3.3.2. Hazard selection

Tropical cyclones are rapidly rotating storm systems characterized by a low-pressure cell, a closed low-level atmospheric circulation, strong winds, and a spiral arrangement of thunderstorms that produce heavy rain (i.e., atmospheric phenomena). These severe atmospheric pressure changes and winds alter the sea surface causing large waves and storm surge (i.e., met-ocean phenomena), which generate actual coastal hazards such as coastal flooding and erosion (note that rain-driven flooding has not been included in this study). In this context, the distinction between hazards and dynamics (see both definitions in section 2.2) can cause confusion and needs to be clarified (see Figure 13). The selected hazards for this study in The Bahamas are:

- Tropical Cyclone (TC) hazards, including the effects of wind, precipitation and storm surge at the national scale (the whole territory of The Bahamas).

- Coastal floods and coastal erosion (driven only by marine dynamics) at three local study areas: 1) south coast of Grand Bahama, 2) east coast of Andros and 3) 17 km along the east coast of Long Island (from Gray's settlement to Scrub Hill).

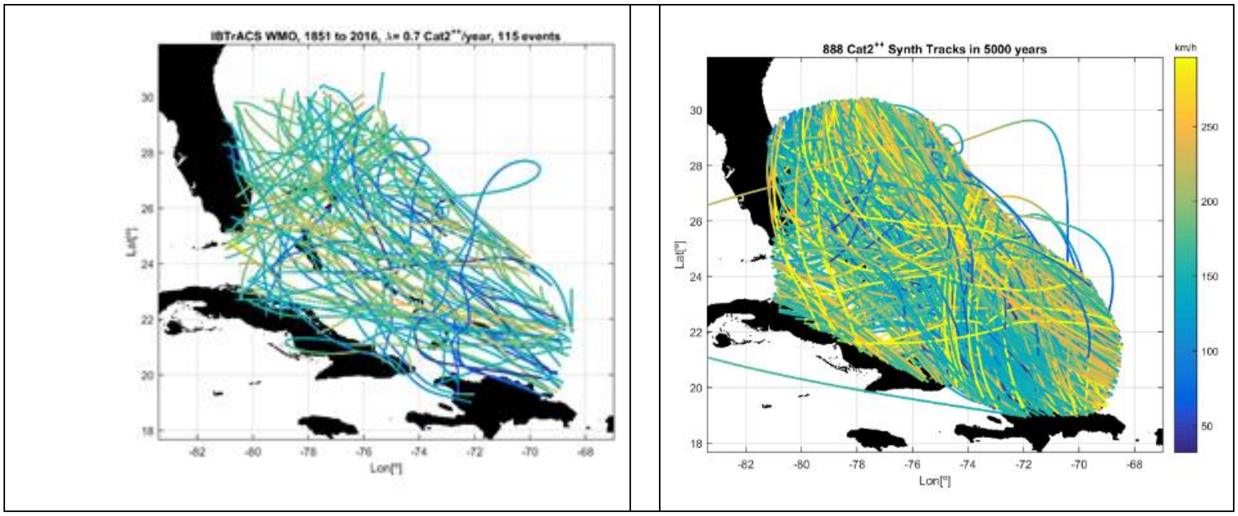
In this study, the following atmospheric or oceanic phenomena associated to the TC are considered as hazard drivers: wind, atmospheric pressure, rainfall, storm surge and waves. The following dynamics contribute to hazards that have the potential to cause some negative impacts are considered in this study: **wind**, **coastal flooding** (driven by storm surge and rainfall) and **coastal erosion** (driven by storm surge and waves). Annex 1 provides an extended explanation on hazards and dynamics (hazard drivers) in the framework of this study.

3.3.3. Methodology for the probabilistic characterization of hurricanes, coastal flooding and erosion

TCs produce extreme wind, waves and surges in coastal areas leading to coastal flooding and coastal erosion associated with severe impacts. However, even in TC-prone areas such as The Bahamas, the probability of occurrence is relatively low and therefore the number of registered historical tropical cyclones is limited, thus a larger sample of events is necessary in order to characterize statistically the occurrence of TCs in terms of likelihood/probability (e.g., probability of exceeding certain hazard thresholds or the intensity of the hazard induced by a TC of certain return period). Therefore, the first step of this study has been the elaboration of a **synthetic TC database** populated with thousands of events. Based on the available TC track information, a stochastic model based on the joint probability functions of the TC parameters (location of the cyclogenesis and minimum atmospheric pressure) and temporal correlations (Markov's chains) has been used to extend the historical TC record from 115 events (TCs of category 2 and higher) in the historical record of 150 years in The Bahamas (see left panel of Figure 15) to 3,500 in 5,000 simulated years (see details on the development of the synthetic TC database in Annex 1, Hazard Assessment). Although more than 5,700 synthetic TCs have been generated of all categories, a set of 888 TCs have been selected as representative of the whole dataset (see right panel of Figure 15) in order to avoid duplication: low intensity events (including category 1 TCs and tropical storms) and short duration events.

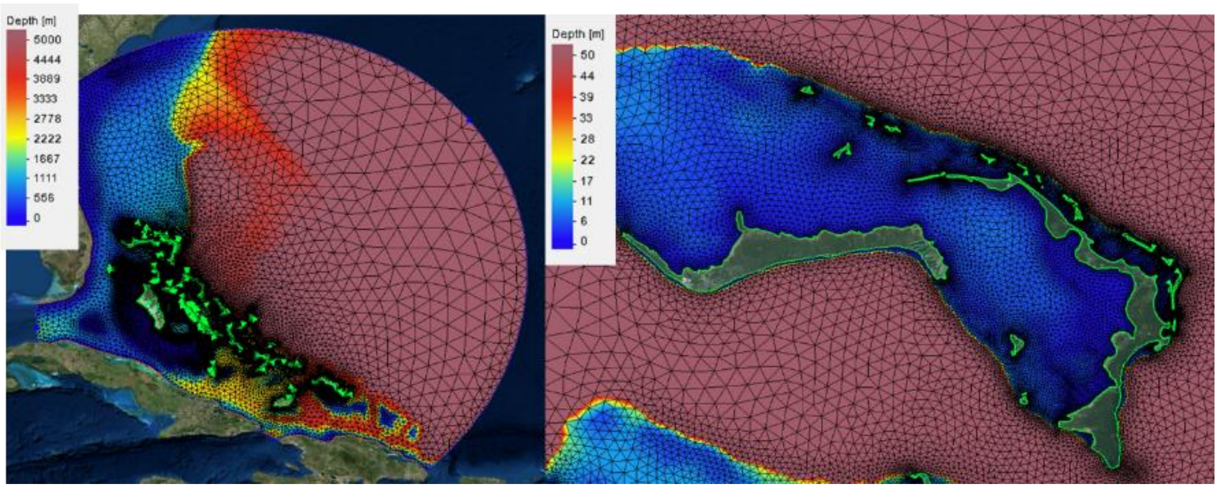
Figure 15. Historical and Synthetic Tracks of TCs in the Bahamas

Source: Self-elaborated. Synthetic tracks of TCs (left) and synthetic tracks generated for the study (right). Colors refer to wind speeds in km/h.



The second step of this study aims to obtain **sea level pressure (SLP)**, **wind** fields and **rain** patterns for each historical and synthetic TC in the database (more than 5,700 events) through three simple parametric models (see further details on the modelling of atmospheric dynamics associated to TC in Annex 1. Hazard Assessment): Emanuel and Rotunno, 2011 (wind); Holland, 1980 (sea level pressure) and Tuleya et al., 2007 (rainfall). The reconstructed TC wind and pressure fields have been used as forcing of **waves and surges** numerical models "ADCRIC+SWAN" (see a detailed description of the modelling of marine dynamics associated to TC in Annex 1, Hazard Assessment), which also takes into account coastal features (geometry and bathymetry). Waves and surges in the whole computational domain (see Figure 16) have been obtained for each of the 1,003 selected events (115 historic + 888 synthetic).

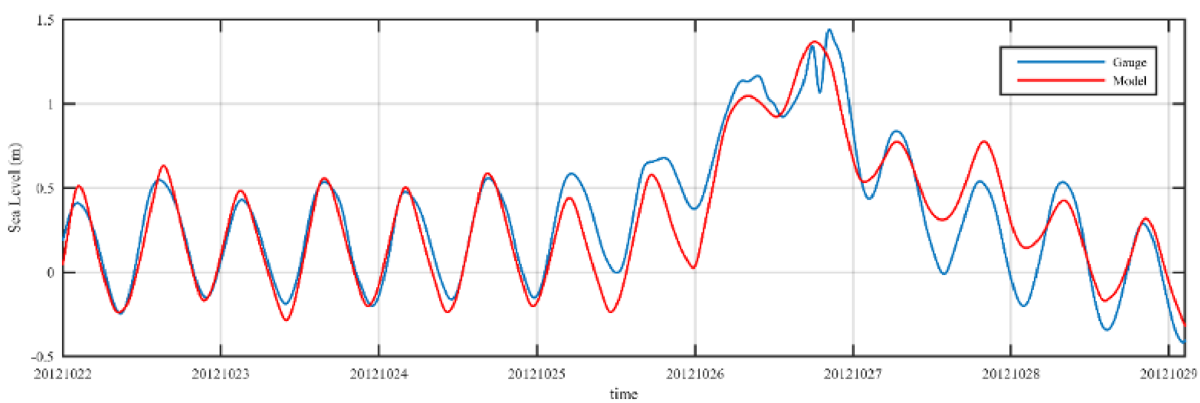
Figure 16. Computational Domain and Bathymetry for Storm Surge and Wave Modelling



Source: Self-elaborated.

The results obtained for the atmospheric and marine dynamics have been validated with instrumental records from meteorological stations or tide gauges (see example of validation in Figure 17 and complete validation in Annex1, Hazard Assessment).

Figure 17. Storm Surge Validation for Hurricane Sandy in West End in Grand Bahama

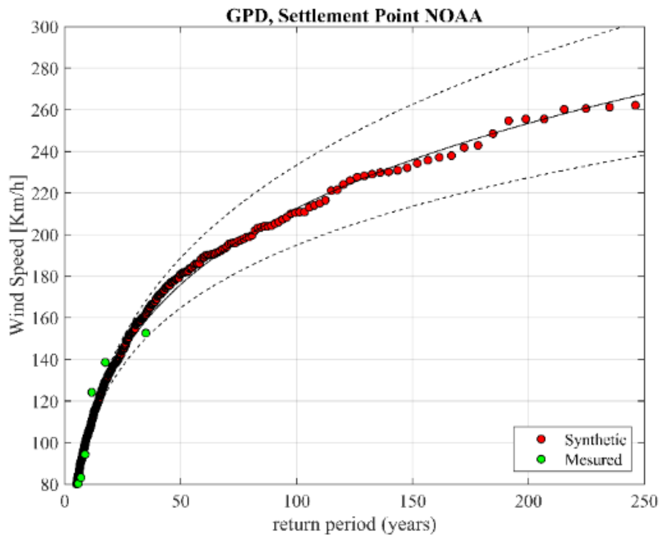


Source: Self-elaborated. *Dates for this figure are October 2012.*

Finally, a statistical analysis has been performed to the historical and synthetic wind, rainfall, surge and wave parameters data sets obtained through the above-mentioned simple parametric models or complex numerical models, in order to obtain return period values or design parameters for the probabilistic characterization of the target hazards as follows:

- The maximum **wind speed** distribution obtained for more than 5,700 events has been fitted to a Generalized Pareto Distribution in order to develop the wind maps for the national scale (Figure 18. See also wind results in section 3.4.3).

Figure 18. Settlement Point Station Example



Source: Self-elaborated. *Settlement Point station of the Generalized Pareto Distribution obtained from measured (historic) TC maxima 10 m wind speed (green dots) and from synthetic TC simulations (red dots).*

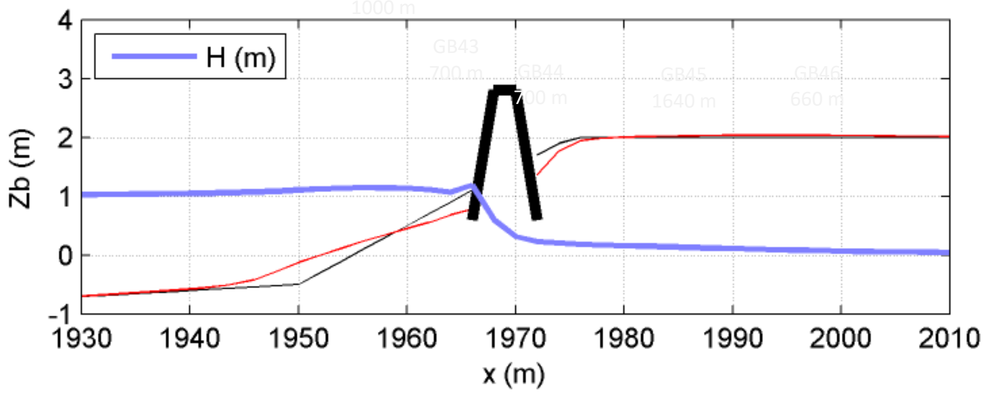
- The sea level (storm surge, wind set-up and wave set-up) associated to a particular return period has been used as input of the "bathtub" **flooding** model (see an extended description of the flood modelling in Annex 1, Hazard Assessment), which has allowed for the elaboration of flooding hazard maps for the national scale (see flooding results in section 3.4.4).
- The proposed approach to obtain the **erosion** hazard results is slightly different (see details of the proposed methodology for the erosion modelling in Annex 1, Hazard Assessment):
    1. First, the three local study sites have been segmented in coastal cells of circa 1 km length (See Figure 19).

Figure 19. Grand Bahama Coastal Cells Example

Source: Self-elaborated. *Coastal cells (GB39 to GB46).*

2. Waves and surges obtained for the selected 1,003 TCs have been used as inputs of the numerical **erosion model** “XBEACH” to estimate erosion caused by each event in each one of the coastal cells (see Figure. 20).

Figure 20. Example of Modelled Erosion Associated to Hurricane Matthew

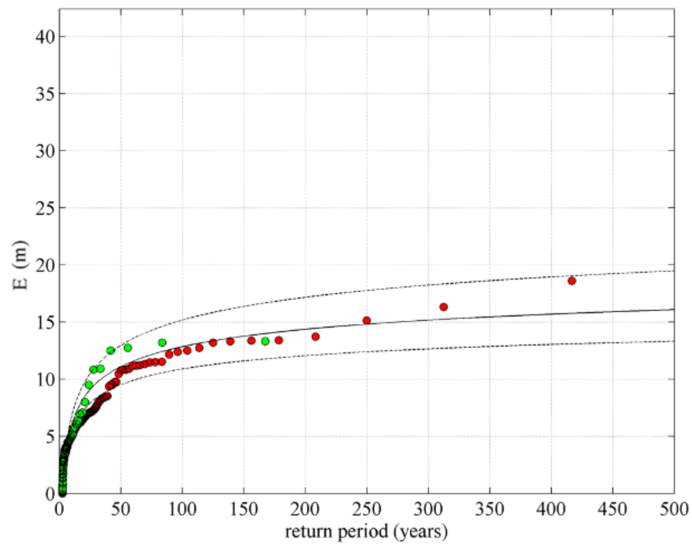


Source: Self-elaborated. *Example of modeled erosion associated to Hurricane Matthew at coastal cell GB45 in Grand Bahama. Beach profile before (thin black line) and after the event (red line), seawall (thick black line) and wave height (blue line). Axis are in meters (m). X= Distance to the offshore limit of the modelled beach profile.*

Evidence of erosion after Hurricane Irma (September 2017) and Hurricane Matthew (October 2016) in Grand Bahama was used to validate the modelled erosion of seawalls, beaches and coastal vegetation (see complete validation of results in Annex 1. Hazard Assessment).

3. Finally, a statistical analysis was performed to obtain erosion results associated to each target return period and plot the erosion maps at the local scale for three study sites (see coastal erosion results in section 3.4.5).

Figure 21. Example of Shoreline Recession in Lucaya Beach and Grand Bahama



Source: Self-elaborated. *Example of Generalized Pareto Distribution of the recession of the shoreline due to erosion (E) in the coastal cell GB46 (Lucaya Beach, Grand Bahama). Green points are historical events, red ones are synthetic*.

This study does not include the effects of climate change impacts on land-falling TCs. Despite statistical correlations that show changes in patterns between sea surface temperature and hurricane activity in the Atlantic Ocean in recent decades, IPCC (2014) states that non-conclusive evidence links to anthropogenic influence on greenhouse gas emissions, which causes global warming. Additional literature argues that it has already caused a detectable change in the Atlantic Ocean's hurricane activity (Knutson et al., 2013; Bender et al., 2010). Despite this uncertainty, flooding and erosion caused by TCs will increase as a result of the undeniable climate change-derived **sea-level rise (SLR)**. Therefore, the hazard assessment has been completed to estimate the effects of an SLR scenario in a target year on coastal flooding and erosion hazards. In this study, regional sea-level projections under scenario RCP8.5 (AR5; IPCC, 2014) for the horizon year 2050 have been adopted, which yields a projection for sea-level rise of 291 mm (Slangen, 2014) in The Bahamas (see the justification for the selection of scenario, horizon year and sea-level rise projection in Annex1, Hazard Assessment).

3.4. Results

3.4.1. Introduction

This section presents the obtained probabilistic characterization of the selected target hazards:

- Wind
- Coastal flooding
- Coastal erosion

Additional results for rainfall and storm surge can be found in Annex 1 (Hazard Assessment). The scale of the study assesses wind and coastal flooding for the whole national territory. Coastal erosion and coastal flooding have been analyzed at local scale in the three study sites (see section 1.3). In addition, some results have been integrated at the district level in Grand Bahama and Andros; the borders of districts are shown in Figure 22.

Figure 22. District Borders in Grand Bahama and Andros

Source: Self-elaborated.

Wind hazard has been characterized only at the time of the study, since evidence of impacts of climate change on tropical cyclone activity (intensity or frequency) are not conclusive according to IPCC (2014) (see the full dissertation in Annex 1, Hazard Assessment). Nevertheless, coastal flooding and erosion maps have been obtained at the time of the study and for the year horizon 2050.

Results for all time horizons (present and year 2050) are shown in hazard maps corresponding to several return periods (10, 50, 100 and 500 years). Only a selection of these maps is shown herein in order to illustrate the main conclusions (see all hazard maps in Annex 1, Hazard Assessment).

3.4.2. Study limitations

It should be noted that results of this study are conditioned by the following limitations:

- The low resolution of the available Digital Elevation Model (DEM) for this study (90m x 90m), which means that only major features are properly described in the flooding modeling exercise and leads to selecting a simple bathtub model to estimate coastal floods. This flood model is based on the hydraulic connectivity between cells and assumes that coastal flooding is stationary, which means that the run-off during the flooding event and the time required for the flood to happen are not properly modeled. This limitation has a lower impact on flood results for large return periods, but flood results for smaller return period can be highly affected by the inability to represent man-made structures and small features that ensure or disrupt hydraulic connectivity.
- The available DEM for this study has been corrected by eliminating major error components such as vegetation. After this error removal, river networks and hill-valley structures became clearly represented in flat regions where height errors are larger than topography variability. Nevertheless, there are still some limitations related to the vertical accuracy, which is of the same order of magnitude as the storm surge heights and limits the validity of flood results (see the comparison of available DEMs and filters in Annex 1, Hazard Assessment).
- The extent of the local study sites (of hundreds of kilometers) conditions the resolution of the erosion assessment, based on study units (coastal cells) of approximately 1 km of alongshore length, which means that the variability of coastal structures and beach profiles within the coastal cell is not represented. Furthermore, several assumptions for the characterization of beach profiles and coastal structures were necessary for the erosion modeling exercise. Some important characteristics of assets exposed to coastal erosion have been hypothesized to be homogeneous in the whole study area, such as beach berm height, the foundation depth of seawalls, or the size of rip-rap revetments (see further details on the assumed characteristics in Annex 1, Hazard Assessment), which have some influence on the estimated erosion of beaches and failure of coastal structures.

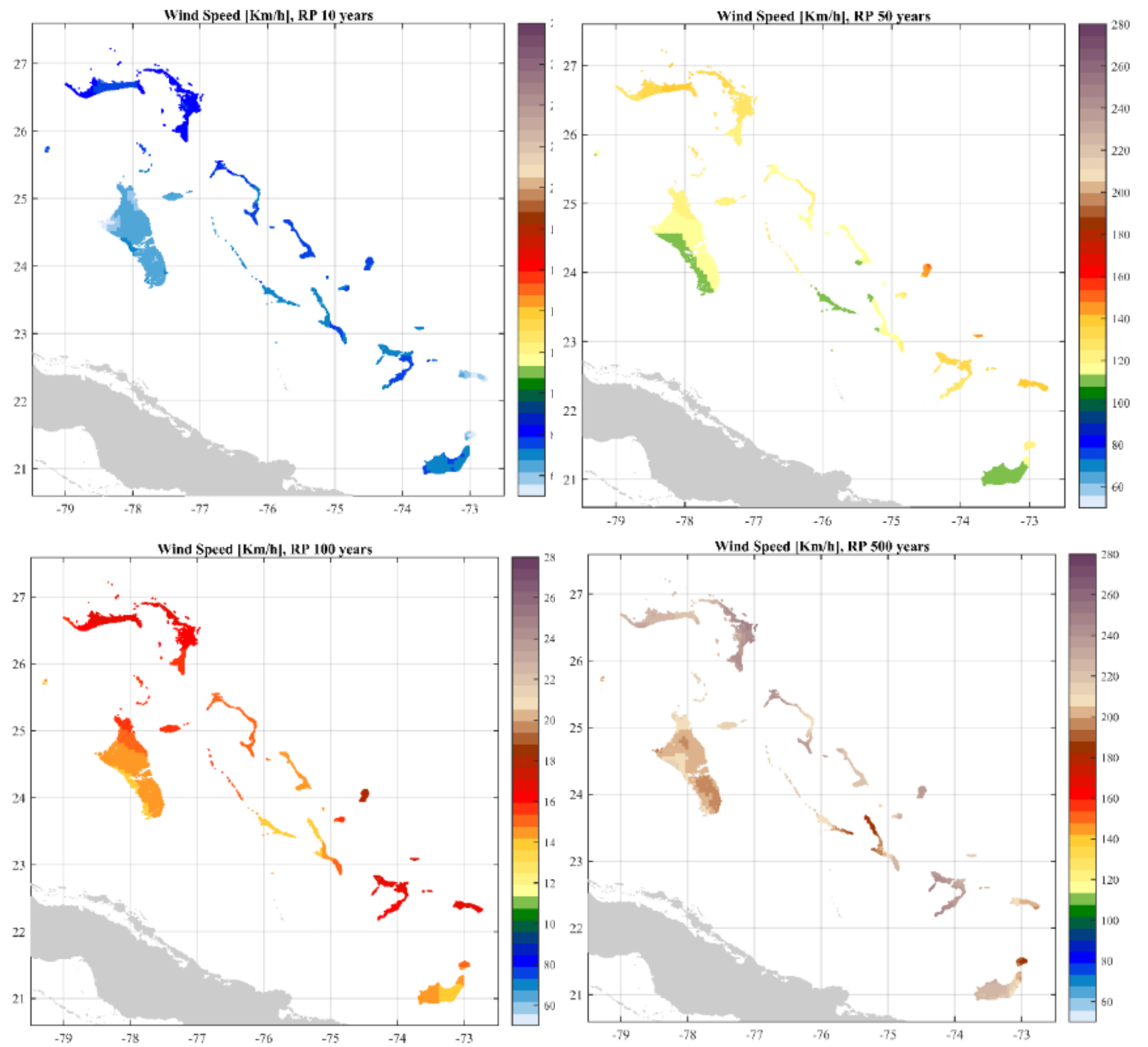
- The limited available data for a proper quantitative model validation limits the accuracy of the obtained results. Hazard results have been validated with scatter measurements and qualitative validation based on aerial and conventional historical pictures and the testimony of local witnesses of past flooding and erosion events gathered during a field survey in Grand Bahama in December 2017 (see complete validation in Annex1, Hazard Assessment).

3.4.3. Wind

The process of obtaining the wind maps based on the atmospheric modelling of each TC in the developed database is described in detail in Annex 1. The obtained probabilistic wind maps presented in this section do not represent the wind map associated to a particular event (e.g., Hurricane Matthew). Instead, they are a composite map integrating the wind speed patterns of more than 5,700 tropical cyclones (historic and synthetic) in the developed database. As an example of the proper interpretation of these wind maps, the district of South Andros is expected to experience winds of 60 km/h once every 10 years (return period) (see top-left panel in Figure 23).

Figure 23 shows that the northern islands (e.g., Abaco Island and Grand Bahama) and southern islands (e.g., Crooked Island) of The Bahamas is expected to experience more intense winds than the central islands as well as the western central islands (e.g., Andros, Exuma), located on the leeward side of the archipelago, which get lower speed winds. Averaged 10-year winds range from 50 km/h to 100 km/h, whereas in the case of the 500-year winds, average values range from 180 km/h to 280 km/h.

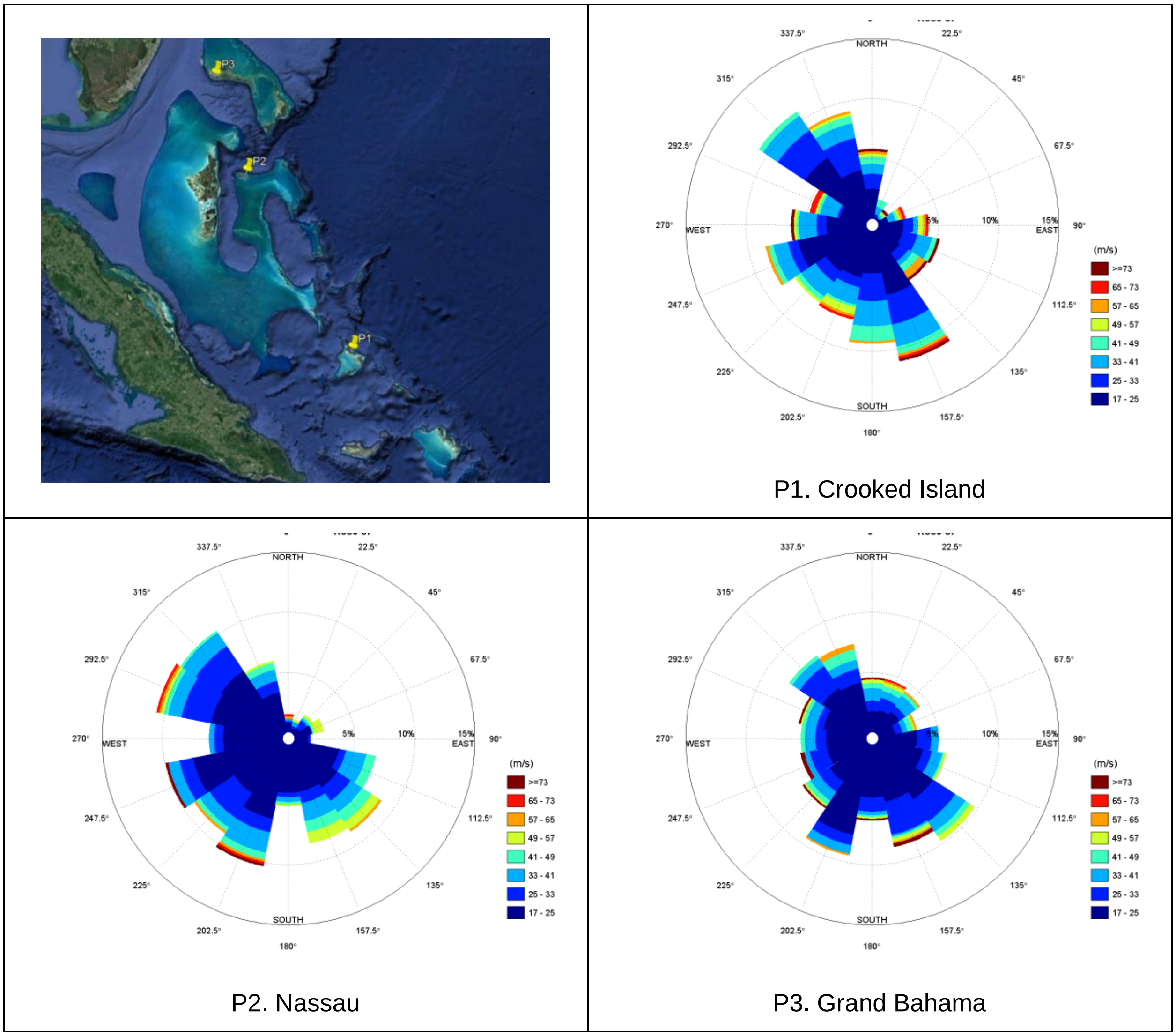
Figure 23. Wind Speed Maps



Source: Self-elaborated. *10, 50, 100 and 500-year return period maps of the 10 m height and 10 min averaged wind speeds in Km/h.*

Figure 24 shows wind roses (graphic tool used to give a succinct view of how wind speed and direction are typically distributed at a particular location) in 3 locations in The Bahamas of maximum wind speeds (at 10m height and 10min averaged wind speeds) obtained from the developed database (historical and synthetic events). Three sets of predominant directions can be observed: SSE, NNW and SW.

Figure 24. Historical and Synthetic Wind Roses in The Bahamas



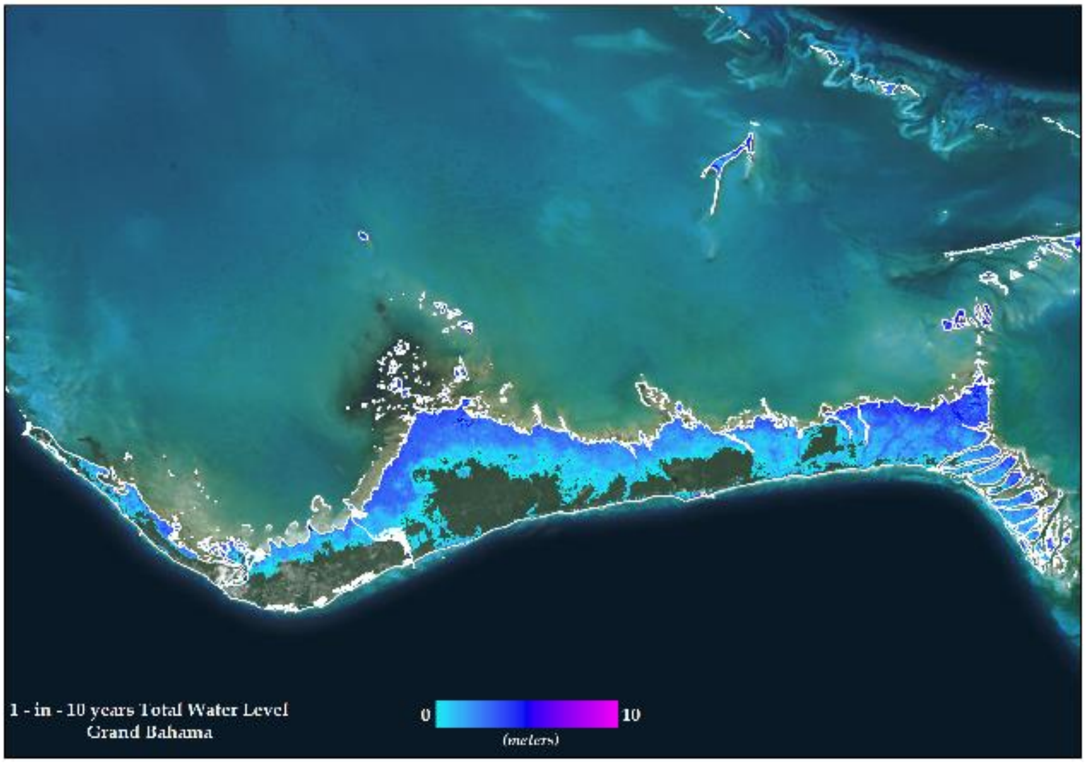
Source: Self-elaborated. *Wind roses of maximum wind speed (in m/s) for more than 5700 hurricanes (historical and synthetic) in 3 locations in The Bahamas.*

3.4.4. Coastal flooding

The detailed methodology used to develop coastal flooding maps is described in detail in Annex 1 (Hazard Assessment). An example of the proper interpretation of these flooding maps is as follows: points with 1 meter of water depth in the 10-year flooding map are expected to be flooded with 1 meter of water once every 10 years. But this flooding could be due to various events, each of them in a different area of the map.

Grand Bahama results show more severe floods on the northern coast, which is not part of the local study area. On the southern coast, the central part of the island is less affected than the rest (see Figure 25)

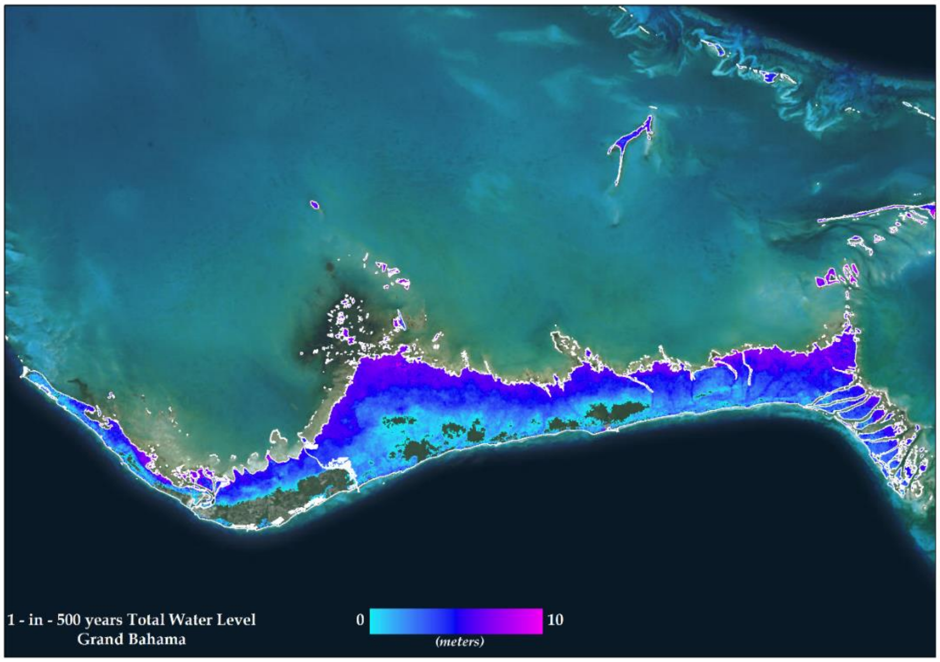
Figure 25. Extent of Coastal Flooding in Grand Bahama



Source: Self-elaborated. *Coastal flooding extent in Grand Bahama for the 10-year return period.*

Some areas on the southern coast of Grand Bahama (local study site), around the city of Freeport, are not expected to experience flooding. Not even once with a 500 year return period (see Figure 26).

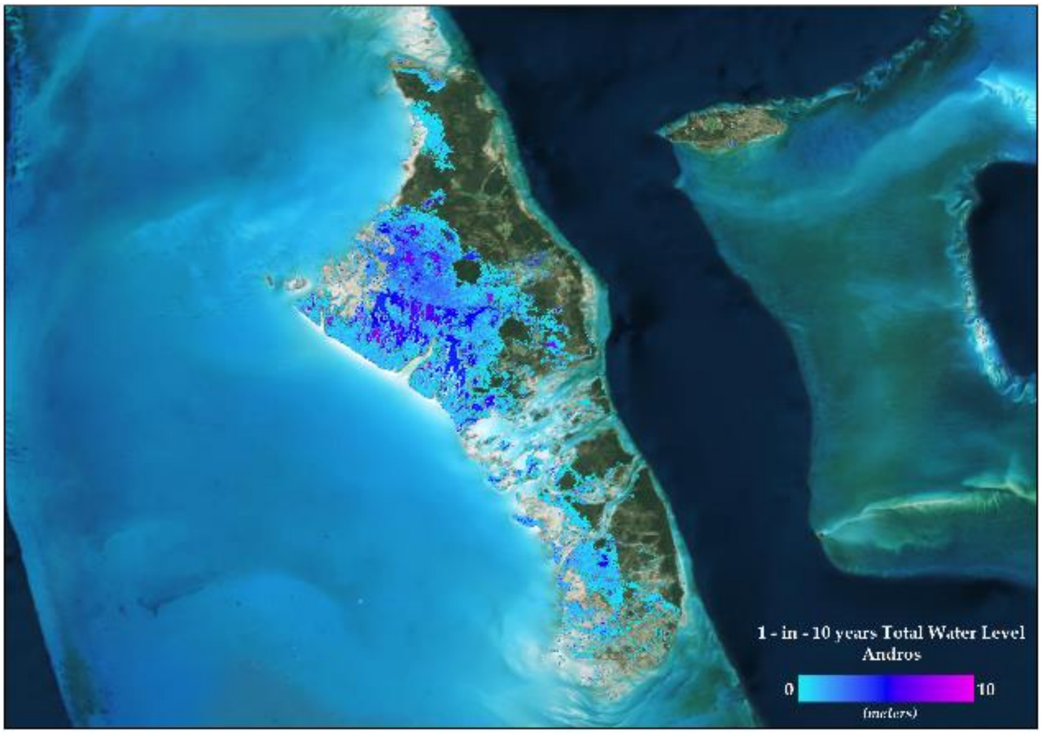
Figure 26. Extent of Coastal Flooding in Grand Bahama



Source: Self-elaborated. *Coastal flooding extent in Grand Bahama for 500-year return period.*

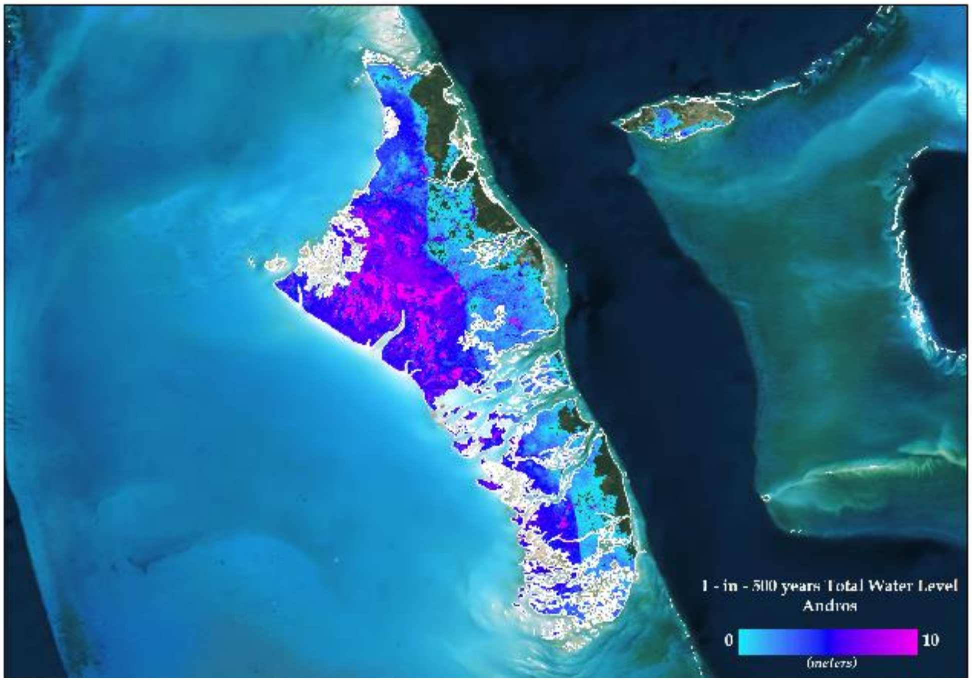
The west side of Andros is expected to suffer from severe coastal floods. On the eastern coast (local study site), only scatter locations of Central Andros and along with the southern boundary of South Andros are expected to be flooded once with a 10 year return period (see Figure 27) and large areas of the eastern coast are not expected to be flooded, not even once with a 500 year return period, despite the generalized floods in the island for this probability function (see Figure 28).

Figure 27. Extent of Coastal Flooding in Andros - 10 Year Return Period



Source: Self-elaborated.

Figure 28. Coastal Flooding Extent in Andros - 500 Year Return Period



Source: Self-elaborated.

Finally, coastal flooding along with the coastal stretch under study at the local scale in Long Island (17 km from Gray's settlement to Scrub Hill) is rare even for a 500-year return period, with very few flooded locations of very small extent (see Figure 29). On the contrary, a large extent of the western coast of Long Island is expected to be flooded at least once with a 10 year return period (see Figure 30).

Figure 29. Extent of Coastal Flooding in Long Island - 10 Year Return Period

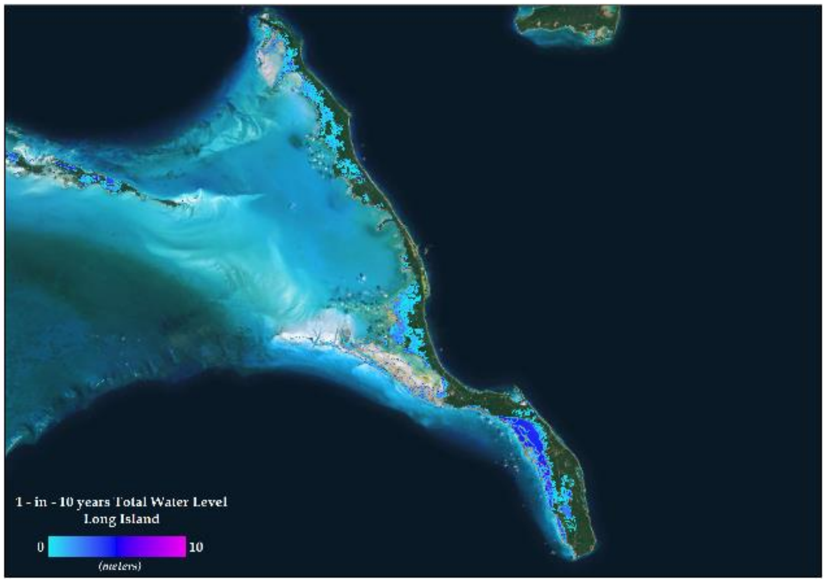
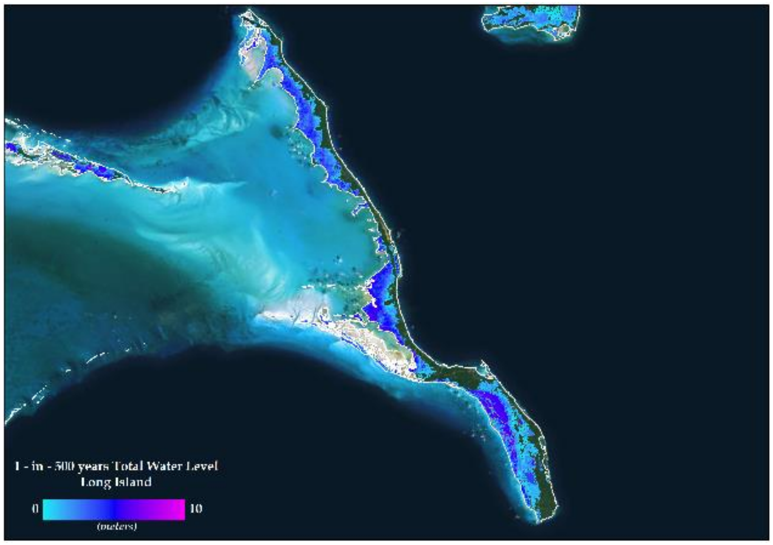


Figure 30. Extent of Coastal Flooding in Long Island – 500 Year Return Period



Source: Self-elaborated.

3.4.4.1. Impacts of climate change on coastal flooding

Table 2 shows the total flood exposed area (km²) at the national level, in the three local study sites and at the district level for the selected return periods. Table 3 shows the increase of the same results in the year horizon 2050 in percentage.

Table 2. Inundation extent for Grand Bahama, Andros and Long Island (per district and island) and for the whole national territory of The Bahamas

Island	District	Return period (years)				
		10	**50**	**100**	**500**	
Grand Bahama	City of Freeport	0.25	0.69	0.96	2.11	
	East Grand Bahama	375.99	428.70	437.81	450.66	
	West Grand Bahama	231.00	298.85	318.74	343.22	
	Total	607.24	728.25	757.51	796.00	
Andros	North Andros	1,211.65	1,631.36	1,721.65	1,931.45	
	Central Andros	590.33	937.31	996.72	1,049.55	Km²
	South Andros	345.28	536.27	583.56	665.02	
	Mangrove Cay	135.83	242.21	272.78	305.18	
	Total	2,283.10	3,347.17	3,574.72	3,951.20	
Long Island		164.99	214.79	228.18	255.15	
National	**National**	**4,546.91**	**6,187.95**	**6,622.21**	**7,385.85**	

Source: Self-elaborated. *Inundation Extent in km² for various return periods (10, 50, 100 and 500 years).*

Table 3. Percentage Increase in Inundation Extent due to the Climate Change (%)

Island	District	Return period (years)				
		10	**50**	**100**	**500**	
Grand Bahama	City of Freeport	46.9	48.3	91.1	39.3	%
	East Grand Bahama	6.0	2.8	2.7	1.9	
	West Grand Bahama	9.8	7.3	5.0	4.3	
	Total	7.5	4.7	3.8	3.0	
Andros	North Andros	11.5	5.1	5.6	4.2	
	Central Andros	20.4	5.5	2.7	1.1	
	South Andros	19.8	10.1	9.5	5.6	
	Mangrove Cay	24.2	9.4	5.3	4.2	
	Total	15.8	6.3	5.4	3.6	
Long Island		15.7	9.8	7.8	4.4	
National	**National**	**12.6**	**6.9**	**6.0**	**13.3**	

Source: Self-elaborated. Increase *in inundation externs in percentage for various return periods (10, 50, 100 and 500 years) for Grand Bahama, Andros and Long Island (per district and island) and for the whole national territory of The Bahamas in the horizon year 2050.*

Freeport shows the largest increase in flooded area (in %) particularly for a 100-year return period. The total extension of flooding area in Freeport is limited, with less than 3 km^2 of flooding once in a 500 year return period, including the impacts of climate change. The three target islands, Grand Bahama, Andros and Long Island show increases in probable flooded area to the horizon year 2050, that range between 3 and 15.8%, with higher values for the lower return periods. At the national scale, increases in the total flooded area to the horizon year, range between 6% and 13.3%.

3.4.5. Coastal erosion

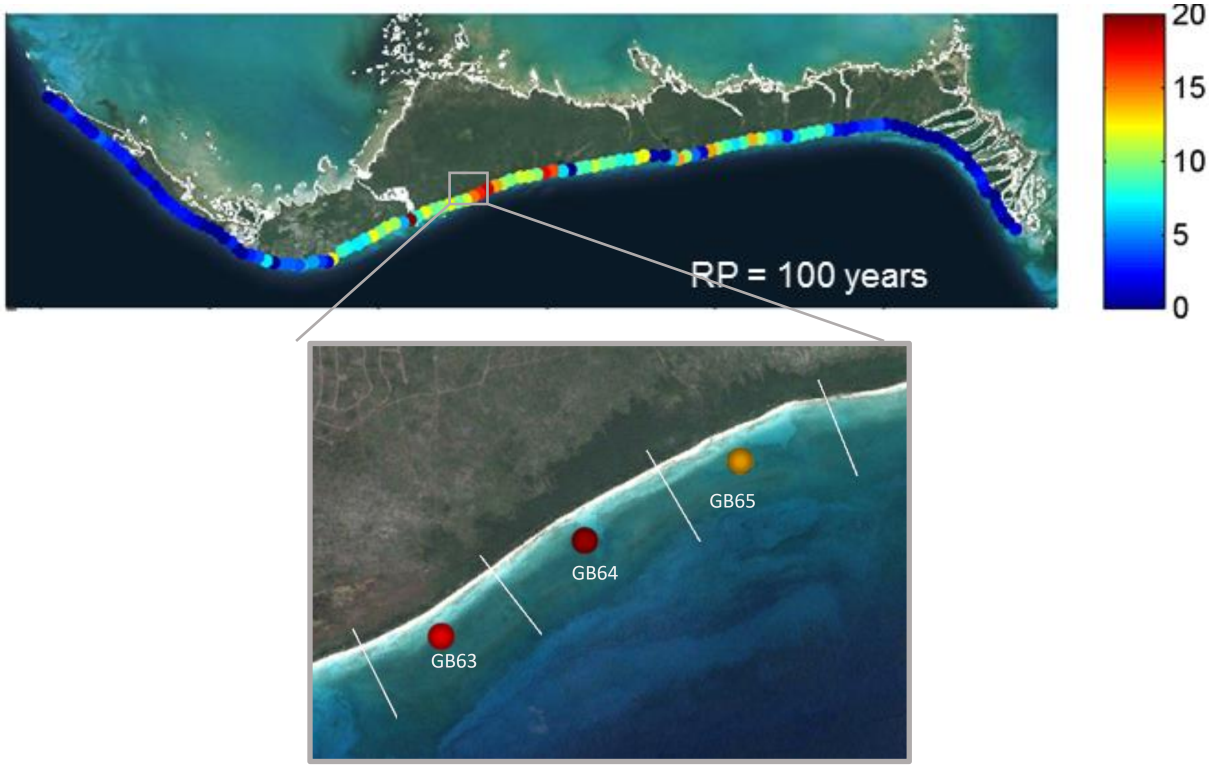
The hazard assessment performed in this study has addressed several kinds of impacts related to coastal erosion. Consequently, the hazard modelling in this study has been designed to address the characterization of the following impacts, providing specific hazard results for:

- The loss of dry beach area per alongshore linear meter.
- The collapse of existing coastal structures.

The obtained results for both types of impacts are detailed in the following sections.

3.4.5.1. Loss of dry beach area

Figure 31. Dry Beach Area Loss Probabilistic Maps



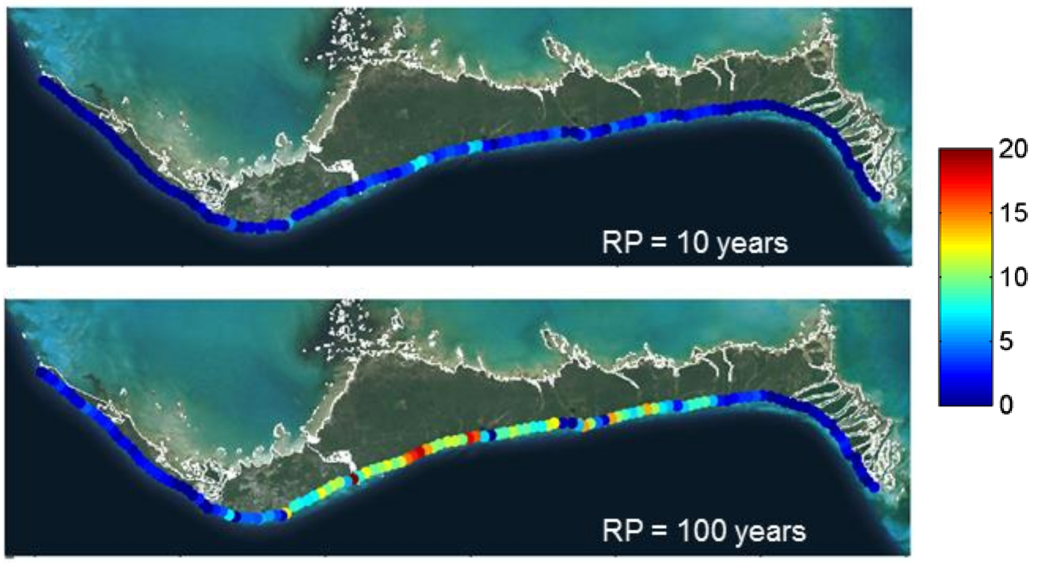
Source: Self-elaborated. *The probabilistic maps of loss of dry beach area per alongshore linear meter presented in this section show the maximal expected shoreline recession associated to a particular return period by means of colored dots in each coastal cell. An illustrative example of the erosion maps can be found in Figure 31, which shows results of a 100 -year erosion map in three coastal cells in Grand Bahama. Example of 100-year return period map of the loss of dry beach area (in m^2/m) in coastal cells GB63, GB64 and GB65 in Grand Bahama. Units of m2/m are equivalent to the averaged recession of the coast in meters (m).*

Figure 31 suggests that the shoreline along coastal cell GB64 is expected to recede 20m once with a 100-year return period, as a result of a tropical cyclone. This recession would cause a loss of $20m^2$ per alongshore linear meter in this particular coastal cell. Note that this recession is the maximal expected recession after a hypothetical TC due to storm surge and waves and does not include long term erosion trends due to other natural causes such as: imbalances in the littoral drift or human activities such as the disruption of the natural sediment transport due to the construction of coastal structures or alterations in the natural sedimentation processes due to dredging. The analysis of these other drivers for erosion requires a detailed resolution working scale, and it is out of the scope of this study.

In summary, results in Grand Bahama show higher erosions in the central part of the island, reaching shoreline recessions of less than 10m once in 10 years but more than 20m once in 100

year at three hotspots: 1) east of Fortune Beach by the inlet jetty, 2) in the three coastal cells shown below at Gold Rock Beach.

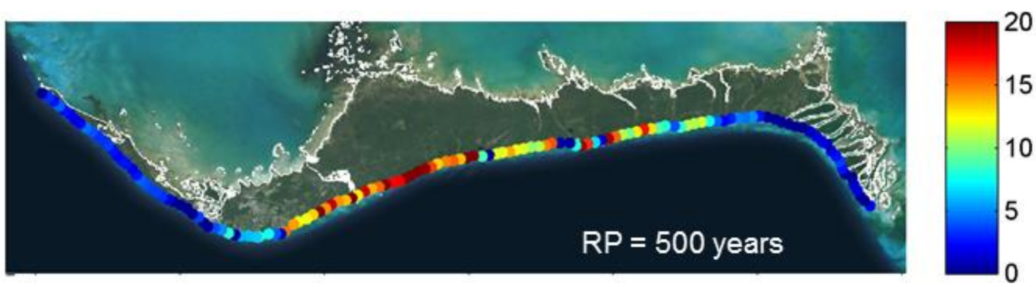
Figure 32. Return Period Maps in Dry Beach Area Loss in Coastal Grand Bahama – 10 and 100 Years



Source: Self-elaborated*. 10-year (upper panel) and 100-year (lower panel) return period maps of the loss of dry beach area (in m^2/m) in coastal in Grand Bahama.*

The 500-year erosion map shows a generalized recession of over 15m is in the central part of the island.

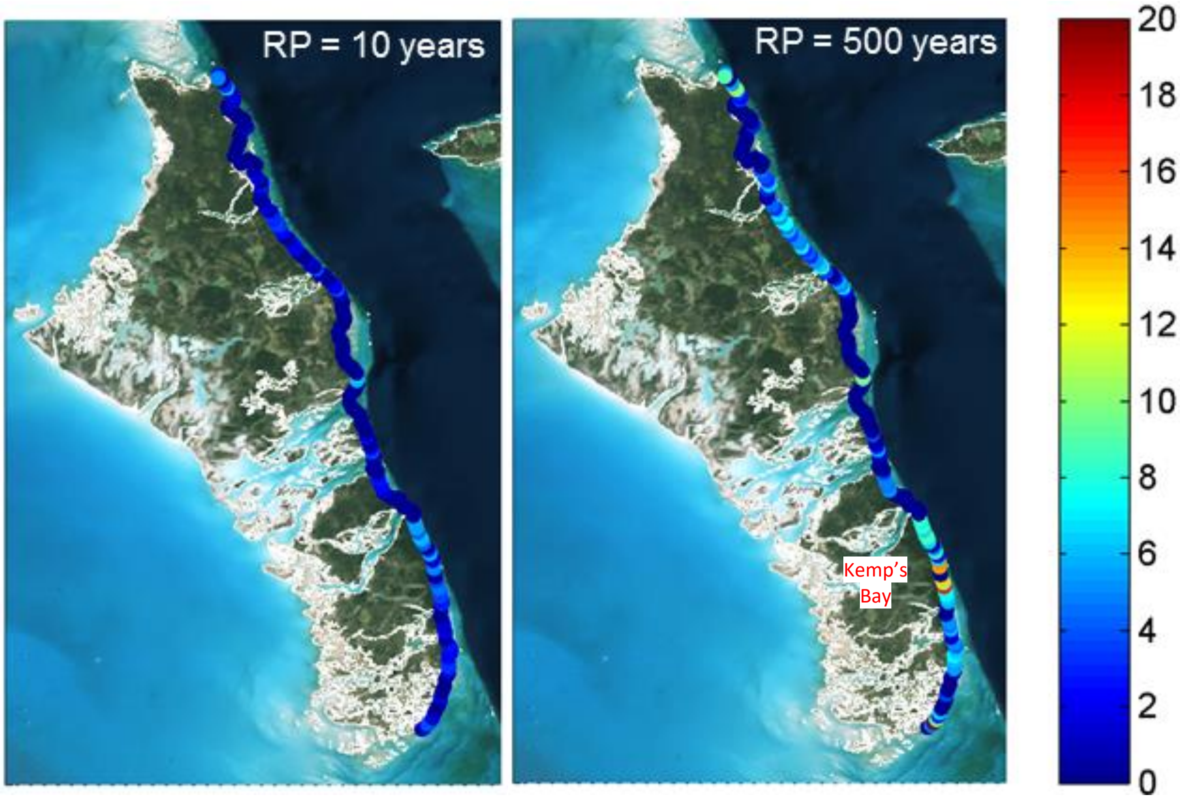
Figure 33. Return Period Map in Dry Beach Area in Coastal Grand Bahama – 500-year Return Period



Source: Self-elaborated. *500-year return period map of the loss of dry beach area (in m^2/m) in coastal in Grand Bahama*

Andros' overall erosion is less relevant than in Grand Bahama reaching shoreline recessions of less than 5m once for every 10 year return period and less than 12m once in a 500 year return period. Results show shoreline recessions of up to 17m once in a 500 year return period (see Figure 34) in Kemp's Bay in South Andros only.

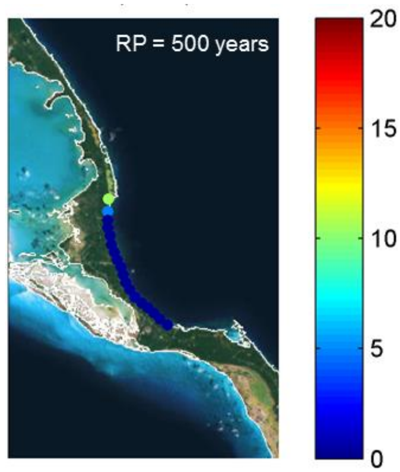
Figure 34. Return Period Maps in Dry Beach Area Loss – Ten and 500 Years



Source: Self-elaborated. *10-year (left panel) and 500-year (right panel) return period maps of the loss of dry beach area (in m^2/m) in coastal in Andros.*

Finally, the results in Long Island show some coastal recession only in the north boundary of the coastal stretch under study (see Figure 35) since most of the study area is rocky.

Figure 35. Return Period Map in Loss of Dry Beach Area in Coastal Long Island – 500 Year



Source: Self-elaborated. *500-year return period map of the loss of dry beach area (in m^2/m) in coastal in Long Island.*

Regarding the failure of coastal structures (damages or collapse under tropical cyclones), two different typologies have been considered:

- Rip-rap revetments, groins and jetties.
- Vertical seawalls at the back of beaches.

Failure of the former is related to the exceedance of the design wave height of the structure, whereas the collapse of the latter takes place when the scour depth exceeds the base of the seawall foundation (see Annex 1, Hazard Assessment, for further details).

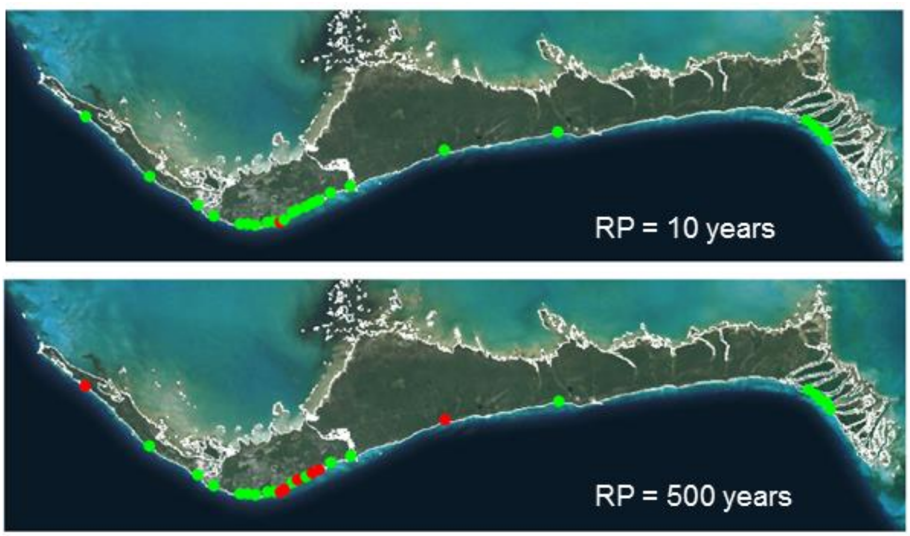
3.4.5.2. Reference – specific hazard impacts analysis on coastal structures

This section focuses as references on the hazard assessment of existing specific coastal structures that have been identified in the local study area. Note that there are no coastal structures in the local study area of Long Island.

The methodology applied in this section is as follows: the threshold for collapse (either design wave height for rip-rap revetments, groins and jetties or scour next to the foundation of vertical seawalls) is exceeded at least once in a 10 year return period, in coastal cells marked with red dots of the previous Figures 31-35 (or not exceeded in green dots) in the 10-year return period map. But this collapse could be due to different events in different areas of the map.

Results show that seawalls at the back of beaches in Grand Bahama withstand tropical cyclones better than rip-rap revetments, groins and jetties because the beach in front of the seawall provides some protection whereas other kinds of coastal structures are directly exposed to waves and surges. Additionally, it is worth noting that the required hypotheses on some unknown characteristics of the coastal structures, i.e., the foundation depth of seawalls or the size of rip-rap revetments (see section 3.4.2) might have an influence on the obtained results (see further details on the assumed characteristics in Annex 1, Hazard Assessment). The 10-year return period map shows collapse of vertical seawalls in only one coastal cell, whereas the 500-year return period map shows collapse of seawalls in several locations along Freeport, the West end and the east boundary of West Grand Bahama (see Figure 36).

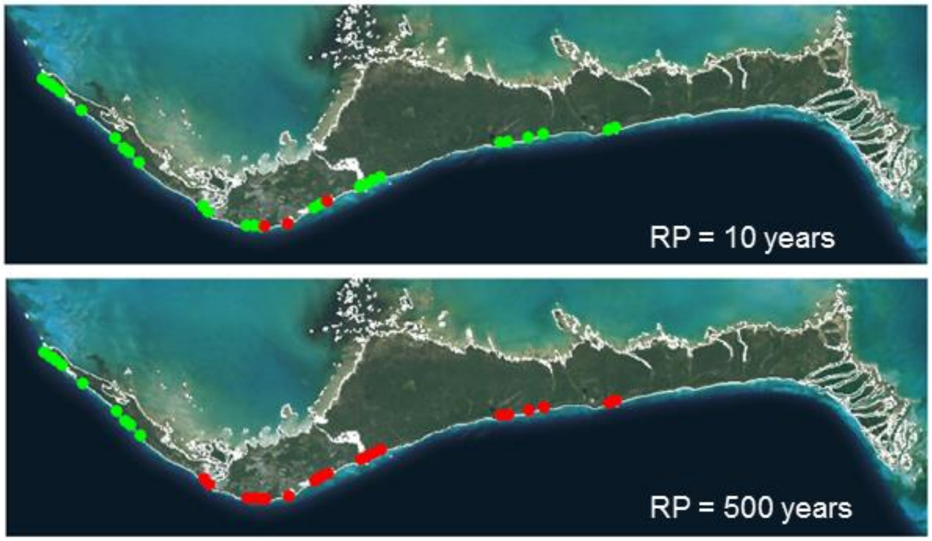
Figure 36. Vertical Seawalls Potential Collapse in Grand Bahama



Source: Self-elaborated. *10-year (upper panel) and 500-year (lower panel) return period maps of the collapse of vertical seawalls in Grand Bahama (red dots: exceedance of threshold for collapse).*

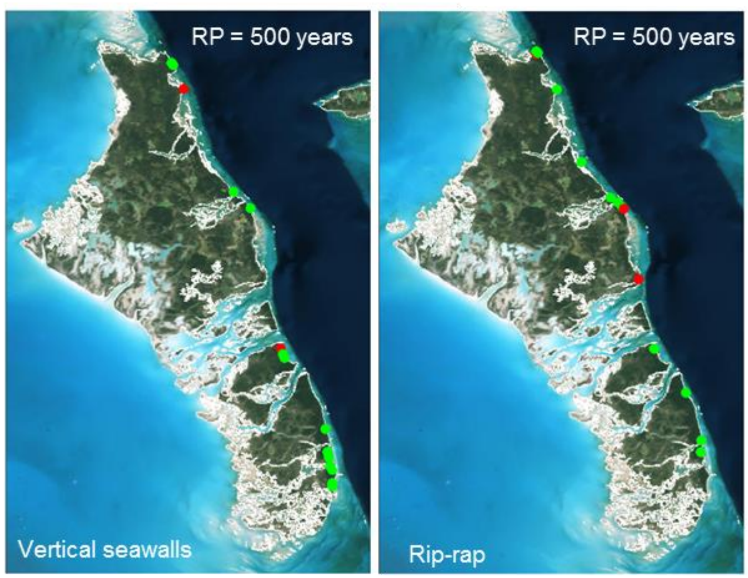
The 10-year return period map shows the collapse of rip-rap revetments, groins and jetties in several locations along Freeport and the 500-year return period map shows a generalized collapse of coastal structures in the central part of the island (see Figure. 36).

Figure 37. Potential Collapse of Rip-Rap Revetments, Groins and Jetties in Grand Bahama



Source: Self-elaborated. *10-year (upper panel) and 500-year (lower panel) return period maps of the collapse of rip-rap revetments, groynes and jetties in Grand Bahama (red dots: exceedance of threshold for collapse).*

Figure 38. Seawall Behavior in Andros



Source: Self-elaborated. *In Andros, results show that seawalls have a similar behavior than rip-rap revetments, groynes and jetties. The 10-year return period map shows no collapse of structures and the 500-year return period map shows collapse of both seawalls and coastal structures only in two coastal cells (see Figure 34). 500-year (lower panel) return period maps of the collapse of seawalls (left panel) and rip-rap revetments, groynes and jetties (right panel) in Andros (red dots: exceedance of threshold for collapse).*

3.4.5.3. Impacts of climate change on erosion

Table 4 shows the total dry beach area potentially eroded for the selected return periods in the three local study sites (whole study area and per district). Table 5 shows the percentage increase of the same results due to the climate change in the year horizon 2050.

Table 4. Potential Erosion in Dry Beach Area (m^2)

Island	District	Return period (years) 10	50	100	500	
Grand Bahama	City of Freeport	46,958	76,220	86,154	97,668	m^2
	East Grand Bahama	158,603	185,164	189,032	190,903	
	West Grand Bahama	146,145	187,405	206,829	259,012	
	Total	351,706	448,789	482,015	547,584	
Andros	North Andros	89,029	129,307	136,756	143,960	
	Central Andros	6,947	7,450	7,450	7,450	
	South Andros	117,828	132,326	134,276	135,906	
	Mangrove Cay	13,015	19,152	19,363	19,472	
	Total	226,818	288,235	297,845	306,788	
Long Island		2,997	4,448	6,640	6,640	

Source: Self-elaborated. *(in m^2) for various return periods (10, 50, 100 and 500 years) in Grand Bahama, Andros and Long Island (per district and island).*

Table 5. Increase in Potential Erosion (due to the Climate Change) in Dry Beach Area (%)

Island	District	Return period (years) 10	50	100	500	
Grand Bahama	City of Freeport	75.2	11.3	5.5	0.1	%
	East Grand Bahama	69.1	15.0	11.3	5.7	
	West Grand Bahama	106.6	22.7	14.1	4.9	
	Total	83.8	17.4	11.4	4.3	
Andros	North Andros	48.3	11.7	11.2	9.6	
	Central Andros	18.7	0.0	0.0	0.0	
	South Andros	17.5	2.7	2.3	1.2	
	Mangrove Cay	54.4	14.7	8.3	3.5	
	Total	29.9	7.2	6.5	5.1	
Long Island		48.4	28.9	17.4	9.1	

Source: Self-elaborated. Increase *(%) for various return periods (10, 50, 100 and 500 years) in Grand Bahama, Andros and Long Island (per district and island) in the horizon year 2050 due to climate change.*

The results show that climate change impacts are more severe for lower return periods, which is due to high intensity tropical cyclones (RP=500 years) that already erode most of the at the time of this study. Therefore, the increase in expected erosion under the future scenario with a mean sea level 29cm higher cannot be expected to increase. On the contrary, low-energy storms that barely erode beaches at the time of the study, can cause larger damages under this sea level rise.

In view of the results for the 10-year return period, Grand Bahama is the most affected of the three local study sites with an increase of total dry beach area of more than the 80% for the year horizon 2050. Particularly, West Grand Bahama is highly affected with a doubled increase in eroded dry beach area in the year horizon 2050 compared to current eroded dry beach area. On the contrary, results show that Andros is less affected by climate change, with less than 30% of increase of the total dry beach area. Regarding the higher return periods, all three areas show similar increase of the eroded dry beach area with values ranging from 4.3 % in Grand Bahama to 9.1% in Long Island and 5.1% in Andros.

Finally, Table 6 shows the total length of coastal structures (including all typologies) that are expected to collapse in the three local study sites (whole study area and per district), for the selected return periods in the current situation, and Table 7 shows the net increase in the horizon year 2050. Each structure has been measured along the direction of its main alignment, e.g., groins in cross-shore direction and seawalls in longshore direction.

Table 6. Length of Potentially Collapsed Vertical Seawalls, Rip-Rap Revetments, Groins and Jetties (m)

Island	District	Return period (years)				
		10	50	100	500	
Grand Bahama	City of Freeport	990	2,070	2,190	2,190	Linear meters
	East Grand Bahama	0	2,190	2,190	2,190	
	West Grand Bahama	440	3,075	3,075	4,155	
	Total	1,430	7,335	7,455	8,535	
Andros	North Andros	0	0	175	450	
	Central Andros	0	800	800	800	
	South Andros	0	0	0	0	
	Mangrove Cay	0	450	450	450	
	Total	0	1,250	1,425	1,700	
Long Island		0	0	0	0	

Source: Self-elaborated. *Length in m of potentially collapsed vertical seawalls, rip-rap revetments, groins and jetties for various return periods (10, 50, 100 and 500 years) in Grand Bahama, Andros and Long Island/ district/island at time of study,*

Table 7. Net Increase of the Length of Potentially Collapsed Vertical Seawalls, Rip-Rap Revetments, Groins and Jetties Under Climate Change (m)

Island	District	Return period (years)				
		10	50	100	500	
Grand Bahama	City of Freeport	400	-380	0	200	Linear meters
	East Grand Bahama	2,120	0	0	0	
	West Grand Bahama	1,620	1,230	1,230	203	
	Total	4,140	850	1,230	403	
Andros	North Andros	20	625	745	870	
	Central Andros	800	0	0	0	
	South Andros	0	205	205	240	
	Mangrove Cay	450	0	0	0	
	Total	1,270	830	950	1,110	
Long Island		0	0	0	0	

Source: Self-elaborated. *Net increase (m) of potentially collapsed vertical seawalls, rip-rap revetments, groynes and jetties for various return periods (10, 50, 100 and 500 years) in Grand Bahama, Andros and Long Island/ district/island) in horizon year 2050 under a climate change scenario. Negative values indicate a net decrease in the length of potentially collapsed vertical seawalls.*

In this case, there is no correlation between the increase of the total length of collapsed coastal structures and the return period under analysis. The overall increase ranges between 400 and 4,000 linear meters and there are even negative values at the district level which correspond to

the fact that scour in front of seawalls can be reduced due to the rise of the mean sea level as the capacity of waves to mobilize sediment decreases for deeper seafloors. Again, in some cases, the net increase of the total length of collapsed coastal structures is higher for lower return periods, due to the fact that the relative impact of the sea level rise is more important for low-energy events that are not expected to cause major destruction of structures in the current situation than for high-energy tropical cyclones that already destroyed most of the structures in the current situation.

Table 8 shows the total length of only vertical longshore seawalls that are expected to collapse in the current situation and Table 9 shows the net increase in the horizon year 2050.

Table 8. Length of Potentially Collapsed Vertical Seawalls in Grand Bahama, Andros and Long Island at Time of Study (m)

Island	District	Return period (years)				
		10	50	100	500	
Grand Bahama	City of Freeport	210	1,060	1,180	1,180	Linear meters
	East Grand Bahama	0	0	0	0	
	West Grand Bahama	0	130	130	180	
	Total	210	1,190	1,310	1,360	
Andros	North Andros	0	0	20	20	
	Central Andros	0	0	0	0	
	South Andros	0	0	0	0	
	Mangrove Cay	0	450	450	450	
	Total	0	450	470	470	
Long Island		0	0	0	0	

Source: Self-elaborated. *Length of Potentially Collapsed Vertical Seawalls for Various Return Periods (10, 50, 100 and 500 years) in Grand Bahamas, Andros and Long Island/ district/island at time of study.*

Table 9. Net Increase of Length of Potentially Collapsed vertical seawalls in Grand Bahama, Andros and Long Island in the Horizon Year 2050 under CC Senario (m)

Island	District	Return period (years)				
		10	50	100	500	
Grand Bahama	City of Freeport	350	-380	0	200	Linear meters
	East Grand Bahama	0	0	0	0	
	West Grand Bahama	0	200	200	150	
	Total	350	-180	200	350	
Andros	North Andros	20	20	20	420	
	Central Andros	0	0	0	0	
	South Andros	0	100	100	135	
	Mangrove Cay	450	0	0	0	
	Total	470	120	120	555	
Long Island		0	0	0	0	

Source: Self-elaborated. *Net increase of length (m) of potentially collapsed vertical seawalls for various return periods (10, 50, 100 and 500 years) in Grand Bahama, Andros and Long Island district/island in horizon year 2050 under a climate change scenario. Negative values indicate a a net decrease in the length of potentially collapsed vertical seawalls.*

Table 10 shows the total length of rip-rap coastal structures (both longshore) only that were expected to collapse at the time of the study. Table 11 shows the net increase in the horizon year 2050. The length of each structure has been measured along the direction of its main alignment, e.g., riprap groins in cross-shore direction and rip-rap revetments in longshore direction.

Table 10. Length of Potentially Collapsed Rip-Rap Structures in Grand Bahama, Andros and Long Island at Time of Study (m)

Island	District	Return period (years)				
		10	50	100	500	
Grand Bahama	City of Freeport	780	1,010	1,010	1,010	Linear meters
	East Grand Bahama	0	2,190	2,190	2,190	
	West Grand Bahama	440	2,945	2,945	3,975	
	Total	1,220	6,145	6,145	7,175	
Andros	North Andros	0	0	155	430	
	Central Andros	0	800	800	800	
	South Andros	0	0	0	0	
	Mangrove Cay	0	0	0	0	
	Total	0	800	955	1,230	
Long Island		0	0	0	0	

Source: Self-elaborated. *Length in (m) of potentially collapsed rip-rap structures for various return periods (10, 50, 100 and 500 year) in Grand Bahama, Andros and Long Island/ district/ island at time of study.*

Table 11. Net Increase of Length of Potentially Collapsed Rip-Rap Structures in Grand Bahama, Andros and Long Island in Horizon Year 2050 under CC Scenario (m)

Island	District	Return period (years)				
		10	50	100	500	
Grand Bahama	City of Freeport	50	0	0	0	Linear meters
	East Grand Bahama	2,120	0	0	0	
	West Grand Bahama	1,620	1,030	1,030	53	
	Total	3,790	1,030	1,030	53	
Andros	North Andros	0	605	725	450	
	Central Andros	800	0	0	0	
	South Andros	0	105	105	105	
	Mangrove Cay	0	0	0	0	
	Total	800	710	830	555	
Long Island		0	0	0	0	

Source: Self-elaborated. *Length in (m) of potentially collapsed rip-rap structures for various return periods (10, 50, 100 and 500 year) in Grand Bahama, Andros and Long Island/ district/ island in horizon year 2050 under CC.*

4. EXPOSURE AND VULNERABILITY ASSESSMENT

4.1. Introduction

The purpose of this section is the identification of the elements exposed to the selected hazard in the study area, and characterization of their associated vulnerability. For this purpose, the first step is selecting the representative elements for the Bahamas' socioeconomic environment. The set of elements include population and assets, residential and productive, and infrastructures and public capital.

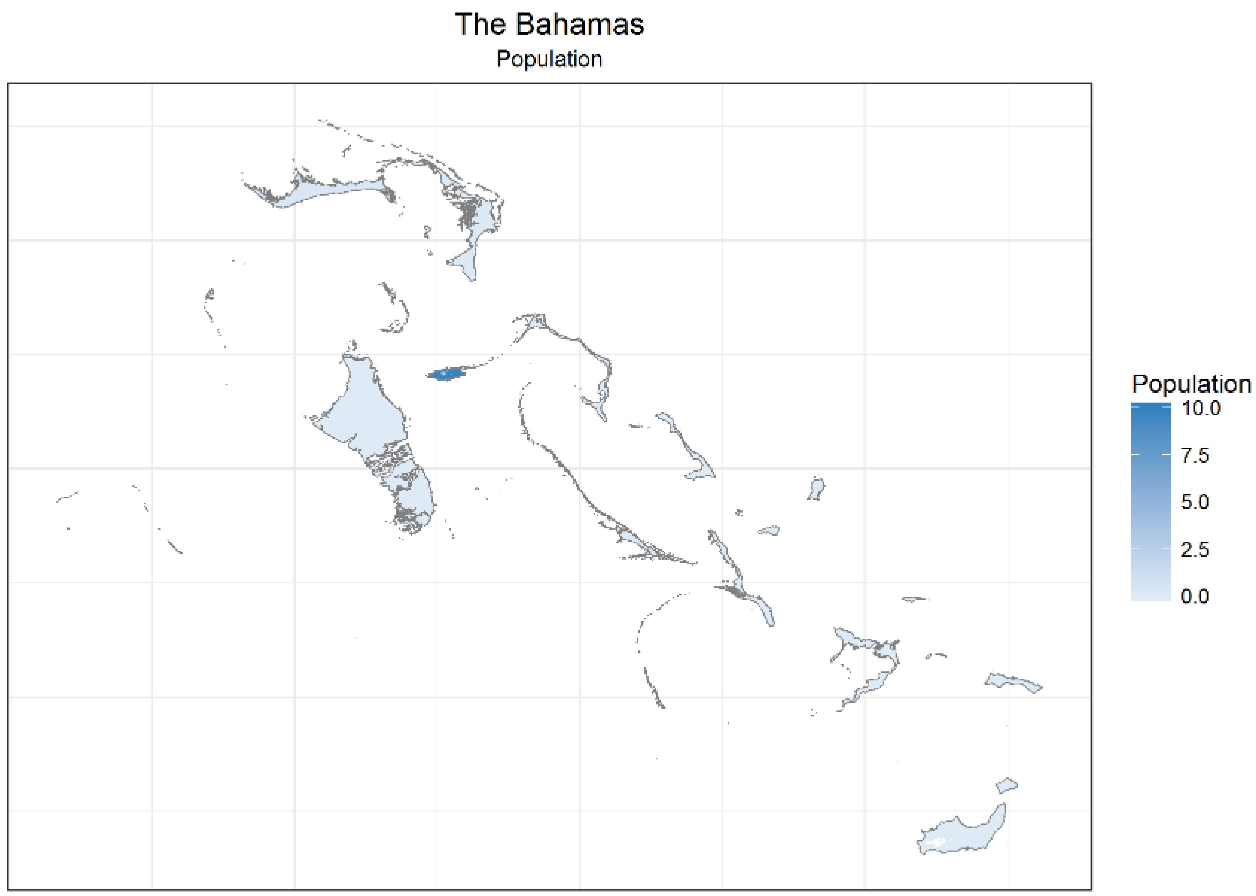
There were some challenges of this study in terms of data availability, whether these data are updated, current and accurate. Downscaling techniques and careful data collection, to find the most up to date data and the most representative damage functions, were taken into account to overcome these challenges.

This section produces two main outputs. The first output is a characterization and economic-value assessment of each hazardous event that potentially affected the elements with associated probabilities. The second output is a determination of a series of vulnerability functions that are representative for each hazard-exposed element.

The distribution of population and assets in The Bahamas results from the country's historical evolution heavily conditioned by its archipelagos and the physical dissemination of the islands. The Bahamas territory consists of more than 700 islands, with only 24 of them currently inhabited. The scale economies and the increasing returns on spatial concentration show a heavy concentration of activity distribution in the island of New Providence, where Nassau as the capital city, is located and 70% of where the total population resides. Secondarily is the island of Grand Bahama, where another 15% of the total population is located. This fact conditions the methodology followed, and the results obtained, as national results closely resemble Nassau and Freeport characteristics.

Figure 39 shows the population distribution in The Bahamas where the main component of population exposure occurs in the island of New Providence. The remaining total population has a low density and homogeneous distribution.

Figure 39. Population Distribution Across The Bahamas



Source: Self-elaborated. *Person/Pixel.*

4.2. Characterization of the hazard exposure

At a national scale, the procedure for the spatial characterization of assets relies on the availability and quality of population data. To register spatial distribution of the population is the best proxy to characterize the nationwide distribution of economic activities. The data serves to locate potential impacts on people and downscale economic aggregates, thus enhancing the available spatial distributions.

The analysis of the spatial distribution of economic activity creates some paradoxical situations to be addressed. Since luxury tourism is the country's primary industry, the eventual impacts on population can be analyzed on a twofold basis: on the one hand, population exposure identified through the gridded population can be obtained. On the other hand, the floating population located on resorts in less populated areas may introduce an additional exposure component.

4.2.1. Input Data

Table 12 presents the data used for the characterization of The Bahamian society. Although international data for the spatial distribution of assets and population was used in this study, the most updated local and national information has also been incorporated when available for calibration and adjustment of the results. To characterize the population and its distribution, a combination of two different categories of sources has been used: First, the Official 2010 National Census of The Bahamas to guarantee that the downscaled population matches the official registries. A projection for the local scale population has been estimated based on past observed growth trends per island. Second, a number of spatially disaggregated sources for the population are introduced by using: “The Gridded Population of the World (GPW), v4 SEDAC” generated by the University of Columbia’s Earth Institute based on different geospatial sources; and the gridded population from WorldPop (http://www.worldpop.org.uk) that generates similar results based on random forest techniques from the same geospatial data. The gridded data have a spatial resolution of 1km and are downscaled to the 90m cell used as a basic unit in this project.

Finally, a review of demographic projection from the World Population Prospects database by the United Nations Population Division has been taken into account (Table 13). However, the inherent uncertainty of demographic parameters at the local scale, highly connected with internal migration, and the projected peak population in the second half of the twenty-first century seems to be conservative in the demographic scenario.

Table 12. Population in Each Island

Island	2010 Census	% Population	%Growth rate	Estimate 2020	Pop /sq Mile
New Providence	246,329	70.09	1.7	345,091	3,079
Grand Bahama	51,368	14.62	0.9	61,449	97
Abaco	17,224	4.90	3.1	31,718	27
Acklins	565	0.16	3.2	1,060	3
Andros	7,490	2.13	-0.25	7,124	3
Berry Islands	807	0.23	1.4	1,065	67
Bimini	1,988	0.57	1.68	2,774	181
Cat Island	1,522	0.43	-0.7	1,322	10
Crooked Island	330	0.09	-0.571	294	4
Eleuthera	8,202	2.33	0.25	8,621	58
Exuma and Cays	6,928	1.97	9.4	8,453	62
Harbour Island	1,762	0.50	0.75	1,946	58
Inagua	913	0.26	-0.6	809	2
Long Island	3,094	0.88	0.34	3,311	13
Mayaguana	277	0.08	0.69	318	3
Ragged Island	72	0.02	0	72	5
San Salvador	940	0.03	-0.3	885	12
Rum Cay	99	0.27	2.4	155	12
Spanish Wells	1,551	0.44	0.16	1,601	58
Total Bahamas	**351,461**	100%	+1.6	482,782	65.3

Source: Self-elaborated from 2010 Census.

Table 13. Bahamas Demographic Projections

Year	Projected Population (Thousands)
2020	407
2030	440
2040	461
2050	475
2060	482
2070	483
2080	480
2090	474
2100	468

Source: United Nations Population Division[3]. *Medium Variant.*

This study used the Global Assessment Risk (GAR2015) data of the United Nations Office for Disaster Risk Reduction (UNISDR) report to estimate the economic value of the capital stock. GAR15 shows the distribution of employment and capital stock on a 5km grid resolution (1km along the coastline). Moreover, it also provides an aggregated summary per country on capital stock, and gross domestic product (GDP). GDR15's available data includes;

- Residential capital distributed by income level;
- Capital stock distributed by sector (industrial, services, education, among others), both public and private;
- Employment distributed by sector; and
- Population distributed by income level.

The critical infrastructure loss estimation typically involves digital cartography, OpenStreetMap, GoogleMaps, or specific shapefiles obtained from organizations operating in relevant sectors, depend on the study category. For example, the local sites' exposure analysis

3 https://population.un.org/wpp/

uses a combination of fieldwork and aerial or satellite images. Data adjustments are required, other than collecting data to create shapefiles when needed.

4.2.2. Downscaling Process

The disaggregated data at 5km and 1km pixel are both used as a source of this study necessary for a downscaling process form global data.

The downscaling processes developed in this study covers the following variables:

- Population obtained at a 1km grid definition downscaled to the working grid size in the project (90m) assuming homogeneous distribution within the pixel;
- Residential, industrial and services capital stock are downscaled using the spatial distribution of populations as drivers for downscaling, assuming constant residential capital per person within the pixel. Spatial interpolation is then done based on the inverse distant wedge algorithm to generate a spatial distribution of per capita capital stock. Finally, the total exposure value is obtained from the integration of the population in each pixel.
- GDP is distributed across the grid, assuming constant ratio GDP/capital stock for each aggregated sector.

Items located in collected GIS data are used as drivers to this downscale global data model that is not spatially distributed, such as population, residential stock, etc.

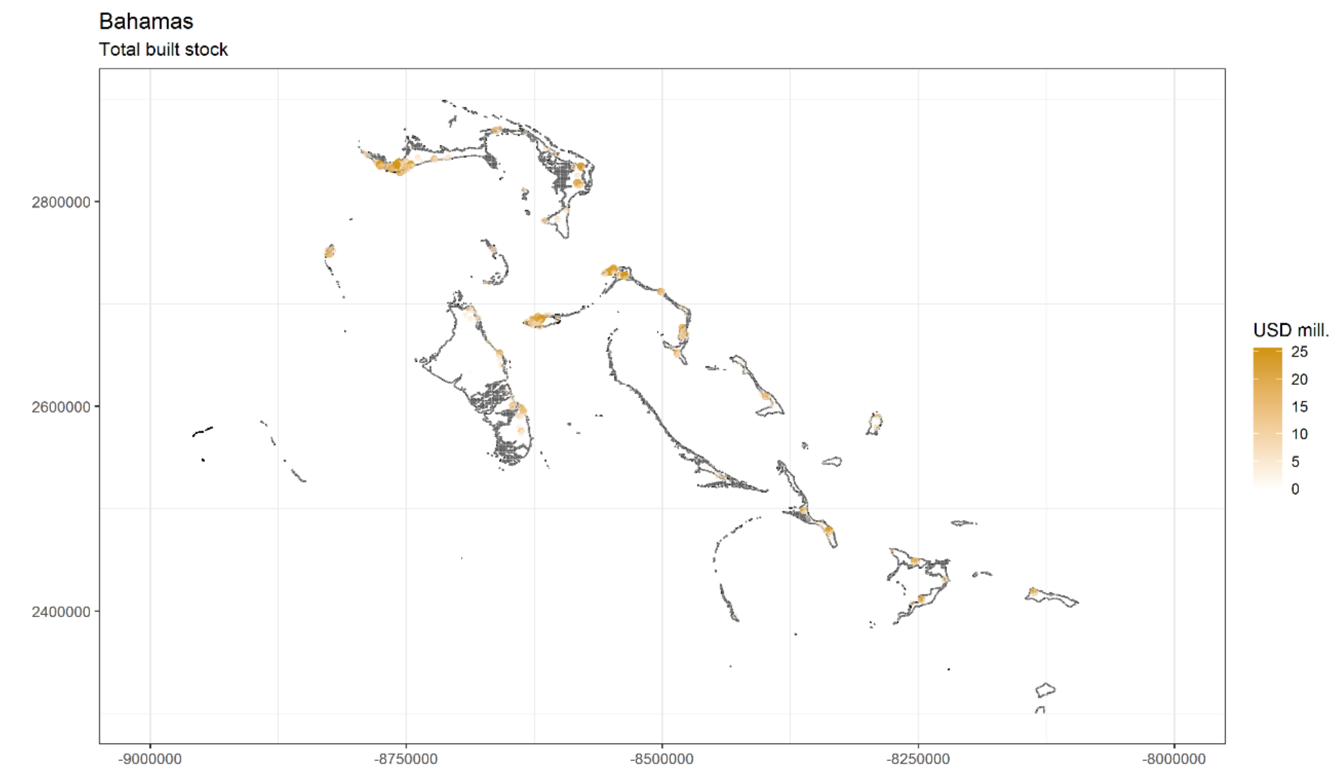
4.2.3. Physical Characterization

The results of the previous process have generated a distribution map of the different components of hazard exposed areas. Because different hazards are included in this study, global characterization of the existing elements are presented first. The assessment of the specific exposure associated with each of the hazard scenarios is then presented. This study includes the two level of exposure model: the spatial distribution of elements susceptible to hazards (exposure model); second, the spatial extent of the magnitude of the hazards (vulnerability model in combination with the exposure model).

4.2.3.1. Building stock characterization

Figure 40 shows the result of the exposure value of the capital stock. The largest concentration of capital stock is located on the New Providence, followed by Freeport. The remaining islands show a quasi-uniform spatial distribution with marginal values. This polarization is seen both residential and industrial, and services capital stock.

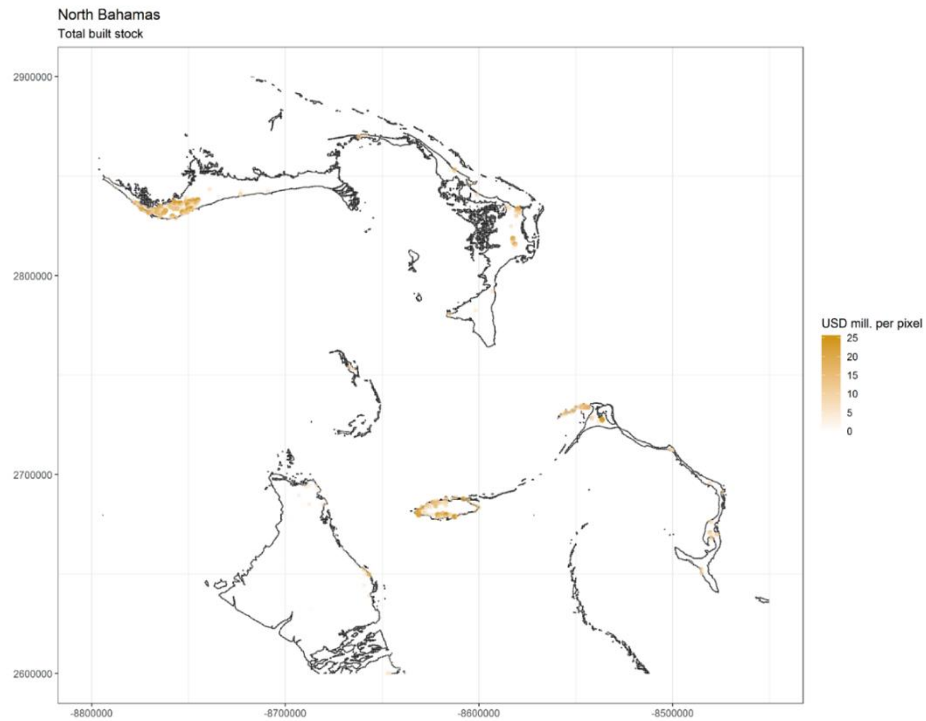
Figure 40. Spatial Distribution of Capital Stock in 2015



Source: Self-elaborated. *US$ M/Pixel.*

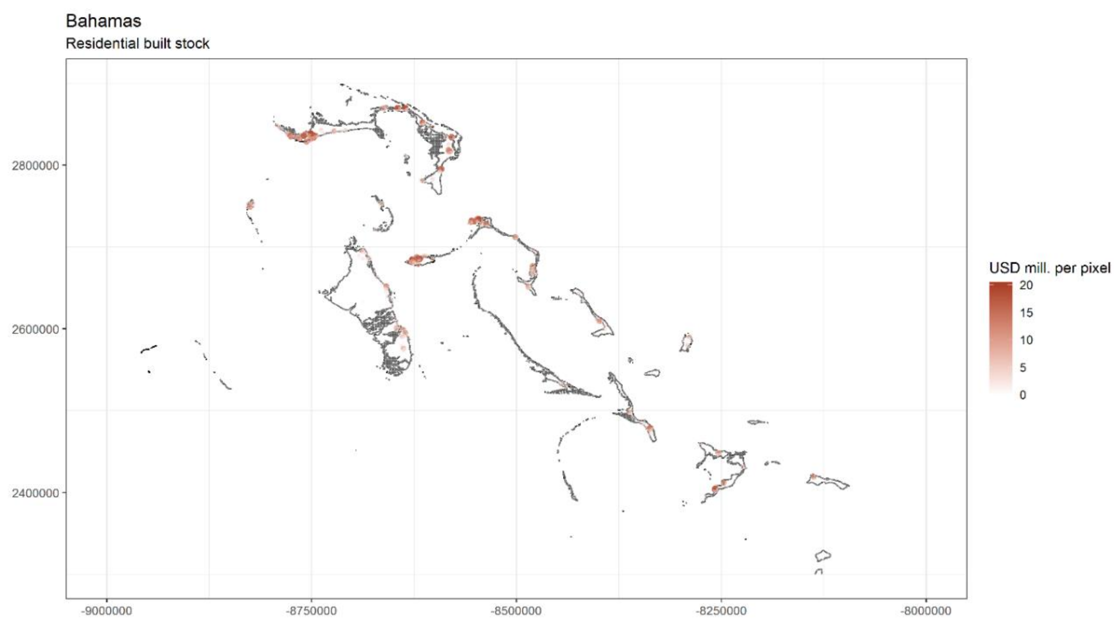
The residential capital stock is concentrated in the populated areas, specifically, in New Providence. This is relevant to understand the importance of hurricane trajectories on and around New Providence as a predictor for damage levels. This fact does not preclude that, at the local scale, any event affecting peripheral areas should be considered catastrophic in relative terms, although the magnitude of the consequences may not be considered relevant. Figure 41-44 show detailed illustrations of the capital stock in the populated areas.

Figure 41. Spatial Distribution of Capital Stock in the Northern Part of the Country (in 2015)



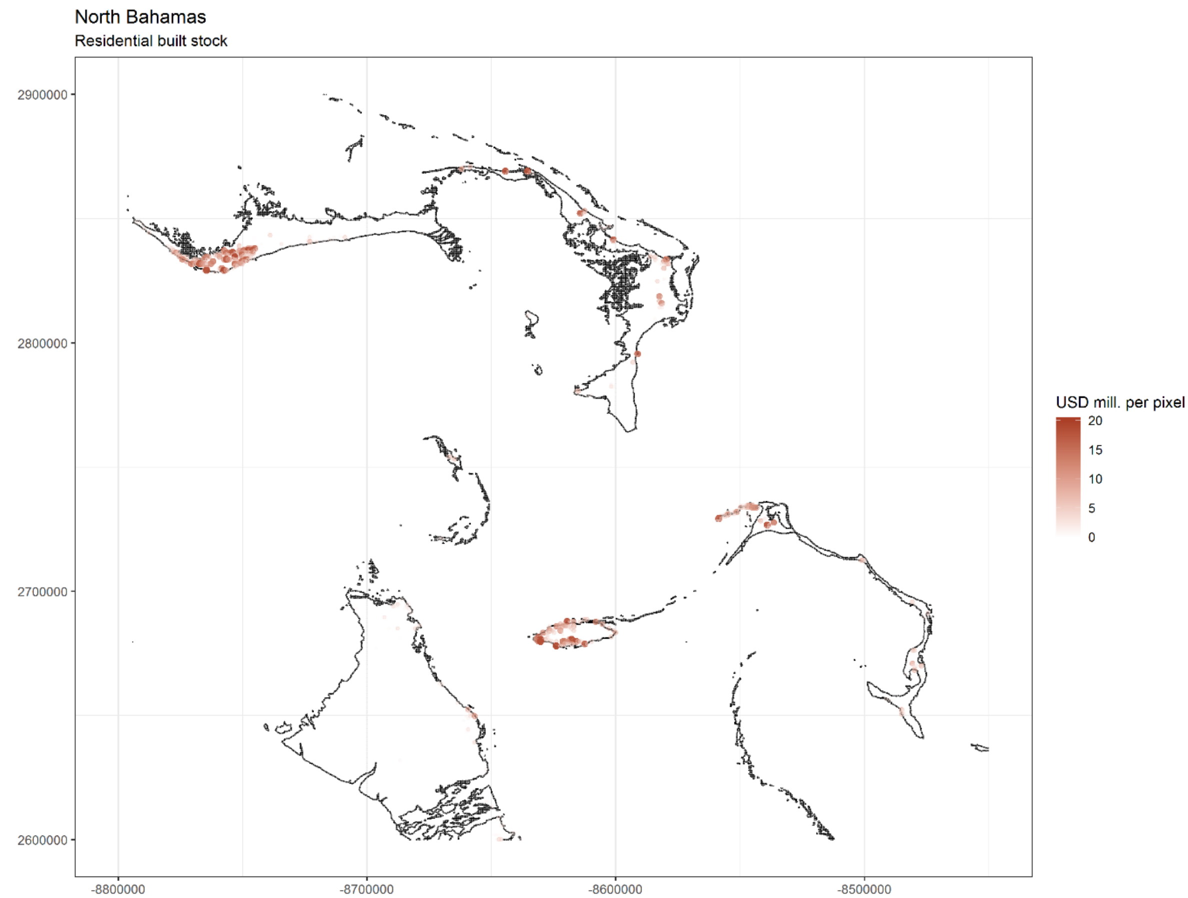
Source: Self-elaborated.*US$ M/Pixel.*

Figure 42. Spatial Distribution of Residential Capital Stock in The Bahamas (in 2015)



Raising the scale by zooming into the set of northern islands where the population is concentrated shows a detailed view of this distribution but does not alter the pattern (Figure 43). It should be noted that this distribution shows the influence of population data as a driver for downscaling.

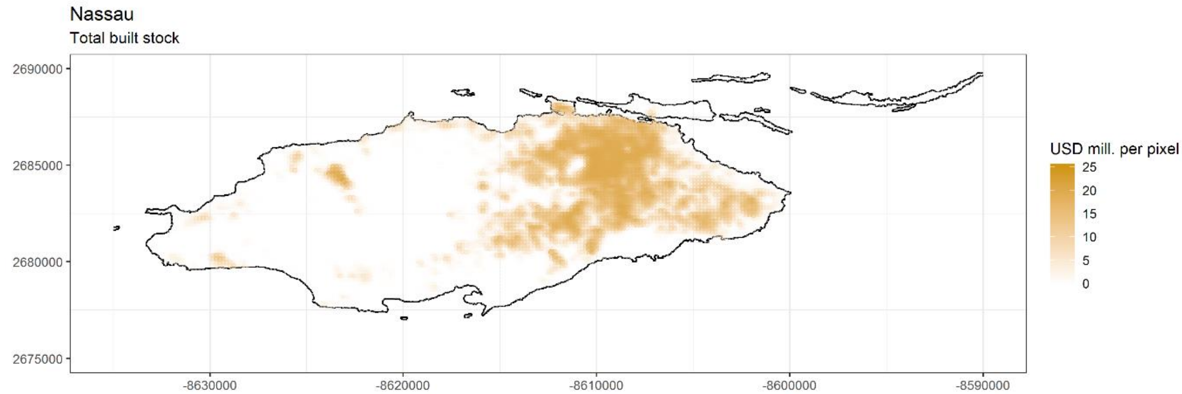
Figure 43. Spatial Distribution Capital Stock in Northern Bahamas (in 2015)



Source: Self-elaborated. *US$ M/Pixel.*

However, these results look different depending on the spatial scale of the map. If the whole territory of Bahamas is presented, the map shows a heavy concentration of data in New Providence, with small differences among other less populated islands that are hardly visible. If, on the contrary, a focus is made in local areas, differences become visible (Figure 44).

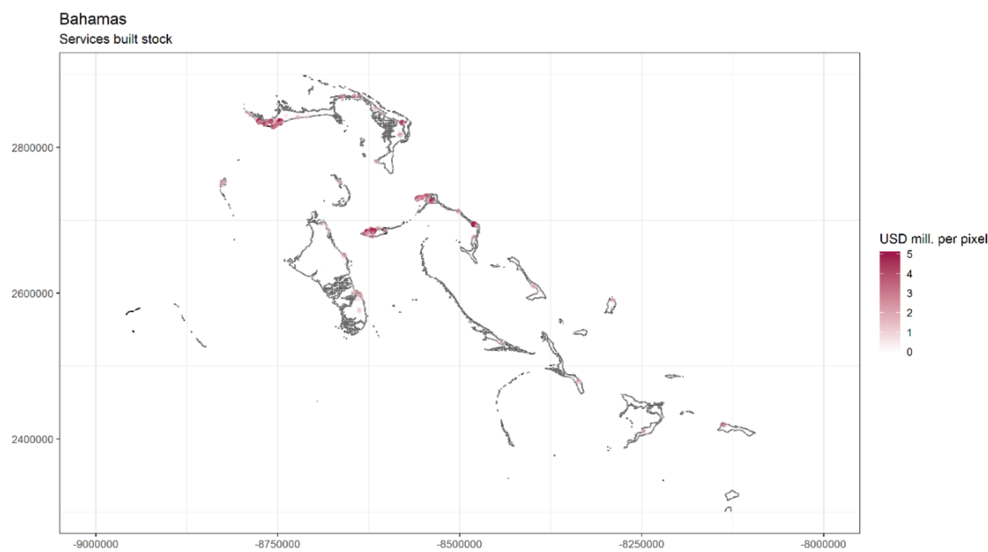
Figure 44. Spatial Distribution Capital Stock in New Providence, Bahamas for 2015



Source: Self-elaborated. *US$ M/Pixel.*

Concerning non-residential capital stock in each sector, population influence as a driver of downscaling can be observed again. This distribution should be more realistic than the demographic projection from the World Population Prospects database of the United Nations Population Division. Due to the country's relative specialization in financial services and tourism, the scope of the analysis focuses on the capital stock in services. The non-developed areas where no touristic activity exists are identified in the maps as white areas. Although no economic assets are in those areas, they should not be considered an empty space as natural assets because natural resources (or ecosystems) exist in the area with the potential to become an eventual source of economic services. Additional satellite image analysis was carried out to identify the number of touristic, administrative, health, and education facilities.

Figure 45. Spatial Distribution of Capital Stock for Services



Source: Self-elaborated. *US$ M/Pixel.*

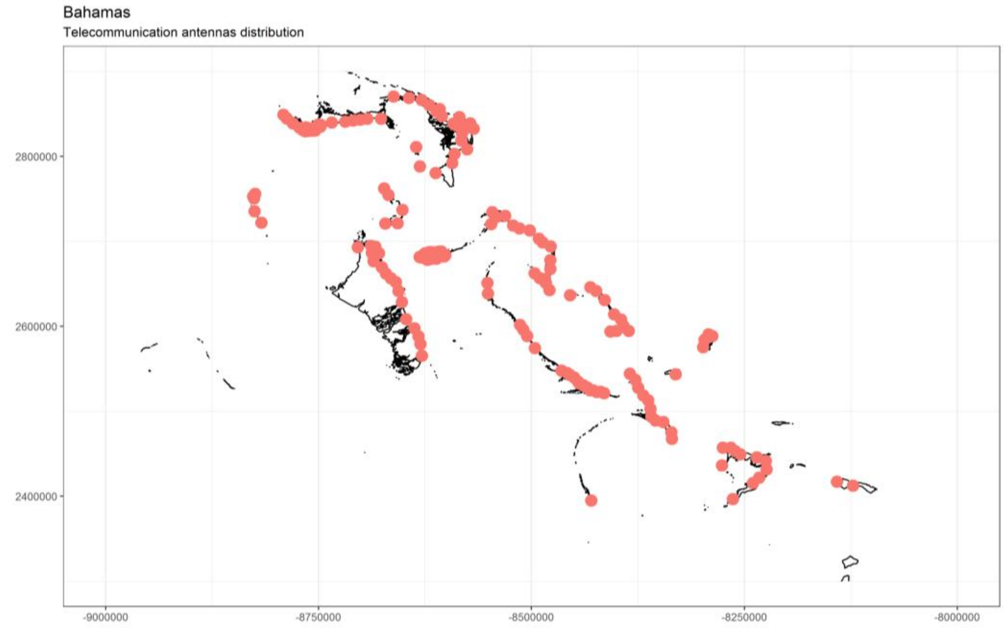
4.2.3.2. Inventory of critical infrastructure

The inventory of critical infrastructures in this study covers the basic services. Its damage produces a cascade negative effect and may alter the citizens' livelihoods. This study categorizes the following infrastructures as "critical":

- Education (e.g., schools);
- Health (e.g., hospitals);
- Administration (e.g., government offices);
- Energy networks;
- Transport nodes (e.g., airports) and networks; and
- Communication systems.

This study gave special attention to road infrastructure as it is representative of the infrastructure of the country. The compiled node information obtained (e.g., ports and airports) has also been used to calibrate the study sites. Data limitation for some elements was a challenge to develop an accurate result of the detailed exposure model, but fieldwork was made to try to fulfill this challenge. Figure 46 shows communication antennas as an example.

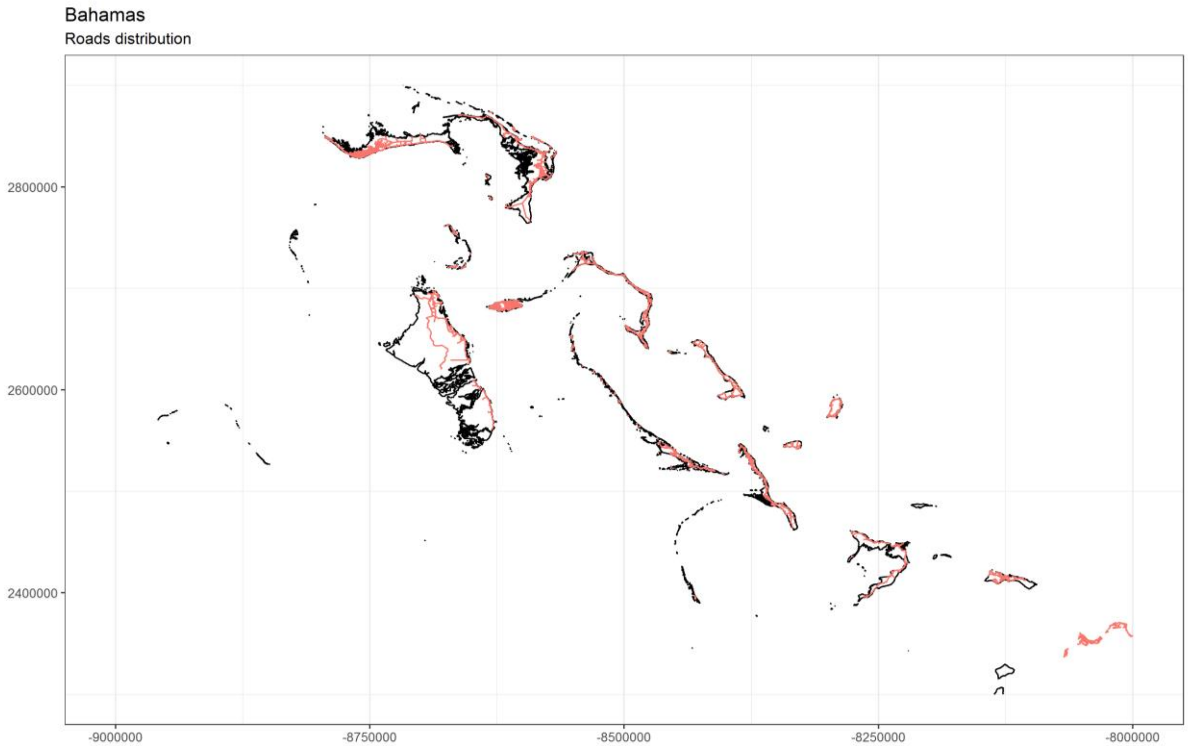
Figure 46. Spatial Distribution of Communication Antennas in Bahamas



Source: Self-elaborated.

Figure 47 presents the distribution of roads across the island. Most of the existing connections are located in New Providence.

Figure 47. Road Network Distribution in The Bahamas



Source: Self-elaborated.

The allocations of the infrastructure exposure values are estimated based on the services coverage of the population related to each type of infrastructure including the country's energy production, the number of mobile and fixed communication lines, and the level of exploited hydrocarbons. The exposure values are additionally estimated in combination with the population density and production centers in each geographical area.

Table 14. Exposure Value of the Critical Infrastructures in The Bahamas

Concept	Value (US $)
Roads (all Categories) 10,639.2 Km	6,787,809
Electrical supply equipment	7,029,140
Communication services equipment	5,974,769
Water Supply Networks	23,196,132
Water Sanitation equipment	11,598,081
Airports Terminals	882,003,549
Airports Runaway 67,5 km Asphalt 10.6 km Gravel	437,096
Ports (3 study sites)	1,456,489

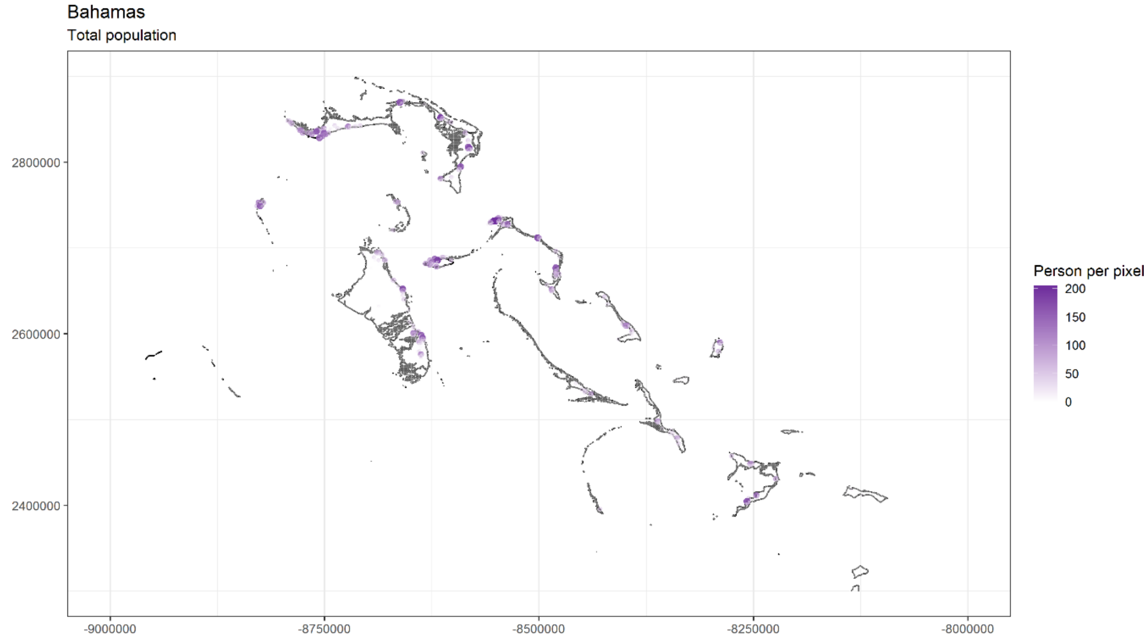
Source: Self-elaborated

4.2.4. Human Exposure

4.2.4.1. Characterization of population

The population analysis in The Bahamas indicates that most of the population is concentrated in New Providence. Any natural hazard affecting this island will reflect higher negative impacts. However, it should also be considered very relevant in relative terms as it still affects a high quota of local population and wealth.

Figure 48. Spatial Distribution of Exposed Population



Source: Self-elaborated. *Person/Pixel.*

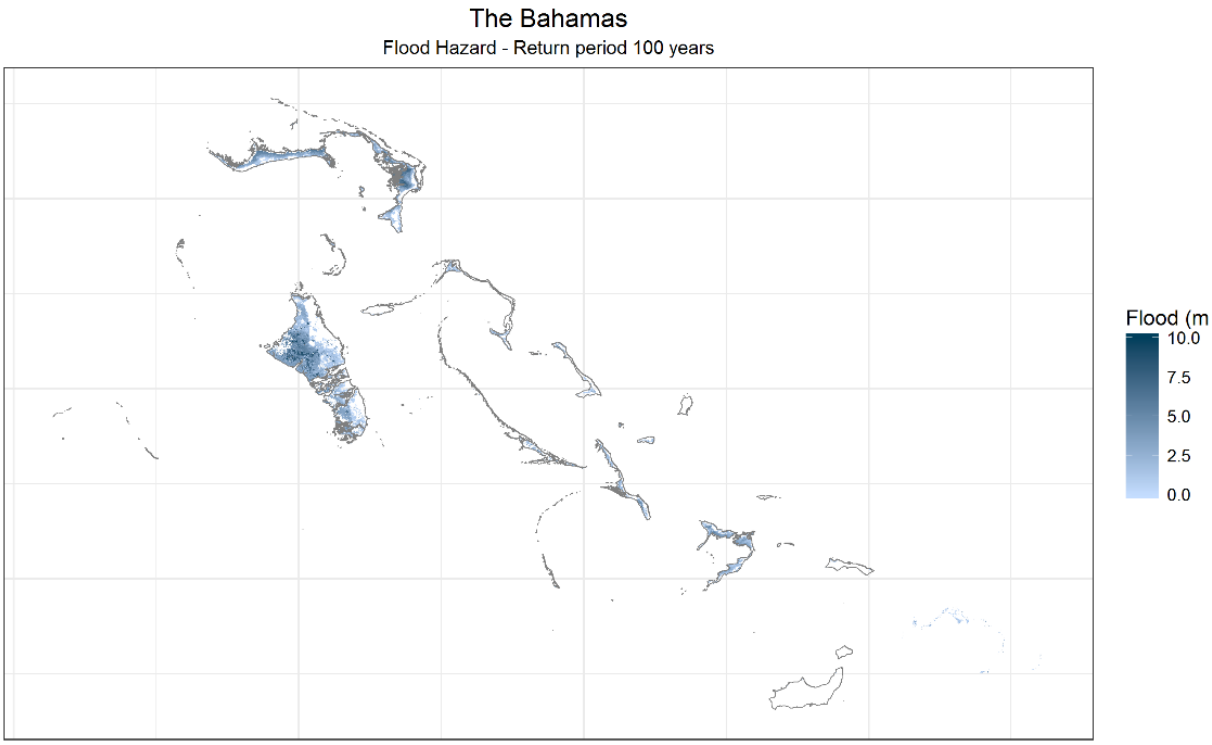
4.3. Exposure assessment under different hazard scenarios

This section assesses the different assets affected by potential hazards characterized by their occurrence probability. This information is presented as a function that offers the value of the elements at risk, or the population affected by the events associated with different probability levels located at different spatial nodes or units.

Exposure value estimation, to estimate the exposed value of the elements located in the hazard area, requires a combination of three hazard event attributions; first is a spatial distribution of local consequences of hazardous events (e.g., flood depth or wind speed) to determine whether existing assets are potentially affected. Second is the magnitude of the intensity in each local area of each event (e.g., flood depth or wind speed). The third is the probability hazard model (e.g., return period) to develop a probabilistic risk model.

The exposure model's result is conditioned by the spatial distribution, magnitude, and frequency of each hazard. Different exposure values are developed for each hazard of this study, including hurricane wind (covering the whole country) and flooding (covering specific study areas).

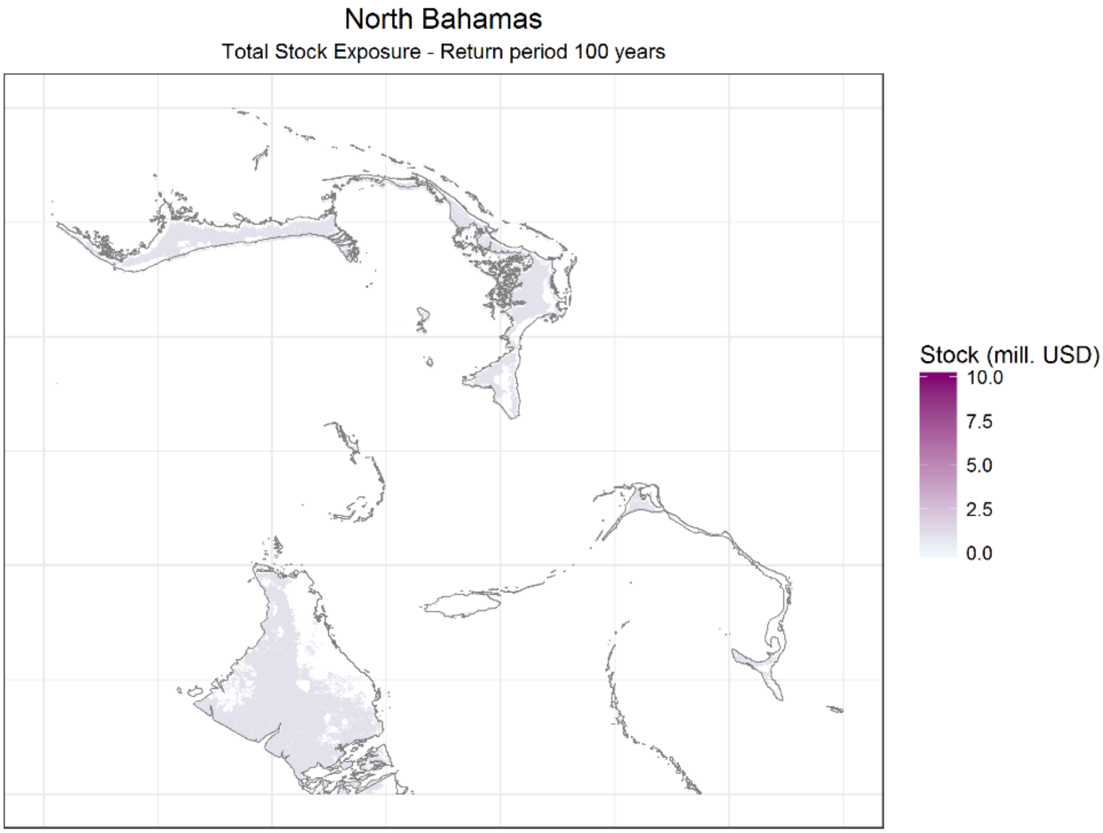
Figure 49. Spatial Distribution Hazard Intensity (100-year return period as a reference)



Source: Self-elaborated. *Flood depth (m) for a 100 year return period.*

Following this approach, some counterintuitive results can be observed as an area characterized by a high density of population and assets might not be exposed to a given hazard and hence an empty exposure map can be obtained in a heavily used area. This result may be confusing if characterization is identified with exposure independently of the hazard, which is a common assumption when dealing with multi hazard events. As can be seen in the previous figure, one can expect to obtain the highest values for exposure in Andros Island if hazard distribution is observed but the results are different when asset distribution is characterized.

Figure 50. Total Stock Exposure for a 100 Year Return Period of Flooding in North Bahamas



Source: Self-elaborated.

4.3.1. Exposure Results

The described procedure has been developed for the different return periods and a summary of the results is presented in this sub-section. Detailed results are included as an Annex.

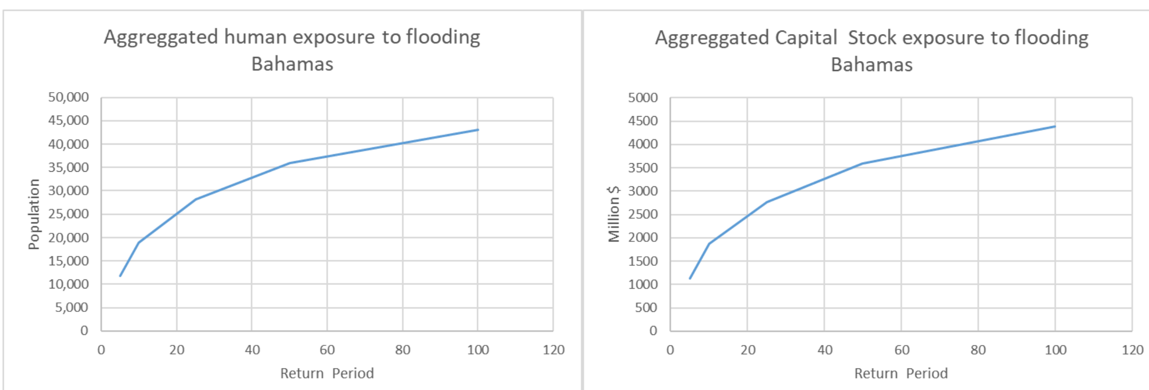
The global results obtained are described in Table 15 presenting the population and exposure value for different flooding return periods. The wind exposure is identical to the global characterization as described previously.

Table 15. Aggregated Exposure value in The Bahamas

Hazard	Scenario	Population (persons)	Assets (Million US$)
Wind	Characterization	351,461	45,282
Flooding	5 years Return Period	11,808	1,130
	10 years Return period	18,863	1,873
	25 years Return period	28,180	2,771
	50 years Return period	35,910	3,597
	100 years Return period	43,121	4,384

Source: Self-elaborated

Figure 51. Exposure value to Flooding in different return periods (the whole country)



Source: Self-elaborated.

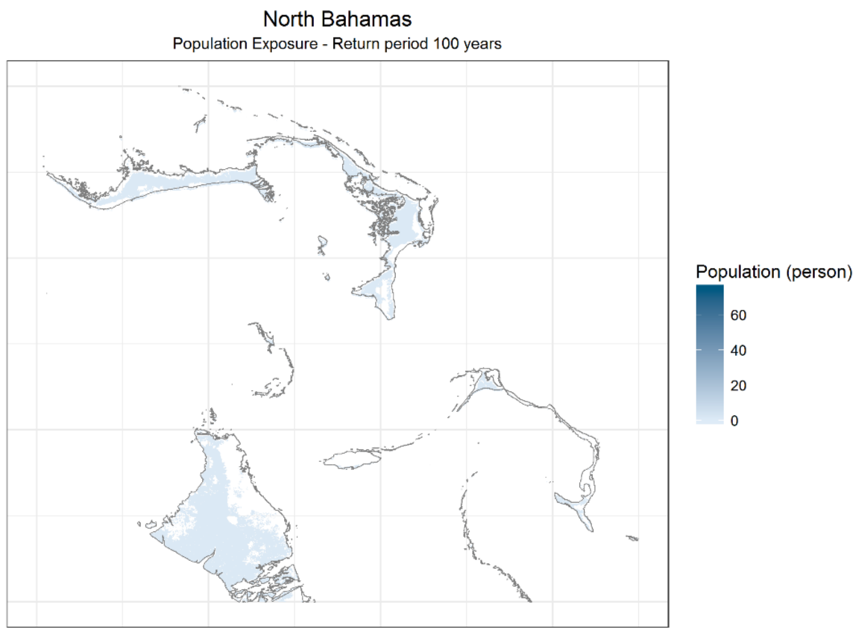
4.3.1.1. Exposure to flooding

The exposure of a 100-year return period is presented as example for demonstration purposes although a complete analysis is included as an annex.

Population Exposure

Figure 52 illustrates the current distribution of the population in the potential flood areas. In this figure there are some areas where no exposure is shown due to a lack of relevant hazards, while some areas show no exposure because of no flood hazards.

Figure 52. Human Exposure to Flooding in N Bahamas

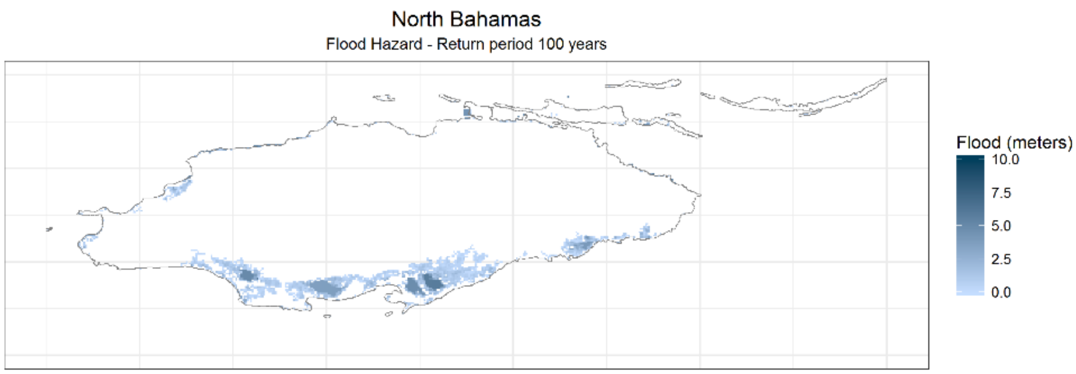


.

Source: Self-elaborated. *Population/person.*

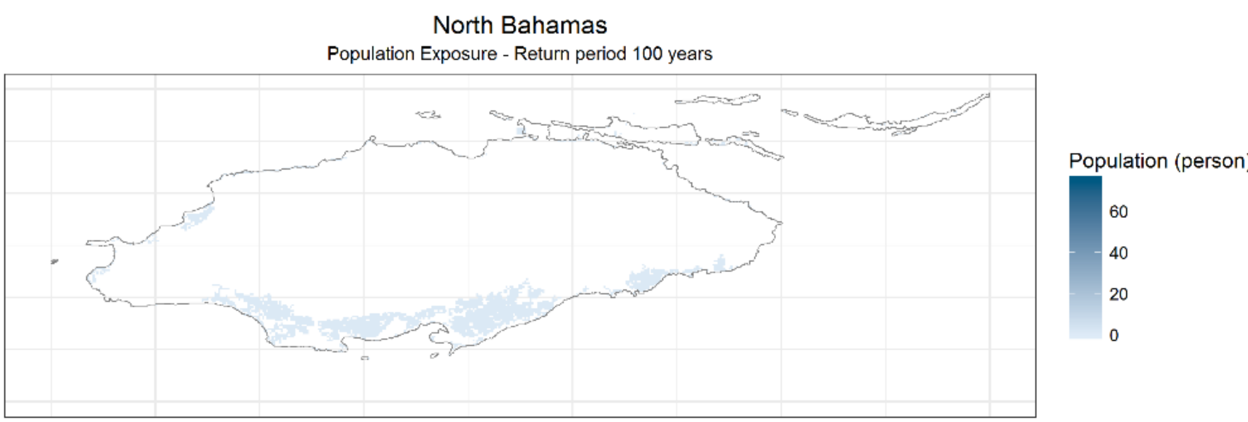
A more detailed view of New Providence's situation is presented in Figure 53, showing the small size of the potential flood hazard area. In contrast, the actual exposure in Figure 54 indicates that a small portion of the population live in these hazardous areas.

Figure 53. Hazard Impact in New Providence for a 100 Year Flooding Event



Source: Self-elaborated.

Figure 54. Population Exposure to a 100 Year Flooding Event in New Providence

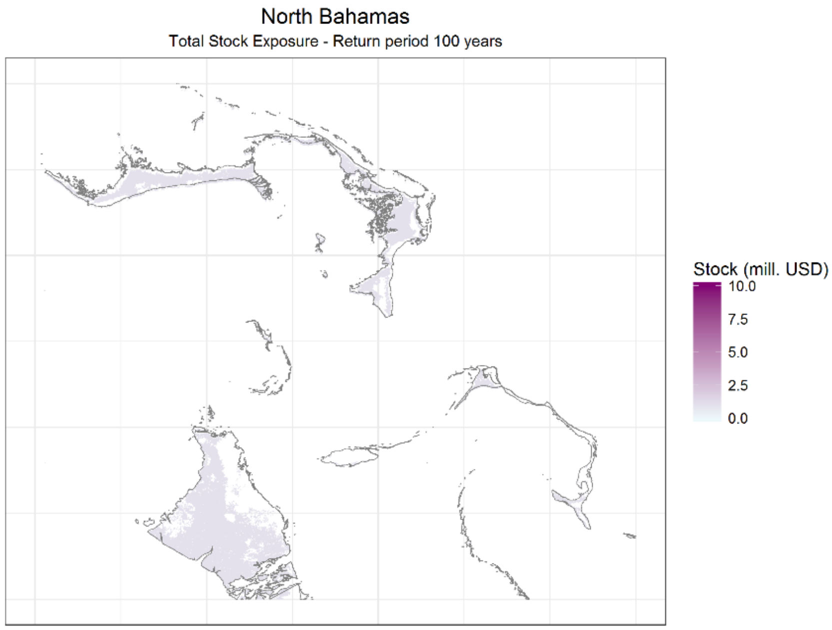


Source: Self-elaborated.

Capital Stock exposure

Figure 55 presents the distribution for capital stock exposure to flooding for North Bahamas.

Figure 55. Total Stock Exposure to a 100 Year Flooding Event in The Bahamas

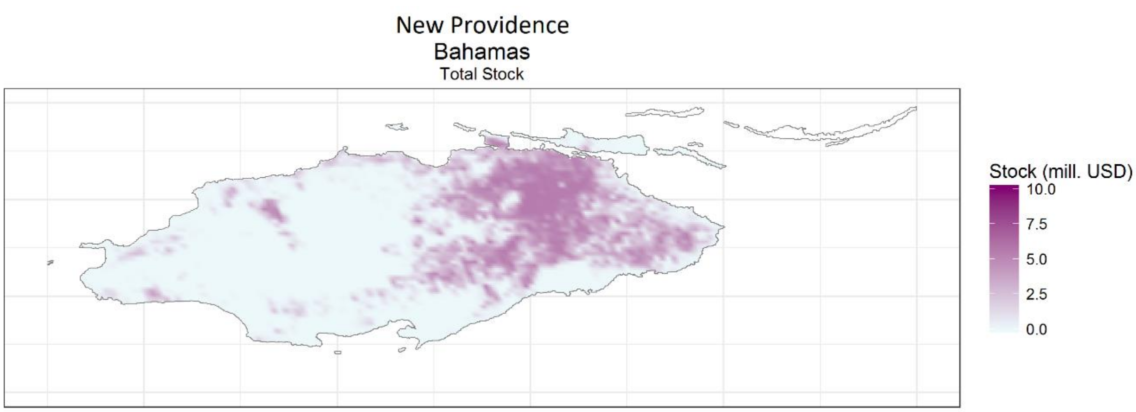


Source: Self-elaborated.

4.3.1.2. Exposure to wind

For exposure to wind, this study assumed that global characterization of assets and population are used as exposure. Therefore, the results for exposure to wind is the same as the characterization included in section 4.2.

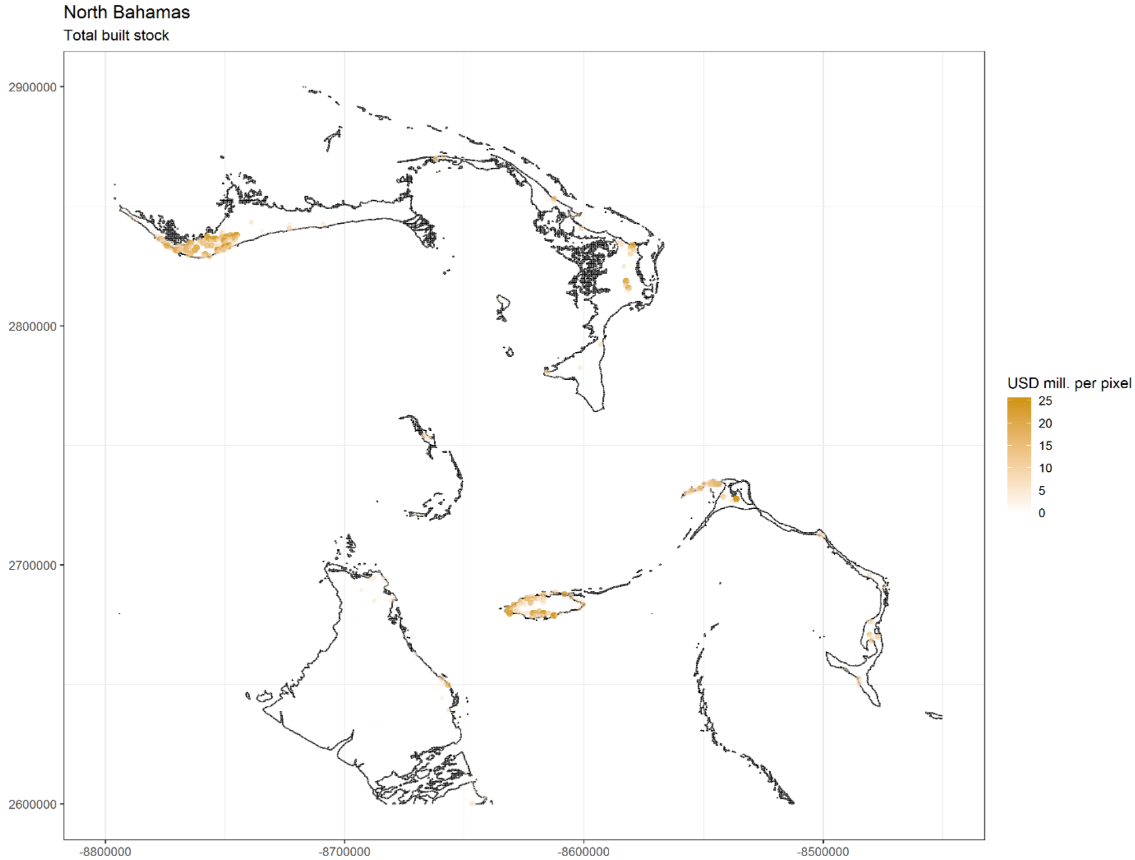
Figure 56. Capital Exposure to Wind in New Providence



Source: Self-elaborated.

Additional views at different scales can be seen as previously described in the introduction.

Figure 57. Capital Exposure to Wind in Northern Bahamas



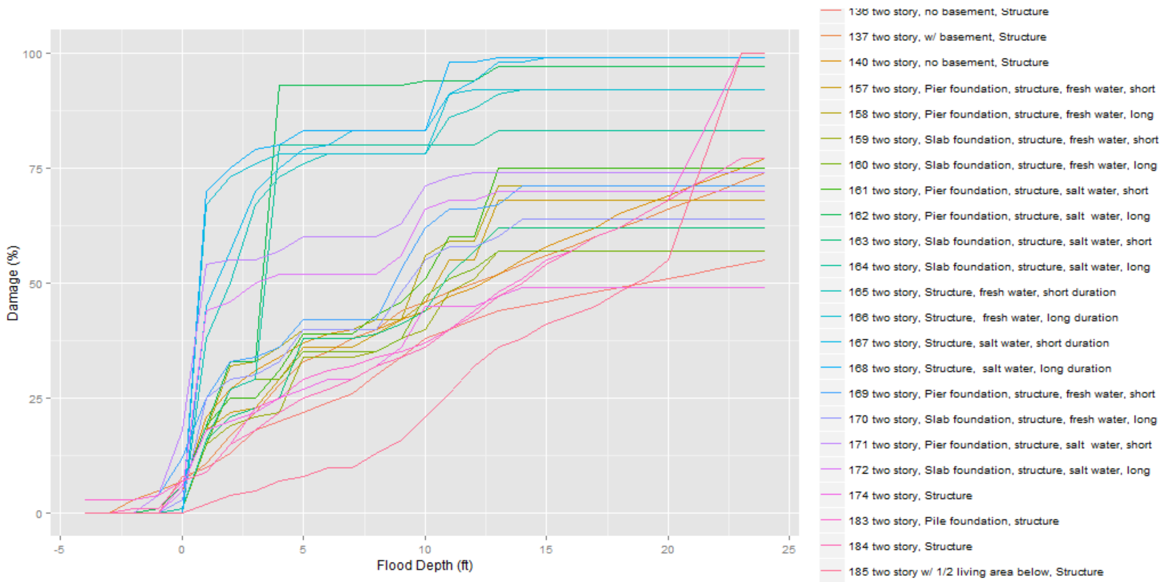
Source: Self-elaborated.

4.4. Vulnerability Functions

In this study, vulnerability is referred to as a measure of the relative impact derived from the range of potential hazards at each point over the exposed element. The result is presented as a percentage of exposed value damaged. A set of vulnerability functions are used in this study. The following sources were used for this purpose:

- HAZUS: The US Federal Emergency Management Agency (FEMA) platform Hazus (Hazus, 2009) has compiled an extensive set of functions for different built elements covering both contents and structure (typical curves for specific building typology and elements of different hazards e.g., coastal flooding, river flooding, and wind. See Figure 58). This source provides a semi-empirical solution to estimate potential damages on a general basis.

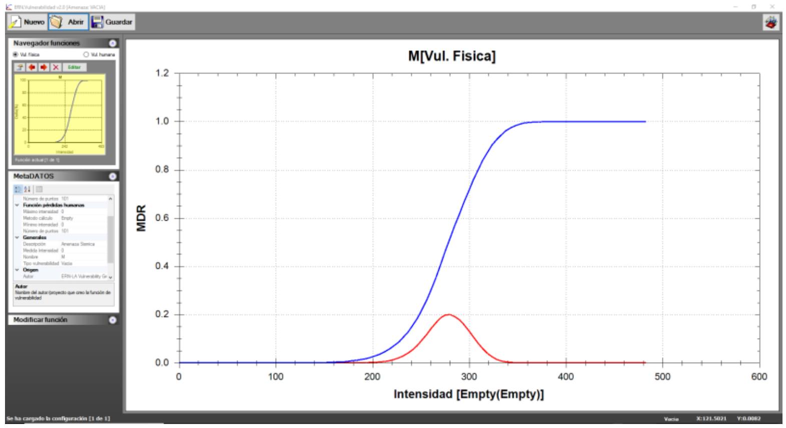
Figure 58. FEMA-HAZUS Damage Functions Example



Source: HAZUS/FEMA, 2009.

- CAPRA (Figure 59): Under the Capra Initiative, a platform with a broad set of damage functions have been compiled and adapted to the Latin-America and Caribbean regional conditions. This source covers different typologies of elements and hazards. This approach is essentially a theoretical proposal applicable when empirical data are absent, though calibration is required.

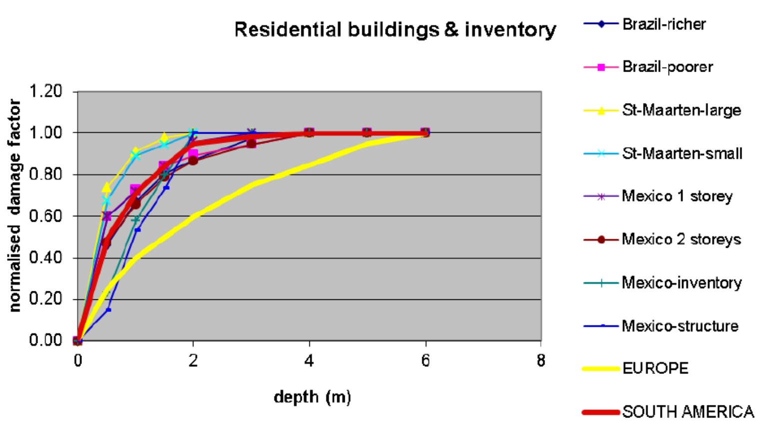
Figure 59. CAPRA Vulnerability model



Source: CAPRA.

- JRC (Figure 60): The Joint Research Centre of EU has surveyed all the existing vulnerability functions across countries (Huizinga et al., 2017). In this survey, transnational comparatives are introduced, and differences connected with different asset robustness and cultural issues can be observed.

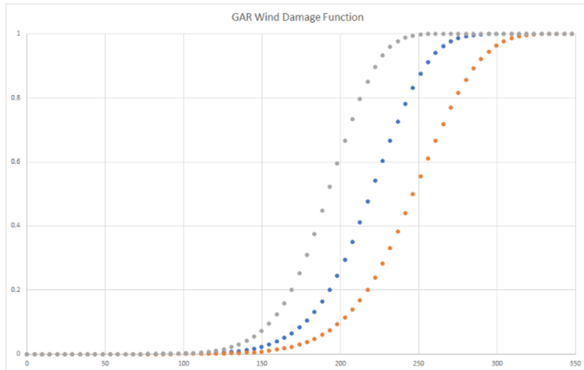
Figure 60. JRC Transnational Comparative Depth Damage Functions



Source: Self-elaborated from Huizinga et al., 2017.

- UNISDR has also developed a broad set of vulnerability functions covering a detailed set of hazards for a conventional structural typology of assets (Figure 61). As can be seen, mathematically smooth functions have been selected, and dose-response ratios for limit cases have been calibrated.

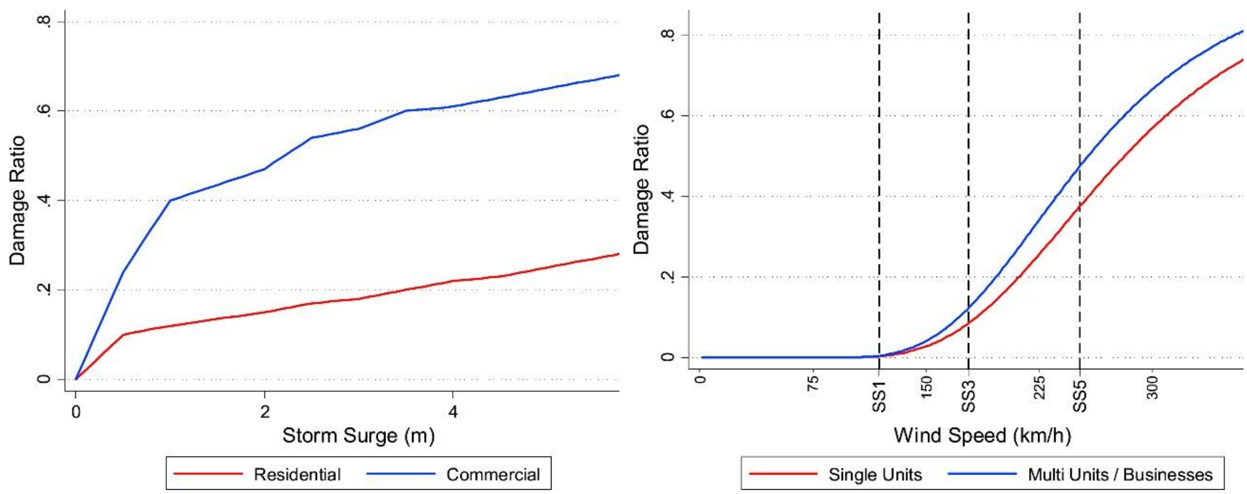
Figure 61. GAR 15 Selected Damage Functions



Source: Self-elaborated from Yamin et al., 2014.

Relevant work has been obtained in the literature review, presenting results that can be transferred to our case. Specifically, Sealey et al. (2017) present an interesting analysis of hurricane impact on the island in Great Exuma with ad-hoc calibrated vulnerability functions (Figure 62).

Figure 62. Local Vulnerability for Storm Surge and Wind in Great Exuma



Source: Sealey et al., 2017.

- Finally, under the UK government initiative, a set of functions were also collected from the Multi-Coloured Manual (Penning-Rowsell, E et alt 2013). This solution is country sensitive, and its measurements are in sterling pounds for a given year.

The sources used have been adapted to the study's specific needs:

- Among the broad databases found in the literature, the vulnerability functions that better match the structure and typology of the specific condition of The Bahamas' assets and the hazards were selected;
- A balance was made to select the vulnerability functions between empirical and theoretical contributions. Empirical sources help to determine the specific behavior of the impact, and theoretical sources are useful to calibrate and validate.

Specific functions were calibrated for the conditions present in the exposed areas. Following the standards, the vulnerability functions were expressed in relative terms (% of exposure destroyed) and were adapted to specific hazards. In this regard, it should be noted that vulnerability to flooding will be obtained with a lower level of uncertainty as it is realistic to express the prediction based on depth as a single explanatory variable. The situation is different when vulnerability to the wind is expressed only in connection with wind speed, be it maximum or average. Finally, vulnerability to erosion was specifically defined for local sites through a semi-empirical analysis of the impact.

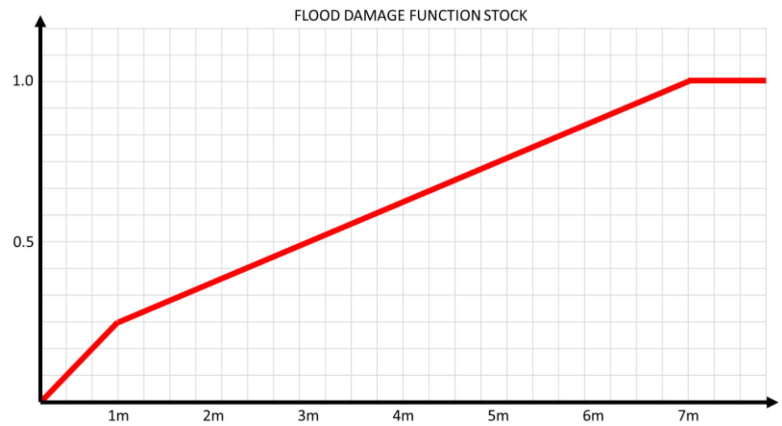
4.4.1. Physical and human vulnerability

4.4.1.1. Damage functions for residential buildings

Summarizing all the available information, a set of specific vulnerability functions has been compiled and calibrated for the study sites. Figure 63 and 65 indicates the selected vulnerability functions for coastal flooding and hurricane winds.

Figure 63. Flooded Homes in Grand Bahama

Source: The Bahamas Weekly[4] (in 2012).



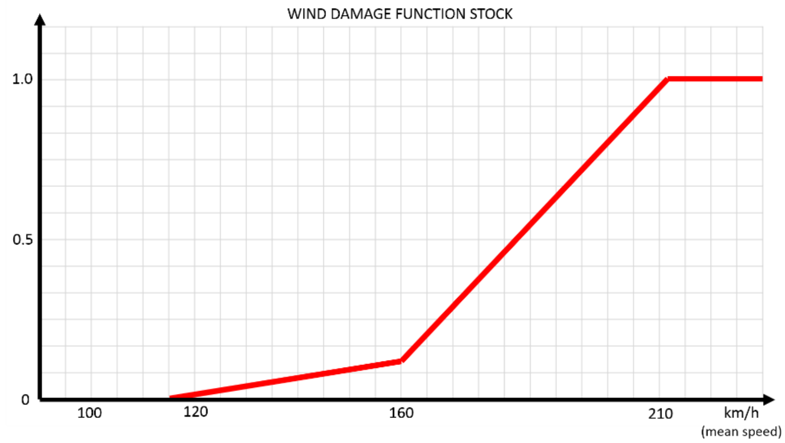
Source: Self-elaborated.

Figure 64. Houses Damaged by Wind in Grand Bahama

Source: Self-taken.

4 www.thebahamasweekly.com/publish/grand-bahama-bahamas/GBPA_Building_Development_Officials_Urge_Inspections_in_Flood_Areas24854.shtml.

Figure 65. Example of Depth Damage Functions for Capital Stock Due to Wind



Source: Self-elaborated.

The selected functions combine and simplify the existing alternatives collected in the previous step of the analysis and were calibrated with damages from historic events. The wind damage function has been adjusted by integrating both the peak wind and mean wind speed (see Table 16).

Table 16. Adopted Equivalences

Mean wind speed		Conversion factor	Peak wind speed	
Mph	km/h		mph	km/h
50	80	1.90	93	150
62	100	1.75	109	175
75	120	1.66	125	200
100	160	1.56	155	250
130	210	1.37	180	290

Source: Self-elaborated

4.4.1.2. Critical infrastructures damage functions - roads

The focus of the analysis for roads is made on the length of affected (or potentially flooded) roads, hence no damage function is introduced to assess the different impacts on the road at points with different depths. An identity function is used, considering a road section affected when the eventual flood height reaches 0.5 meters. The purpose of this threshold is to avoid including minor flooding events that are not damaging infrastructure and whose treatment should be included in regular maintenance. No damages are considered for road networks caused by extreme winds.

4.4.1.3. Human vulnerability

The hypothesis for this study's human vulnerability is that all people residing in areas affected over a certain threshold are identified as victims, affected by the event with equal affection intensity. This hypothesis implicitly suggests that people will eventually receive emergency support, not assuming their condition of mortal victims, and not qualifying the degree of impacts suffered. The vulnerability function is then the identity function that characterizes all the exposed people as affected when the eventual flood height reaches 0.5 meters and when wind peak speed reaches 175 km/h.

5. RISK ASSESSMENT

5.1. Introduction

This chapter presents and discusses the Risk Assessment results based on previous chapters' all methodologies and results. This risk assessment is based on:

- evidence and historical records of damage due to hurricanes;
- an analysis of the probabilistic damage based on the distribution of synthetic events; and
- the integration into the Hybrid Loss Exceedance Curve of both analyses.

The description of historical damages and their probabilistic estimates is presented in section 5.2, and the analysis of the probabilistic hurricane damage is provided in section 5.3. Then, the Hybrid Loss Exceedance Curve is computed by combining both historical and probabilistic sources. Finally, these results are discussed in section 5.4.

5.2. Historical disaster loss assessment

The Bahamas is located in the Atlantic hurricane belt. This archipelagic state has a long record of land-falling hurricanes. Historical events have been registered from the early 19th century (e.g., 1804, Hurricane of Antigua Charleston) to recent times (e.g., 2017, Hurricane Irma). The evidence of impacts and damages from tropical cyclones in various islands of The Bahamas reveal a vision of the hurricane exposure to the Bahamian society as an intrinsic component of its history.

In this section, first, the sources of information for historical records of damages triggered by hurricanes in The Bahamas are enumerated, the applied methodology to estimate a Historical Loss Exceedance curve is roughly described (further details can be found in Annex 2, Historical Disaster Loss Assessment) and the obtained results are presented and discussed.

5.2.1. Sources of information

In this study, effects and impacts caused by historical hurricanes in The Bahamas have been extracted from several reports:

- The Caribbean Catastrophe Risk Insurance Facility (CCRIF); and
- The Economic Commission for Latin America and the Caribbean (ECLAC).

Additionally, the probabilistic characterization of past events in this Historical Disaster Loss Assessment is based on the Probabilistic Hazard Assessment presented in Chapter 3 of this report (see corresponding sources of information in section 3.2).

5.2.2. Methodology

This section describes the methodologies that have been applied to develop the risk assessment. On the one hand, the damages associated with selected historical events have been characterized and, on the other, the ex-ante probability of occurrence associated with each event has been estimated.

Regarding the records of damages, not all available information from historical hurricanes is suitable, but only a small set of truly representative events have been included in this study, focusing on recent experiences and detailed ex-post analysis of impacts.

Concerning the ex-ante probability of occurrence associated with an event (see section 5.2.2.2), it has been estimated as the observed relative frequency of similar events (in terms of trajectories and intensities) among all historical and synthetic tropical cyclones in the developed database for the Hazard Assessment (see section 3.3.3). Details of the methodology for estimating the probability of occurrence of historical events can be found in Annex 2 (Historical Disaster Loss Assessment).

5.2.2.1. Selection of historical records of damages

Regarding the records of damages, as mentioned before, not all available information from historical hurricanes is suitable. In order to assess this suitability, the following two criteria have been considered in the data selection process:

1. Records of damage from remote events are less accurate predictors of current and future expected damages. Past events can provide valuable statistical information related to the atmospheric dynamics, but they do not reflect the evolving socioeconomic framework properly; and

2. The quality of available post-event analyses is far from being homogeneous and the reliability of recorded data decays with time.

According to these criteria, this study has pre-selected only those events that under socioeconomic circumstances that are similar to the current situation. Of these pre-selected events, only records of damages that were reliably estimated have been used in the analysis.

A selected sample of events with registered damages collected from the available sources of information is presented in Table 17.

Table 17. Collected Data on Damages Caused by Hurricanes in The Bahamas

Year	Name	Return Period of Max wind (1)	Peak Wind in The Bahamas (1)	Categories	Damages in millions of US$ (2)	
					Current US$	Constant 2016 US$
1928	San Felipe II	250	230 km/h	5	100.0	1,127.7
1929	Bahamas	400	264 km/h	4	676.0	7,608.1
1947	Fort Lauderdale	200	190 km/h	4	-	-
1992	Andrew	500	260 km/h	5	250.0	394.7
1999	Floyd	300	250 km/h	5	21.0 **(3)**	29.2
2001	Michelle	**(4)**	-	4	-	-
2004	Frances	75	200 km/h	4	1,454.6	1,828.6
2004	Jeanne	50	195 km/h	3	-	-
2005	Katrina	-	-	TS	-	-
2015	Joaquin	75	210 km/h	4	120.3	121.8
2016	Mathew	500	260 km/h	5	431.6	431.6

(1) Source: CCRIF (2014);

(2) Source: ECLAC;

(3) Damages not reported; data from IDB used as estimate (Source: Wikipedia); and

(4) Damages derived by heavy precipitation, not wind.

Records of damages in Table 17 from the original sources of information were expressed in current US$. They were transformed into constant 2016 US$ using the implicit deflator method, so that the result is free of monetary perturbation. However, even after this monetary transformation, older records of damages (such as those of the Hurricane of 1929) have not been used in the study due to the changes in the relative importance of damages for the Bahamian society of 1929 compared to the current Bahamian society. Indeed, the extreme values in Table 18 related to events occurring almost a century ago, when exposure and vulnerability were very different from to the current situation, cannot be integrated into the analysis of the Bahamas' current socioeconomic reality.

Finally, although the registry of historic damages due to hurricanes in The Bahamas starts in the 19th century, the series of reliable data starts by the end of the 20th century.

As a result of the proposed criteria along with the data assessment that has been performed, records of damage from only a small set of truly representative events have been included in the analysis (see Table 18), focusing on recent experiences and accurate ex-post analysis of impacts.

Table 18. Records of Damages for the Selected Sample of Hurricanes in The Bahamas

Hurricane	Year	Damages Constant 2016 US$
Matthew	2016	431,591,212
Joaquin	2015	121,817,417
Frances	2004	1,828,619,561
Andrew	1992	394,714,468
Floyd	1999	30,000,000

Source: IDB and ECLAC.

Additionally, using the data analysis of historical records of damages, some information of relevance for the calibration and validation of the Probabilistic Risk Assessment (see section 5.3) have been collected and processed. A detailed description of this information has been included in Annex 2 (Historical Disaster Loss Assessment), since it is part of the Historical Disaster Loss Assessment. However, this information was not used for the development of the Historical Loss Exceedance Curve.

From this observed distribution of damages for 27 years, the return period of the damage can be obtained. The estimated frequency of harmful events is 0.185 major impact events per year. Assuming high category hurricanes occur every year, major events can only be approximately observed every 5.4 years.

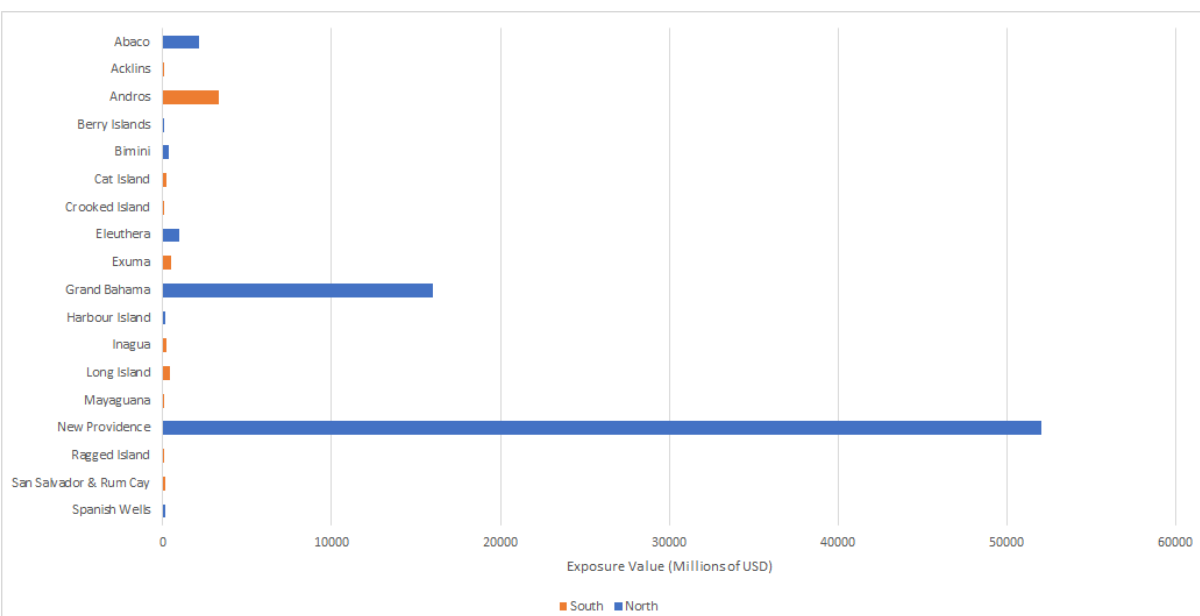
Table 19. Return Period for the Historical Damage Series

Hurricane	Year	Damages Constant 2016 US$	Probability being overpassed in 27 years	Return period for a single year Years
Floyd	1999	30,000,0000	0.185	5.4
Joaquin	2015	121,817,417	0.148	6.75
Andrew	1992	394,714,468	0.111	9
Matthew	2016	431,591,212	0.074	13.5
Frances	2004	1,828,619,561	0.037	27

5.2.2.2. Probability of occurrence of historical events

Table 20 reveals that neither the peak of the wind, nor the maximum wind's return period are reliable proxies of the economic impact. This can be due to other concomitant hazards that might increase the damages associated with an extreme wind event (e.g., coastal flooding or erosion) dramatically, and also to the fact that the track of the cyclone is key in the analysis. Indeed, the amount of damages depends critically on which island is hit by the hurricane, since the final impact is related to hazard intensity and exposure spatial distribution, which varies dramatically among islands (see Figure 66).

Figure 66. Exposure Distribution in The Bahamas/Island

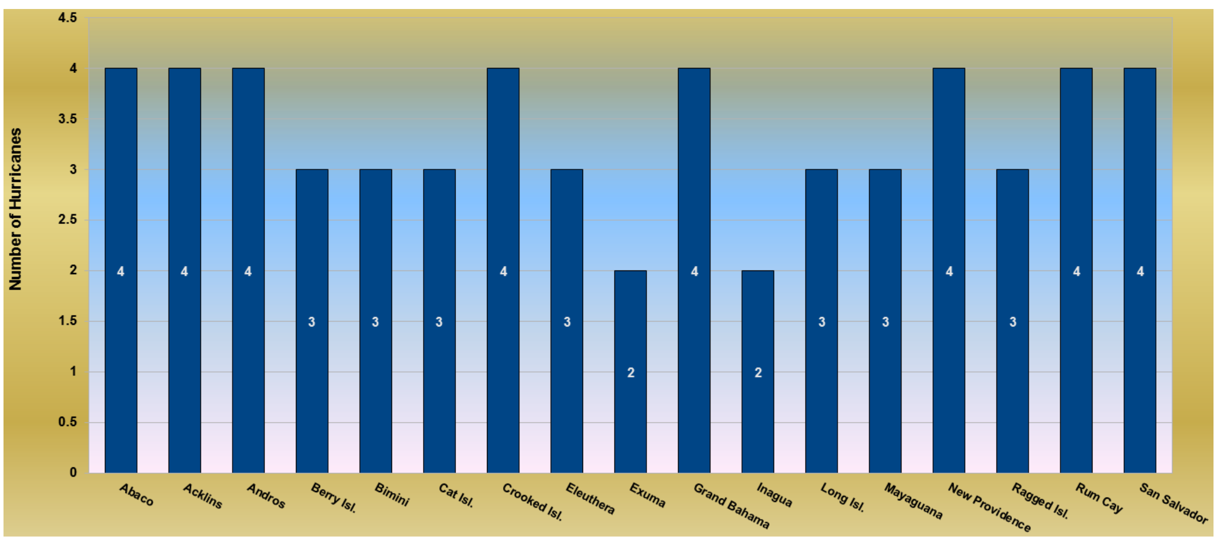


Source: Adapted from CCRIF (2014).

The strong variability of exposed assets and activities among islands justifies that events associated with intense tropical cyclones (in terms of strong winds) derive from catastrophes (global or local), depending on the island or islands where the tropical cyclone landfalls. Thus, the most serious damages are associated with New Providence and Grand Bahama, where most of the Bahamas' economic activities are concentrated. There is an obvious asymmetry in the distribution of expected damages along the archipelago of The Bahamas in general terms. Massive damages take place when hurricanes landfall on northern islands that concentrate most of the population and economic activities, whereas low damages can be triggered by either low intensity events in the north or high intensity events in the south of the country.

Irrespective of the damages caused, a review of the more recent events per island is presented in Figure 67, which shows that most islands are affected by significant hurricanes approximately once in 15 years, as additional evidence.

Figure 67. Number of Hurricanes Impacting Individual Bahamas Islands for 1960-2008



Source: Bahamas Met Office.

There is an intrinsic uncertainty associated with the return period of the tropical cyclones that caused those damages because of a small set of registered historical events. Therefore, to calculate the return period associated with each of the selected historical events, this study used a database including historical and synthetic tropical cyclones.

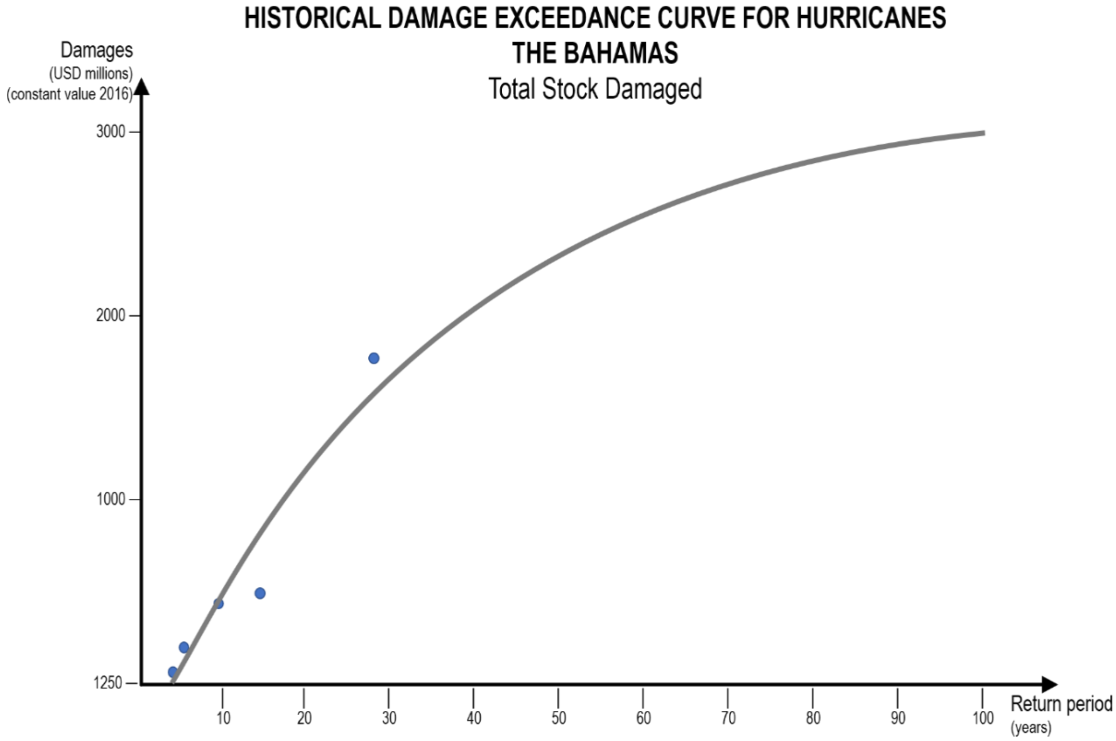
In summary, this study includes the influence of both hurricane trajectory and intensity with the return period associated with the event. Consequently, the probability of a historical cyclone (with a certain trajectory and intensity) is estimated as the probability of events with similar trajectory events, times the probability of events with the same intensity (conditioned to the

selected similar trajectories). This probability is based on the relative frequency calculated as the absolute frequency of similar events normalized by the total number of tropical cyclones in the database developed for the Hazard Assessment (historical and synthetic events, see Chapter 3).

5.2.3. Results

The combination of the observed damages in Table 19 and the estimated return period in Table 20 for the selected historical events yields the Historical Loss Exceedance Curve presented in Figure 68, which includes only records of damages that can contribute to the perception of the risks faced by the Bahamian society at the time of this study (damages recorded in the early years of 20th century have been discarded due to the dramatic changes in the exposure and vulnerability of The Bahamas after 1950). In spite of the reduced set of historical events in the historical loss exceedance curve presented in Figure 68, which has a limited capacity to represent events with high return periods, note that an extrapolation of results is presented based on the regression fit to the selected events. A series of representative phenomena covering 26 years is built.

Figure 68. Historical Loss Exceedance Curve for Hurricanes in The Bahamas



Source: Self-elaborated. *Selected sample of events (blue dots), analytical approximation (gray line).*

A comparative analysis for cross validation of these results with other similar studies has been performed:

- In comparison to the assessment by Landry (2017), observed differences in results are due to differences in the selected sample to estimate the probability of damages for the current society: Landry (2017) included remote events in the analysis, whereas in this study only data corresponding to recent events that affect a society that resembles the current situation of the country has been included in the analysis. This approach is more restrictive than a simple update of monetary values. As an example, The Bahamas in 1928 presented a lower level of exposure in comparison to the current situation in terms of the number of houses and quality of services, which means that the catastrophic hurricane in 1928 affected a country with only 24% of the current population and lower wealth. Therefore, those damages are not representative of the current situation. Additionally, differences can be partially explained by the kind of index used for monetary update: in this study, the GDP deflator (representative of overall products in the economy) has been used, instead of the consumption-based price index used in Landry (2017).

- A similar discussion can be applied to differences between results in this study and the Global Assessment Report on Disaster Risk Reduction (GAR) by UNISDR (2015), since GAR included the same data as Landry (2017). Moreover, there are differences in the applied statistical analysis to obtain the probability of recorded damages: in this study, return periods have been estimated from the probability of the selected hurricanes, whereas in GAR, return periods are based on the observed frequency of damages. Additionally, this study does not cover all kinds of hazards (e.g., earthquakes) and focuses on hurricanes, coastal floods and erosion. Finally, GAR results are expressed as maximum probable damage, whereas in this study expected damages have been estimated, hence the obtained results are not comparable.

For the sole purpose of validation, this curve's compatibility with the impact of the 1928 Okeechobee Hurricane has been tested. According to the proposed methodology, an approximate 100-year return period has been obtained for this hurricane. The proposed Historical Loss Exceedance Curve in Figure 68 yields damage of circa US$3,000 million. Following the implicit deflator method, this damage is equivalent to US$300 million in 1928. These results are within the range of the estimates obtained for the damages expressed in 2016 US$, using various value transfer methods ranging from US$1,200 million to US$6,000 million worth in 2016.

In summary, the proposed approach for the estimation of the return period associated with the damages caused by a particular historical event is aligned with the scale of this study (national coverage) and also with its scope (multiple sources of damage derived from the hurricanes, such as rainfall, flooding, erosion and wind). Based on the frequency of similar tropical cyclone in terms of tracks and intensities, this approach aims to overcome some of the limitations of classical approaches, based on the maximum wind speed at one location. Nevertheless, some uncertainties remain in the obtained results due to uncontrolled variables associated with tropical cyclones' trajectories.

It is also important to highlight that the sequence of successive events close in time is not considered in the analysis. Previous events can alter exposure and vulnerability, and therefore the return period associated with the event is far from being a good predictor of the expected damages. This means that there are still relevant uncertainties associated with the hazard exposure's temporal and spatial volatility.

Complementary to the previous analysis on the event return period, the definition of damage return periods has been obtained from the observed distribution of recorded damages that have

been selected based on the affinity between current conditions at the moment of the event and at present.

5.2.3.1. Limitations of the proposed approach

The global (national scale) impact analysis of historical catastrophic events was challenging due to the high uncertainty in the registered data. A careful discussion should be required prior to integrating of the obtained results in the probabilistic risk assessment, following a hybrid approach. The main limitations to be considered are as follows:

- Quality of records decreases for remote past events/times; hence, the probability of findings that are biased, incomplete or missing information on older records, increases;
- The values recorded are only those that overpass the catastrophic level; hence, the records may be incomplete, since they may lack relevant data to develop the synthetic model that are not classified as hurricanes;
- Estimating the exposure in past events is a difficult task, especially in very remote events; hence, the probability of specific damage that occurred in past events/times is not representative of equivalent damage in the present time;
- The cumulative damage of successive events is poorly represented. Exposure and vulnerability may be altered by a first hurricane and when a second event takes place after little time, the intense and temporal modifications in the exposure and vulnerability that may remain due to the first event are not included in the estimation of damages caused by this second event;
- Furthermore, exposure and vulnerability of the study area can experience changes due to other causes than tropical cyclones such as the construction of new urban developments, managed realignment, environmental restoration of ecosystems. These changes over time in the exposure and vulnerability, are not considered in the analysis;
- Spatial heterogeneity of exposure and vulnerability represents another challenge as the consequences of past events are registered on a spatially aggregated basis. In The Bahamas, the impacts derived from a hurricane depend on which island is affected and on the spatial trajectory of the tropical cyclone. Therefore, events with similar intensities may trigger different damages;

- Although the global impact on the islands is typically predicted based on the hurricane intensity, the actual damages may vary dramatically with local conditions impossible to monitor. Therefore, the expected variability of the damages is extremely high; and
- In the development of series of historical damage, there is an intrinsic uncertainty about the return period associated with the events, due to the reduced number of registered hurricanes that are not representative of all feasible events. In this analysis, the historical events' return period is based on the synthetic database developed for the Probabilistic Hazard Assessment (see chapter 3).

5.3. Probabilistic Risk Assessment

This section provides the Bahamian society's probabilistic risk assessment. This assessment presents the variety of expected damages caused by the different magnitudes of eventual hazard events. The results generated at previous steps of this project are combined in a synthetic function with the historical records.

This section produces two main results: the maximum probable losses (PML) and the annual average losses (AAL), both for population, capital stock, road network, and tourism economic activities.

The results are presented separately for each of the potentially affected populations, the capital stock losses, and the road network damages, using the assigned vulnerability functions. The potentially affected population results are expressed in terms of the number of individuals affected by the events. For the economic losses related to damages over stock, results are expressed in monetary terms according to the different hazard intensity levels at each study island. Lastly, for the road network, results are presented in terms of kilometers eventually affected by coastal hurricane flooding.

The probabilistic analysis of damages and losses focuses on the selected hazards: coastal hurricane flooding and winds. The analysis requires spatial homogenization due to the different spatial definitions for both sources of damage.

This study covers return periods of 5, 10, 25, 50, and 100 years as PML for coastal hurricane flooding. The AAL is computed as the expected damage corresponding with this probabilistic distribution. For the impact of wind, an additional once every 500 year-scale event is additionally performed in this study.

5.3.1. Social risk

5.3.1.1. National scale

This study assesses the potentially affected population as a social risk by accounting for people exposed to a specific hazard level. In the case of flooding, and for comparative and scaling, four different results are produced.

- The number of people exposed to the potential coastal floods, irrespective of the depth is calculated for each return period event. This is called the potentially affected people and represents people living in areas reached by water;
- Secondly, the proportion of these potentially affected people over the total population is used to characterize the severity of the problem;
- The number of persons living in areas where the water level reaches a threshold of 0.5m represents the quota of the population suffering socio-economic activities and requiring assistance under each return period; and
- The proportion of potentially affected people suffering relevant damages from flooding is identified.

The damage exceedance curve is computed from the number of affected people instead of PML for different flooding return period events, and the annual average damage, instead of AAL, is then obtained from this distribution.

For the impacts derived from extreme winds due to the spatial definition of the results and data, only the number of people residing in the affected area and their proportion over the total population is computed. People are considered as affected when the wind speed peak reaches 175 km/h (which is the threshold considered by public administrations to start evacuations).

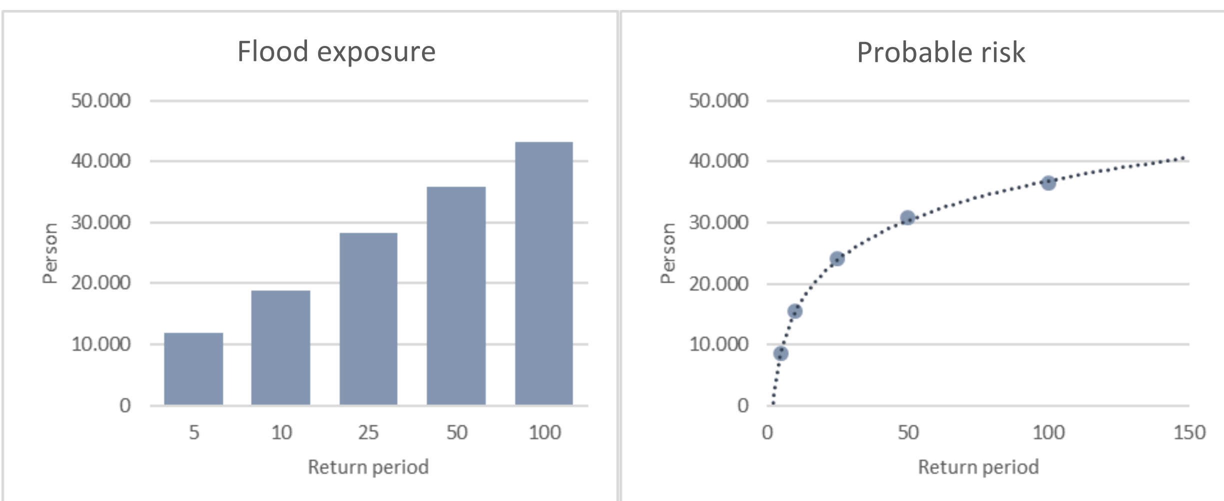
Tables 20 and 21, and Figures 69-73 present the results of each flooding and winds. The results indicate that the 100 years RP flooding will affect an area where just 12% of the total population live. As a complementary index this study has tested which proportion of this population is seriously flooded with 50 cm or more in-depth. This shows the sensitivity of risk on the population if minor flooding is discarded, and the results show that, for example, for 100 years return-period (RP) flooding, most of the affected population (84%) is seriously flooded whereas this number is reduced to 73% for the 5 years RP.

Table 20. Coastal Flooding Risk (Population)

Country	BAHAMAS	Hazard	COASTAL FLOODING			
POPULATION		**Return period**	**Potentially affected (Exposed)**	**% over total**	**Affected**	**% over total**
TOTAL POPULATION		5	11,808	3.36%	8,634	2.46%
351,461		10	18,863	5.37%	15,447	4.40%
		25	28,180	8.02%	24,062	6.85%
ANNUAL AVERAGE AFFECTED		50	35,909	10.22%	30,744	8.75%
4,137		100	43,121	12.27%	36,503	10.39%

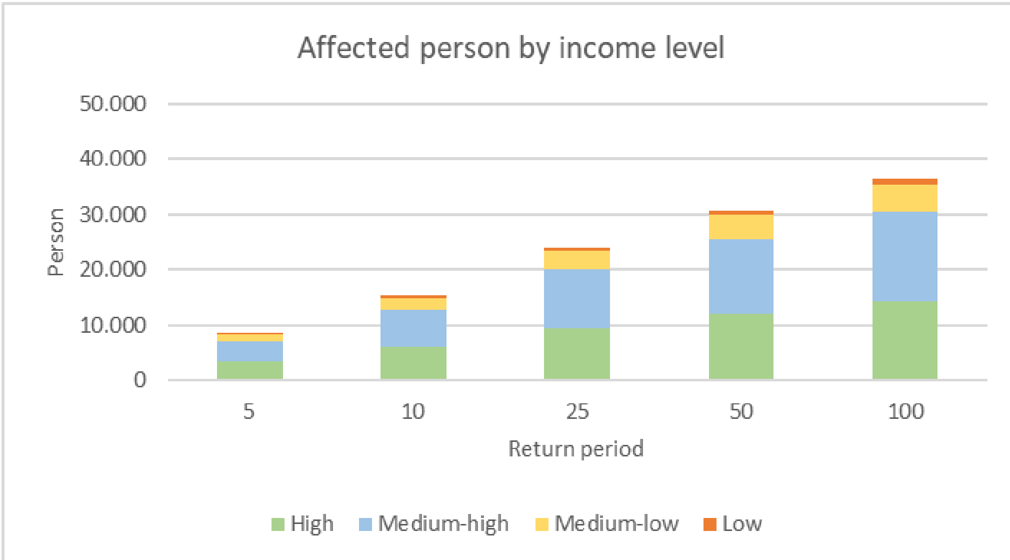
Source: Self-elaborated.

Figure 69. Flood Exposure and Probable Risk (Population)



Source: Self-elaborated. *Distribution of exposed population per RP and Loss Exceedance Curve for Affected Population.*

Figure 70. Probable Affected Person/Income Level



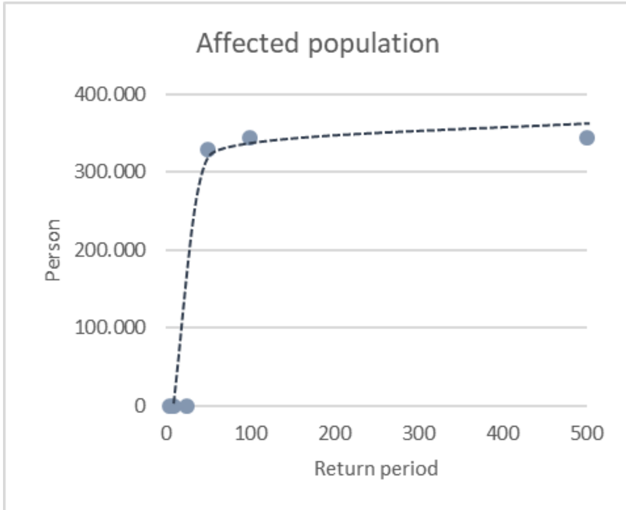
Source: Self-elaborated.

Table 21. Hurricane Wind Risk (Population)

Country	**BAHAMAS**	Hazard	**HURRICANE WIND**	
POPULATION		**Return period**	**Affected**	**% over total**
TOTAL POPULATION		5	0	0,00%
351,461		10	0	0,00%
		25	0	0,00%
ANNUAL AVERAGE AFFECTED		50	327,991	93.32%
9,395		100	344,279	97.96%
		500	344,279	97.96%

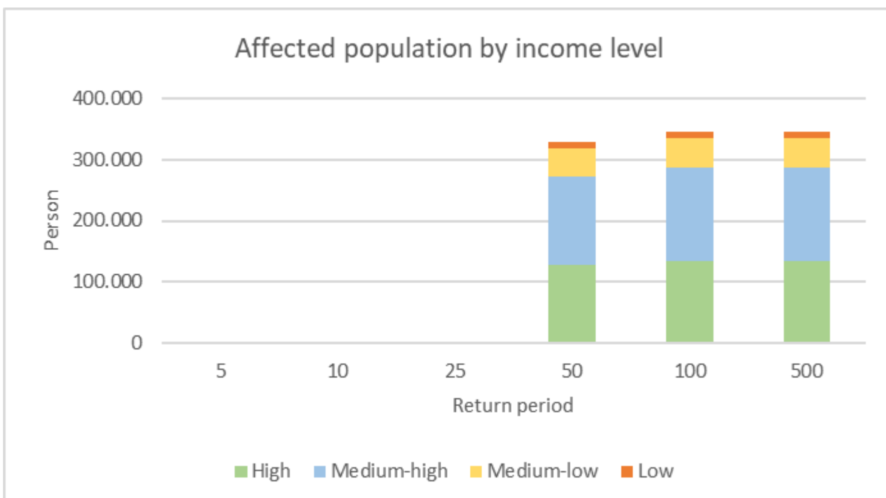
Source: Self-elaborated.

Figure 71. Distribution of Affected Population to Hurricane Winds



Source: Self-elaborated.

Figure 72. Hurricane Wind Affected Population by Income Level

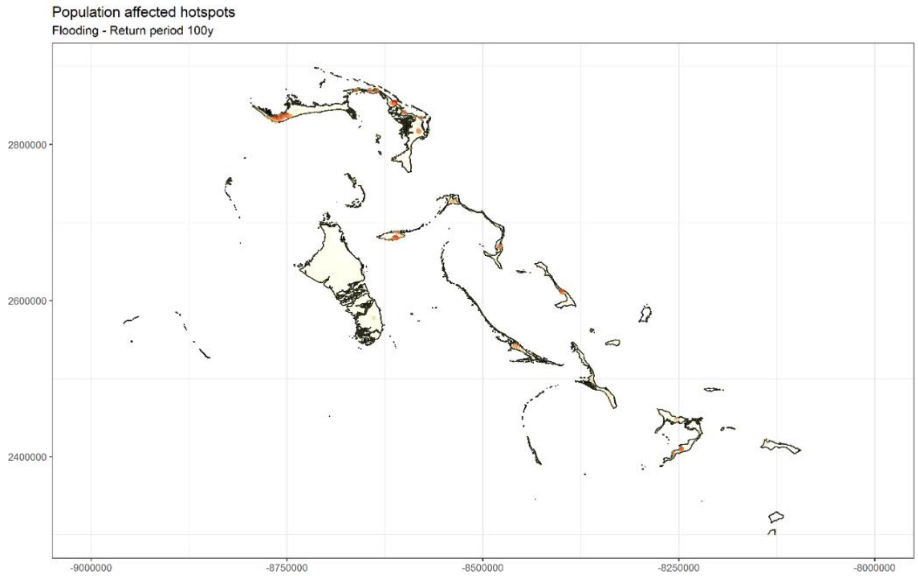


Source: Self-elaborated.

The results also show that wind damages exist only for high return periods and that some substantial damages exist for return periods below 100 km/h. It is also visible the wind affects the Bahamas' total population, whereas flooding only affects 12%.

The results can be spatially disaggregated, identifying the areas where damage concentration is high.

Figure 73. Affected Population Hotspots for Coastal Flooding



Source: Self-elaborated.

As shown in Figure 73, the main damaged hotspots are located in Grand Bahama, Great Abaco and Nassau. As might be expected, relevant points appear in areas where there is a high population concentration.

5.3.1.2. Local study sites

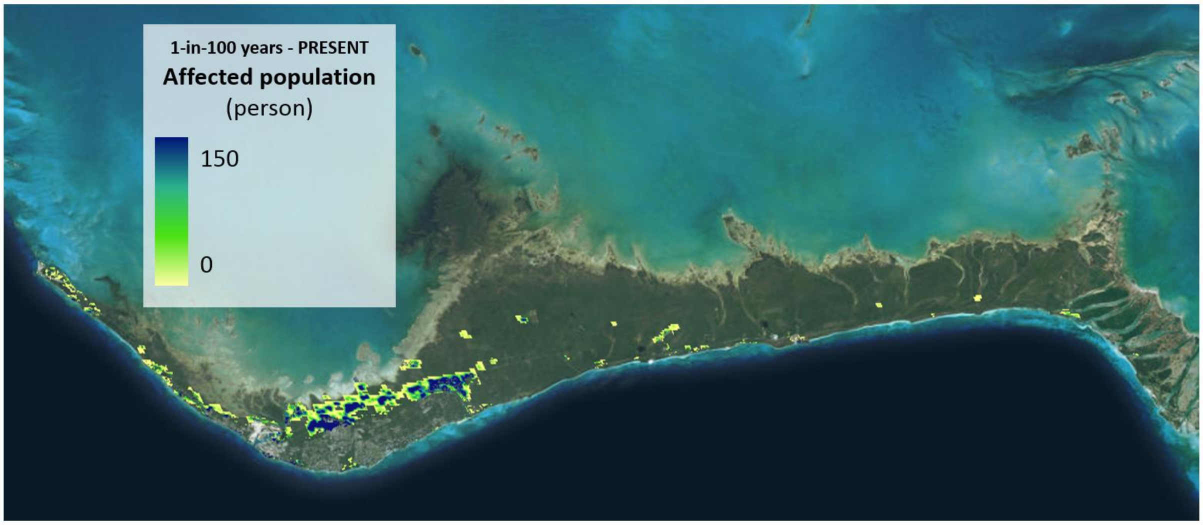
Tables 22-23, and Figure 74-76 show the result of the local sites' social risk analysis.

Table 22. Summary of the Results Per Study Site

Flood risk (person)								
Island	Total	RP 5	RP 10	RP 25	RP 50	RP 100		**AAL**
Central Long Island	165	131	153	154	155	156		**41**
West Andros	3,747	10	29	36	50	69		**6**
Grand Bahama	35,244	253	537	938	1,332	1,739		**147**
Hurricane wind risk (person)								
Island	Total	RP 5	RP 10	RP 25	RP 50	RP 100	RP 500	**AAL**
Central Long Island	165	0.00	0.00	0.00	0.00	156.77	157	**2**
West Andros	3,747	0.00	0.00	0.00	2,472	3,309	3,309	**80**
Grand Bahama	35,244	0.00	0.00	0.00	34,155	34,155	34,155	**956**

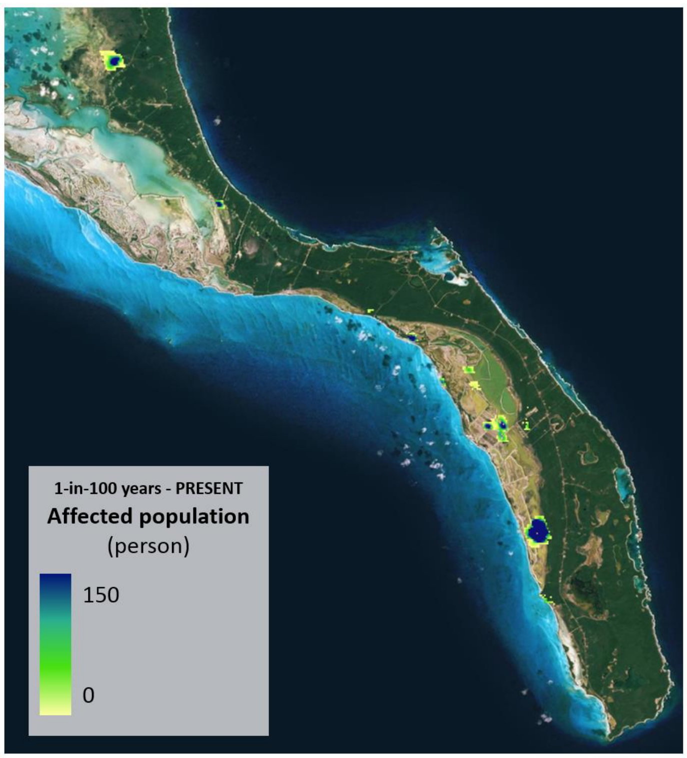
Source: Self-elaborated.

Figure 74. Affected Population in Grand Bahama Study Site



Source: Self-elaborated. 100 years RP.

Figure 75. Affected Population in Long Island Study Site



Source: Self-elaborated. 100 years RP.

Table 23. Coastal Flooding Risk per Island (Population)

COASTAL FLOODING							
	RP 5	*RP 10*	*RP 25*	*RP 50*	*RP 100*	**AAL**	**Total, Population**
Acklins	*560*	*599*	*625*	*626*	*640*	**170**	*737*
Berry Islands	*33*	*50*	*84*	*123*	*125*	**15**	*798*
Biminis	*24*	*50*	*50*	*87*	*90*	**11**	*1,989*
Black Point	*0*	*0*	*0*	*0*	*0*	**0**	*0*
Cat Island	*120*	*219*	*277*	*608*	*729*	**59**	*1,337*
Central Abaco	*3,149*	*5,497*	*7,730*	*9,473*	*10,579*	**1,416**	*14,139*
Central Andros	*14*	*25*	*29*	*43*	*57*	**6**	*228*
Central Eleuthera	*0*	*0*	*0*	*27*	*62*	**1**	*1,338*
City of Freeport	*13*	*20*	*25*	*30*	*46*	**5**	*11,046*
Crooked Island	*58*	*188*	*226*	*244*	*249*	**38**	*288*
East Grand Bahama	**17**	**33**	**62**	**80**	**102**	**9**	*497*
Exuma	*268*	*446*	*4,025*	*4,156*	*4,349*	**321**	*8982*
Grand Cay	*10*	*10*	*10*	*10*	*10*	**3**	*11*
Harbour Island	*10*	*23*	*31*	*54*	*64*	**6**	*1,467*
Hope Town	*0*	*0*	*0*	*0*	*0*	**0**	*0*
Inagua	*0*	*0*	*0*	*0*	*0*	**0**	*814*
Long Island	*2,220*	*2,313*	*2,428*	*2,441*	*2,479*	**664**	*2,894*
Mangrove Cay	*19*	*24*	*58*	*64*	*75*	**8**	*531*
Mayaguana	*0*	*1*	*4*	*5*	*106*	**1**	*259*
Moore's Island	*38*	*41*	*47*	*56*	*58*	**12**	*80*
New Providence	*175*	*344*	*515*	*861*	*1,612*	**95**	*247,286*
North Abaco	*762*	*831*	*888*	*2,266*	*2,779*	**264**	*3,409*
North Andros	*3*	*18*	*24*	*29*	*47*	**4**	*3,017*
North Eleuthera	*1*	*78*	*177*	*275*	*457*	**20**	*1,184*
Ragged Island	*3*	*3*	*3*	*3*	*3*	**1**	*65*
Rum Cay	*6*	*7*	*9*	*25*	*35*	**2**	*101*
San Salvador	*28*	*28*	*29*	*29*	*41*	**8**	*884*
South Abaco	*31*	*56*	*61*	*76*	*97*	**13**	*611*
South Andros	*20*	*34*	*66*	*92*	*195*	**11**	*3,163*
South Eleuthera	*50*	*82*	*95*	*114*	*1,105*	**25**	*4,892*
Spanish Wells	*52*	*55*	*74*	*83*	*98*	**17**	*1,199*
West Grand Bahama	*951*	*4,373*	*6,411*	*8,764*	*10,213*	**931**	*38,211*
TOTAL, BAHAMAS	***8,635***	***15,448***	***24,063***	***30,744***	***36,502***	**4,136**	***351,457***

Source: Self-elaborated.

The results presented in the table were obtained from spatial disaggregation of the National census in 2020, hence some minor differences may exist with the official census. Some islands show interesting results. On the one hand, New Providence and Grand Bahama (blue) show low values for their actual population and on the other, Long Island, Exuma, and Abaco (orange) show values higher than what can be expected according to their demography. With respect to the intensity of the flooding, this study observes differences between Exuma, where the damages escalate when RP reaches 50 years, and Long Island where minor differences exist in expected damages with the intensity.

Table 24. Hurricane Winds Risk per Island (Population)

EXTREME WINDS							
	RP 10	*RP 25*	*RP 50*	*RP 100*	*RP 500*	**AAL**	**Total, Population**
Acklins	*0*	*0*	*735*	*735*	*735*	**21**	*737*
Berry Islands	*0*	*0*	*784*	*784*	*784*	**22**	*798*
Biminis	*0*	*0*	*0*	*1,278*	*1,278*	**17**	*1,989*
Black Point	*0*	*0*	*0*	*0*	*0*	**0**	*0*
Cat Island	*0*	*0*	*0*	*1,336*	*1,336*	**17**	*1,337*
Central Abaco	*0*	*0*	*14,067*	*14,067*	*14,067*	**394**	*14,139*
Central Andros	*0*	*0*	*67*	*224*	*224*	**4**	*228*
Central Eleuthera	*0*	*0*	*1,338*	*1,338*	*1,338*	**37**	*1,338*
City of Freeport	*0*	*0*	*10,984*	*10,984*	*10,984*	**308**	*11,046*
Crooked Island	*0*	*0*	*288*	*288*	*288*	**8**	*288*
East Grand Bahama	*0*	*0*	*497*	*497*	*497*	**14**	*497*
Exuma	*0*	*0*	*0*	*8,981*	*8,981*	**117**	*8982*
Grand Cay	*0*	*0*	*6*	*6*	*6*	**0**	*11*
Harbour Island	*0*	*0*	*861*	*861*	*861*	**24**	*1,467*
Hope Town	*0*	*0*	*0*	*0*	*0*	**0**	*0*
Inagua	*0*	*0*	*0*	*814*	*814*	**11**	*814*
Long Island	*0*	*0*	*2,635*	*2,872*	*2,872*	**77**	*2,894*
Mangrove Cay	*0*	*0*	*0.00*	*436*	*436*	**6**	*531*
Mayaguana	*0*	*0*	*259*	*259*	*259*	**7**	*259*
Moore's Island	*0*	*0*	*80*	*80*	*80*	**2**	*80*
New Providence	*0*	*0*	*244,569*	*244,569*	*244,569*	**6,848**	*247,286*
North Abaco	*0*	*0*	*3,337*	*3,337*	*3,337*	**93**	*3,409*
North Andros	*0*	*0*	*2,795*	*2,795*	*2,795*	**78**	*3,017*
North Eleuthera	*0*	*0*	*1,112*	*1,112*	*1,112*	**31**	*1,184*
Ragged Island	*0*	*0*	*0*	*0*	*0*	**0**	*65*
Rum Cay	*0*	*0*	*99*	*99*	*99*	**3**	*101*
San Salvador	*0*	*0*	*868*	*868*	*868*	**24**	*884*
South Abaco	*0*	*0*	*611*	*611*	*611*	**17**	*611*
South Andros	*0*	*0*	*0*	*3,048*	*3,048*	**40**	*3,163*
South Eleuthera	*0*	*0*	*4,821*	*4,821*	*4,821*	**135**	*4,892*
Spanish Wells	*0*	*0*	*0*	*0*	*0*	**0**	*1,199*
West Grand Bahama	*0*	*0*	*37,179*	*37,179*	*37,179*	**1,041**	*38,211*
TOTAL, BAHAMAS	***0***	***0***	***327,992***	***344,279***	***344,279***	**9,390**	***351,457***

Source: Self-elaborated.

The results show that when high winds (or PR100 and more) are present, no difference is observed between the distribution of population and the affected people.

5.3.2. Hurricane Risk Analysis from Macroeconomic Perspective.

This section presents the results of the study from macroeconomic perspective.

5.3.2.1. National scale

The results obtained for probable damages at national scale includes the total capital stock, residential, services and others. Tables 25 – 27 and Figures 76-79 show the results in case of coastal hurricane flood.

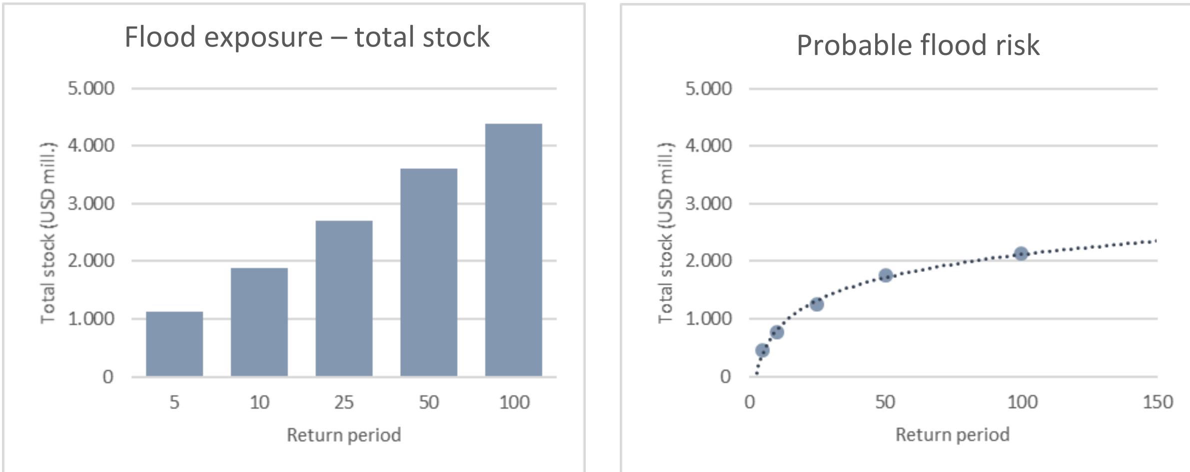
Table 25. Probable Damages on Total Stock Due to Flooding

Country	BAHAMAS	Hazard	COASTAL FLOODING			
TOTAL STOCK		**Return period (year)**	**Total Exposed (US$ million)**	**% over total stock**	**Probable damage stock (US$ million)**	**% over total stock**
TOTAL STOCK		5	1,130.33	2.56%	446.59	1.01%
US$ 44,214.64 million		10	1,873.31	4.24%	764.38	1.73%
		25	2,711.22	6.13%	1,260.68	2.85%
ANNUAL AVERAGE LOSSES		50	3,597.64	8.14%	1,747.82	3.95%
US$ 215.46 million		100	4,383.98	9.92%	2,135.63	4.83%

Source: Self-elaborated.

The above table's first column identifies the return period, the second shows the assets exposed to flood in each return period. The third column shows the proportion of this magnitude over the total existing stock in the country. The fourth column shows the probable damage after applying the corresponding vulnerability function, the fifth column quantifies this result relative to the probable damage of total stock previously defined. The results show that 3.95% of the computed probable damage over the total stock occurs for the 50 years return period.

Figure 76. Total Stock Exposed and Probable Damage due to Coastal Flooding



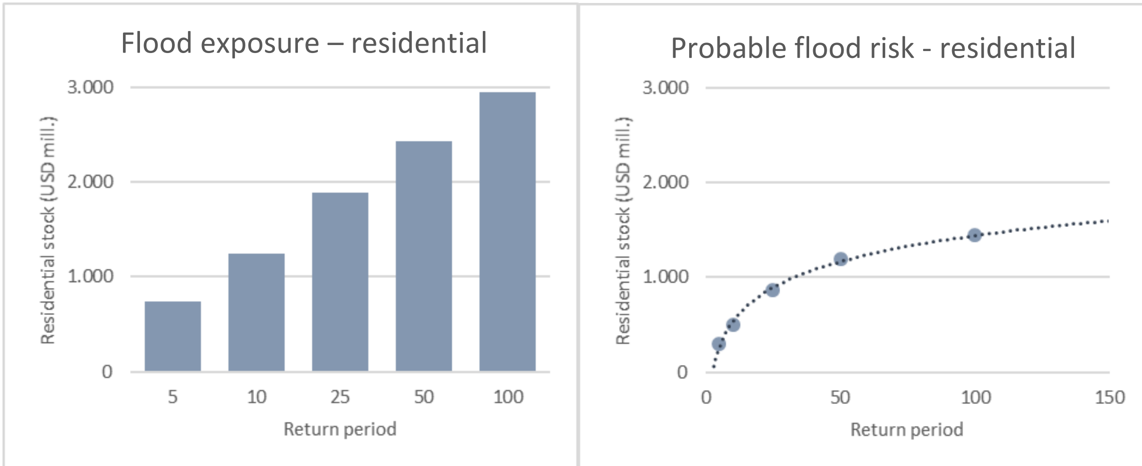
Source: Self-elaborated.

Table 22. Probable Damages on Residential Stock Due to Flooding

Country	**BAHAMAS**	Hazard	**COASTAL FLOODING**			
RESIDENTIAL STOCK		**Return period (year)**	**Total Exposed (US$ million)**	**% over total stock**	**Probable damage stock (US$ million)**	**% over total stock**
TOTAL RESIDENTIAL STOCK		5	739.05	2.46%	291.39	0.97%
US$ 30,087.47 million		10	1,237.87	4.11%	503.39	1.67%
		25	1,886.79	6.27%	862.46	2.87%
ANNUAL AVERAGE LOSSES		50	2,432.18	8.08%	1,187.11	3.95%
US$ 143.51 million		100	2,951.18	9.81%	1,444.63	4.80%

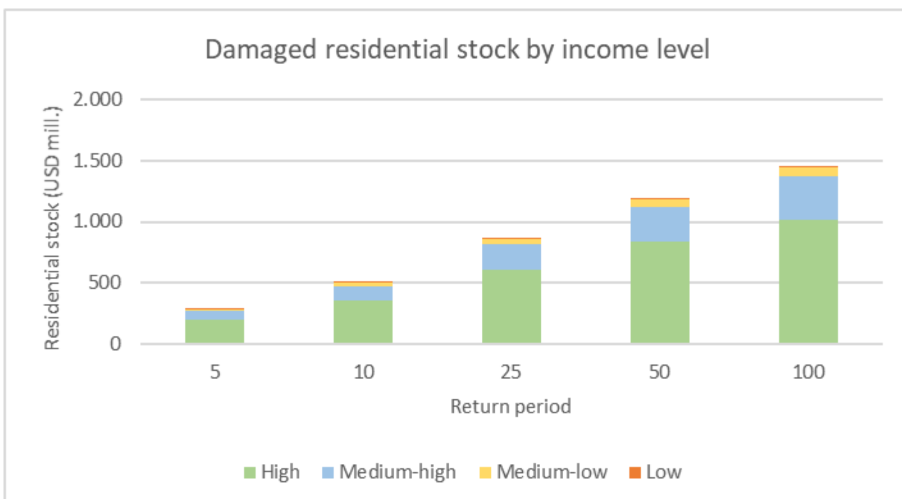
Source: Self-elaborated.

Figure 76. Residential Capital Stock Exposed and Probable Damage by Coastal Flooding



Source: Self-elaborated.

Figure 77. Distribution of Probable Damage on Residential Stock/Income Level



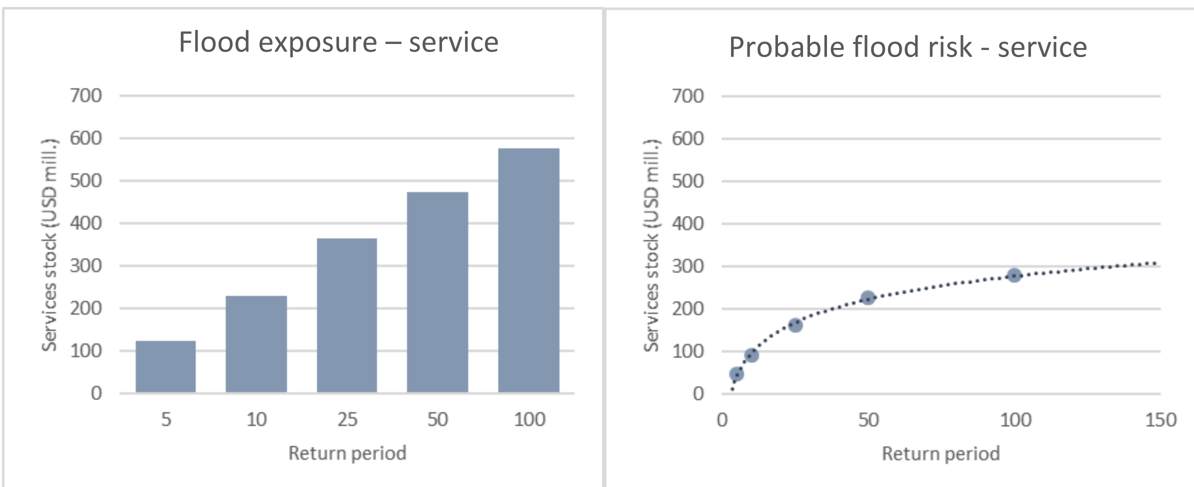
Source: Self-elaborated.

Table 23. Damages on Services Stock Due to Flooding

Country	BAHAMAS	Hazard	COASTAL FLOODING			
SERVICES STOCK		**Return period (year)**	**Total Exposed (US$ millions)**	**% over total stock**	**Probable damage stock (US$ millions)**	**% over total stock**
TOTAL SERVICES STOCK		5	122.52	1.42%	47.04	0.54%
US$ 8,640.22 millions		10	228.53	2.64%	89.73	1.04%
		25	364.95	4.22%	161.65	1.87%
ANNUAL AVERAGE LOSSES		50	473.87	5.48%	224.42	2.60%
US$ 25.5 millions		100	574.67	6.65%	278.01	3.22%

Source: Self-elaborated. *With a 0.5m Flooding Threshold.*

Figure 78. Service Stock Exposed and probable Damage by Coastal Flooding



Source: Self-elaborated.

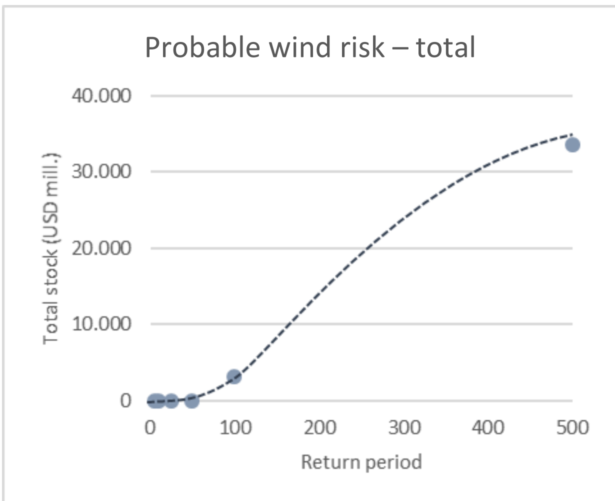
Tables 28 – 30 and Figures 80-83 show the results in case of hurricane winds.

Table 24. Damages on Total Stock Due to Wind

Country	BAHAMAS	Hazard	HURRICANE WINDS	
TOTAL STOCK		**Return period**	**Probable damage stock (US$ millions)**	**% over stock**
TOTAL STOCK		5	0	0.00%
US$ 44,214.64 millions		10	0	0.00%
		25	0	0.00%
ANNUAL AVERAGE LOSSES		50	5.24	0.01%
US$ 161.67 millions		100	3,043,25	6.88%
		500	33,551.66	75.88%

Source: Self-elaborated.

Figure 79. Damage on Total Stock - Wind



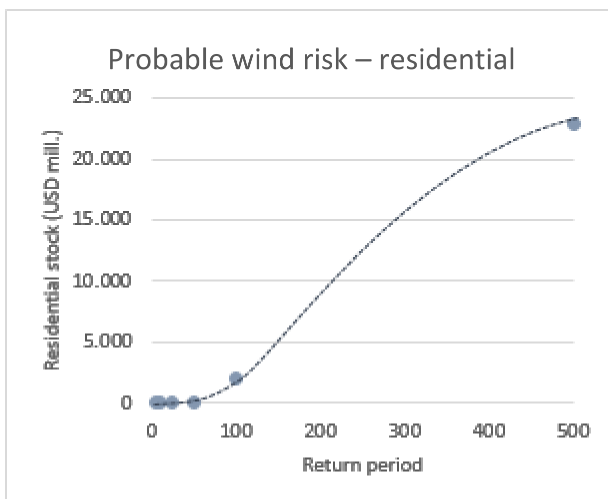
Source: Self-elaborated.

Table 25. Probable Damages on Residential Stock Due to Wind

Country	BAHAMAS	Hazard	HURRICANE WINDS	
RESIDENTIAL STOCK		**Return period**	**Probable damage stock (US$ millions)**	**% over total**
TOTAL RESIDENTIAL STOCK		5	0	0.00%
US$ 30,087.47millions		10	0	0.00%
		25	0	0.00%
ANNUAL AVERAGE LOSSES		50	3.5	0.01%
US$ 109.92 millions		100	2,068.76	6.88%
		500	22,813.24	75.82%

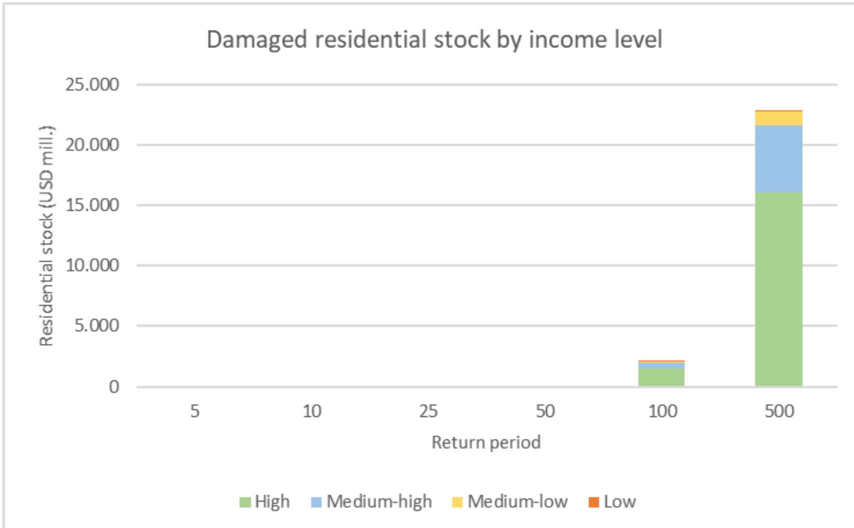
Source: Self-elaborated.

Figure 80. Probable Maximum Loss Distribution for Residential Stock Due to Extreme Winds



Source: Self-elaborated.

Figure 81. Distribution of Probable damage on Residential by Income Level - Wind



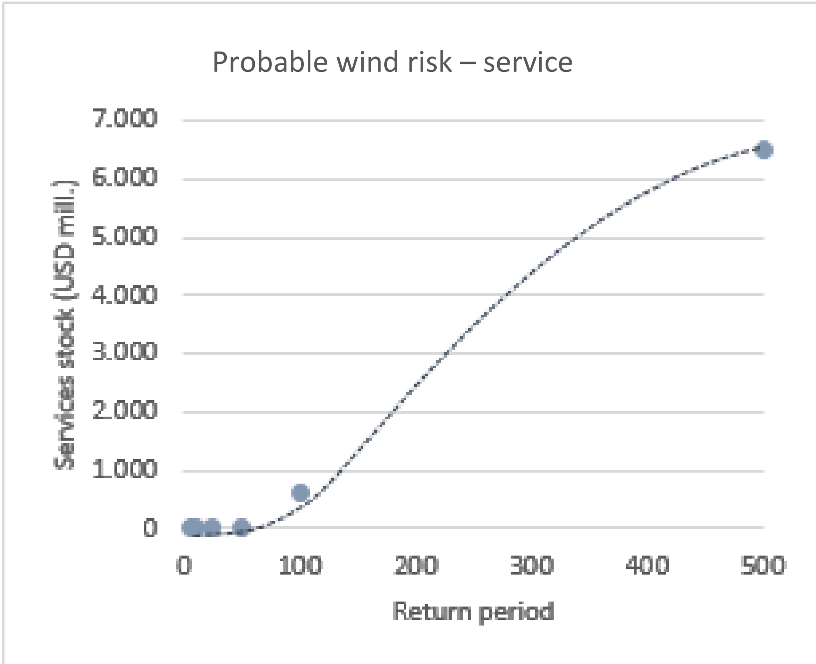
Source: Self-elaborated.

Table 30. Damages on Services Stock Due to Winds

Country	**BAHAMAS**	Hazard	**HURRICANE WINDS**	
SERVICES STOCK		**Return period**	**Probable Damage stock (US$ millions)**	**% over total**
TOTAL SERVICES STOCK		5	0	0.00%
US$ 8,640.22 millions		10	0	0.00%
		25	0	0.00%
ANNUAL AVERAGE LOSSES		50	0,79	0.01%
US$ 31.44 millions		100	597.28	6.91%
		500	6,513.79	75.39%

Source: Self-elaborated.

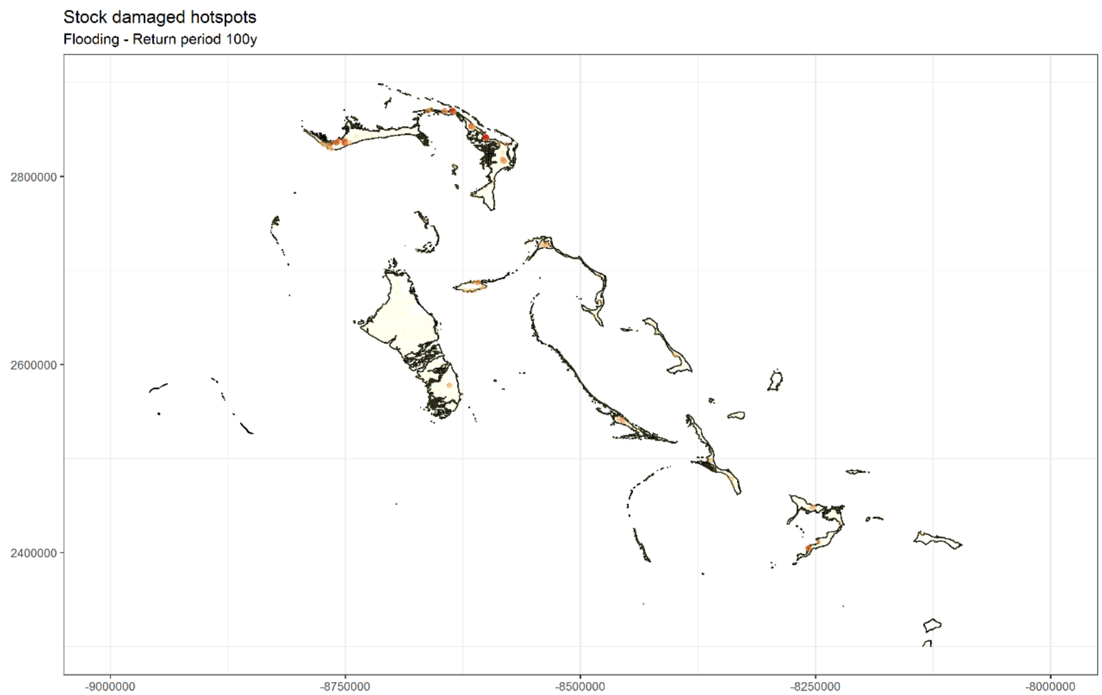
Figure 82. Probable Maximum Loss for Service Stock due to Winds



Source: Self-elaborated.

Figure 84 shows the spatial distribution of probable total stock damage due to a 100-year (RP) flood:

Figure 83. Probable Damage - Total Stock (flooding, 100-year return period)

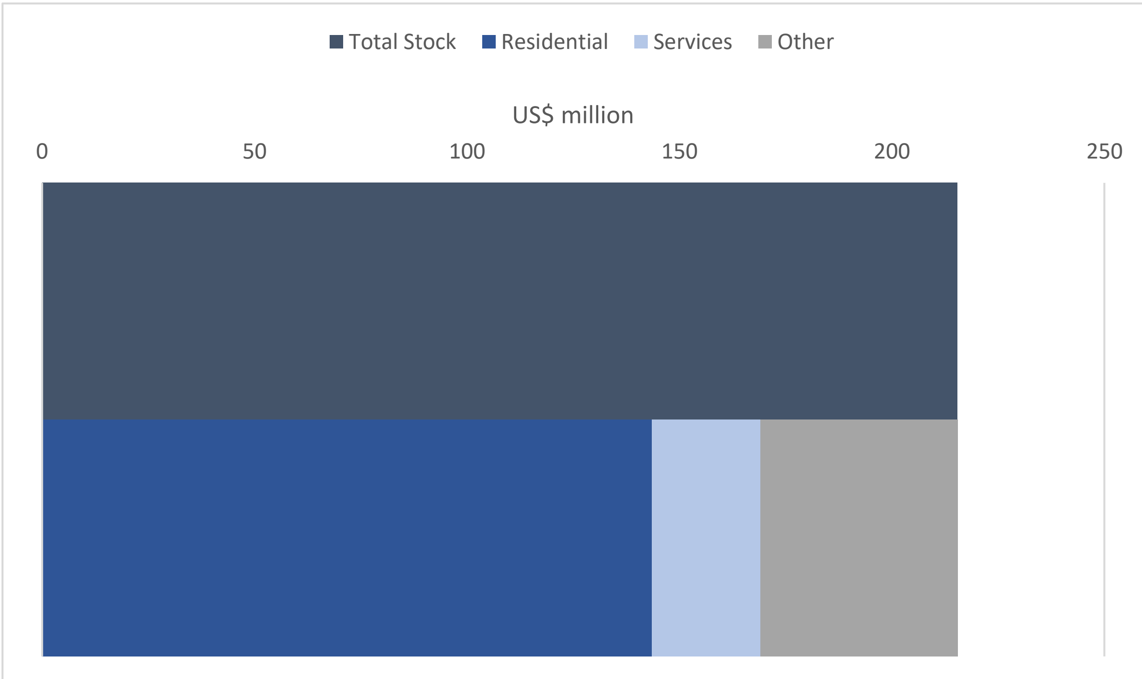


Source: Self-elaborated.

Figure 84 shows the main probable damaged hotspots in Grand Bahama and Great Abaco, with some other relevant points in those areas with higher infrastructure and population density (higher exposure and concentrated stock assets).

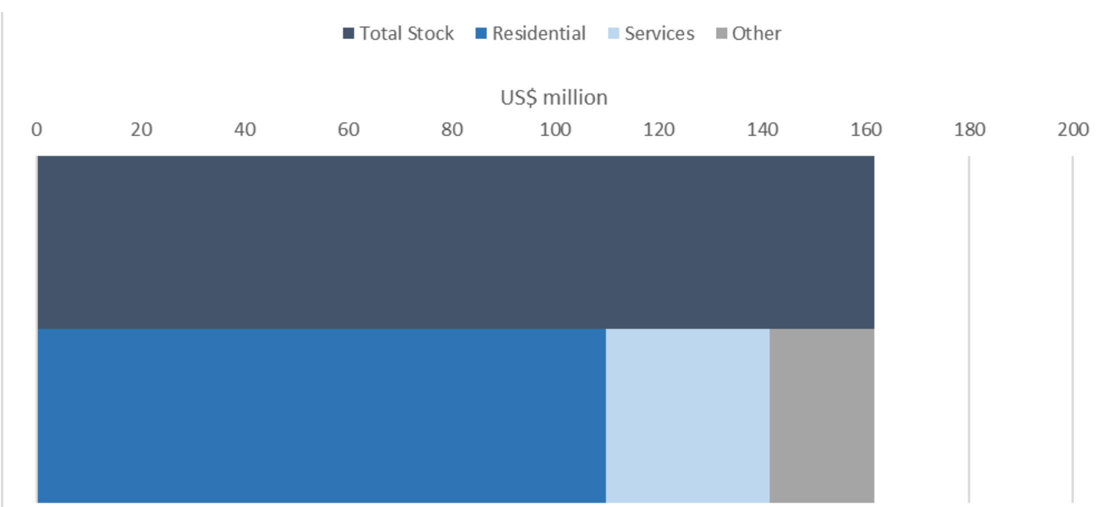
Figure 85 and 86 show the results of AAL.

Figure 84. Distribution of Annual Average Loss Related to Flooding



Source: Self-elaborated.

Figure 85. Annual Average Losses Related to Hurricane Winds



Source: Self-elaborated.

Damages related to coastal flooding are considerably lower than those caused by winds (i.e. for a return period of 500 years, flooding produces around US$ 2,135 million damages, while for winds, this figure is more than US$ 33,000 million).

However, when AAL is obtained, probable damages are more significant in the case of flooding than in the wind. This is because the events of reduced return periods (from 5 to 25 years) are those that mostly contribute to the AAL, and in the case of extreme winds, these events do not produce any damage, while in the case of flooding, even small return period events already produce impacts and damage to stock.

5.3.2.2. Local Study sites

This section presents the results spatially disaggregated per study site and island (Tables 31 and 32).

Table 31. Summary of Results of Risk Over Capital Stock Per Site for Flooding

Damages on total stock due to coastal flooding (US$ million)								
Island	Total	RP 5	RP 10	RP 25	RP 50	RP 100		**AAL**
Central Long Island	25.5	5.91	8.63	10.09	11.62	13.25		**2.22**
West Andros	381.3	0.74	1.02	1.77	2.15	2.67		**0.31**
Grand Bahama	4.343.8	15.35	26.99	43.17	60.85	81.87		**7.51**
Damages on residential stock due to coastal flooding (US$ million)								
Island	Total	RP 5	RP 10	RP 25	RP 50	RP 100		**AAL**
Central Long Island	16.2	3.77	5.51	6.44	7.41	8.45		**1.42**
West Andros	252.7	0.48	0.66	1.15	1.39	1.74		**0.20**
Grand Bahama	2,968,8	10.25	18.04	28.83	40.67	54.80		**5.02**
Damages on services stock due to coastal flooding (US$ million)								
Island	Total	RP 5	RP 10	RP 25	RP 50	RP 100		**AAL**
Central Long Island	0.9	0.24	0.35	0.41	0.47	0.54		**0.09**
West Andros	56.6	0.08	0.12	0.21	0.25	0.32		**0.04**
Grand Bahama	821.4	2.07	3.80	6.23	8.97	12.20		**1.06**

Source: Self-elaborated.

The results confirmed the influence of exposure on risk and indicated that the critical issue for the impacts derives from the probability of the event hitting on heavily populated areas or not.

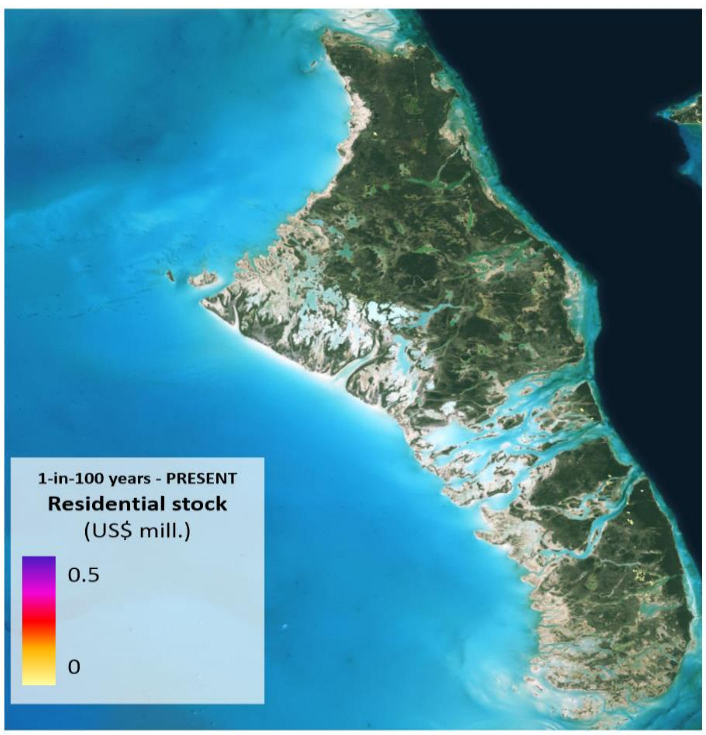
Table 26. Summary of Results of Risk Over Capital Stock Per Site for Extreme Winds

Damages on total stock due to extreme winds (US$ million)							
Island	RP 5	RP 10	RP 25	RP 50	RP 100	RP 500	**AAL**
Central Long Island	0.00	0.00	0.00	0.00	0.68	13.76	0.06
West Andros	0.00	0.00	0.00	0.00	17.52	209.06	0.99
Grand Bahama	0.00	0.00	0.00	0.58	349.63	4,089.40	19.51
Damages on residential stock due to extreme winds (US$ million)							
Island	RP 5	RP 10	RP 25	RP 50	RP 100	RP 500	**AAL**
Central Long Island	0.00	0.00	0.00	0.00	0.44	8.78	**0.04**
West Andros	0.00	0.00	0.00	0.00	11.62	138.37	**0.66**
Grand Bahama	0.00	0.00	0.00	0.38	238.58	2,791.65	**13.32**
Damages on services stock due to extreme winds (US$ million)							
Island	RP 5	RP 10	RP 25	RP 50	RP 100	RP 500	**AAL**
Central Long Island	0.00	0.00	0.00	0.00	0.03	0.55	**0.00**
West Andros	0.00	0.00	0.00	0.00	2.62	30.65	**0.15**
Grand Bahama	0.00	0.00	0.00	0.07	66.72	783.13	**3.73**

Source: Self-elaborated.

Wind impact is relevant only when high return periods are considered.

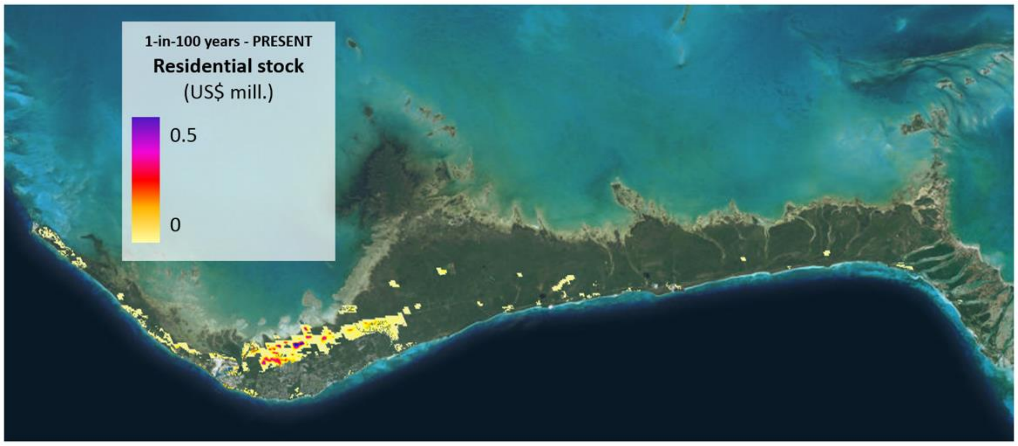
Figure 86. Flooding Damages on Residential Stock at Andros Study Site with 100 Years RP



Source: Self-elaborated

Detailed results for each island are presented in Tables 33, 34 and Figures 87 and 88. A Review of the results shows the difference between the perceived results between national and local scales. What is not relevant at the national scale due to the low absolute value of damages can be very relevant at the local scale due to the relative scale.

Figure 87. Flooding Damage on Residential Stock at Grand Bahama Study Site



Source: Self-elaborated. *RP 100.*

Table 33. Total Stock Probable Damages and AAL Caused by Coastal Flooding/Island

COASTAL FLOODING ($US M.)							
	RP 5	RP 10	RP 25	RP 50	RP 100	**AAL**	**Total, Stock**
Acklins	*34.57*	*43.57*	*50.53*	*54.35*	*58.50*	**11.80**	*103.9*
Berry Islands	*1.12*	*1.82*	*3.01*	*3.75*	*4.44*	**0.51**	*73.9*
Biminis	*1.24*	*1.45*	*1.69*	*3.42*	*3.71*	**0.44**	*183.2*
Black Point	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	**0.00**	*0*
Cat Island	*7.05*	*11.81*	*15.92*	*33.22*	*40.13*	**3.34**	*185.6*
Central Abaco	*127.52*	*229.23*	*326.77*	*458.70*	*534.26*	**60.09**	*1,497.9*
Central Andros	*0.65*	*1.10*	*1.98*	*2.56*	*3.15*	**0.32**	*27.8*
Central Eleuthera	*0.00*	*0.00*	*0.73*	*1.83*	*3.38*	**0.07**	*197.4*
City of Freeport	*0.69*	*0.95*	*1.14*	*1.35*	*2.15*	**0.26**	*1,339.2*
Crooked Island	*4.28*	*9.31*	*10.58*	*12.27*	*13.51*	**2.06**	*43.2*
East Grand Bahama	*0.89*	*1.72*	*3.27*	*4.28*	*5.04*	**0.49**	*66.6*
Exuma	*10.45*	*16.96*	*264.07*	*287.61*	*309.43*	**19.35**	*991.3*
Grand Cay	*0.35*	*0.41*	*0.46*	*0.50*	*0.53*	**0.11**	*1.1*
Harbour Island	*0.86*	*1.18*	*1.65*	*2.19*	*2.92*	**0.34**	*164.7*
Hope Town	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	**0.00**	*0*
Inagua	*0.01*	*0.01*	*0.01*	*0.01*	*0.01*	**0.00**	*78.1*
Long Island	*131.89*	*150.95*	*161.92*	*172.92*	*182.46*	**41.84**	*390.0*
Mangrove Cay	*0.65*	*0.91*	*2.49*	*3.02*	*3.50*	**0.33**	*57.5*
Mayaguana	*0.01*	*0.01*	*0.18*	*0.23*	*3.45*	**0.03**	*25.1*
Moore's Island	*1.83*	*2.32*	*2.81*	*3.17*	*3.49*	**0.64**	*10.8*
New Providence	*11.18*	*15.73*	*28.58*	*47.06*	*91.90*	**5.24**	*31,719.6*
North Abaco	*36.84*	*49.14*	*65.34*	*123.79*	*152.62*	**14.69**	*451.0*
North Andros	*0.41*	*0.65*	*0.90*	*1.24*	*2.39*	**0.18**	*310.5*
North Eleuthera	*0.15*	*3.50*	*7.47*	*16.31*	*22.28*	**0.96**	*155.9*
Ragged Island	*0.14*	*0.16*	*0.17*	*0.17*	*0.20*	**0.04**	*6.9*
Rum Cay	*0.33*	*0.40*	*0.49*	*1.18*	*1.72*	**0.13**	*13.4*
San Salvador	*0.89*	*1.22*	*1.60*	*1.72*	*1.82*	**0.33**	*92.6*
South Abaco	*2.00*	*2.79*	*3.73*	*4.77*	*5.77*	**0.77**	*81.2*
South Andros	*1.06*	*1.52*	*3.37*	*4.51*	*10.85*	**0.54**	*353.1*
South Eleuthera	*2.70*	*3.47*	*4.60*	*6.56*	*64.80*	**1.29**	*630.3*
Spanish Wells	*2.07*	*2.58*	*3.33*	*3.97*	*4.55*	**0.73**	*137.7*
West Grand Bahama	*64.76*	*209.54*	*291.91*	*491.18*	*602.66*	**48.53**	*4,825.1*
TOTAL, BAHAMAS	***446.60***	***764.39***	***1,260.69***	***1,747.83***	***2,135.63***	**215.46**	***44,214.6***

Source: Self-elaborated,

Two different situations can be observed. On the one hand, New Providence and Grand Bahama as highly populated islands, experience observed probable damages that match the

expectations. On the other hand, Abaco, Exuma and Long Island are found to have substantial damage over the expectations based on existing assets.

Table 34. Total Stock probable damage and AAL Caused by Extreme Winds/ Island

EXTREME WINDS ($USM)							
	RP 10	RP 25	RP 50	RP 100	RP 500	**AAL**	**Total, Stock**
Acklins	*0.00*	*0.00*	*0.00*	*9.49*	*103.61*	**0.50**	*103.9*
Berry Islands	*0.00*	*0.00*	*0.00*	*5.05*	*55.32*	**0.27**	*73.9*
Biminis	*0.00*	*0.00*	*0.00*	*2.54*	*67.14*	**0.29**	*183.2*
Black Point	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	**0.00**	*0*
Cat Island	*0.00*	*0.00*	*0.00*	*7.12*	*153.22*	**0.68**	*185.6*
Central Abaco	*0.00*	*0.00*	*0.00*	*136.76*	*1,486.27*	**7.18**	*1,497.9*
Central Andros	*0.00*	*0.00*	*0.00*	*1.03*	*15.74*	**0.07**	*27.8*
Central Eleuthera	*0.00*	*0.00*	*0.00*	*10.77*	*132.12*	**0.63**	*197.4*
City of Freeport	*0.00*	*0.00*	*0.00*	*114.55*	*1,325.75*	**6.33**	*1,339.2*
Crooked Island	*0.00*	*0.00*	*0.00*	*6.26*	*43.22*	**0.23**	*43.2*
East Grand Bahama	*0.00*	*0.00*	*0.55*	*8.62*	*59.36*	**0.32**	*66.6*
Exuma	*0.00*	*0.00*	*0.00*	*18.45*	*629.46*	**2.68**	*991.3*
Grand Cay	*0.00*	*0.00*	*0.01*	*0.07*	*0.47*	**0.00**	*1.1*
Harbour Island	*0.00*	*0.00*	*0.00*	*4.87*	*83.96*	**0.38**	*164.7*
Hope Town	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	**0.00**	*0*
Inagua	*0.00*	*0.00*	*0.00*	*2.23*	*68.34*	**0.29**	*78.1*
Long Island	*0.00*	*0.00*	*0.00*	*18.53*	*327.95*	**1.48**	*390.0*
Mangrove Cay	*0.00*	*0.00*	*0.00*	*1.75*	*26.66*	**0.12**	*57.5*
Mayaguana	*0.00*	*0.00*	*0.50*	*2.78*	*16.40*	**0.10**	*25.1*
Moore's Island	*0.00*	*0.00*	*0.00*	*0.89*	*9.67*	**0.05**	*10.8*
New Providence	*0.00*	*0.00*	*0.00*	*2,151.87*	*22,775.81*	**110.47**	*31,719.6*
North Abaco	*0.00*	*0.00*	*0.42*	*47.14*	*433.22*	**2.16**	*451.0*
North Andros	*0.00*	*0.00*	*0.00*	*16.61*	*183.75*	**0.88**	*310.5*
North Eleuthera	*0.00*	*0.00*	*0.00*	*8.07*	*142.85*	**0.64**	*155.9*
Ragged Island	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	**0.00**	*6.9*
Rum Cay	*0.00*	*0.00*	*0.00*	*0.84*	*10.82*	**0.05**	*13.4*
San Salvador	*0.00*	*0.00*	*3.71*	*27.58*	*91.04*	**0.67**	*92.6*
South Abaco	*0.00*	*0.00*	*0.00*	*5.80*	*81.04*	**0.38**	*81.2*
South Andros	*0.00*	*0.00*	*0.00*	*11.18*	*181.78*	**0.83**	*353.1*
South Eleuthera	*0.00*	*0.00*	*0.00*	*31.93*	*525.40*	**2.39**	*630.3*
Spanish Wells	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	**0.00**	*137.7*
West Grand Bahama	*0.00*	*0.00*	*0.05*	*390.46*	*4,521.30*	**21.60**	*4,825.1*
TOTAL, BAHAMAS	***0.00***	***0.00***	***5.25***	***3,043.25***	***33,551.66***	**161.67**	***44,214.6***

Source: Self-elaborated.

The results show that when high winds are present, no difference exists between the distribution of population and the affected people. It is possible to find protected areas for flooding, but it is not easy to do the same for strong winds. The existing threshold of 50 years RP is also visible.

5.3.3. Probable Impact on economic flows

This section analyzes the impact on economic flows (or economic losses) derived from eventual hurricanes. A hurricane represents an additional risk of economic flow from the direct capital stock damage. Therefore, the total probable risk includes the direct capital loss and indirect losses due to the temporal lack of capacity to generate productive flows.

In doing so, the study first needs to identify relevant sectors in The Bahamas. For this purpose, the impact on touristic services is selected in this study due to GDP contribution and the sensitivity to climate change. Some clarifying information in this regard are:

- The consequences of extreme events and catastrophic damages on the evolution of economic flows in the long term, may derive from the loss of business activity during the events, and additional psychological perception of the potential customers about the safety of the island. However, these eventual behavioral changes altering global trends on touristic flows are out of the scope of this study;
- The estimated impact on losses due to business disruption is essentially at the island level, and it can easily represent just a spatial redistribution of activities. A reduction of activity in New Providence Island, for example, can be partially assumed by Grand Bahama's being undetermined, in the final balance of the global analysis. The analysis will assume that a reduction in the flows will represent a total loss for the economy; and
- The seasonal characteristic of the touristic business connected with annual holiday seasons in a visitor's homeland, and the hurricane seasons, affect the influence of the direct damages on the indirect losses, as during the periods of low activity the operational loss will be lower and easy to recirculate.

5.3.3.1. National Scale

To estimate the hurricane economic flow impact at national scale, this study collected the basic statistics for the Bahamas's Touristic sector (Table 35). Descriptive sectorial rates are obtained and applied:

Table 27. Basic Tourism Statistics for The Bahamas (in 2010)

Magnitude	Value
Number of visitors	6.27 million/year
Number of visitors requiring accommodation	1.48 million/year
Number of visitors based on Cruisers	4.79 million/year
Average accommodation duration	6.7 nights/person
Total Expenses flow	US$ 2,600 million/year
Expenses per tourist	US$ 1,756.75 per person
Expenses per day and Tourist	US $ 262.2 /person/day
Total capital stock sector services	US$ 8,640.22 million
Direct Contribution of Tourism to GDP (2016)	US$ 1,604.49 million
Indirect Contribution of Tourism to GDP (2016)	US$ 1,369.60 million
Induced Contribution of Tourism to GDP (2016)	US$ 658.8 millions
Total Contribution of Tourism to GDP (2016)	US$ 3,633.11 millions
Flow of Expenses per Capital stock value	27% /year
GDP per capital stock ratio touristic	42%/year
Tourism GDP per visitor accommodation.	US$ 2,454.72 /person
Tourism GDP per visitor – night	US$ 366.32 /person/day

Source: The Bahamas ministry tourism

Table 36 shows the seasonal distribution of visitors, where the ratio of the actual visitors over the average visitors is presented. Months where the number of visitors is below the average show index values below 100%, whereas months where the number of visitors is above the average show index values above 100%.

Table 28. Monthly Touristic Activities

Index of monthly touristic activities											
Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
85%	97%	133%	121%	107%	118%	127%	100%	50%	71%	87%	104%

Source: The Bahamas ministry tourism (https://www.bahamas.com/vendor/bahamas-ministry-tourism)

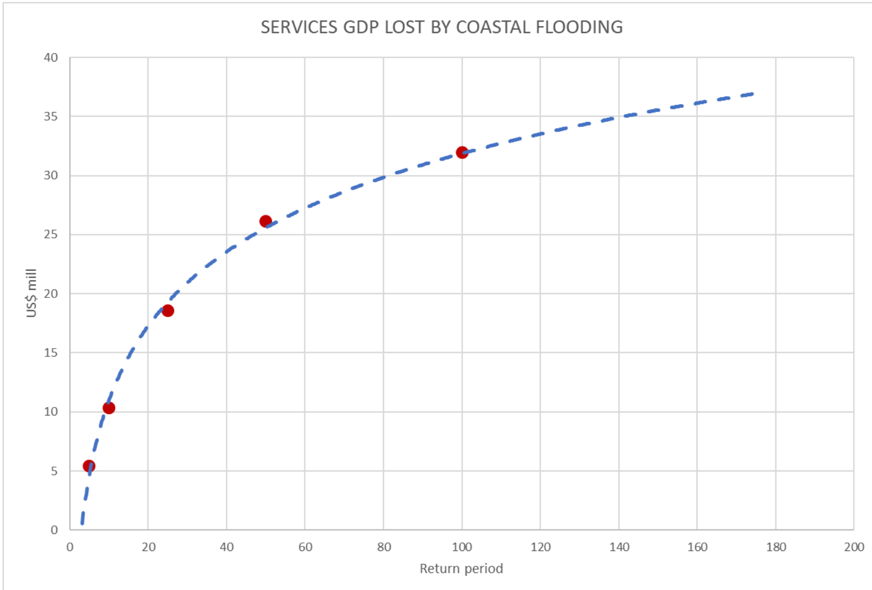
The conclusion of this table shows that a business disruption extended of three months during September, October and November may be 73% higher (or lower tourists) than an equivalent disruption during March, April and June (this means an additional US$137 million of the economic flow affected over three months). The impacts on tourism will be calculated assuming a three-month disruption on an average month representing 11.5% of indirect losses over direct damages.

Table 29 Probabilistic Distribution of Economic Flow Losses in Tourism Due to Flooding

Return Period	**Hurricane Exposed economic flow (US$ M./year)**	**% over total Flow**	**Probable losses (US$ M/year)**	**% over potential flow**	**Marginal Damage (US$ M)**
5	*50.96*	*1.42%*	*5.06*	10%	NA
10	*95.08*	*2.62%*	*13.84*	15%	8.78
25	*151.84*	*4.18%*	*30.36*	20%	16.52
50	*197.16*	*5.43%*	*49.29*	25%	18.92
100	*239.09*	*6.58%*	*71.73*	30%	22.44
TOTAL Tourism GDP	3,633.11				
AAL	4.3				

Source: Self-elaborated.

Figure 88. Service Stock Damaged by Coastal Flooding



5.3.3.2. Local sites

To analyze the spatial distribution of the economic flow impact, this study computed the quota of visitors per island (Table 38). This result will be used to distribute generated GDP among the different islands. The study then introduces the services capital stock per island. The ratio of GDP/Stock will show the differences in capital intensity in the touristic sector showing, for example, New Providence obtains GDP with less Capital than Grand Bahama.

Table 30. Tourism Activity per Island Damages and Losses

Island	Quota visitors	Quota of capital	GDP Tourism US$ Millions	Tourism GDP/Stock	Indirect Losses Coef.
New Providence	76.17%	72.77%	2,767.4	44.01%	11.00%
Grand Bahama	8.77%	14.30%	294.4	25.81%	6.45%
Abaco	5.96%	4.62%	216.6	54.31%	13.58%
Andros	0.62 %	1.59%	22.4	16.38%	4.1%
Berry Island	0.57%	0.17%	20.7	141.49%	35.4%
Bimini	1.18%	0.42%	42.7	117.98%	29.5%
Cat Cay	0.40%	0.43%	14.5	8.93%	2.2%
Cat Island	0.09%	0%	3.2	8.93%	2.2%
Eleuthera	2.59%	2.15%	94.1	51.55%	12.9%
Exuma	2.32%	2.27%	84.3	43.69%	10.9%
Inagua	0.02%	0.18%	0.8	5.70%	1.4%
Long Island	0.13%	0.89%	4.7	6.24%	1.5%
San Salvador	1.17%	0.21%	42.4	235.63%	58.9%
Total BHM	100%	100%	3633.11	41.69%	10.4%

Source: Self-elaborated.

5.3.4. Probable Impact on Roads

5.3.4.1. National scale

This section presents the impact on roads. The structure followed resembles what has been previously presented for economic assets with the specific methodology adopted for infrastructures (Table 39).

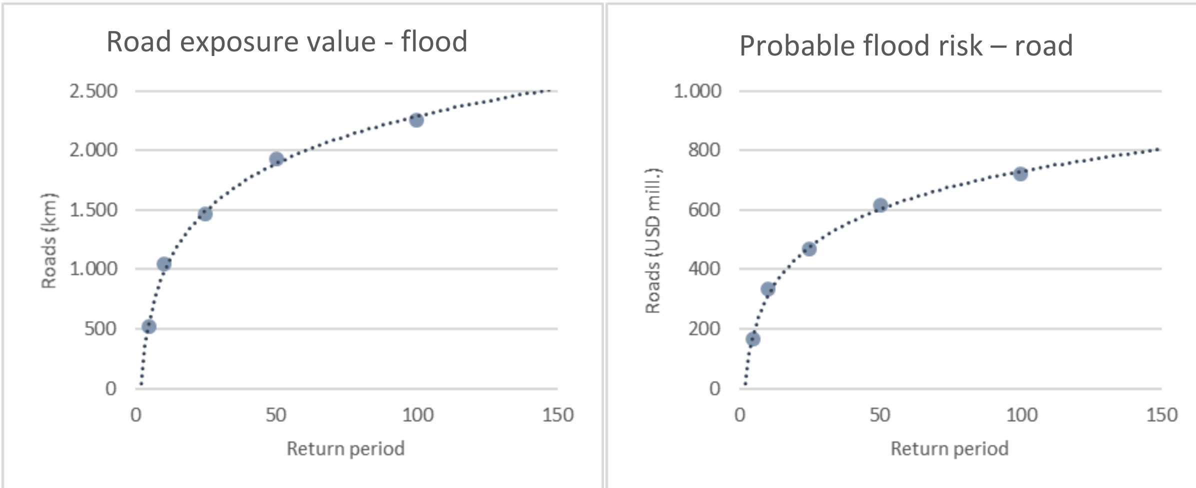
For a national scale, roads have been identified as the relevant infrastructures to survey due to the lack of additional data, and the character of roads has been a proxy for all the public capital. The indicators provided are the total amount of flooded roads and the fraction represented over total network.

Table 31. Probabilistic Distribution of Damage on Road Network Due to Coastal Flooding

Country	**BAHAMAS**	Hazard	**COASTAL FLOODING**		
ROAD NETWORK		**Return period**	**Exposed roads (km)**	**% over total**	**Probable road damages (US$ million)**
TOTAL ROADS		5	519	4.88%	165.56
10639,2km		10	1,042	9.79%	332.40
US$ 6,787.80 million		25	1,465	13.77%	467.34
ANNUAL AVERAGE LOSSES		50	1,930	18.14%	615.67
US$ 82.97 million		100	2,256	21.20%	719.66

Source: Self-elaborated.

Figure 89. Damage Exceedance Function for Road Network Due to Coastal Flooding



Source: Self-elaborated.

5.3.4.2. Local study sites

This section analyzes the impacts on infrastructures at the specific sites. The structure resembles what has been presented at national scale with some differences. The results for roads are presented with the same structure as seen at the national scale (Table 40). However due to the lower spatial scope of the local sites and after the contribution of local agents' categories of nodal infrastructures have been spatially identified: airports, ports and roads in the transport sector, health facilities, educational and administrative elements in the social infrastructure and water supply, communication and energy facilities for basic supplies. For these categories a critical return period for flooding, defined as the threshold to be flooded, is provided.

Table 32. Flooding Impacts on Infrastructures Per Study Site

Damages on road infrastructure due to coastal flooding (km)						
Island	RP 5	RP 10	RP 25	RP 50	RP 100	**AAL (km)**
Long Island	5.90	29.40	49.40	63.10	74.90	**6.53**
Andros	2.40	3.30	5.70	8.60	11.20	**1.04**
Grand Bahama	30.40	63.40	116.30	165.90	200.70	**17.78**
Damages on road infrastructure due to coastal flooding (US$ million)						
Island	RP 5	RP 10	RP 25	RP 50	RP 100	**AAL**
Long Island	1.88	9.38	15.75	20.12	23.90	**2.08**
Andros	0.76	1.05	1.82	2.74	3.57	**0.33**
Grand Bahama	9.70	20.22	37.10	52.92	64.02	**5.67**

Source: Self-elaborated.

The spatial distribution of relative and absolute damages for roads show different results per island. About the absolute values, the higher concentration of urban areas in Grand Bahama explains the different scale of absolute risk compared with Long Island or Andros. For the case of Long Island, the 25 years return period flooding generates the highest quota of damages, the impact of higher return periods follows a diminishing trend from that level. However, for the Andros and Grand Bahama sites, this reduction does not exist.

Table 33. Distribution of Flooding Impact on Nodal Infrastructures Per Site

Island	Infrastructure	Critical Return Period	Comments
Andros	San Andros Airport	>100	No probable Damages observed
Andros	South Andros Airport	100	
Andros	Port	>100	No probable Damages Observed
Andros	Educational Center Staniard Creek	>100	
Andros	Educational Center Andros Town	>100	
Andros	Medical Center Staniard Creek	>100	
Grand Bahama	Intl Airport	5	
Grand Bahama	Freeport Port	100 (*)	Minor probable damages
Grand Bahama	Water supply facilities	25-50	Several points provided by local agents
Grand Bahama	Educational Center Freeport	50	Minor probable damages
Grand Bahama	Medical Center Freeport	>100	
Long Island	Airport	10	
Long Island	Port	>100	Out of study site. No probable damages observed.
Long Island	Educational Center Lower Deadman's Cay	25	Minor probable damages

Source: Self-elaborated.

Table 41 shows the probable impacts on nodal infrastructure. Note that “no damage observed” is included if there is marginal affection with no damage, and blank is attributed when no affection exists.

A specific analysis has been developed for the mobile telephone network, the number of elements at risk are located per island and the summary is presented in Table 42. The affection is higher for Grand Bahama although the 50 years RP flooding is required to substantially affect

the network. No specific damage is expected for Andros, and minor affections are expected for Long Island.

Table 34. Summary of Impacts on Mobile Network Due to Flooding

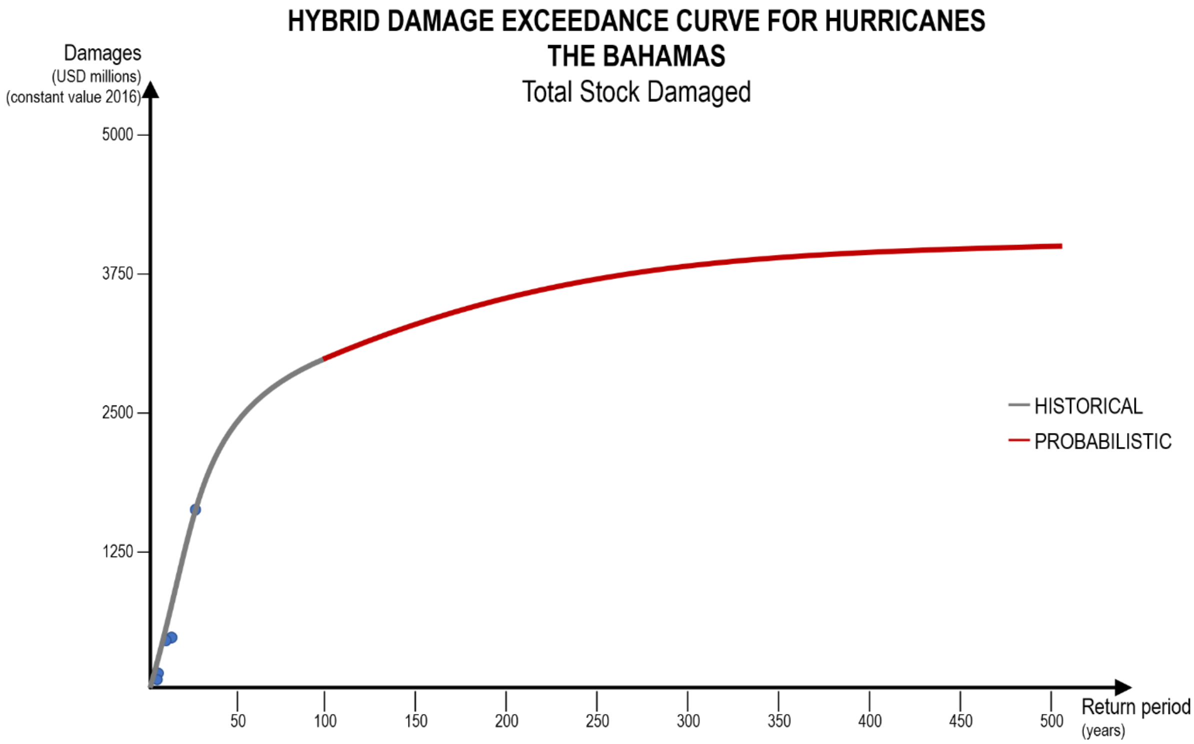
Island	Infrastructure	Number of antennas affected by 5yr return period	Number of antennas affected by 10yr return period	Number of antennas affected by 25yr return period	Number of antennas affected by 50yr return period	Number of antennas affected by 100yr return period
Andros	Telecommunications	0	0	0	0	0
Grand Bahama	Telecommunications	1	2	5	7	7
Long Island	Telecommunications	0	1	1	2	2
TOTAL BAHAMAS	Telecommunications	11	22	32	39	45

Source: Self-elaborated.

5.3.5. Hybrid loss exceedance curve

This section presents the combination of the historical loss assessment curve with the probabilistic risk estimation. The combination of both instruments in a single curve serves to create a synthesis of the empirical registered results obtained in the past, associated to low return periods, with the statistical scenarios produced applying Montecarlo techniques used to replace the non-existing results associated to long return periods. The curve is obtained for damage on total capital stock as the damages to people are not easy to integrate in the process. The damage for low return periods is mainly associated with flooding whereas the damage for higher cases derive from wind. The result is presented in Figure 92.

Figure 90. Hybrid Loss Exceedance Curve - Total Stock



Source: Self-elaborated.

5.3.6. Climate change effects

This section presents the additional impact of climate change on The Bahamas. The impact is characterized through a comparative analysis between the situation at the time of this study and the projected situation for 2050. The changes between these results will be generated by introducing sea level rise that alters the impacts of coastal flooding. The following hypotheses will be stated:

1. Climate change in the Bahamas only affects coastal flooding. There is likely no change in extreme events apart from the fact that local sea level rise may amplify damages;
2. The horizon year has been established in 2050, therefore, long term projections for climate change are not considered in the analysis;
3. The climate scenario selected by The Bahamas Government is RCP 8.5; and
4. To avoid discussions on socioeconomic scenarios, the exposed society considered in the year 2050 will be equivalent to the present. Therefore, no change can be attributed to the political evolution of society.

5.3.6.1. National scale

This section aims to present the impact of climate change on final results and give visibility to its relative relevance at the national scale.

The results are presented in Table 43. The provided indicators include the projected damage and the observed increase from the previous base case where no climate change effects were considered. The categories of damages under analysis are: Damage on population, total stock and road infrastructure.

Table 35. Damage Due to Coastal Flooding in 2050 Horizon with Effects of Climate Change (CC)

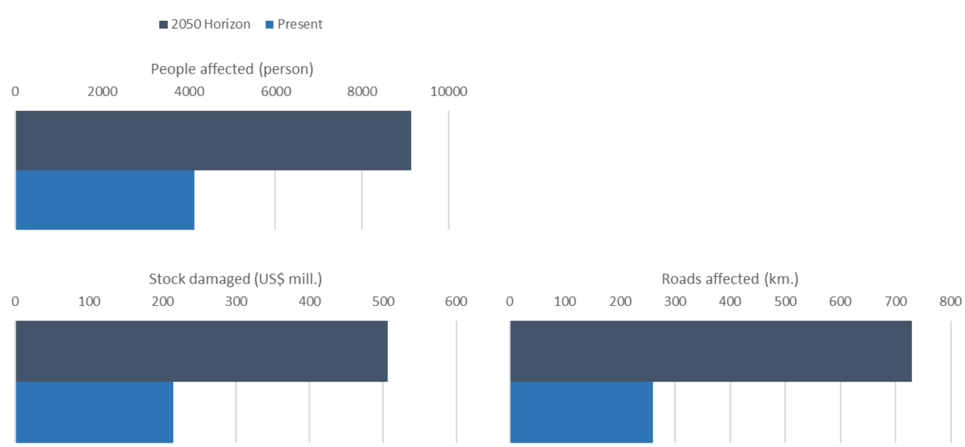
Return Period	No. of probable affected people	% change due to CC	Probable Stock damage (US$ million)	% change due to CC	Roads (km.)	% change due to CC
5	29,615	*243.01%*	1,639.76	*266.94%*	2,319	*346.94%*
10	32,316	*109.19%*	1,787.14	*133.80%*	2,628	*152.09%*
25	34,451	*43.17%*	1,914.44	*51.86%*	2,799	*90.99%*
50	36,059	*17.29%*	1,997.38	*14.28%*	2,943	*52.52%*
100	37,675	*3.21%*	2,181.85	*2.16%*	3,131	*38.76%*
AAL	9,134	*120.80%*	506.23	*134.95%*	730	*180.64%*

Source: Self-elaborated.

The results show that the significant impact is derived from enlarging damages for low return periods, which are the main contributors to AAL, and therefore the value of this magnitude is significantly enlarged.

The impact of additional permanent flooding represents a substantial change when low return periods flooding is involved as they lay in the same magnitude order. On the contrary, when extreme flooding events with high return periods are present, the contribution of permanent flooding becomes less relevant. An additional conclusion is that infrastructures show higher risk increase due to CC than population and assets.

Figure 91. Changes in AED Due to Climate Change



Source: Self-elaborated.

5.3.6.2. Local study sites

This section aims to present the influence of climate change on local sites. The basic hypothesis is the same as those presented at the national level. No change is applied to the extreme wind events and only flooding is affected due to sea level rise.

The results are summarized in the increase of AAL (Table 44) observed per study site for the different categories of exposure used in the project, population, total capital stock, and distribution among residential and services sectors and finally infrastructures.

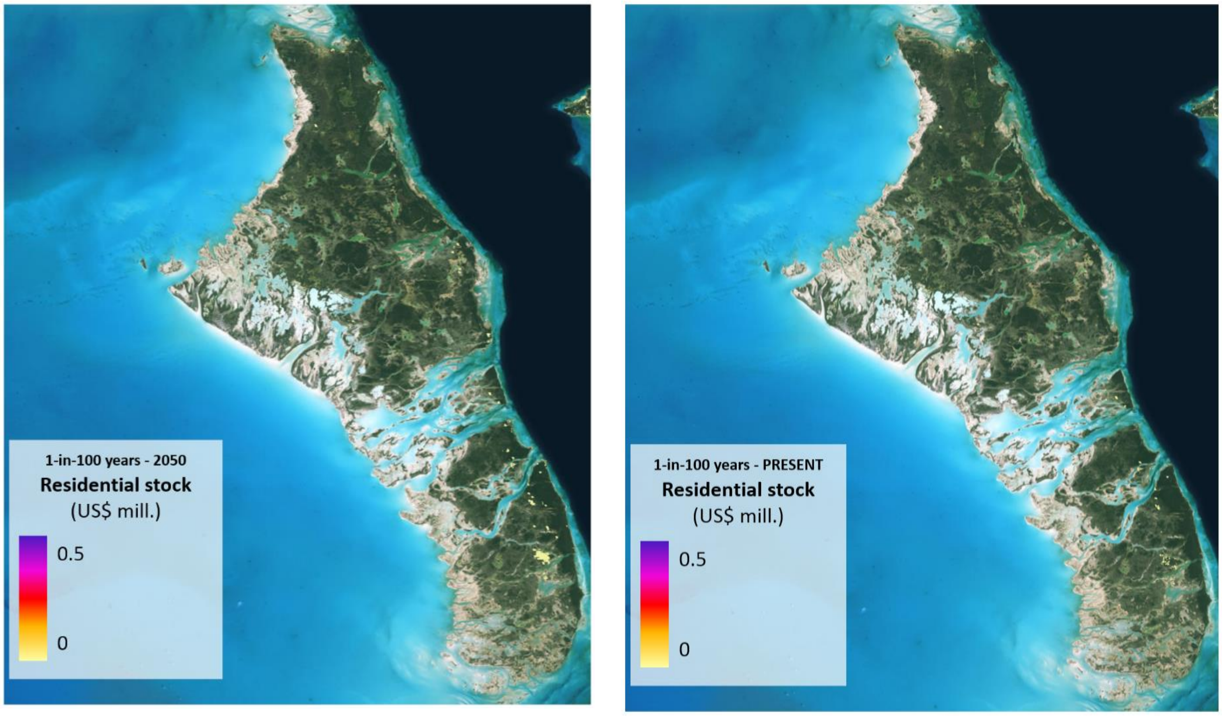
Table 44. Climate Change Impact on Study Sites Per Sectors

Island	AAL	AAL	Diff
Affected population (person)			
Long Island	41	45	*9.27%*
Andros	6	35	*449.70%*
Grand Bahama	147	568	*286.70%*
Total stock damages (US$M)			
Long Island	2.22	2.94	*32.59%*
Andros	0.31	1.90	*513.94%*
Grand Bahama	7.51	30.56	*306.91%*
Residential stock damages (US$M)			
Long Island	1.42	1.88	*32.62%*
Andros	0.20	1.24	*517.80%*
Grand Bahama	5.02	20.53	*309.10%*
Services stock damages (US$M)			
Long Island	0.09	0.12	*32.29%*
Andros	0.04	0.24	*557.72%*
Grand Bahama	1.06	4.49	*323.79%*
Road infrastructure damaged (km)			
Long Island	6.53	24.55	*275.74%*
Andros	1.04	6.86	*561.97%*
Grand Bahama	17.78	60.99	*243.09%*

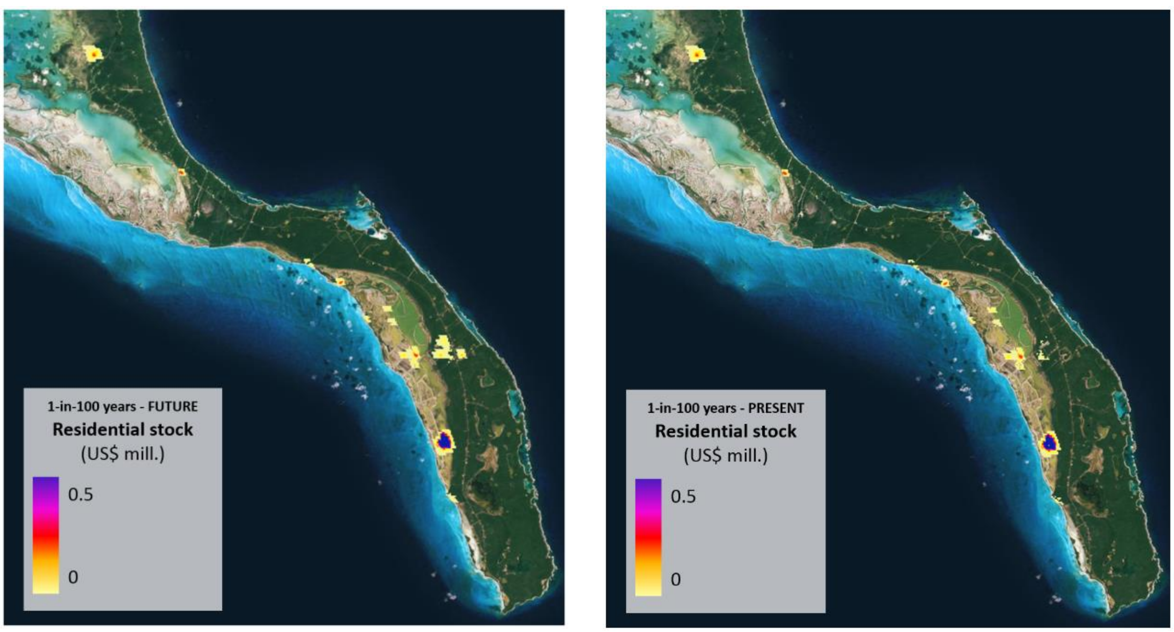
Source: Self-elaborated.

The difference between absolute and relative increase can again be observed. The former is more representative at the Andros study site and the latter at Grand Bahama.

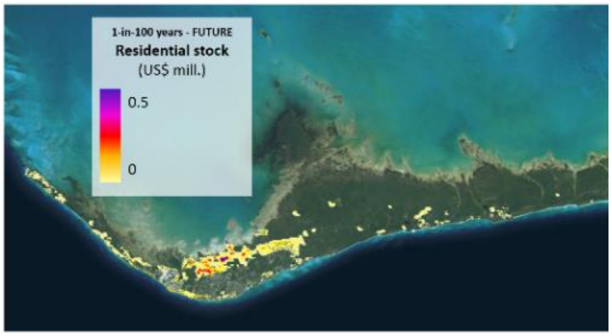
Figure 92. Comparative Damage on Residential Capital for Andros Due to CC

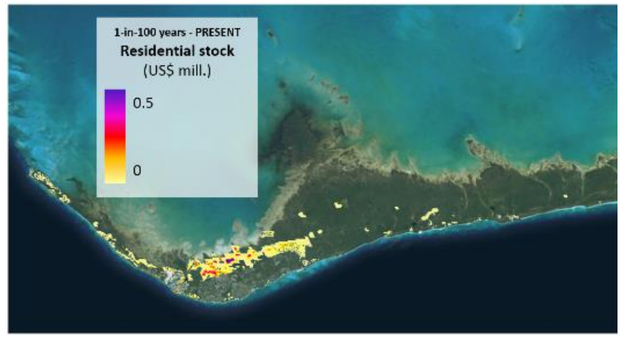


Source: Self-elaborated. *Rcp8.5, 2050*



Source: Self-elaborated. *Rcp8.5, 2050*





Source: Self-elaborated. *Rcp8.5, 2050*

5.3.7. Conclusions and comments

- The spatial distribution of the Bahamian society across the territory shows high concentrations around Nassau and Freeport, where only parts of these locations are included in this study. Despite significant risk is observed as the result of this study, this concentration should be reviewed carefully for future risk assessment studies;
- The distribution of probable damage assessments per island allows identifying areas where severe eventual damages emerge for relatively low return period events, whereas in other areas, the observed damages grow proportionally with the severity of the events.
- The probable risk assessment at the national scale coincide with the observed historical events; and
- Future evolution of the risk scenario is also included in this study by analyzing the additional climate change risk through SLR (Sea Level Rise).

5.3.8. Results per study site

Tables 45-50 reformulate the results of this study, to show a detailed view of these per local study site.

Table 36. Summary of Results in Long Island

Flooding								
Concept	Total	RP 5	RP 10	RP 25	RP 50	RP 100		**AAL (US$M)**
"# of probable affected people	165	131	153	155	155	156		**41**
Total Capital Stock US$M	25.5	5.91	8.63	10.09	11.62	13.25		**2.22**
Residential Stock US$M	16.2	3.77	5.51	6.44	7.41	8.45		**1.42**
Services Stock US$M	0.9	0.24	0.35	0.41	0.47	0.54		**0.09**
Tourism GDP US$M	4.7	3.7	5,4	6.3	7.2	8.3		**1.38**
Road Infrastructures Km		5.9	29.40	49.40	63.10	74.90		**6.53**
Wind								
Island	Total	RP 5	RP 10	RP 25	RP 50	RP 100	RP 500	**AAL**
"# of probable affected people	165	0.00	0.00	0.00	0.00	157	157	**2**
Total Capital Stock US$M	25.5	0.00	0.00	0.00	0.00	0.68	13.76	**0.06**
Residential Stock US$M	16.2	0.00	0.00	0.00	0.00	0.44	8.78	**0.04**
Services Stock US$M	0.9	0.00	0.00	0.00	0.00	0.03	0.55	**0.01**
Tourism GDP US$M	4.7	0.00	0.00	0.00	0.00	0.46	8.45	**1.54**
Road Infrastructures Km	NA							

Source: Self-elaborated.

For the study site of Long Island, we can observe that the impact on population is generated for the 10 years RP flooding, because the marginal contribution due to a longer RP flooding is not representative. However, the impact on capital stock and touristic GDP shows a different profile when flooding RPs are increased, since the results are continuously increasing. For the case of wind impacts, the existing 50 years RP threshold is clearly seen.

About the nodal infrastructures for long Island, we can observe that airport is at risk under a 10 year RP flooding scenario. An educational center is also expected to suffer minor damages for a 25 year RP flooding scenario.

Table 37. Risk on Nodal Infrastructures for Long Island

Infrastructure	Critical RP	Comments
Airport	10	
Port	>100	Out of study site. No damages observed.
Educational Center Lower Deadman's Cay	25	Minor damages

Source: Self-elaborated.

For the case of Andros island, the summary of results is presented in the following table:

Table 38. Summary of Results Per Site for Andros Island

Impacts on Andros Study Site (Flooding)								
Concept	Total	RP 5	RP 10	RP 25	RP 50	RP 100		**AAL Million US$**
"# of probable affected people	3,747	10	29	36	50	65		**6**
Total Capital Stock US$ million	381.3	0.74	1.02	1.77	2.15	2.67		**0.31**
Residential Stock US$ million	252.7	0.48	0.66	1.15	1.39	1.74		**0.20**
Services Stock US$ million	56.6	0.08	0.12	0.21	0.25	0.32		**0.04**
Tourism GDP US$ thousand/year	22,400	3.40	5.1	8.9	10.6	13.6		**0.0017**
Infrastructures Km		2.40	3.30	5.70	8.60	11.20		**1.04**
Impacts on Andros Study Site (Wind)								
Island	Total	RP 5	RP 10	RP 25	RP 50	RP 100	RP 500	**AAL Million US$**
Population (person)	3,747	0.00	0.00	0.00	2,472	3,309	3,309	**80**
Total Capital Stock US$ million	381.3	0.00	0.00	0.00	0.00	17.52	209.06	**0.99**
Residential Stock US$ million	252.7	0.00	0.00	0.00	0.00	11.62	138.37	**0.66**
Services Stock US$ million	56.6	0.00	0.00	0.00	0.00	2.62	30.65	**0.15**
Tourism GDP US$ thousand/year	22,400	0.00	0.00	0.00	0.00	1,036.9	12,130	**0.05936**
Infrastructures Km	NA							

Source: Self-elaborated,

The results for Andros Island show a continuously increasing path for all the observed variables, although the absolute value of the results are smaller than the Long Island case study, reflecting the differences in exposure between both areas. In Andros, the only element susceptible to flooding is the South Andros Airport for a 100 year RP flooding scenario.

Table 39. Risk on Nodal Infrastructures for Andros Island

Island	Infrastructure	Critical RP	Comments
Andros	San Andros Airport	>100	No Damages observed
Andros	South Andros Airport	100	
Andros	Port	>100	No Damages Observed
Andros	Educational Center Staniard Creek	>100	
Andros	Educational Center Andros Town	>100	
Andros	Medical Center Staniard Creek	>100	

Source: Self-elaborated.

Table 40. Summary of Results Per Site in Grand Bahama

Impacts on Grand Bahama Study Site (Flooding)								
Concept	Total	RP 5	RP 10	RP 25	RP 50	RP 100		**AAL US$M**
Population (person)	35,244	253	537	933	1,332	1,739		**147**
Total Capital Stock US$M	4.343.8	15.35	26.99	43.17	60.85	81.87		**7.51**
Residential Stock US$M	2,968,8	10.25	18.04	28.83	40.67	54.80		**5.02**
Services Stock US$M	821.4	2.07	3.80	6.23	8.97	12.20		**1.06**
Tourism GDP US$ thousand/year	294,400	741.9	1,362	3,537	4,211	5,390		**0.674**
Infrastructures Km		30.40	63.40	116.30	165.90	200.70		**17.78**
Impacts on Grand Bahama Study Site (Wind)								
Island	Total	RP 5	RP 10	RP 25	RP 50	RP 100	RP 500	**AAL Million US$**
Population (person)	35,244	0.00	0.00	0.00	34,155	34,155	34,155	956
Total Capital Stock US$M	4.343.8	0.00	0.00	0.00	0.58	349.63	4,089.40	19.51
Residential Stock US$M	2,968,8	0.00	0.00	0.00	0.38	238.58	2,791.65	13.32
Services Stock US$M	821.4	0.00	0.00	0.00	0.07	66.72	783.13	1.34
Tourism GDP US$ thousand/year	294,400	0.00	0.00	0.00	25.1	23,913	280,683	1.7
Infrastructures Km	NA							

Source: Self-elaborated.

The results for the Grand Bahama Study site show a magnitude according to the conditions of the site - the only case where a big town is involved. About the profile, a continuous growth of

the impact is observed, both for population and capital stock. About the results for nodal infrastructure, Grand Bahama shows a higher risk than the previous sites. The airport is expected to flood for a 5 year RP flooding scenario, whereas some additional elements are expected to be flooded for 50 year RP flooding scenario.

Table 41. Damages on Grand Bahama Study Site

Island	Infrastructure	Critical RP	Comments
Grand Bahama	Intl Airport	5	
Grand Bahama	Freeport Port	100 (*)	Minor damages
Grand Bahama	Water supply facilities	25-50	Several points provided by local agents
Grand Bahama	Educational Center Freeport	50	Minor damages
Grand Bahama	Medical Center Freeport	>100	

Source: Self-elaborated.

6. CONCLUSIONS

This report presents the results obtained for the Risk Profile of The Bahamas and the detailed analysis for three study sites: Grand Bahama, Long Island and Andros Island.

A specific analysis has been developed for the exposure analysis to characterize the representative flooding and hurricane events for the country of The Bahamas. The consequences of extreme events have been combined with regular atmospheric and sea level conditions to generate the coastal flooding events' probability distribution. The analysis has been adapted for different scales to capture the different phenomena and the results have been then aggregated as required for the final output.

The exposure analysis has been largely based on international sources and local field work that have extensively been made to calibrate and describe the situation at different scales. The exposure irregularities that characterize the territory of The Bahamas have represented a strong condition for the results obtained in the project.

The vulnerability survey has focused on the identification of specific damage functions for the representative assets at risk. Specifically, for the study sites, field work has allowed the team to calibrate the vulnerability of the territory, combining impact on different infrastructure elements.

The results show a heavy concentration of risk on New Providence Island due to the spatial concentration of assets and population in this island. Among the study sites, Andros shows a lower profile for risk due to the low presence of population and activity, and Grand Bahama concentrates a higher set of elements at risk. Long Island shows an intermediate profile.

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