THE BAHAMAS

NATIONAL STANDARD FOR DISASTER RISK ANALYSIS

2025 Edition

Technical Note

DRM AUTHORITY

IDB

This document was originally prepared by the consulting firm: ERN (Evaluación de Riesgos Naturales) through the Technical Cooperation Project: Capacity Strengthening for a More Resilient Bahamas (BH-T1078) funded by the Japan Special Fund of the Inter-American Development Bank (IDB) and was subsequently revised as necessary by the IDB, the DRM Authority and the Department of Meteorology.

The Disaster Risk Management Authority was established by the Disaster Risk Management Act 2022 and came into being in June 2024. This document was originally prepared by the consulting firm: ERN (Evaluación de Riesgos Naturales) through the Technical Cooperation Project: Capacity Strengthening for a More Resilient Bahamas (BH-T1078) funded by the Japan Special Fund of the Inter-American Development Bank (IDB) and was subsequently revised as necessary by the IDB, the DRM Authority and the Department of Meteorology. The development of The Bahamas National Standard for Disaster Risk Analysis (NSDRA) was driven by the need to establish a technical benchmark for assessing disaster risks across the country. This is especially critical given The Bahamas' vulnerability to natural hazards such as hurricanes, flooding, and storm surges, and the increasing urgency to align national practices with international standards and frameworks. The publication aims to: Standardize methodologies for disaster risk analysis across sectors and institutions; Support evidence-based decision-making in public investment, urban planning, and emergency preparedness; Enhance institutional capacity for risk-informed development and climate resilience; Facilitate inter-agency coordination by providing a shared framework for risk assessment; Align national practices with global frameworks such as the Sendai Framework for Disaster Risk Reduction and IDB's DRM policy guidelines. It is also intended to be a living document, subject to updates and refinements as national capacities evolve and new data becomes available

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ABBREVIATIONS

AAL	Average Annual Loss
AIM	All-Hazard Impact Model
DEM	Digital Elevation Model
DRM	Disaster Risk Management
ECLAC	Economic Commission for Latin America and the Caribbean
EP Curve	Exceedance Probability Curve
ELT	Event Loss Table
GFCF	Gross Fixed Capital Formation
GoBH	Government of The Bahamas
IDB	Inter-American Development Bank
IH-Cantabria	Instituto de Hidráulica Ambiental de la Universidad de Cantabria
IPCC	Intergovernmental Panel on Climate Change
LEC	Loss Exceedance Curve
LiDAR	Light Detection and Ranging
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
PDC	Pacific Disaster Center
PML	Probable Maximum Loss
PSHA	Probabilistic Seismic Hazard Analysis
SEEA	System of Environmental-Economic Accounting
SLOSH	Sea, Lake, and Overland Surges from Hurricanes model
UNDRR	United Nations Office for Disaster Risk Reduction

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1. Introduction

The objective of this report is to generate the technical bases for a national standard for disaster risk analysis in The Bahamas, specifically for hurricane wind and storm surge[1] modelling, with the aim of mainstreaming climate risk into The Bahamas' national development strategies and plan implementation.

For this report's objective, the following definition for the technical "*standard for disaster risk analysis*" has been adopted, bearing in mind the objective and scope of this technical material: "*the minimum processes, procedures and results for identifying hazard intensity levels or with the quantifying of potential losses that can be materialized from by hazard events, especially hurricanes*". It should be noted that potential losses due to natural resource hazards are not included in this framework because methodologies have not been firmly established internationally.

With The Bahamas being one of Latin America and the Caribbean (LAC) region's countries that has historically experienced significant impacts from climate-influenced hazards, The Government of The Bahamas saw the need to update and improve its Disaster Risk Management (DRM) governance framework and public policy. In 2022, The Government of The Bahamas (GoBH) passed the Disaster Risk Management Act (DRM Act) which provides the legislative framework for a comprehensive, holistic, integrated and coordinated approach to reducing disaster risk and enhancing resilience across all sectors of society. Central to the Act is the integration of disaster risk considerations into development planning and decision-making processes at all levels, ensuring that risk reduction becomes a shared responsibility and a core component of national development.

In support the DRM Act's implementation, The Bahamas National Technical Standard for Disaster Risk Analysis was developed to provide a consistent, evidence-based methodology for assessing disaster risk in the context of two of the most frequent hazard types for the country. These standards ensure that all natural hazard risk assessments—whether conducted by government agencies, private companies, non-governmental partners, or other stakeholders—adhere to a common framework, enabling comparability and quality assurance across all sectors and islands in The Bahamas. These standards directly support the operationalisation of the DRM Act by providing a framework to establish a baseline of acceptable multi-hazard disaster risk for the country (*DRM Act, 2022, Section 12*). By creating a standard for disaster risk analysis that generates more accurate assessments of potential risk that also quantify potential risks from both a human and economic impact standpoint, The Bahamas can make more effective policy development, planning and investment decisions that are aligned national, regional and global disaster risk reduction goals.

[1] As an added value of this document, the state-of-the-art review and qualification criteria has included too hurricane induced precipitation.

This report is arranged into sections, where besides this introduction, Section 2 provides a summary of the state-of-the-art for the modelling of the different components of probabilistic hurricane risk analysis, which have been followed by the qualification criteria as technical standards and specifications proposed in The Bahamas. Section 3 provides an overview of several available studies for The Bahamas that could be used as a reference (or inputs) for conducting future disaster risk analysis studies in The Bahamas. Based on these two sections, a set of opportunities and recommendations for future updates, upgrades and enhancements for The Bahamas disaster risk analysis studies is presented in Section 4. The final chapter (Section 5) briefly summarises the conclusions and recommendations of this technical document. It is expected that the technical standard proposed in this document will result in effective planning and the continued development of the disaster risk assessment studies that can be used for effective disaster risk management (DRM) plans and risk reduction measures by the GoBH.

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2. TECHNICAL METHODOLOGY STANDARD FOR DISASTER RISK ANALYSIS

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2. TECHNICAL METHODOLOGY STANDARD FOR DISASTER RISK ANALYSIS

This section presents the technical procedures and methodologies required for developing a state-of-the-art hurricane wind and storm surge hazard and risk analysis in The Bahamas, indicating the needs in terms of completeness, resolution level, geographical coverage and risk assessment framework for the different components involved in its development (e.g., historical tracks catalogue, land cover data, etc.).

The scope of this report is limited to considering only **two hurricane hazard intensities:** strong winds and storm surge.

However, as an added value, a review of the state-of-the-art for hurricane precipitation and inland flood modelling has been included too, setting the bases for possible future studies that may be of interest in the country. Having mentioned this, it should be considered that since in the case of hurricanes different hazard intensities can occur in an almost simultaneous manner, the interactions between them in the loss assessment procedures are relevant and should be explicitly addressed.

2.1 General Framework

This document recommends a Probabilistic Risk Assessment as the general technical approach for disaster risk analysis standards in The Bahamas. There are two reasons for this. The first is that it allows for a more accurate assessment of potential risk by considering a variety of scenarios, including the most severe hurricane tracks that have not yet occurred (e.g., a potential Category 5 hurricane hitting New Providence). In other words, probabilistic risk assessment enables the appropriate assessment of low-probability, high-impact risks that have not yet experienced but could occur e.g., once in a hundred or two hundred years. This point is a particularly important consideration for disaster risk management public policy in the present and future, when the patterns and intensity of hazards are changing due to climate change. In addition, probabilistic risk assessment can include social change scenarios such as future population trends and urbanisation projections.

Second, the probabilistic risk assessment allows for the visualisation and quantification of potential risk from both a human impact perspective (e.g., number of fatalities and people affected by potential hazards) and an economic impact perspective (i.e., expected loss and damage). Quantified potential impacts can be expressed in terms of Annual Average Loss (AAL) and Probable Maximum Loss (PML) (see Section 2.2.4). These measures are used as easy-to-understand indicators for government officials and the general public to objectively understand current national or local risks (alt.: baseline risks) and to set specific targets for future risk reduction (i.e., benchmarks). In addition, these measures can be incorporated into cost-benefit analyses during the project development and design phase and used to determine optimal investments in disaster risk reduction.

The Components of Probabilistic Risk Assessments

When conducting probabilistic risk assessment, it is necessary to build models for hazard, exposure and vulnerability:

HAZARD MODEL

The hazard model is used to quantitatively assess the probability of an intensive natural phenomenon occurring. In general, it simulates the frequency of occurrence, intensity, spatial distribution, among other factors, for each type of hazard. There are two types of hazard models: probabilistic models and scenario-based assessments (deterministic models). This document mainly refers to the former. Generally, hazard models use different observational statistical data for each hazard (specifically, data from the fields of geophysics, hydrology, and meteorology). Examples of hazard models include the Hurricane Wind & Storm Surge Model, the Probabilistic Seismic Hazard Analysis (PSHA), the Hydrodynamic Flood Model, and the Rainfall-Runoff Model.

EXPOSURE MODEL

The exposure model is used to illustrate the distribution and characteristics of populations, assets, infrastructure, which may be affected by hazardous events. Generally, this model utilizes spatial data (GIS data, satellite images, building and population distribution maps, for example) to identify which assets and populations are exposed to the target hazard. In particular, the characteristics of the asset exposure model reflect the structure of the building (particularly its seismic and wind resistance), the number of residents and visitors, type of infrastructure and the value of the asset. Ideally, the exposure model should be developed specifically for each land area using census data and other relevant information, but if this is not possible, proxy data may be used based on other similar geographical features or socioeconomic conditions.

VULNERABILITY MODELS

Vulnerability models are used to assess the extent to which exposed assets and people are affected by a particular hazard. This is an important factor in assessing the potential damage that can be expected from each hazard that occurs. The output of a specific vulnerability model is a two-dimensional function that shows the hazard intensity and damage level for each building or infrastructure (in other words, a graph that shows wind resistance or earthquake resistance). Generally, this model is presented for each type of hazard and each type of structure or infrastructure. Vulnerability models are developed based on data obtained from experiments conducted in laboratory facilities such as structural testing sites, wind tunnel testing facilities, and seismic shake tables. In cases where access to implementing such tests is not possible, there are also standardized models (such as the Hazus model) that can be used as alternatives.

By integrating these three models, it is possible to conduct a comprehensive probabilistic risk assessment (see Section 2.2.4).

2.2 State-of-the-Art Technical Requirements for Disaster Risk Analysis (technical standards)

In order to objectively ensure the robustness, completeness, level of updating, and quality of The Bahamas disaster risk analysis, a review of state-of-the-art modelling of the various components was conducted. They are summarized here in the form of a list of requirements to facilitate understanding of each case. The list of requirements should be understood as the *optimal requirements*, as of today, based on the current knowledge, technical and computational capabilities.

The aims of having defined this list of requirements are mainly to:

1. Establish technical criteria to ensure that hazards and risk assessment studies in the future in The Bahamas meet the required technical framework quality.
2. Identify the opportunities for improvements, enhancements and upgrades that should be considered in the development of future analyses in the country, based on existing studies.

The definition of the optimal requirements also considers whether the hazard and risk analysis can provide accurate information for the decision-making processes in developing relevant planning instruments. These planning instruments include territorial and land use planning, DRM national and local planning, emergency planning among others. Additionally, the definition of requirements can be included in building codes for new and existing structures, as well as in reconstruction activities aiming to 'build back better' and avoid reconstructing vulnerabilities in the aftermath of a disaster event.

Domain of Risk Analysis

An optimal hurricane wind hazard and/or risk assessment for The Bahamas should cover the totality of the national territory where population and assets are exposed. At least, the following islands should be prioritized in terms of population size or number of socioeconomic activities: New Providence, Grand Bahama and Abaco. Around 70% of the total population of The Bahamas lives on New Providence, whereas 15.5% live in Abaco and Grand Bahama[2]. The remaining people live scattered on other cays and islands[3]. However, given the geographical distribution of the occupied and unoccupied islands, a general domain of study as the one shown in Figure 1 is considered as optimal. Hazard analyses should provide wind speed estimations for any point within the national territory whereas risk assessments should provide loss estimations for points where assets of any type, susceptible to be damaged by strong winds, exist. In other words, for risk assessments, the domain of study can be smaller since not all of the more than 700 islands that belong to The Bahamas have built infrastructure or assets that can be damaged by hurricanes.

[2] Department of Statistics, Government of The Bahamas. 2025. *2022 Census of Population and Housing Report: First Release*. https://www.bahamas.gov.bs

[3] Government of The Bahamas. "About The Bahamas: Overview." Accessed May 7, 2025. https://www.bahamas.gov.bs/wps/portal/public/gov/government/SubmitCustomerService?1dmy=&urile=wcm%3Apath%3A%2FMOF_Content%2Finternet%2FThe+Government%2FGovernment%2FAbout+The+Bahamas%2FOverview%2F

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FIGURE 1. Ideal domain of study for hurricane wind hazard analyses for The Bahamas

Source: https://srv1.worldometers.info/maps/bahamas-political-map/#google_vignettel

Resolution Level (Hazard)

A national hurricane hazard analysis should have the highest possible resolution level, based on the characteristics of a digital elevation model (DEM) and land surface coverage layer available. These characteristics condition the wind speed distributions at different heights and locations (i.e. coastal vs. inland). The Bahamas is a relatively flat country so no major variations caused by topographic conditions occur. However, land coverage and use are varied and can change from nearby places to the other and then, for this, it is recommended that at least a 90m resolution be used.

A key component for the development of storm surge hazard models is the bathymetry. These data can be obtained with very high resolution levels using LiDAR imagery, although because of its associated cost, are available usually for limited locations. Currently available open bathymetry datasets have a resolution level of up to 90m.

Resolution Level (Risk and Exposure)

A key aspect to be considered when performing a risk assessment, is the consistency between the resolution levels of the different inputs. If for instance, a very high resolution level exists for the hazard component, but a coarsed-grain is available for the exposure one, the risk results tend to be controlled by the lowest one. At this point, differentiations between the hurricane intensities should be made since they change, from one place to another one nearby, in a different manner. For instance, in the absence of large topographical variations, maximum wind speed transitions between adjacent locations are typically smooth. However, flooding and storm surge variations with large variations can exist within short distances.

When developing a risk model, a balance between accuracy and efficiency is usually sought, and, based on today's computational capabilities, exposure at coastal areas should be of at least 200m, whereas at inland locations of up to 500m.

2.2.1 Technical Standard for the Hazard Model

Hurricanes (specifically Cat 3 or more) are classified as high impact events, which in practical terms can be understood as a phenomena that for a comprehensive understanding, cannot rely only on the observation of past events. Even if the historical records of hurricanes in the North Atlantic Basin (where The Bahamas islocated) have more than 120 years, it is not a complete database and even if it were, it would be very difficult to provide with enough robustness the recurrence of different hazard values at the points of interest.

Because of this, a prospective and probabilistic approach is considered as the best alternative for the analysis of hurricane hazard. The main objective of a probabilistic and prospective hurricane wind hazard analysis is to obtain long-term relationships between wind speed values and their occurrence frequencies. The larger the wind speed, the lower its occurrence frequency. This approach relies on historical data, for which a series of simulations are performed to generate synthetic hurricane tracks that, although have not (yet) occurred, are feasible to do so in the future.

There are different approaches for the generation of these synthetic tracks, such as random walk techniques, where defining a set of parameters, several perturbations of historical tracks are performed to obtain the new ones. Each synthetic track should provide information about the location of the eye and a timestamp from the beginning to the end of the storm. These characteristics are dependent on the location of the eye, since for instance, the behaviour and transit speed of any storm changes if the eye is at open water or at inland locations, among other characteristics. Once the synthetic tracks are generated, making use of the wind field equations (described later in this document), the estimation of the intensities at any site of interest is performed for each of the tracks.

Besides the prospective (forward-looking) approach, a probabilistic framework should be adopted to consider the different uncertainties that are associated to the hurricane occurrence and transit patterns. By adopting a probabilistic approach, besides the estimation of the mean value of the wind hazard intensities at the sites of interest, a dispersion measure can be included too.

General Criteria for Storm Surge Hazard Modelling

Storm surge levels and corresponding flooded areas are determined by the characteristics of a particular storm (intensity of the wind and pressure, radius of the storm, speed of translation, angle of approach, etc.), together with the receptor characteristics (morphology and topo-bathymetry). Due to the storm surge level dependence on the forcing and receptor, the change in storm surge and flood severity cannot be directly inferred from the change in storm intensity. This is exemplified with the larger storm surge created by Hurricane Katrina as a category 3 event, than those created by categories 5 and 4 events (e.g., Camille in 1969, and Ida in 2021) as a result of the former event having a larger size and lower speed of translation. This also indicates the importance of the receptor characteristics towards the storm parameters, so that the information during landfall is not enough to determine storm surge, making it essential to consider the hours previous to landfall or approach to the coast by the event. As such, similar storm characteristics can produce different storm surges depending on the topological characteristics such as the presence of coastal lagoons, wide continental shelves, or concave coasts, which may amplify the resulting surge. Due to the different factors affecting storm surge, quantifying storm surge hazards and associated flooding requires an explicit modelling of storm development and induced storm surge and flooding at regional scales.

The use of explicit models to determine storm surge hazards poses the challenge of highly demanding computational costs for modelling large numbers of events with the required resolution to accurately resolve flooded areas. To deal with the computational cost issue, several methodologies using different approaches have been developed. There is a set of methods that do not model storm history and associate a given storm surge to the landfalling characteristics of the events. Such methods are applied, for instance in Mexico, by the National Disaster Prevention Center to develop the risk atlases (CENAPRED, 2006).

Probabilistic approach methodologies, that is, those that use synthetic events obtained through statistical methods and perform explicit modeling of the storm surge can be organized into those that perform explicit modelling of the storm surge but limit the simulations to the coastline (*mean sea level*) and those that do perform the inland flooding. Simulations limited to the coastline cannot perform flood simulations inland, and mainly extrapolate the water levels obtained at the coastline towards land, flooding the inland areas correspondingly, so that the flood area is a result of a topography below the storm surge level, usually provided by a Digital Elevation Model. While this method provides a more accurate estimation, it fails to consider the effect of the terrain over the storm surge propagation, usually leading to the overestimation of flood levels.

The last set of methods employ explicit modeling of the storm surge considering the evolution of the events, but focusing on reducing the number of events needed to determine the storm surge and flood levels. For example, Ruiz-Salcines *et al.* (2020) developed a method that employs sets of hypothetical events based on an ensemble approach of event key parameters from the synthetic events obtained from GCMs under climate change projections. The hypothetical events consist of a special class of synthetic events, which have a constant intensity during their lifetime and approach the area of interest from a specific direction and at constant translation velocity. The events are organized into sets with similar properties (wind intensity, minimum central pressure, storm size, and speeds of translation), approaching the area of interest with a linear trajectory and consisting of parallel paths which cover all possible directions of motion. The hypothetical events are used by The National Weather Service's (NWS) National Hurricane Center (NHC) from the National Oceanic and Atmospheric Administration (NOAA) as a composite approach to provide inundation maps as an approach for determining storm surge vulnerability for an area. Nevertheless, the method proposed by Ruiz-Salcines *et al.* (2020), extends the analysis to a probabilistic method that takes into account climate change and can perform inland flooding with reduced computational demand.

Frequency Analysis

To accompany the probabilistic representation of hurricane hazard, the occurrence frequency to the synthetic storms is a crucial parameter. To assign values that are representative and coherent with the observation, different verifications and validations, in particular related to the completeness of the data, are needed. Frequency analyses can be performed at basin or local level.

Cut-off Date for the Historical Catalogue

An internationally accepted dataset as reliable and complete for the historical tracks is the one known as Hurdat2 and published on a regular basis by NOAA. The dataset includes information from past hurricane seasons, although the last year is only made available by May/June of the following one (i.e. data about the 2020 hurricane season for the North Atlantic basin were released on June 2021). If a study is to be developed as of December 2021, the optimal cut-off date of the historical storm catalogue is December 2020, to include all the hurricanes that occurred in the North Atlantic Basin during the 2020 season that have already been included in the Hurdat2 dataset. This information has been subject to exhaustive reviews and verifications by specialists at NOAA and amended, when needed, based on observations from aerial surveys and measurements of intensities at ground level. In any case, there is no need to be limited by this NOAA restriction when using data sets managed by the Bahamas itself.

Wind Field Estimation

Once the synthetic tracks are generated, a wind field for each storm needs to be calculated. Typically, parametric models are preferred, for which, depending on the location of the eye of the hurricane and the central pressure value, the wind field and other relevant values such as the radius of maximum wind, are obtained.

There are different parametric equations for the calculation of wind fields and for the case of The Bahamas, those that have been developed specifically at least for the North Atlantic Basin should be used. Ideally, locally calibrated models should be used to capture any particularity that exists within the domain of interest for the country.

The equations for the wind speed calculations depend too on the length of the sustained gusts and the height for which the modelling is performed. The standard values for these parameters have changed over time depending on the requirements of the risk assessments (by finding the measure that better correlates with damages and losses) and on the requirements of building codes, traditionally those that follow the ASCE guidelines[4]. As of today, the ideal wind speed estimation is to be done in terms of 3 second gusts and at 10m height above the terrain[5]. Previous standards have included wind speed estimations at the same time but averaged on 5seconds up to 1minute gusts.

Run-off Model

Run-off models describe the rainfall-runoff relations of a catchment area or basin, generating a surface runoff hydrograph. In a nutshell, the model converts rainfall into runoff. There are different approaches for modelling the runoff, such as linear and non-linear reservoirs, excess rainfall (aka as recharge) and the Nash model. It is important that the model used for these purposes is suitable and valid for the domain of study, and takes into consideration the different characteristics of the terrain, either in terms of soil classes, geology conditions and topography.

[4] ASCE are not official for The Bahamas but are used.

[5] PAHO, *'Wind Speed Maps for the Caribbean for Application with the Wind Load Provisions of ASCE 7'*.

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Use of Satellite Data for Heavy Rainfall and Flood Modelling

State-of-the-art techniques related to earth observation have provided valuable and robust data that are useful for the modelling and validation of rainfall and flood events. Hurricane modelling has benefitted too from these data and when available, should be used particularly in the modelling of heavy rainfall and floods.

Variations Between Coastal and Inland Locations

The formulation of most wind field equations has been made for open and flat terrains. This assumption is valid for most coastal locations, but hurricane wind can also cause damage and losses inland , for which certain modifications are needed. For this, a **set of correction factors need to be included in the hazard analysis to reflect the following conditions:**

- **Topography:** variations in the terrain affect the wind profile in height, besides creating "exposed" and "protected" zones. For this, the estimation of hurricane wind intensities at inland locations require adding a digital elevation model (DEM) to the hazard model. Results are highly sensitive to the resolution level of the DEM and for this, the minimum of 30m is recommended.

  In the case of coastal flooding, the elevation levels inland are required to determine the flooded areas and the propagation of the storm surge inland. The resolution shall resolve the main topographic features and shall include data up to a level where no storm surge is expected. To determine this level, previous tests can be performed using a land boundary at the coastline and simulating those events that are expected to create the largest storm surge (based on intensity, size, and translation velocity). The resulting water levels can be used as a reference to the topography levels needed in the model, as it is not expected that the storm surge propagation inland exceeds the values obtained when considering a land boundary at the coastline. Results are highly sensitive to the resolution level of the DEM and for this, the minimum 30m is recommended.

- **Land use:** another factor that modifies the wind profile in height at inland and coastal locations is the roughness of the terrain and for this, information about land use and coverage is needed. Depending on the type of coverage for the land (e.g., urban, forest, etc.) a factor that modifies the wind speed distribution needs to be added in the analysis. The minimum resolution level for these land use data should be 30 m.

- **Bathymetry:** the bathymetric data should increase its resolution as it approaches shallow water to provide a better description of the hydrodynamics. The resolution should describe the bathymetric features that can affect hydrodynamics in nearshore areas, as they will influence the storm surge levels. The minimum resolution level should be 30m. However, for local studies, more refined resolution levels should be use, taking advantage of recent techniques, such as the satellite-derived bathymetry, that allow characterisations of up to 2x2m.

- **Computational mesh:** a computational mesh is required to perform numerical simulations. This mesh should present the required resolution to resolve the relevant topo-bathymetric features affecting the hydrodynamics. Flexible meshes are convenient as they can have a coarser resolution in deep waters and increasing resolution towards land. The use of rectangular grids will require the use of nested/telescopic grids to improve computational times by only providing high resolution in the required areas near the coast and inland.

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- **Bottom coverage:** sea bottom material is an important parameter as it is related to bottom roughness, which depending on the material will create different resistance to the hydrodynamics generated by the event. These data characterize the material that compose the seafloor, in terms of the grain size, or a generic coverage for which a roughness coefficient is assigned (i.e. Manning or Chezy).

Consideration of Moon Tides in the Storm Surge Model

Storm surge acts over the astronomical tides so that the total water level is known as storm tide. Depending on the astronomical tides, the total flood levels may be less or higher than when only considering storm surge.

Waves are considered part of storm surge due to their contribution to wave setup, and when considering particular events, it is advisable to include waves to provide at least a sense of the contribution of wave setup to the total water levels. Relative sea level rise should be included in long-term assessments, such as in the case of climate change, sea-level rise is an important factor that should be considered, as it provides the water level reference over which storm surge is propagated. Sea level rise could be a result of climate change due to the melting of the ice caps, but also a result of subsidence due to oil, gas, water extraction, or geological processes. Ideally, long-term assessments could also consider the changes in the land use, which is of particular relevance in the storm surge hazard and risk modelling.

State-of-the-art Numerical Methods for the Surge Modelling

Storm surge models in general share some requirements and needs, such as the hurricane information (for example historical or synthetic tracks), the bathymetry of the domain of study and a grid (or a mesh) for which the calculations are to be made. Depending on the scope and needs of the analyses, two or three-dimensional models could be required. The former are typically sufficient to capture the variations of the water level caused by hurricanes, whereas the latter are needed in more detailed applications, such as the transportation of pollutants.

Several well-known models have been used in different storm surge applications, such as Delft3D, the one by the Japan Meteorological Agency, SLOSH (by the US National Weather Service), and ADCIRC, among others.

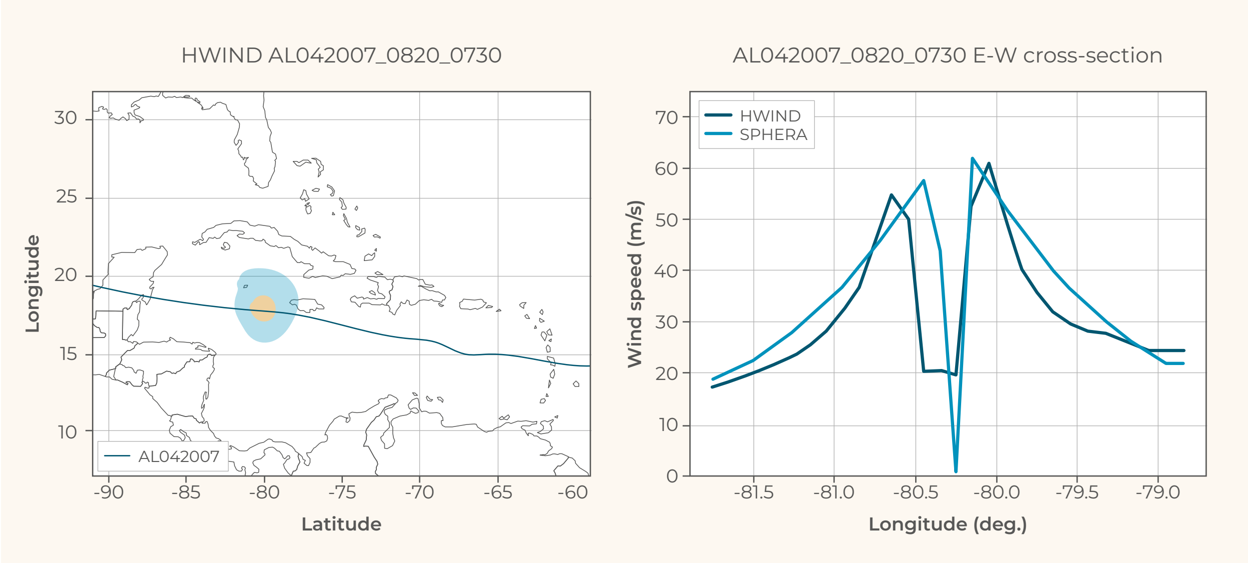
Validation, Verification and Calibration of the Hazard Results

Ideally, hazard analyses should be fully documented and all the relevant details about the components, data source, methodology and tools are to be disclosed. A key part of the documentation is a validation and calibration section on which the robustness of different components of the model are assessed, and some other assumptions can be better explained. As a result of the validation and verification process, some useful findings for calibration purposes may arise that if needed, can be incorporated in the model.

The minimum reviews of the components are:

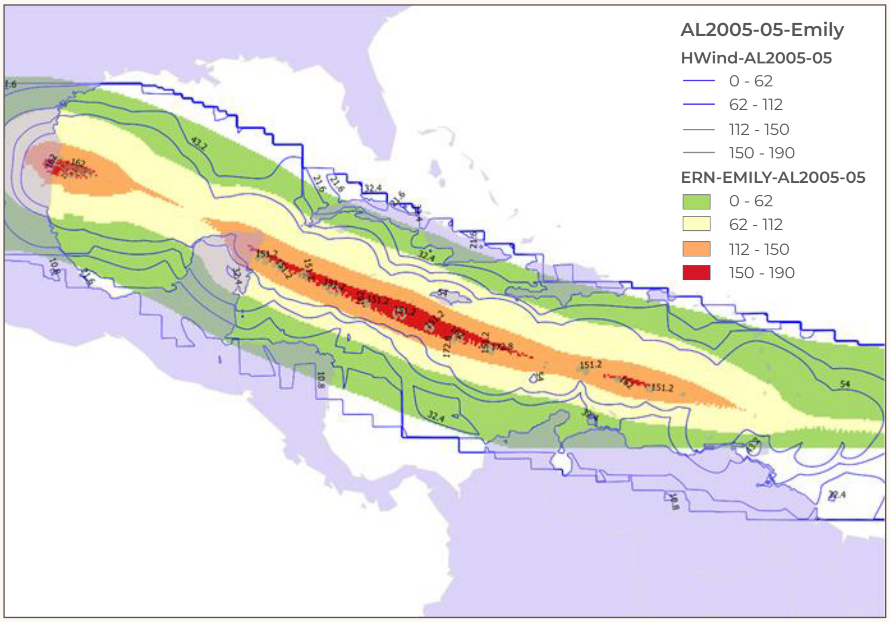
- **Frequency analyses:** for which the verification and comparison of observed and modelled frequencies for hurricanes of different categories are performed. These analyses are typically performed over geographical boxes.
- **Wind field comparisons between modelled and published for a given time step of a storm:** the comparison of the modelled wind field against measured values for a given point of the storm, as shown in Figure 2, provides valuable information about the validity of the equations and assumptions used in the model.
- **Wind field comparison for the maximum speeds over the complete storm:** the comparison of the maximum modelled wind speeds against those measured, over the course of the storm provide too valuable information and allow reviewing the assumptions for different conditions (i.e. open and flat terrain and protected areas). Figure 3 shows an example of these comparisons for Hurricane Emily.

FIGURE 2. Comparison of modelled (light blue line) and measured (blue line) wind fields for a given point of a hurricane



Source: ERN.

FIGURE 3. Comparison of modelled (polygons in color) and measured (lines) maximum winds for a complete hurricane

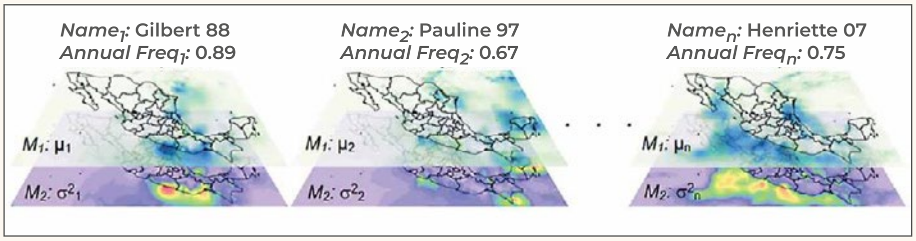


Source: ERN.

Hazard Representation

To define the optimal hazard representation, the objective of the hazard analysis should be disclosed. If for instance, the results are to be used in a building code, the representation of maximum intensities through hazard maps for one or more return periods is enough. However, if the hazard analysis outputs are to be used in a subsequent risk assessment, the optimal hazard representation is a stochastic event-set which is the only one that allows estimating the complete disaster risk panorama for the area under study. A schematic representation of a hurricane stochastic event-set is shown in Figure 4.

FIGURE 4. Example of hurricanes in a stochastic event-set



Source: Torres *et al.*, 2013

A stochastic event-set includes several (thousands) of synthetic hurricanes, for which the wind speeds are modelled and are assigned to an occurrence frequency. The storms included in the event-set should be mutually exclusive (i.e. independent) and collectively exhaustive (i.e. altogether represent all the feasible forms on which the hazard may manifest in the future).

Multi-Intensity Compatibility

As explained in the introduction of this report, the main hurricane intensity measures are: strong winds, heavy rain and storm surge. The first two are relevant at coastal and inland locations, whereas the last one is relevant only at coastal sites. This generation of standards addresses only the wind and storm surge modelling. The base components of the hurricane hazard model should be the same, regardless the intensity(ies) of interest and, for example, the same synthetic tracks (with the same occurrence frequencies) can be used to estimate several hazard intensity measures. This allows then, for each of the synthetic storms, calculating the intensity values for hurricane wind, rainfall and storm surge, which is valuable when performing comprehensive risk assessments, as discussed later in this section.

Climate Change Considerations

Being a climate-influenced hazard, the characteristics of hurricanes are susceptible to be modified by climate change. Even if no formal agreement exists about the degree of the variations, different IPCC reports have indicated that intensity and frequency characteristics of moderate and large hurricanes are expected to increase in the mid-term. The consideration of climate change in hurricane hazard analyses can be done through different ways, by for instance modifying the occurrence frequencies by a factor larger than 1. Another approach is to make use of climate models that allow forecasting future storms. Considering climate change adds significant uncertainty to the hazard model and, as much as possible, those uncertainties should be too acknowledged, identified, quantified and propagated.

2.2.2 Technical Standard for Exposure Model

An exposure model for natural hazards refers to a set of information (or database) that systematically compiles the inventory of buildings and infrastructure (as well as their structural, economic, and demographic attributions) that may be susceptible to hazard impacts. Exposure models are typically expressed in terms of assets and population. It can be constructed at various levels, including national, sub-national, and municipal. If sufficiently detailed information is not available, it is possible to use so-called proxy exposure models with greater granularity by referring to similar geographic forms and socio-economic conditions in other area/countries. It would be even better if the exposure model could include exposure factors such as agricultural land (crops) and environmental factors (forests, mangrove forests, national reserves).

DATA SPECIFICATIONS

Data specifications for exposure models should include the following elements: spatial resolution (geographic information about the structures of interest), time scale (when referring to structure and population data), and building and infrastructure attribute information (physical structure type, structural characteristics, etc.).

In addition to statistical data, there are also methods for developing original image data, such as automatic or manual analysis of satellite images or aerial photographs taken by drones.

DATABASE SETUP

The exposure information should be organized in a database. The database should contain data attributes such as geographic information, structural physical information, economic value information, and human information (e.g., number of users of the structure).

It is easier to understand the overall picture of the exposure model if the structures are roughly divided into categories according to their purpose. The following is an example of such a division, but it is also possible to use a different division based on purpose: urban constructions, urban infrastructure, and national infrastructure.

URBAN CONSTRUCTIONS

In general, urban structures include the following: Low Income Housing (LP), Middle Income Housing (MP), High Income Housing (HP), Commercial, Industrial, Private Health, Private Education, Public Health, Public Education, and Government. Each of these structures should have data attributes such as geographic information, land area, number of floors, total capacity (total area), occupancy, structure type, and asset value. Note: To create an exposure database, it is also necessary to have attributes to distinguish between the public and private sectors. In this case, low-income housing, which is often supported by the government in the event of a disaster, can be counted as public sector.

URBAN INFRASTRUCTURE

In general, Urban Infrastructure should include the following: Bridges in urban areas, Airports, Ports, Energy substations and adjacent network, Telecommunication substations and antennas, Water and sewage network, Water treatment plants, Gas network. The database attributes to be given to these structures can be the same as those for Urban constructions.

NATIONAL INFRASTRUCTURE

In general, national infrastructure should include the following: main road network, secondary road network, hydroelectric power plants, dams, thermal power plants, power substations and networks, telecommunications substations and antennas, fuel and gas substations and networks. The database attributes to be given to these infrastructures are basically the same as those for urban constructions, but it is preferable that the road network include information on its length and characteristics (e.g. whether drainage channels are in place, whether landslide countermeasures have been taken, etc.).

VALIDATION PROCESS

After the database has been constructed, it is desirable that the validity of the location of the structures, the type of structure, the asset value, etc. be verified using various information sources. The main information sources that can be used for this purpose are generally statistical data held by the Statistics Bureau or individual ministries, international statistical information held by international organisations such as ECLAC, and open data such as OpenStreetMap.

(GRAPHIC) DISPLAY OF EXPOSURE MODELS

After the exposure database has been constructed, the asset value and structural vulnerability (in terms of the age of the building and the road network) **of each structure or each land area division can be displayed using GIS or tables and figures.**

2.2.3 Technical Standard for Vulnerability Model

Vulnerability is a concept that can encompass multiple dimensions, such as physical (structural), human (casualties), environmental (coastal erosion and water pollution) and socioeconomic (fiscal shocks). Typically, hurricane risk assessments have addressed the physical dimension for which, an estimation of the direct losses is performed using probabilistic and prospective approaches.

A vulnerability analysis is a mandatory component of a risk assessment, understanding risk as something that is a function of the hazard and the vulnerability of an exposed asset. Vulnerability can be quantified using quantitative (e.g., vulnerability functions) or qualitative methodologies (e.g., vulnerability indexes), being the first ones the preferred for comprehensive risk assessments. However, within the quantitative methodologies, different representations of the vulnerability can be found, such as damage matrixes, fragility curves and vulnerability functions. From these, the latter are the optimal ones for fully probabilistic risk assessments since they provide a quantitative and continuous representation, besides considering directly the uncertainties of the loss values.

There is not a unique approach to develop the vulnerability functions and different methodologies are available, from analytical to experimental ones. If possible and if data are available, these vulnerability models can be calibrated too for the local conditions.

Vulnerability Dimensions

The type and number of vulnerability dimensions to be included within a risk assessment depends too on the scope and expected use of the results. For country risk assessments, the required dimension is the physical one, although it can be complemented by considering too the impact of hurricanes on the exposed population. Ideally, a hurricane risk assessment should consider these two dimensions, although if only one is included, such as for instance the physical one, it does not decrease the level of quality and robustness of the studies.

2.2.4 Risk Assessment Methodology

Risk assessments can be classified in two broad categories: retrospective and prospective. The first category groups the assessments that look back at historical events only and can consider one or multiple events that have already happened. Although valuable information can be gathered from these retrospective assessments, the complete risk panorama cannot be viewed since the observation timeframe is incomplete for hurricanes, known to be low-frequency and high impact events. Damage surveys fall within this category, for which after the occurrence of a hurricane, a reconstruction of the hazard intensities from measurements and a quantification of losses after field surveys are performed.

The second category groups the forward-looking analyses, that as previously mentioned, can be considered as optimal for several disaster risk management activities. These analyses not only consider the contribution to the damages and losses from historical events, but from those that, even if have not yet occurred (or registered), are feasible to do so as per the knowledge about the hazard in the area under study. The basic hazard output for developing a prospective risk assessment is a hazard curve, which is a collection of points that relate different intensity values (e.g., wind speeds) and their occurrence frequencies. If that data are available, when combined with vulnerability functions, the average annual loss can be computed. However, the AAL does not provide the complete risk panorama and for this, additional metrics such as the exceedance probability curve (EP curve) are needed. For the estimation of the EP curve, a stochastic event-set, complying with all the requirements mentioned in the previous section is required.

A fully probabilistic risk assessment is what is considered as state-of-the-art for the estimation of hurricane losses in any domain under study. A requirement of a fully probabilistic risk assessment is the existence of a stochastic event set that allows for a probabilistic representation of the hazardous events. That approach is known in the technical literature as an event-based risk assessment, on which, for each synthetic storm, the probability density function of the losses is calculated and finally aggregated at portfolio level.

Types of Risk Analysis Results

As explained above, risk results from prospective assessments can be obtained in terms of different metrics. Ideally, **the results available from a fully probabilistic risk assessment should be the following:**

- **Average Annual Loss (AAL):** that provides a long-term overview of the risk levels at the area under study by considering the contribution of large and infrequent events, besides the contribution of small and recurrent ones.
- **Exceedance Probability Curve (EP Curve):** that provide a relationship between different (e.g., 50) loss values and their occurrence frequencies and/or probabilities. These curves allow a better understanding of the risk levels in the area under analysis.
- **Event Loss Tables (ELT):** these are intermediate results used for the estimation of the AAL and/or the EP curve. The ELT consists of a list on which all the stochastic storms are included and, besides their occurrence frequencies, all relevant parameters for determining the probability density function for the loss are listed too.

Optimal results should be provided in the form of ELT from which, as explained, the other metrics can be directly derived.

Validation and Verification of Loss Results

As in the case of the hazard analyses, validation and verification of the loss results are critical steps within a hurricane wind risk assessment. These validations and verifications can be done in terms of comparison between reported and modelled losses, bearing in mind that several limitations may exist for robust comparisons. For instance, reported losses in most cases limit the possibility to differentiate direct from indirect losses, besides being available for events that have occurred in the past, for which trending of the values are needed.

Regardless these limitations, comparisons and validations should be performed and all the constraints and problems listed and identified. Direct calibration of the losses is never recommended, although the calibration of the vulnerability component, as previously mentioned, can be done based on local recordings.

The optimal hurricane hazard and/or risk assessment should include a dedicated section for the validation, verification and calibration process of the results and the different components of the analysis. These validations should be explicitly disclosed and any limitation and restriction should be made clear too.

Table 1 shows a summary of the list the requirements identified for the different components of state-of-the-art hurricane hazard and risk assessments.

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TABLE 1. Summary of the list of requirements by category/component

Topic/Component	Requirement (minimum)
Domain of study	Entire land area of The Bahamas where population and assets are exposed
Hazard analysis approach	Prospective
Cut-off date of the historical catalogue	Last year available in Hurdat2 dataset
DEM	30m
Land use	30m
Bathymetry	30m
Wind hazard resolution level	90m
Types of assets	Buildings, infrastructure, and population
Inland exposure resolution level	500m
Coastal exposure resolution level	200m
Wind field model	Parametric and calibrated with local data
Computational mesh for storm surge	Flexible meshes or rectangular grids
Moon tides consideration	Yes, for storm surge modelling
Hazard representation	Stochastic event-set
Minimum length of the synthetic catalogue	5000 years
Multi-intensity compatibility	Yes, for hurricane winds, storm surge, and precipitation
Hazard validation (part 1)	Frequency validations at given locations
Hazard validation (part 2)	Wind field comparisons at a given time step
Hazard validation (part 3)	Comparison of maximum speeds over the complete storm
Vulnerability representation	Vulnerability functions
Vulnerability models	One function for each representative building typology and per hazard
Vulnerability dimensions	Physical (direct losses)
Vulnerability calibration	When post-event damage surveys are available
Risk assessment methodology	Fully probabilistic
Risk metrics	EP curve, AAL and ELT's
Loss validation	Comparison of modelled vs. reported losses
Other comments	Consideration of simultaneous loss occurrences

2.3 Quality Standards for Disaster Risk Analysis Studies to be Developed in The Bahamas

This section aim to set the bases for the development and/or enhancement and upgrade of climate hazard and risk assessments in The Bahamas, in particular, for those that address hurricanes and storm surges. The methodology used in this document is based on the definition of a list of requirements that includes all the characteristics, input data, methodologies and results of the different components that belong to hurricane hazard and/or risk models. For this, the baseline is taken as the state-of-the-art in their modelling, based on the recent advances in each field. This list of requirements is then used as the qualification criteria for assessing the robustness and quality of the studies to be developed in the future.

For a better understanding of the list of desirable characteristics, these have been divided first into the four components of disaster risk: hazard, exposure, vulnerability and loss assessment. Each of these components can also be further disaggregated into subcategories. It is worth noting that the loss assessment component can include different dimensions, such as the impact assessment on population (e.g., estimation of IDPs, fatalities and injured), and the impact on the built environment (e.g., damages and losses in the housing and infrastructure sectors). In addition, a reference evaluation score from 0 to 1 is given for each sub-criterion, depending on the degree of achievement of the criterion.

For Hazard Analyses

Geographical coverage:

- The whole territory of The Bahamas: 1.0.
- Some priority islands of The Bahamas with detail: 0.75.
- Regional level (Caribbean) including The Bahamas with detail: 0.60.
- Regional level (Caribbean) including the Bahamas without detail: 0.50.
- Global level with detail: 0.25.
- Global level without detail: 0.10.

Analysis type:

- Prospective with synthetic storms: 1.0.
- Prospective with extreme value theories: 0.70.
- Retrospective for a given event: 0.50.
- Retrospective only: 0.20.
- Only methodological: 0.20.

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Analysis approach:

- Probabilistic: 1.0.
- Deterministic for a given probabilistic event: 0.50.
- Deterministic based on past disaster only: 0.10.
- Only methodological: 0.20.

Cut-off date for the historical catalogue:

- To date: 1.0.
- 2015-2019: 0.75.
- 2004-2014: 0.50.
- Before 2003: 0.10.
- N/A: 0.10.

Were rain gauges installed in the country used as data input in the development of the model?

- Yes: 1.0.
- No: 0.0.

Number of years with historical rainfall records:

- More than 60 years: 1.0.
- Between 40 – 59 years: 0.75.
- Between 20 – 39 years: 0.50.
- Less than 19 years: 0.1.

Were satellite data used for the development of the flood model?

- Yes: 1.0.
- No: 0.0.

Development of a frequency analysis:

- Yes: 1.0.
- No: 0.0.

Climate change scenario considerations:

- Yes: 1.0.
- No: 0.0.

Intensity measures considered:

- Wind, storm surge and precipitation/flood: 1.0.
- Only 2 of the above: 0.75.
- Only 1 of the above: 0.5.

Length of the stochastic catalogue of storms:

- 10,000+ years: 1.0.
- Between 5,000 and 9,999 years: 0.50.
- Less than 4,999 years: 0.20.
- N/A: 0.20.

Hazard representation:

- Synthetic storms: 1.0.
- Hazard maps for different return periods: 0.75.
- Hazard map for a single return period: 0.30.
- Hazard intensity map for a given event: 0.30.
- Other: 0.1.

Validation of the hazard results:

- Yes: 1.0.
- No: 0.0.
- N/A: 0.0.

Is the windfield parametric model suitable for the region?

- Yes: 1.0.
- No: 0.0.

Is the run-off model suitable for the region?

- Yes: 1.0.
- No: 0.0.

Resolution level for the DEM:

- Less than 30m: 1.0.
- Between 90 and 30m: 0.75.
- Less than 90m: 0.20.
- N/A: 0.20.

Resolution level for the land use (roughness):

- Less than 30m: 1.0.
- Between 90 and 30m: 0.7.
- More than 90m: 0.20.
- N/A: 0.20.

Resolution level for geological characterisation (to model infiltration):

- Less than 30m: 1.0.
- Between 90 and 30m: 0.7.
- More than 90m: 0.20.
- N/A: 0.20.

Resolution level for the bathymetry:

- 2m or less: 1.0.
- Between 2 and 10m: 0.85.
- Between 10 and 30m: 0.75.
- More than 30m: 0.2.
- N/A: 0.2.

Are tides considered in the storm surge hazard model?

- Yes: 1.0.
- No: 0.0.

Is the numerical method for the storm surge model well documented?

- Yes: 1.0.
- No: 0.0.

For Exposure Modelling

What assets are included in the exposure database?

- Buildings, infrastructure, people and crops: 1.0.
- Buildings and infrastructure: 0.75.
- Infrastructure (GDP) and population: 0.75.
- Only buildings or infrastructure: 0.50.
- Only crops: 0.30.

What is the resolution level of the exposure database? – for coastal assets

- Less than 200x200m: 1.0.
- Between 500x500 and 201x201m: 0.75.
- 1x1km: 0.50.
- More than 1x1km: 0.2.
- N/A: 0.2.

What is the resolution level of the exposure database? – for inland assets

- Less than 1x1km: 1.0.
- Between 5x5 and 1x1km: 0.75.
- More than 5x5km: 0.20.
- N/A: 0.20.

For Vulnerability Analysis

What vulnerability dimensions are covered in the study?

- Physical and human: 1.0.
- Only physical or human: 0.75.

What is the representation of the vulnerability?

- Vulnerability functions: 1.0.
- Fragility curve: 0.50.
- Damage matrix: 0.30.
- Exposure and hazard overlaying: 0.10.
- N/A: 0.1.

Are the vulnerability components validated and/or calibrated?

- Yes: 1.0.
- No: 0.0.
- N/A: 0.0.

For Risk Assessments

Geographical coverage:

- The whole territory of The Bahamas: 1.0.
- Some priority islands with detail: 0.75.
- Regional level (Caribbean) without detail: 0.50.
- Global level with detail: 0.25.
- Global level without detail: 0.10.

Analysis type:

- Prospective: 1.0.
- Retrospective for a given event: 0.50.
- Retrospective only: 0.20.

Analysis approach:

- Probabilistic (event-based): 1.0.
- Probabilistic (other): 0.70.
- Deterministic for a given event: 0.50.
- Deterministic only: 0.1.

What are the risk results?

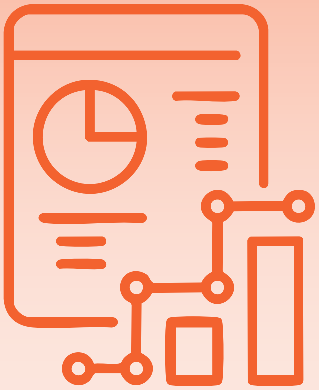
- Event loss tables for both human and economic loss: 1.0.
- Only average annual loss, either human or economic: 0.50.
- Probable maximum losses for one or more return periods: 0.50.
- Losses for a given event: 0.50.
- Qualitative results (low/medium/high): 0.10.

Are simultaneous losses caused by different hazard intensities considered?

- Yes: 1.0.
- No: 0.0.
- N/A: 0.0.

Validation of risk results:

- Yes: 1.0.
- No: 0.0.
- N/A: 0.0.



3. REVIEW OF AVAILABLE STUDY RESULTS, MODELS, AND DATA

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3. REVIEW OF AVAILABLE STUDY RESULTS, MODELS, AND DATA

This section reviews the available climate hazard and risk related studies for The Bahamas using the criteria explained in Section 2 that has been derived after identifying, component by component, the requirements for its proper inclusion in hurricane wind and/or storm surge modelling. In this sense, the models that were not fully accessible to the models, raw datasets and input data (i.e. synthetic hurricane tracks) were also considered for review if they were fully documented.

With this, it should be noted that the reviews here were performed under the specific objective of contributing to the mainstreaming climate risk analysis into national development planning, and, therefore, a low review rating does not necessarily mean that the quality of the study is insufficient.

In this section, 22 available studies were collected and analysed to serve as a reference for future hurricane wind and storm surge hazard and risk modelling studies in The Bahamas. Based on the results of the analysis and findings, the different activities of the action plan presented in Section 4 of this report have been defined.

The results of this analysis should be understood only as indicative, with respect to the standards that incorporate the state-of-the-art in the framework of a development process for hurricane hazard and/or risk modelling. This indicates that the overall quality of the 22 reviewed studies has not been assessed and there may be the case of a complete and detailed study that, if compared to what is actually needed in the light of the standard defined in this project, may seem incomplete because certain type of data were not available (e.g., having the results only presented in terms of hazard maps and not having available the synthetic storms).

3.1 List of Available Climate Hazard and Risk Studies in The Bahamas

The title, publication year and author(s) of each of the 22 reviewed studies are shown in Table 2. The publications in this list have been shared during the development of an earlier/original version of the present study with the specialists in the Bahamas and validated by the Meteorology Department of Bahamas (Met Office, thereafter). Also, the list of the available studies was socialized and validated by stakeholders from various agencies of the GoBH during a virtual workshop held on December 9th, 2021.

TABLE 2. Title, publication year and authors of the available hurricane hazard and/or risk analyses for The Bahamas

ID	Title	Publication Year	Author(s)
1	A Sentinel-1 Based Processing Chain for Detection of Cyclonic Flood Impacts	2020	Alexandre *et al.*
2	Caribbean storm surge mapping – an overview towards guidelines	2013	Branton and Dowding
3	Advancing global storm surge modelling using the new ERA5 climate reanalysis	2020	Dullaart *et al.*
4	Mapping Tropical Cyclone Wind Risk of the World	2015	Fang *et al.*
5	Assessment of storm surge and structural damage on San Salvador Island, Bahamas, associated with Hurricane Joaquin (2015)	2019	Fuhrmann *et al.*
6	Data-Driven Modeling of Global Storm Surges	2020	Tadesse *et al.*
7	A database of global storm surge reconstructions	2021	Tadesse and Wahl
8	Assessments of the Effects and Impacts Caused by Hurricane Joaquin - The Bahamas	N/A	IDB and ECLAC
9	Assessments of the Effects and Impacts of Hurricane Matthew - The Bahamas	N/A	IDB and ECLAC
10	Hazard and Risk Study – Sustainable Nassau Action Plan	2016	IDB and ERM
11	Assessments of the Effects and Impacts Caused by Hurricane Irma - The Bahamas	N/A	IDB and ECLAC
12	Assessments of the Effects and Impacts of Hurricane Dorian in The Bahamas	N/A	IDB and ECLAC
13	Disaster Risk Profile for The Bahamas	2020	IH Cantabria and IDB
14	A High-Resolution Global Dataset of Extreme Sea Levels, Tides, and Storm Surges, Including Future Projections	2020	Muis *et al.*
15	Return Period Estimation of Hurricane Perils in the Caribbean	1999	USAID and OAS
16	Wind Speed Maps for the Caribbean for Application with the Wind Load Provisions of ASCE 7	N/A	PAHO
17	Impacts of climate change on the tourism sector of a Small Island Developing State: A case study for the Bahamas	2021	Pathak *et al.*
18	A hurricane loss risk assessment of coastal properties in the caribbean: Evidence from the Bahamas	2017	Sealy and Strobl
19	Mapping Storm Surge Risk of the World	2015	Sun *et al.*
20	Update on the probabilistic modelling of natural risk at global level: global risk model	2015	Cardona *et al.*
21	Development of design wind speed maps for the Caribbean for application with the wind load provisions of ASCE 7-16 and later	2019	Mudd *et al.*
22	National Disaster Preparedness Baseline Assessment (NDBPA): The Bahamas	2021	Pacific Disaster Center (PDC)

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3.2 Characteristics of Existing Studies

This section presents the characteristics of the 22 existing available hurricane hazard and/ or risk related studies in The Bahamas, based on the technical standards established in the previous section. The review process considered the consistency of each parameter of the technical standard with respect to the scope and content of each study. For instance, if a publication only considered the wind hazard component, none of the requirements about storm surge and flood hazard exposure model were discussed, neither the ones related to the exposure, vulnerability and risk components.

Table 3 shows the characteristics of each study obtained through the review, classified by the technical standard.

TABLE 3. Classification of the available hurricane hazard and risk analyses by domain of analysis, scope, content, and approach (1 of 2)

ID	Title	Publication Year	Author(s)	Study Domain	Hazard only or Risk	Prospective or Retroactive	Probabilistic Risk Assessment	Economic loss or human impact
1	A Sentinel-1 Based Processing Chain for Detection of Cyclonic Flood Impacts	2020	Alexandre *et al.*	Subnational	hazard	retroactive	-	-
2	Caribbean storm surge mapping – an overview towards guidelines	2013	Branton and Dowding	Regional (Caribbean)	hazard	**prospective**	-	-
3	Advancing global storm surge modelling using the new ERA5 climate reanalysis	2020	Dullaart *et al.*	Global	hazard	**prospective**	-	-
4	Mapping Tropical Cyclone Wind Risk of the World	2015	Fang *et al.*	Global	risk	**prospective**	-	**Economic**
5	Assessment of storm surge and structural damage on San Salvador Island, Bahamas, associated with Hurricane Joaquin (2015)	2019	Fuhrmann *et al.*	Subnational	risk	retroactive	-	Economic
6	Data-Driven Modeling of Global Storm Surges	2020	Tadessse *et al.*	Regional (Caribbean)	hazard	**prospective**	-	-
7	A database of global storm surge reconstructions	2021	Tadessse and Wahl	Global	hazard	retroactive	-	-
8	Assessments of the Effects and Impacts Caused by Hurricane Joaquin – The Bahamas	N/A	IDB and ECLAC	Subnational	-	retroactive	-	**Both**
9	Assessments of the Effects and Impacts of Hurricane Matthew – The Bahamas	N/A	IDB and ECLAC	Subnational	-	**prospective**	-	**Both**
10	Hazard and Risk Study – Sustainable Nassau Action Plan	2016	IDB and ERM	Subnational	risk	**prospective**	Yes	**Both**
11	Assessments of the Effects and Impacts Caused by Hurricane Irma – The Bahamas	N/A	IDB and ECLAC	Subnational	-	retroactive	-	**Both**
12	Assessments of the Effects and Impacts of Hurricane Dorian in The Bahamas	N/A	IDB and ECLAC	Subnational	-	retroactive	-	**Both**
13	Disaster Risk Profile For the Bahamas	2020	IH Cantabria and IDB	National/ Subnational	risk	**prospective**	Yes	**Both**

TABLE 3. Classification of the available hurricane hazard and risk analyses by domain of analysis, scope, content, and approach (2 of 2)

ID	Title	Publication Year	Author(s)	Study Domain	Hazard only or Risk	Prospective or Retroactive	Probabilistic Risk Assessment	Economic loss or human impact
14	A High-Resolution Global Dataset of Extreme Sea Levels, Tides, and Storm Surges, Including Future Projections	2020	Muis *et al.*	National/ Subnational	hazard	**prospective**	-	-
15	Return Period Estimation of Hurricane Perils in the Caribbean	1999	USAID and OAS	Regional	hazard	**prospective**	-	-
16	Wind Speed Maps for the Caribbean for Application with the Wind Load Provisions of ASCE 7	N/A	PAHO	Regional (Caribbean)	hazard	**prospective**	-	-
17	Impacts of climate change on the tourism sector of a Small Island Developing State: A case study for the Bahamas	2021	Pathak *et al.*	Regional/ National	risk	**prospective**	-	**Both**
18	A hurricane loss risk assessment of coastal properties in the caribbean: Evidence from the Bahamas	2017	Sealy and Strobl	Subnational	risk	**prospective**	-	**Both**
19	Mapping Storm Surge Risk of the World	2015	Sun *et al.*	Global	hazard	**prospective**	-	-
20	Update on the probabilistic modelling of natural risk at global level: global risk model	2015	Cardona *et al.*	Global	risk	retroactive	Yes	Economic
21	Development of design wind speed maps for the Caribbean for application with the wind load provisions of ASCE 7-16 and later	2019	Mudd *et al.*	Regional (Caribbean)	hazard	**prospective**	-	-
22	National Disaster Preparedness Baseline Assessment (NDPBA): The Bahamas	2021	Pacific Disaster Center (PDC)	National/ Subnational	risk	**prospective**	-	**Both**

3.3 Missing Elements of the Standard in the Reviewed Studies

This section includes, for each of the 22 reviewed studies, the elements of the standard that are not present in them. Before presenting these conclusions, some caution is needed when interpreting these findings since, again, the review of the missing elements is being performed against the list defined for the standard hurricane hazard/risk assessment for The Bahamas, and does not mean that past studies are wrong, neither incomplete. In summary, the listing of the missing elements with respect to the standard is performed, on the one hand, to facilitate the understanding of the review process shown in Table 3, and on the other hand, to link these findings with the identification of an action plan for performing hurricane hazard and risk assessments in The Bahamas in the future.

To facilitate the understanding of the missing elements on each study by the reader, the findings have been aligned with the Subsection 2.2.

It is worth noting that there are some cases where all the elements listed in Subsection 2.2 of this report are not applicable, as for instance, a hazard analysis, such as the one by Mudd *et al.*, (2019), where the exposure, vulnerability and risk assessment components have not been addressed, simply because these were out of the scope of their work. There are also simplified methods such as PDC (2021) that present the results of exposure, vulnerability, and risk assessments. This could be very useful, for example, as a macro reference for emergency response planning. However, it is not entirely consistent with the framework of probabilistic risk assessment needed to mainstream climate risk in national development planning (note: this should include aspects such as designing engineering of structures for civil protection).

Finally, to avoid a large repetition of missing elements for each study and present the main findings in a concise way, if a study has been developed using a deterministic framework for the hazard and/or risk components, it is clear that the availability of the results in certain types of representations such as for instance, synthetic hurricane catalogues or event loss tables, is impossible. In those cases, the list of missing elements for those studies start with a "deterministic" classification, indicating that most of the state-of-the-art elements are missing.

Hurricane Wind and/or Storm Surge Hazard Analyses

Alexandre *et al.*, (2020)

- Deterministic.
- The study covers only some islands with detail, but not the complete domain of study relevant for a national analysis.
- The hazard analysis does not use a prospective approach.
- Only one intensity measure is considered in the analysis.
- No climate change considerations.

Banton and Dowding (2013)

- This document does not include any results for The Bahamas, but includes a set of requirements and guidelines for the development of storm surge hazard analyses in the Caribbean.

Dullaart *et al.*, (2020)

- Deterministic.
- The results of the analysis are included at global level without the appropriate level of detail for a national study in The Bahamas.
- The prospective estimation is not developed using a set of synthetic storms.
- No climate change considerations.
- Deterministic results are used in conjunction with extreme value theories to obtain the results.
- Hazard results are available only in terms of a map with a single return period.
- Resolution level for DEM and land use is higher than 90m (because of the global scope of the analysis).

IDB and ECLAC (No Date) – post-damage reports for Hurricanes Joaquin, Matthew, Irma and Dorian

The following observations are valid for the four IDB and ECLAC post-damage surveys, developed in the aftermath of Hurricanes Joaquin, Matthew, Irma and Dorian in The Bahamas. These correspond to the studies identified as 8, 9, 11 and 12 in this project.

- Deterministic.
- The hazard analysis approach for these four hurricanes is the same and deterministic in nature, by focusing only in a single event.
- The risk assessment is performed in a retrospective manner, meaning that the loss estimation has been made after a post-event damage and needs survey.

Mudd *et al.*, (2019)

- Only the wind hazard intensity is considered.
- The event set with synthetic storms is not available, results are presented in terms of hazard maps for different return periods.
- No climate change considerations are included in the analysis.
- Resolution level for DEM and land use is higher than 90m.

Muis *et al.*, (2020)

- Only one hurricane hazard intensity measure is considered (storm surge).
- The hazard representation available correspond to hazard map for a single return period.
- No climate change considerations.
- Resolution level for DEM and land use is higher than 90m (because of the global scope of the analysis).
- The bathymetric data has a resolution level higher than 30m.
- No tidal considerations are included in the storm surge hazard modelling.

PAHO (No Date)

- The historical catalogue of storms is outdated.
- The analysis has been performed at regional level (The Caribbean) but without enough level of detail for a national study.
- No climate change considerations are included in the study.
- Resolution level for DEM and land use is higher than 90m.

Tadesse and Wahl (2021)

- The hazard analysis approach is deterministic in nature, by focusing only in a single event.
- The DEM's resolution level is higher than 90m.
- The bathymetric data has a resolution level higher than 30m.

Tadesse *et al.*, (2020)

- The analysis scale is global without providing the required details for a national study in The Bahamas.
- There is no information about the cut-off date of the historical catalogue.
- No climate change considerations.
- The bathymetric data has a resolution level higher than 30m.
- The analysis methodology is probabilistic in nature, although the hazard intensities are estimated using extreme value theories instead of the generation of synthetic storms.

USAID and OAS (1999)

- The study has been performed at regional level (the Caribbean) without the required level of detail for a national analysis for The Bahamas.
- Hazard analysis type is only retrospective.
- Historical catalogue of hurricanes is outdated.
- The DEM's resolution level is higher than 90m.
- The bathymetric data has a resolution level higher than 30m.
- No validation of hazard results has been performed.

Hurricane Wind and/or Storm Surge Risk Assessments

Cardona *et al.*, (2015)

- The cut-off date of the historical catalogue is 2015.
- The DEM's resolution level is higher than 90m.
- The bathymetric data has a resolution level higher than 30m.
- Different intensity measures are considered in this study, but the simultaneous occurrence of losses is not addressed in the loss assessment framework.
- Risk results are only available for the islands with the higher exposure concentrations. Exposure located in several islands is missing from the database.
- There are no validations of the hazard and/or risk results.
- Coastal resolution level is of 1x1km, which is coarsed-grained for national studies and incompatible with the resolution levels of detailed storm surge analyses.

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Fang *et al*., (2015)

- The risk assessment is performed at global level without the required level of detail for a national study for The Bahamas.
- The cut-off date for the historical catalogue is before 2015.
- Hazard results are not available in terms of a stochastic event set, but only in terms of maps for different return periods.
- Resolution level for DEM and land use is higher than 90m (because of the global scope of the analysis).
- Coastal resolution level for the exposure characterisation is coarse-grained.
- Physical vulnerability modelling is not well defined.
- No validation of the risk results is available.
- Although the risk assessment is prospective, the methodology for estimating the losses is fully deterministic.

Fuhrmann *et al*., (2019)

- The hazard analysis is performed for a single event, being deterministic.
- Resolution level for the exposure database at inland locations is higher than 5x5km.
- Resolution level for the exposure database at coastal locations is higher than 1x1km.
- The risk assessment approach is retrospective for only one event, and therefore, the loss methodology used is deterministic.

IDB and ERM (2016)

- The hazard analysis, although detail, does not provide information for the totality of the domain of study that should be considered when developing a national study.
- Hazard representation is not available in terms of synthetic storms (i.e. stochastic event sets), but in terms of hazard maps for different return periods.
- The vulnerability representation is neither continuous, nor quantitative.

IH-Cantabria and IDB (2020)

- Cut-off date of the historical catalogue is before 2020.
- A stochastic set of storms has been generated to represent hurricane hazard, although not long enough to consider the possibility of occurrence of all feasible types of events (i.e., the event set must be collectively exhaustive).
- No details about the resolution level for the DEM, land use and bathymetric conditions are included.
- Tidal aspects are not considered in the storm surge modelling.
- The vulnerability representation is captured through vulnerability functions, although a generic (weighted) function is used for all types of assets. Individual functions for each typology are needed.

- It is not clear if an event-based approach was used to perform the hurricane risk assessment.
- Main risk metrics are available (AAL, PML's for different return periods), but not event loss tables are included.
- Different intensity measures are considered in this study, but the simultaneous occurrence of losses is not addressed in the loss assessment framework.
- There are no validations of the hazard and/or risk results.

Pathak *et al.*, (2021)

- The analysis type, for both hazard and risk assessment, is retrospective and deterministic.
- The DEM's resolution level is higher than 90m.
- The bathymetric data has a resolution level higher than 30m.
- Resolution level for the exposure database at inland locations is higher than 5x5km.
- Resolution level for the exposure database at coastal locations is higher than 1x1km.
- The vulnerability modelling is overlooked.

Sealy and Strobl. (2017)

- Cut-off date of the historical catalogue is before 2015.
- No climate change considerations are included.
- The DEM's resolution level is higher than 90m.
- Resolution level for the exposure database at inland locations is higher than 5x5km.
- Resolution level for the exposure database at coastal locations is higher than 1x1km.
- Different intensity measures are considered in this study, but the simultaneous occurrence of losses is not addressed in the loss assessment framework.
- Risk results are not available in the form of an event loss table.

Sun *et al.*, (2015)

- Deterministic.
- The risk assessment is performed at global level without the required level of detail for a national study for The Bahamas.
- The cut-off date for the historical catalogue is before 2015.
- Hazard results are not available in terms of a stochastic event set, but only in terms of maps for different return periods.
- The bathymetric data has a resolution level higher than 30m (because of the global scope of the analysis).
- Coastal resolution level for the exposure characterisation is coarse-grained.
- Physical vulnerability modelling is not well defined.
- No validation of the risk results is available.

- Although the risk assessment is prospective, the methodology for estimating the losses is fully deterministic.

PDC (2021)

- Includes the entire territory of the Bahamas.
- Comprehensive hazard analysis is achieved, including hurricane and storm surge damage.
- Uses Munich Mutual's Natural Hazards World Map as primary information (i.e., does not directly use climate data recorded by the Met Office within the Bahamas as an event catalog).
- The proprietary All-Hazard Impact Model (AIM) is used as the exposure model. This is a comprehensive and superior model that assesses population, capital, and infrastructure presence on a 30-meter grid scale.
- No vulnerability model is used - a simple study model is used, i.e., exposure to hazard equals risk. As a result, the damage estimates are presented in a deterministic manner, i.e., the maximum loss is interpreted as if exposed to the largest hazard external force.
- The assessment of human risk is presented qualitatively (low, medium, and high risk).

3.4 What is Available and What is Missing?

A major missing aspect from the list of requirements is a proper integration of multiple hazard intensities, such as strong winds and storm surge. The starting point for harmonizing the results is the development of a single synthetic hurricane catalogue, with a long enough timeframe, that properly represents all the events that are feasible to occur in the domain under study and includes too the relevant parameters for the modelling of these two intensities.

The consideration of climate change is of uttermost importance for The Bahamas, and because of this a comprehensive revision of the available climate and global emission scenarios that are suitable and representative for the domain under study are needed. Information from these studies can be used to inform any changes and adjustments on the hazard and/or intensities of the modelled hurricanes, which has not been developed, with a national scale, in The Bahamas.

In recent years, major advances have been made for the exposure modelling by the development of exposure databases for different types of assets, such as the one updated in 2020 using census data and validated through field visits, or the one for critical infrastructure such as schools and hospitals. The most difficult data to obtain is already available and only a harmonisation of the attributes for the proper and coherent characterisation of the exposed assets is needed, all this with the objective of defining a list of representative typologies for which vulnerability models are available. The AIM model developed by PDC (2021) is also worth noting as a simplified proxy (but detailed, e.g., a 30m grid unit estimation) exposure model.

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Complete and updated wind hazard maps are available for The Bahamas. Although having this information in this representation is useful for communication purposes and for defining different zones in the case of building codes, it is not enough to perform state-of-the-art and fully probabilistic risk assessments, that require hazard to be represented through stochastic event-sets.

The most complete hurricane risk assessment available for The Bahamas is the country risk profile developed in 2020 by IH-Cantabria and the IADB. However, a major shortcoming of that study is the oversimplification of the vulnerability representation by using a single vulnerability function as representative for all the buildings and houses in The Bahamas. Since the characteristics of the exposure are different, even within the same cities, it is known too that the behavior of the structures when subjected to strong winds and/or storm surge is a function of its construction material, height, openings, etc. Without a set of vulnerability functions, one for each representative building typology, the estimation of more accurate loss results cannot be achieved. This study is, however, the only one of the 22 available studies reviewed here that has retrospectively estimated the potential impact of human impact in a probabilistic and quantitative manner.

The availability of post-event damage surveys for major hurricanes in The Bahamas brings too an interesting opportunity to calibrate and customize the vulnerability models for strong winds and storm surge so that they are truly representative of the building characteristics of The Bahamas. Data from recorded damages and losses is typically scarce at global level and, therefore, its availability in The Bahamas represents a good opportunity for addressing this challenge.

Some of the key risk metrics such as the AAL and LEC are available for The Bahamas and have been recently published, so that they can be considered as updated. However, the shortcomings mentioned above related to the use of a single vulnerability model for all the buildings, together with not considering the simultaneous loss occurrences for aggregating the damages of strong winds and storm surge, still hold true and should be the motivation for enhancing the current models. From the country risk profile developed by IHC and IDB (2020), and the results of UNDRR's Global Risk Model (Cardona *et al*., 2015), some of these values are available. For instance, Table 4 reproduces the prospective risk results for storm surge at The Bahamas by IHC and IDB (2020), whereas Table 5 reproduces the prospective risk results for hurricane wind at The Bahamas in the same study.

TABLE 4. Damages on total stock because of storm surge in The Bahamas. Reproduced after IHC and IDB (2020)

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%

TABLE 5. Damages on total stock because of hurricane wind in The Bahamas. Reproduced after IHC and IDB (2020)

Country	BAHAMAS	Hazard	HURRICANE WINDS	
TOTAL STOCK		Return period	Probable damage stock (US$ million)	% over total 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%

From these tables, it can be read that the estimated future maximum economic damage in the Bahamas for a 100-year hurricane event, for example, is approximately US$2,150 million for a storm and US$3,000 million for a hurricane storm. The Annual Average Loss is US$215M and US$162M, respectively. In other words, if the Bahamian government does not take action, the damage shown here could occur in the future. **These quantitative damage estimates can serve as a clear indicator and reference for decision-making in the context of the specific objective of mainstreaming climate risk in national development planning.**

Finally, Tables 6 and 7 show the AAL and PML results estimated in UNDRR's Global Risk Model for hurricane wind and storm surge for The Bahamas, bearing in mind that these estimations only consider public and private buildings. For the case of the AAL, the value is compared against other figures of interest from the governmental perspective, such as the gross fixed capital formation (GFCF), the social expenditure, the total reserves and the gross savings.

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TABLE 6. Hurricane wind and storm surge AAL in The Bahamas

Hazard	Absolute [Million US$]	Capital stock [%]	GFCF [%]	Social exp [%]	Total Reserves [%]	Gross Savings [%]
Wind	846.3	1.9	32.6	113.7	104.8	97.0
Storm Surge	1343.7	2.9	51.7	180.5	166.4	154.0

Source: Cardona *et al*., 2015.

TABLE 7. Hurricane wind and storm surge PML for different return periods in The Bahamas

Hazard	20yr	50yr	100yr	250yr	500yr	1000yr	1500yr
	Million US$						
Wind	5,445	11,651	16,596	20,456	21,537	23,700	25,862
Storm Surge	9,544	12,500	12,516	12,564	12,643	12,802	12,960

Source: Cardona *et al*., 2015.

As a concluding remark for this section, it is valid from a scientific and technological perspective to select one of the various studies that exist in The Bahamas, or to compile the results of several studies in a reasonable manner, and refer to it as the official baseline risk recognized by the Government of The Bahamas. Even if from the reviewed 22 studies there is not any that fulfills all the requirements to comply with the standard defined over this project, major progresses have been achieved over the past years from where improvements and enhancements can be built upon, so there is a good opportunity for the GoBH to build on this progress to develop more accurate and detailed climate risk analysis studies in the future.

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4. OPPORTUNITY IDENTIFICATION AND ACTION PLAN

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4. OPPORTUNITY IDENTIFICATION AND ACTION PLAN

Sections 2 and 3 of this report have shown the available data, models and/or datasets regarding hurricane hazard and/or risk for The Bahamas. These studies have encompassed a wide range of results, with different degrees of quality, completeness and update. Each of these studies has been assessed against an objective and quantitative criterion, for which a list of missing elements, compared to those defined for the standard as the main objective of this project, which is to identify what actions are critically needed to mainstream climate risk in national development plans, has been included.

Based on these results, **this section identifies a set of concrete opportunities and recommendations that should be addressed in the update or development of new hurricane hazard and risk models for The Bahamas.** For this, an action plan for the update and enhancement of hurricane hazard analyses for The Bahamas is first listed, including all the relevant considerations for the modelling of multiple intensities. Next, a parallel action plan has been drafted for the development of hazard and risk assessments, that lists some activities related to the modelling of exposure and vulnerability.

On each case, the different activities have been classified into short, mid and long-term timeframes. The first one corresponds to activities that can start now and take up to 2 years, whereas the second timeframe involves the development of activities in 2 to 5 years, whereas the last one includes the activities to be developed in more than 5 years. Next to each activity, the timeframe on which it should be developed is indicated in brackets. Also, when possible, a general profiling of companies, institutions or specialists to carry out these activities is included.

The objective of the action plan is the development of a national standard that adopts a common methodological framework for the estimation of climate hazard and risk assessments in The Bahamas that incorporates the state-of-the-art in the different components of the analysis. The results of these studies should ideally be consistent among them and provide valuable results for territorial and sector development planning allowing making risk-informed decisions. In a nutshell, this report (including the state-of-the-art review, review of the available studies and the action plan), is intended to be used as a guideline for understanding, using and updating hurricane hazard and risk models, which are country specific for The Bahamas, so that results are consistent and useful in different disaster risk management and mitigation activities.

Progress has been made on different activities of the proposed Action Plan and their inclusion in the list does not mean that what is currently available is not useful or that a new work should be developed. In most of the cases, for the purpose of fulfilling the requirements set for the standard, updates, refining and/or harmonisation tasks are needed and will be carefully described next, at each point.

There may be cases on which there are data access and use restrictions, limiting the recommendation of using specific datasets. Because of this, for some of these component's recommendations, general aspects regarding the minimum requirements (mostly about the required resolution level) are listed.

4.1 Action Plan to improve the quality of climate hazard risk analysis as required by international standards in mainstreaming climate risk into the Bahamas' National Development Plan

Establish a Bahamian government standard for climate hazard and risk analysis in accordance with international standards

The Bahamian government should first widely present the standard for climate hazard risk analysis based on this report in an official form both domestically and internationally. At the same time, the current climate risk estimates for The Bahamas (as reference or baseline values) should also be presented in a quantitative form to the public both domestically and internationally. In this way, investors could objectively understand the climate risks in The Bahamas and use them as a reference when considering investments. In other words, this action will help to renew interest in The Bahamas among investors who have been hesitant to invest due to the lack of climate risk data presented.

Note that this study defines a climate hazard risk study as "a minimal process, procedure, and outcome for identifying the hazard intensity level or quantifying the probable losses that can be realized due to a climate hazard". It has also argued that it is reasonable to present quantitative values such as average annual losses (AAL), probable maximum losses (PML), and excess probability curves (EP curves) as its outputs. The reason for this is that these quantitative (and simple) risk assumptions make it easier to set benchmarks (or policy targets) for how much (or by what percentage) risk should be reduced in future disaster risk management plans or national development plans, and also make it easier to monitor the achievement of these targets after the fact.

In this case, as objectively analysed in this report, the most reliable AAL, PML, and EP curves that the Bahamas currently has are the study by IHC and IDB (2020). The estimated future maximum economic losses in the Bahamas shown here, for example, for a 1-in-100 year hurricane event, would be approximately US$2,150 million in the case of a storm, and US$3,000 million for a hurricane storm. The Annual Average Loss is US$215M and US$162M, respectively.

The National Development Plans in the Bahamas are an opportunity to attempt to reduce this reference risk (or baseline risk) through various development actions and efforts in the future. This information should be widely disseminated as official Bahamian information (i.e., reference or baseline for the current risk), for example, through press releases.

However, as evaluated in the previous chapter, the IHC and IDB (2020) study, as well as other available studies, still faces some challenges. The following is a list of specific actions that can be taken to address these issues.

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THEME 1: HAZARD ANALYSIS

Update of a synthetic hurricane catalogue (short-term action)

Even if works such as the developed by IHC-IDB (2020) have developed synthetic hurricane catalogues, a starting point for a unified methodology to comprehensively analyze hurricane hazard, is the integration and homogenization of a base synthetic catalogue with the objective of providing a long-term overview of the storms, by including not only those that have been recorded, but also those that, given the understanding of the hazard occurrence processes, can do so in the future. As mentioned in Section 2, the main input for the synthetic catalogue is the historical hurricane catalogue. The most reliable and complete database about historical storms in the North Atlantic Basin is the one developed and published by NOAA. After a hurricane occurs, different datasets are published by NOAA. However, the most complete and reliable database is the one denoted as HURDAT2[6] and that usually publishes the data of the past hurricane season during April/May of the following year.

There have been several cases where synthetic catalogs have been developed for hurricanes in the Bahamas, the most recent being the study by the IHC-IDB (2020). However, even in this case, the synthetic hurricane catalog used is from before 2017, which is a bit outdated in light of the recent extreme effects of climate change. Therefore, this action plan proposes to reevaluate the hazard by creating a synthetic hurricane catalog using the latest data. This activity would most reasonably be developed by an organization with extensive experience in hurricane hazard modeling and a particular understanding of North Atlantic Basin conditions, such as the Met Office.

This database includes, for each historical storm, the data about location, central pressure and maximum wind speeds at 3 to 6h intervals. These data can be then used for the generation of artificial storms using different techniques. Among the most robust approaches for this purpose, the random-walk technique has proven to be useful and, based on different parameters, allows obtaining new storms based on the perturbation of historical ones.

These synthetic storms, should be used for the estimation of multiple hazard intensities, such as hurricane winds, storm surge and heavy rainfall, so that a proper aggregation of simultaneous losses can be performed. To date, the available synthetic catalogue has been used only for the estimation of hurricane wind hazard. Because of the inclusion of random methods in the generation of synthetic catalogues, the exact replication of an existing one is virtually impossible. Because of this and to keep a complete track and documentation of the methodologies, tools and analysis procedures, it is suggested that based on the common historical data, a new synthetic catalogue is generated.

[6] https://www.nhc.noaa.gov/data/#hurdat

A synthetic catalog length is recommended to be at least 5,000 years, in light of international best practices. And this is an activity to be developed by a company or research institution with wide experience in the modelling of hurricane hazard, with particular understanding of the conditions of the North Atlantic Basin, so that the applicable relationships are used during the process.

Also, a separate synthetic catalogue can be generated considering the effects of climate change, by adopting one or more emission scenarios and taking into account the findings of special reports about the variation in future patterns of hurricanes, regarding intensity and frequency. Updates of the synthetic hurricane catalogues should be performed on a regular basis, between each 3 to 5 years.

Incorporation of climate change models into hazard analysis for The Bahamas (short-term action)

Additional risks from climate change should be incorporated when reassessing the hazards described above. Specifically, assess which of several global climate models (and downscaling techniques) that have already been developed are more consistent with the current climate change trends in the Bahamas, and then incorporate the more consistent models into the hazard assessment described above.

This component has to do with the considerations of climate change (CC) in the hurricane hazard analyses and is an important activity to be included in this Action Plan, since there is a variety of models, including future emission scenarios, which validity and suitability need to be further assessed for The Bahamas. This type of review is beyond the scope of this project, for which subsequent tasks are suggested to be considered to identify which dataset(s) can provide reliable information for the domain under study.

This is an activity to be developed by a company or research institutions which are experts in climate models, emission scenarios modelling and global climate models, including the relevant aspects of the downscaling. **Support and interaction with the Bahamas Met-Office should be promoted since this institution, because of its familiarity with the type of data, can provide valuable recommendations and validations.**

Regular update of digital geographic and cartographic information (short-term action)

This activity is of high relevance in the modelling of hurricane hazard, in particular in the cases of cyclonic winds and flood caused by heavy rainfall. The characteristics of the terrain do condition the hazard intensities and at the same time, are dynamic and closely related to territorial and development issues. For this, it is desirable to have available a high-resolution (30m) land cover database which is regularly updated and made publicly available.

This is an activity would most reasonably be developed by BNGIS, which is responsible for maintaining digital map information in the Bahamas.

Enhancement and development of high-resolution bathymetric data and maps of coastal areas (short/mid-term action)

Bathymetry describes the topographical conditions of the sea floor, and is a determinant parameter when modelling coastal hazards, among them, storm surge. The data acquisition process can be lengthy and costly, reason why, the high-resolution bathymetric data are only available for given areas where specialized studies have taken place. Since it is not viable to develop a country level high-resolution bathymetric database, what is proposed is the centralisation of the available data, when possible, and the development of new studies for areas of interest.

Bathymetric maps would have the capacity to be developed by several agencies, for example, the Ministry of the Environment and the Ministry of Public Works. In any case, these should be managed centrally (e.g., by BNGIS) to facilitate their reuse by a wide range of users.

Continuous recording of hazard intensities at points of interest (short/mid-term action)

It goes without saying that the accumulation of regular daily weather observation data is important for precise analysis of future hazards. In this sense, the Met Office has been continuously conducting daily weather observations at 27 stations in the Bahamas since the 1960s. However, some of this data (or most of it, depending on the station) is recorded on paper. Therefore, if all of this data were digitised, it would be possible to precisely analyse wind speed and direction, precipitation, temperature, humidity, etc. of gusty winds during storms. In other words, valuable information for validation and calibration of hazard models can be obtained.

In the future, it is desirable to automate observations at all weather stations in the Bahamas. Once this becomes possible, real-time, openly accessible meteorological data will be available not only to the Met Office, but also to domestic and foreign institutions and investors as needed.

Update of the maximum wind speeds for different return periods (mid-term action)

Once the aforementioned meteorological data is digitised, it will be possible to recalculate (future) maximum wind speed assumptions using state-of-the-art methodologies. That is, using parametric equations with input data e.g., the location, central pressure and radius of maximum winds, the calculation of the maximum wind speeds can be done using regional relationships, as the ones by Silva *et al.*, (2002) and Vickery an Wadhera (2008). This event-based approach for analysing hurricane hazard is fully compatible with the probabilistic frameworks and allows using the results too in risk assessments, providing an added value in disaster risk management activities.

By performing an integration over the intensity values, the exceedance rates for wind speeds can be calculated at all the points of interest obtaining therefore what is known as a hazard curve. Figure 5 schematically shows a wind hazard curve. By setting an exceedance rate (or its inverse value which is the return period), the associated hazard intensity at each point can be obtained. These data, when presented in a graphical format, is what is known as a hurricane hazard map, as the ones shown in Figure 6 for different return periods (associated to the IHC-IDB, 2020 study).

FIGURE 5. Example of a hazard curve

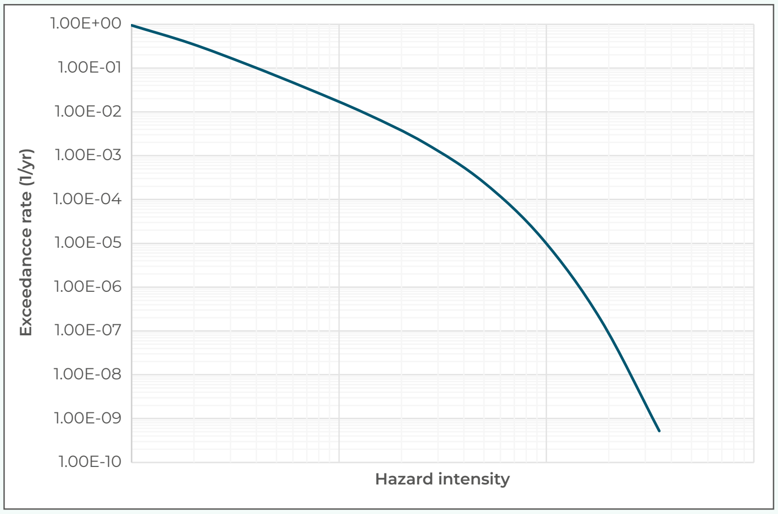
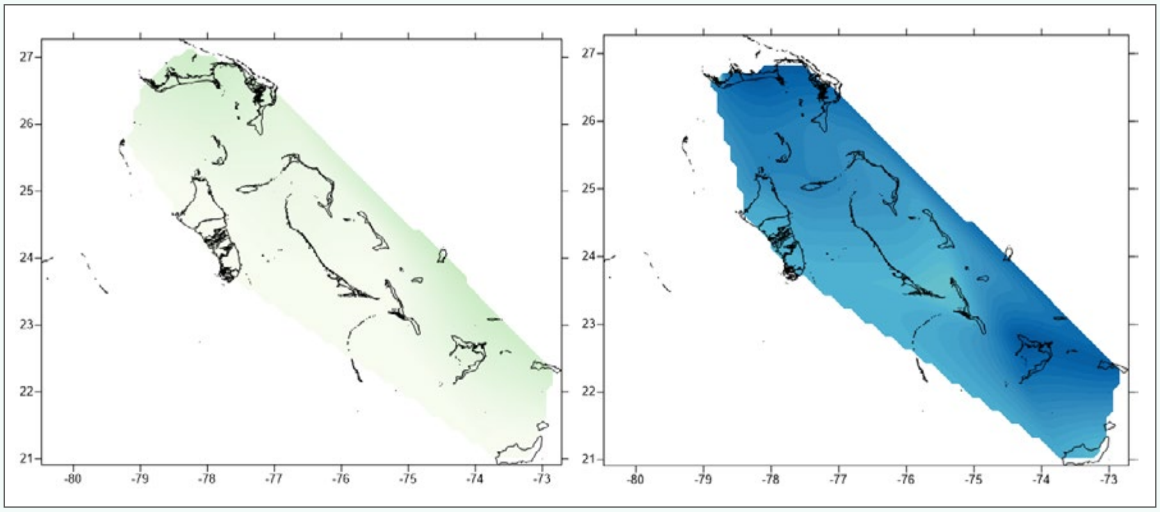


FIGURE 6. Example of hurricane wind hazard maps for different return periods Left: 25-yr return period. Right: 100-yr return period



Source: IHC-IDB, 2020.

This is an activity to be developed by a company or research institution with wide experience in the modelling of hurricane hazard, with particular understanding of the conditions of the North Atlantic Basin, so that the applicable relationships (i.e. parametric wind field estimations) are used during the analysis.

Estimation of hurricane rainfall (mid-term action)

Another notable aspect of the above-mentioned digitisation of weather data is that it will enable analysis of intense rainfall. By itself, it is not an intensity that cause major disruption but, in excess, can generate flooding events that have the potential of affecting and damaging assets of different types, ranging from the built environment to the agropastoral sector. Making use of models that allow modelling the precipitation using as input values the parameters reported in the homogenized and unified synthetic hurricane catalogue. Then, for each modelled storm, different precipitation values will be available to be used in flood analyses, that make use of hydraulic modelling or run-off relationships.

The Weather Research and Forecasting Model (WRF) is one of the tools capable of representing both the state of the atmosphere and predicting precipitation associated with meteorological phenomena, including hurricanes (Dudhia *et al.*, 2008). The meteorological model, through meshes or spatial domains of different resolution (usually km), considers as input information provided by the National Center for Environmental Prediction (NCEP – Dattore, 2010).

For the modeling or simulation of precipitation events, such as those generated by hurricanes, the WRF model allows the creation of precipitation fields (or ensembles) through methods such as the multi-physics parameter variation method proposed by several authors (Bukovsky and Karoly 2009; Evans *et al.*, 2012; Efstathiou *et al.*, 2013).

This is would be most reasonably done by the Met Office, which has extensive experience in hurricane hazard modeling and particularly understands the conditions in the North Atlantic Basin.

Update of storm surge modelling (mid-term action)

Analogous to the other hazard intensity measures, the modelling of the storm surge hazard can be performed for each of the synthetic hurricane tracks to be included in the unified and homogeneized synthetic catalogue. Because this is perhaps one of the hazard modelling fields where more advances have occurred in the recent years, on which besides the increasing data availability, the use of computers with higher performance have allowed the development of much more detailed analyses, it is relevant to perform regular updates. Depending on the data availability and quality, there are different approaches for modelling storm surge, as previously explained in Section 2 of this report. With the estimation of storm surge run-up heights for each synthetic hurricane, the estimation of exceedance rates for different hazard intensity levels can be performed and the hazard results can be represented in terms of hazard curves and hazard maps.

There are different numerical and analytical types of models that can be used for flood modelling in coastal areas. In general these kind of models use as input data information of the bathymetry of the study area, topography, as well as data of the hurricane track, such as central pressure, wind speed and direction to the coastline. The water run-up estimation is performed based on characteristics of zones (i.e. offshore, near-shore, shoreline response and flood inundation zones). One of the most common models used by modellers was introduced by Vellinga (1982), although more recently, complex and sophisticated models like Delft 3D have been also used to complement other coastal flood models, especially for the modelling of beach erosion and breach scenarios.

This action should be developed by a company or research institute with extensive experience in hurricane hazard modeling and a particular understanding of North Atlantic Basin conditions, i.e., the Met Office in the case of the Bahamas. Ideally, this action should be performed by the same institution in charge of the wind and precipitation hazard model to guarantee the consistency between the inputs and outputs of the analysis. Depending on the numerical method to perform the coastal flood analyses, interaction and participation from specific model developers may be needed.

Development of a national multi-intensity hurricane hazard analysis at national level (mid-term action)

With a unified and common synthetic catalogue of hurricanes, the probabilistic and prospective of hurricane hazard can be performed. This, on the one hand, will allow consistency in one of the most sensitive inputs of any hazard model (i.e. the synthetic catalogue) and, on the other hand, will allow the estimation of multiple intensities (i.e., wind, precipitation and storm surge) for each case, allowing the development of a robust hurricane hazard analysis.

The results of this study should be published in an integrated manner, where, besides the technical documentation of the model with all the details and assumptions, the results for each hazard intensity of interest are made available. As minimum results, hazard curves at points of interest for each intensity should be estimated, besides presenting the hazard results in terms of hazard maps, at least for 5, 10, 25, 50, 100, 250 and 500 years return period.

This technical document should be made publicly available together with the associated datasets. Also, as mentioned before, regular updates in 7 to 10yr intervals should be planned to allow updates and enhancements of the hurricane hazard data in The Bahamas. The major variations in these updates will have to do with the historical hurricane catalogue (allowing adding additional years in each release), and the use of newer methodologies and/or relationships that are expected to improve the results.

A key aspect for the sustainability and usability of the hurricane hazard results, is the involvement of local institutions and academics in different processes of the development. The first component should be designed around capacity building activities, that must not necessarily aim to capacitate local specialists into hazard modellers, but that should provide them with enough understanding about the scope, limitations and usability of the models. Also, this process would guarantee the inclusion of local experience and knowledge in different aspects of the modelling, and serve as a double check for using updated, reliable and representative data during the development of the models.

The results of the probabilistic and multi-intensity hurricane analysis for The Bahamas, are to be uploaded in an online data repository. For this, the web-based tool developed in the framework of this project can be used since it has the complete flexibility to accept new data, as long as it is made available in any of the traditional GIS formats (e.g., *.shp, *.grd, *.tiff).

Even if different institutions, companies and/or research centres can take part of the overall activity, this activity should be led by a company or research institution with wide experience in the modelling of hurricane hazard, with particular understanding of the conditions of the North Atlantic Basin, such as the Met Office.

Socialisation of the hurricane hazard analysis results (mid/long-term action)

Once the results of the multi-intensity hurricane hazard model for The Bahamas are available, a dissemination and socialisation of the results should be done. This activity will raise awareness about the existence of the new information, and at the same time will allow explaining in detail different aspects of the models, the expected use of the results and indicate where the datasets will be available. As mentioned above, a periodic official press release by the government could be a means for this dissemination and socialisation. Of course, this could also be done through other communication channels. **It is recommended that the Disaster Management Unit (DMU), which is responsible for disaster risk management policy within the Government of The Bahamas, should be responsible for the dissemination of this information.**

THEME 2: CLIMATE RISK ASSESSMENT

Regular update of the exposure databases for buildings and infrastructure (short-term action)

Exposure databases should be updated on a regular basis (3 to 5 years). In the Bahamas, there are exposure models such as the infrastructure-themed exposure model by IHC-IDB (2020) or the All-hazard Impact Model (AIM) developed by PDC, which comprehensively assesses population, capital, and infrastructure exposures. In any case, hazard exposure is dynamic and requires regular updating of this activity. Also, as new data becomes available, ways to easily integrate it should be considered. The web-tool developed in this project allows the addition of new data in the form of exposure layers that can be curated in *.shp files.

As previously mentioned, different resolution levels can be used when developing exposure databases and a balance between accuracy and efficiency is to be sought. Whereas the resolution level at inland location can be coarser than at coastal areas, because of the size of The Bahamas planning a high-resolution exposure database of between 30-90m is feasible, regardless the location of the assets. For critical infrastructure (e.g., ports, power plants, airports, hospitals, schools), the specific locations of the assets can be used. The aforementioned AIM model developed by PDC is a 30-m grid exposure model. It would be effective to adopt this model as the official government exposure model and continue to operate it on an ongoing basis.

The development and updating of exposure models requires coordination among multiple ministries. Therefore, it is preferable that the DMU in charge of disaster risk management in the central government be the organisation in charge of continuous coordination and implementation.

Identification of the representative building typologies in The Bahamas (short-term action)

To complete the characterisation of the exposed assets in The Bahamas, an identification and listing (as inventory) of the representative building typologies needs to be completed. This activity can be developed in the short-term making use of the recent data (2020) based on the censal information and complemented through a comprehensive field effort. **The objective of this process is to have a comprehensive list of the representative types of buildings that exist in the country, so that the appropriate assignment of damage and loss models can be performed.** There can be as many as needed building typologies, which usually group assets that share the same characteristics in terms of construction material, structural system, height and age, among others. Data from the housing census, if available, can be used for this purpose, complemented by local field surveys on which the participation of local engineers should be sought.

An interesting issue about these data for The Bahamas, is that separate activities for the characterisation of critical assets such as education and touristic infrastructure have been performed too in the past. Based on it, specific typologies for these two critical sectors can be defined too, for a better representation of the physical vulnerability, as explained later in this section.

This is an activity to be developed by the local institutions of the Bahamas, that can be included within a housing census. Once the results of the initial listing are available, experts in the field of structural engineering can participate in the validation process of the findings.

Development of country-specific hurricane vulnerability models (short-term action)

As for hurricane vulnerability models, there is a wide variety, generally ranging from various internationally standardized vulnerability functions referenced in country-specific risk profiles by IHC and IDB (2020) to those such as the regional functions in the GAR15 model (Cardona *et al.*, 2015).

These functions, besides being country specific, need to be developed for each of the hurricane hazard intensities so that the loss estimation can be done for each of them. Although there are different ways to represent and model the vulnerability, state-of-the-art approaches tend to use what are known as vulnerability functions, that provide a continuous, probabilistic and quantitative relationship between different hazard levels and the losses. These functions can be developed to estimate the physical damage (e.g., direct losses) and the human losses (e.g., casualties). There should be a vulnerability function for each identified typology and for each hazard intensity. So, for instance, if there are 10 representative building typologies, there would be needed at least 30 vulnerability functions: 10 for hurricane wind, 10 for storm surge and 10 for floods caused by heavy rainfall. However, these do not have to be developed by the government itself from the beginning. It is sufficient to refer to existing international data. The key here is which reference to select (in the sense of selecting one that is close to the nature of Bahamian architecture and structures) and how to formalize it as a government reference.

These vulnerability models can be modified, calibrated and updated in the future based on recorded data. For this, post-event damage surveys have a critical role and would allow the continuous enhancement of the model. Also, if new building typologies exist in the future in The Bahamas, additional vulnerability functions must be developed for future risk assessments.

Note that this activity should not inherently (or in the medium to long term) use references as described above, but should be developed by expert structural engineers with proven experience in the analysis of structures subject to wind, surge and flood solicitations. Ideally, the group behind the development of such a set of functions must have experience in catastrophe risk modelling, so that all the relevant characteristics of the structures in the framework of a probabilistic loss assessment, are included.

Development of a hurricane consequences database (short/mid-term action)

Although historical data by itself do not provide the complete overview for the development of a robust risk assessment, very valuable information can be extracted from it for the validation and calibration of different components of the risk models. The Government of the Bahamas is currently preparing to develop a National Disaster Risk Information System based on the DRM Act, which was enacted in 2022, and as defined in the DRM Act, past disaster data (e.g. damage situation registered at the disaster occurrence site) should be accurately incorporated into this system.

Development of a fully probabilistic multi-intensity hurricane risk assessment (mid-long/term action)

Once all of the above actions are implemented, all inputs for the quantitative evaluation of future probabilistic damage/loss estimates from hurricanes will be in place. That is, a synthetic hurricane catalog (the main output of probabilistic hurricane hazard analysis), an exposure model, and a vulnerability model will be in place. Combined, these will allow for the development of a national level risk assessment.

This approach which makes use of a synthetic hurricane catalogue is known as event-based (see Ordaz, 2000 for the full details[7]) and allows obtaining what is known as an event loss table (ELT). This table, includes for each of the synthetic storms, its identification characteristics (i.e., date, name, ID), the occurrence frequency, and the parameters that allow obtaining the loss probability distribution (i.e. expected loss, total exposed value within the hazard footprint, etc.). With these data, it is then possible to estimate, for different loss levels (either monetary or human), the exceedance rate and, if this task is repeated for different values, the loss exceedance curve (LEC) can be obtained.

With the LEC, other useful risk metrics can be obtained, such as the average annual loss and the probable maximum loss for different return periods. Each of these metrics has different properties and for its proper estimation in a multi-intensity context, some adjustments are needed, as explained in the following step.

Since risk assessment requires a very high level of experience and skill in operating computer platforms (e.g. HAZUS and CAPRA), outsourcing this operation may be considered. At the very least, it would be reasonable for the study to be managed by a government agency with extensive experience in disaster risk modeling, such as the Met Office. The results obtained should be approved by the cabinet as official government data and disseminated through press releases and other means. In any case, as mentioned above, **these risk analysis studies need to be incorporated into the National Disaster Risk Information System, which is currently being prepared in light of the DRM Act that was enacted in 2022.**

[7] This reference focuses on earthquake risk, but, conceptually is the same for hurricanes.

4.2 Timeframe for the Activities Proposed in the Action Plans (Hurricane Hazard and Risk)

Table 8 shows the proposed timeframes for the different activities that have been included in the hurricane hazard and risk assessment action plans for The Bahamas. These timings are indicative and aim to propose the order of actions, taking into consideration that some of the activities can be performed in a parallel manner, and that for beginning some others, the outputs from a different activity are required to be available.

TABLE 8. Timeframes for the development of the hazard and risk assessment Action Plans for The Bahamas

Action Plan	Activity	Time frame		
		Short-term	Mid-term	Long-term
Hazard	Synthetic hurricane catalogue			
	Review of suitable climate models for The Bahamas			
	Update of land coverage data			
	Enhancement of bathymetric data			
	Monitoring and recording of hazard intensities			
	Hurricane wind hazard maps			
	Flood (caused by heavy rainfall) hazard maps			
	Storm surge hazard maps			
	Country-specific multi-intensity hazard analysis			
	Socialization of the results			
Risk	Update of exposure databases			
	Definition of representative building typologies			
	Development of country-specific vulnerability models			
	Hurricane consequences database			
	Fully probabilistic hurricane risk assessment			

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5.CONCLUSIONS AND RECOMMENDATIONS

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5. CONCLUSIONS AND RECOMMENDATIONS

This report has included the summary of an objective and quantitative grading process, on which 22 previously developed studies for hurricane hazard or risk in The Bahamas have been subjected too. This qualification has been performed against a list of requirements (or elements) that should be addressed when performing hurricane hazard and/or risk assessments, based on the state-of-the-art review for each of the main components.

The results of this qualification have allowed identifying the most relevant missing elements on the 22 studies, so that different opportunities for improving and complementing the hurricane hazard and risk data for The Bahamas are identified, all this with the objective of developing a national level probabilistic hazard and risk assessment that fulfills the requirements of the standard generated during the course of this project.

The following bullets present, as a summary, the main conclusions and recommendations of this project.

- **The Bahamas is located in a hurricane-prone pathway.** As a result, there are several studies related to hurricane risk. However, the frameworks, objectives, and output styles of these studies vary widely, making it difficult to systematically reference the results of these studies.
- **The study defined a climate hazard risk study as "a minimal process, procedure, and outcome to identify hazard intensity levels or to provide a quantitative indication of the expected damage from a hurricane."** It also concluded that it is reasonable to present quantitative values for its outputs, such as average annual losses (AAL), probable maximum losses (PML), and exceedance probability curves (EP curves). The reason is that these quantitative (and simple) risk assumptions make it easy to set targets for how much (or by what percentage) risk should be reduced in future development plans, and also make it easy to monitor the achievement of these targets after the fact.
- **Of the 22 studies, the IHC-IDB (2020) is the one that could serve as an effective reference for mainstreaming climate risk in national development planning.** The reason for this is that the study follows the procedures of the Synthetic Hurricane Catalogue (the main outcome of probabilistic hurricane hazard analysis), the Exposure Model, and the Vulnerability Model, all of which are in accordance with international standards. The estimated future maximum economic loss in the Bahamas, as shown in this study, is approximately US$2,150 million for a once-in-a-century hurricane event in the case of a storm and US$3,000 million in the case of a hurricane wind. Annual Average Loss is US$215M and US$162M, respectively. The Bahamas government should use this reference data (or baseline risk) as a reference for future development planning.
- **The IHC-IDB (2020) and other related studies in the Bahamas present several challenges.** The study therefore presents an action plan to improve it and a tentative timeframe for each activity.
- **State-of-the-art hurricane hazard and risk assessments follow event-based methodologies.** This should be seen as an advantage since it allows a proper articulation between the studies and, the outcomes of the former, can be directly used as inputs in the latter.

- **There is room for improvement in activities related to the update and enhancement of country-specific hurricane hazard and risk assessments for The Bahamas.** For this, different activities have been included in the hazard and risk assessment action plans, together with the estimated timeframes for their development.
- **The involvement of local institutions and specialists in the development of future hurricane hazard and risk model is critical** to achieve a sustainable process and the generation of a standard.
- **The main task in the hazard analysis to achieve a standard, is the generation of a synthetic catalogue of hurricanes** for which, making use of the appropriate models and relationships, estimations about maximum wind speeds, precipitation and storm surge heights can be completed.
- **Currently, there are no country specific vulnerability models for the representative typologies in the country.** Although the simplified approaches used in the existing studies have allowed initial estimations of damages and losses, this is a highly sensitive component of a probabilistic risk assessment and, therefore, having local models will allow increasing the robustness of the results and facilitate their use in local decision-making purposes.
- **It is desirable to have a complete multi-intensity hazard and risk assessment for The Bahamas,** instead of individual studies, developed with big differences in the data used. This will facilitate the existence of a standardized and commonly understood way to assess hurricane hazard and risk at country level.
- **Public data availability is an aspect that should be promoted and that may facilitate achieving the sustainability of the process.** By creating for instance, a national database where all the relevant data (and documentation) for the hazard, exposure, vulnerability and risk models are made available, awareness about the existence will be risen and these data and results can be used in different DRR and DRM activities.
- **Local capacity must be built via technical training to the different agencies that are involved in hurricane hazard and risk assessment,** either as modellers (i.e. in charge of the evaluation), or as users of the results (i.e. fiscal budgeting, land-use planning). This, with the objective of guaranteeing the understanding and proper use of state-of-the-art hurricane hazard and risk models. These activities should not be aimed at the formation of hazard and risk modellers, but on the use of the results, by different specialties, in activities associated to disaster risk management. This understanding will facilitate too the update and enhancement of future releases of the model and the planning of activities related to data gathering for one or more components, at the local level, as explained previously in this report. **The management of expertise and knowledge related to climate risk analysis should be incorporated into the development and operation processes of the National Disaster Risk Information System,** which will be developed in accordance with the DRM Act that was enacted in 2022.

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