Disaster Risk Profile for Jamaica

Update 2020

Environment, Rural Development and Risk Management Division

Inter-American Development Bank

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CONTEXT AND BACKGROUND

1.1 INTRODUCTION

One of the key strategic activities of disaster risk management (DRM) at the country or regional level is the assessment of the risk of disaster associated with extreme natural events, which requires the use of reliable methodologies that allow an adequate estimation and quantification of potential losses in a given exposed time. Although there are several international methodologies for detailed risk assessment for different types of natural hazards, few of them allow analysis at the country level for two main reasons: first, there is a lack of detailed information that prevents the formation of a robust database to describe the exposure and, second, there is a lack of an integrated and consistent methodology to assess the probabilistic modelling of different natural hazards, considering simultaneously the vulnerability of the exposed elements and their associated risk.

To achieve the overall goal of identifying and quantifying catastrophic risk, it is necessary to include relevant natural hazards in an integrated manner, considering both their individual intensities and frequencies of occurrence. Moreover, the approach should capture the main features of the information of the exposure model of infrastructure assets and components. These will define for every class of component, its corresponding vulnerability for each one of the hazards considered. The vulnerability representation, together with the hazard, will define the associated risk. The assessment will be undertaken using a consistent probabilistic based model which considers both the hazard intensity distribution and the frequency of occurrence, in addition to their associated uncertainties. The resulting probabilistic risk parameters shall be interpreted considering the defined exposure resolution and the inevitable limitations of the information used, both in terms of quality and completeness.

For an assessment at the national, regional and local level, it is necessary and critical to define the resolution for the exposure model. In certain cases, an analysis based on individual units of the infrastructure could make the assessment unfeasible. Considering that, the higher the resolution the most expensive the risk assessment in terms of cost and time, an optimum level should be defined in order to obtain the best possible results with the available budget in the minimum time. Usually, for disaster risk management applications, the required level of resolution is not always the most detailed and expensive one. In any case, a simplified vulnerability and risk assessment

will be adopted to minimize data collection and computing time. Priority will be given to all relevant parameters that will control the overall component´s expected performance.

This report presents the catastrophe risk assessment for Jamaica considering the two-main controlling natural hazards that can impact the island: hurricanes and earthquakes. An additional assessment is performed at Kingston Metropolitan Area (KMA) to estimate flood hazard and its associated risk. The probabilistic methodology used is considered the most robust for this type of modeling and identifies the most important aspects of catastrophe risk for different DRM applications. The results of the analysis are particularly useful in guiding the priorities of the country's disaster risk management in general. The methodological and technical foundations of the selected risk assessment model correspond to the CAPRA platform (Comprehensive Approach for Probabilistic Risk Assessment), an open architecture platform designed with support from the IDB, the World Bank and the UN International Strategy for Disaster Reduction. More information about the methodology and the software can be found at www.ecapra.org.

This report provides relevant inputs for the formulation and updating of the country risk disaster management plan. It provides valuable information about hazards and risks associated to different natural hazards. It includes risk figures like the expected annual and probable maximum economic losses at the country and regional level for seismic and hurricane wind hazards. Discrete results are presented for different building types and for primary use classes of buildings. Scenario based results conform the basis for the design and implementation of emergency response plans. Maximum probable losses, expected annual losses for critical scenarios and the geographical distribution of losses support a financial strategy to protect the country against catastrophic risk. With this information, it is possible to evaluate the possible risk retention and transfer mechanisms. Valuable information is provided to estimate the order of magnitude of the contingent liabilities due to extreme disasters and to explore feasible alternatives to finance the design of the coverage of the country's fiscal responsibility.

This study corresponds to an update and complementation of previous work done by the IDB in 2009 corresponding to the Catastrophe Risk Profile for Jamaica. The report summarizes all the work developed for a consistent risk assessment at the country and regional level for the main controlling hazards in the region. In Chapter 2, the national, regional and local exposure models are presented including the geographical distribution of the most representative building typologies, its economic valuation and the human occupation model used to estimate economic

and social impact of catastrophic events; in Chapter 3 the hurricane wind hazard and risk models are presented in detail including the visual representation of results; Chapter 4 presents the corresponding results for the seismic hazard and risk models; Chapter 5 establishes the comparison between risk results from earthquakes and hurricanes; Chapter 6 presents the final results for the simplified and preliminary KMA flooding risk assessment and finally Chapter 7 presents the conclusions and recommendations of the complete work.

1.2 OBJECTIVE AND METHODOLOGY

The objective of this study is to present a robust risk assessment profile for Jamaica in the context of the Caribbean islands. It will support the identification of important disaster risk issues to define the country's development priorities and orient the settings for a consistent medium-term risk management program. In doing so, the results presented in this report will serve as the basis for updating and reformulation of the DRM Bank´s strategy for Jamaica and the corresponding dialogue with the country officials and institutions.

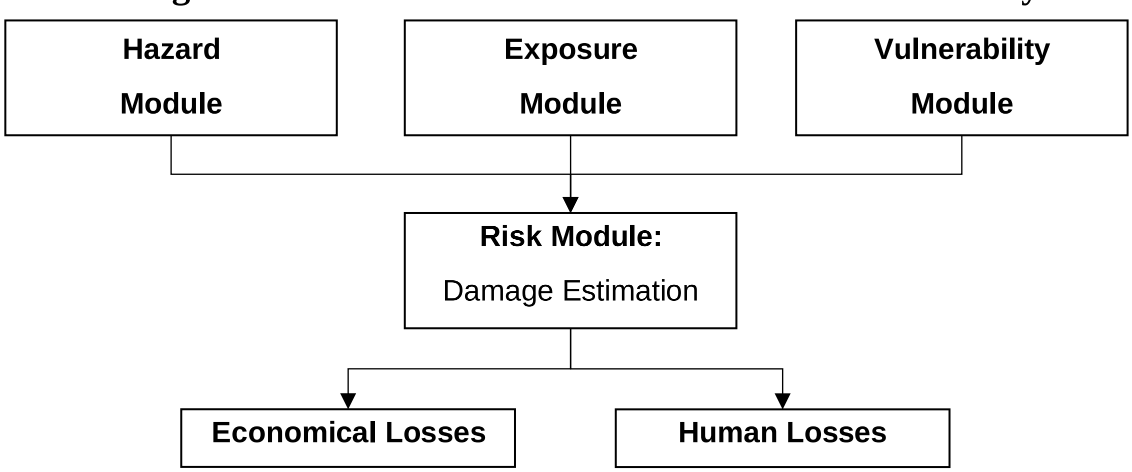
The risk assessment process for a country like Jamaica should consider the relative low frequency of occurrence of catastrophic events. Information of such events with high destructive potential is generally very limited considering the long recurrence times between them. Considering this same aspect, the risk assessment shall be supported in rigorous probabilistic models which use the limited historic information available to forecast, considering the high uncertainties involved, the consequences and expected impacts of futures events.

Jamaica, as most other Caribbean islands, is subject to catastrophic events originated by geologic and hydrometeorological hazards. From the geologic point of view, earthquakes and tsunamis are the main hazardous events. The ground accelerations generated by high magnitude earthquakes can in turn trigger additional threats to infrastructure and population such as landslides, liquefaction or other undesirable secondary effects. From the hydrometeorological point of view, hurricanes usually generate the worst possible consequences due to the high wind velocities, the intensive rainfall and the coastal storm surges generated in the vicinities of the hurricane eye trajectory. Intensive rain can in turn trigger other devastating events such as flooding and landslides both in rural and urban areas. Without discarding the possibility of other types of hazards which may generate catastrophic situations, the present report concentrates on threats that have resulted in the past to the worst possible consequences at regional, national and city level. These

include the land shaking generated by large earthquakes, the extreme hurricane winds originated in hurricanes passing at certain distances from the island and flooding effects in zones of high concentration of assets and population, in the present case the Kingston Metropolitan Area (KMA). All these events can certainly generate critical and catastrophic situations and the consequences must be considered in any DRM plan at regional, country or city level.

The risk estimate must be prospective, anticipating possible events that might occur in the future according to historic information and the potential of new unrecorded events. For the case of seismic events, seismological and engineering bases are used to develop earthquake forecasting models that allow the estimation of damages, losses and effects as a result of catastrophic events. For the case of hurricane-winds, the hydrometeorological information available on historic hurricanes that have affected the area of study is used jointly with engineering methodologies, to estimate the effects of these phenomena upon the exposed assets. For future possible flooding events, the precipitation information of past events is required together with the digital elevation model (DEM) and the characteristics of the land and the infrastructure components susceptible to damage. Due to the high uncertainties inherent to these types of forecasting models, especially in relation to the severity and frequency of occurrence of the most intense events, the risk model is based on probabilistic formulations incorporating said uncertainty in the risk evaluation. The probabilistic risk model (PRM) is constructed from a sequence of modules and quantifies the potential losses that may arise from a given event (see **Error! Reference source not found.**).

Figure 1 General Scheme of the Probabilistic Risk Analysis



The suggested analysis modules have the following specific functions:

- Hazard module: this module allows the calculation of the threats associated with all possible events that could occur in the area of analysis. The group of events that characterizes the hazard at a particular zone are called stochastic events. For each one of them, the distribution of maximum values of particular intensities is calculated and represented by maps in raster format. The collection of maps with mean expected maximum values and the corresponding variances are collected in a digital file known as the AME file type (.ame from *amenaza* in Spanish). In order to maintain the consistency in the frequency analysis, each stochastic scenario is assigned a specific annual return period which is consistent with the historic recurrence observed for different intensity levels. The intensity parameters usually selected for the damage and loss assessment are the maximum spectral acceleration for the case of the ground shaking, the maximum wind speed for the case of hurricane wind and the maximum flooding depth or water velocity for the case of inundation.

- Exposure Module: this module deals with the description of the exposed elements or assets that may be affected by any given event. It is based on files in "shape" format corresponding to the exposed infrastructure that will be included in the risk analysis. Each exposed component included in the file shall be characterized by the following information:
    - Identification
    - Location in geographical units
    - Economic replacement value (cost of the building without the cost of the land)
    - Human occupation (when social impact is to be estimated).
    - Vulnerability function associated to each type of hazard

  Usually the exposure module is developed based on a simplified and aggregated description of the exposed assets (proxy model).

- Vulnerability Module: this module allows the generation and selection of vulnerability functions. A vulnerability function for a particular construction typology represents the expected damage or loss for different intensity parameters. A library of vulnerability

functions is usually available (see for example Hazus, GAR-2013 or www.ecapra.org). One particular vulnerability function is assigned to each component of the exposure model.

- Risk Module: this module performs the convolution of the hazard, the exposure and the vulnerability in order to assess the risk measured by means of the expected potential damages, losses or impact of each stochastic event over the complete portfolio for exposed components. The risk can also be expressed in terms of probabilistic variables, such as, the annual expected loss of each component, or this same figure and the maximum probable loss of the entire portfolio. In terms of social impact, the risk can me expressed through the average annual or maximum probable impact on the population in terms of variables such as number of persons affected, injured or killed.

Once the expected damage or loss and its dispersion is estimated for each one of the stochastic events, it is possible to estimate various parameters or metrics useful for the proposed analysis such as the Loss Exceedance Curve (LEC). This curve contains all the information required for the complete description of the risk. In the present case, the risk assessment is made at country level and therefore the results can be disaggregated by use sector (e.g., private, public, government, etc.) and geographical units. For earthquake ground shaking, hurricane wind and flooding, the Expected Annual Loss (EAL) as well as the Probable Maximum Loss (PML) are estimated at the portfolio level.

Based on these results, several DRM applications become possible. For example the geographical distribution and quantification of the physical damage or losses for specific critical stochastic scenarios informs the basis for the development of an emergency plan; using the concentration of risk at country level for particular sectors (i.e., government institutions, low socio-economic sectors of the population or the public infrastructure) indicators about the contingent liabilities of the government can be estimated; knowing the relative risk within different use sectors, specific risk mitigation plans can be developed consisting in the adoption of structural and/or non-structural mitigation measures; and the values of PML and EAL for particular use sectors, can be used to design a financial protection strategy which can include risk retention (financing) or risk transfer instruments.

The detailed methodological approach for the risk assessment has been published and the reader is referred to additional references (Yamin et al., 2013a, Yamin et al., 2013b, Cardona et al., 2014, Yamin et al., 2017,).

1.3 INFORMATION

A great effort has been made to collect all available information at country and regional levels for the purpose of risk assessment. In this process it is recognized the support of the local representatives of the IDB and the active participation of several national entities with special support from the Office of Disaster Preparedness & Emergency Management - ODPEM. Table 1 to Table 5 summarize the main sources of information used.

Table 1 Main Sources of Information for Building Exposure Model in Jamaica

Description	Type	Date	Institution
General indicators	Web	2018	CIA World Factbook
			Statistics Institute of Jamaica (STATIN)
			Bank of Jamaica
			World Bank
			Index Mundi
Geographical Units	Web	2018	STATIN
			Geo-names
Population characteristics	Web	2018	Jamaica Information Service
			STATIN
Age composition	Web	2018	Jamaica Information Service
Educational level and literacy	Web	2018	STATIN
Economic activity	Web	2018	STATIN
Employment status			
General population activities			
Labor Force			
Public & private education distribution	Web	2018	STATIN

Description	Type	Date	Institution
Public & private health distribution	Web	2018	World Bank
Parishes GDP	Web	2018	St. Catherine Municipal Corporation
Population socio-economic distribution	Shapefile (*shp)	2018	National Land Agency (NLA)
Exposure comparison	Web	2018	Interamerican Development Bank (IDB)
			World Bank
			NLA
Georeferenced urban units	Shapefile (*shp)	2018	STATIN
			Google Maps
			Google Earth
			Esri Maps
			IDB
KMA spatial definition	Shapefile (*shp)	2018	STATIN
			The Jamaica Gazzete Supplement
KMA districts information	Web	2018	STATIN
			University of west Indies
			Jamaica post service
Socio-economic spatial distribution	PDF	2004	The Geographical Journal
Districts characteristics	Web	2018	Kingston & St.Andrew Municipal Corporation
Commercial valuation	Web	2018	Coldwell Banker
			Century 21
			NLA
Building information	Shapefile (*shp)	2018	Google Earth
Building information	Web	2018	Google Maps
Proxy indicators	PDF	2011	IDB
Caribbean Countries identification and information	Web	2018	CIA World Factbook
			World Bank

Description	Type	Date	Institution
			Institut national de la statistique et des études économiques
			Centraal Bureau voor de statistiek
Caribbean Geographical information	Shapefile (*shp)	2018	Esri Maps
			Google Earth
Caribbean exposure valuation proxies	PDF	2011,2012	IDB

Table 2 Main sources of Information for Infrastructure Exposure Model in Jamaica

Description	Type	Date	Institution
National Infrastructure Information	Web	2012	DIGJamaica
Specific Projects and Project Costs per Yard	Web	2018	DIGJamaica
Airports in Jamaica	Web	2018	Aircraft Charter World
Airport Fact Sheet	Web	2018	NMIA
Airport Facilities	Web	2018	MBJ Airport
Operational/Technical Information	Web	2018	IF Intl Airport
Domestic Aerodromes	Web	2018	Airports Authority of Jamaica
Annual Report	PDF	2016	Airports Authority of Jamaica
Norman Manley International Airport	Web	2018	Airport Technology
World Small Hydropower Development Report 2016	PDF	2016	United Nations
Grid Impact Analysis and Assessment for Increased Penetration of Renewable Energy into the Jamaican Electricity Grid	PDF	2013	Ministry of Science, Technology, Energy and Mining
Wind Farms	Web	2018	Wind Energy Market Intelligence

Description	Type	Date	Institution
PetroJam Products	Web	2018	PETROJAM LIMITED
Port Index	Web	2018	World Port Source

Table 3 Main Sources of Information for Hurricane Hazard Model in Jamaica

Description	Type	Date	Institution
Country limits	Shapefile (*.shp)	30/06/2018	Social Development Corporation (SDC)
Urban centers and internal political division maps	Shapefile (*.shp)	30/06/2018	Social Development Corporation (SDC)
Urban perimeter of principal cities	Shapefile (*.shp)	30/06/2018	Social Development Corporation (SDC)
Land use map	Shapefile (*.shp)	30/06/2018	Forestry Department
Country digital elevation model (DEM)	Raster	12/04/2018	NSDMD/ODPEM
Country digital elevation model (DEM) – ALOS PALSAR	Raster	24/08/2018	Japan Aerospace Exploration Agency - JAXA
Country digital elevation model (DEM) – ALOS World 3D	Raster	24/08/2018	Japan Aerospace Exploration Agency – JAXA
Country digital elevation model (DEM) – ASTER	Raster	24/08/2018	National Aeronautics and Space Administration – NASA
Country digital elevation model (DEM) – ALOS PALSAR	Raster	24/08/2018	National Aeronautics and Space Administration – NASA
Hurricane Catalog	TXT	6/01/2018	National Hurricane Center

Description	Type	Date	Institution
Database of most important hurricanes with impact to the country	Excel	7/11/2018	Met Office/ODPEM
Damage assessment reports and economic losses from recent events	PDF	8/01/2018	ODPEM and Ministry of Economic Growth and Job Creation
The State of the Jamaican Climate 2015	PDF	23/09/2018	Climate Studies Group UWI Mona

Table 4 Main Sources of Information for Seismic Hazard Model in Jamaica

Description	Type	Date	Institution - Authors
Geological map at national level	Shapefile (*.shp)	2018	Mines and Geology Division
Geological fault map	Shapefile (*.shp)	2018	Mines and Geology Division
Seismic catalog with the recorded date, hour, geographic location of the epicenter, depth, magnitude, scale and recorded accelerograph	Shapefile (*.shp)	2017	Earthquake Unit UWI Mona
Disaster Risk Profile for Jamaica	PDF	2014	IDB
Interaction of reactivated faults within a restraining bend: Neotectonic deformation of southwest Jamaica	PDF	2014	Benford, Tikoff & DeMets
Probabilistic Seismic Hazard Assessment for Jamaica	PDF	2013	Salazar, Brown & Mannette
Seismic Risk Exploratory Mission Kingston, Jamaica	PDF	2013	Calais
Seismic hazard along the southern boundary of the Gonave microplate: block modelling of GPS velocities from Jamaica and nearby islands, northern Caribbean	PDF	2012	Benford et al.
ISC-GEM: Global Instrumental Earthquake Catalogue: (1900-2009), III. Re-computed MS and	PDF	2014	Giacomo et al.

Description	Type	Date	Institution - Authors
MB, proxy MW, final magnitude composition and completeness assessment			

Table 5 Main Sources of Information for Flood Hazard Model in Jamaica

Description	Type	Date	Institution
Precipitation records in hydro-meteorological stations in and around the country with location of the stations.	Shapefile (*.shp) Excel	29/08/2018	Met Office
Mean annual precipitation map	Shapefile (*.shp)	7/11/2018	Met Office
Main and secondary rivers map	Shapefile (*.shp)	29/06/2018	Water Resources Authority
Main and secondary basin maps	Shapefile (*.shp)	29/06/2018	Water Resources Authority
Database of historic flood events and its cause	Excel	7/09/2018	Water Resources Authority/Met Office/ODPEM/DesInventar
Precipitation and flood hazard studies	PDF	14/07/2018	Climate Studies Group UWI Mona/Water Resources Authority/ODPEM
Storm and flood damage assessment reports and economic losses	PDF	14/07/2018	ODPEM/Ministry of Economic Growth and Job Creation
Geotechnical classification of Jamaican ocks	PDF	14/07/2018	Mines & Geology Division
Flood events reports	PDF	16/11/2018	OPDEM
Master Drainage Report – KMA section of the report	PDF	12/12/2018	IADB
KAM Gully Network	Shapefile (*.shp)	12/06/2018	OPDEM
IPCC Fifth Assessment Report (AR5)	PDF	30/09/2013	Intergovernmental Panel on Climate Change – IPCC
Impact of Climate Change on Gulf of Mexico Hurricanes	PDF	8/01/2017	National Center for - NCAR

ASSET´S EXPOSURE MODEL

1.4 INTRODUCTION

A national exposure model consists of an inventory of all the building constructions and infrastructure components susceptible to damages and losses due to natural disasters such as earthquakes, hurricanes or floods. The aftermath of any of these events represents physical damage to buildings and infrastructure, economic losses (direct and indirect) and human impact (affected, injured or loss of lives). The exposure inventory must include the most representative infrastructure components susceptible to damage that are critical to the normal operation of the country, region or any specific administrative area.

For the case of Jamaica, the exposure inventory considers the following types of building and infrastructure (critical components):

- Urban Buildings
- Rural Buildings
- Urban Infrastructure
- (Island wide) National Infrastructure

As explained before, the definition of the exposure model, requires the determination of the resolution. A higher resolution produces more precision and reliability, but also requires more resources (human, computational and economic) to acquire the necessary information. Considering this, the present study defines the resolution according to the best available information from national, regional and local governmental institutions and other types of sources previously described in section 1-3. To represent the urban and rural building stock model, the resolution that best matches the available information is a simplified urban area model (proxy model). This type of simplified model is frequently used for the purposes of generating the basic information for emergency response plans, the identification and implementation of risk mitigation programs to reduce risk, the design of a financial protection program, or the definition and dimensioning of national response and post-disaster recovery strategies. This proxy model is based mainly on existing statistics and different kinds of correlations between population, use sectors, density, unit costs, urban and economic indicators that allows the determination of geographical distribution and quantity of building constructions for the different sectors. To estimate similar parameters for the urban and

national infrastructure, correlation between the population and the type and quantity of infrastructure needs to cope with the demand, and visual and virtual inspection of particular components are used as the best possible way to build a comprehensive infrastructure database for risk assessment purposes.

1.5 BUILDING CONSTRUCTIONS AT NATIONAL LEVEL

1.5.1 General methodology

In general terms, to build a proxy model, the basic inputs are political, social and economic information together with development indicators that represent urban areas of the parishes of the country. The exposure model consists of the geographical distribution of different construction typologies characterized by their economic replacement value and a vulnerability function associated with each one of the hazards (earthquakes, hurricanes and floods). In addition, and as explained before, a human exposure model is also required to quantify the total impact of a natural disaster. This model allows the estimation of the expected occupancy of the building stock. The human exposure model is built for two different scenarios, day and night, considering that the relative distribution of the population varies significantly according to the use of each building. The exposure model considers the following use sectors for each urban center:

- High residency: high-income housing
- Medium residency: medium-income housing
- Low residency: low-income housing
- Public education
- Private education
- Public health
- Private health
- Commercial
- Office
- Industrial
- Administrative or institutional.

In summary, the building exposure model is developed in a consistent and rational way using all the available information. The methodology to build the exposure model consists of the following main steps:

a) Define the general resolution to make a reasonable geographical distribution of the building construction typologies and values. In the present case the level of resolution adopted is the urban center for each one of the parishes.

b) Define the level of complexity of each one of the parishes and urban centers. The level of complexity is defined using the total population, the portion of urban population as compared with the rural one and the parish participation in GDP (Gross Domestic Product). A parish's complexity partially defines the kind of infrastructure and its characteristics that may be found. Based upon this information, different kinds of relationships exist between population density parameters, total population by use sector and economic parameters (such as GDP) with characteristic and economic valuation of each exposed asset or groups of assets. The level of complexity is assigned to each parish due to the resolution of the model and the lack of detailed information from each urban center.

c) Define the use sectors and the population in each group. The basis of the proxy model is the population distribution among the different use sectors. The information of population distribution in the different use sectors is collected using institutional information such as the general census, the labor force, the population in different levels of education, the health coverage and total number of public employees in different economic activities in each parish. In addition, information from previous studies and proxies for similar Caribbean countries, provides estimates of population's distribution. Using the distribution of population in each sector and estimates of the number of persons per unit area of construction, it is possible to estimate the total built area in each sector. Then using the relative proportion of construction typologies, a final built area for each typology can be assigned. Sectors such as education and health must be assessed using similar but more specific information. Information on specific infrastructural components such as important hospitals, schools or administrative buildings is usually collected separately and included in the data base.

d) Define the relative distribution of building construction typologies. Using the available information, visual inspections and data collection from satellite imagery and Google Street View and the complexity of each parish and urban area, the predominant distribution of construction typologies is defined. The usual construction typologies are concrete frames, masonry walls, timber, and others. Relative distribution of typologies is geographically assigned.

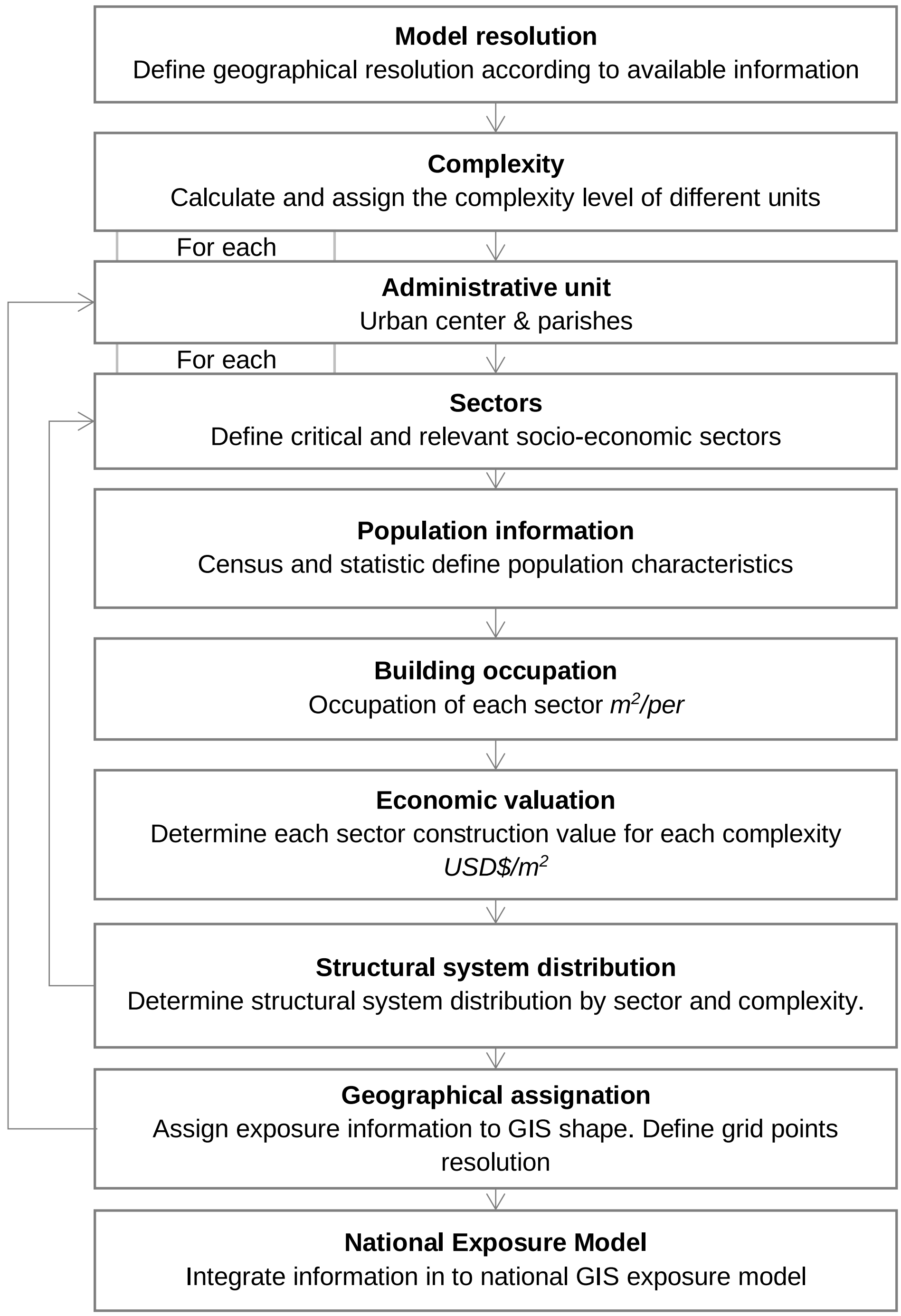
e) Using the population distribution and the mean density indicators, the total built area (for building constructions to accommodate such demand) is estimated for each urban center and use of each building.

f) Using the reference unit costs (cost per m^2) for the different use sectors, the total replacement value is estimated (cost of the building without the cost of the terrain) for each urban center and use sector. The unit values are defined using the collected information of real estate, commercial value and land uses.

g) Finally, using the building construction typology distribution matrices, the total exposure in each urban center is assigned. The exposed values and typologies are then uniformly distributed in the geographical areas of urban zones according to a uniformly distributed grid, which is prepared previously.

h) All the information is stored in a GIS shape file with dot elements defining the distribution of building construction typologies and relative replacement values.

Error! Reference source not found. **Procedure to Conform the Exposure Model.**



Following the above-mentioned methodology, it is possible to conform a georeferenced model containing the exposed assets in terms of building constructions at national level classified according to selected use sectors at each urban center and/or parish. The following sections explain in detail the methodology followed to construct the exposure model and the specific information used in each situation.

1.5.2 Basic National Information

The exposure model is built upon political, social and economic information. **Error! Reference source not found.** presents basic indicators from which the proxy model is built. The 2018 projected population is calculated linearly using information from STATIN (statistics Institute of Jamaica).

Table 6 Indicators and General Parameters of Jamaica

Index	Unit	Value
Population in 2018	[Population]	2,728,148
Area	[km^2]	10,991
Density	[Population/km^2]	251.88
GDP 2018	[US$ billions]	14.8
GDP per capita	[US$]	4,682.5
Minimum wage 2018	[US$]	275

Moreover, the *National basic information* is collected by parish, supported on information from the last census (2011). The information of the 2011 census is available at the statistical web-portal of STATIN. Based upon such information, data can be obtained, including: population density, population distribution in urban and rural centers, age distribution and labor force per parish. **Error! Reference source not found.** presents de urban/rural population and age distribution.

Table 7 Population by Parish

Parish	Urban Population	Rural Population	% Urban	% Rural
Hanover	7 550	62 324	10.80%	89.20%
St. Elizabeth	23 449	127 544	15.53%	84.47%

Parish	Urban Population	Rural Population	% Urban	% Rural
St. James	101 848	82 814	55.15%	44.85%
Trelawny	15 570	59 988	20.61%	79.39%
Westmoreland	41 142	103 675	28.41%	71.59%
Clarendon	85 454	160 868	34.69%	65.31%
Manchester	69 285	121 527	36.31%	63.69%
St. Ann	55 142	118 090	31.83%	68.17%
St. Catherine	392 224	126 121	75.67%	24.33%
St. Mary	31 281	82 946	27.38%	72.62%
Kingston	89 057	-	100.00%	0.00%
St. Thomas	28 171	66 239	29.84%	70.16%
Portland	21 159	61 024	25.75%	74.25%
St. Andrew	502 889	70 480	87.71%	12.29%
Jamaica	1 464 222	1 243 639	54.07%	45.93%

Figure 2 Population Distribution by Urban/Rural Zone

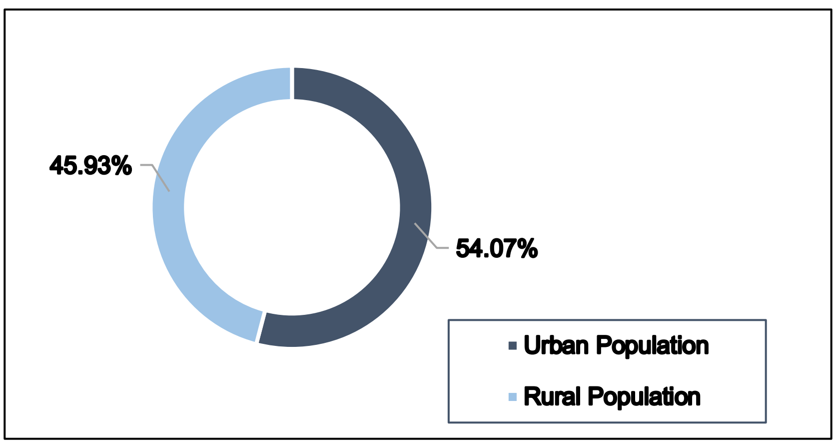
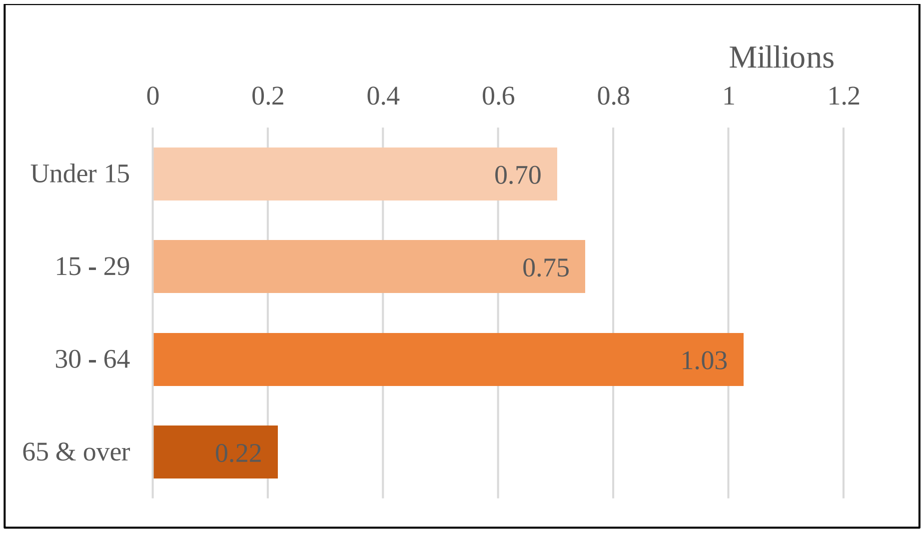


Table 8 Age Distribution by Parish

Parish	Under 15	15 - 29	30 - 64	65 & Over
Hanover	19 764	18 870	25 802	5 097
St. Elizabeth	39 999	39 068	55 967	15 171
St. James	49 591	53 199	68 082	12 939
Trelawny	20 813	20 273	27 155	6 923
Westmoreland	41 320	39 029	51 415	12 339
Clarendon	70 163	67 051	87 125	20 764
Manchester	48 314	50 254	72 844	18 385
St. Ann	46 806	47 611	63 101	14 844
St. Catherine	134 976	144 432	200 911	35 899
St. Mary	30 776	30 891	41 152	10 796
Kingston	24 860	25 451	33 326	5 420
St. Thomas	25 319	26 036	34 152	8 395
Portland	20 722	22 097	31 564	7 361
St. Andrew	129 412	167 227	233 457	43 273
Total	702 835	751489	1026053	217606

Figure 3 illustrate that the urban population is more than half of the population of Jamaica (54%) and the rural population is close to 46%. Moreover, it may be said that Jamaica is a young country with 26% of its population under 15 years, 27% between 15 and 29 years, 38% between 30 and 64 and only 8% percent of the population is over 65 years.

Figure 3 Jamaica's Population Composition by Age



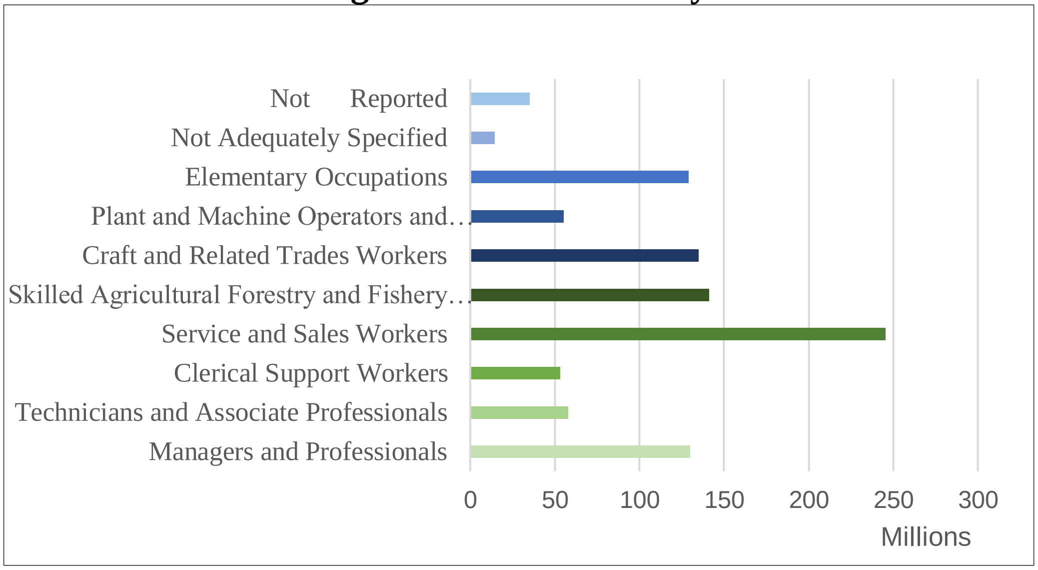
1.5.3 Development index

Parish development indexes are fundamental to define each parish complexity. One of the main variables considered in this classification is the labor force (active population) and the non-active population that may include students and health patients. These variables are essential to develop the human exposure model and build the occupation scenarios for the day and night situations.

Table 9 Labor Activities

Population Activities	Population
Working	1 178 500
With job not working	7 300
Looking for work	60 900
Keeping house	479 700
At school	303 800
Incapable of working	55 800
Other	4 800

Figure 4 Labor Force by Activities



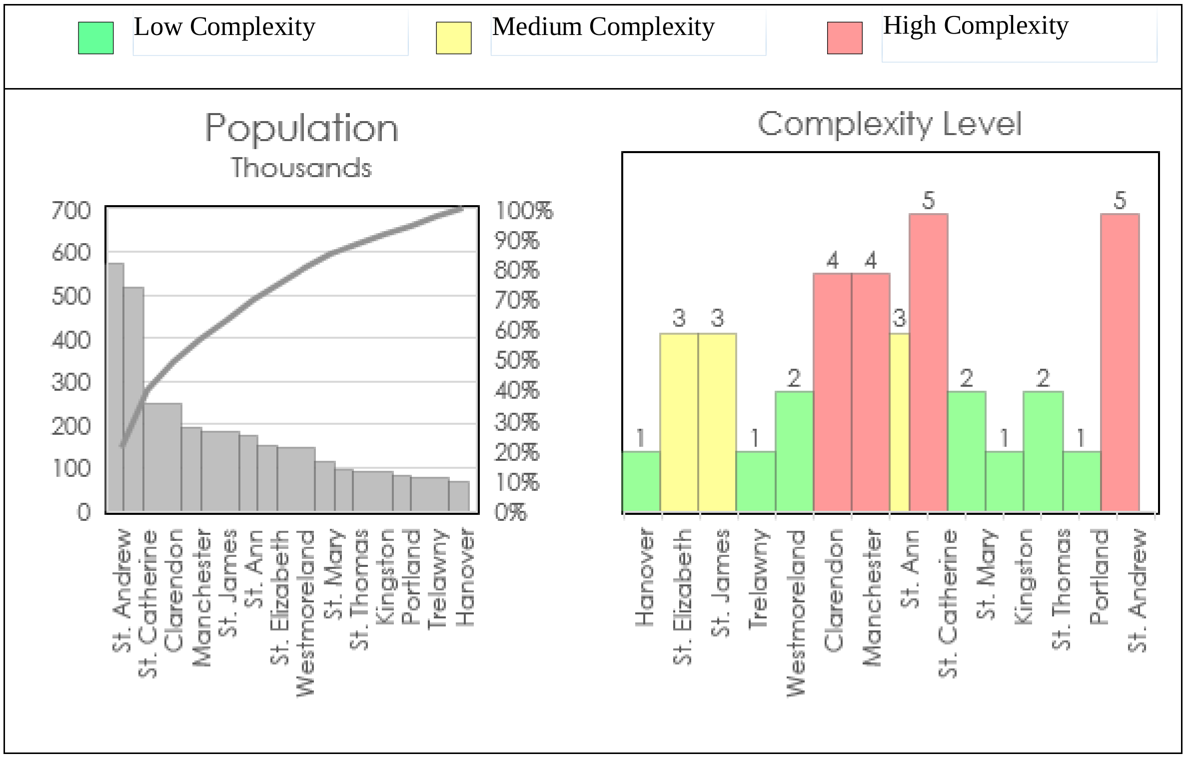
1.5.4 Complexity level

Parish complexity level is classified based upon the following parameters:

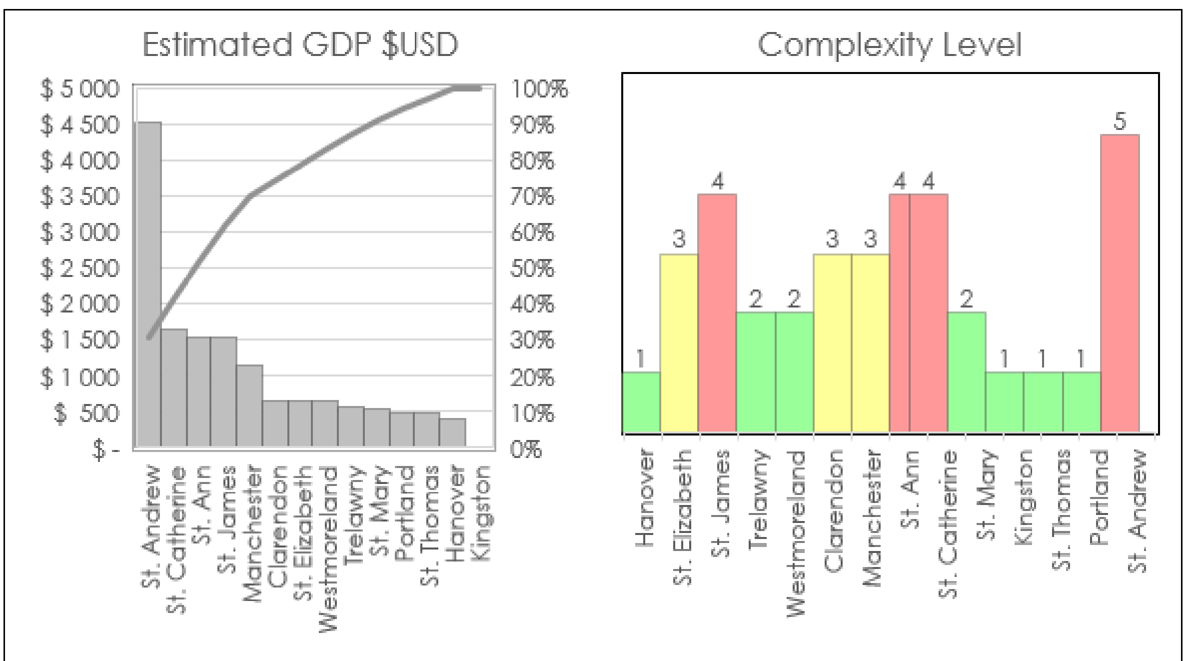
- Total population
- Percentage of urban population
- Calculated GDP participation

These parameters have a direct correlation that allows the estimation of each parish complexity. Through a statistical analysis that categorizes the data in quartiles, it is possible to quantify the calculated complexity with values between 1 and 5. Each parameter qualification is weighted to estimate the total parish complexity. The parish of Kingston is treated in a separate way. Although this parish population and GDP don't sum enough to qualify as a high complexity area, since the city of Kingston and its metropolitan area are inside its boundaries, the whole parish category is defined as "high complexity". The quantification of parameters for the assignment of the complexity index to each parish is shown in Figure 5.

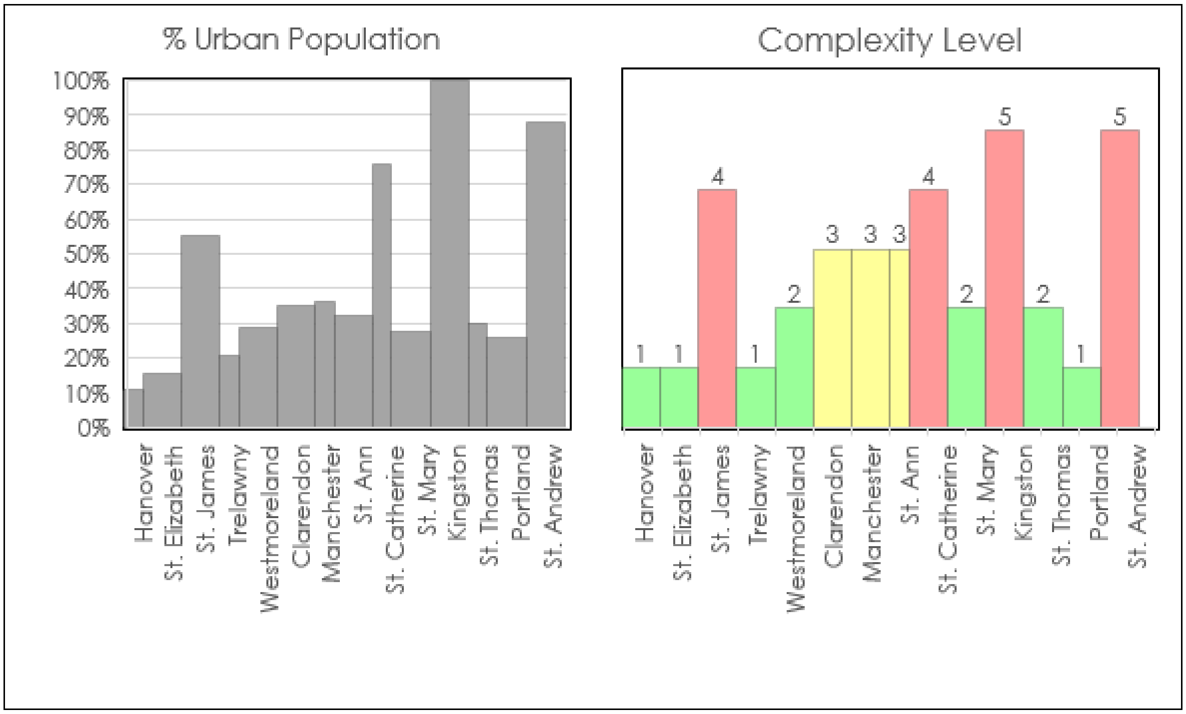
Figure 5 Parish Complexity- (a) by population (b) by GDP Participation and (c) by Urban Population Percentage



(a)



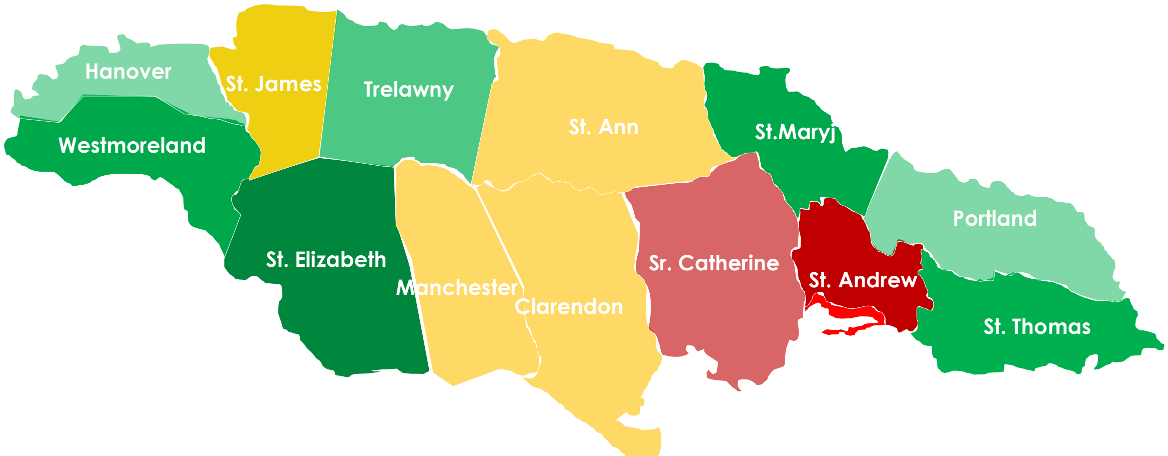
**Kingston Parishes computed with St. Andrew*

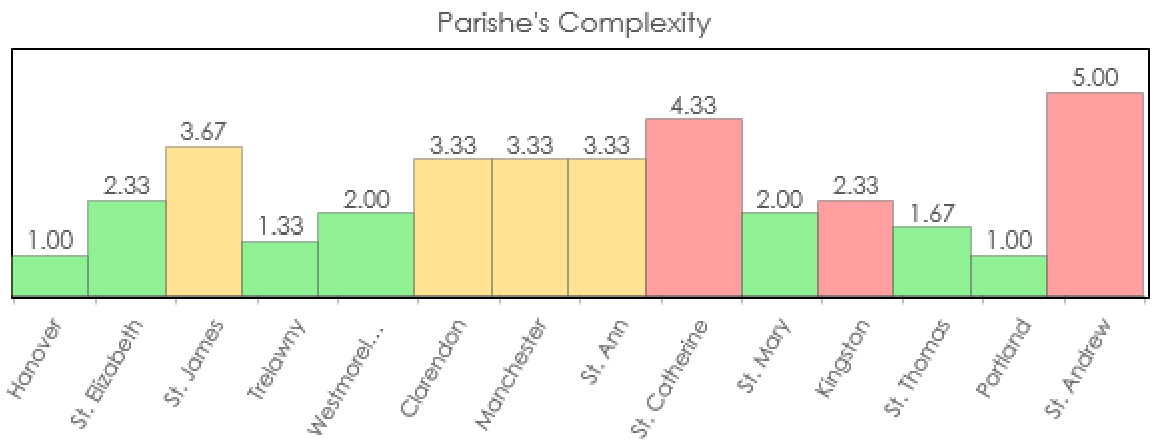


(c)

The final result of the explained qualification process indicates that the parishes of St Andrew, Kingston and St Catherine turn out to be classified in the highest complexity due to the their total population, the urban area population and the high level of economic activity. Other parishes such St James, St Ann, Manchester and Clarendon are classified in the mid-range complexity, considering they all have important urban areas and produces a large part of the national GDP. Less complex parishes like Hanover, St Elizabeth, Trelawney, Westmoreland, Portland, St Thomas and St Mary have less population with lower percentages living in urban centers. **Error! Reference source not found.** illustrates the final assigned complexity of each Parish and a map containing such information.

Figure 6 Assigned complexity for parishes in Jamaica

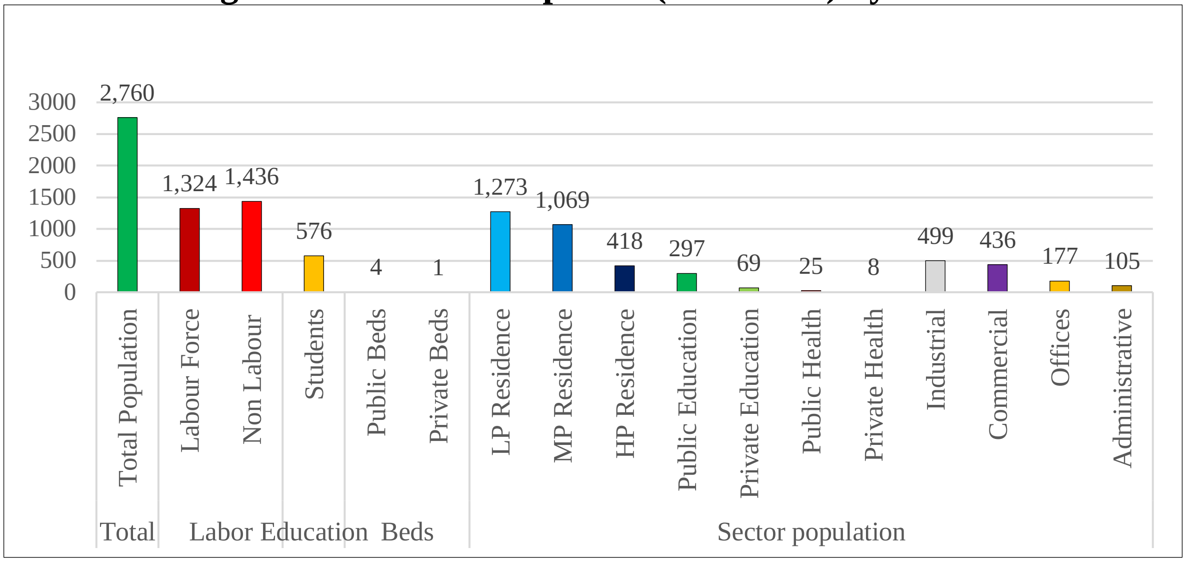




1.5.5 Human occupation

Human occupation distribution is calculated by means of statistics of the population activities, obtained from the 2011 census projected to the year 2018 and the 2018 data of labor force statistics, obtained from STATIN. The geographical unit used to define the information of occupation is the parish. **Error! Reference source not found.** presents the different sector occupation distribution. The health and education sectors are treated as special cases; the first one is defined by the number of beds available and the second one by student distribution. Both of these sectors have public and private participation.

Figure 7 Human Occupation (Thousand) by Sector



Once the relative distribution of human occupation is obtained for each sector (see **Error! Reference source not found.**), it is possible to develop the human occupation model, one for daytime occupation and another for nighttime occupation. For the daytime occupation model, the distribution of the economical active population is likely to be at commercial, offices, industrial, health and educational sectors. In contrast, most of the population is allocated in the residential sector during nighttime. As an example, **Error! Reference source not found.** shows the occupation model for St. Catherine. It becomes evident that there is a large variation in the occupation model during the daytime or nighttime scenarios.

Figure 8 Human Occupation Distribution by Parish

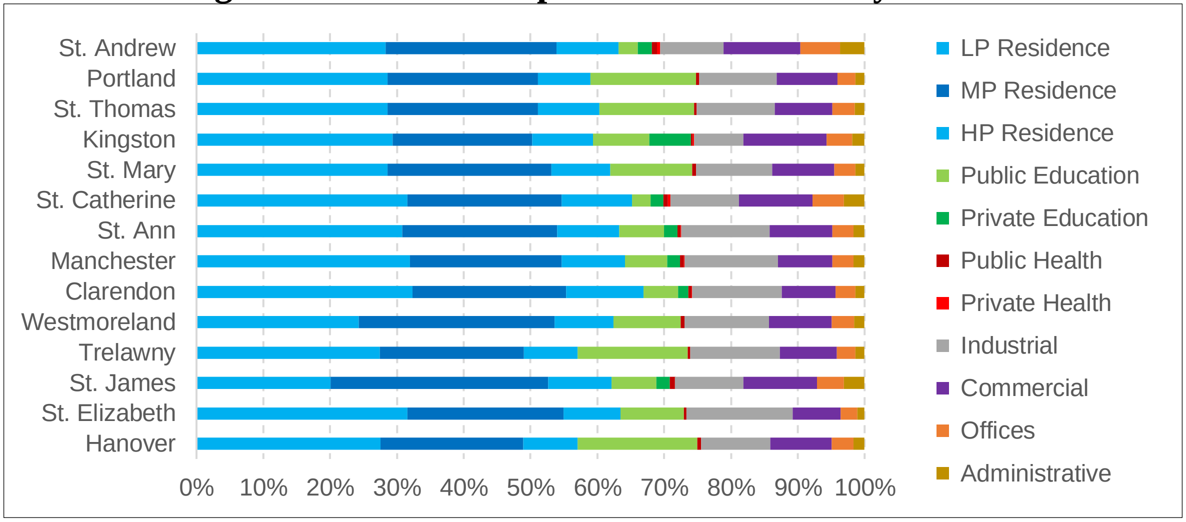


Table 10 St. Catherine Occupation Model

St. Catherine		
ParishID	29	
Complexity level	H	
Socio-economic distribution		
Low	Medium	High
48.4%	35.4%	16.2%
Sector	**Day occupation**	**Night Occupation**
High Residence	43,502	96,670
Medium Residence	108,807	241,794
Low Residence	129,906	288,679
Commercial	138,287	51,858
Offices	50,644	18,991
Industrial	21,375	11,875
Private Health	195	195
Public Health	326	326
Private Education	68,256	-
Public Education	68,256	-
Administrative	32,978	-
Total	662,531	710,388

Similarly, an occupation model was developed for each individual parish. **Error! Reference source not found.** summarizes the occupation model for all parishes for the day and night scenarios. The table also disaggregates the occupation by the use sectors.

Table 11 Day and Night Scenario Occupation by Parish

Day occupation scenario											
ID. Parish	**Parish**	**Population**	**High Residence**	**Medium Residence**	**Low Residence**	**Commercial**	**Offices**	**Industrial**	**Health**	**Education**	**Administrative**
11	**Hanover**	71 151	1 994	6 509	6 721	13 216	4 840	953	16	5 472	2 941
12	**St. Elizabeth**	153 365	5 721	18 810	21 191	35 594	13 035	4 279	85	21 100	8 252
13	**St. James**	188 583	7 489	30 685	15 819	42 033	15 393	5 053	334	31 359	9 745
14	**Trelawny**	76 790	2 112	7 089	7 230	14 263	5 223	1 029	24	5 268	3 175
15	**Westmoreland**	147 468	5 687	22 654	15 704	34 288	12 557	4 122	122	21 451	7 950
26	**Clarendon**	250 663	11 641	27 692	32 434	55 870	20 461	6 717	197	46 911	12 953
27	**Manchester**	193 604	7 652	21 954	25 825	43 152	15 803	5 188	315	26 946	10 005
28	**St. Ann**	176 268	6 859	20 720	22 889	39 288	14 388	4 723	192	27 718	9 109
29	**St. Catherine**	531 795	43 502	108 807	129 906	138 287	50 644	21 375	521	136 513	32 978
30	**St. Mary**	115 832	4 583	15 120	14 768	26 835	9 828	3 226	133	15 034	6 222
31	**Kingston**	90 735	7 015	18 417	22 719	23 595	8 641	3 647	218	44 334	5 627
32	**St. Thomas**	95 874	4 046	11 921	12 599	22 239	8 144	2 674	114	12 940	5 156
33	**Portland**	83 335	2 168	7 786	7 877	15 479	5 669	1 117	37	5 445	3 445
34	**St. Andrew**	584 172	43 439	135 276	131 295	151 907	55 632	23 480	1 404	130 100	36 226
	Total	**2 759 634**	**153 909**	**453 439**	**466 977**	**656 048**	**240 259**	**87 582**	**3 713**	**530 591**	**153 783**
Night occupation scenario											
ID. Parish	**Parish**	**Population**	**High Residence**	**Medium Residence**	**Low Residence**	**Commercial**	**Offices**	**Industrial**	**Health**	**Education**	**Administrive**
11	**Hanover**	4 432	14 464	14 935	4 956	1 815	530	4 432	16	-	-
12	**St. Elizabeth**	12 211	40 147	45 228	12 820	4 695	2 283	12 211	81	-	-
13	**St. James**	16 643	68 188	35 154	15 762	5 773	2 807	16 643	334	-	-
14	**Trelawny**	4 693	15 752	16 067	5 349	1 959	572	4 693	24	-	-
15	**Westmoreland**	12 115	48 264	33 458	12 327	4 515	2 196	12 115	117	-	-
26	**Clarendon**	25 869	61 538	72 076	20 951	7 673	3 731	25 869	197	-	-
27	**Manchester**	17 004	48 786	57 389	16 182	5 926	2 882	17 004	315	-	-
28	**St. Ann**	15 241	46 045	50 863	14 733	5 396	2 624	15 241	192	-	-

29	**St. Catherine**	96 670	241 794	288 679	51 858	18 991	11 875	96 670	521	-	-
30	**St. Mary**	9 801	32 332	31 578	9 683	3 546	1 725	9 801	128	-	-
31	**Kingston**	15 590	40 926	50 487	8 848	3 240	2 026	15 590	218	-	-
32	**St. Thomas**	8 642	25 460	26 909	8 015	2 935	1 427	8 642	110	-	-
33	**Portland**	4 817	17 302	17 505	5 805	2 126	620	4 817	37	-	-
34	**St. Andrew**	96 532	300 613	291 766	56 965	20 862	13 044	96 532	1 404	-	-
	Total	**340 260**	**1 001 611**	**1 032 094**	**244 255**	**89 451**	**48 343**	**340 260**	**3 695**	**-**	**-**

1.5.6 Building occupation

Building occupation is defined in the model through the “quantity of square meters per person” for each specific sector. This indicator is obtained through institutional statistics (STATIN) and other official information or previously published similar studies. The exposure model requires the estimation of the built area of each sector of Jamaica’s urban centers, cities and towns. Using the assigned expected occupation or population by sectors, and standard expected construction area indexes, it is possible to calculate the representative built area of each sector. This information is compared and validated with IDB or other institution´s previous technical studies with similar characteristics. **Error! Reference source not found.** summaries the final building occupation indicators collected for each sector population for each parish.

Table 12 Building Occupation Indicators – Built Area by Person (m^2/person)

ID. Parish	Parish	High Residence	Medium Residence	Low Residence	Commercial	Offices	Industrial	Health*	Education	Administrative
11	**Hanover**	33	16	12	14	5	6	5	5	20
12	**St. Elizabeth**	34	15	11	14	5	6	11	10	33
13	**St. James**	30	11	17	13	5	6	4	12	11
14	**Trelawny**	34	15	12	13	5	6	4	5	24
15	**Westmoreland**	35	13	15	15	5	7	5	10	24
26	**Clarendon**	25	16	11	15	5	6	5	15	25
27	**Manchester**	30	16	11	14	5	6	4	12	20
28	**St. Ann**	30	14	11	13	5	6	8	10	20
29	**St. Catherine**	27	15	11	12	4	5	6	31	11
30	**St. Mary**	32	14	12	14	5	6	5	7	25
31	**Kingston**	31	16	11	14	5	6	3	6	18
32	**St. Thomas**	31	15	12	15	5	6	6	6	23
33	**Portland**	36	15	12	15	5	6	4	5	25
34	**St. Andrew**	31	14	12	12	4	5	5	37	10

**Health had been computed with the total hospital beds available per parish*

1.5.7 Economic valuation

The economic valuation of building constructions is calculated based upon a series of available statistics, previous similar studies and commercial and cadastral reported and published values. The commercial valuation is obtained by the consultation of information of different kind of real estate agencies that have online information. Web sites such as *Realtor* or *Century 21* publish summarized information from most of the selected sectors including residential (all complexities), commercial and office buildings, industrial warehouses and others (hotel, land, administrative buildings, etc.). Once a commercial value can be estimated, the required construction replacement value can be assessed using indexed ratios between the two figures. Finally, a validation of final assigned values is done consulting previous studies. **Error! Reference source not found.** summarize information of replacement values by square meter by sector. These values correspond to the estimated direct costs associated to a possible reconstruction of the equivalent built area including

structural and non-structural components. They do not include the building contents, the land value or factors such as market forces or macroeconomic shocks.

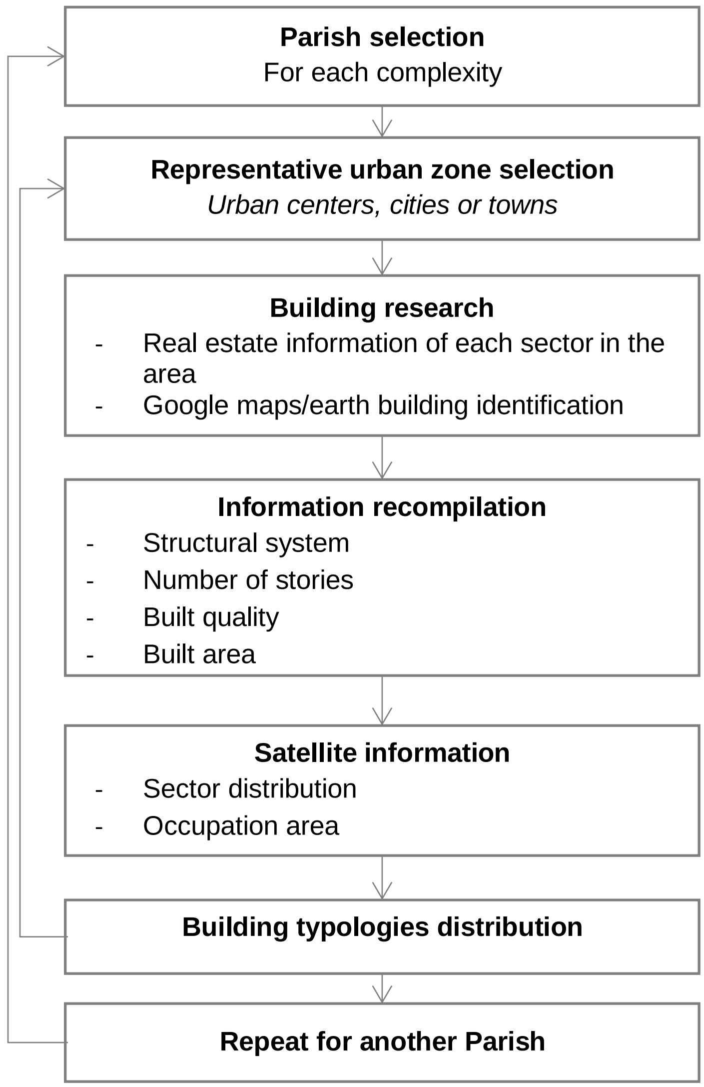
Table 13 Unit Replacement Values by Square Meter

USD/m^2	H	M	L
High Residence	$ 818	$ 572	$ 409
Medium Residence	$ 589	$ 410	$ 347
Low Residence	$ 255	$ 230	$ 161
Commercial	$ 507	$ 231	$ 165
Offices	$ 547	$ 383	$ 274
Industrial	$ 467	$ 327	$ 234
Private Health	$1200	$ 760	$ 514
Public Health	$ 840	$ 580	$ 420
Private Education	$ 420	$ 380	$ 320
Public Education	$ 360	$ 320	$ 272
Administrative	$ 536	$ 375	$ 268

1.5.8 Building construction typologies

Distribution matrices are generated for the building construction typologies using statistical information, observations from GIS platforms such Google Maps Street View and Google Earth and real estate information such as *Realtor* and *Century 21*. The information was applied to each of the urban centers identified in each parish. Especial treatment was applied to the KMA region which has more detailed information. **Error! Reference source not found.** summarizes the methodology to determine the building construction typology distribution.

Figure 9 Building Construction Typologies Distribution



The distribution of building construction typologies is illustrated in **Error! Reference source not found.**. This format contains information about the most predominant construction typologies identified in Jamaica's urban and rural areas. Selection of the construction typology and the number of stories is the two main parameters that determine the seismic, hurricane and flood building vulnerability.

Table 14 Building Construction Typologies

Construction Typology	Abbrev	Typical Values		
		Stories	Built quality	Sector
Precarious (Earth walls, old timber, steel sheets)	PREC	1	Low	Residence
Confined masonry walls	MC	1-2	Medium	Residence
Reinforced masonry walls	MR	1-2	Medium-High	Residence
Non-reinforced masonry walls with slab diaphragm	MSP	1-2	Low-Medium	Residence
Non-reinforced masonry walls without slab diaphragm	MS	1-2	Low-Medium	Residence
Concrete frames	PCR	1-3	Medium-High	Commercial
Concrete frames with masonry	PCRMM	1-3	Medium-High	Commercial-Education
Column-slab concrete frames with masonry	LCCRMM	>3	Medium-High	Commercial-Offices
Concrete frames or column-slab with masonry and weak facade	PLCMMED	>3	Medium-High	Offices
Concrete frames and concrete walls	CCR	>3	High	Residential-offices
Concrete walls	MCR	1-3	Medium-High	Residential-Commercial
Non-braced Steel frame	PNAC	1	Medium-High	Industrial
Braced Steel frame	PAAC	>3	High	Commercial
Masonry warehouse	BM	1	Medium	Industrial
Reinforced concrete warehouse	BCR	1	Medium	Industrial
Steel warehouse	BA	1	High	Industrial
Timber frames	PM	1-2	Low-Medium	Commercial

With this information it is possible to conform building construction typologies relative distribution matrices for the different use sectors previously identified. The relative distributions of building construction typologies vary according to the complexity assigned to each urban center. **Error! Reference source not found.**, **Error! Reference source not found.** and **Error! Reference source not found.** present those relative distributions for the different complexity levels assigned before. **Error! Reference source not found.**, **Error!**

Reference source not found. and **Error! Reference source not found.** presents the results in the form of bars. With this information it is then possible to complete the exposure model for building construction in the main urban areas of the country.

Table 15 Structural Typologies Distribution - High complexity

Sector	Precarious	Masonry	Concrete frames	Industrial	Timber frames	Others
High Residence	-	42.9%	38.9%	-	-	18.2%
Medium Residence	-	77.1%	11.9%	-	-	11.0%
Low Residence	-	87.3%	12.5%	-	-	0.2%
Commercial	2.9%	11.0%	64.8%	5.1%	0.9%	15.4%
Offices	-	29.5%	64.4%	-	-	6.1%
Industrial	-	-	1.1%	98.9%	-	-
Private Health	-	19.5%	56.8%	-	-	23.7%
Public Health	-	19.5%	56.8%	-	-	23.7%
Private Education	-	13.8%	66.3%	0.9%	-	19.0%
Public Education	-	13.8%	66.3%	0.9%	-	19.0%
Administrative	-	0.1%	78.3%	8.7%	4.0%	8.9%

Figure 10 High Complexity Structural Typologies Distribution

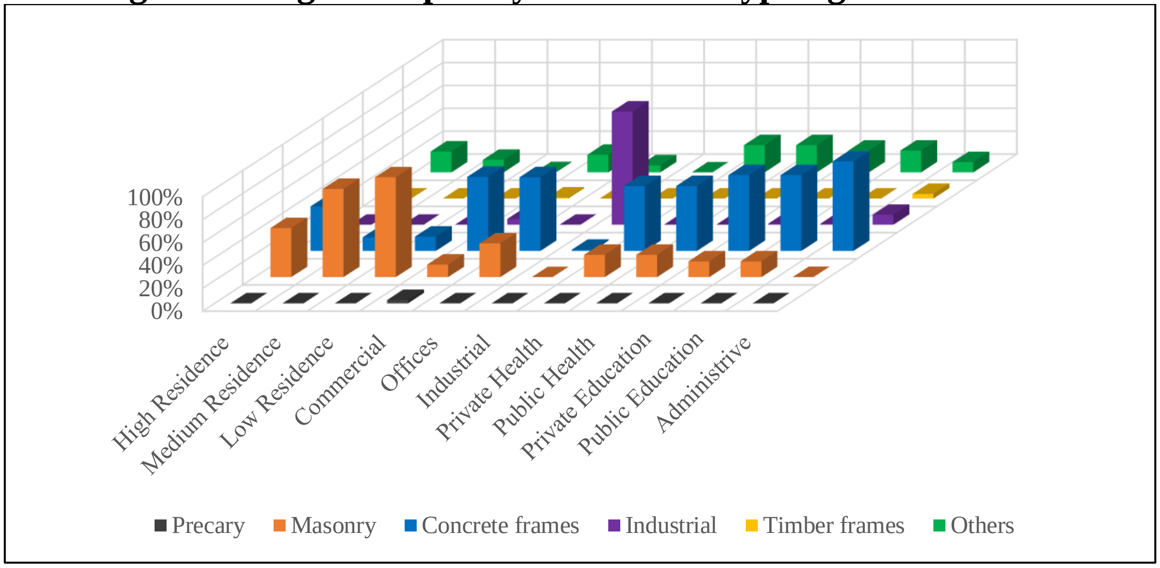


Table 16 Structural Typologies Distribution - Medium Complexity

Sector	Precarious	Masonry	Concrete frames	Industrial	Timber frames	Others

High Residence	-	60.5%	26.9%	-	-	12.6%
Medium Residence	3.8%	84.0%	6.4%	-	-	5.9%
Low Residence	7.6%	86.2%	6.1%	-	-	0.1%
Commercial	5.2%	19.5%	56.4%	4.8%	0.8%	13.4%
Offices	-	46.0%	49.3%	-	-	4.7%
Industrial	-	-	0.9%	99.1%	-	-
Private Health	-	19.5%	56.8%	-	-	23.7%
Public Health	-	19.5%	56.8%	-	-	23.7%
Private Education	-	24.3%	57.3%	2.1%	-	16.4%
Public Education	-	24.3%	57.3%	2.1%	-	16.4%
Administrative	-	18.1%	53.4%	19.6%	2.8%	6.1%

Figure 11 Medium Complexity Structural Typologies Distribution

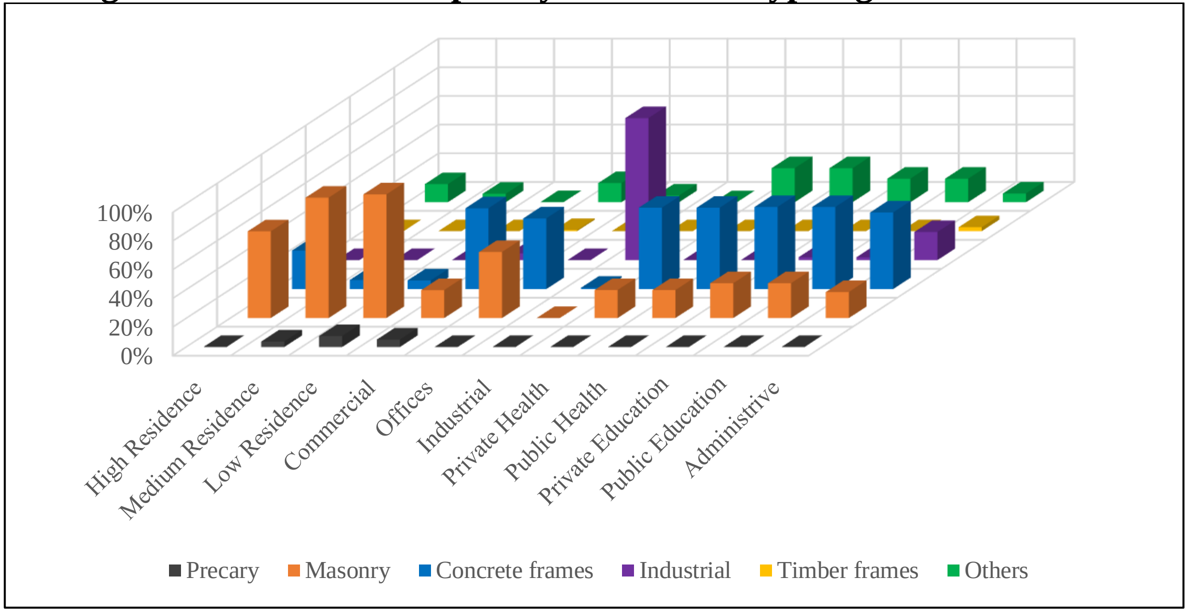
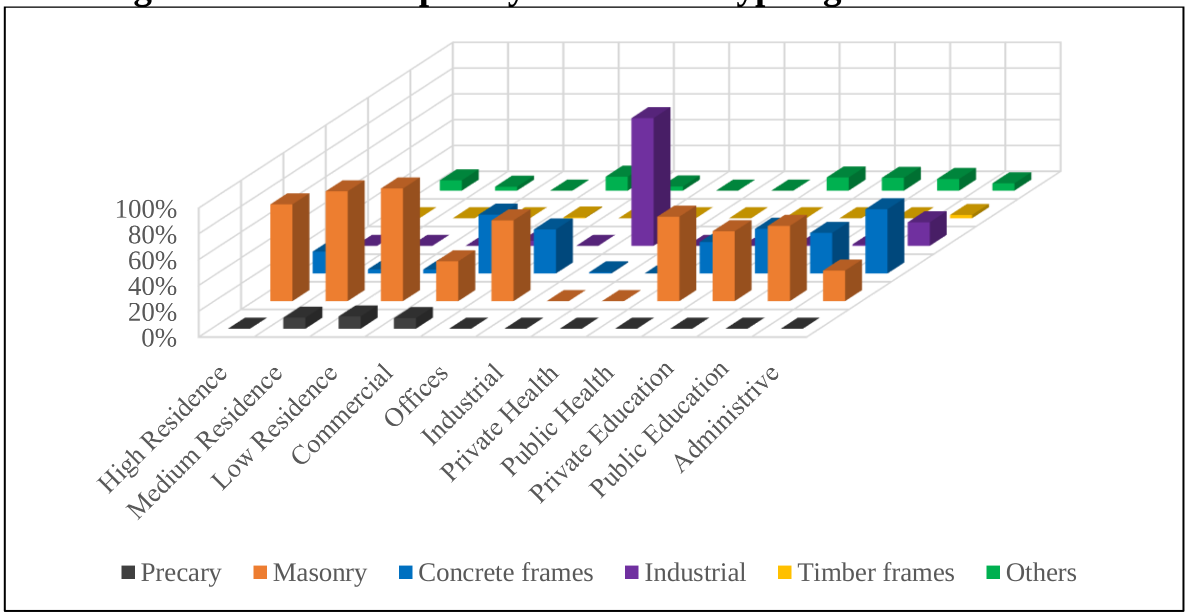


Table 17 Structural typologies distribution. Low complexity

Sector	Precarious	Masonry	Concrete frames	Industrial	Timber frames	Others
High Residence	-	60.5%	26.9%	-	-	12.6%
Medium Residence	3.8%	84.0%	6.4%	-	-	5.9%
Low Residence	7.6%	86.2%	6.1%	-	-	0.1%
Commercial	5.2%	19.5%	56.4%	4.8%	0.8%	13.4%
Offices	-	46.0%	49.3%	-	-	4.7%
Industrial	-	-	0.9%	99.1%	-	-
Private Health	-	19.5%	56.8%	-	-	23.7%
Public Health	-	19.5%	56.8%	-	-	23.7%
Private Education	-	24.3%	57.3%	2.1%	-	16.4%
Public Education	-	24.3%	57.3%	2.1%	-	16.4%
Administrative	-	18.1%	53.4%	19.6%	2.8%	6.1%

Figure 12 Low Complexity Structural Typologies Distribution

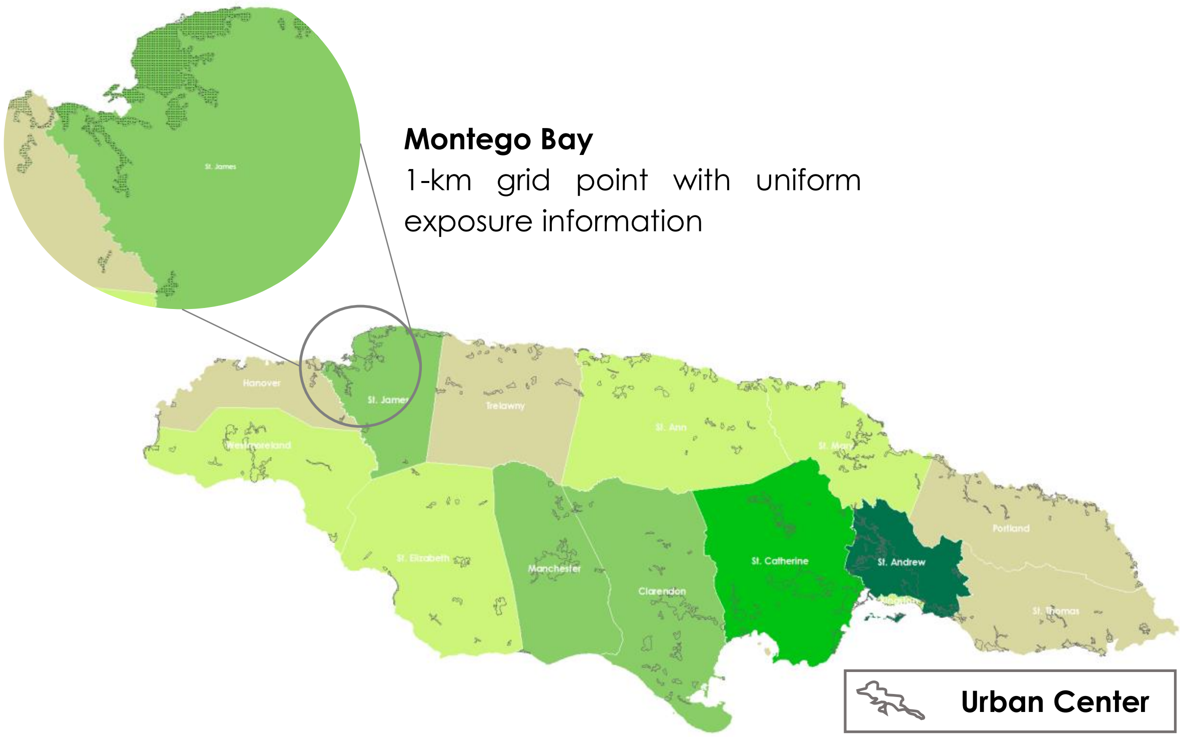


1.5.9 Geographical distribution of the exposure model

The proposed National Exposure Model is developed with a minimum resolution of urban centers in the different parishes. This model includes built area by use sectors and building construction type. For the geographical distribution of the exposed assets, a uniform grid with

a 1 km density is considered adequate for the level of precision required and the type of analysis to be performed. **Error! Reference source not found.** presents an illustration of the georeferenced grid to distribute geographically the exposure model.

Figure 13 Georeferenced Grid for the Exposure Model



1.5.10 Integrated exposure model

Following the previous methodology an integrated building construction model was conformed at country level. **Error! Reference source not found.** summarizes the main figures of the model.

Table 18 Main Figures of the Exposure Model

Indicator	Units	Value
Population (2018)	-	2,759,634
Number of Urban centers	-	142
Estimated number of building units	-	853,660

Total replacement value	US$ (Millions)	$ 34,839
Replacement value per capita	US$/inhab.	$ 16,850
Replacement value	%GDP	315%
Estimated urban constructed area	m2	81,116,154
Constructed area per capita	m2/inhab.	30
Average economic value	US$/m2	$ 340

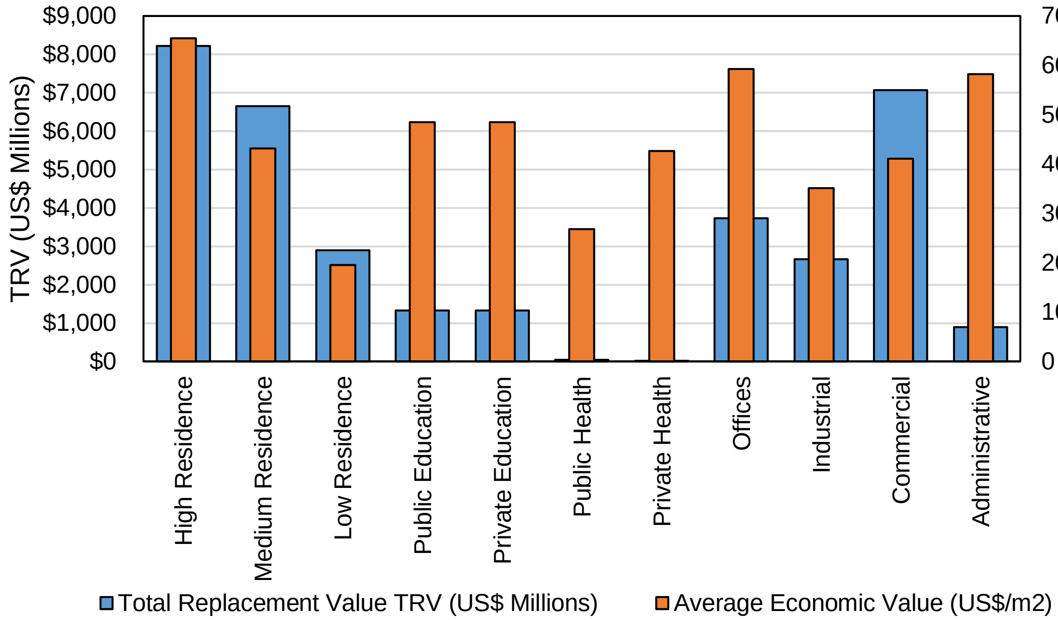
Error! Reference source not found. summarizes the relative distribution of built area, replacement value, Occupation during the day, Occupation during the night for each one of the use sectors.

Table 19 Replacement Value of Buildings by Sector

SECTOR	Total Replacement Value TRV (US$ Millions)	Relative TRV (%)	Constructed Area (m2)	Average Economic Value (US$/m2)	Occupation Day (Inhab.)	Occupation Night (Inhab.)
High Residence	$ 8,227	24%	12,561,593	$ 655	153,909	340,260
Medium Residence	$ 6,650	19%	15,392,009	$ 432	453,439	1,001,611
Low Residence	$ 2,900	8%	14,878,025	$ 195	466,977	1,032,094
Public Education	$ 1,329	4%	2,745,303	$ 484	348,531	0
Private Education	$ 1,331	4%	2,745,303	$ 485	182,060	0
Public Health	$ 47	0%	174,975	$ 268	2,802	2,784
Private Health	$ 13	0%	30,480	$ 426	911	911
Offices	$ 3,724	11%	6,290,703	$ 592	240,259	89,451
Industrial	$ 2,669	8%	7,593,940	$ 352	87,582	48,343
Commercial	$ 7,061	20%	17,177,331	$ 411	656,048	244,255
Administrative	$ 888	3%	1,526,490	$ 582	153,783	0
Total	**$ 34,839**	**100%**	**81,116,154**	**$ 430**	**2,746,301**	**2,759,709**

Error! Reference source not found. presents the exposed value in each sector plus the average replacement value (US$/m2).

Figure 14 Exposed Value (Total and Average) by Sector



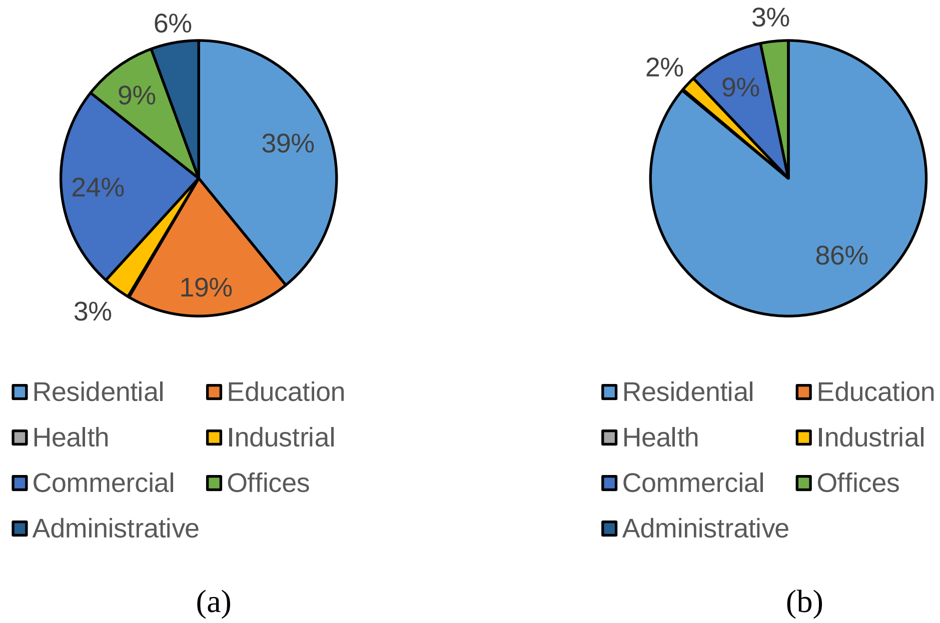
As a comparison, **Error! Reference source not found.** shows the total replacement value disaggregated between public sector (Low residence, public health and education and administrative) and private sector (Medium and high residence, private health and education, offices, industrial and, commercial).

Table 20 Exposed Value: Private and Public Sectors

SECTOR	Replacement Value (US$ Millions)	Value per capita (US$/inhab.)	%GDP
Private Buildings	$ 29,676	$ 10,791	202%
Public Buildings	$ 5,164	$ 1,878	35%
Total	**$ 34,839**	**$ 12,669**	**237%**

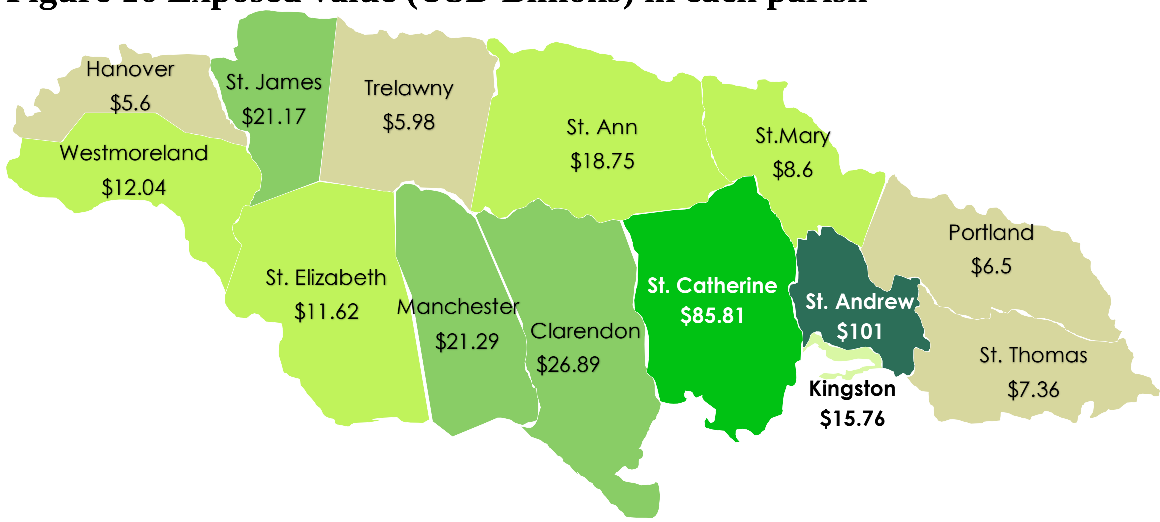
Error! Reference source not found. presents the relative distribution of population in the day and night scenarios for the different use sectors.

Figure 15 Relative Distribution of Population (a) Day Scenario, (b) Night Scenario



illustrates the exposed value disaggregated by parish.

Figure 16 Exposed value (USD Billions) in each parish



1.6 INFRASTRUCTURE EXPOSURE MODEL

1.6.1 Methodology and Scope

The exposure model for infrastructure components consists of the geographical distribution of different infrastructure components characterized by their ID and description, economic replacement value and a vulnerability function associated with each one of the hazards (earthquakes, hurricanes and floods).

For purposes of risk assessment, the infrastructure is classified in the following categories:

(a) Transportation system

  i. Main road network
  ii. Secondary road network
  iii. Bridges
  iv. Ports: building constructions and docks
  v. Airports: building constructions and airstrips

(b) Energy System

  i. Electric substations (at national and urban level)
  ii. Transmission and distribution lines
  iii. Hydroelectric: power plants and damns
  iv. Renewable and fossil energy

(c) Hydrocarbons and oil derivatives

  i. Refineries
  ii. Polyducts
  iii. Gas pipelines

(d) Telecommunication

  i. Substations
  ii. Towers and antennas (fixed lines and mobile lines)

(e) Water supply, sanitation and urban pipes systems

  i. Aqueducts networks (tanks and pipes)
  ii. Sewage network (tanks and pipes)
  iii. Gas networks
  iv. Water treatment plants
  v. Wastewater treatment plants

With the objective of conforming the exposure database of infrastructure components information was collected from sources such as public agencies in charge of the infrastructure, local and regional utility companies, recent infrastructure projects and direct interpretation of satellite images from Google Earth.

In cases where direct inventories of components were not available from government agencies indirect simplified methods were used to estimate the location, value and expected characteristics of main components of infrastructure. In some cases, the public utilities coverage is estimated together with simplified economic valuation of systems and its expected characteristics using standard figures of similar infrastructure systems in other countries in the region based on the level of complexity of the parish and the population density, production centres and coverage level of each of these services. In those cases, the public coverage of utility systems from the last available housing census is helpful to estimate the size and value of the different infrastructure components of the different systems.

1.6.2 Infrastructure database setup

The available information allows the consolidation of all the data related to national transport and public utility's infrastructure, so as to estimate the exposure values in each of the sectors included in the assessment. Table 0-21 to Table 0-25 presents the results of this estimation.

Table 0-21 Exposure values of transportation system

Parish	ParishID	Complexity (H–High M–Medium L–Low)	TRANSPORTATION SYSTEM						
			Main Road Network (US$x10⁶)	Secondary Road Network (US$x10⁶)	Bridges (US$x10⁶)	Ports: Building constructions (US$x10⁶)	Ports: Docks (US$x10⁶)	Airports: Building constructions (US$x10⁶)	Airports: Airstrip (US$x10⁶)
Clarendon	26	M	$ 409,0	$ 354,1	$ 46,0	$ 0,2	$ 0,1	$ 0,5	$ 4,9
Hanover	11	L	$ 193,2	$ 73,2	$ 2,7	$ 0,0	$ 0,0	$ 0,0	$ 0,0
Kingston	31	L	$ 0,0	$ 30,7	$ 0,0	$ 113,8	$ 1,8	$ 34,5	$ 11,1
Manchester	27	M	$ 330,3	$ 256,8	$ 2,0	$ 0,0	$ 0,0	$ 1,3	$ 2,1
Portland	33	L	$ 235,6	$ 73,8	$ 13,1	$ 0,7	$ 0,2	$ 0,3	$ 2,9
St. Andrew	34	H	$ 228,4	$ 486,1	$ 63,6	$ 0,0	$ 0,0	$ 0,0	$ 0,0
St. Ann	28	M	$ 331,2	$ 310,6	$ 27,9	$ 5,9	$ 1,0	$ 0,0	$ 0,0

Parish	Paris hID	Complexity (H–High M–Medium L–Low)	TRANSPORTATION SYSTEM						
			Main Road Network	Secondary Road Network	Bridges	Ports: Building constructions	Ports: Docks	Airports: Building constructions	Airports: Airstrip
			(US$x10⁶)	(US$x10⁶)	(US$x10⁶)	(US$x10⁶)	(US$x10⁶)	(US$x10⁶)	(US$x10⁶)
St. Catherine	29	H	$ 342,0	$ 513,4	$ 48,9	$ 5,3	$ 0,8	$ 2,3	$ 2,3
St. Elizabeth	12	L	$ 377,9	$ 405,8	$ 3,8	$ 7,8	$ 0,2	$ 0,0	$ 1,5
St. James	13	M	$ 243,4	$ 263,0	$ 8,3	$ 5,7	$ 0,8	$ 59,5	$ 8,4
St. Mary	30	L	$ 321,4	$ 98,9	$ 12,6	$ 0,0	$ 0,0	$ 1,7	$ 4,0
St. Thomas	32	L	$ 332,7	$ 112,9	$ 8,0	$ 0,0	$ 0,0	$ 0,0	$ 0,0
Trelawny	14	L	$ 238,2	$ 171,6	$ 2,0	$ 2,5	$ 0,4	$ 0,0	$ 0,0
Westmoreland	15	L	$ 282,4	$ 264,4	$ 3,9	$ 3,1	$ 0,2	$ 0,4	$ 1,9
		Total	$ 3.865	$ 3.415	$ 243	$ 145	$ 6	$ 101	$ 39

Table 0-17 Exposure values of energy system

Parish	Parish ID	Complexity (H–High M–Medium L–Low)	ENERGY SYSTEM				
			Electric substations	Transmission and distribution lines	Hydroelectric: Power plants	Hydroelectric: Dams	Renewable Energy
			(US$x10⁶)	(US$x10⁶)	(US$x10⁶)	(US$x10⁶)	(US$x10⁶)
Clarendon	26	M	$ 10,07	$ 2,07	$ 2,22	$ 4,23	$ -
Hanover	11	L	$ 0,75	$ 0,59	$ 0,63	$ 1,20	$ -
Kingston	31	L	$ 1,00	$ 0,90	$ 0,80	$ 1,53	$ -
Manchester	27	M	$ 4,75	$ 1,66	$ 1,71	$ 3,27	$ 87,28

Parish	Parish ID	Complexity (H–High M–Medium L–Low)	ENERGY SYSTEM				
			Electric substations	Transmission and distribution lines	Hydroelectric: Power plants	Hydroelectric: Dams	Renewable Energy
			(US$x10⁶)	(US$x10⁶)	(US$x10⁶)	(US$x10⁶)	(US$x10⁶)
Portland	33	L	$ 0,80	$ 0,71	$ 0,74	$ 1,41	$ -
St. Andrew	34	H	$ 52,86	$ 5,84	$ 5,17	$ 9,86	$ -
St. Ann	28	M	$ 4,37	$ 1,55	$ 1,56	$ 2,97	$ -
St. Catherine	29	H	$ 47,75	$ 4,95	$ 4,71	$ 8,97	$ -
St. Elizabeth	12	L	$ 1,35	$ 1,18	$ 1,36	$ 2,59	$ 55,02
St. James	13	M	$ 4,73	$ 1,72	$ 1,67	$ 3,18	$ -
St. Mary	30	L	$ 1,11	$ 0,98	$ 1,03	$ 1,95	$ -
St. Thomas	32	L	$ 0,92	$ 0,82	$ 0,85	$ 1,62	$ -
Trelawny	14	L	$ 0,71	$ 0,63	$ 0,68	$ 1,30	$ -
Westmoreland	15	L	$ 1,40	$ 1,23	$ 1,31	$ 2,49	$ -

Total	$ 132,56	$ 24,83	$ 24,44	$ 46,56	$ 142,31

Table 0-18 Exposure values of hydrocarbons

Parish	ParishID	Complexity (H–High M–Medium L–Low)	HYDROCARBONS AND OIL DERIVATIVES		
			Refineries	Polyducts	Gas Pipelines
			(US$x10⁶)	(US$x10⁶)	(US$x10⁶)
Clarendon	26	M	$ -	$ 18,92	$ 4,98
Hanover	11	L	$ -	$ 5,37	$ 1,78
Kingston	31	L	$ 774,19	$ 6,85	$ 2,50
Manchester	27	M	$ -	$ 14,62	$ 4,35
Portland	33	L	$ -	$ 6,29	$ 2,02
St. Andrew	34	H	$ -	$ 44,10	$ 16,27
St. Ann	28	M	$ -	$ 13,31	$ 4,06
St. Catherine	29	H	$ -	$ 40,15	$ 14,17
St. Elizabeth	12	L	$ -	$ 11,58	$ 3,06
St. James	13	M	$ -	$ 14,24	$ 5,08
St. Mary	30	L	$ -	$ 8,75	$ 2,74
St. Thomas	32	L	$ -	$ 7,24	$ 2,23
Trelawny	14	L	$ -	$ 5,80	$ 1,67
Westmoreland	15	L	$ -	$ 11,13	$ 3,51
		Total	$ 208,35	$ 774,19	$ 68,42

Table 0-19 Exposure values of communication

Parish	ParishID	Complexity (H–High M–Medium L–Low)	TELECOMMUNICATION	
			Substations	Towers and antennas
			(US$x10⁶)	(US$x10⁶)
Clarendon	26	M	$ 5,37	$ 1,36

Parish	ParishID	Complexity (H–High M–Medium L–Low)	TELECOMMUNICATION	
			Substations	Towers and antennas
			(US$x10⁶)	(US$x10⁶)
Hanover	11	L	$ 0,17	$ 0,41
Kingston	31	L	$ 0,22	$ 0,71
Manchester	27	M	$ 4,14	$ 1,25
Portland	33	L	$ 0,20	$ 0,56
St. Andrew	34	H	$ 35,40	$ 5,43
St. Ann	28	M	$ 3,77	$ 1,06
St. Catherine	29	H	$ 32,22	$ 4,54
St. Elizabeth	12	L	$ 0,36	$ 0,82
St. James	13	M	$ 4,04	$ 1,37
St. Mary	30	L	$ 0,28	$ 0,71
St. Thomas	32	L	$ 0,23	$ 0,71
Trelawny	14	L	$ 0,18	$ 0,47
Westmoreland	15	L	$ 0,35	$ 0,80
		Total	$ 86,93	$ 20,22

Table 0-25 Exposure values of water supply, sanitation and urban pipes

Parish	ParishID	Complexity (H–High M–Medium L–Low)	WATER SUPPLY, SANITATION AND URBAN PIPES SYSTEMS				
			Aqueducts network	Sewage network	Gas networks	Water treatment plants	Wastewater treatment plants
			(US$x10⁶)	(US$x10⁶)	(US$x10⁶)	(US$x10⁶)	(US$x10⁶)
Clarendon	26	M	$ 18,31	$ 1,43	$ 1,51	$ 3,57	$ 2,45

Parish	ParishID	Complexity (H–High M–Medium L–Low)	WATER SUPPLY, SANITATION AND URBAN PIPES SYSTEMS				
			Aqueducts network (US$x10⁶)	Sewage network (US$x10⁶)	Gas networks (US$x10⁶)	Water treatment plants (US$x10⁶)	Wastewater treatment plants (US$x10⁶)
Hanover	11	L	$ 6,12	$ 0,13	$ 0,20	$ 0,96	$ 0,65
Kingston	31	L	$ 2,88	$ 1,28	$ 0,25	$ 0,05	$ 0,41
Manchester	27	M	$ 12,99	$ 0,01	$ 1,17	$ 2,99	$ 0,16
Portland	33	L	$ 5,24	$ 0,08	$ 0,23	$ 1,12	$ 0,16
St. Andrew	34	H	$ 62,35	$ 13,27	$ 9,18	$ 15,81	$ 15,53
St. Ann	28	M	$ 13,20	$ 0,82	$ 1,06	$ 4,05	$ 1,80
St. Catherine	29	H	$ 56,70	$ 12,00	$ 8,36	$ 12,20	$ 24,92
St. Elizabeth	12	L	$ 12,41	$ 0,02	$ 0,42	$ 1,22	$ 0,25
St. James	13	M	$ 18,74	$ 2,03	$ 1,14	$ 5,05	$ 4,09
St. Mary	30	L	$ 7,94	$ 0,13	$ 0,32	$ 1,27	$ 0,33
St. Thomas	32	L	$ 5,88	$ 0,20	$ 0,26	$ 1,32	$ 0,41
Trelawny	14	L	$ 5,94	$ 0,04	$ 0,21	$ 1,10	$ 0,08

Parish	ParishID	Complexity (H–High M–Medium L–Low)	WATER SUPPLY, SANITATION AND URBAN PIPES SYSTEMS				
			Aqueducts network (US$x10⁶)	Sewage network (US$x10⁶)	Gas networks (US$x10⁶)	Water treatment plants (US$x10⁶)	Wastewater treatment plants (US$x10⁶)
Westmoreland	15	L	$ 7,89	$ 0,96	$ 0,41	$ 0,76	$ 1,14
		Total	$ 236,60	$ 32,42	$ 24,72	$ 51,47	$ 52,38

1.7 KMA BUILDING CONSTRUCTION EXPOSURE MODEL

1.7.1 General methodology

For the flood risk assessment, a more detailed exposure model was developed for the Kingston Metropolitan Area (KMA). The model contains information about building construction typologies, number of stories, built area and replacement values. The methodological approach to conform the database is similar as the one presented in section 2.2. As mentioned before, commercial reference values were obtained using real state agencies such as *Coldwell Banker* and *Century 21*. The replacement values indicated correspond to the direct costs associated with a possible reconstruction of the same built area including structural and non-structural components. These values do not include the building contents, the land value or factors such as market forces or macroeconomic shocks. The information available in the indicated references include commercial prices for residential, commercial, office and industrial assets. These web sites are useful to determine geo-localization of buildings and characterize districts. The construction types reported, and the reference home page are presented in **Error! Reference source not found.** and Figure 17.

Table 0-21 Construction types available in real state

Residential	Commercial, Offices & Industrial
Apartment	Commercial Buildings & Offices
House	Commercial Lot
Residential Lot	Commercial Spaces/Offices

Rental Space	Industrial
Studio Apt.	Hotel

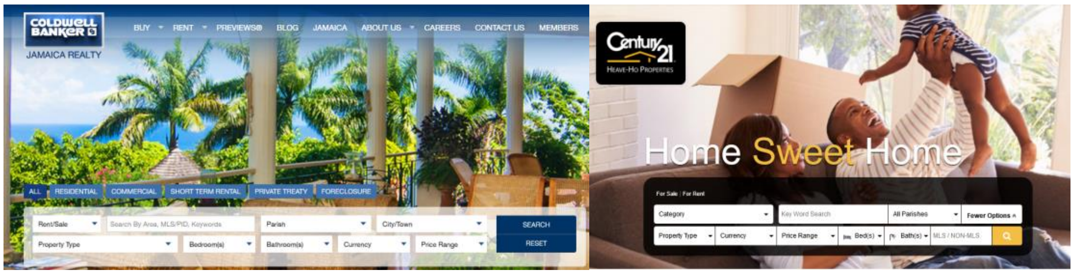


Figure 17 Real estate on-line home page

For the purposes of building the exposure model, the KMA is divided into districts, as recognized by the Statistical Institute of Jamaica (STATIN). The distribution of KMA districts and the complete list of them are presented in Figure 18 and

Table 0-22. The total number of districts in the KMA region is 112.

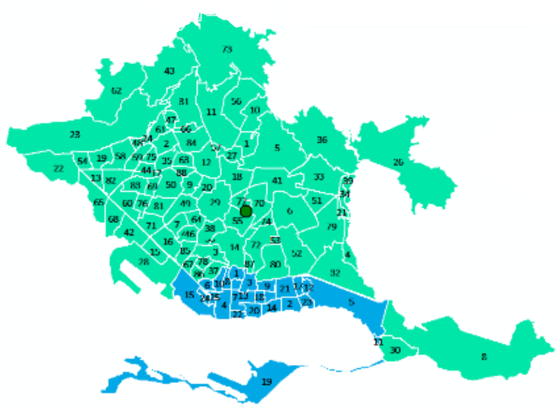


Figure 18 Kinston Metropolitan Area (KMA)

Table 0-22 Kingston Metropolitan Area districts

Ref	Districts						
1	Acadia	29	Half-Way-Tree	57	Oaklands	85	Whitfield Town
2	Arlene Gardens	30	Harbour View	58	Patrick City	86	Wilton Gardens/Rema

3	Arnett Gardens	31	Havendale	59	Pembroke Hall	87	Woodford Park
4	August Town	32	Hermitage	60	Penwood	88	Zaidie Gardens
5	Barbican	33	Hope Pastures/Utech	61	Queensborough/Tunbridge	89	Allman Town
6	Beverley Hills	34	Hope Tavern	62	Red Hills/Sterling Castle	90	Bournemouth Gardens
7	Boucher Park	35	Hughenden	63	Red Hills Gardens	91	Campbell Town
8	Bull Bay/Seven Mile	36	Jacks Hill	64	Richmond Park	92	Central Down Town
9	Cassia Park	37	Jones Town	65	Riverton City	93	D'aguilar Town/Rennock Lodge
10	Cherry Gardens	38	Kencot	66	Roehampton	94	Denham Town
11	Constant Spring	39	Kintyre	67	Rose Town	95	East Down Town
12	Constant Spring Gardens	40	Lawrence Tavern	68	Seaview Gardens	96	Fletchers Land
13	Cooreville Gardens	41	Liguanea	69	Seaward Pen	97	Franklyn Town
14	Cross Roads	42	Majestic Gardens	70	Seymour Land	98	Hannah Town/Craig Town
15	Delacree Park/Union Gardens	43	Manning’s Hill	71	Cockburn Gardens/Seivwright Gardens	99	Johnson Town
16	Delacree Pen	44	Marverley	72	Stadium Gardens	100	Kingston Gardens
17	Drews Land	45	Mavis Bank	73	Stony Hill	101	Manley Meadows
18	Drumblair	46	Maxfield Park	74	Swallowfield	102	Newport East
19	Duhaney Park	47	Meadowbrook	75	Three Oaks/Glendale	103	Newton Square
20	Eastwood Park Gardens	48	Meadowbrook Estate	76	Tower Hill	104	Norman Gardens
21	Elletson Flats/Mona Commons	49	Molyne’s/Four Roads	77	Trafalgar Park	105	Passmore Town

22	Ferry	50	Molyne's Gardens	78	Trench Town	106	Port Royal
23	Forest Hills/Plantation Heights	51	Mona Heights	79	University	107	Rae Town
24	Forest Hills Gardens	52	Mountain View Gardens	80	Vineyard Town	108	Rollington Town
25	Golden Spring	53	Nannyville	81	Waltham Gardens	109	South Side
26	Gordon Town	54	New Haven	82	Washington Gardens	110	Springfield
27	Grants Pen	55	New Kingston	83	Waterhouse	111	Tivoli Gardens
28	Greenwich Town/Newport West	56	Norbrook	84	Whitehall	112	West Down Town

The general methodology to conform the KMA exposure database is illustrated in Figure 19.

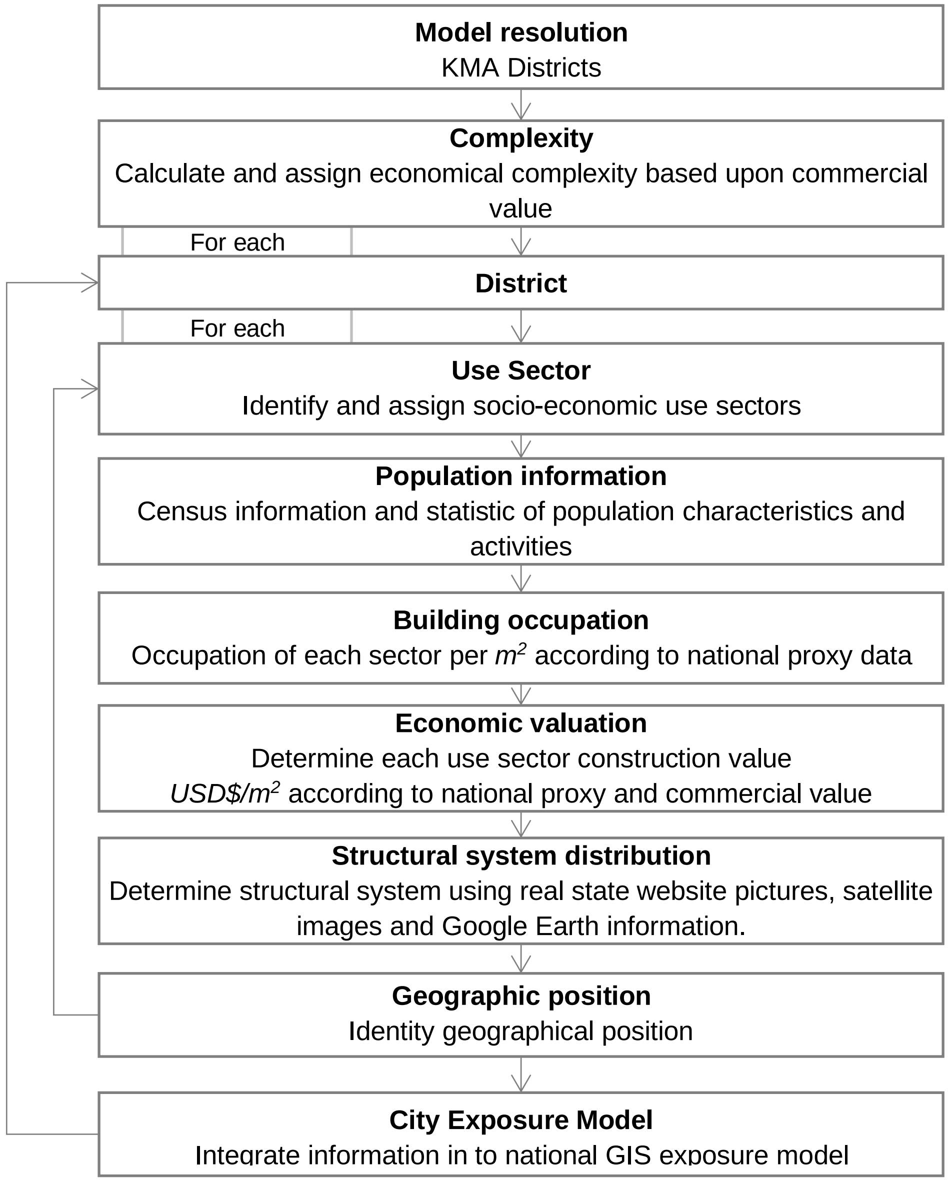


Figure 19 KMA exposure model methodology

1.7.2 Use sectors

The main use sectors with available commercial values within the KMA are residential (houses and apartments), commercial (retail, supermarkets, malls, restaurants, etc.), offices and Industrial. The representative location of buildings with commercially reported values for the model are indicated in Figure 20.

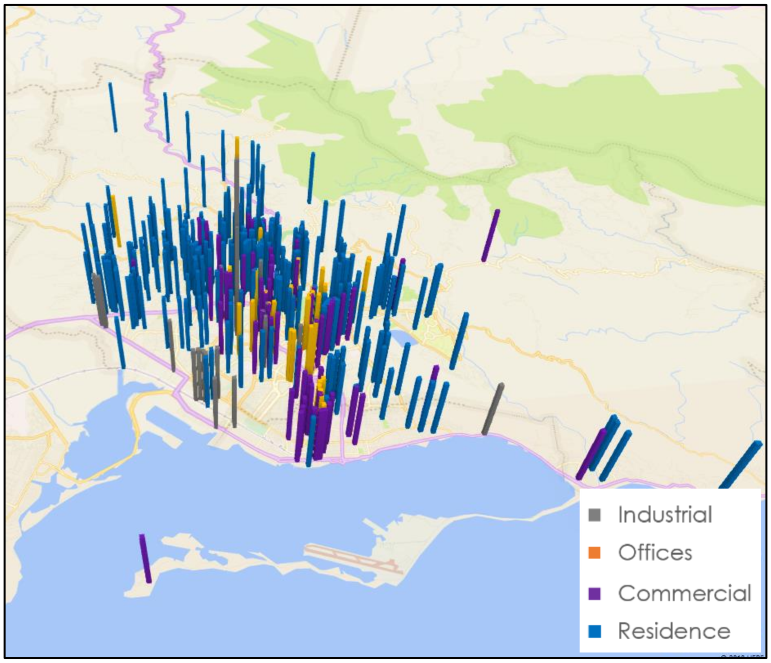


Figure 20 Kingston Residential, commercial, office and industrial sectors

Considering the lack of available public information, sectors such as education, health and administrative had to be identified individually. Using GIS georeferenced information, private and public schools from all districts were identified. Using basic interpretation of representative pictures, the proportion of predominant building construction typologies, the number of stories and the construction quality was assigned for each one of the use sectors at the district level. A similar procedure was applied to health centers (hospital, clinics and health institutions) both for public and private buildings and for administrative and institutional buildings. Figure 21 presents the identification of a typical school building by means of available public pictures. In addition, Figure 22 presents representative locations of buildings in the administrative, health and educational sector in the KMA region.

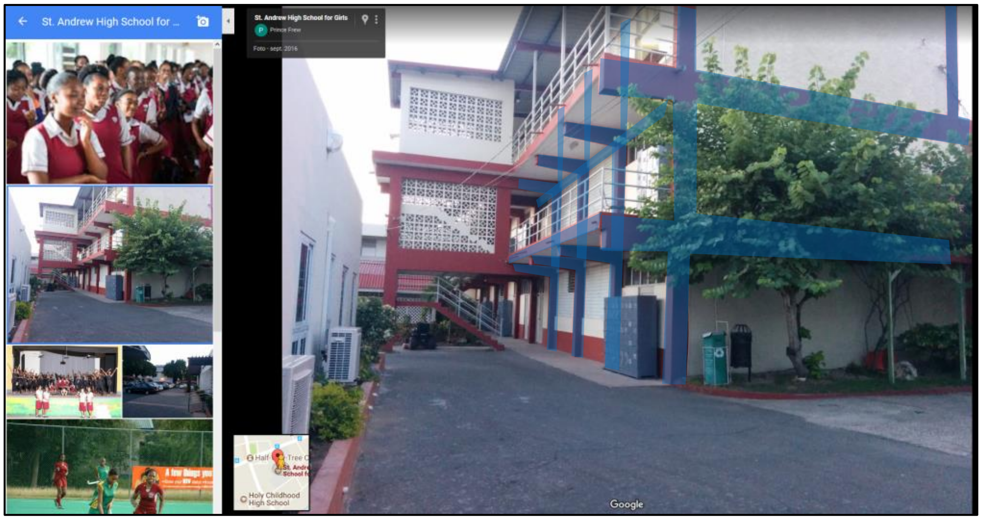


Figure 21 School example. St. Andrew High School

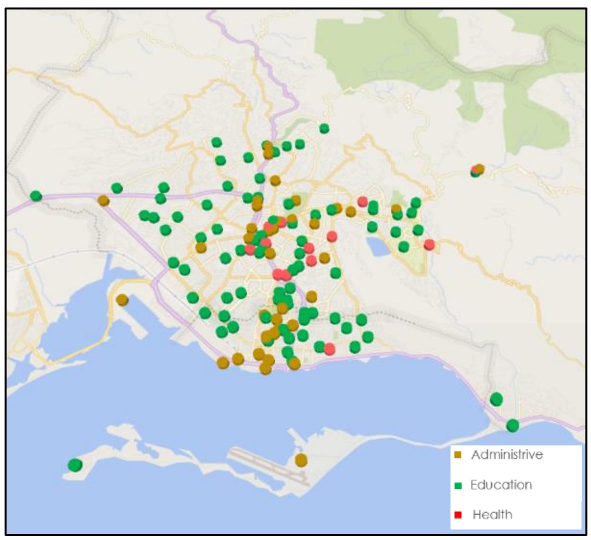


Figure 22 KMA administrative, health and educational sector

1.7.3 Districts complexity

As in the exposure models presented previously, a complexity index was used to assign information related to the kind of infrastructure and its characteristics that may be found in each district. The index is useful to characterize structural systems distribution and construction values. The complexity index was determined using the observed construction quality (materials, structure visual quality, size, etc.) and the commercial prices of each district and use sector. Higher complexities could be found in central Kingston where

important financial and commercial centers are located, as well as in south-west where important industrial warehouses, factories and some periphery houses with high quality can be found. Some medium complexities could be found in historic Kingston center-west areas. Most low complexity are found in south, south-west and west Kingston. Figure 23 illustrates the location of Districts of different complexities.

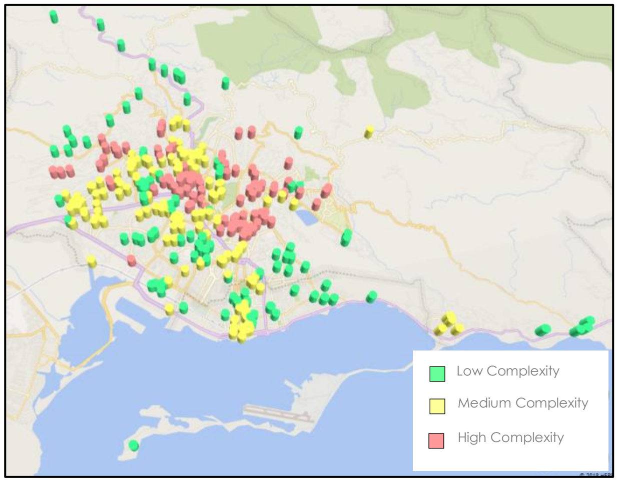


Figure 23 Kingston complexities

1.7.4 Occupation model

Using statistical information, labor force and population activities, an occupation model was detailed for the KMA region. The methodology used was the same as the one mentioned in section 1.5.5. Daytime and nighttime scenarios are shown in Table 0-23 and Figure 24.

Table 0-23 Occupation scenarios for the KMA region

Day occupation scenario										
Parish	**Population**	**High Residence**	**Medium Residence**	**Low Residence**	**Commercial**	**Offices**	**Industrial**	**Health**	**Education**	**Admin.**
KMA	602 066	45 009	137 105	137 392	156 740	57 156	24 199	1 447	155 608	37 335
Night occupation scenario										
Parish	**Population**	**High Residence**	**Medium Residence**	**Low Residence**	**Commercial**	**Offices**	**Industrial**	**Health**	**Education**	**Admin.**
KMA	602 066	100 021	304 678	305 315	58 777	21 434	13 444	1 447	-	-

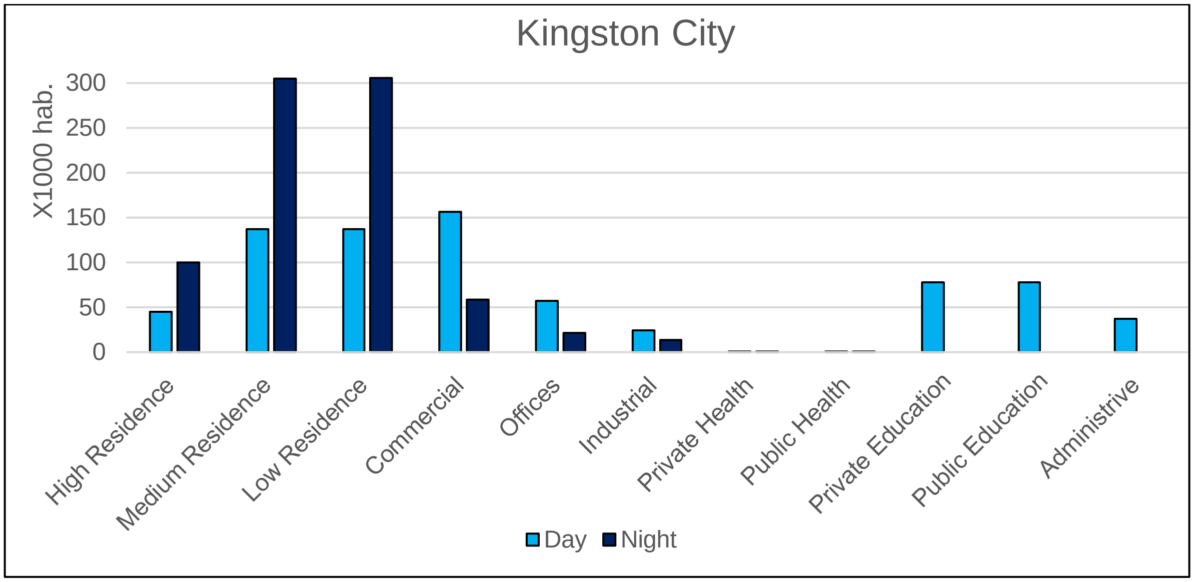


Figure 24 Day and night occupation scenarios for the KMA region

1.7.5 Economic valuation

KMA as part of the parishes of Kingston and St. Andrew has construction prices similarly to a high complexity parish (see Table 0-24). Using this information as well as available local commercial prices, it is possible to determine the variations in replacement values at district level. Illustrative variations in prices per square meter for the KMA region are presented in Figure 25.

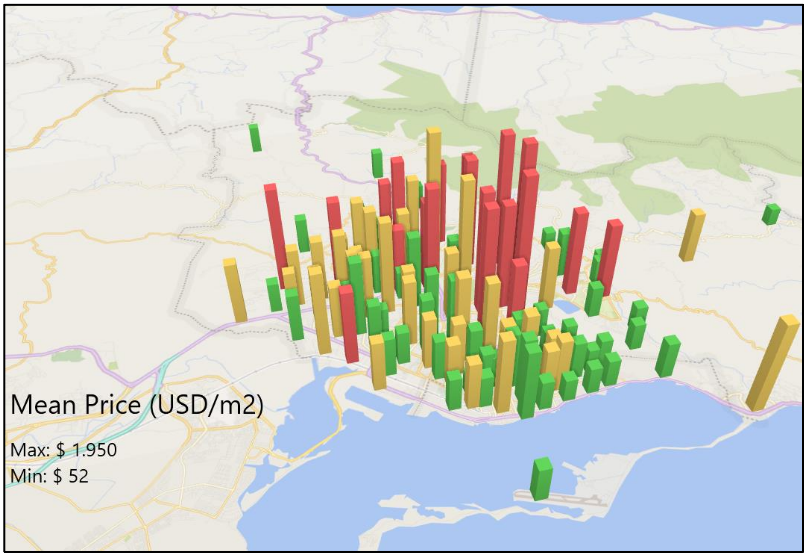


Figure 25 Price per square meter in KMA

The level of complexity, as explained before, depends partially in the level of prices usually found in each district. The most expensive building prices per square meter are found in high complexity districts. Table 0-24 illustrates representative commercial prices for the different use sectors and for different levels of complexity.

Table 0-24 Representative commercial prices per sector

USD/m^2	High	Medium	Low
High Residence	$2045	$1430	$1023
Medium Residence	$1473	$1025	$ 868
Low Residence	$ 638	$ 575	$ 403
Commercial	$ 780	$ 355	$ 254
Offices	$ 842	$ 589	$ 422
Industrial	$ 718	$ 503	$ 360
Private Health	$1200	$ 760	$ 514
Public Health	$ 840	$ 580	$ 420
Private Education	$ 420	$ 380	$ 320
Public Education	$ 360	$ 320	$ 272
Administrative	$ 536	$ 375	$ 268

Using the methodology explained in section 1.5.10 and the commercial prices reported, it is possible to estimate the construction replacement values, using equivalent indexed ratios between the two figures. As before, the replacement values correspond to the estimated direct reconstruction costs of the equivalent built area including structural and non-structural components. They do not include the building contents, the land value or factors such as market forces or macroeconomic shocks. Figure 26, Figure 27 and Figure 28 summarize information of replacement values by square meter by sector and different structural typologies for high, medium and low complexity respectively. Once unit replacement values are estimated, using the relative distribution of use sectors and their estimated built areas,

exposed values are totaled for each district. The final exposure values per district are presented in Figure 29.

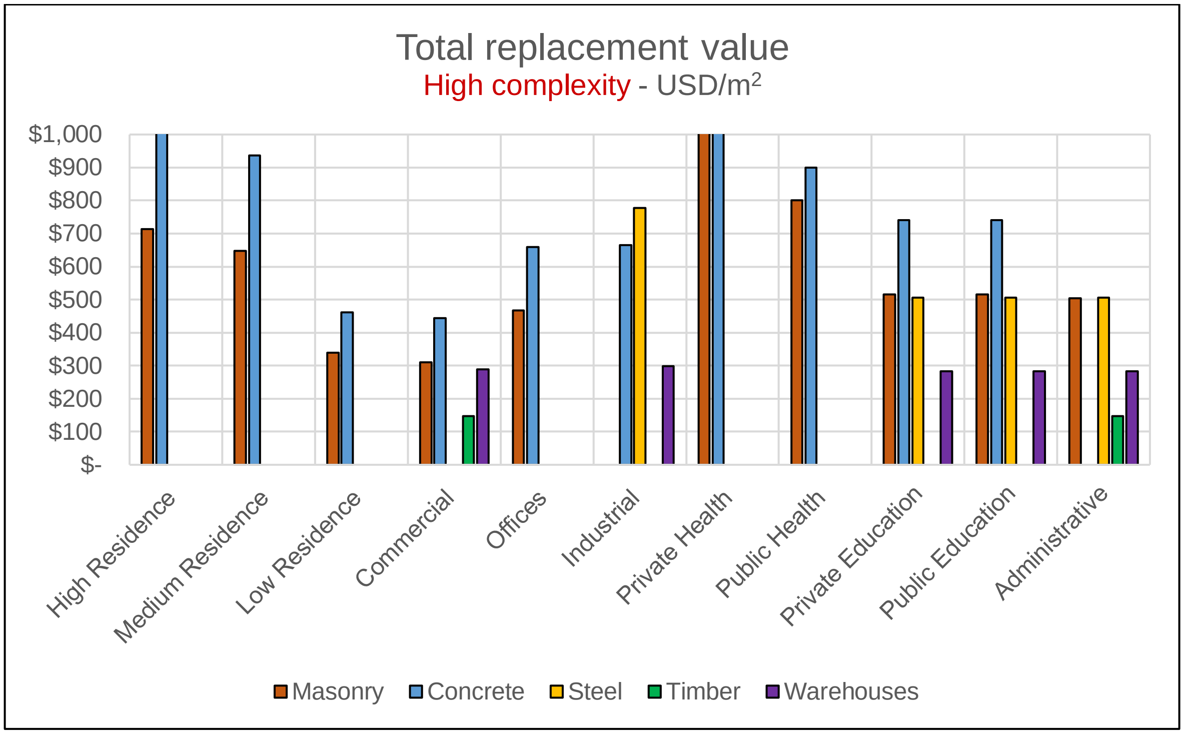


Figure 26 Replacement values of high complexity

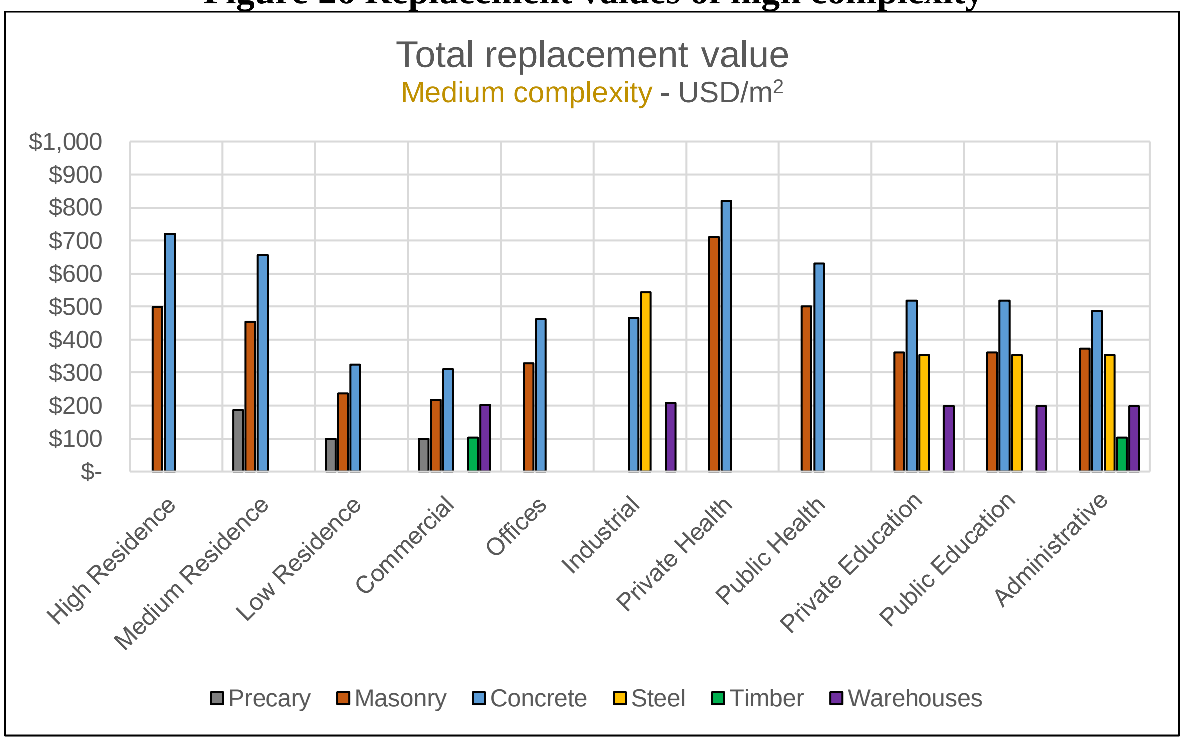


Figure 27 Replacement values of medium complexity

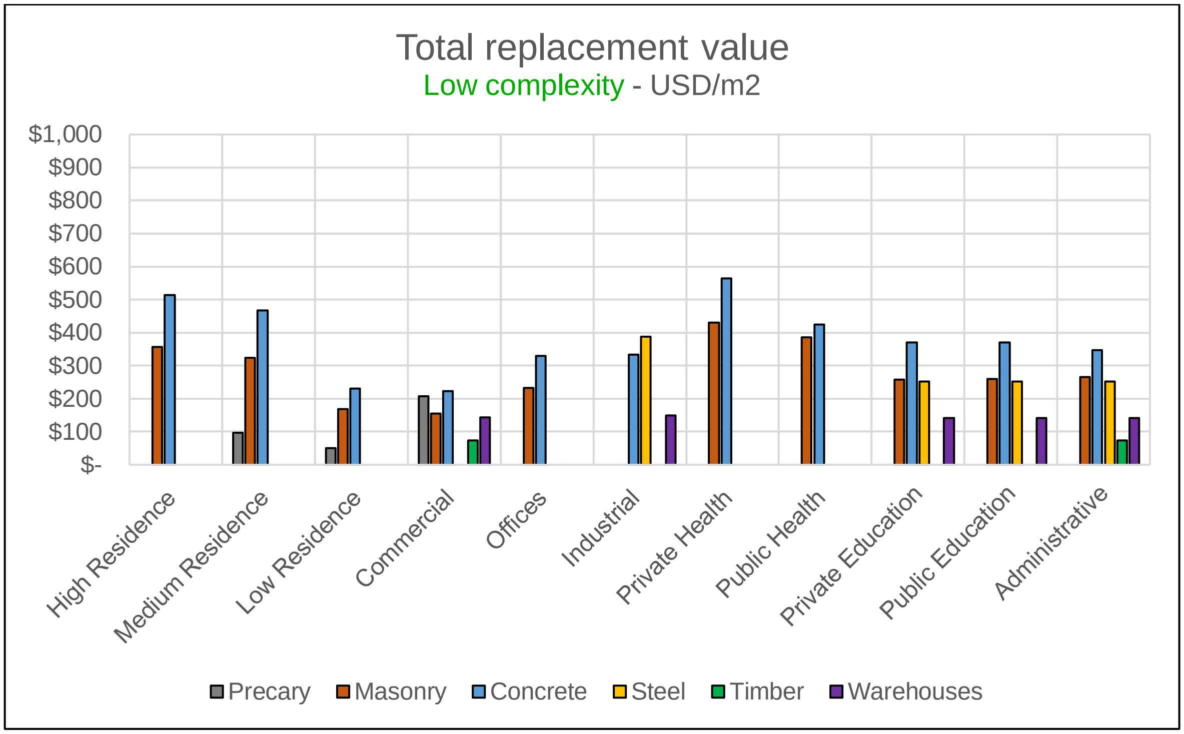


Figure 28 Replacement values of low complexity

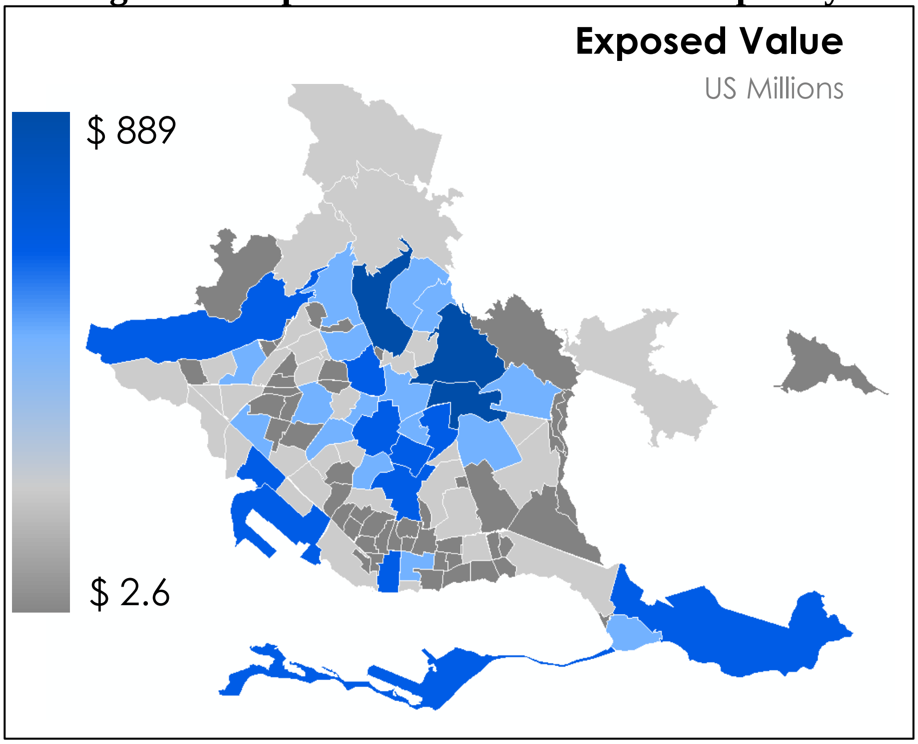


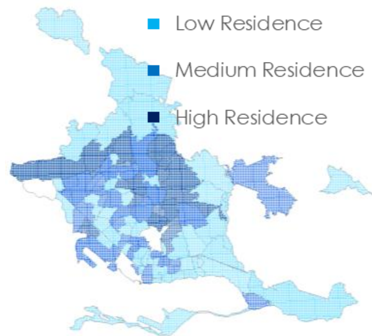
Figure 29 KMA Exposed Value

1.7.6 Geographical distribution of exposed values and typologies

The proposed KMA exposure model, with a minimum resolution of district at the urban level, includes replacement values by use sectors and building construction types. For the geographical distribution of the exposed assets, a uniform grid with distances of 40 m was adopted. A GIS shape represents the exposure model of KMA. The information for a single dot contains all the district representative information such structural typologies, complexity, stories, built area and replacement value.

Table 0-25 presents illustrative geographical distribution of assets for the different use sectors in the KMA (colored districts have a predominant existence of use sectors those that are not colored have few or none of them).

Table 0-25 Predominant districts use sectors

<table>
<tr><th colspan="3">Residential</th></tr>
<tr><td colspan="3">
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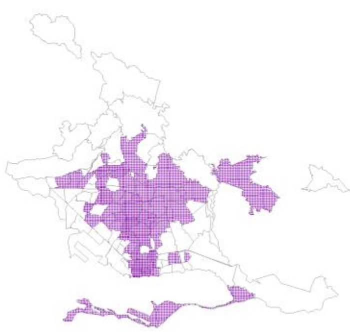
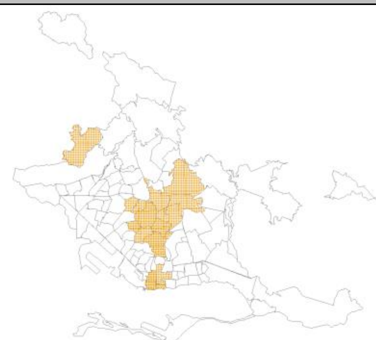
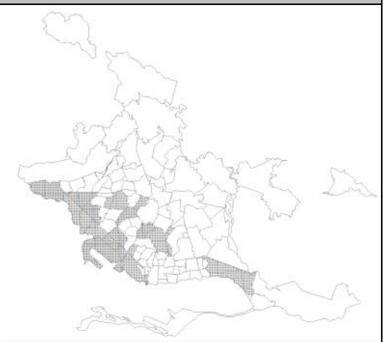
<tr><td></td><td></td><td></td></tr>
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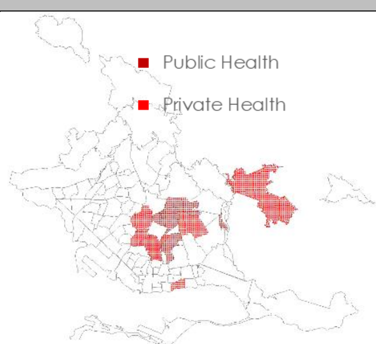
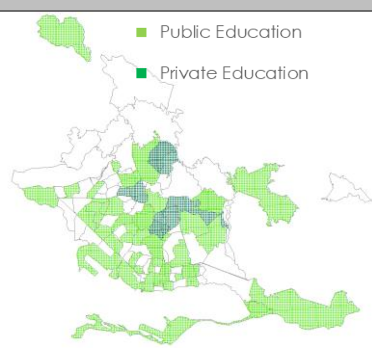
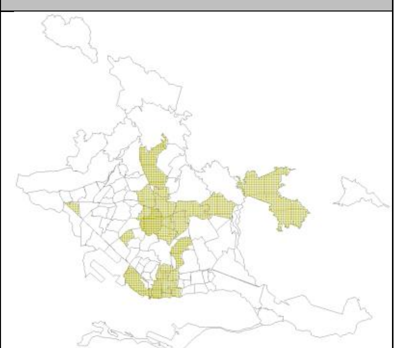
<tr><td>
</td><td>
</td><td></td></tr>
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CHAPTER

3

HURRICANE WIND HAZARD AND RISK

2.1 HURRICANE WIND HAZARD

2.1.1 General Aspects

Despite the high relative frequency of hurricane occurrences in the Caribbean region, for any specific island in the zone (i.e., Jamaica) the frequency of catastrophic events remains relatively low. Therefore, the hurricane risk assessment shall be approached using probabilistic models that consider the frequency of occurrence of different intensity level events taking into consideration in addition the high uncertainties involved in the analysis.

A comprehensive hurricane wind risk assessment shall include a probabilistic hazard model, the exposure representation and the corresponding vulnerability assessment of the predominant construction typologies. For risk assessment purposes, the hazard is usually represented by a set of mutually exclusive and collectively exhaustive stochastic events each one representing a potential hurricane occurring in the influence area and characterized by an intensity distribution and an annual frequency of occurrence. The model parameters are calibrated using the available historical records. The most common intensity measures used to represent the hurricane hazard are the maximum wind speed, the maximum precipitation intensity and the maximum height of waves generated by the storm surge along the coastline. In accordance with this, different vulnerability functions shall be developed for the representative building construction typologies and for each intensity measure. These functions will estimate the expected damage for different intensity parameters, i.e. the maximum wind speed at the location of each infrastructure component.

The CAPRA platform used in this study can estimate the effects of the three main effects of the hurricanes, namely the wind speed, the precipitation and the storm surge, occurring independently or simultaneously. The present study focuses mainly on the hurricane wind

impact over the exposed elements. However, the hazard model built to estimate the wind speed is the same as the one required for the precipitation or the storm surge. Little additional effort would be required to complete the hurricane hazard model considering the three main effects mentioned. An example of this is the flood risk assessment for the KMA region, originated in hurricane induced precipitation, which is presented in Chapter 6.

For the hurricane wind model, the intensity measure corresponds to the maximum wind speed field in the area under analysis, considering the variation of the hurricane eye location and the corresponding intensity at each location. In this way a collection of maximum wind speed fields is calculated together with a measure of its uncertainty, one for each stochastic scenario with their corresponding annual frequency of occurrence. The collection of all maximum wind speed fields are stored in a file with extension ".AME".

The probabilistic wind hazard can be commonly represented in the following ways:

- The complete collection of maximum wind speed fields, each one for each specific stochastic scenario.
- The maximum wind speed exceedance rate curve at each geographical location in the study area.
- The probabilistic maximum wind speed map for different return periods of analysis.
- The maximum wind speed distribution in the study area for particular catastrophic scenarios.

A hurricane wind hazard model was developed nationwide for the purposes of this assignment. The evaluation was made using the Hurricane Wind Hazard Model of the CAPRA platform: ERN-Hurricane Version 1.0 (https://ecapra.org/topics/ern-hurricane). The main sources of information for this analysis are the following:

- National Spatial Data Management Division of Jamaica.
- Forestry Department of Jamaica.
- Meteorological Service of Jamaica.
- National Hurricane Center of the United States

2.1.2 Information for the hazard model

First, all information about historic hurricane tracks has been revised and complemented. Figure 30 illustrates all hurricanes in the period range from 1851 – 2017 including tropical depressions and tropical storms.

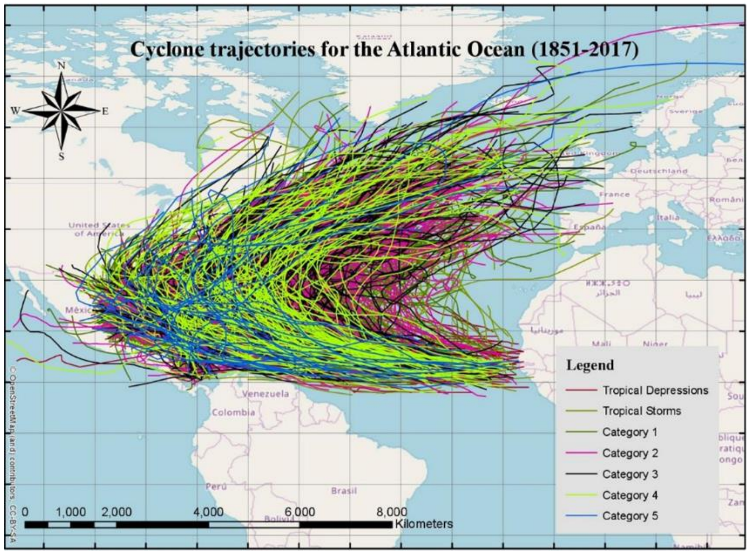
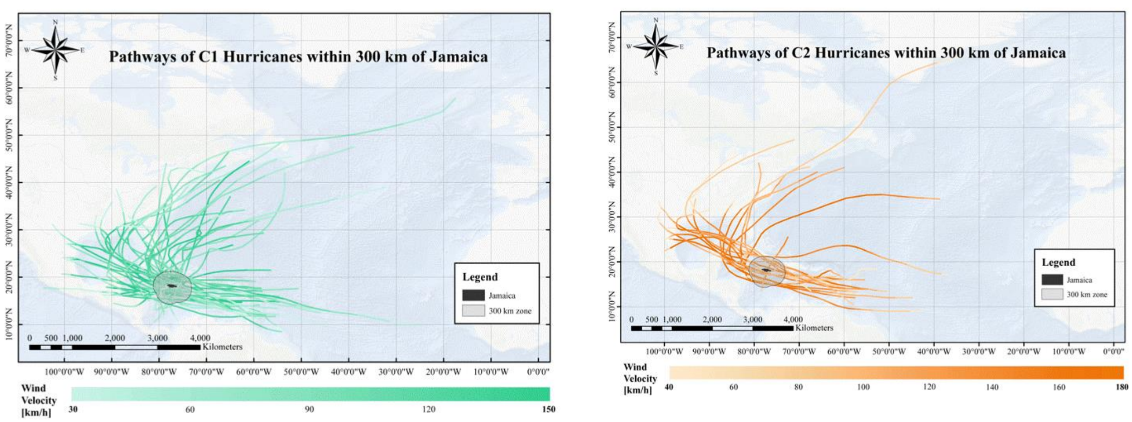


Figure 30 Hurricanes and storms recorded in the Atlantic Basin from 1851 – 2017

In Figure 31 hurricanes are aggregated and grouped by category. Only hurricanes where the eye passed within 300 km of the Jamaican coastline are considered in this classification.



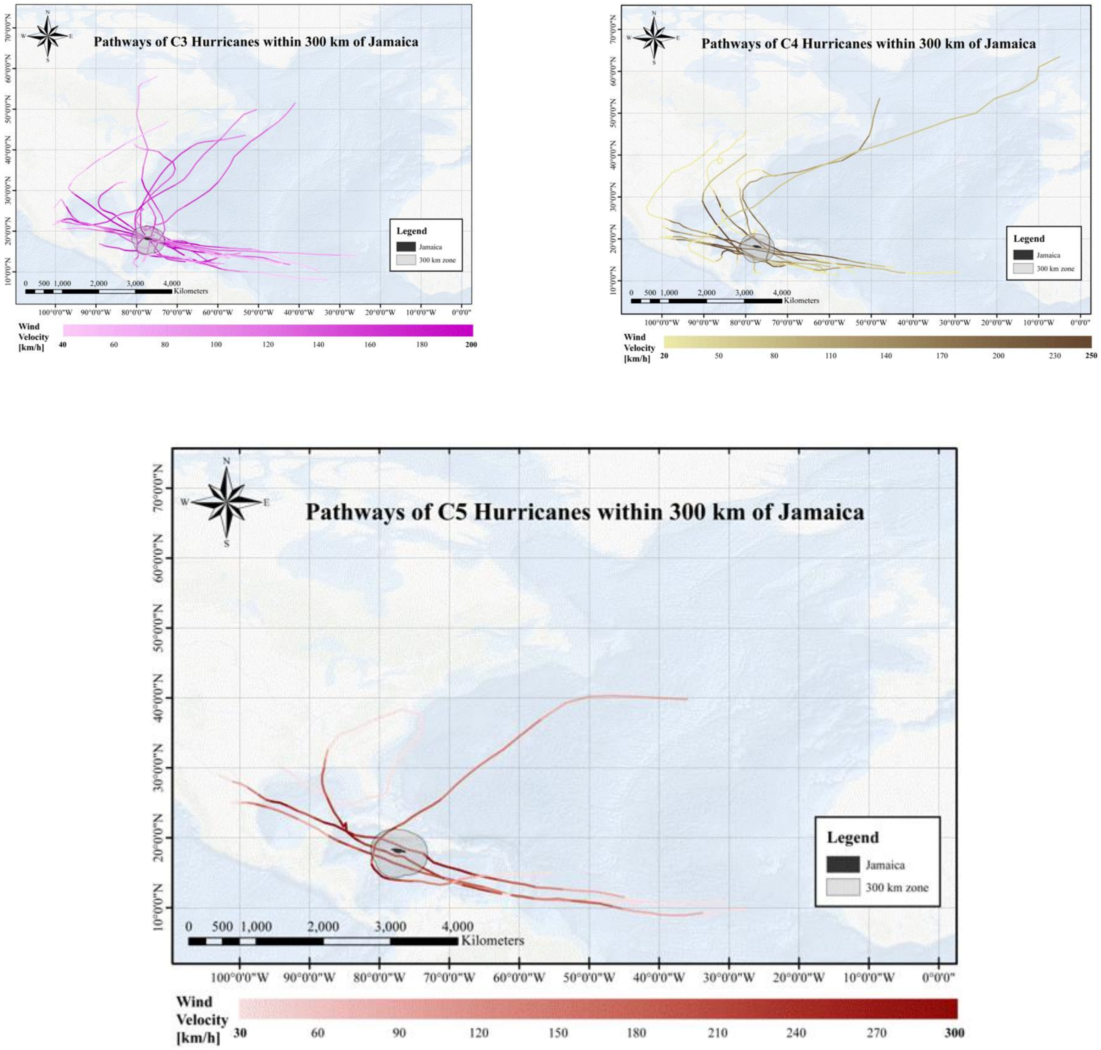


Figure 31 Hurricanes and storms recorded in the Atlantic Basin from 1851 – 2017near Jamaica

Other information includes a digital elevation model, the wind exposure factors, the land use and the roughness factors (see Figure 32).

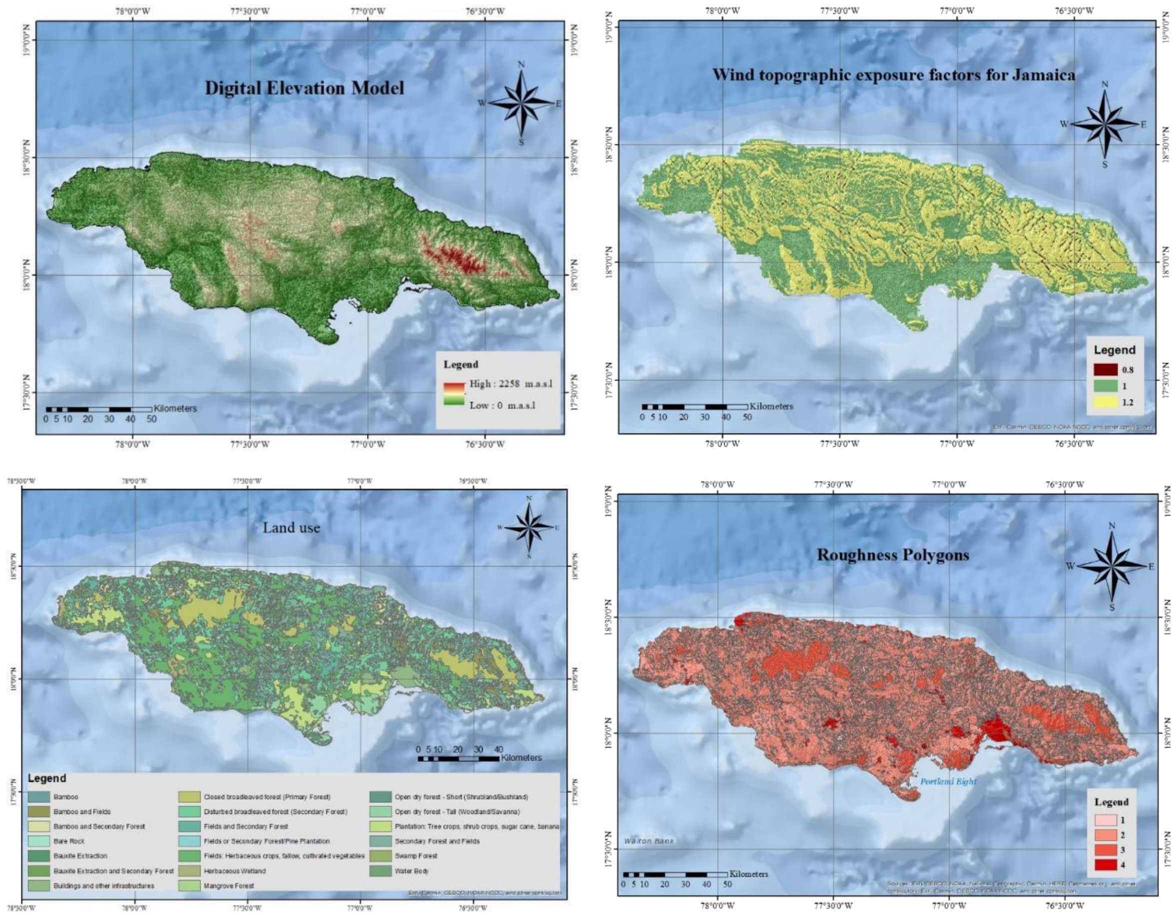


Figure 32 Information for the wind hazard model

2.1.3 Wind hazard stochastic events

The hurricane wind hazard can be represented by means of a series of stochastic events that adequately represent the effects of any possible hurricane in the area of influence. Each event is defined by the eye trajectory and a distribution of wind pressure along it. The set of scenarios generated must adequately represent all the possible combinations of trajectories and categories considering the historical hurricane paths in the influence zone. From each historic hurricane in the area, a series of simulated events are considered to modify possible trajectories and variations in intensity. A “random-walk” simulation strategy is used to generate virtual hurricanes from each historic one. The annual frequency of occurrence of each family of hurricanes is consistent with the historic records.

For the case of Jamaica, a total of 91 historical hurricane scenarios was selected to perform the hazard assessment. These 91 hurricanes correspond to a depurated catalog of hurricanes

of the Atlantic Basin from 1851 to 2017. The selection criteria is based on hurricanes with magnitude higher than or equal to one in the Saffir-Simpson scale in a radius of 300 km around the island. Figure 33 presents the total number of hurricanes in the Atlantic Ocean and Figure 34 the ones used for the analysis per category. The hurricanes that do not meet these criteria, probably wouldn´t have a significant damage potential to affect the local infrastructure.

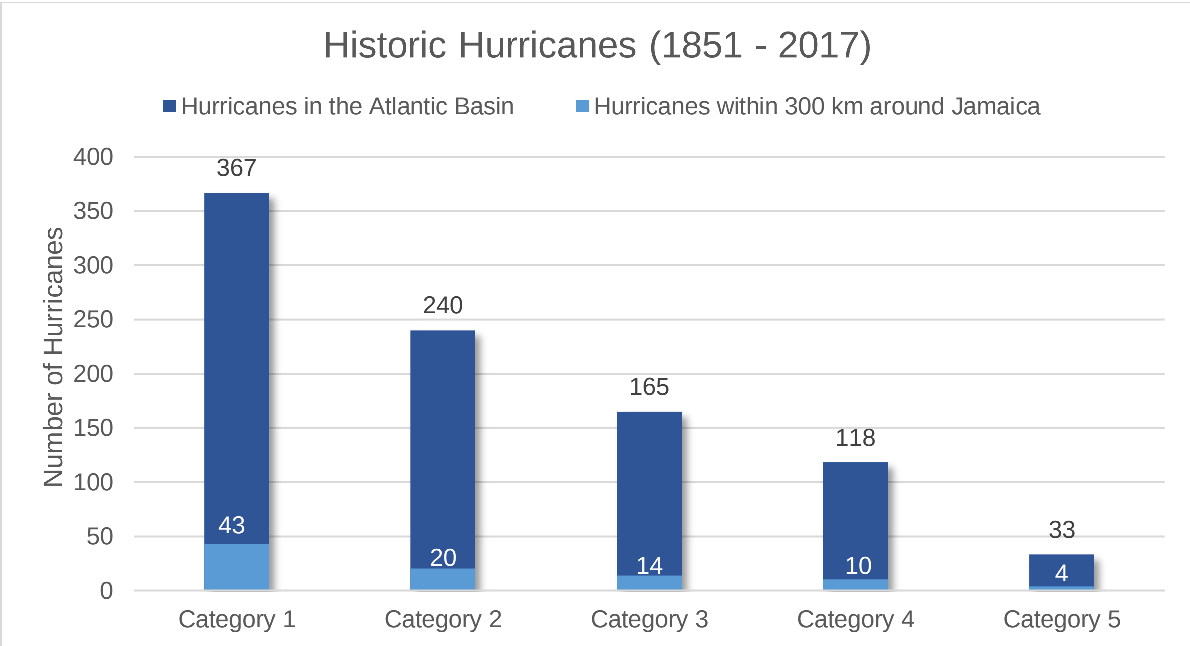
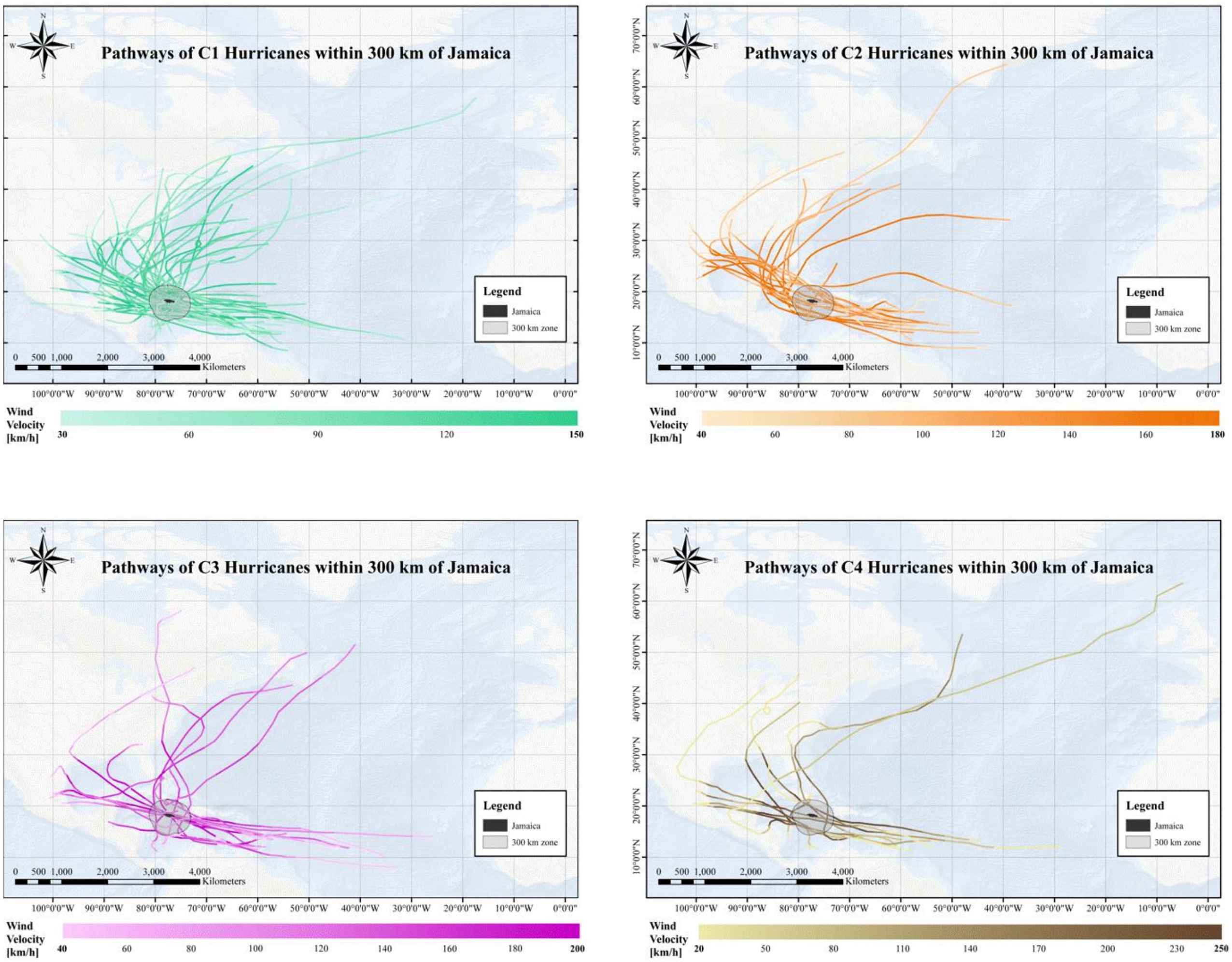


Figure 33 Number of hurricanes per category in the Atlantic Basin and in the depurated catalog for Jamaica

For each historical hurricane selected previously, 100 simulations were performed by means of a random-walk technique with the aim of producing a significant number of feasible tracks and distribution of intensities that could eventually affect the island. A total of 9,100 hurricane events were modeled. Figure 35 and Figure 36 show examples of the group of simulated events generated from particular historic events, whose eye trajectories are presented in red. As mentioned before, the maximum wind field for each hurricane is calculated by taking into account general factors such as the central pressure, the distance from the eye, the local topography and the land use distribution in the area of interest among others. Figure 37 presents an example of the maximum wind field calculated in the model for

hurricane Sandy which occurred in 2012 and Figure 38 for hurricane Dean occurred in 2007. As shown in the figures, the inland distribution of intensities considers the particular local effects in Jamaica.



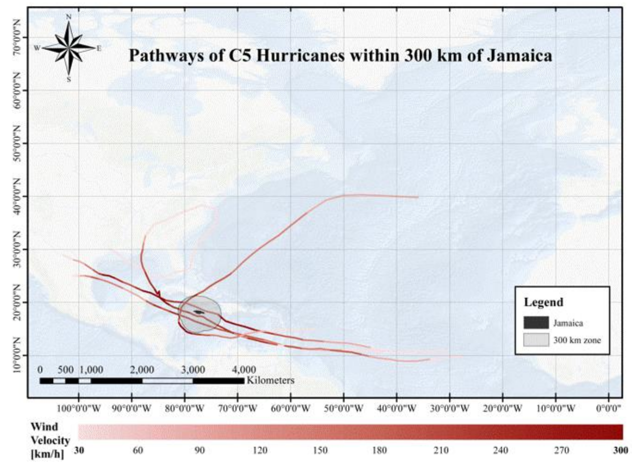


Figure 34 Pathways of hurricanes per category in the depurated catalog for Jamaica

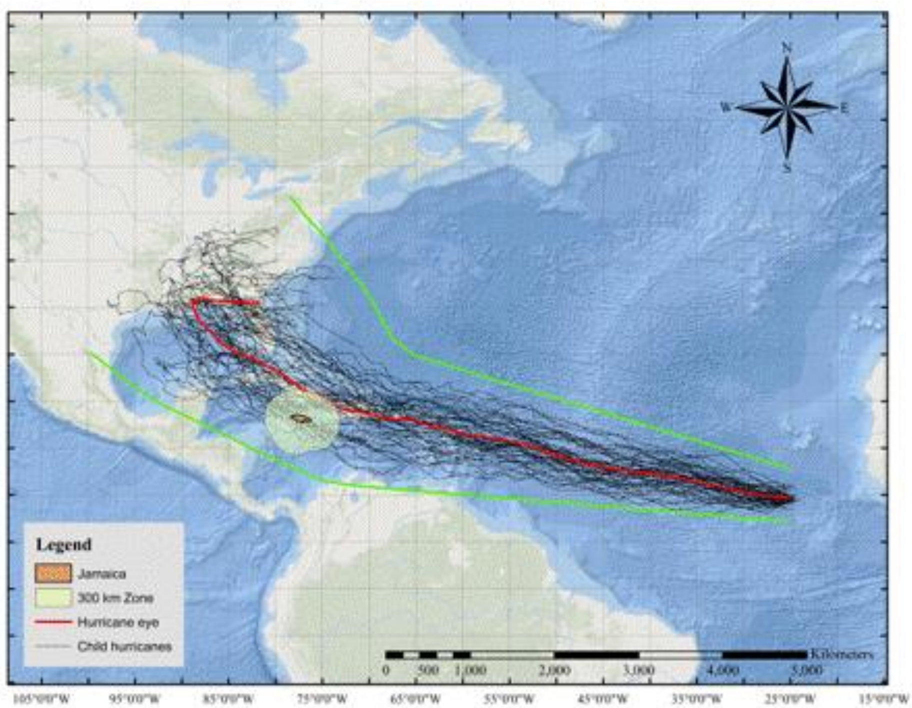


Figure 35 Simulated hurricane tracks for an historic event – Example 1

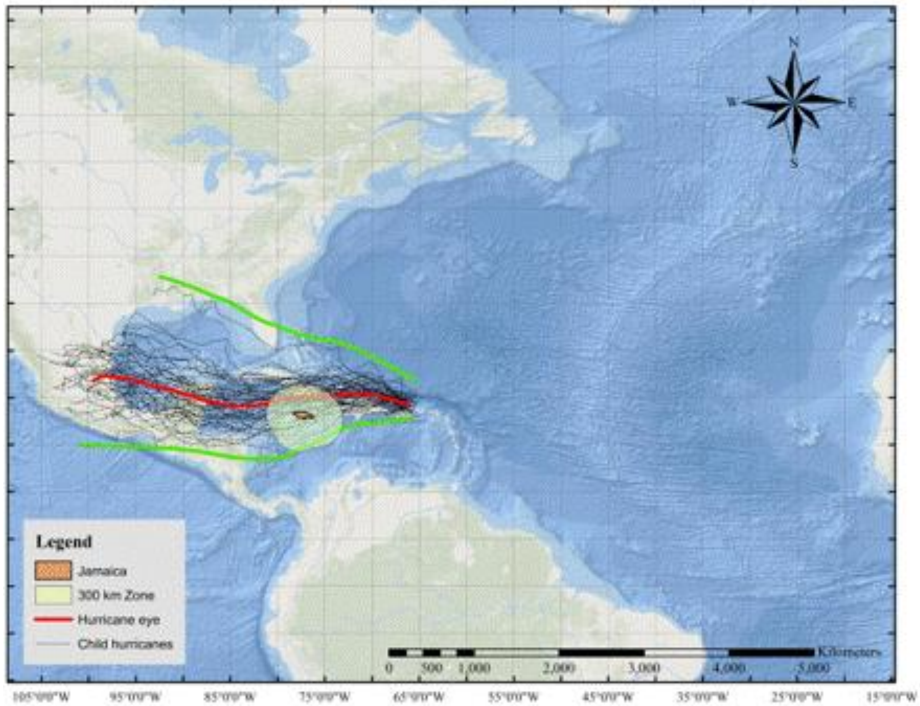


Figure 36 Simulated hurricane tracks for an historic event – Example 2

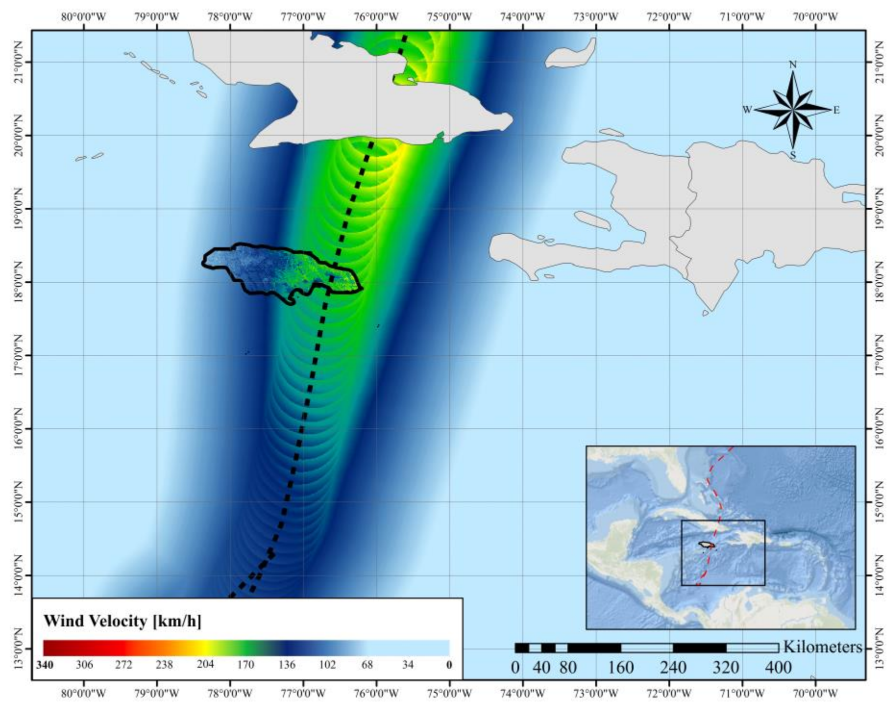


Figure 37 Maximum wind field for hurricane Sandy

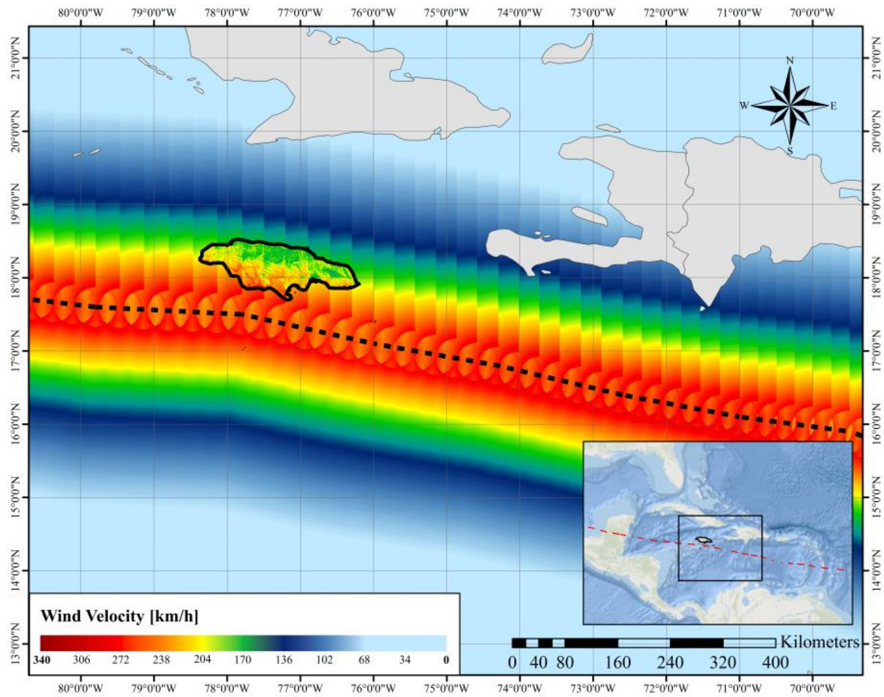


Figure 38 Maximum wind field for hurricane Dean

2.1.4 Probabilistic wind hazard maps nationwide

The probabilistic wind hazard maps at the national level are calculated by the integration of all stochastic scenarios generated. At each geographical location, the probability of exceedance of different intensities are calculated, integrating the maximum wind fields of the 9,100 stochastic events. Then selecting a particular annual exceedance probability (whose inverse is the return period) the corresponding intensities at all locations are evaluated in order to generate the probabilistic representation of intensities. Figure 39 shows the maximum hurricane wind velocity maps for different return periods.

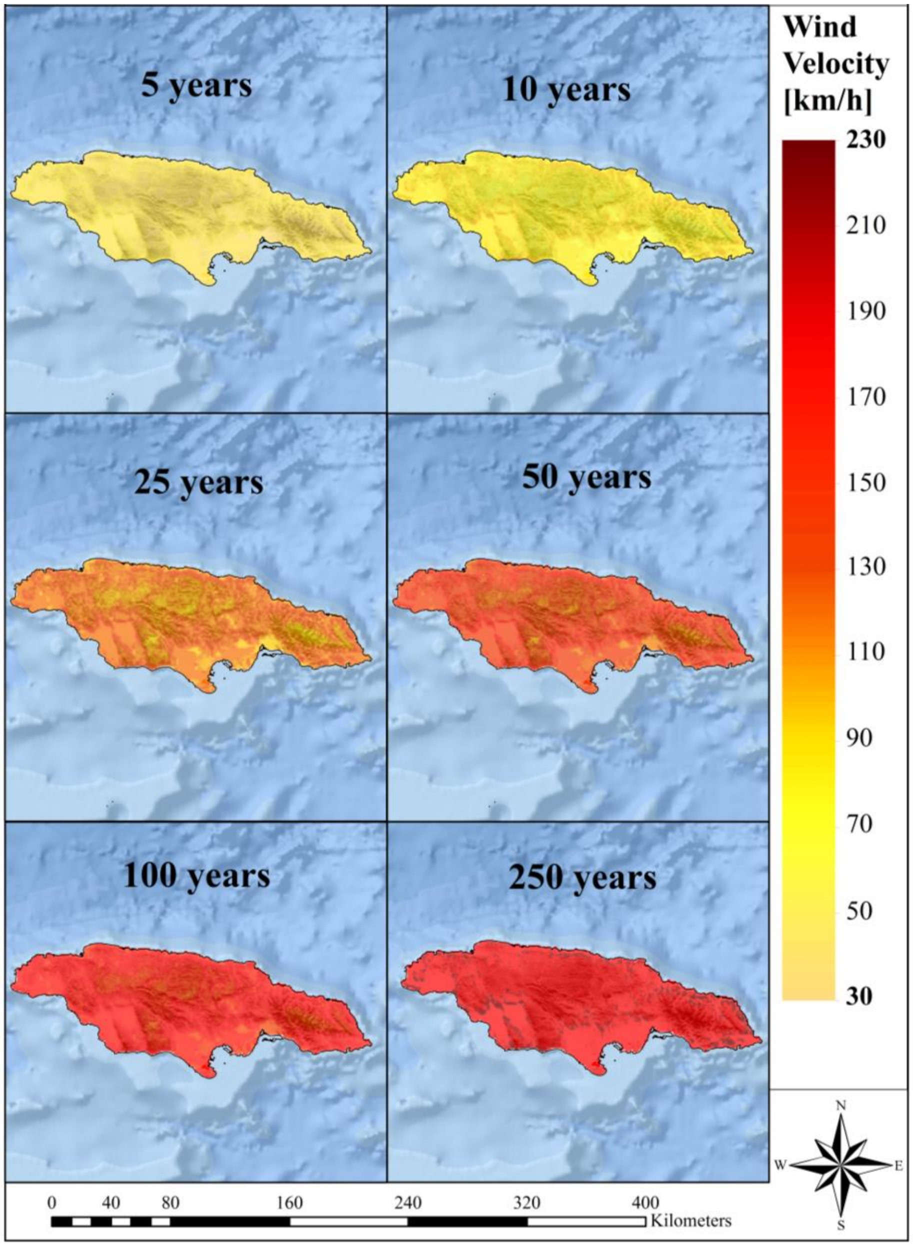


Figure 39 Maximum velocity wind maps for different return periods nationwide

In addition, for illustrative purposes, wind hazard curves are evaluated and shown in Figure 40 for the following four cities in the country: Black River, Kingston, Montego Bay and Port Antonio. The selection of cities attempts to illustrate the geographic variation of the final intensities in extreme locations around the country.

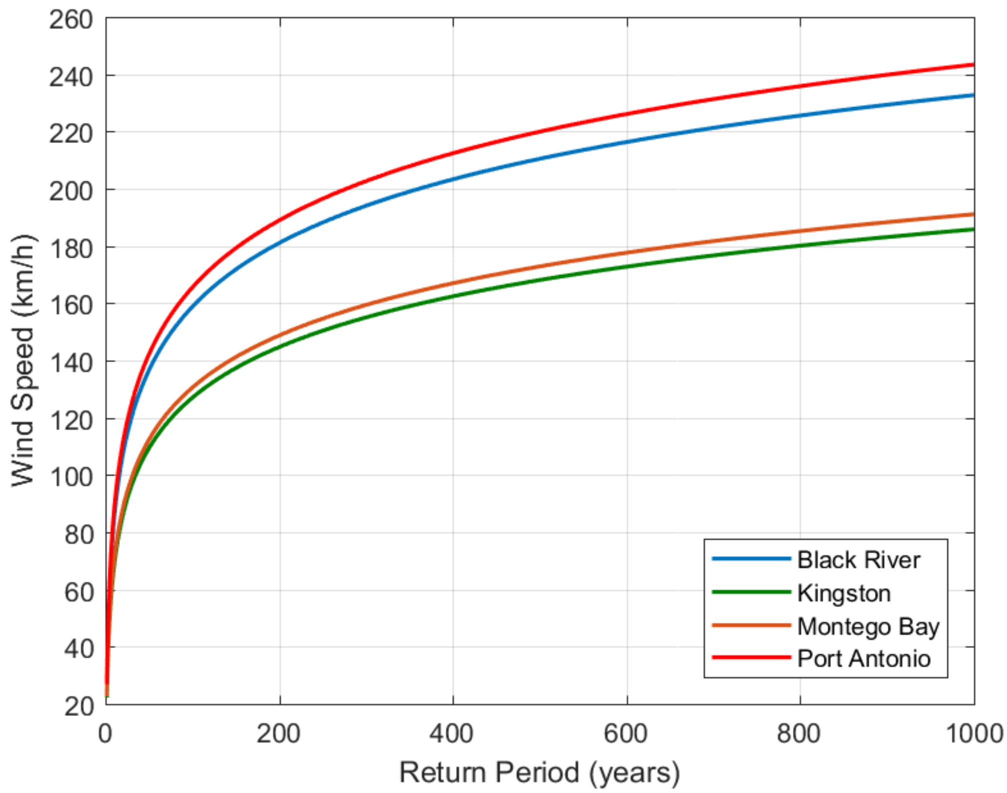


Figure 40 Wind hazard curve for different cities

2.1.5 Climate change considerations

For the present study a simplified consideration for climate change is made in order to estimate possible worst-case scenarios. The following considerations are made:

- Observed regional climate variability generally represents a complex convolution of natural and anthropogenic factors, and the response of tropical cyclones to each factor is not yet well understood (IPCC, 2013).
- Assessing changes in regional tropical cyclone frequency is still limited because confidence in projections critically depend on the performance of control simulations and current climate models still fail to simulate observed temporal and spatial variations in tropical cyclone frequency (IPCC, 2013).
- The projected results highly depend on the future scenario selected (Emission Scenarios for IPCC4 or Representative Concentration Pathways for IPCC5). Special attention should be taken in the moment of using results.

- The available modeling studies project substantial increases in the frequency of the most intense cyclones and it is more likely than not that this increase will be larger than 10% in some basins (IPCC, 2013).
- Under a RCP8.5 scenario, hurricanes exhibit an increased proportion of category 3, 4, and 5 storms in the North Atlantic (NCAR, 2017).
- Change in the average over period 2081–2100 relative to 2000–2019, under an A1B-like scenario, based on expert judgement after subjective normalization of the model projections (IPCC,2013):

Considerations on climate change show an increase in the annual frequency of occurrence of category 3 hurricanes or higher, as shown in the Figure 41.

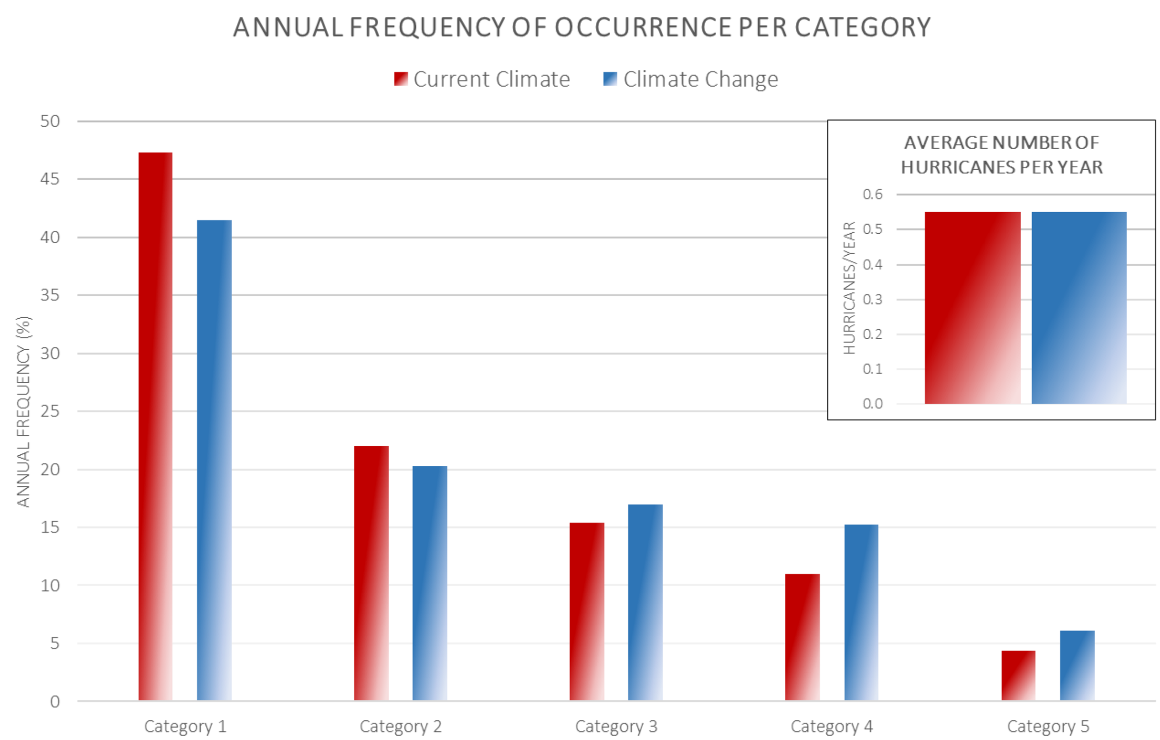


Figure 41 Hurricane annual frequency of occurrence in current and climate change

Based on these considerations, the rain hazard model was modified to contemplate the new frequency distribution of hurricanes. The results of maximum wind velocity of hurricanes under climate change for different return periods are shown in Figure 42. Additionally, Figure

43 shows the winds hazard curves obtained for principal cities of Jamaica: Black River, Kingston, Montego Bay and Port Antonio.

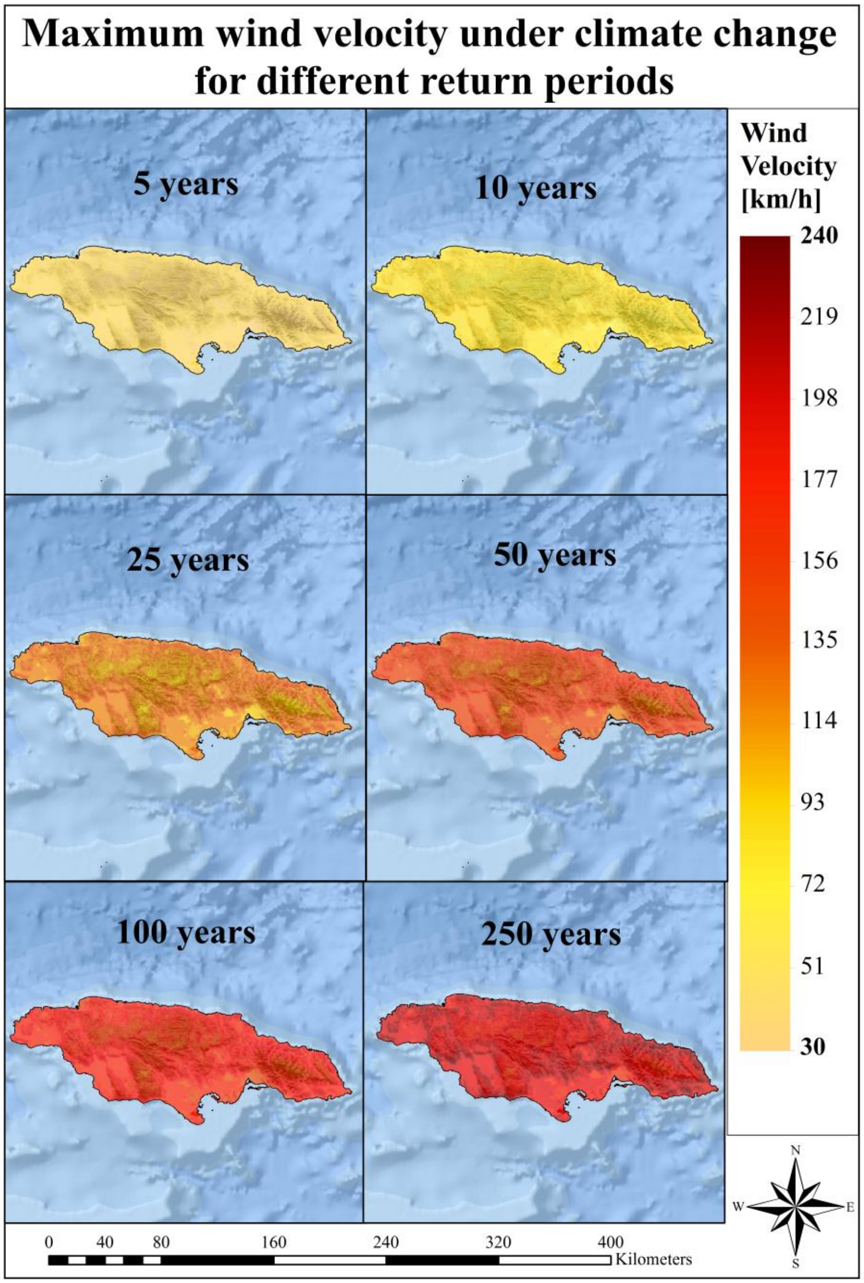


Figure 42 Maximum wind velocity of hurricanes under climate change

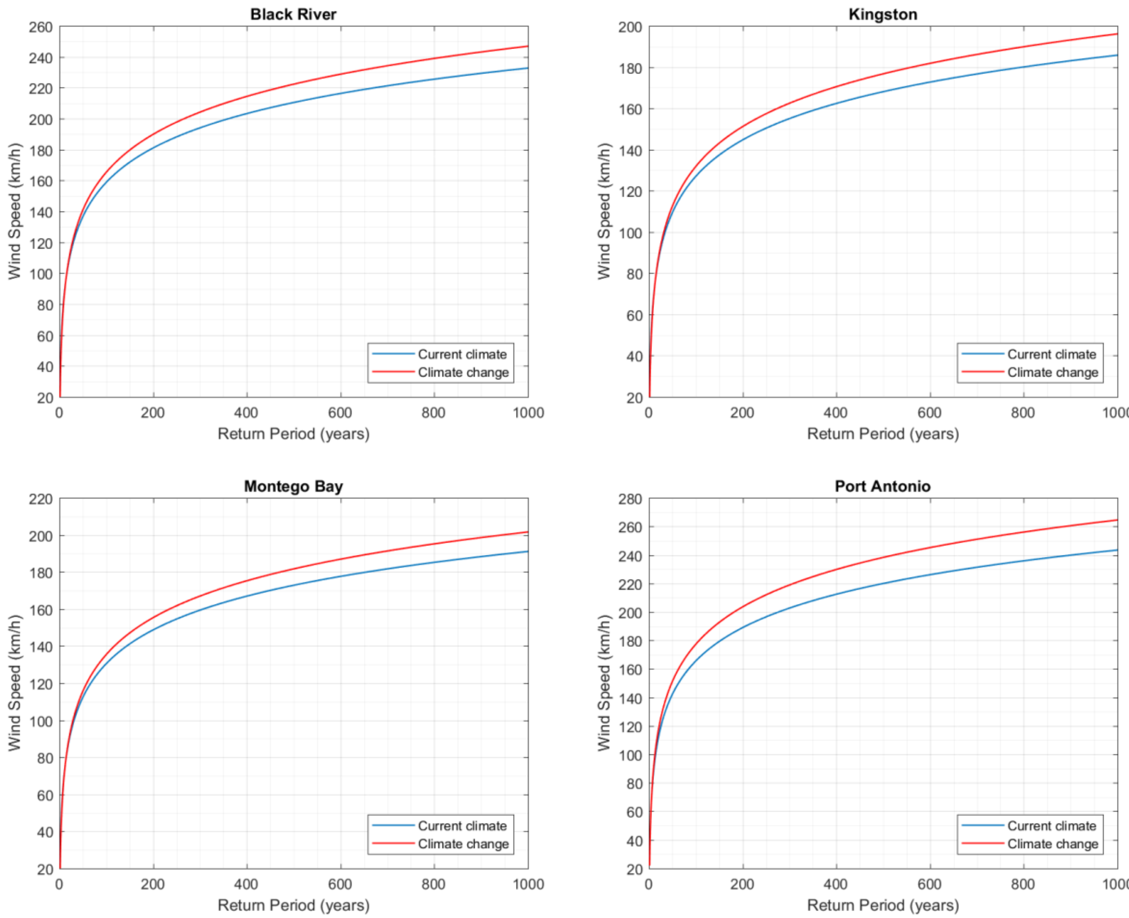


Figure 43 Hurricane wind hazard curves for different cities

The results obtained using this simplified approach correspond to expected trends and orders of magnitude. In Section 3.4 results of the risk assessment model considering climate change scenario are presented.

2.2 HURRICANE WIND VULNERABILITY

For the case of hurricane winds, the vulnerability is represented by a function that relates the level of damage to each construction typology with the maximum wind speed at the location of the analyzed exposed element. The procedure for developing and assigning the vulnerability functions to each individual component of the database is based partially on existing information and observation of the behavior of existing building constructions and includes the following main activities:

(a) Identify the predominant construction classes from the categories of exposed elements that share the same structural behavior.

(b) Select specific vulnerability functions for the predominant representative construction classes. Most published vulnerability functions are based on analytical models and direct observation of the behavior during previous events.

(c) Adjust if necessary the vulnerability functions to the observed behavior of similar construction typologies during recent events of high intensity.

(d) Assign a characteristic construction class and an associated vulnerability function to each element of the exposed inventory of assets.

Once the vulnerability function of each element is assigned, a hurricane risk analysis can be conducted.

2.2.1 Vulnerability functions for buildings

The vulnerability functions for the different building construction types exposed to wind actions were taken from the GAR13 study (Yamin et al, 2013) and adapted to the national context according to the observed behavior in recent events. The original curves of the study for a country of medium complexity, such as Jamaica, are shown in Figure 44.

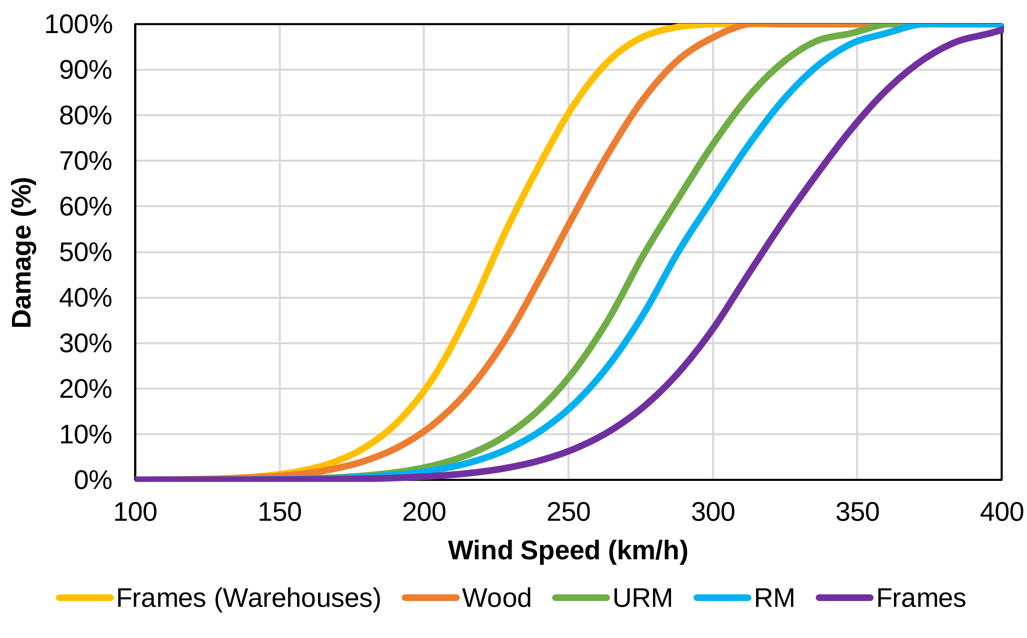


Figure 44 Wind vulnerability functions GAR13.

In order to adapt the functions to the national context, damage reports from past hurricane events were compiled (see CEPAL, the Planning institute of Jamaica and the National Hurricane Center). In particular, information about damage to the housing sector caused by the most severe hurricanes that have affected the island in recent years was used to calibrate the vulnerability functions. Figure 45 summarizes the estimated damage to the housing sector in US millions as a function of the maximum wind speed measured in critical locations in the island during each particular historic event for which reports were published.

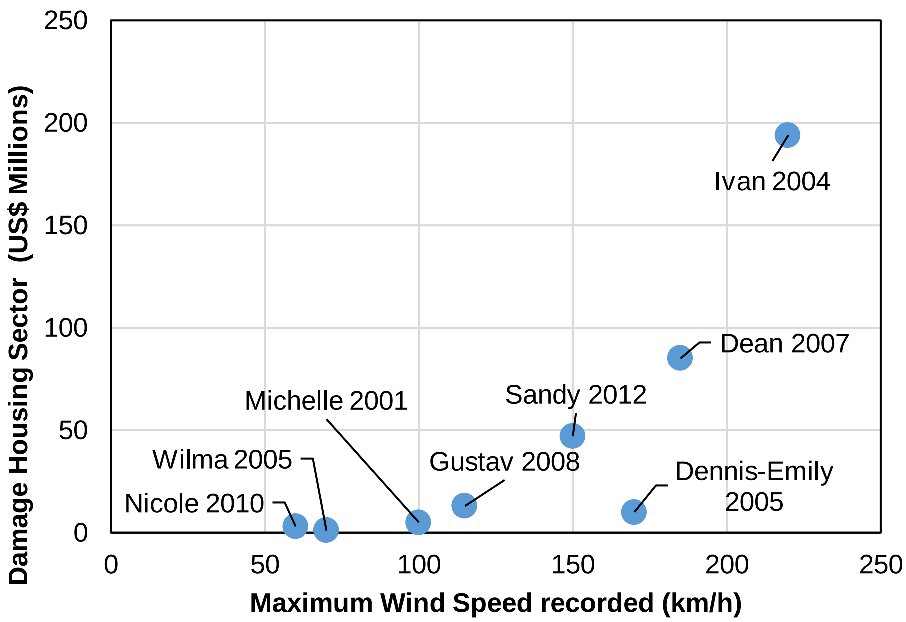


Figure 45 Housing sector damages for Jamaica.

Previous information is modified in order to express the damages in percentage and not in absolute value. For this, it is assumed that the highest intensity hurricane would destroy most of the low-quality construction typologies, which represent approximately 45% of the exposed portfolio. In other words, from this information, it can be assumed that hurricane Ivan in 2004 would represent the event which could damage about the 45% of the housing sector. In that way the rest of the events can be normalized accordingly. With this information, obtained from observations during real events, the vulnerability function for unreinforced masonry systems is adjusted to fit this historic information. Similar adjustments are made to other representative building construction classes as shown in Figure 46 and Figure 47.

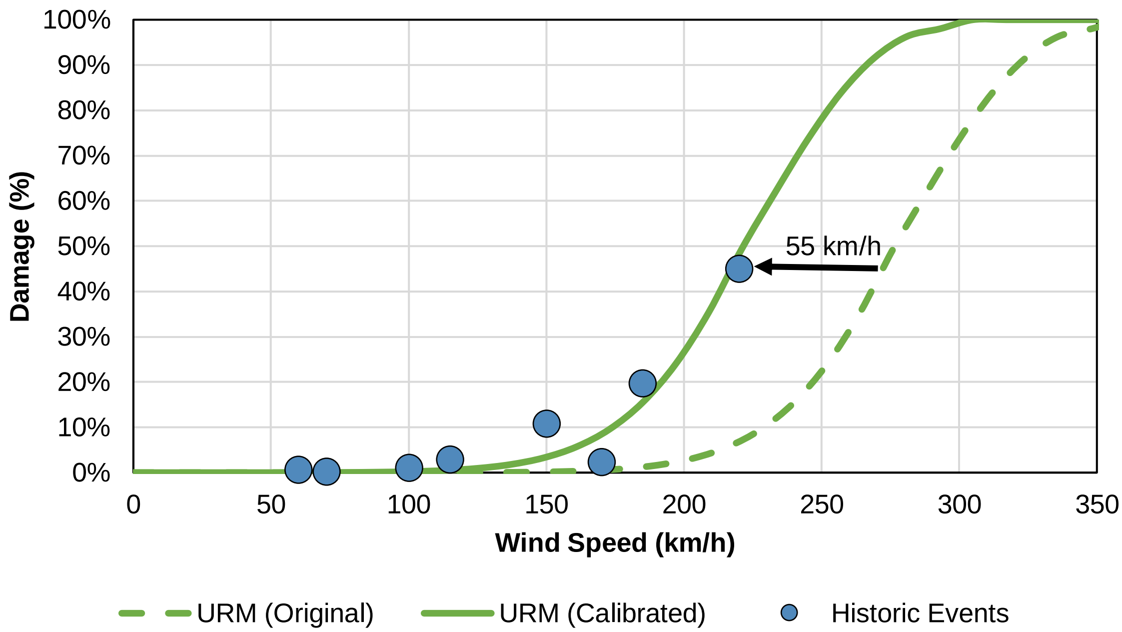


Figure 46 Adjustment process for URM (Unreinforced Masonry)

Figure 47 shows the calibrated wind vulnerability functions used for the risk analysis.

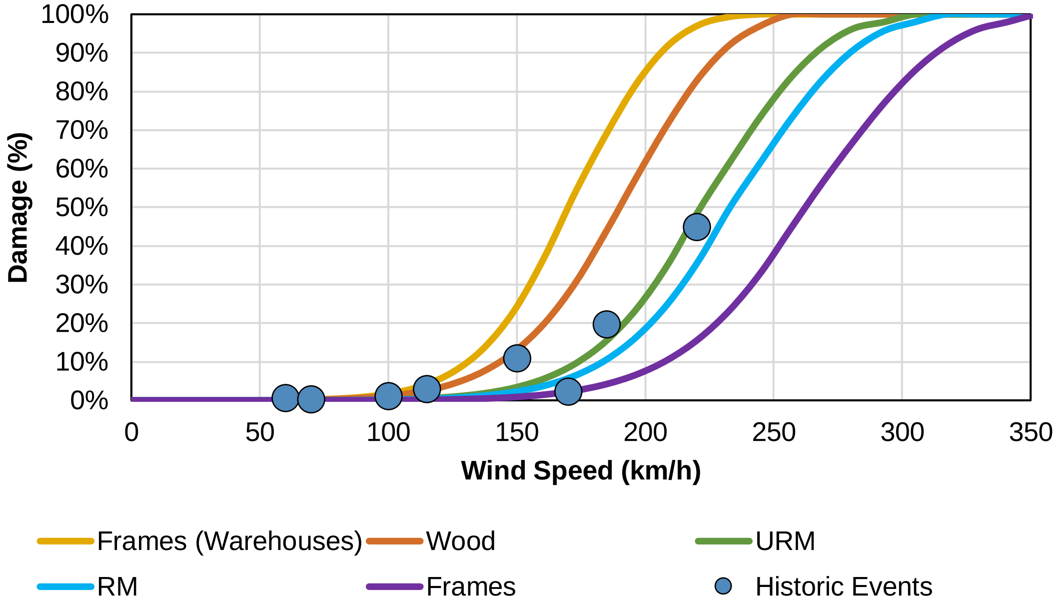


Figure 47 Adjusted wind vulnerability functions for Jamaica

2.2.2 Vulnerability Functions for Infrastructure

For infrastructure components, the vulnerability functions were taken from the Catastrophe Risk Profile of Jamaica (IDB, 2014). These functions had already been adjusted for the national context. Several infrastructure components such as hydroelectric plants, pipe systems, road networks and others are in general only slightly susceptible to the direct effect of the wind, hence the reason why their vulnerability is assumed as nil for the analysis (No Damage function). Figure 48 presents the vulnerability functions used for the predominant infrastructure components.

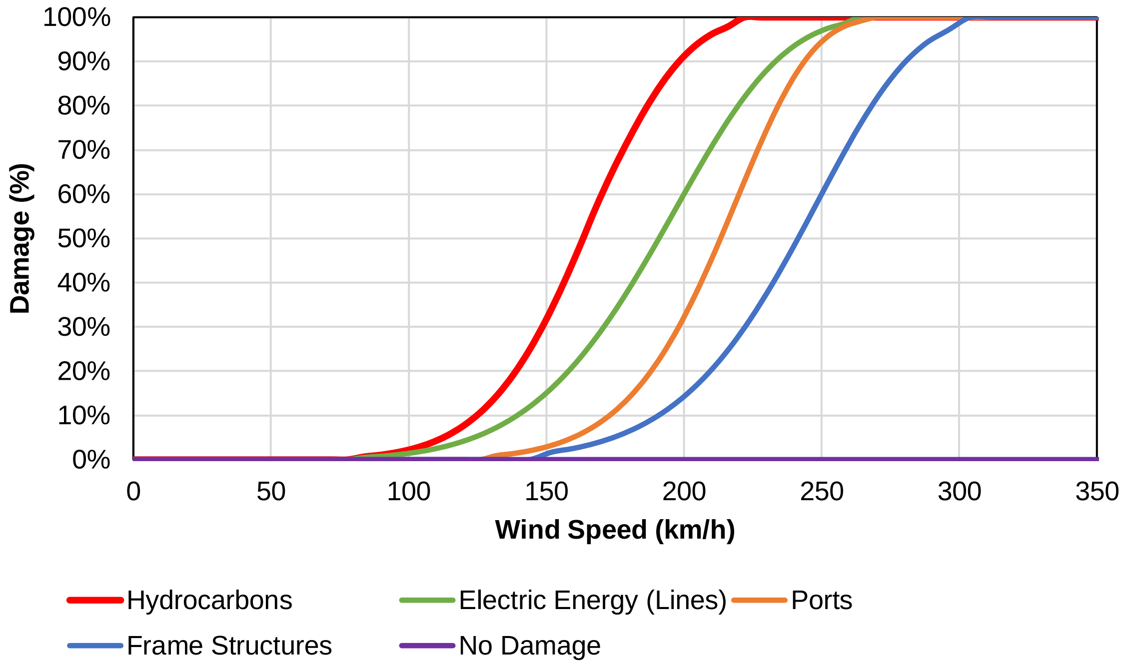


Figure 48 Wind vulnerability functions for infrastructure components

2.3 HURRICANE WIND RISK

Using the above-mentioned hazard, exposure and vulnerability information, a probabilistic risk assessment was developed for hurricane winds in the country using the CAPRA platform (www.ecapra.org). Table 2-1 presents the most relevant figures for the total exposed values, the Expected Annual Losses (EAL) and the probable maximum losses (PML) for different return periods. Some relative figures are presented with respect of the GDP or the total population using figures presented in Table 2-1.

Table 2-1 Hurricane wind – EAL and PML – Total

Total Exposed Value: TEV	**US$ (Millions)**	$ 44,576
Expected Annual Loss: EAL	**US$ (Millions)**	$ 127

	‰ of TEV	2.84
Probable Maximum Loss: PML		
Return Period	US$ (Millions)	%
100	$ 3,005	6.7
250	$ 5,991	13.4
500	$ 9,194	20.6
1000	$ 11,800	26.5

In addition, Table 2-2 presents results with the building constructions and infrastructure stocks discriminated. The results are presented in absolute terms as well as percentages of the country annual GDP and per capita figures. Useful indicators to compare the risk assessment results between countries as EAL as percentage of the total exposed value, of the GDP or divided in the number of inhabitants are included.

Table 2-2 Hurricane wind – EAL and PML - Buildings and Infrastructure

	Buildings		Infrastructure	
Total Exposed Value: TEV	US$ (Millions)	$ 34,839	US$ (Millions)	$ 9,736
Expected Annual Loss: EAL	US$ (Millions)	$ 124	US$ (Millions)	$ 3
	‰ of TEV	3.6	‰ of TEV	0.3
	% of GDP	0.84%	% of GDP	0.02%
	US$/Inhabitant	$ 46	US$/Inhabitant	$ 1
Probable Maximum Loss: PML				
RP	US$ (Millions)	%	US$ (Millions)	%
100	$ 2,965	8.5	$ 51	0.5
250	$ 5,858	16.8	$ 154	1.6
500	$ 9,000	25.8	$ 297	3.0
1000	$ 11,065	31.8	$ 443	4.5
PML1000 (%GDP)	75%		3%	

PML1000 (US$/inh.)	$ 4,098	$ 164

Moreover Figure 49 shows the PML at the national level, and the disaggregated values for building construction and infrastructure stock. These results indicate that the building stock represents more than 95% of the expected national losses.

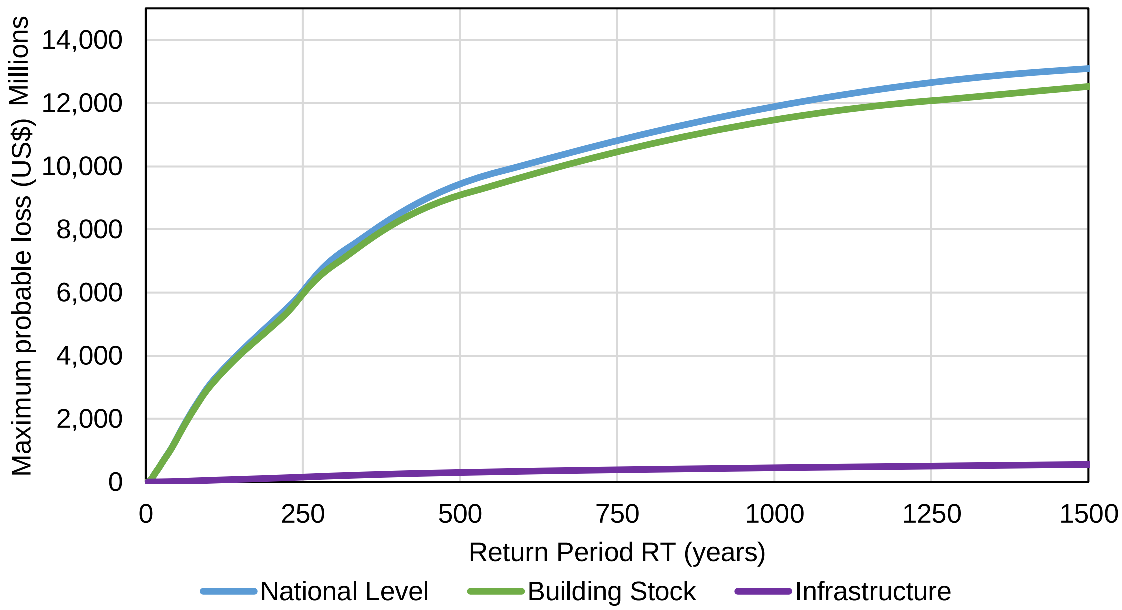


Figure 49 Hurricane Wind - PML curves at National level

Table 2-3 presents hurricane wind risk results discriminated by public and private sector. In summary, the private sector has a much higher total expected loss than the public sector, because it represents a much higher value in the exposed model.

Table 2-3 Hurricane Wind - risk results disaggregated by private and public sectors

SECTOR	Total Exposed Value TEV (US$ Millions)	EAL (US$ Million)	Relative EAL (‰ of TEV)
Private Buildings	$ 29,676	$ 105	3.5
Public Buildings	$ 5,164	$ 19	3.6
Infrastructure	$ 9,736	$ 3	0.3
Total	**$ 44,576**	**$ 127**	**2.8**

On the other hand, Table 2-4 shows the results aggregated by the main use sectors. The Residential, Industrial and Commercial sectors concentrate the highest total risk, whereas the Industrial, Residential and Administrative have the highest relative risk.

Table 2-4 Hurricane wind risk disaggregated by sub-sectors

SECTOR	Total Exposed Value TEV (US$ Millions)	EAL (US$ Million)	Relative EAL (‰ of TEV)
Residential	$ 17,777	$ 60	3.4
Education	$ 2,660	$ 6	2.2
Health	$ 60	$ 0.15	2.5
Administrative	$ 888	$ 3	3.1
Industrial	$ 2,669	$ 32	11.9
Commercial	$ 7,061	$ 17	2.3
Offices	$ 3,724	$ 7	2.0
Transportation	$ 7,814	$ 0.83	0.1
Energy System	$ 643	$ 0.78	1.2
Hydrocarbons and oil derivatives	$ 774	$ 0.63	0.8
Telecommunication	$ 107	$ 0.23	2.2
Water supply, sanitation and urban pipes systems	$ 398	$ 0.08	0.2
Total	**$ 44,576**	**$ 127**	**2.8**

Figure 50 shows the EAL (total and relative) for each sub-sector included in the analysis.

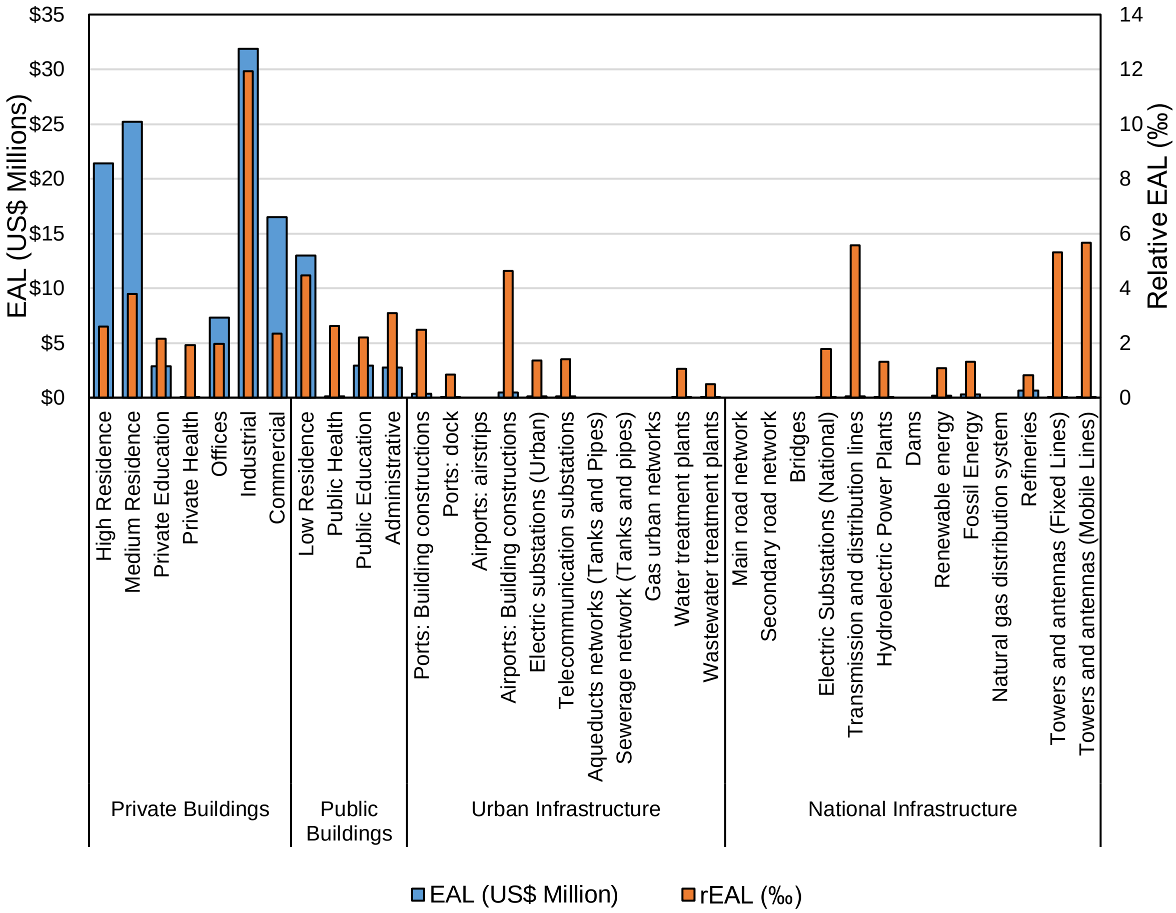


Figure 50 Hurricane Wind - EAL for sub-sectors

2.4 HURRICANE WIND RISK CONSIDERING CLIMATE CHANGE

2.4.1 General results and comparison

Table 2-5 shows the risk results for the entire exposure portfolio compared between hurricane wind in the current scenario and the projected climate change model. It shows that under this climate change model, the total wind risk would rise by around 20% in Annual Average loss and Probable maximum loss for a return period of 500 years.

Table 2-5. Risk Results Comparison.

Hurricane Wind Current Scenario	Hurricane Wind w/ Climate Change

Total Exposed Value: TEV	US$ (Millions)		$ 44,576	
Expected Annual Loss: EAL	US$ (Millions)	$ 127	US$ (Millions)	$ 149
	‰ of TEV	2.8	‰ of TEV	3.3
	% of GDP	0.86%	% of GDP	1.01%
	US$/Inhabitant	$ 47	US$/Inhabitant	$ 55
Probable Maximum Loss: PML				
RP	US$ (Millions)	%	US$ (Millions)	%
100	$ 3,005	6.7	$ 3,855	8.6
250	$ 5,991	13.4	$ 7,358	16.5
500	$ 9,194	20.6	$ 10,054	22.6
1000	$ 11,424	25.6	$ 11,528	25.9
PML1000 (%GDP)	78%		78%	
PML1000 (US$/inh.)	$ 4,231		$ 4,270	

Figure 51 shows the PML curves for hurricane wind with and without climate change. Once again, climate change could increase the overall risk assessment of the country.

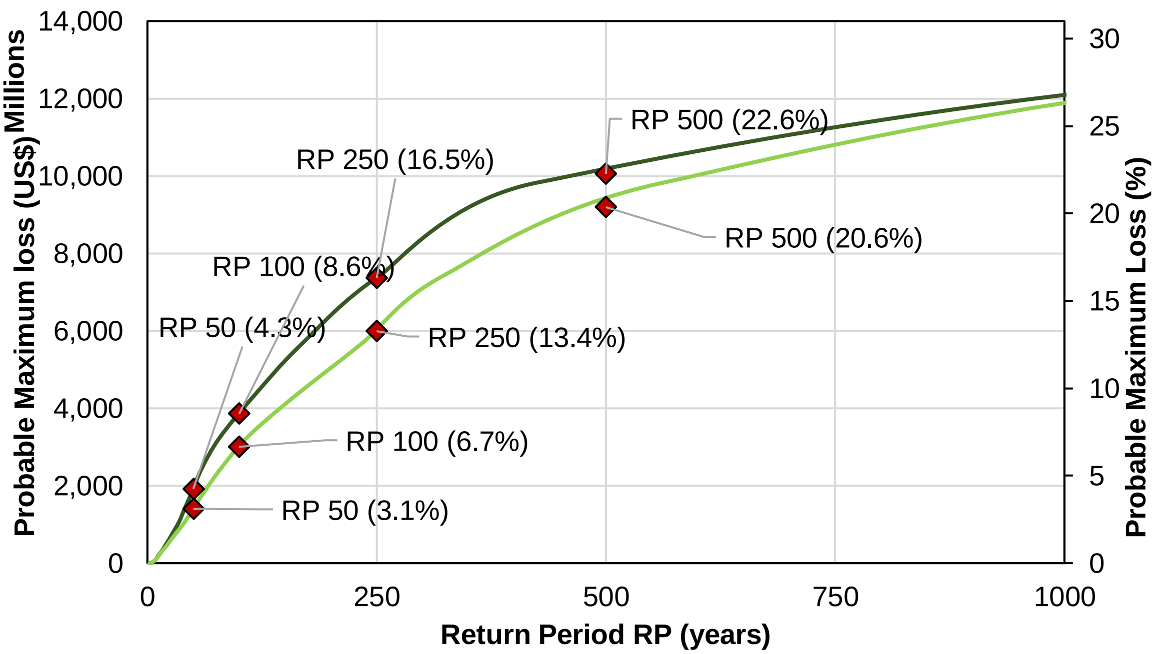
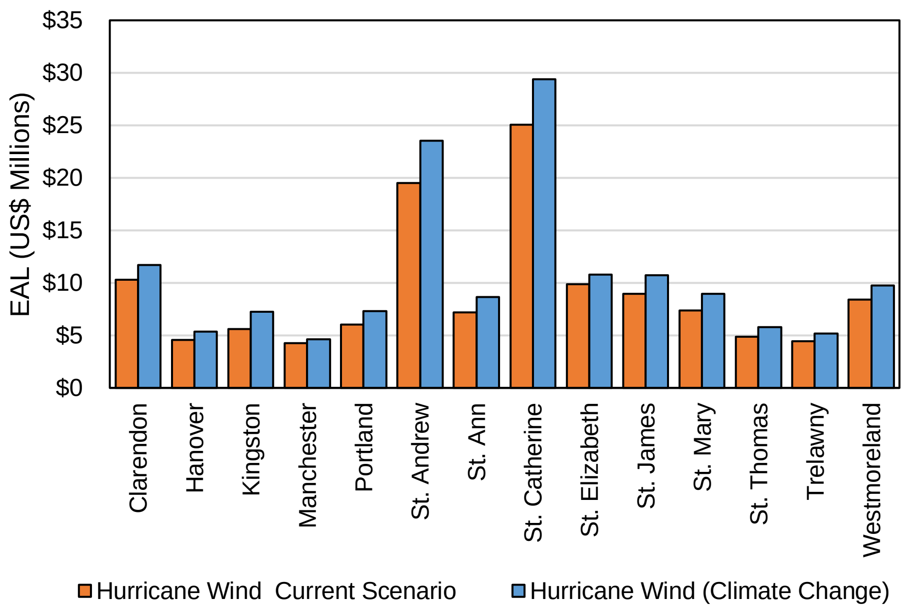


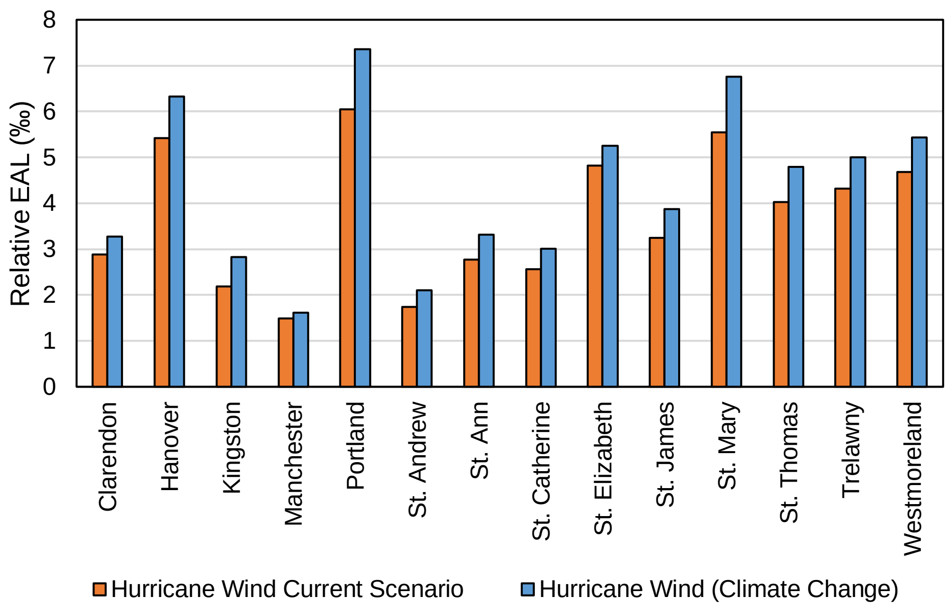
Figure 51. Probable Maximum Losses curve comparison.

2.4.2 Expected annual loss per parish

Figure 52 shows the expected annual losses results by parish, comparing between the current scenario and the climate change model, figures are presented in terms of absolute values (US$) and relative values of the TEV (%). Results indicate that that in general, climate change increases the losses in all of the parishes, once again by an average of around 20%, except for the parish of St. Andrew where results are nearly equal.



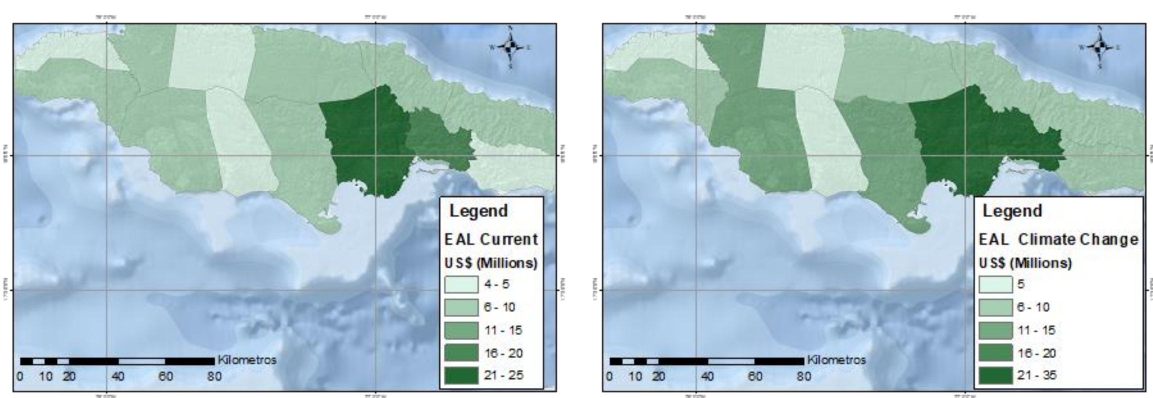
(a) Expected Annual Losses - EAL (Total)



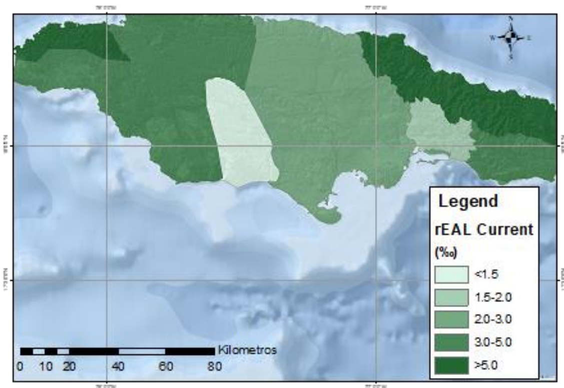
(b) Relative Expected Annual Losses - EAL

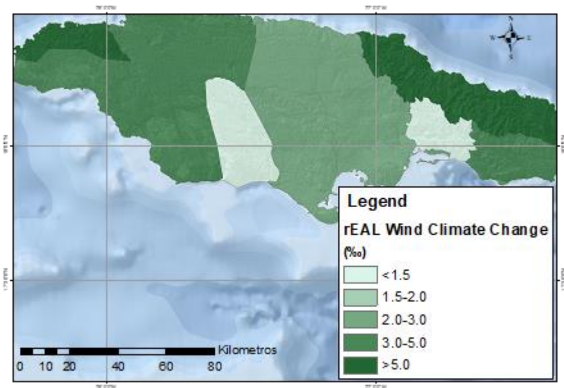
Figure 52. Expect annual Losses by Parish

On the other hand, Figure 53 shows the annual losses results geographically, comparing both situations and showing the total increase as a percentage for each parish. The highest total increase in economic losses results in Portland (Around US$130 million increase), and the highest increase in percentage is likely to occur in Kingston (around 30% increase).

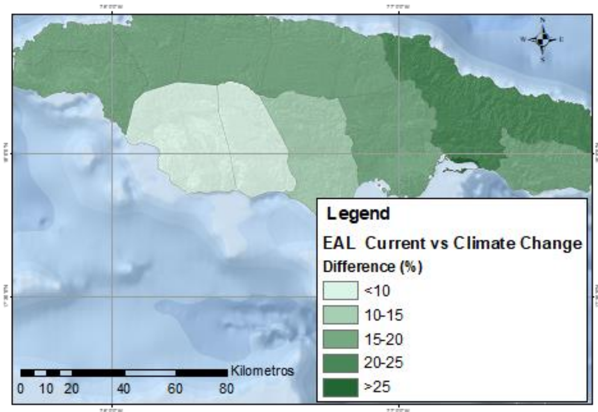


(a) EAL Current Scenario (Left) vs. Climate Change Model (Right) (US$ Million)





(b) Relative EAL Current Scenario (Left) vs. Climate Change Model (Right) (%)



(c) Difference in economic losses as a percentage

Figure 53. EAL Comparison per Parish Current vs. Climate Change model

2.4.3 Expected annual loss by sectors

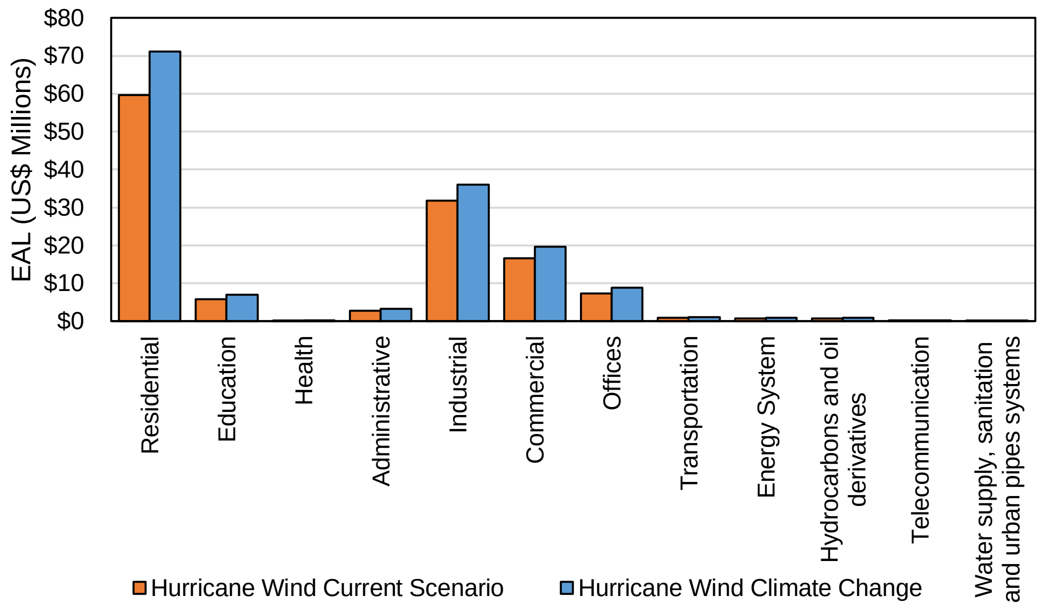
Table 2-6 shows the expected annual losses for hurricane wind divided by sector, comparing the results in the current scenario with those of the climate change model. It shows that the climate change scenario increases total economic losses by around 20% in all sectors analyzed in the exposure model.

Table 2-6. Expected Annual Losses by sector

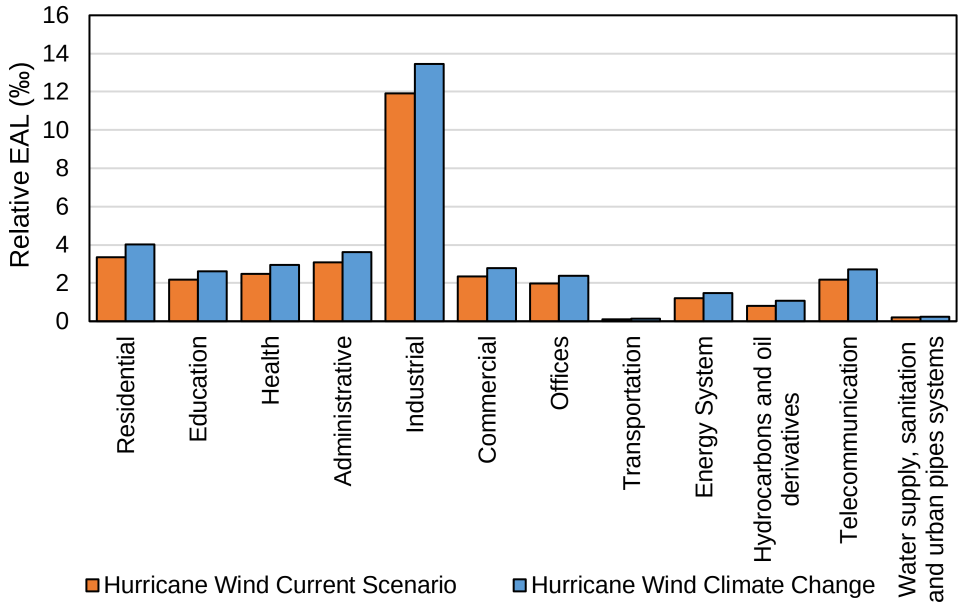
		Hurricane Wind Current Scenario		Hurricane Wind w/ Climate Change		Difference
SECTOR	**Total Exposed Value TEV (US$ Millions)**	**EAL (US$ Million)**	**Relative EAL (‰ of TEV)**	**EAL (US$ Million)**	**Relative EAL (‰ of TEV)**	**(%)**
High Residence	$ 8,227	$ 21	2.6	$ 26	3.1	20%
Medium Residence	$ 6,650	$ 25	3.8	$ 30	4.5	19%
Low Residence	$ 2,900	$ 13	4.5	$ 15	5.3	19%
Residential	$ 17,777	$ 60	3.4	$ 71	4.0	19%
Private Education	$ 1,331	$ 2.9	2.2	$ 3.4	2.6	20%
Public Education	$ 1,329	$ 2.9	2.2	$ 3.5	2.6	20%
Education	$ 2,660	$ 5.8	2.2	$ 6.9	2.6	20%
Private Health	$ 13	$ 0.02	1.9	$ 0.03	2.3	19%
Public Health	$ 47	$ 0.12	2.6	$ 0.15	3.1	19%
Health	$ 60	$ 0.15	2.5	$ 0.18	2.9	19%
Administrative	$ 888	$ 2.7	3.1	$ 3.2	3.6	17%
Offices	$ 3,724	$ 7.3	2.0	$ 8.8	2.4	20%
Industrial	$ 2,669	$ 32	11.9	$ 36	13.5	13%
Commercial	$ 7,061	$ 17	2.3	$ 20	2.8	19%
Buildings	$ 34,839	$ 124	3.6	$ 146	4.2	18%
Transportation	$ 7,814	$ 0.8	0.1	$ 1.1	0.1	32%
Energy Systems	$ 643	$ 0.8	1.2	$ 1.0	1.5	22%

Hydrocarbons and oil derivatives	$ 774	$ 0.63	0.8	$ 0.84	1.1	33%
Telecommunication	$ 107	$ 0.23	2.2	$ 0.29	2.7	25%
Water supply, sanitation and urban pipe systems	$ 398	$ 0.08	0.2	$ 0.10	0.3	24%
Infrastructure	$ 9,736	$ 2.6	0.3	$ 3.3	0.3	28%
Total	**$ 44,576**	**$ 127**	**2.8**	**$ 149**	**3.3**	18%

Figure 54 shows the results in a graphic comparison. The highest increase in economic losses is US$ 5 million for the medium residence, and the highest increase in relative losses is 34% for the transportation sector.



(a) EAL comparison (Total)



(b) EAL comparison (Relative)

Figure 54. Expected annual losses by sector

2.4.4 Expected annual loss for the public and private sectors

Table 2-7 shows the results disaggregated by private and public sectors. It shows once again that economic losses due to climate change could increase by around 20%. It is also important to notice that there is a 27% increase in economic losses in the infrastructure sector, whereas this increase is closer to 20% for both the public and private buildings.

Table 2-7. Expected Annual Losses for Public and Private Sectors

		Hurricane Wind Current Scenario		Hurricane Wind w/ Climate Change		Difference
SECTOR	Total Exposed Value TEV (US$ Millions)	EAL (US$ Million)	Relative EAL (‰ of TEV)	EAL (US$ Million)	Relative EAL (‰ of TEV)	(%)
Private Buildings	$ 29,676	$ 105	3.5	$ 124	4.2	17%
Public Buildings	$ 5,164	$ 19	3.6	$ 22	4.3	19%

Infrastructure	$ 9,736	$ 3	0.3	$ 3	0.3	28%
Total	$ 44,576	$ 127	2.8	$ 149	3.3	18%

Figure 55 shows the results graphically.

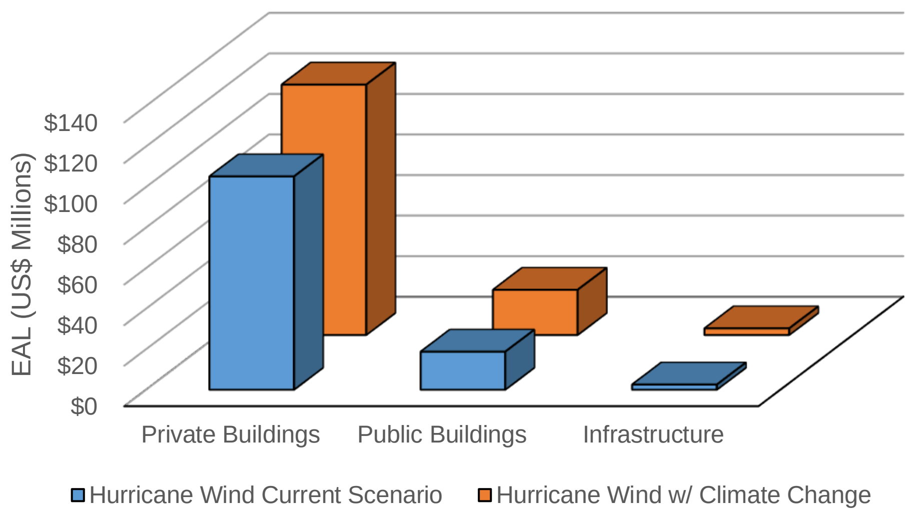


Figure 55. Graphic Comparison Private Vs Public Sector

CHAPTER 4

SEISMIC HAZARD AND RISK

3.1 SEISMIC HAZARD

3.1.1 General Aspects

The usual form of representing seismic hazard is by annual exceedance rates of selected seismic intensities such as PGA, or spectral accelerations. It can also be represented by probabilistic maps of maximum ground accelerations, velocities and displacements for different return periods or specific seismic intensity distributions for selected scenarios. By means of the estimation of the seismic demand for each one of the exposed components, it is possible to estimate the expected damage, and economic and human losses.

A seismic hazard assessment was developed for Jamaica in 2014 in the framework of the project to assess the Disaster Risk Profile for Jamaica (IDB, 2014). This model was based on the classic seismological theory that allows estimation of the exceedance probability of relevant seismic intensities for structures of different dynamic characteristics. This assessment included the generation of probabilistic hazard maps at the country level and the estimation of spectral accelerations at any location within the country. Previous studies also generated information to be used in the framework of the International Building Code (Salazar, Brown, & Mannette, 2013).

In the present study, an update of the seismic hazard and risk assessment is presented. A new seismic source model and a revised and updated catalog is used for the assessment. The seismic hazard was calculated using the software CRISIS 2007 (Ordaz, Aguilar, & Arboleda, 2007). This model allows the probabilistic integration of the uncertainty of different parameters (seismic sources, distribution of event magnitudes, attenuation laws, etc.) to evaluate the seismic intensity expected in the different points of analysis. Furthermore, the model allows the estimation of annual exceedance rates of different acceleration values over an area of study, from which the hazard curves, uniform hazard spectra and acceleration maps

for different structural periods and a variety of return periods can be obtained. More details of the seismic hazard model are presented at www.ecapra.org.

3.1.2 Information for the updated probabilistic hazard model

Recent studies have compiled valuable information related to active seismic zones in the area of influence around Jamaica. The main sources of information are Wiggins-Grandison, 2001, Wiggins-Grandison & Atakan, 2005, Salazar & Brown, 2013. The available information has been validated and revised in order to be included in the new version of the model. Figure 56 shows the updated seismic sources used for the seismic hazard calculation.

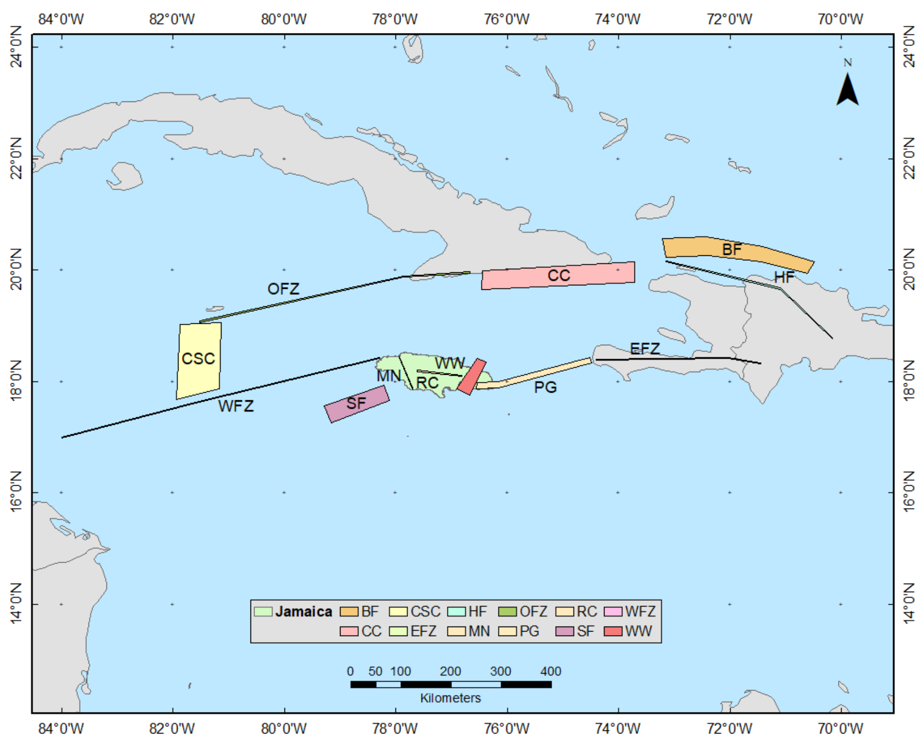


Figure 56 Geometry Seismic Sources Model

In addition, a revised seismic catalog was used for the characterization of the seismicity of each one of the seismic sources. The new catalog was based in the information collected from the following sources:

- Local catalog: provided by the Earthquake Unit of the UWI Jamaica
- Reviewed ISC bulletin
- ISC - GEM catalog
- USGS catalog

With this information a total of about 2248 seismic events was identified since 1692, with a depth range of 0 to 200 km and a magnitude range (Mw) from 0.4 to 7.7.

After a depuration process using an updates algorithm (Uhrhammer, 1986), the following revised and updated catalog was used:

- Period range: from 1985 to 2015 (period where information is complete).
- Magnitude (Mw) range from 4.0 to 7.7.
- Maximum distance from Jamaica: 250 km.
- Total number of events: 214

Figure 57 presents the location of the seismic events in this new depurated catalog.

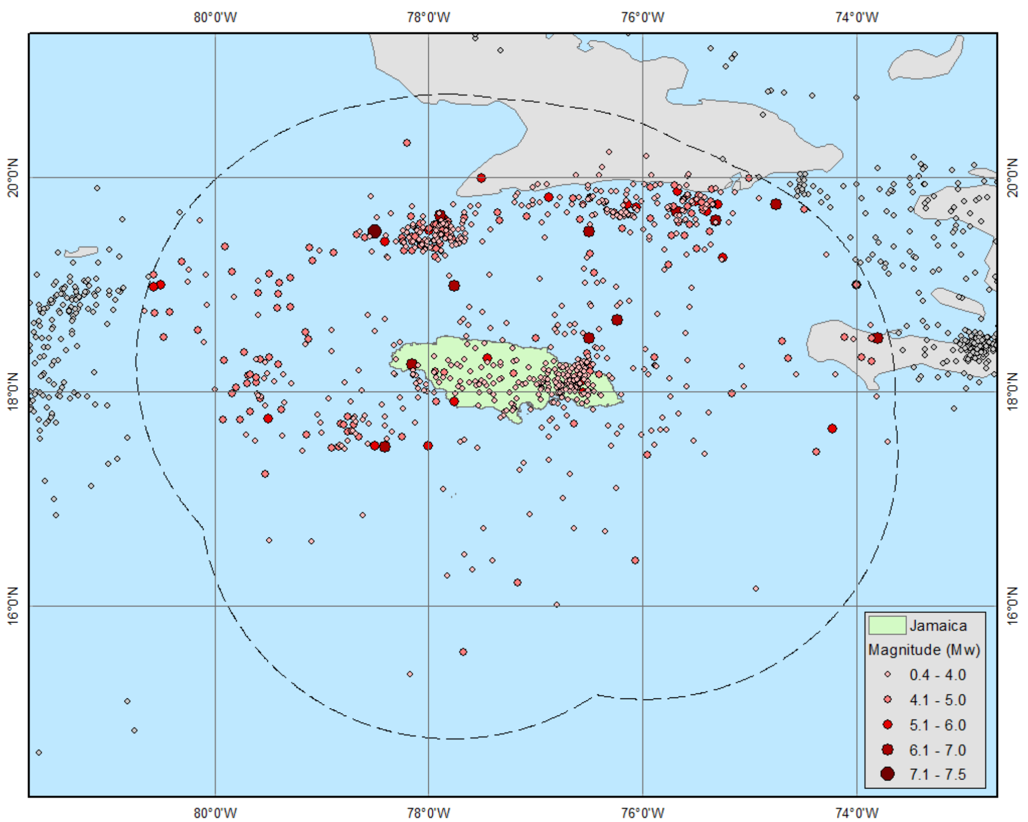


Figure 57 Depurated seismic catalog

In addition, Figure 58 presents the magnitude recurrence curve for this same catalog.

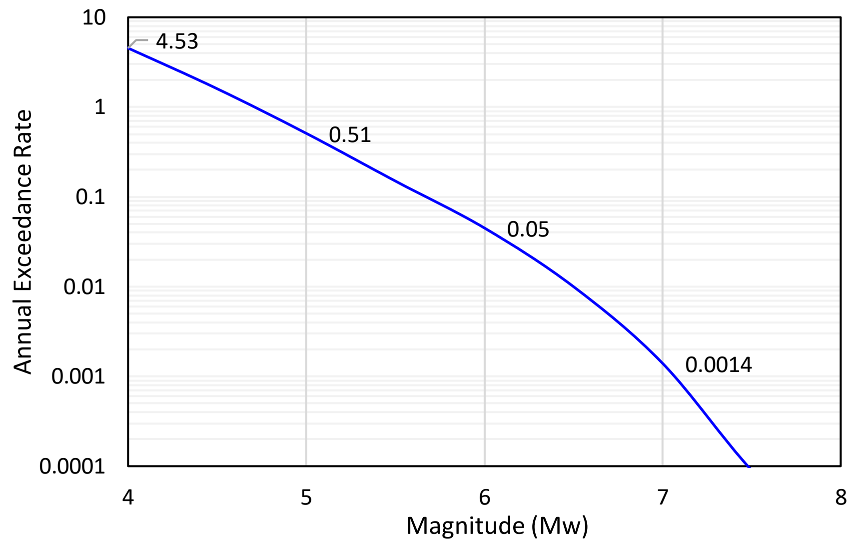


Figure 58 Magnitude recurrence curve for the depurated seismic catalog

Finally, after a process of seismic assignment to the different sources, the basic seismic parameters of all the seismic sources were evaluated. Table 3-1 summarizes the new parameters for each one of the seismic sources.

Table 3-1 Parameters for seismic sources

N°	Source Name	Cod	Fault Type	M0	λ0	β	CV β	Mu
1	Bahamas Subduction Fault	BF	Subduction - Reverse	4	2.04	3.44	0.46	7.1
2	Cuba Subduction Zone	CC	Subduction - Reverse	4	1.85	2.28	0.32	6.8
3	Cayman Spreading Center	CSC	Spreading center	4	0.96	1.30	0.25	6.8
4	Enriquillo Fault Zone	EFZ	Crustal Strike-slip	4	1.07	1.58	0.29	7.6
5	Hispaniola Fault	HF	Crustal Strike-slip	4	5.48	2.84	0.23	8.0
6	Montpelier-Newmarket Faults	MN	Crustal -Reverse	4	0.15	1.90	0.95	6.6
7	Oriente Fault Zone	OFZ	Crustal Strike-slip	4	1.74	1.98	0.29	7.8
8	Plantain Garden Fault	PG	Crustal Strike-slip	4	0.11	4.29	2.47	7.6
9	Rio Minho Crawle River Fault	RC	Crustal Strike-slip	4	0.15	3.33	1.67	6.0
10	South Fault	SF	Crustal Strike-slip	4	0.56	4.29	1.11	7.3
11	Walton Fault Zone	WFZ	Crustal Strike-slip	4	1.74	1.75	0.25	7.4
12	Wag-water Faults	WW	Crustal Strike-slip	4	0.41	2.16	0.65	6.5

Finally, new ground motion prediction equations (GMPE) were selected for the updated hazard version. The GMPE used are the following:

- For Crustal earthquakes: Sadigh, 1997
- For subduction earthquakes: Youngs, 1997

Figure 59 presents the corresponding GMPE.

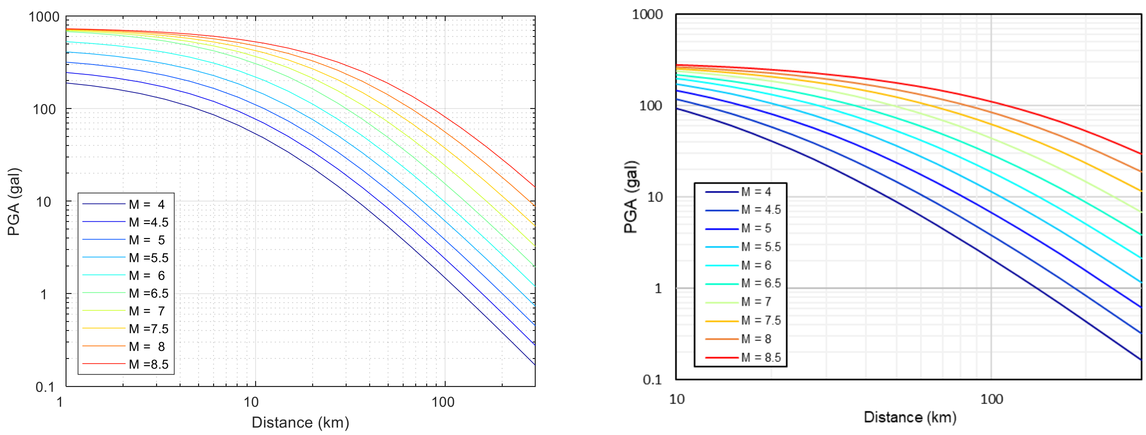


Figure 59 GMPE used for modeling seismic sources

The results of the model developed in this study were validated with the results of the previous studies available in the country. It was found that, in general terms, the new proposed model yields result that are consistent with the results of previously developed seismic hazard models. Accordingly, for the purposes of the risk assessment, the proposed model is considered valid and adequate.

3.1.3 Seismic hazard assessment

3.1.3.1 <u>Contribution of the different seismic sources</u>

The probabilistic hazard assessment allows the estimation of the annual exceedance rate of specific seismic intensities at particular locations, including the participation of the different seismic sources in the region. Figure 60 presents, for illustration purposes, the results for a representative point in downtown Kingston in terms of the maximum peak ground acceleration, PGA.

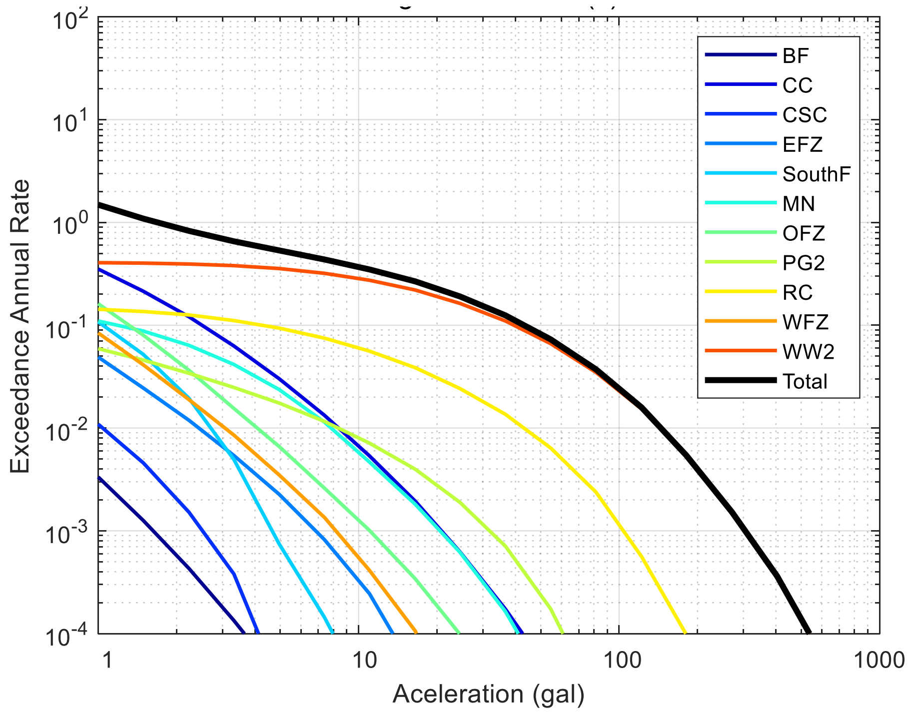


Figure 60 Annual exceedance rates of maximum acceleration for Kingston

3.1.3.2 Uniform hazard spectra

Selecting specific annual exceedance rates, maximum values of PGA can be obtained from the previous figure. For example, for an annual exceedance rate of about 0.002/year, corresponding to a return period of about 500 years, a maximum peak ground acceleration (PGA) on the bedrock of the order of 22% of gravity (220 gal) is obtained.

Extending the previous procedure for other spectral ordinates, it is possible to construct uniform hazard spectrums, for which all calculated seismic intensity values have the same exceedance probability. Figure 61 presents uniform hazard spectrums for different return periods at the same previous location in center of downtown Kingston.

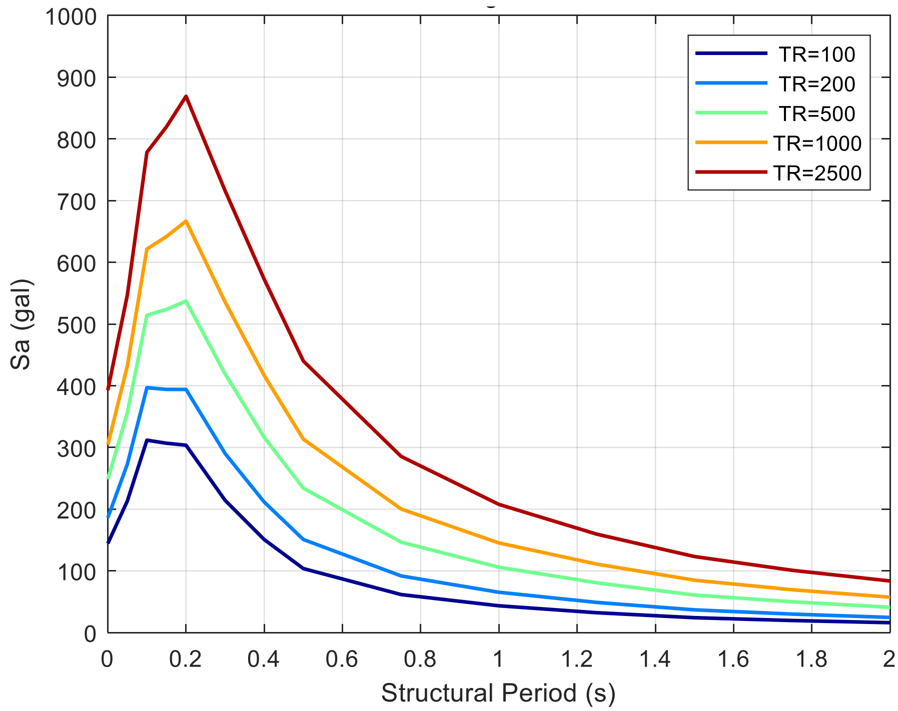


Figure 61 Uniform hazard spectrums for different return periods in Kingston

The results obtained from the present study were compared with other recent similar studies. Figure 62 compares the resulting uniform hazard spectrum in Kingston for a return period of 500 years from previous studies and the present one, illustrating the good degree of consistency.

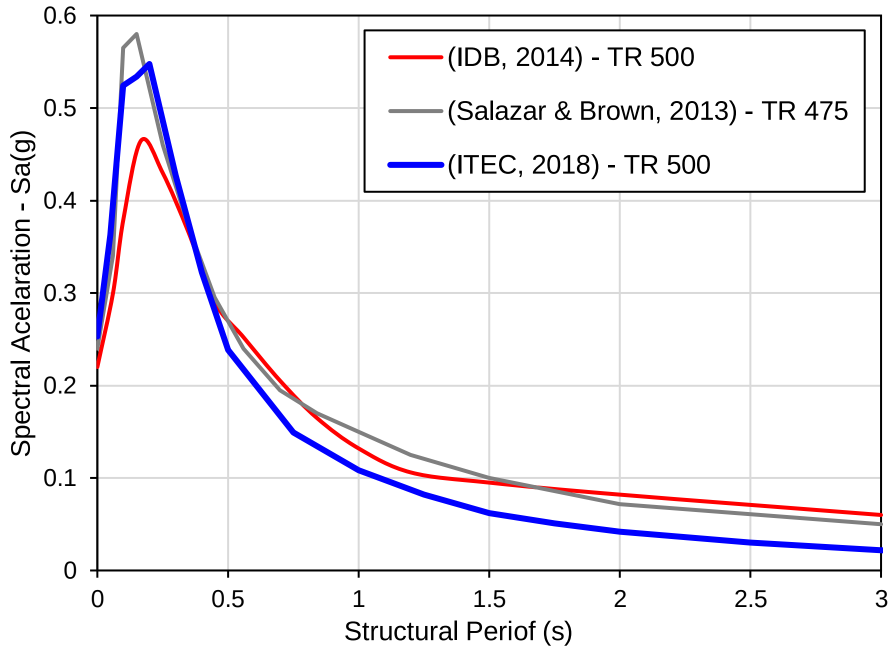
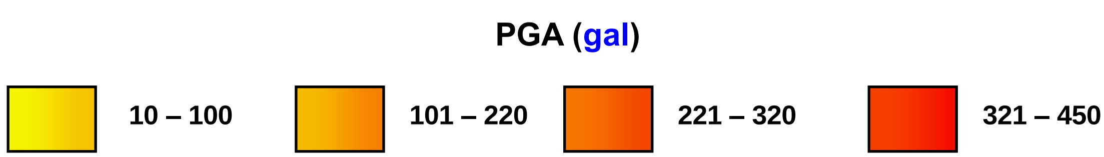


Figure 62 Results validation

3.1.3.3 Probabilistic hazard maps

The results of seismic hazard on bedrock for the whole country taking into consideration all the seismic sources are summarized as follows. Figure 63 presents the seismic hazard maps in terms of spectral acceleration for different return periods, for selected structural periods. The hazard maps presented correspond to the expected response of the geological formations of the bedrock, with shear wave velocities of the order of 750 m/s or more.



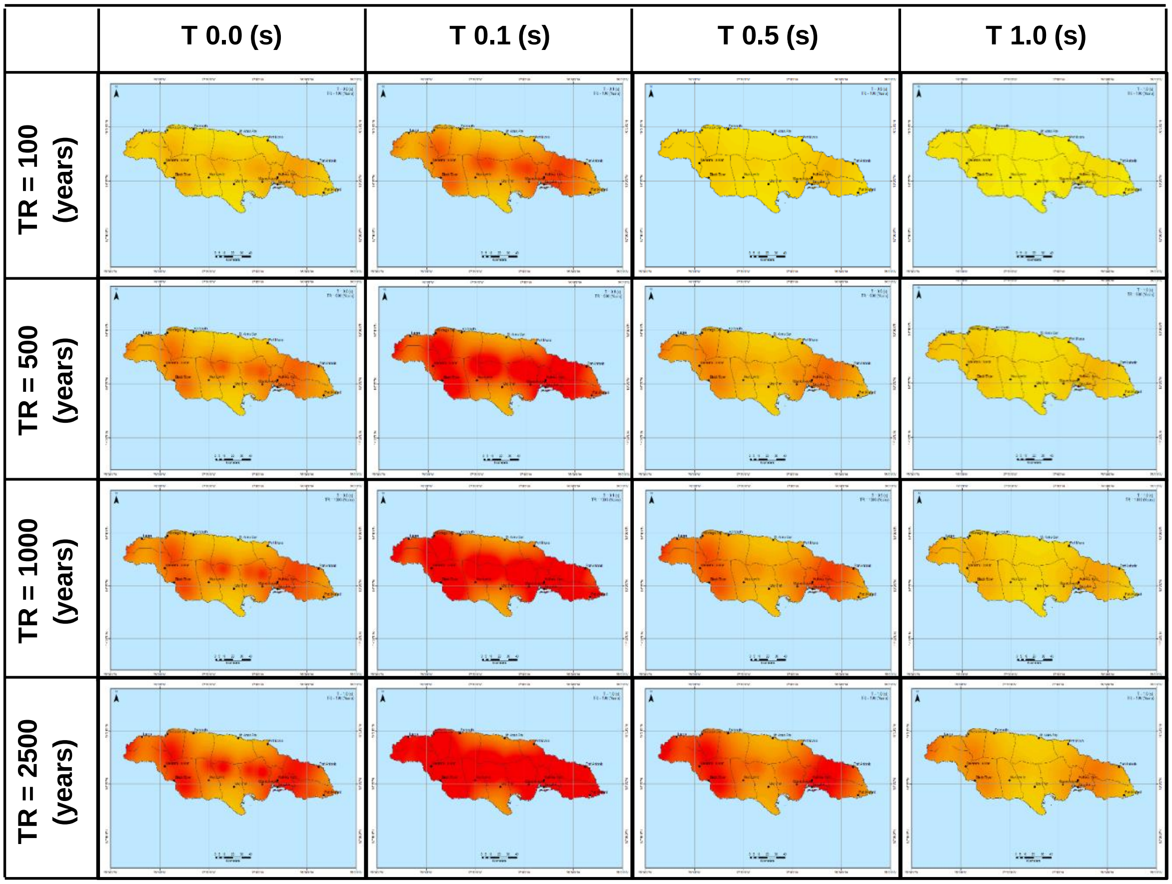


Figure 63 Maximum ground acceleration maps for different return periods

3.1.3.4 <u>Stochastic events for hazard analysis</u>

When conducting probabilistic risk analyses, a series of stochastic events are simulated, each one representing the effects of a feasible earthquake location and magnitude that could arise in the area of influence. The set of generated scenarios must represent all possible hypocenters and the whole range of possible magnitudes associated to a specific hypocenter location. Each of these events or scenarios will have a specific associated frequency of occurrence. Naturally, the scenarios associated to low magnitude earthquakes will have a higher probability of occurrence, than those scenarios associated to high magnitude earthquakes, which will have a relatively low probability of occurrence.

The procedure for calculating probabilities comprises evaluating the desired risk parameters, such as damage percentage, associated economic losses, effects on the population and others, for each of the hazard scenarios, and then, using the occurrence frequencies of each

earthquake scenario, integrating the obtained results. For the case of Jamaica, a total of 2,412 seismic hazard scenarios was generated, like those illustrated in Figure 64 to Figure 66.

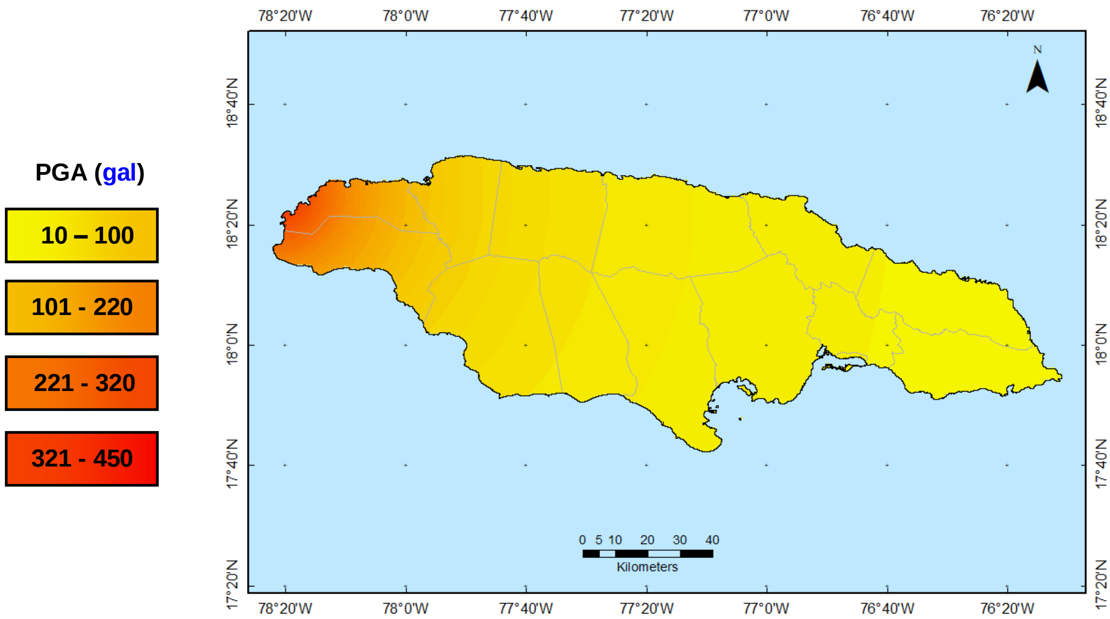


Figure 64 Maximum ground acceleration map for a 7.2 magnitude earthquake in WFZ fault

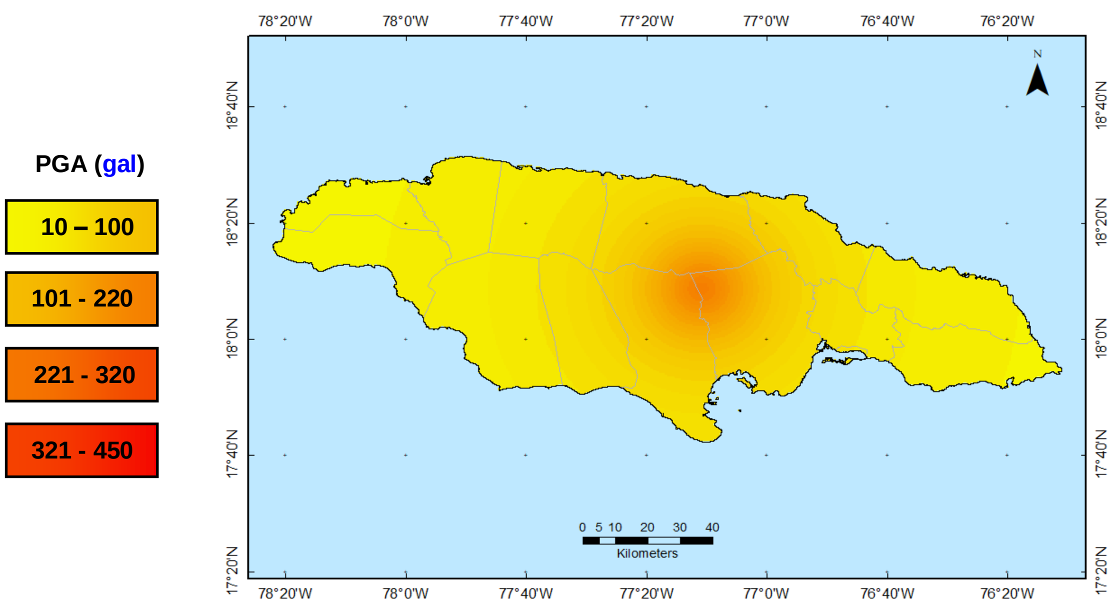


Figure 65 Maximum ground acceleration map for a 5.9 magnitude earthquake in RC fault

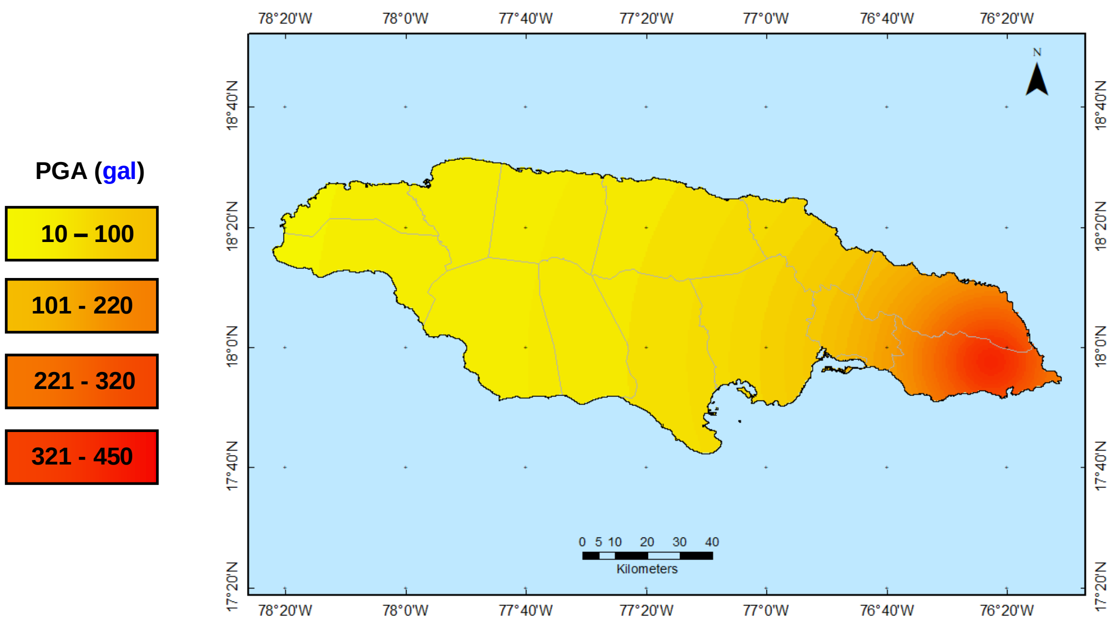


Figure 66 Maximum ground acceleration map for a 7.4 magnitude earthquake in PG fault

3.1.3.5 Hazard assessment including local soil amplification

For the consideration of the local soil amplification, a simplified methodology is adopted following the recommendations of Wald and Allen (2007). A simplified mean shear wave velocity for the upper 30 m of soil deposits, Vs30, is proposed following the indicated reference. Figure 67 presents the resulting approximate Vs30 map for Jamaica.

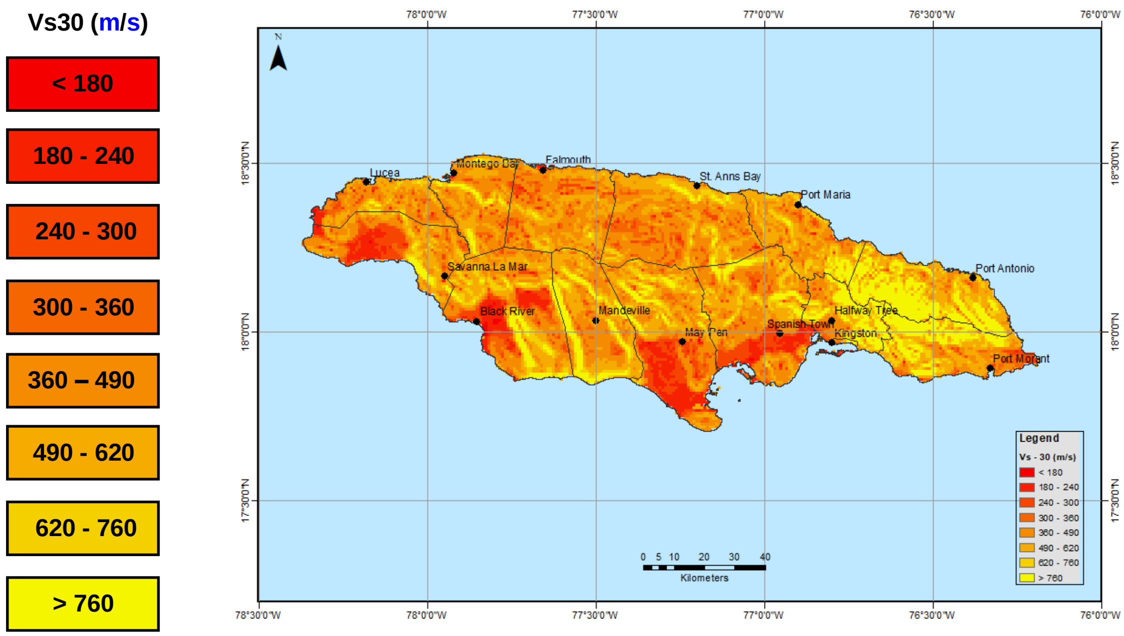


Figure 67 Mean shear wave velocity for the upper 30 m of soil deposits - Vs30

Using this proposed zonation, eight (8) different representative soil profiles are selected to estimate the soil amplification effects in each one of them. Figure 68 summarizes the resulting amplification functions for each one of these representative profiles.

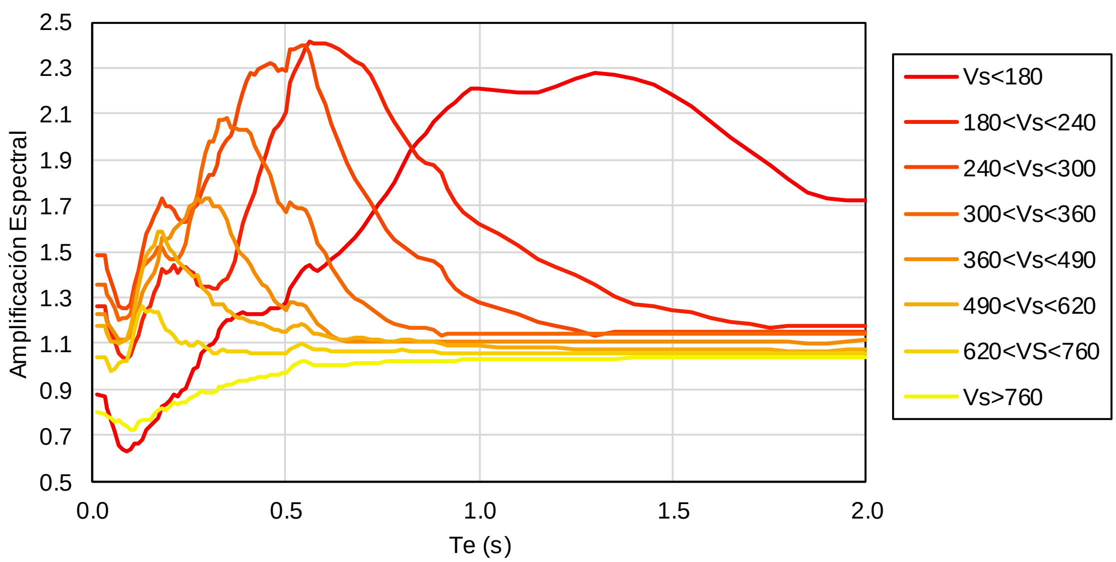


Figure 68 Amplification functions for each soil profile

The methodology for the consideration of the soil amplification effects is explained in detail in Yamin et al (2018). Following this methodology, the new probabilistic hazard maps are obtained at the surface level including the expected soil amplification effects. Figure 69 summarizes the new results.

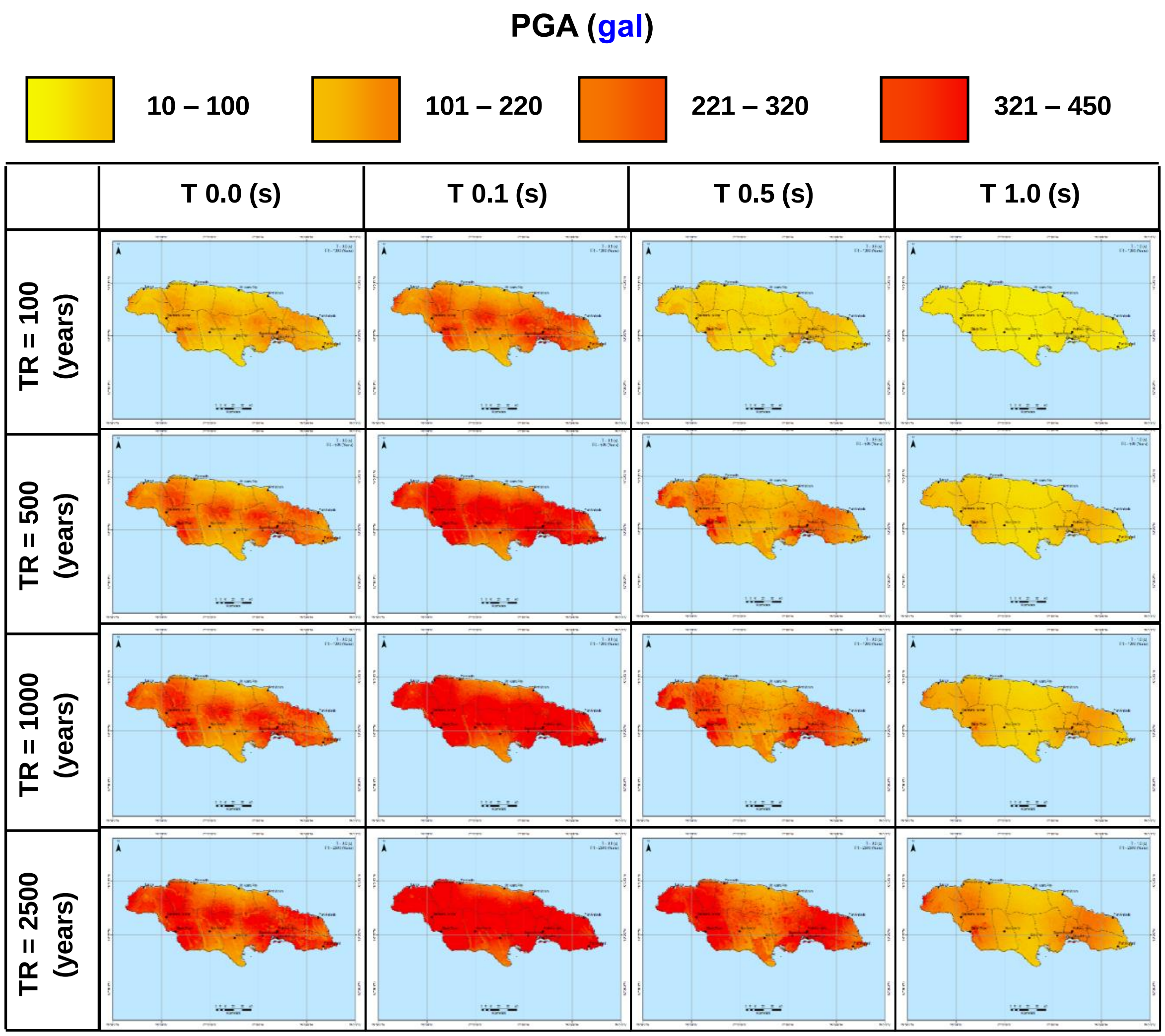


Figure 69. Maximum ground acceleration map with site effects

3.2 SEISMIC VULNERABILITY

3.2.1 Introduction

Seismic vulnerability functions relate the mean damage ratio and its variance with a selected hazard intensity measure. The seismic intensity measure most commonly used is the PGA or the spectral acceleration for a 5% damping at any given structural period (*Sa(T)*). Figure 70

presents a typical seismic vulnerability function for a representative building construction typology.

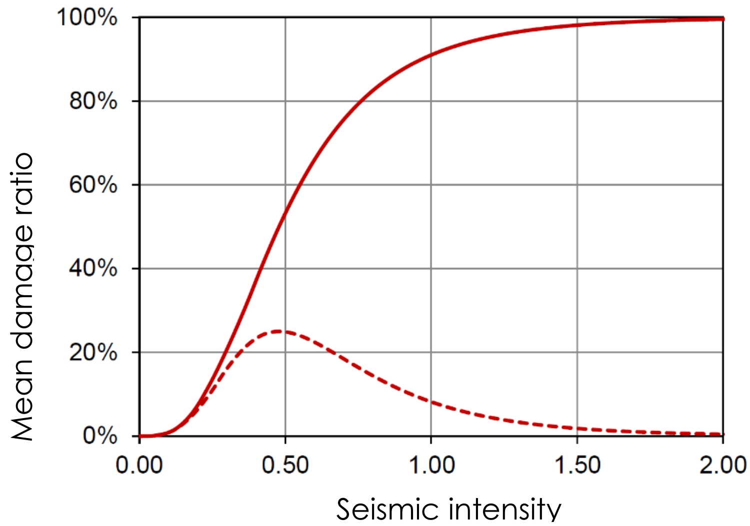


Figure 70 Typical seismic vulnerability function

The procedure for developing and assigning the seismic vulnerability functions to each individual component is the following:

(a) Identify the predominant constructions classes from the categories of exposed elements that share the same structural behavior.

(b) Select specific vulnerability functions for the predominant representative construction classes. Most published vulnerability functions are based on analytical models and direct observation of the behavior during previous events.

(c) Assign a characteristic construction class and an associated vulnerability function to each element of the exposed inventory of assets.

Once the vulnerability function of each element is assigned, the seismic risk analysis can be conducted.

Several international initiatives have proposed libraries of seismic vulnerability functions for representative building constructions. The most common being Hazus (FEMA, 2017), the GAR13 project (Global Assessment Report) (Yamin et al., 2013) and the GEM initiative

(Global Earthquake Model) (D'Ayala et al., 2015). In the present study, vulnerability functions are selected from the GAR 13 project, considering that these functions have been developed considering the construction systems, quality and material commonly found in different parts of the world, particularly in the Caribbean region.

3.2.2 Building predominant typologies

Based upon the proposed exposure model, predominant building construction typologies are identified. Table 3-2 presents predominant typologies found in the analysis region together with the representative height and a qualification of the building construction quality.

Table 3-2 Predominant building construction typologies

Building construction typologies	Abbrev	Representative height
Precarious (Earth walls, old timber, steel sheets)	PREC	Low rise
Confined masonry walls	MC	Low-mid rise
Reinforced masonry walls	MR	Low-mid rise
Non-reinforced masonry walls with slab diaphragm	MSP	Low rise
Non-reinforced masonry walls without slab diaphragm	MS	Low rise
Concrete frames	PCR	Mid-high rise
Concrete frames with masonry	PCRMM	Mid rise
Column-slab concrete frames with masonry	LCCRMM	Mid rise
Concrete frames or column-slab with masonry and weak facade	PLCMMED	Mid rise
Concrete frames and concrete walls	CCR	Mid-high rise
Concrete walls	MCR	Low-mid rise
Non-braced Steel frame	PNAC	Low-mid rise
Braced Steel frame	PAAC	Mid rise
Masonry warehouse	BM	Low rise
Reinforced concrete warehouse	BCR	Low rise
Steel warehouse	BA	Low rise
Timber frames	PM	Low rise

High	Medium	Low

Table 3-3 Building construction predominant typologies in Jamaica (Photos from Century 21 and Google Maps 2018)

Precarious

Non-reinforced masonry walls with slab diaphragm

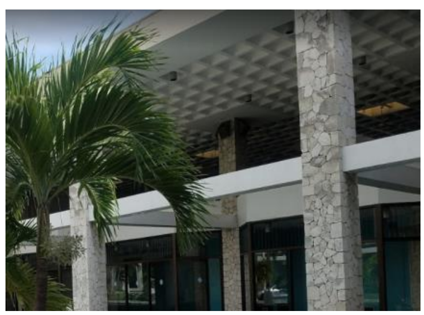
Non-reinforced masonry walls without slab diaphragm

Confined masonry walls

Reinforced masonry walls

Concrete frames

Concrete frames with masonry



Column-slab concrete frames with masonry

Timber frames

Concrete frames or column-slab with masonry and weak facade

Steel frame

Concrete walls & frames

Reinforced concrete warehouse

Masonry warehouse

Steel warehouse

3.2.3 Typical building vulnerability functions

As mentioned before, seismic vulnerability curves for the present study are selected from the catalog of vulnerability function from the GAR13 project (Yamin et al., 2013). Some of the functions were also adapted to national context based on the expected behavior and information of seismic performance in historical events in Jamaica and similar countries. Figure 71 presents the collection of seismic vulnerability functions used for the risk assessment. Each building constructions typology is identified by the abbreviation and is followed by the numbers of stories. The main typologies being: PCR: reinforced concrete frames, URM: unreinforced masonry, MC: confined masonry, MR: reinforced masonry, MS, MSP and MSCB: different categories of unreinforced masonry and C1 to C5: different categories of reinforced concrete structures.

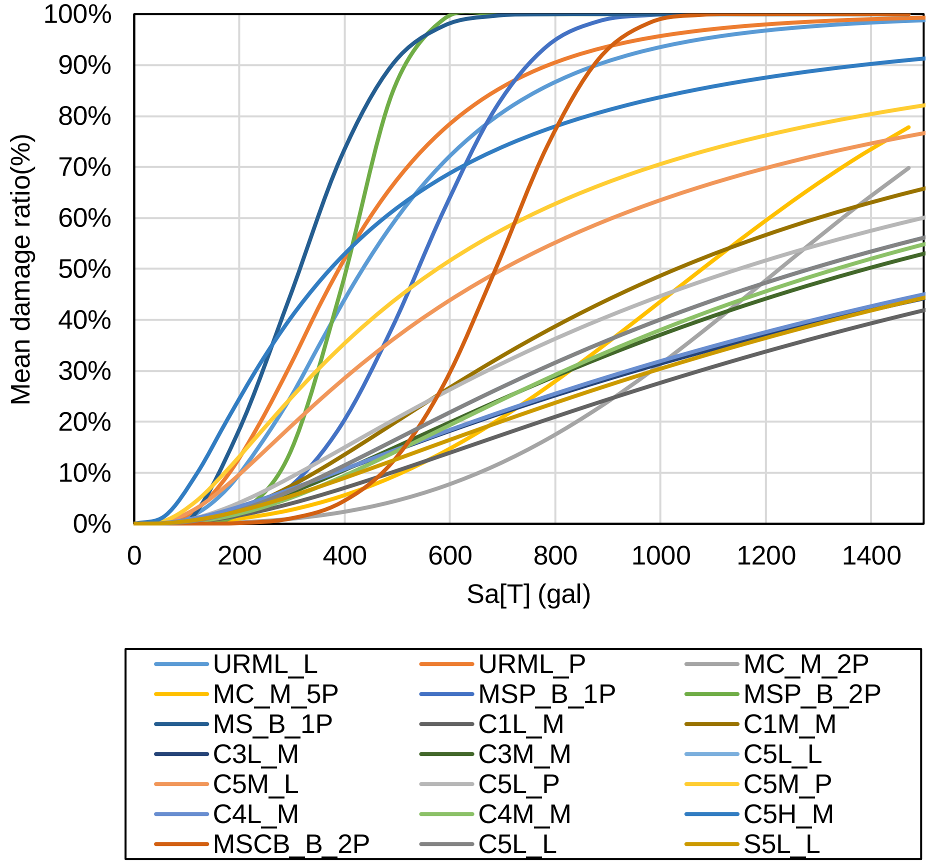


Figure 71 Selected seismic vulnerability curves

3.2.4 Building construction assignment

In order to assign a representative building construction typology to each one of the exposed components included in the database the following procedure was adopted:

a) Identify building construction typology.
b) Obtain number of stories from the database.
c) Assign the built quality depending on the complexity of the parish (High built quality is assigned in high complexity)
d) Assign a vulnerability function from the GAR13 (Yamin et al, 2013) that matches the characteristics of each building.

There are three main parameters that allow vulnerability functions to be assigned: structural system or typology, stories and quality of construction. According to defined structural systems and collected information results, vulnerability functions that represents expected behavior are selected from the literature.

As result of this procedure, Figure 72 presents the distribution of building construction typologies and Figure 73 illustrates the final distribution considering the main building construction material. In these figures, each building constructions typology is identified by the abbreviation and is followed by the numbers of stories, for example: PCR_1_3 is a concrete frame in which stories can vary from 1 to 3.

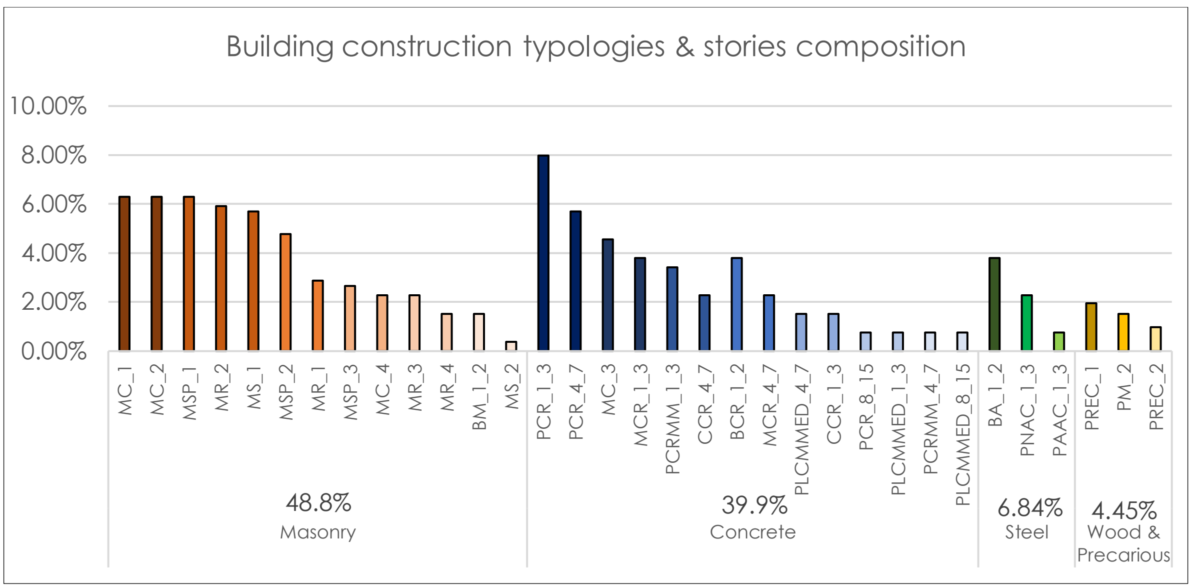


Figure 72 Distribution of building construction typologies

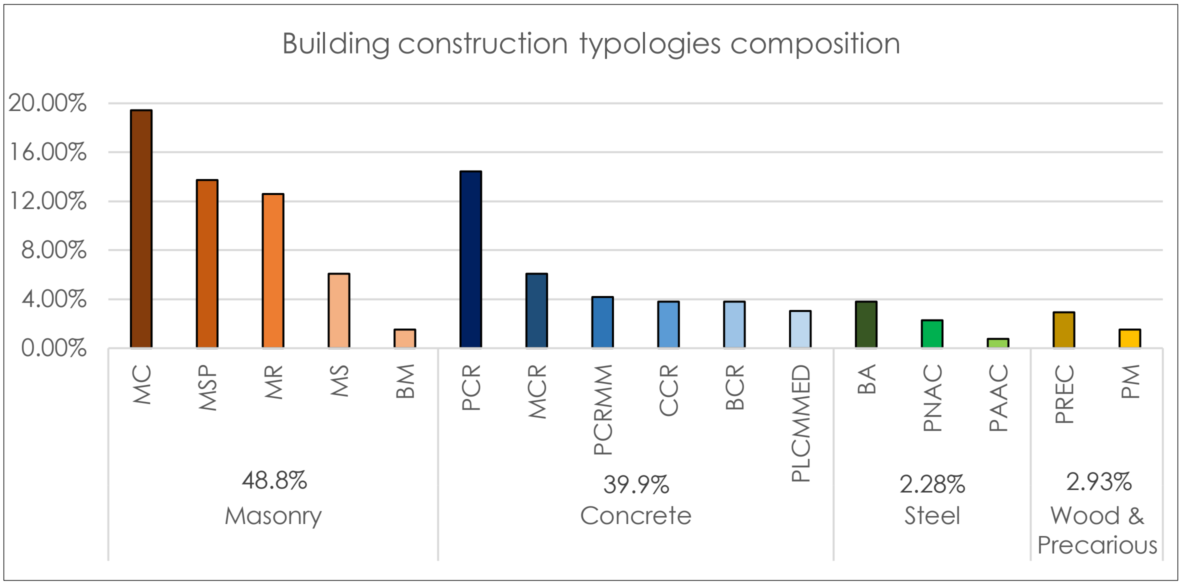


Figure 73 Distribution of building construction by material type

The results indicate that the predominant typologies in Jamaica are the concrete frames PCR_1_3, and confined and unreinforced masonry systems MC_1 and MSP_1. Other important typologies are reinforced masonry and taller concrete frame buildings. The most common structural system is confined and reinforced masonry, unreinforced masonry and concrete frames. These systems accounts for the 60% of the entire building stock.

3.3 SEISMIC RISK

Using the above-mentioned hazard, exposure and vulnerability information, a probabilistic seismic risk assessment was developed at the country level using the CAPRA platform (www.ecapra.org). Table 3-4 presents the most relevant figures for the total exposed values, the Expected Annual Losses (EAL) and the probable maximum losses (PML) for different return periods. Some relative figures are presented with respect of the GDP or the total population using figures presented in Table 2-1.

Table 3-4 Seismic risk – EAL and PML – Total

Total Exposed Value: TEV	**US$ (Millions)**	$ 44,576
Expected Annual Loss: EAL	**US$ (Millions)**	$ 37
	‰ of TEV	0.83
Probable Maximum Loss: PML		
Return Period	**US$ (Millions)**	**%**
100	$ 1,054	2.4
250	$ 2,033	4.6
500	$ 2,838	6.4
1000	$ 3,638	8.2

In addition, Table 3-5 presents the results discriminated between the building constructions and infrastructure stocks. The results are presented in absolute terms as well as percentages of the country annual GDP and per capita figures.

Table 3-5 Seismic risk - EAL and PML - Buildings and Infrastructure

	Buildings		**Infrastructure**	
Total Exposed Value: TEV	**US$ (Millions)**	$ 34,839	**US$ (Millions)**	$ 9,736
Expected Annual Loss: EAL	**US$ (Millions)**	$ 36	**US$ (Millions)**	$ 0.4
	‰ of TEV	1.0	**‰ of TEV**	0.04
	% of GDP	0.25%	**% of GDP**	0.003%
	US$/Inhabitant	$ 13	**US$/Inhabitant**	$ 0
Probable Maximum Loss: PML				
RP	**US$ (Millions)**	**%**	**US$ (Millions)**	**%**

100	$ 1,041	3.0	$ 10	0.1
250	$ 2,007	5.8	$ 27	0.3
500	$ 2,815	8.1	$ 45	0.5
1000	$ 3,595	10.3	$ 66	0.7
PML1000 (%GDP)	24%		0.5%	
PML1000 (US$/inh.)	$ 1,332		$ 25	

Moreover Figure 74 shows the PML curves at the national level, and the discriminated values for building construction and infrastructure stock. These results indicate that the building stock represents more than 95% of the expected national losses.

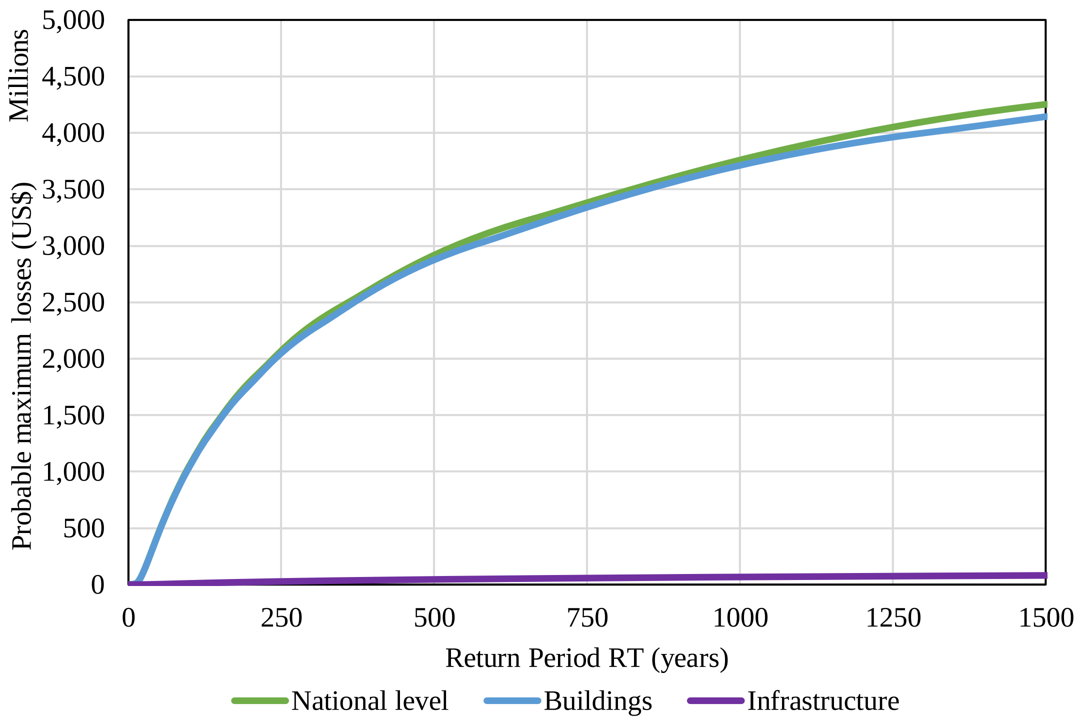


Figure 74 Seismic risk - PML curves at National level

Table 3-6 presents the seismic risk results disaggregated by public and private sector. In summary, the private sector has a much higher total expected loss than the public sector, because it represents a much higher value in the exposure model.

Table 3-6 Seismic risk - results disaggregated by private and public sectors

SECTOR	Total Exposed Value TEV (US$ Millions)	EAL (US$ Million)	Relative EAL (‰ of TEV)
Private Buildings	$ 29,676	$ 30	1.0
Public Buildings	$ 5,164	$ 7	1.3
Infrastructure	$ 9,736	$ 0.4	0.04
Total	$ 44,576	$ 37	0.8

On the other hand, Table 3-7 shows the results aggregated by the main use sectors. The Residential, Commercial and Offices buildings have the highest total risk, whereas the Residential, Education and Health have the highest relative risk.

Table 3-7 Seismic risk disaggregated by sub-sectors

SECTOR	Total Exposed Value TEV (US$ Millions)	EAL (US$ Million)	Relative EAL (‰ of TEV)
Residential	$ 17,777	$ 22	1.2
Education	$ 2,660	$ 3	1.0
Health	$ 60	$ 0.06	1.1
Administrative	$ 888	$ 1	0.9
Industrial	$ 2,669	$ 2	0.8
Commercial	$ 7,061	$ 6	0.9
Offices	$ 3,724	$ 3	0.9
Transportation	$ 7,814	$ 0.07	0.01

Energy System	$ 643	$ 0.18	0.3
Hydrocarbons and oil derivatives	$ 774	$ 0.02	0.0
Telecommunication	$ 107	$ 0.09	0.8
Water supply, sanitation and urban pipes systems	$ 398	$ 0.09	0.23
Total	**$ 44,576**	**$ 37**	**0.8**

Figure 75 shows the EAL (total and relative) for each sector included in the analysis.

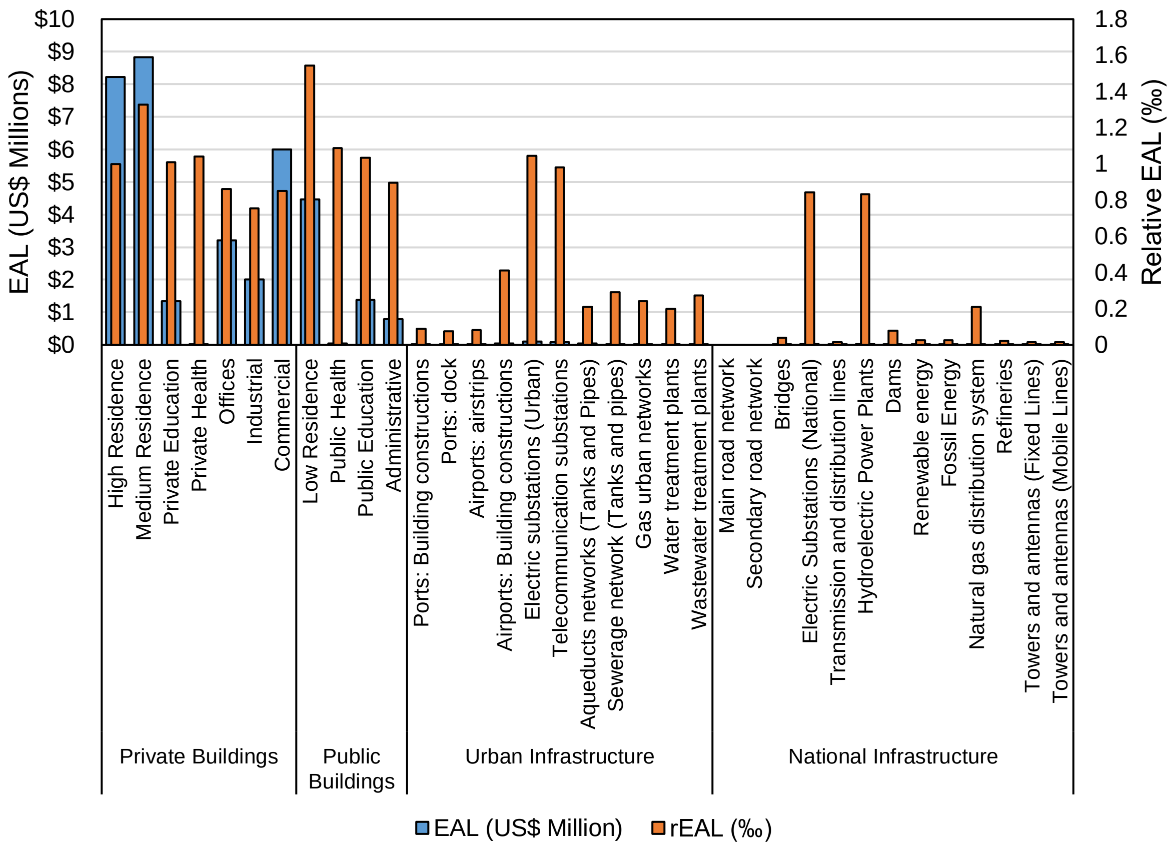


Figure 75 Seismic risk- EA and relative EAL (rEAL) for sub- sector

CHAPTER
5

RISK RESULTS ANALYSIS

4.1 EXPECTED ANNUAL AND PROBABLE MAXIMUM LOSSES

In the previous Chapters, the risk assessment for Jamaica has been presented for both the hurricane wind and the seismic ground vibration hazards. The potential impacts of those events can certainly be categorized as catastrophic and therefore they shall be considered in the risk assessment profile at the country level. The comparison between them is certainly of interest to the Government and institutions in charge of the disaster risk management at country, regional or local level.

Table 4-1 shows the risk results for the entire exposure portfolio for the two worst possible natural events in terms of potential impacts, the hurricane wind and the seismic ground vibrations (earthquake). As can be easily concluded from the results presented, the hurricane wind risk is higher than the earthquake risk, by a factor of more than 3.

Table 4-1 Risk Results Comparison

	Hurricane Wind		Earthquake	
Total Exposed Value: TEV	**US$ (Millions)**		$ 44,576	
Expected Annual Loss: EAL	**US$ (Millions)**	$ 127	**US$ (Millions)**	$ 37
	‰ of TEV	2.8	**‰ of TEV**	0.8
	% of GDP	0.86%	**% of GDP**	0.25%
	US$/Inhabitant	$ 47	**US$/Inhabitant**	$ 14
Probable Maximum Loss: PML				
RP	**US$ (Millions)**	**%**	**US$ (Millions)**	**%**
100	$ 3,005	6.7	$ 1,054	2.4
250	$ 5,991	13.4	$ 2,033	4.6
500	$ 9,194	20.6	$ 2,838	6.4

1000	$ 11,800	26.5	$ 3,638	8.2
PML1000 (%GDP)	80%		25%	
PML1000 (US$/inh.)	$ 4,370		$ 1,347	

Figure 76 presents the PML curves for hurricane wind and earthquake risk. Once again, the figure indicate that hurricane wind risk is much higher than earthquake risk at the country level. This means that the worst possible expected scenarios would be produced by a hurricane that could impact the island in the future. It also means, that the combination intensity and frequency will be also controlled by hydrometeorological events as opposed to geologic events. However, earthquake risk is not to be sub estimated, as it also represents a significant values of the GDP.

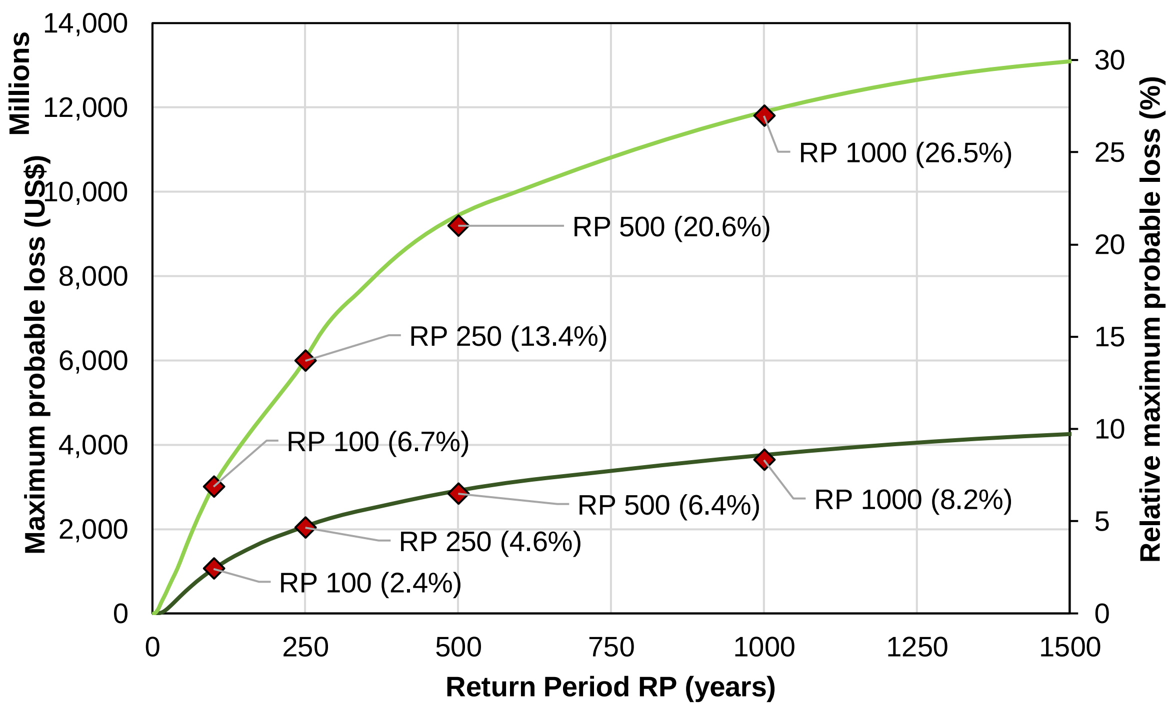


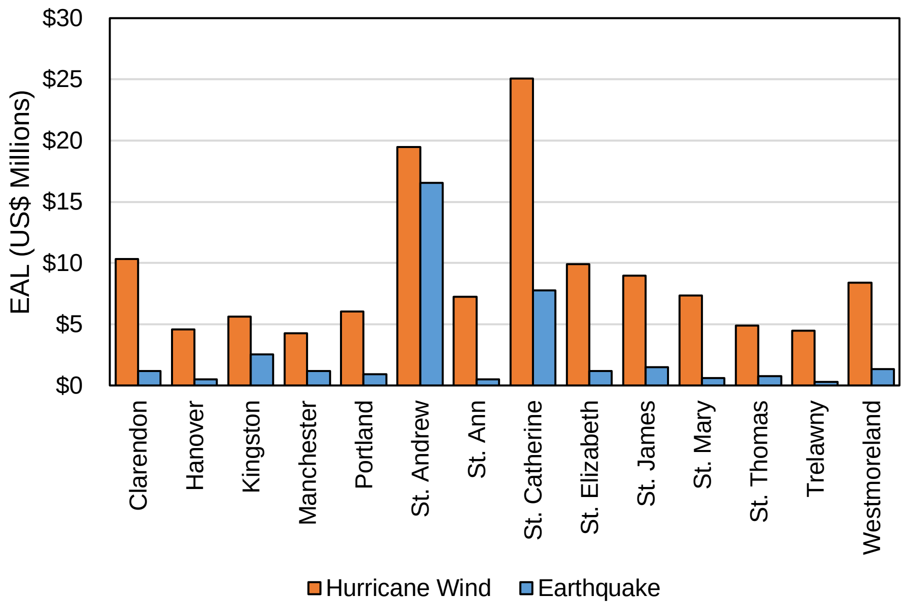
Figure 76 Probable Maximum Losses curve comparison.

4.2 EXPECTED ANNUAL LOSS PER PARISH

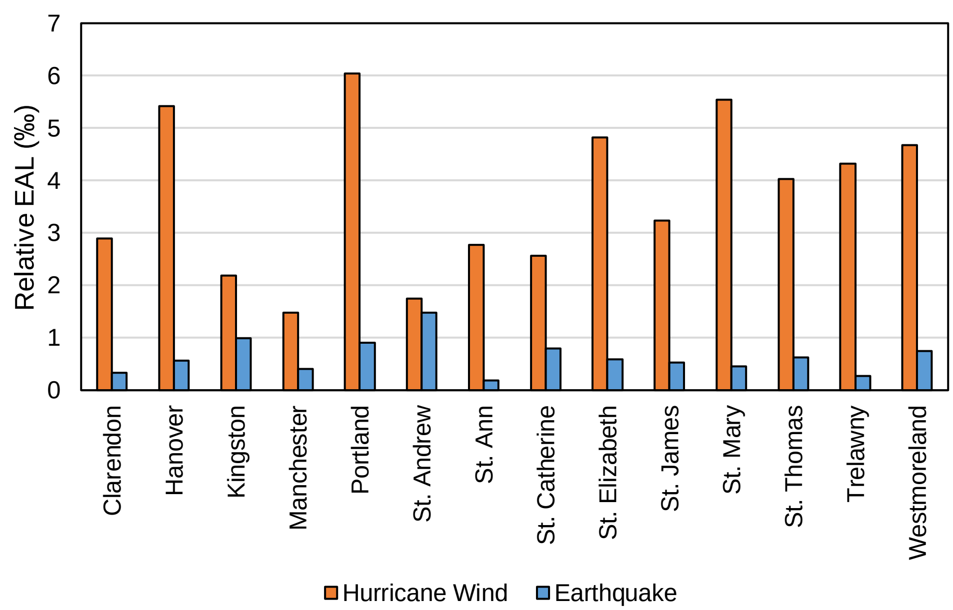
The comparison can also be done at the regional level. Figure 77 a) presents the expected annual losses results by parish, for both hurricane wind and earthquakes. These results indicate that, in general, the hurricane wind risk controls in almost all parishes except in St.

Andrew, where the EAL are very similar for the two types of events. Moreover Figure 77 b) indicates that in general the building stock has a higher relative wind vulnerability than a seismic one, considering simultaneously the corresponding levels of hazard in the two cases. In other words, the relation between hazard and vulnerability turns out to be higher for hurricane wind than for earthquakes.

In addition, Figure 78 shows the geographical distribution of the Expected Annual Losses (EAL) by parish.

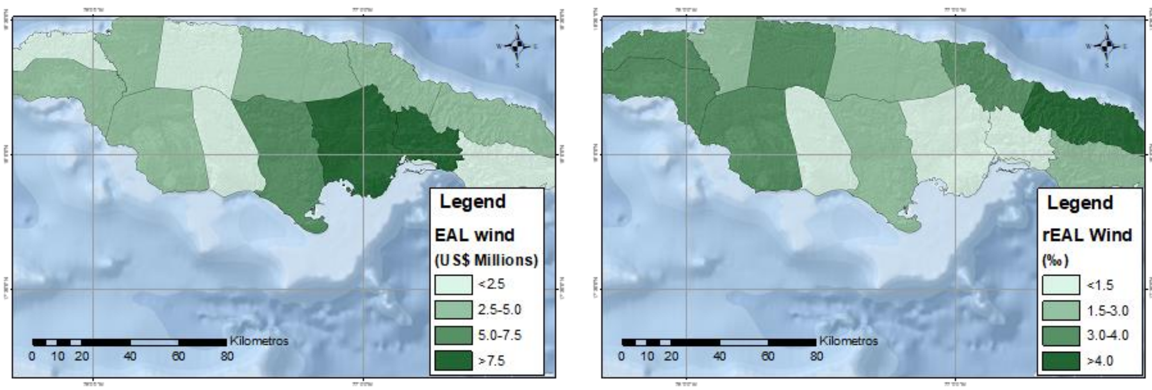


(c) Expected Annual Losses (Total)

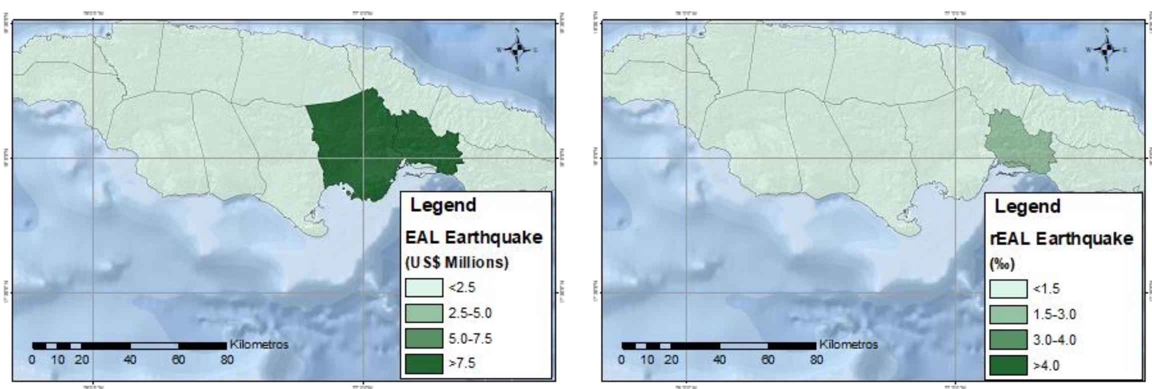


(d) Expected Annual Losses (Relative)

Figure 77 Expect annual Losses by Parish



(d) Hurricane wind risk



(e) Earthquake risk

Figure 78 EAL Comparison per Parish, Left: relative EAL; Right: Absolute EAL

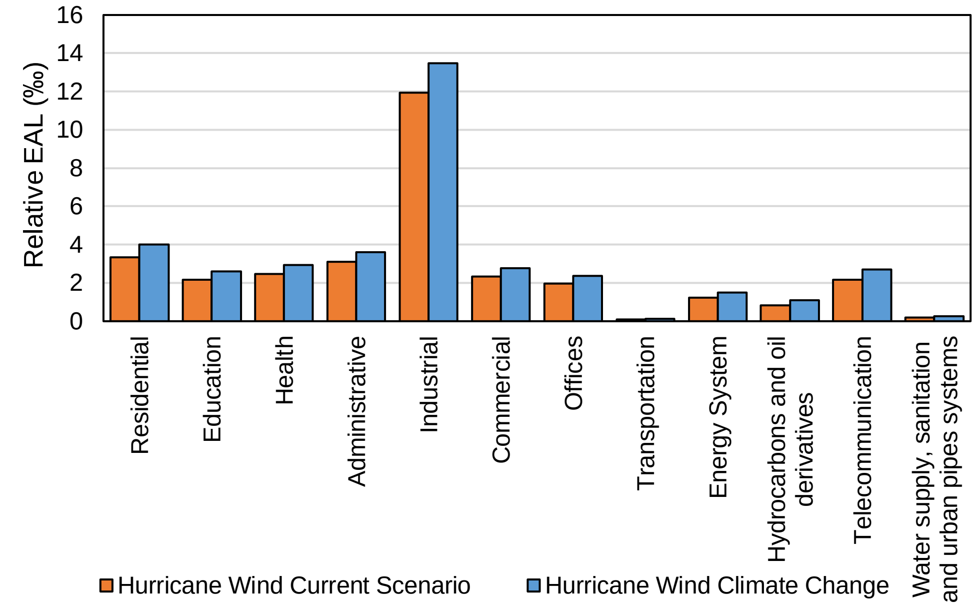
4.3 EXPECTED ANUAL LOSSES BY USE SECTORS

The comparison of risk results by use sectors is also relevant to the Government and institutions. Table 4-2 shows the expected annual losses for hurricane wind and earthquake risk, discriminated by the proposed use sectors. It can be concluded that hurricane wind risk is much higher than earthquake risk in all sectors. Figure 79 presents the results graphically.

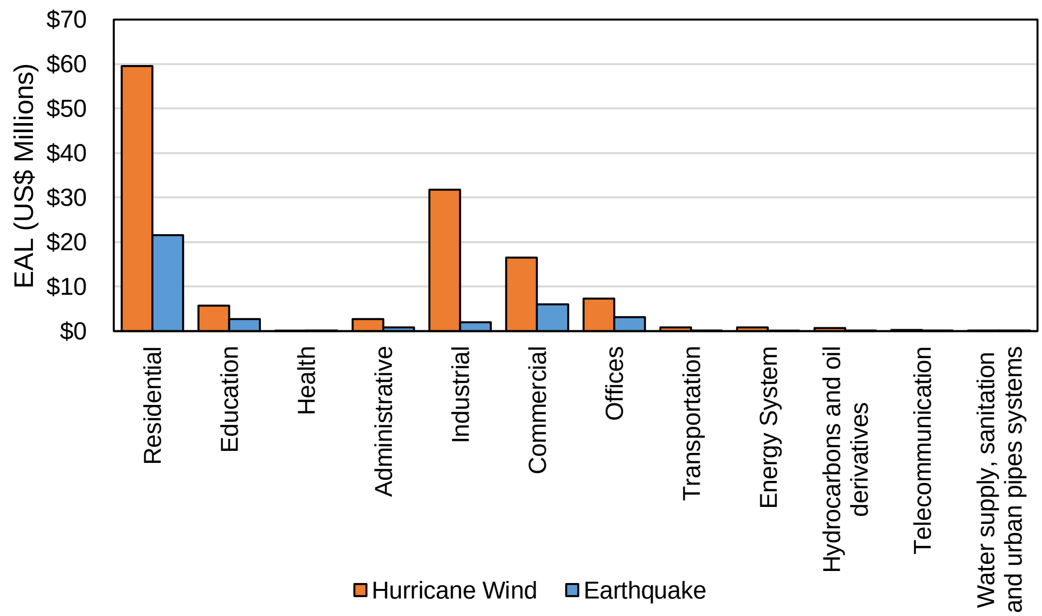
Table 4-2 Expected Annual Losses by use sector

		Hurricane Wind Current Scenario		Earthquake		Difference
SECTOR	**Total Exposed Value TEV (US$ Millions)**	**EAL (US$ Million)**	**Relative EAL (‰ of TEV)**	**EAL (US$ Million)**	**Relative EAL (‰ of TEV)**	**(%)**
High Residence	$ 8,227	$ 21	2.6	$ 8	1.00	62%
Medium Residence	$ 6,650	$ 25	3.8	$ 9	1.33	65%
Low Residence	$ 2,900	$ 13	4.5	$ 4	1.54	66%
Residential	$ 17,777	$ 60	3.4	$ 22	1.21	64%
Private Education	$ 1,331	$ 2.9	2.2	$ 1.3	1.01	53%
Public Education	$ 1,329	$ 2.9	2.2	$ 1.4	1.04	53%
Education	$ 2,660	$ 5.8	2.2	$ 2.7	1.02	53%
Private Health	$ 13	$ 0.02	1.9	$ 0.01	1.04	46%
Public Health	$ 47	$ 0.12	2.6	$ 0.05	1.09	59%
Health	$ 60	$ 0.15	2.5	$ 0.06	1.08	56%
Administrative	$ 888	$ 2.7	3.1	$ 0.8	0.89	71%
Offices	$ 3,724	$ 7.3	2.0	$ 3.2	0.86	56%
Industrial	$ 2,669	$ 32	11.9	$ 2.0	0.76	94%
Commercial	$ 7,061	$ 17	2.3	$ 6.0	0.85	64%
Buildings	$ 34,839	$ 124	3.6	$ 36	1.04	71%
Transportation	$ 7,814	$ 0.8	0.1	$ 0.09	0.01	89%
Energy Systems	$ 643	$ 0.8	1.2	$ 0.02	0.03	98%
Hydrocarbons and oil derivatives	$ 774	$ 0.63	0.8	$ 0.09	0.11	86%
Telecommunication	$ 107	$ 0.23	2.2	$ 0.18	1.65	24%

Water supply, sanitation and urban pipe systems	$ 398	$ 0.08	0.2	$ 0.07	0.17	17%
Infrastructure	$ 9,736	$ 2.6	0.3	$ 0.4	0.04	83%
Total	**$ 44,576**	**$ 127**	**2.8**	**$ 37**	**0.83**	**71%**



(c) EAL comparison (Total)



(d) EAL comparison (Relative)

Figure 79 Expected annual losses by sector

4.4 EXPECTED ANUAL LOSS FOR THE PUBLIC AND PRIVATE SECTORS

Table 4-3 shows the results aggregated according to private buildings, public buildings and infrastructure. These results indicate that the hurricane wind risk for the private buildings is the highest for these groups. On the other hand, no significant difference can be observed between the relative risk for the public and the private sector.

Table 4-3 Expected Annual Losses for Public and Private Sectors

		Hurricane Wind		Earthquake		Difference
SECTOR	**Total Exposed Value TEV (US$ Millions)**	**EAL (US$ Million)**	**Relative EAL (‰ of TEV)**	**EAL (US$ Million)**	**Relative EAL (‰ of TEV)**	**(%)**
Private Buildings	$ 29,676	$ 105	3.5	$ 30	1.0	72%
Public Buildings	$ 5,164	$ 19	3.6	$ 7	1.3	64%
Infrastructure	$ 9,736	$ 3	0.3	$ 0.4	0.04	83%
Total	$ 44,576	$ 127	2.8	$ 37	2.3	71%

Figure 80 shows the results graphically.

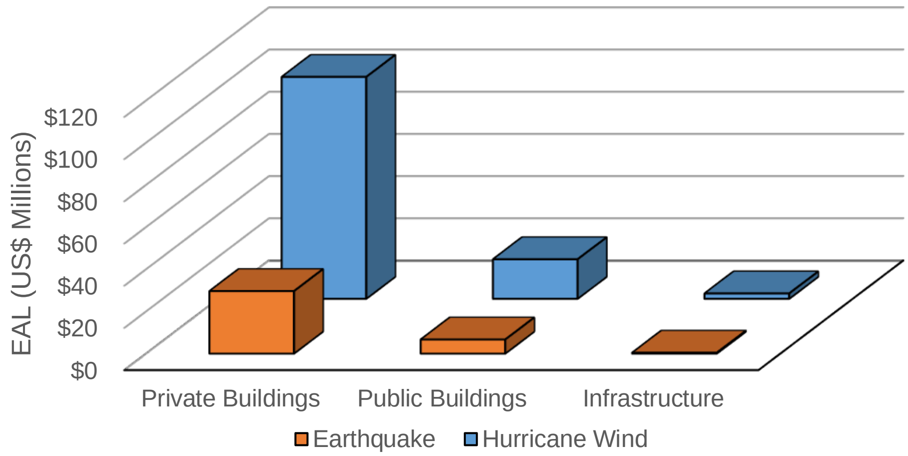


Figure 80 Graphic Comparison Private Vs Public Sector

4.5 CONCLUSIONS

From the previous results, the following conclusions can be obtained for the building stock and infrastructure in Jamaica at country level:

a) The total exposed value (TEV) for building constructions and infrastructure for Jamaica is estimated in US$ 45 billion. From this figure, approximately 75% correspond to building constructions and the rest, 25%, to infrastructure.

b) The expected annual loss, EAL, for hurricane wind is about US$ 127 million (2.8‰ of the TEV and 0.87% of the GDP) and for earthquake ground vibrations is US$ 37 million (0.8‰ of the TEV and 0.25% of the GDP).

c) The probable maximum loss for 1000-year return period, PML_{1000}, for hurricane wind is about US$ 11,800 million (26.5% of the TEV) and for earthquake ground vibrations is US$ 3,638 million (8.2% of the TEV).

d) The highest hurricane wind risk occurs in the parishes of St. Catherine and St. Andrew. In St. Catherine the EAL is about US$ 25 million corresponding to approximately 19% of the total EAL estimated for the country. Hurricane wind

controls the risk figures in almost all parishes except in St. Andrew, where the EAL are very similar for hurricane wind and earthquakes.

e) The Residential, Industrial and Commercial sectors concentrate the highest total risk, whereas the Industrial, Residential and Administrative have the highest relative risk. In all sectors hurricane wind dominates over earthquake risk.

f) The private residential buildings concentrate much of the risk on the building and infrastructure stock. The total EAL for the private sector building stock for hurricane amounts approximately US$ 105 million as compared to the public-sector buildings and infrastructure which accounts for an EAL of about US$ 22 million.

CHAPTER

6

KMA FLOOD RISK (INDICATIVE)

5.1 FLOOD HAZARD ASSESSMENT

5.1.1 General aspects

This Chapter presents the results of an approximate and indicative flood hazard and risk assessment for the urban areas of the Kingston Metropolitan Area (KMA), due to hydrological events associated with hurricane precipitation. The main purpose of this preliminary assessment is to have an insight about the recurrence, intensity and geographical distribution of flooding events in this critical area and understand the potential of damage and losses of the most critical possible events. These results shall indicate the line of action for more detailed assessments and for the dimensioning of this recurrent problem in Jamaica´s Capital City.

In the following sections, the general methodology and the results of the flood hazard and risk assessment are presented for the KMA. Flood hazard results are presented in terms of the expected intensity (inundation depth) and the corresponding geographical distribution for selected return periods of analysis and a flood susceptibility map for KMA. In addition, preliminary figures about the expected impact to the building stock and the population are given in terms of damage, economic losses and potential human effects.

The general methodology for the flood risk assessment in the KMA region includes the following main activities:

a) Precipitation hazard assessment: in the present case only, the hurricane precipitation hazard will be considered. Using the same hurricane model as presented in Chapter 3, the precipitation hazard will be assessed for the same stochastic scenarios as the ones defined previously.
b) Flood hazard assessment: a hydrologic and a hydraulic model are built in order to estimate the inundation footprint and the distribution of inundation depths for any given stochastic scenario.

c) Vulnerability functions will be assigned to each one of the components included in the exposure database. In Chapter 2 the exposure model for the KMA region was presented in detail and is used in this chapter to assess the flood risk.
d) The flood risk will be estimated using the standard probabilistic risk assessment methodology adopted by the CAPRA platform.

Additional and more detailed information on the methodological approach adopted for the flood hazard and risk assessment can be found in www.ecapra.org.

The main considerations/limitations of this preliminary assessment are the following:

a) It only considers hurricane related precipitation events.
b) A uniform precipitation intensity is assumed on the area of analysis.
c) For the assessment, a DEM with a 30 m resolution is used in combination with a 6 m resolution for specific areas where available.
d) The vertical precision of the model is about 5 m. The model does not consider the presence of buildings and streets, but considers the general land use of the city.
e) In the assessment it is supposed that the complete drainage system of the flooded area collapses. This gives therefore an upper bound for the flooding footprints and the risk values.
f) Additional modification as including gullies in the topography were not included due to the coarse resolution of the DEM, in which minor water courses were not detected.

5.1.2 Flood hazard assessment

5.1.2.1 Precipitation hazard

For the present study, the precipitation hazard analysis is restricted to intense rainfall due to hurricanes. The reason for that is the large percentage of missing continuous data in pluviometric stations in the study zone (see Figure 81) with less than 30 years of records. This limitation would imply a series of additional analysis such as a data completeness analysis, the homogenization of information and inconsistency tests. All these activities would generate a highly unreliable data source to perform the hazard analysis in the present case. Therefore, a more reliable precipitation hazard assessment is preferred using the hurricane precipitation hazard model.

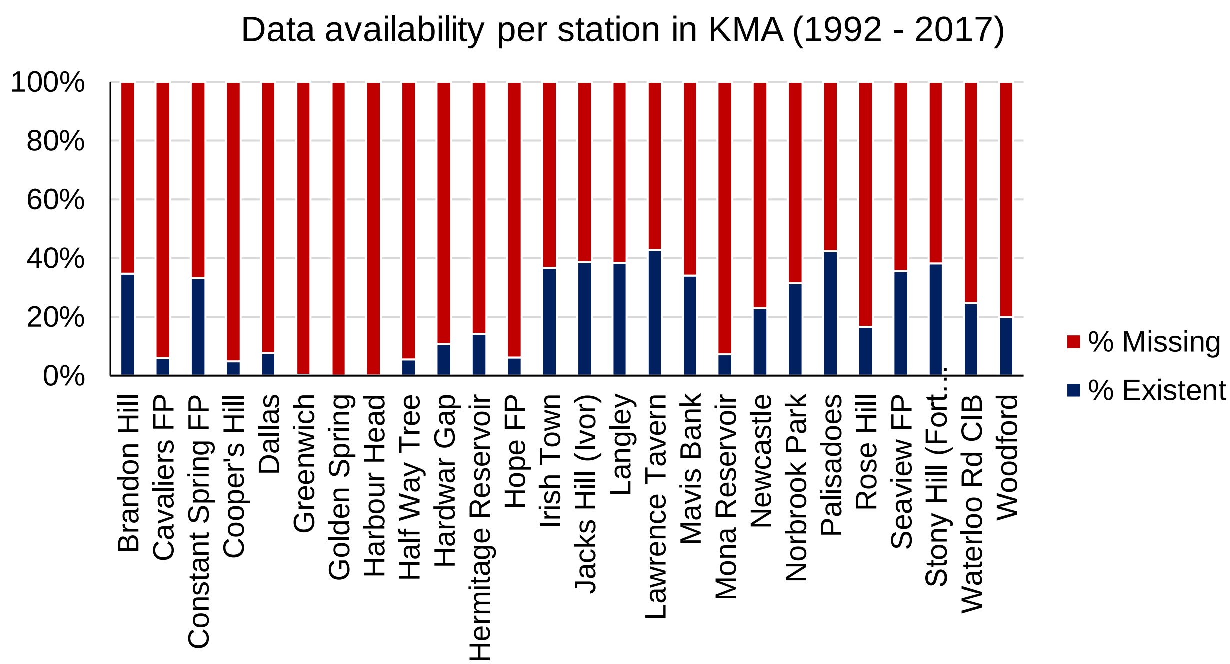


Figure 81. Rainfall data availability in KMA

The same hurricane model presented in Chapter 3 is used as a base for the precipitation hazard model. The model is based on the assumption of an aggregated rainfall field, i.e. the total accumulated rainfall per day that is produced in each point by the passage of a hurricane. The assessment includes the 9,100 simulated events of the database as explained before. The final model is composed of 9,100 stochastic precipitation events, each one with an associated annual frequency of occurrence, corresponding to the annual frequency of hurricanes of different categories.

The results of this assessment are presented at national level, even though the information is only employed for the KMA flood hazard and risk assessment. Figure 82 shows some illustrative critical stochastic scenarios of precipitation at national level, each one associated with a historical or simulated event. Figure 83 presents the probabilistic daily maximum accumulated rainfall maps (in mm/day) for different return periods nationwide. Finally, Figure 84 presents the precipitation hazard curve for the center of KMA for illustrative purposes.

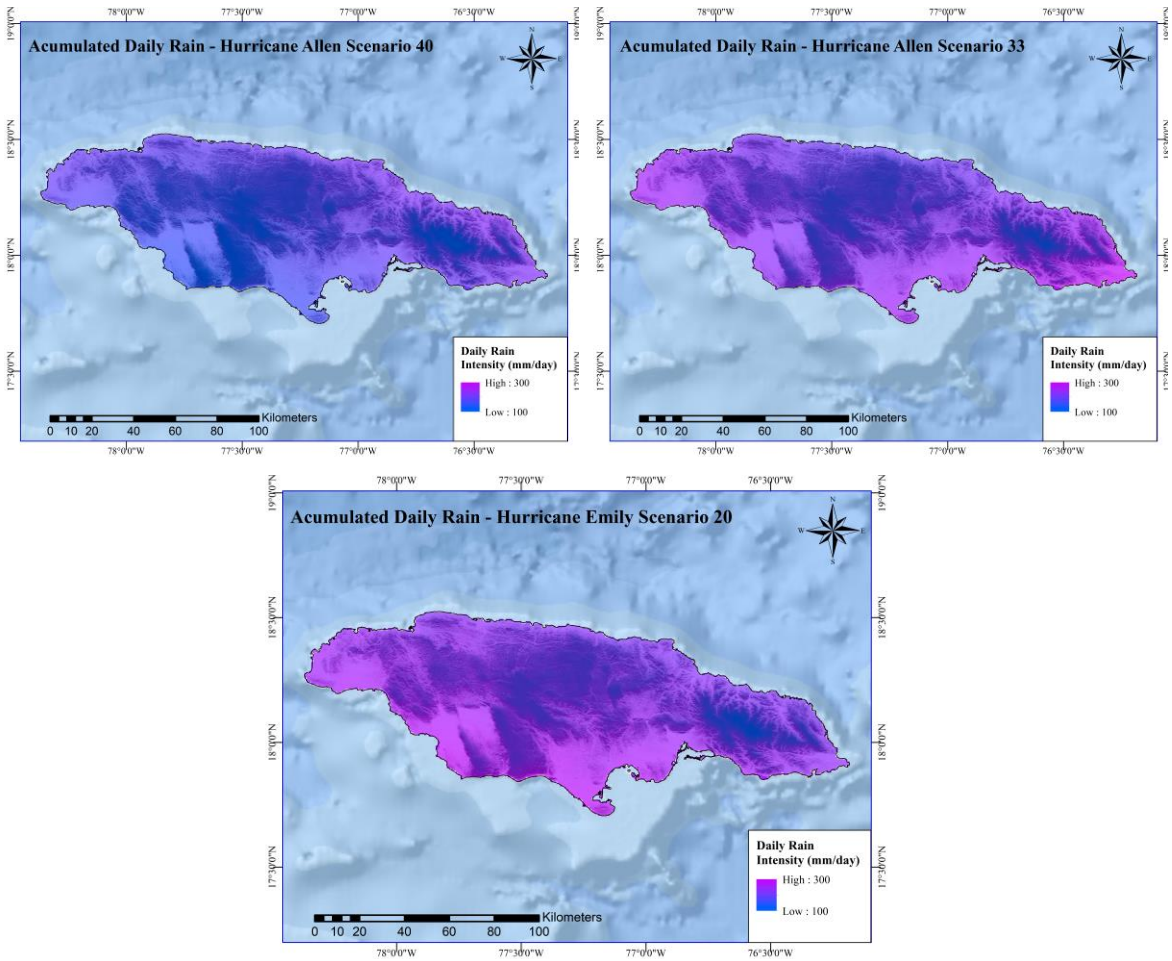


Figure 82 Critical stochastic scenarios of precipitation

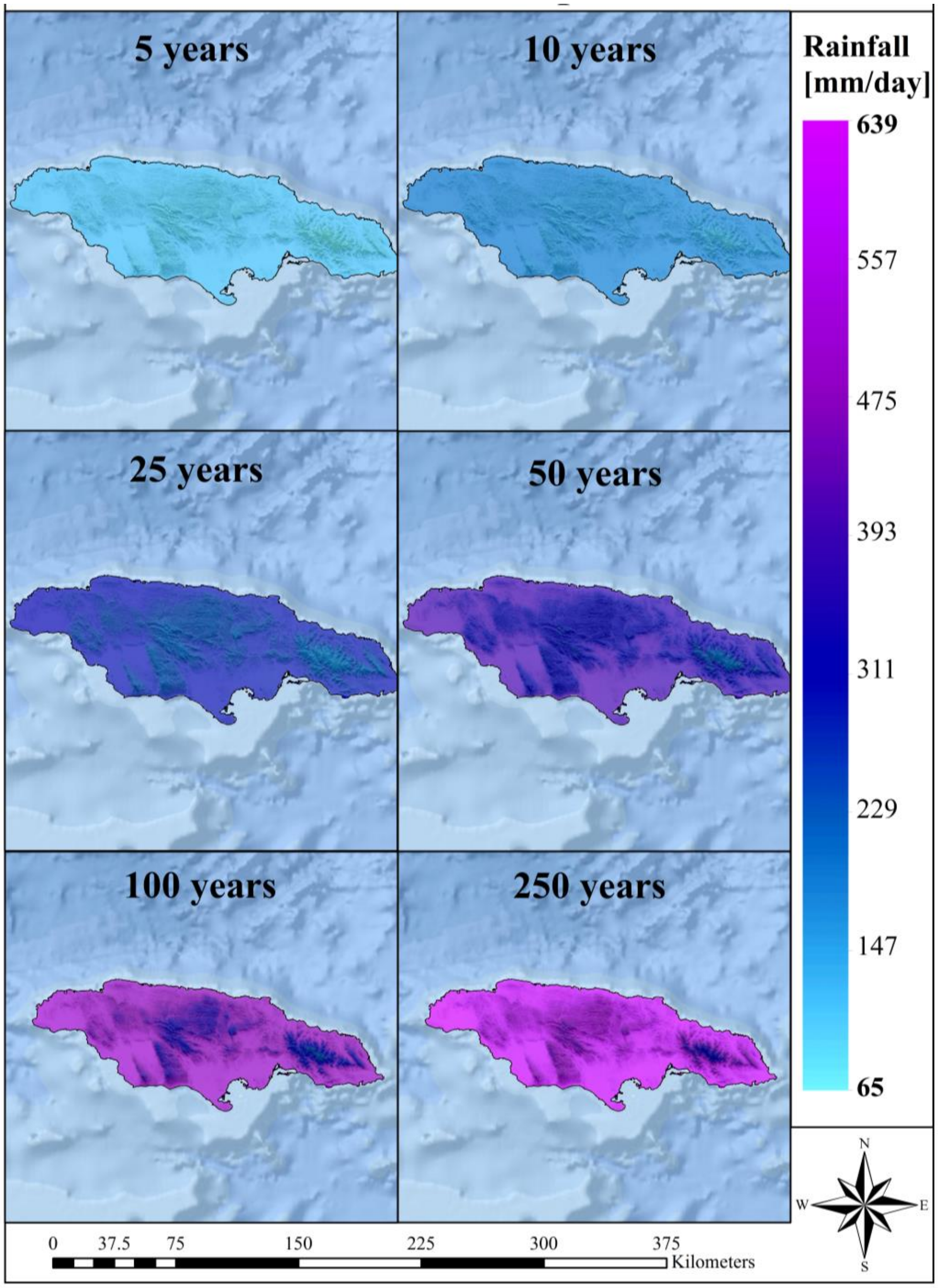


Figure 83. Hurricane probabilistic rainfall maps for different return periods nationwide

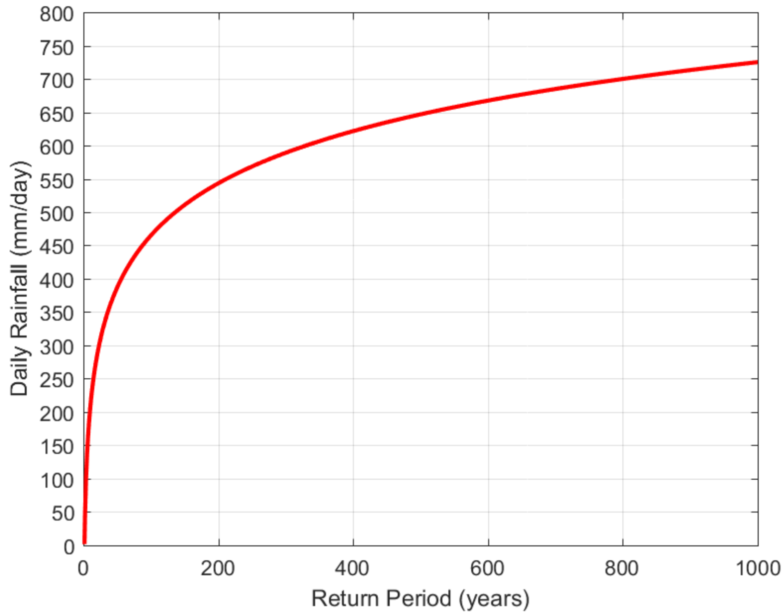


Figure 84. Hurricane rainfall hazard curve for KMA

5.1.2.2 Flood hazard assessment

The flooding hazard is directly related to the rainfall intensity in the influence area or basin, the topographic characteristics of the terrain, the land use and the type of soil of the terrain. Considering this, hydrologic and hydraulic models are used to determine the run-off generated by a precipitation event. The overall methodology requires a hydrological analysis and a hydraulic analysis as follows:

a) Hydrological analysis: a hydrological analysis determines the relationship between rainfall in an area and the quantity of water which runs off of the surface; if the latter is excessive, it produces flooding.

b) Hydraulic analysis: the dynamic character of the flooding processes and the influence of the displacement of water towards lower areas make it necessary to use mathematical models which include two-dimensional horizontal flow equations. The equations are based on the conservation of the quantity of movement and continuity. This model requires topographically detailed information as well as the characteristics of the terrain.

With the precipitation hazard results and the hydrologic and hydraulic model, it is possible to derive the flood hazard of the city and identify the most prone areas to inundation.

The main sources of information for the development of this flood model are:

- Meteorological Service of Jamaica
- Mines and Geology Division of Jamaica
- Office of Disaster Preparedness & Emergency Management of Jamaica

5.1.2.3 Hydrologic model

The hydrologic model was developed in HEC-HMS V4.2 with the aim of evaluating the general rain losses with the method of the Soil Conservation Services (SCS). This was obtained by calculating the curve numbers (CN) at city level (Figure 85) with information of the soil type distribution provided by the Mines and Geology Division of Jamaica and the land use derived for this evaluation using satellite images and the information from the exposure model. The final visualization of the hydrologic model is presented in Figure 86. Due to the extension of the analysis zone it was necessary to simplify the model by aggregating zones with the criteria of similar land use and soil type.

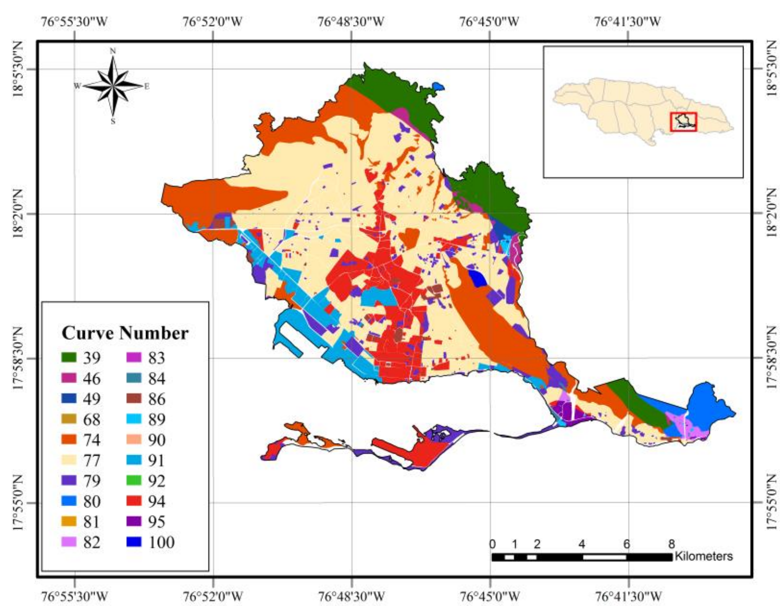


Figure 85. CN numbers for KMA

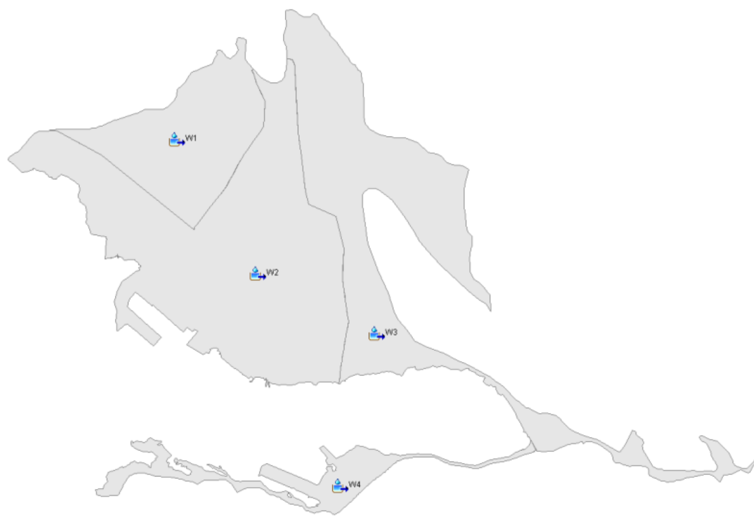


Figure 86. HEC-HMS model for KMA

5.1.2.4 Hydraulic model

The hydraulic model was developed in the software HEC-RAS V5.4. The model uses a bi-dimensional direct rainfall approach in which an effective rainfall pattern is introduced as a boundary condition. This information is routed through the entire city to obtain flood depth maps. The following information is employed as input:

1. An effective rainfall pattern obtained from the hydrologic model.
2. A detailed topography processed for this application using sources such as ALOS3D (30 m horizontal resolution) and SRTM model provided by OPDEM (with 6 m horizontal resolution).
3. A Manning's N map derived using the land use map (see Figure 87).

The final hydraulic model is presented in Figure 88. The mesh conformed for the model has the following characteristics:

- Total area: 100 km^2.
- Number of cells: 14,529
- Minimum cell size: 30 m
- Maximum cell size: 200 m
- Typical run time for a rain scenario: 15 minutes

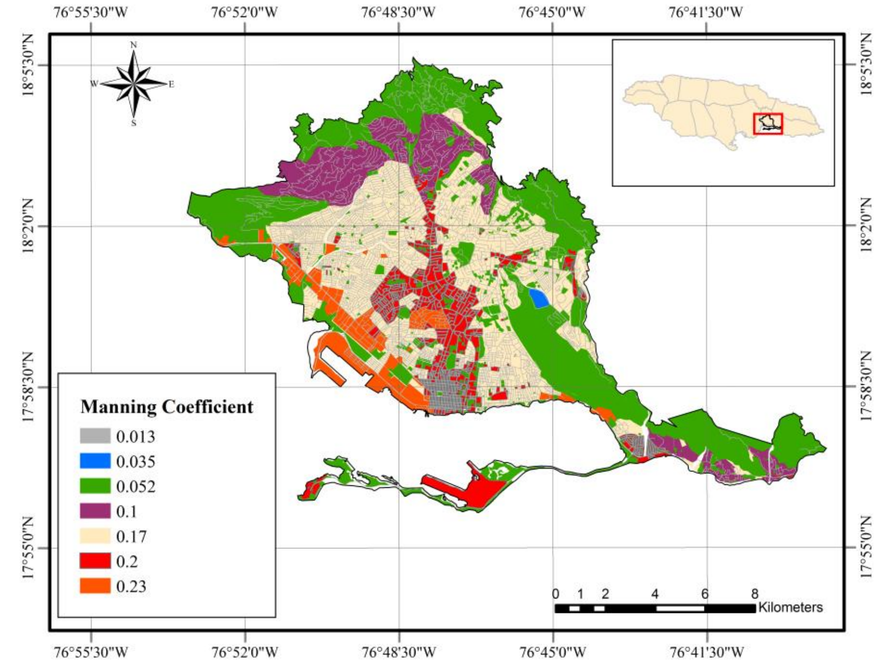


Figure 87- Manning's N information for KMA

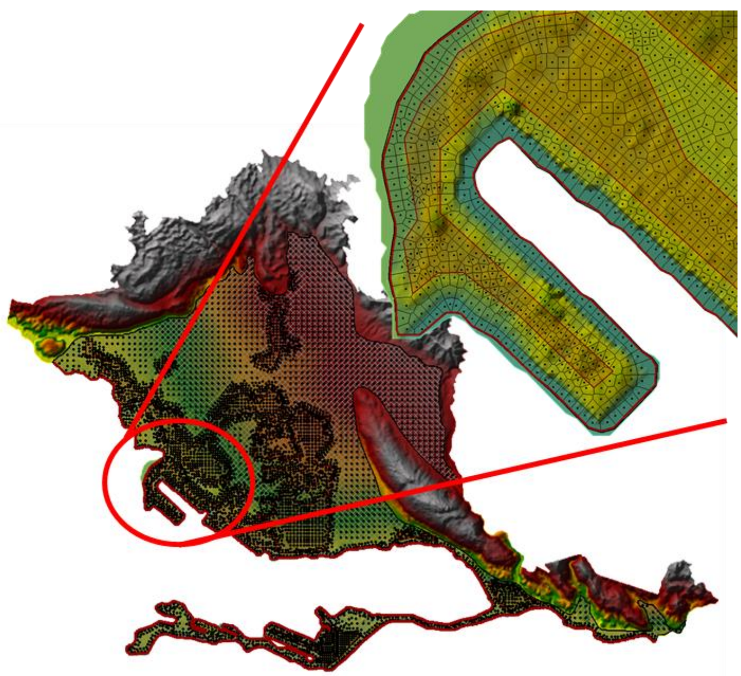


Figure 88. HEC-RAS model for KMA

The hydraulic model has a series of limitations due to the level of resolution of the basic information and the coarse level of analysis employed at the city level:

1. Use of free access DEMs with coarse resolutions. The DEMs are digital surface models with vegetation and buildings. Some minor modifications were performed to correct errors in the available DEM.
2. Hydraulic structures and city's sewer system were not taken into account in the hydraulic models. Due to the DEMs resolution, it is not possible to identify all the minor watercourses of the city.
3. There is no measured data so there is no way to calibrate the model. Validation of models was based mainly on the comparison with historical flood prone areas.

5.1.2.5 City level flood hazard

The sequential analysis starting in the hurricane precipitation and passing through the hydrologic and hydraulic models, generate a series of stochastic flooding scenarios, each one with the same annual frequency of occurrence as the on for the hurricane event that detonated such a flooding event. The maps of Figure 89 represent the integrated flooding scenarios for various return periods at city level. The selected return periods are: 5, 10, 25, 50, 100 and 250 years. Figure 90 presents the same results but focusing the results in a critical flooding area at the southwest part of the city, which is characterized as being the lowest elevated parts of KMA. Finally, for illustrative purposes, a flooding susceptibility map (Figure 91) was developed for the city, using mainly the information from the distribution of flood intensities obtained by the 250 years return period map.

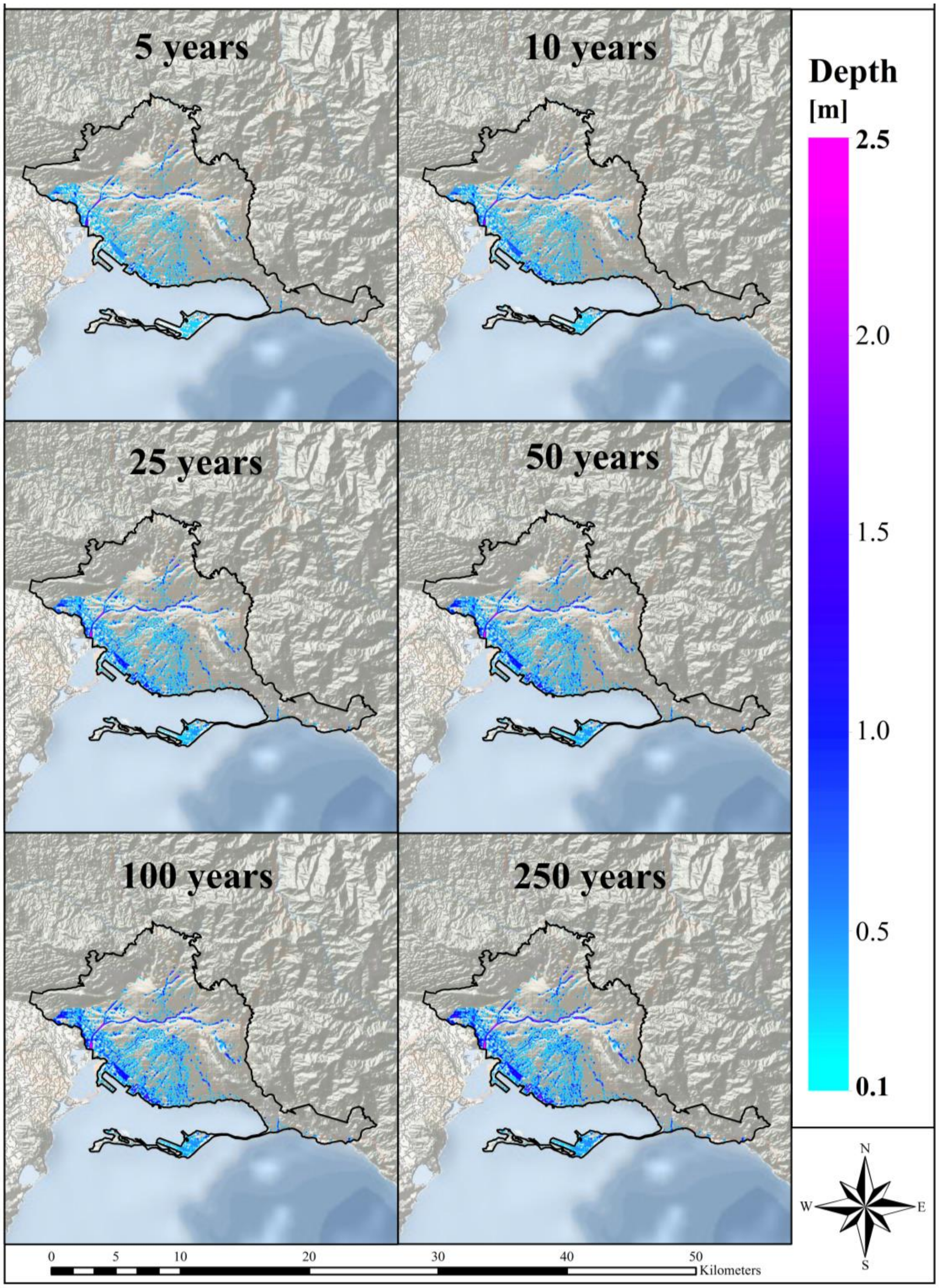


Figure 89. Maximum flood depth for different return periods

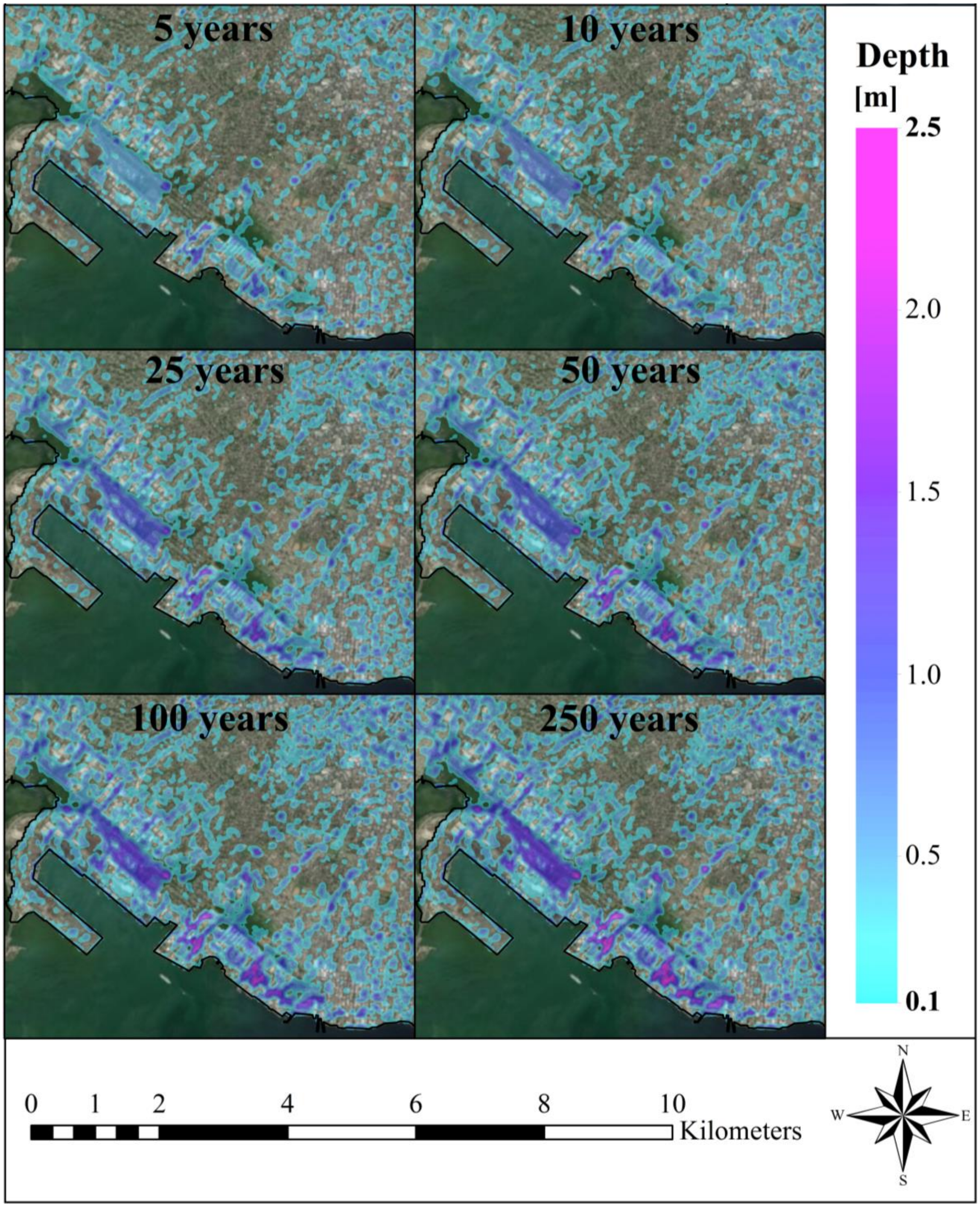


Figure 90. Maximum flood depth for different return periods in prone areas

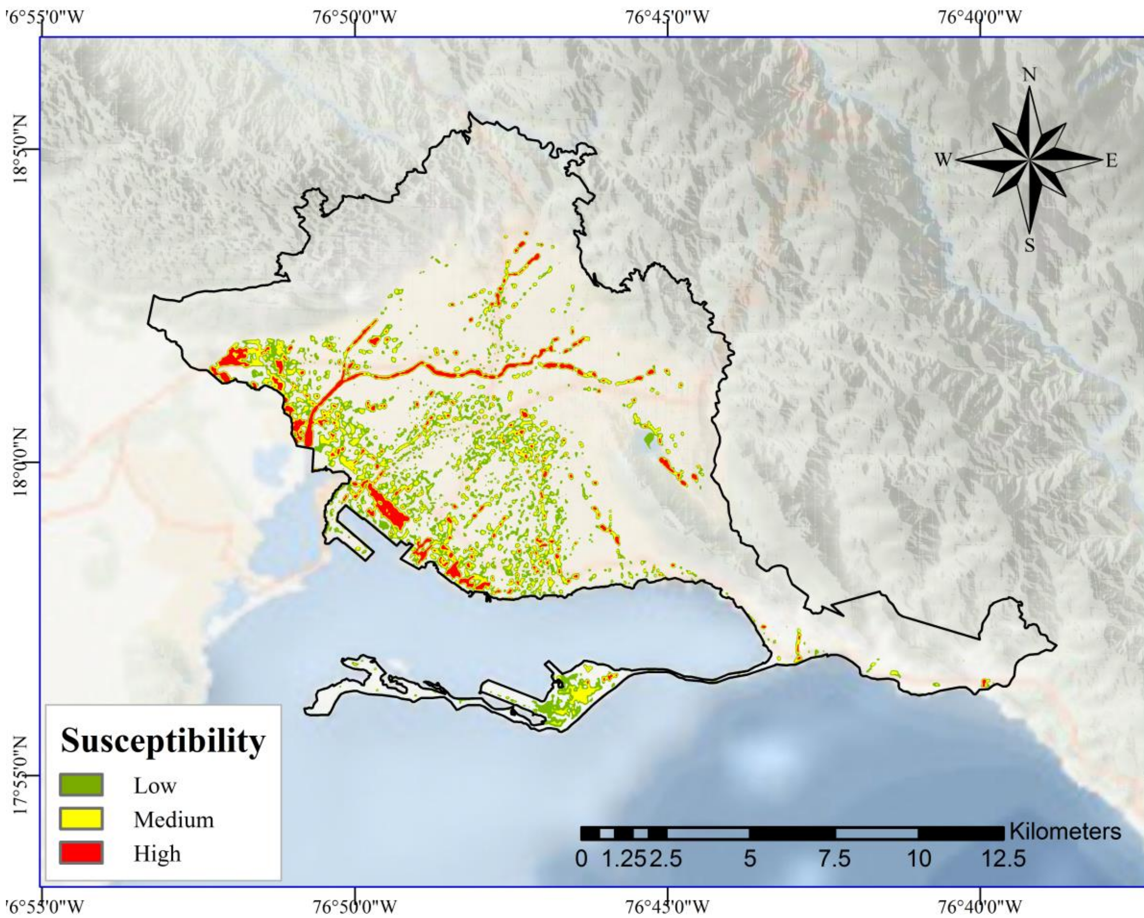


Figure 91. Susceptibility map for KMA

5.2 VULNERABILITY ASSESSMENT

The vulnerability functions for the different building construction typologies exposed to floods were taken from the GAR13 project (Yamin et al, 2013). The curves for a country of medium complexity, such as Jamaica, are shown in Figure 92. In this figure F1L type represents warehouses (>450 square meter), light frame structures (<450 square meter), adobe and other non-engineering materials. The F2 type represents masonry (reinforced and unreinforced), concrete and steel frames, with the L, M and H code representing the height of the building (Low, Medium and High). The detailed information available in the exposure model (see Section 2.4), allows the assignment of one vulnerability function to each one of the components of the database.

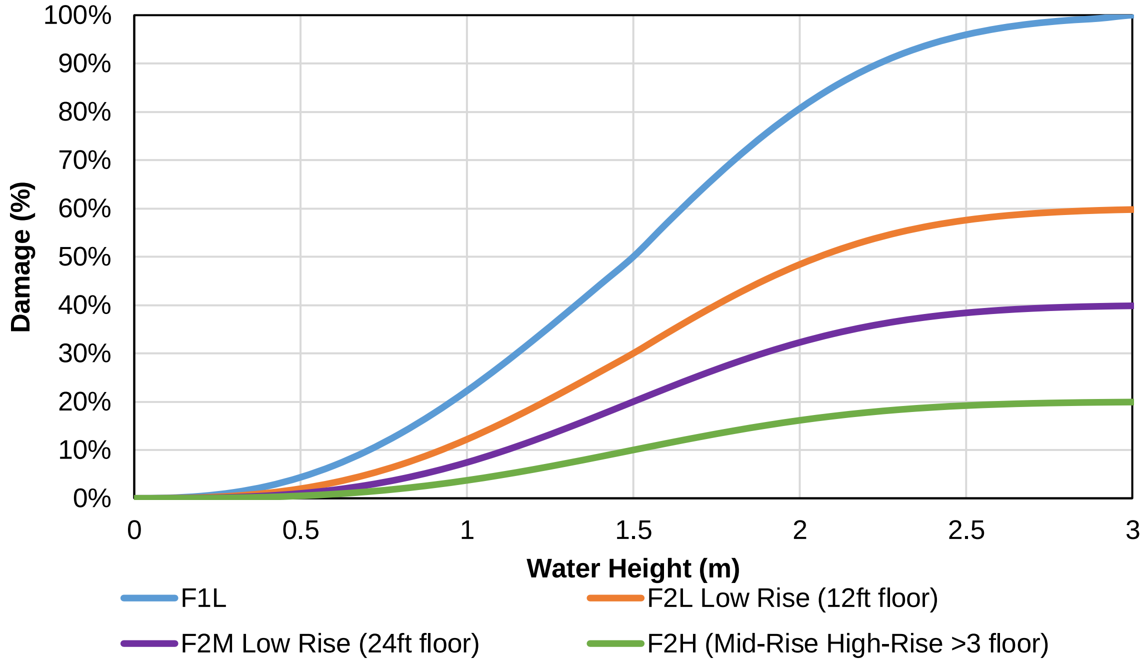


Figure 92 Flood Vulnerability functions

5.3 RISK ASSESSMENT

Following the procedure outlined before (see Sections 1.2 and 6.1.1) the flood risk was estimated for the KMA. As mentioned before, this correspond to a preliminary indicative assessment which allows an estimation of the probable risk figures and flooding footprints that can be expected in this critical area for the city and country. Table 5-1 presents the numeric results for the expected losses at a national level, in particular the EAL and the PML for different return periods. Figure 93 shows the results graphically.

Table 5-1 Flood Risk Results for KMA.

Total Exposed Value TEV	**US$ (Millions)**	$ 9,701
Expected Annual Loss EAL	**US$ (Millions)**	$ 9
	‰ of TEV	0.89
Probable Maximum Losses - PML		
Return Period	**US$ (Millions)**	**% of TEV**
10	$ 23	0.24
25	$ 31	0.32
100	$ 41	0.43

250	$ 49	0.51

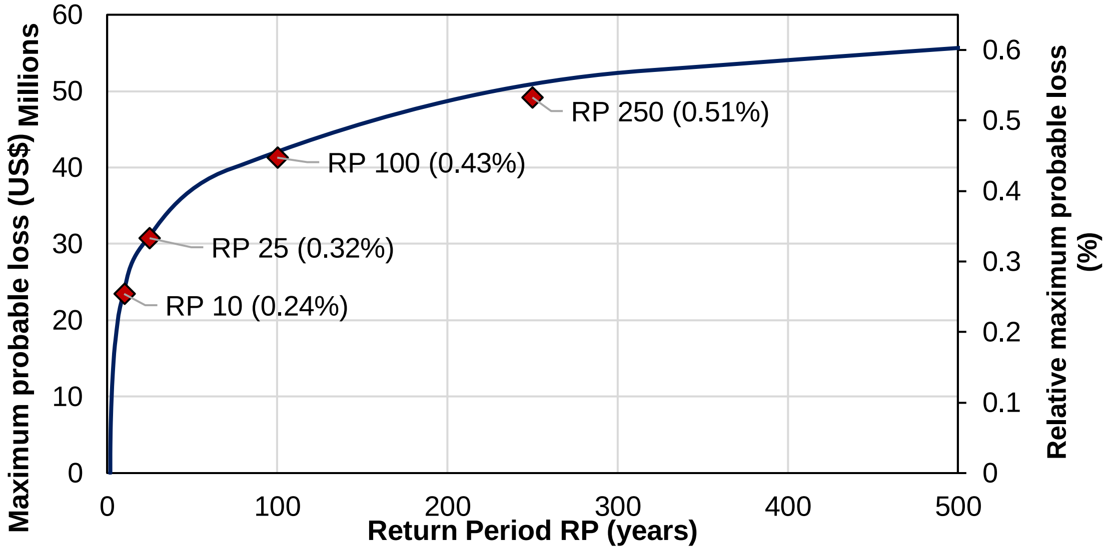


Figure 93 Probable Maximum Loss Curve

Table 5-2 shows the results disaggregated by use sectors meanwhile Figure 94 presents them graphically. As shown in this table, the Industrial, Commercial and Office sectors are the ones with the highest EAL. Whereas the Industrial, Administrative and Education sectors are the ones with the highest relative Expected Annual Losses. This is an indication of the predominant building uses in this part of the city and the associated flooding risk. Again, it is important to recognize that the previous figures correspond only to direct losses associated to the impact on building infrastructure. It doesn´t account for losses in contents, indirect losses or second order impacts. It is also important to recognize that relative losses are with respect of the total estimated exposed value (TEV) in the KMA and the percentage could then vary significantly depending on the exposure area selected for the assessment. It is therefore recommended to consider mainly the absolute figures instead the relative ones.

Table 5-2 Flood Risk Results by Sector

SECTOR	Exposed Value (US$ Millions)	EAL (US$ Thousands)	EALr (‰)
High Residence	$ 1,878	$ 859	0.5
Medium Residence	$ 1,460	$ 707	0.5
Low Residence	$ 1,214	$ 620	0.5
Residential	$ 4,551	$ 2,186	0.5
Private Education	$ 35	$ 37	1.1
Public Education	$ 138	$ 168	1.2
Education	$ 173	$ 204	1.2
Private Health	$ 5	$ 2	0.3
Public Health	$ 2	$ 1	0.3
Health	$ 8	$ 2	0.3
Administrative	$ 142	$ 167	1.2
Offices	$ 1,553	$ 1,509	1.0
Industrial	$ 844	$ 2,564	3.0
Commercial	$ 2,430	$ 1,972	0.8
Total	**$ 9,701**	**$ 8,605**	**0.9**

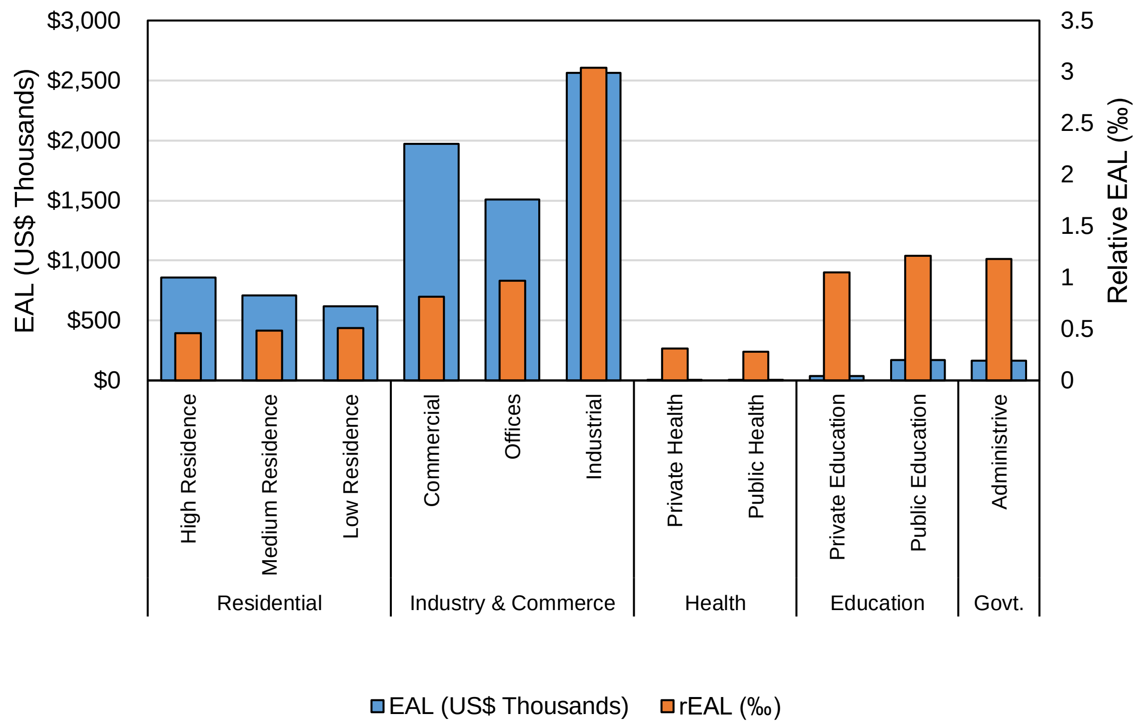


Figure 94 Risk results by sectors

Table 5-3 shows the results aggregated by public and private sectors. The private sector has both the highest total and relative losses compared to the public sector in this area.

Table 5-3 Risk Results Public and Private Buildings

SECTOR	Exposed Value (US$ Millions)	EAL (US$ Million)	EALr (‰)
Private Buildings	$ 8,205	$ 7,649	0.93
Public Buildings	$ 1,496	$ 956	0.64
Total	**$ 9,701**	**$ 8,605**	**0.89**

Figure 95 and Figure 96 show the results geographically. They indicate that the highest risk is concentrated in the districts surrounding the port and the industrial districts located in the margins of the Sandy Gully river.

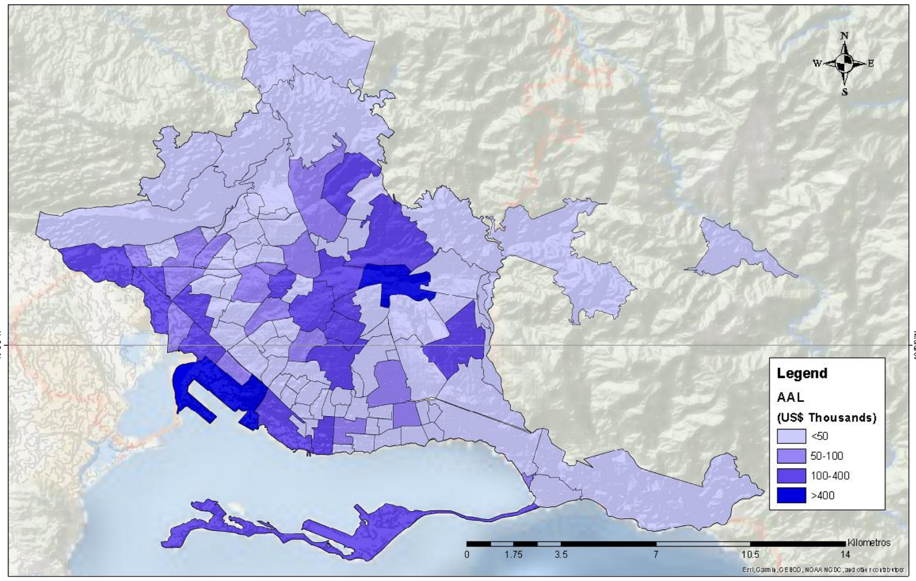


Figure 95 Total EAL results

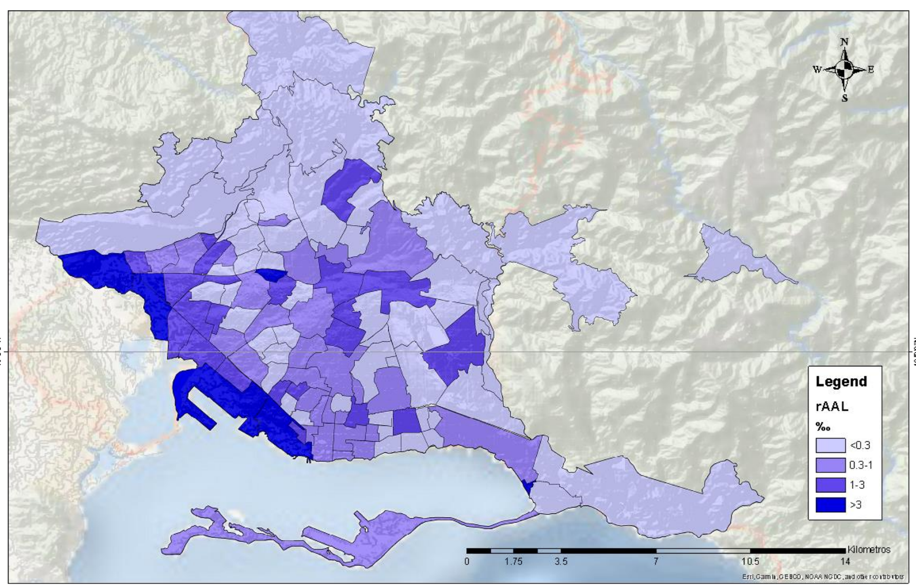


Figure 96 Relative EAL results

5.4 CONCLUSIONS AND RECOMMENDATIONS

The following are the conclusions from the KMA flood risk assessment, where consideration has to be given to the fact that it corresponds to a preliminary indicative assessment:

a) The total exposed value (TEV) for building constructions for the KMA is estimated in about US$ 9.701 million.

b) The expected annual loss, EAL, for hurricane induced floods is about US$ 9 million (0.89 **‰** of the TEV).

c) The probable maximum loss for 250-year return period, PML_{250}, for hurricane induced flood is about US$ 49 million (0.51% of the TEV).

d) In the flood prone area of the KMA, the predominant building uses are the Industrial, the Commercial and the Office sectors, and are the ones with the highest EAL. In addition to the estimated direct impacts, it is important to recognize that these figures do not account for losses in contents, indirect losses or second order impacts (such as business interruption).

Previous assessments indicate that relatively high economic losses and human impact can be expected in the low zones of the KMA for the following reasons:

- The high frequency and intensity of hurricane induced precipitation events.
- The relatively flat topography
- The low capacity and poor maintenance of the drainage system.
- The relatively high tide imposed by the ocean

Considering in addition that in this flood prone area, the predominant building uses are industrial, commercial and offices, it can be concluded that a risk mitigation plan shall be developed for this critical area including the following main components:

- A detailed precipitation hazard assessment considering convective as well as hurricane induced precipitations.

- The generation of a more precise DEM considering the terrain digital model as well as the location of streets and buildings.
- The reconstruction of the information of the drainage system including location, type, depth and diameter or dimensions of pipes or channels.
- The assessment of the flooding hazard considering the participation of the drainage system.
- The final assessment of flood hazard in terms of flood footprints, inundation intensities, and duration of inundation in critical areas.
- The assessment of flooding risk including direct, indirect losses as well as contents and second order losses such as those associated to business interruption, emergency response, recovery and reconstruction.
- The proposal of several structural and non-structural mitigation options, including general dimensions, preliminary budgets and technical, social, financial and political feasibility. The assessment shall include cost-benefit analysis to justify the proposed intervention measures.
- The design of the selected mitigation options.
- A risk financial protection strategy
- An emergency response plan

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