ANALYZING OPEN SOURCE, PYTHON-BASED, TOOLS FOR MULTI-HAZARD RISK ASSESSMENT

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ABSTRACT

Multi-hazard risk assessment is crucial for risk reduction planning by decision makers such as emergency managers and planners. The demand for multi-hazard risk assessment information is increasing due to the expected trend of more frequent disasters, climate change, growth of (urban) population, and increased inequalities. In most cases, risk assessment is still conducted for single hazards using hazard specific models and risk assessment tools. The available tools are very data demanding, have a poor data interoperability, and lacking considering the changing risk and hazard interaction. Proprietary tools for multi-hazard risk assessment are not available for the authorities and research community, and exploration of Open-source tools is very important. The aim of this study is to compare available Open source and Python-based tools (i.e., CLIMADA and RiskChanges) and validate the loss estimation for a documented disaster event: the building losses in Dominica resulting from the 2017 hurricane Maria documented in the Post Disaster Needs assessment report (PDNA). Multi-hazard risk assessment using CLIMADA and RiskChanges requires different formats of input data. For this research, the input data collected consisted of multi-hazard data (flood, landslide, and debris flow hazard data for the 2017 hurricane Maria made through OpenLISEM modelling and: wind hazard maps from IBTrACS), building data collected from OpenStreetMap (OSM) and vulnerability functions (for flood and wind). The OSM building data were classified based on the general occupancy type, construction type, roof type, and roof shape to select representative vulnerability functions of the buildings. The replacement value of buildings was estimated using real estate prices by considering the area of the buildings. CLIMADA uses the hazard intensity within a point location to estimate the loss whereas the RiskChanges calculates the maximum hazard value per building, and also subdivides it into spatial units based on their different hazard levels. To compare the estimated loss of the CLIMADA and RiskChanges with the losses reported by PDNA of Hurricane Maria the loss was categorized into four categories. The result shows that the total building losses for the 2017 Maria Hurricane calculated were both in line with those in the PDNA report. In addition to the loss estimation, the study also compared the capacity of the tools based on five criteria (i.e., data requirement, integration of the hazard interaction, risk calculation component, decision making support capability, and ease of use). Both CLIMADA and RiskChanges have the capacity for data interoperability, but the input data should be prepared based on the data requirements of the respective tools. Both tools do not fully incorporate the uncertainty management in the loss and risk assessment. In addition to this, both tools have difficulty to objectively express the spatial probability of the hazard, and the values should be estimated by expert opinion, whereas this component has a high impact on the loss results. As can be expected, the quality of the results in the tools completely depends on the quality of the input data. The study identified the two most important features that can improve the functionality of the tools. The first one is to represent the spatial variability of the spatial probability, instead of a single value for the entire area. The second aspect is that the tools should incorporate the uncertainty of all risk components into the risk assessment. However, both components would require more detailed input data, which is often not available. Whereas RiskChanges incorporates the hazard interactions into the overall loss assessment, this is not the case in CLIMADA. RiskChanges also need to integrate valuable features of CLIMADA which is the ability in accessing open-source data and visualization capacity in the Python-based version apart from its Graphical User Interface.

Key words: multi-hazard risk assessment, CLIMADA, RiskChanges, OSM building, hazard, hazard interaction, loss estimation

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LIST OF ABBREVIATIONS

AAI	Average Annual Impact
API	Application Programming Interface
BDA	Building Damage Assessment
BF	Building Footprint
CDB	Caribbean Development Bank
CHARIM	Caribbean Handbook on Risk Information Management
EAI	Expected Annual Impact
EAR	Elements-At-Risk
ECA	Economic of Climate Adaptation
ECCB	Eastern Caribbean Central Bank
EU	European Union
GDP	Gross Domestic Product
GEE	Google Earth Engine
GFDRR	Global Facility for Disaster Reduction and Recovery
GIS	Geographic Information Systems
GPS	Global Positioning System
GPW	Gridded Population of the World
GRMI	Global Risk Management Institute
GUI	Graphical User Interface
IBTrACS	International Best Track Archive for Climate Stewardship
ISIMP	Inter-Sectoral Impact Model Intercomparison Project
LIDAR	Light Detection and Ranging
MDD	Mean Damage Degree
MDR	Mean Damage Ratio
NASA	National Aeronautics and Space Administration
NIWA	National Institute of Water and Atmospheric Research
OECDE	Organisation for Economic Cooperation and Development
OGC	Open Geospatial Consortium
OSM	OpenStreetMap
PAA	Percentage of Asset Affected
PDNA	Post Disaster Needs Assessment
RCP	Representative Concentration Pathways
RMS	Risk Management Solution
SRTM	Shuttle Radar Topography Mission
UN	United Nations
UNDP	United Nations Development Program
UNDRR	United Nations Office for Disaster Risk Reduction
USD	United States Dollar
WGS	World Geographic Coordinate System

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1. INTRODUCTION

1.1. Background

Billions of dollars are lost due to natural disasters (Grosfield, 2021) and disasters affect more than 5 billion people since 1994 in the world (ChildFund, 2021; UNDRR, 2020b). According to World Bank (2005) global natural disaster hotspots affect more than 3.4 million km² area and 13% of the world populations are exposed to two or more hazards. Multi-hazard assessment is "*an approach that considers more than one hazard in a given place and the interrelations between these hazards, including their simultaneous or cumulative occurrence and their potential interaction*" (UNISDR, 2016b). According to their triggering mechanism and specific physiographic region, there are different types of multi-hazard interactions. Kappes et al. (2010) and Van Westen et al. (2020) define different types of hazard interactions: *Independent events* are hazardous processes caused by different triggering factors and do not influence each other; *compounding events* occur in a sequence in the same area; *coupled events* have the same triggering factors, may affect the same area, and may occur within the same time; *Cascading events* occurs in a sequence, and where the first hazard triggers the second hazardous process, then the second trigger the third process; and c*onditional events* are the first hazardous event that changes the condition for the other hazard event.

It is important to include those hazard interactions within multi-hazard risk assessment (Gill & Malamud, 2016). A generally accepted standard definition of multi-hazard risk assessment still does not exist (Gallina et al., 2016; Komendantova et al., 2016; Marzocchi et al., 2009); but Schmidt et al. (2011) proposed the following definition: "*Quantitative estimation of the spatial distributions of potential losses for an area (a confined spatial domain), multiple (ideally all) natural hazards, multiple (ideally a continuum of) event probabilities (return periods), multiple (ideally all) human assets and multiple potential loss components (for each of the assets, e.g., buildings, streets, people, etc.).*"

Kappes et al. (2012) stated that one of the challenges of multi-hazard risk assessment is to model these hazard interactions. For instance, a cascading event like an earthquake that triggers landslides, which may block a river, and the dam break may cause flooding. The complexity of multi-hazard risk assessment is that the hazard interaction determines the nature, intensity, and frequency of the hazards (Carpignano et al., 2009; Kappes et al., 2011). Hazard interactions occur in many environments, but hydro-metrological hazard interactions are very frequent in mountainous regions (Terzi et al., 2019).

Hydro-meteorological hazards "*are of atmospheric, hydrological, or oceanographic origin. Examples are tropical cyclones; floods, including flash floods; drought, heatwaves, and cold spells; and coastal storm surges. Hydro-meteorological conditions may also be a factor in other hazards such as landslides, wildland fires, locust plagues, epidemics, and in the transport and dispersal of toxic substances and volcanic eruption material*" (UNDRR, 2016, 2020a). In several regions of the world, hydro-meteorological hazards occur, but the hazard frequency and intensity, the exposure of different elements-at-risk, and vulnerability vary from region to region (Wu et al., 2016). Mountainous or hilly regions are complex and sensitive ecosystems and are often highly affected by climate change. In these regions, hydro-meteorological hazards are dominant (i.e., floods, landslides, and debris flows), often combined with a geological hazard such as earthquakes (Jayawardena, 2013). Understanding the characteristics of these hazards and their interaction, the exposure of elements-at-risk, and the degree of vulnerability will help to quantify multi-hazard risk.

According to Van Westen (2008) hazards, elements-at-risk, and vulnerabilities are the components of risk and risk expresses the probability of loss. Hazards are characterized by their intensity, spatial probability (the likelihood that a particular area is affected by the hazard), and frequency (i.e., return period) (Höppner et al., 2010). Hazard intensity is expressed in different intensity scales for different hazard types which are difficult to compare. For example, flood intensity is measured by water depth, velocity, duration, or impact pressure. Elements at risk have both non-spatial and spatial attributes. For instance, buildings are characterized by the number of floors, occupancy type, floor area, number of people, and construction type. Exposure is the spatial interaction of hazard and elements at risk and provides information on which elements at risk are potentially affected by the hazardous event (UNDRR, 2016). The physical vulnerability evaluates the degree of losses caused by the interaction between hazard intensity and elements-at-risk (Van Westen, and Greiving, 2014).

Risk analysis methods can be classified in qualitative (i.e., based on expert knowledge, and indicator-based approach classify the risk in terms of high, moderate, and low), semi-quantitative (i.e., quantify the exposed elements-at-risk and their exposed monetary value without loss calculation), and quantitative methods (i.e., quantify in monetary, individual, and societal risk) (Alexandru & Cuza, 2009; Altenbach, 1995; Van Westen, 2009).

Quantitative approaches are subdivided into probabilistic or deterministic approaches. Deterministic approaches assess the disaster impact for a specific hazard scenario for which the input values are known, and the output is observed (OECDE, 2012). The parameter values and the initial values determine the output. The deterministic approach might include typical scenarios such as worst-case, best-case, and business as usual. They can also include historical events, for which known damage information is available, and which can be used to calibrate the loss estimation. The deterministic approach has different problems: the full range of possible outcomes is not considered, the uncertainty of the input parameters and the likelihood of each outcome is not quantified, and the potential risk may be underestimated (UNISDR, 2016a). Probabilistic approaches are used to assess the impact of all possible hazard scenarios with several probabilities of occurrence (OECDE, 2012). This approach incorporates randomness in the method because of the parameter values and the initial conditions. The probabilistic approach uses historical events, expert knowledge, and theory for simulation events that are likely to occur (Mauro, 2014; UNDRR, 2015). Knowing the quantitative value of losses and risk with a deterministic or probabilistic approach will support to evaluate the effects of risk reduction alternatives.

Multi-hazard risk assessment is conducted with the help of several tools. According to GRMI (2012), the need for multi-hazard risk assessment tools increases because of the climate change impact, rapid population, and urban growth, especially in developing countries. In addition to this, there are very few multi-hazard risk assessment tools, and few tools are considering the dynamics of multi-hazard risks. Therefore, identifying and comparing their potential in considering hazard interaction, changing environment, loss and risk calculation type, the scale of the analysis, and input data requirement play a significant role for decision-makers and experts to select appropriate tools based on their objectives and scale of analysis. In addition to this, identifying and comparing existing tools help to improve them for future development. This research focuses on analyzing multi-hazard risk assessment using two Open-Source python-based tools: CLIMADA and RiskChanges and compares the tools based on a set of criteria that we developed.

CLIMADA is an Open-source multi-hazard impact modelling platform that applies a probabilistic model. CLIMADA follows the concept of risk in IPCC (2014) and the risk assessments combine the climate and weather-related hazards, the exposure of elements-at-risk to the hazard, and vulnerability of exposed elements-at-risk (Bresch, 2020). Climada is developed by the Weather and Climate Risks Group in the Institute for Environmental Decisions of the ETH Zurich (Switzerland).

The RiskChanges tool is an Open-source standalone multi-hazard risk assessment tool which aims to analyze the effect of risk reduction planning alternatives in reducing the risk at present and in the future (Van Westen et al. 2014). It supports decision-makers to choose the optimal risk reduction alternatives. RiskChanges is developed by the ITC Faculty of Geo-Information Science and Earth Observation

(Enschede, Netherlands) and Geoinformatics Center of the Asian Institute of Technology (Bangkok, Thailand)

1.2. Problem statement

Multi-hazard risk is not just a summation of the risk of a number of single hazards. Multi-hazard risk has a complex nature due to: the hazard interactions (e.g., coupled hazards may affect the same elements-at-risk), temporal changes (i.e., the frequency of one hazard depends on the other hazard and after the occurrence of one hazard the frequency of other hazards might change), changing vulnerability (i.e., if an element at risk is impacted by one hazard it is more vulnerable to the next) and to visualize the risk is difficult (Kappes et al., 2012). Risk assessment is often done by considering only a single hazard but decision-makers, such as emergency managers and planners, require multi-hazard risk information for optimal disaster risk reduction planning (GFDRR, 2015b; Grünthal et al., 2006).

The multi-hazard risk assessment needs to address the emergency managers and planners needs , and the tools should be able to convert the complex nature of multi-hazard risk into understandable information for decision-makers (Van Westen, 2020).

Many of the multi-hazard risk assessment tools are project-based, and when the project ended, the tools are no longer further developed or maintained. The tools are also often developed for a specific project area. In addition to this, different tools have drawbacks related to software architecture, and risk assessment components (Van Westen, 2016). Table 1 shows problems associated with the application of risk assessment tools.

Table 1: Problems associated with the application of risk assessment tools.

Software architecture-related issue	Risk assessment ability
Internet-dependent Installation problems Limited documentation Use of local language in the interface. Complex architecture	Very data demanding, according to fixed data formats. Working with another dataset is complicated. Does not consider the changing risk and hazard interaction. Direct comparison of different scenarios may not be applicable. Absent of risk evaluation, cost-benefit, and cost-effective analysis.

Several scholars theoretically compare multi-hazard risk assessment tools (Kappes et al., 2012). But very few studies compare them in a benchmarking study. There are still limited studies conducted, especially for mountainous areas that integrate multi-hazard risk assessment of hydro-meteorological hazards (Chen et al., 2016). Comparing multi-hazard risk assessment tools based on theoretical aspects is not good enough to compare how the tools perform, while comparing the tools using an actual dataset will give more tangible results. Examining and comparing the multi-hazard risk assessment tools requires testing with an actual dataset and identifying the potential of the tools in how far they help the decision-makers and offer support to choose which tool is best under which circumstances. Therefore, this research conducts a case study-based comparison and calibrate loss estimation of CLIMADA and RiskChanges risk assessment tools using actual datasets.

1.3. RESEARCH OBJECTIVES AND QUESTIONS

1.3.1. General objective

The main objective of this research is to compare two Open-Source and Python-based tools for multi-hazard risk assessment (i.e., CLIMADA and RiskChanges) and calibrate their loss assessment methods with damage data from a reported disaster event (the 2017 Hurricane Maria in the country of Dominica in the Caribbean). Four specific objectives are formulated that could be achieved by answering the research questions.

1.3.2. Specific objectives and research questions

1. To analyze and compare the data requirements and hazard interactions considered within the multi-hazard risk assessment tools.
    i. How data demanding are these models, and what are their input data requirements?
    ii. How are the hazard interactions considered in the hazard and risk assessment component?
    iii. How are elements at risk characterized? At what level of detail and which attributes? How do the models incorporate vulnerability?
2. To analyze and compare the loss assessment capabilities with a dataset for a disaster event (Hurricane Maria in Dominica).
    i. How are the risk components (hazard, elements-at-risk, and vulnerability) considered in the model?
    ii. Which type of losses are calculated, and which risk calculation is carried out?
    iii. Can the result be validated using a recent disaster?
3. To analyze and compare the inclusion of the capabilities to analyze changing risk.
    i. How the tools incorporate the evaluation of risk reduction alternatives?
    ii. Can the tools analyze changes in multi-hazard risk for specific future years under different scenarios?
4. To analyze and compare the decision-making support potential of the tools and formulate requirements for their future development.
    i. What kind of decision-making support options exist in the tools?
    ii. Can the tools be applied by decision-makers with limited technical knowledge?
    iii. Based on the comparison of the various tools, which improvements could be suggested to improve their potential?

1.4. Thesis structure

This research is organized into six chapters. In chapter one background information is given, followed by the statement of the problem, and research objectives are presented. In chapter two related works are discussed for multi-hazard risk assessment, hazard interactions, available multi-hazard risk assessment tools, and different comparison method used to compare the tools. In chapter three the study area, the dataset used in the research, and the method used to prepare the input datasets are discussed. In chapter four the methodology is presented to analyze the loss estimation in CLIMADA, and RiskChanges, and the comparison method which is used to evaluate the loss result, and the method used to compare the tools based on the criteria. In chapter five the loss results from CLIMADA and RiskChanges, comparison of calculated loss with PDNA reported loss, and the comparison result of the tools based on the criteria are presented. Finally, in chapter six the discussion, conclusions, and recommendations are presented.

2. MULTI-HAZARD RISK ASSESSMENT AND AVIALABLE TOOLS

This chapter aims to discuss the related works which focuses on multi-hazard risk assessment, hazard interactions, available multi-hazard risk assessment tool (emphasis on CLIMADA and RiskChanges), and comparison methods used in the previous study.

2.1. Multi-hazard risk assessment and hazard interactions

Multi-hazard risk assessment has been done using different type of methods and approaches due to the lack of multi-hazard risk assessment tools that consider the dynamics of the risk. Even if the risk assessment requires appropriate tool and extensive historical data several studies conducted by developing different approach . Chen et al. (2016) plan to implement a quantitative multi-hazard risk assessment for debris flow and flood but due to lack of historical event data, triggering factors, and the different type of hazard interactions fully quantitative multi-risk assessment did not able to perform and they develop an approach which combines the quantitative method with the assumptions based on expert knowledge. Similarly Johnson et al. (2016) and Ming et al. (2015) perform a multi-hazard risk assessment in district level using GIS based and link the vulnerability surfaces with the intensity of the hazard and losses including current and future risk, which helps the city planners and policymakers to visualize the spatial distribution, concentration of the risk, and to prioritize risk management and adaptation actions. Analytical hierarchal (supported by GIS which is proprietary tool) and quantitative weight-based method also used to make the multi-hazard risk assessment (Skilodimou et al. 2019).

The multi-hazard risk assessment methodologies need to incorporate the interactions of the hazard various studies shows the importance of hazard interaction within multi-hazard risk methodologies (ARMONIA, 2007; Gill & Malamud, 2016; Joel et al., 2014; Kappes et al., 2010, 2012). Gill & Malamud (2016) explain and analyses the importance of integrating hazard interaction with a multi-hazard risk assessment methodology based on the literature review, field observations, and assess the use of interaction networks with example case studies. Gill and Malmud (2014) stated that the relationship of the hazard interaction (i.e., primary, and secondary hazard) can increased the probability of the other hazard and the extent of the hazard interaction can be predicted to a greater or lesser extent in spatial location of secondary hazard occurrence, timing, and magnitude of secondary hazard. Therefore, they conclude that the capacity of the methods to predict the interaction of the hazards are poor, need broad visualization framework, utilizing metrices, and hazard linkage.

Liu et al. (2017) also studied multi-hazard interactions by developing a quantitative model (i.e., model for multi-hazard risk assessment with a consideration of Hazard Interaction (MmhRisk-HI)). Their analysis was done on four hazards: typhoons, floods, landslides, and storm surges. Some approach or models are focus only modelling the hazard interactions. For instance, Han et al. (2007) applied a qualitative descriptions and classifications approach to model the hazard interactions. Van den Bout (2020) developed an integrated physically based multi-hazard model implemented in the OpenLISEM modelling tool, which includes hydro-meteorological hazardous processes and applies multi-hazard interactions. This method was tested in different case study areas; for instance, in Dominica, after the 2017 hurricane Maria impact, the interaction between flash flood and mass movement was modelled. In addition to those models De Pippo et al. (2008) describe the hazard interaction using a descriptive matrix. Schmidt & Kallio (2006) examined the hazard interaction using a binary matrix. Kappes et al. (2010) combine the descriptive and binary matrix to examine the hazard interactions. Van Westen et al. (2014) used a network diagram form to visualized possible hazard interactions, and Neri et al. (2013) used the event tree approach.

2.2. Multi-hazard risk assessment tools

According to Wilkinson & Clark (2008) multi-hazard risk assessment tools are risk management tools that assess the potential losses due to natural hazards to help decision-makers, insurers, reinsurers, and government agencies. The science of loss estimation modeling comes from the fields of property insurance and natural hazards science. Since the late 1980's the insurance sector has developed computer-based models for loss estimation using Geographic Information Systems (Grossi et al., 2005). Van Westen (2016) classified multi-hazard risk assessment tools into commercial catastrophe models, GIS-based tools, freely available standalone tools, and web-based tools (Table 2).

Table 2: Types of multi-hazard risk assessment tool

Category	Tool	Description	Reference
Commercial	RMS (Risk management solution)	A probabilistic risk assessment tool consists of an event module, hazard module, vulnerability module, and financial module. The tool includes hurricanes, earthquakes, floods, and wildfire hazards.	(RMS, 2020)
	AIR Worldwide	Use a probabilistic approach that can analyze earthquake, extratropical cyclone, flood, wildfire, tropical cyclone, and severe thunderstorm hazards	(Kinghorn, 2015)
	RMSI	Provide both probabilistic and deterministic modeling approach. Analyze earthquake, flood, cyclone, tsunami, drought, weather, industrial, and fire hazard risk assessment	(RMSI, 2019)
GIS-based	HAZUS-MH	The deterministic approach considers different hazards. Those are earthquakes, hurricanes, tornadoes, tsunamis, coastal floods, riverine floods, landslides, and wildfires.	(FEMA, 2004)
Standalone and freely available	RISKSCAPE	An event-based risk assessment tool developed to use for different purposes e.g., land-use planning, emergency management contingency planning, cost-benefit analysis. Included earthquake shaking, volcanic ashfall, river floods, windstorms, and tsunami	(RISKSCAPE Wiki, 2020)
	CAPRA	Project-based Probabilistic risk assessment tool includes earthquake, tsunami, volcano, drought, flood, landslide, and hurricane. CAPRA was no longer supported by the World Bank and is publicly available, but in an unusable form	(CAPRA, 2018)
Freely available web and Python-based	CLIMADA	Probabilistic damage model which support climate adaptation and models storm surge, tropical cyclone, torrential rain, earthquake, volcano, windstorm, floods, and mudslides hazards included in the risk assessment	(Climate ADAPT, 2017)
	RiskChanges	A quantitative event-based approach was developed to analyze the effect of risk reduction on minimizing risk today and in the future. Earthquake, volcanic eruption, tsunami, storm surge, river flooding, landslides, and forest fire hazards included.	(CHARIM, n.d.; van Westen et al., 2014)

Source: Van Westen (2016) Inventory of tools for natural hazard risk assessment

According to OECDE (2012) the need for multi-hazard risk assessment tools increases because of the climate change impact, rapid population, and urban growth, especially in developing countries. The number of freely available and Open-Source multi-hazard risk assessment tools are limited. Because many tools are project based and on development stages. For instance, RISKSCAPE is currently unavailable due to development. CAPRA tool is based on the project currently the project s phase out and no longer supported by World Bank but still the tool is publicly available and did not work any longer.

RISKSCAPE is freely available standalone software program designed for analyzing the impact of different hazards such as earthquake shaking, volcanic ashfall, river floods, windstorms, and tsunami (Reese et al., 2007). The tool converts the hazard exposure information into consequences like the number of affected peoples, damages, and replacement costs. The tool was developed by cooperating with the National Institute of Water and Atmospheric Research Ltd (NIWA) and the Institute of Geological and Nuclear Sciences (GNS Science). RISKSCAPE has four modules (i.e., Hazard module, asset module, loss module, and aggregation module). The hazard module allows us to calculate the intensity of the hazard at the location of the assets. The asset module contains the type of elements-at-risk, the asset data (spatial location), and the asset attribute described based on the specification of the asset module. Loss modules use fragility function which allows calculating the potential damage that occurs on a particular building or infrastructure. The RISKSCAPE use deterministic approach for the loss calculation (King et al., 2006).

CAPRA is freely available, modular, standalone multi-hazard risk assessment tool that implements a probabilistic approach integrating the exposure database, hazard and physical vulnerability function (GFDRR & CAPRA, 2012). In terms of physical damage, direct economic and human losses can be estimated. CAPRA implement a multi-hazard risk approach to analyze the interaction effects of the hazards. For example, the intensity of the hurricane is expressed in terms of precipitation, wind speed, and storm surge, and precipitation in turn is used for analyzing flooding and landslide hazards. Primary hazards are considered, such as the effects of an earthquake in terms of ground shaking, as well as the effects of secondary hazards such as (tsunamis) (Linar, 2012). CAPRA provides information for data collection, development of disaster risk management strategies, and creating a community of users to build the capacity of national and regional level decision makers (GFDRR & CAPRA, 2012). But after the project phase out the tool cannot maintain and has a lot of problems when trying to use in practice.

2.3. Comparison method of risk assessment tools used in previous study

Gallina et al. (2016) theoretically compared the multi-hazard risk assessment tools based on the methodology adopted by the tools (i.e., HAZUS, RISKSCAPE, and CAPRA). The authors created fields for comparison of the tools. The fields are the reference (i.e., name of the project), application context (i.e., objective and scale of analysis), multi-hazard, exposure, and vulnerability, multi-hazard risk, and multi-risk outputs. Van Westen (2016) compare multi-hazard risk assessment tools based on the structure of the documentation, adaptability to other country situations, the interface language, dependency on a specific platform, and their multi-hazard risk assessment approach. In general, they conclude that most of the tools are only applicable for software developers and are often still in the development stage, and only some tools consider the inclusion of risk evaluation of reduction measures. Most of the tools only focus on risk assessment, very few incorporate the comparison of risk in the future scenario. Terzi et al. (2019) review the potential application of five modelling approaches for multi-risk assessment and climate change adaptation in mountain regions. The modelling approaches are Bayesian networks, agent-based models, system dynamic models, event and fault trees, and hybrid models. They compare the potential of modelling approaches using seven criteria: spatial and temporal dynamics, uncertainty management, cross-sectoral assessment, adaptation measures integration, data required, and level of complexity.

Based on the literature review of the risk assessment, hazard interactions and comparison methods we identify the most important points to compare the selected tools.

- Data dependency: dealing with the quality, quantity, interoperability, type, and formats of input data of the tools.
- Hazard interaction: type and method of hazard interactions included in the tools.
- Risk calculation methods: probabilistic or deterministic type of loss and risk calculation perform in the tools. In addition to this what level of elements-at-risk detail is needed in the tools and how the tools manage the input data and the method of risk calculation uncertainties.
- Decision making support: different type of decision-making support exist which is depends on the aim of the tools. So, what type and compatibility of the decision-making support included in the tool.
- Ease of use: the installation system, interface language, documentation and visualization system of the tools are good enough to use by non-professionals.

2.4. CLIMADA and RiskChange tool

In this research the CLIMADA and RiskChanges tools were used for the loss estimation of hurricane Maria. This section gives an overview of the two tools.

2.4.1. CLIMADA

This is an overview of the CLIMADA multi-hazard risk assessment tool, version 1.5.0. CLIMADA is based on three main packages: Entity, Hazard, and Engine.

Entity: the socio-economic model which contain four components: the exposure, impact functions, discount rates, and measures. For exposure component the data can be prepared by the user using a specific CLIMADA template in the form of Excel tables and MATLAB tables and online databases in the CLIMADA exposure modules such as BlackMarble and LitPop (CLIMADA contributors, 2020).

Exposures: is the GeoDataFrame of Python's library Geopandas which expressed the exposure. The exposure can be any object or activity that is exposed to a hazard (e.g., geographical distribution of people, buildings, infrastructure, and livelihoods). The exposure input file (Figure 1) includes variables and metadata information. The variables are categorized into two: important and optional variables. The important variables are value of each exposure (in monetary units), latitude, longitude, and the IDs of the related impact functions. The optional variables are Region ID for each exposure (e.g., an administrative unit), Category ID (e.g., building type) for each exposure unit, deductible value for each exposure used for insurance, and cover value for each exposure used for insurance.

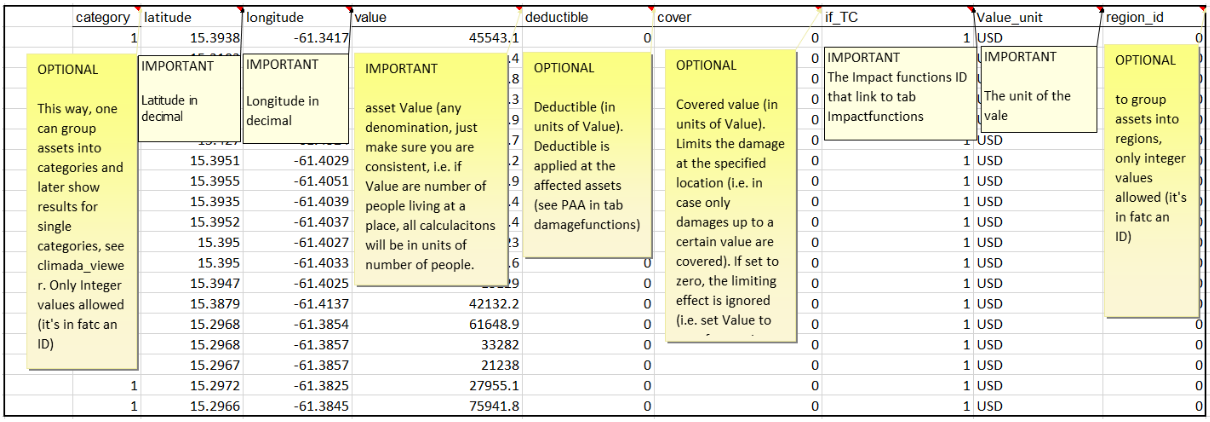


Figure 1:Important and optional variables, Source from CLIMADA entity template

The metadata includes information about the source data, reference year, monetary value unit of the exposure, and meta dictionary used to transform the raster properties (coordinate system, and resolution). The CLIMADA engine can handle the analysis without the optional variables, but the importance variables and meta data are crucial to make the analysis. CLIMADA express the elements-at-risk using different type of input data:

- User input: a user can define the exposed values using different ways in CLIMADA. The first methods are the user can fill the DataFrame (which have labelled rows and columns) and GeoDataFrame (which contain a column with geometry) by providing value range, set geometry attribute, and impact functions for the hazard type and then generate the exposure. The second method is by reading the exposure from an Excel file, raster, shapefile, and any other type of file that supported by GeoDataFrame and DataFrame. To use the raster and shapefile format dataset the user must define as constant variable in CLIMADA script. The third method is to read the exposure generated by CLIMADA. The data are prepared in MATLAB and hdf5 format, these data have 5km resolution data and used only for large area.
- BlackMarble: this models the approximate economic exposure of countries and province by interpolating the country's GDP and income group values for a specific year of the night light intensities (CLIMADA BlackMarble Wiki, 2020). The NASA images for years higher than 2013 with 500m resolution https://earthobservatory.nasa.gov/Features/NightLights and NOAA images used for earlier and 2013 years also it has 1km resolution https://ngdc.noaa.gov/eog/dmsp/downloadV4composites.html. The resolution of the images can be interpolated into higher resolution in CLIMADA based on the user requirements. By using the Pandas-datareader API the data for GDP (nominal GDP at current USD) and income group values collect from the world bank https://data.worldbank.org/. It will assign a value from the closest year value when the value is missing, and it will use the Natural Earth repository https://www.naturalearthdata.com/ values when the World Bank data has no values. Also, the user can access BlackMarble data directly in CLIMADA.
- LitPop: this models the regional economic exposure using NASA nightlight intensity images and a population dataset from the Gridded Population of the World (GPW) http://sedac.ciesin.columbia.edu/data/set/gpw-v4-population-count-rev11/data-download.
  GPW is a spatial World population dataset based on nonspatial and spatial data. The nonspatial datasets are collect from official national statistic agencies. In addition to the GPW and nightlight data the LitPop includes several economic indicators such as produced 20 capitals from World Bank wealth accounting https://datacatalog.worldbank.org/dataset/wealth-accounting, GDP-to-wealth ratio from Global Wealth Report, GDP from World Bank and GRP from various sources. All LitPop datasets can be accessed directly by simple initiating the LitPop class from the CLIMADA> entity>exposure but the GPW required to be downloaded manually by the user who needs to specify the temporal scale (Eberenz et al., 2020). The GPW data must be stored in the Climada Python data system to access the data (CLIMADA LitPop Wiki, 2020).

To compute the impact each class has a check method which verifies whether the necessary data are correctly provided and monitors the optional variables are not present or not in the data. CLIMADA allow to visualize the defined exposures.

Impact Function: in CLIMADA the impact function (vulnerability function) represents the percentage of loss caused by the interaction of hazard and exposed elements-at-risk. The impact function is used to define a single impact function and the impact function set is used to contain different type of impact functions. The class is characterized by the following attributes (Figure 2): hazard type, impact function id, name of the impact function id, hazard intensity and unit, mean damage degree (MDD), and percentage of asset affected (PAA) (CLIMADA Impact Functions Wiki, 2020). The MDD value expresses the level of damage for each intensity of the hazard, and ranges from 0 to 1. For a given hazard intensity the PAA express how many assets are affected by the hazard or the spatial probability of the hazard, and the value range is also between 0 and 1. The method automatically will calculate the mean damage ratio (MDR) by multiplying the MDD and PAA. The impact functions can be in Excel format.

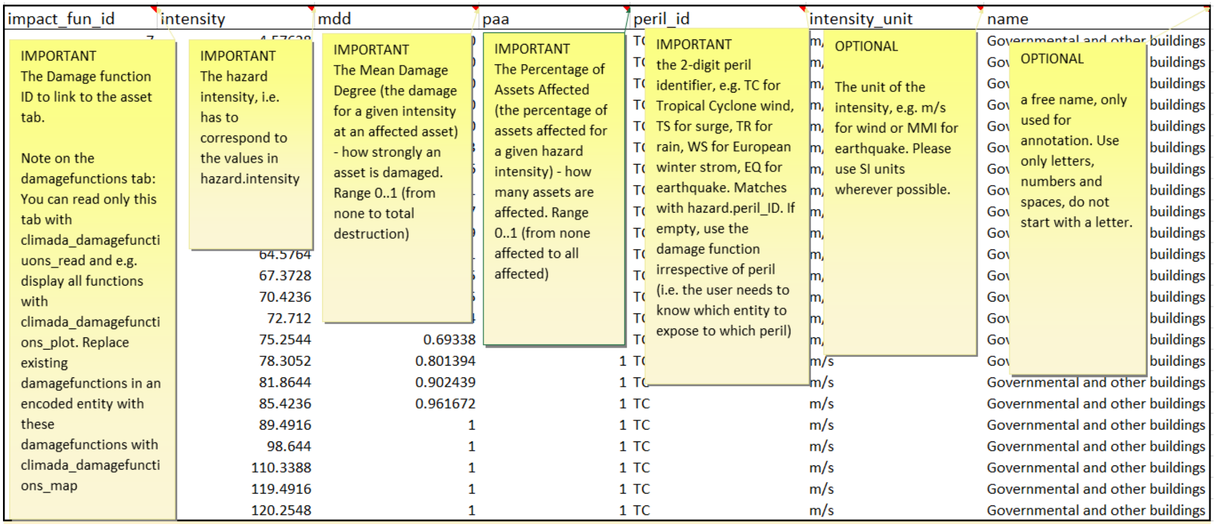


Figure 2: Impact function attribute, Source from CLIMADA entity template

<u>Discount Rates</u>: refers to discount rates per year, and the attribute contains options for entering the source data, years and given value rate information. The discount rate used to compute the adaptation measures (CLIMADA DiscRates Wiki, 2020). The user needs to provide the discount rate in Excel format.

<u>Adaptation Measures</u>: adaptation measures will have an effect on the exposure, hazard, and impact function, and will change the impact. The measure class for impact function have option to define the measure impact on induvial attribute which means it allows to implement the measure on MDD, PAA, and hazard intensity of the impact function separately. The measure attributes need to fill or defined by the users. The attributes are hazard type, name of the measures, RGB colour code of measures, cost of the measures, impact of measure, hazard frequency cut off, changes of hazard intensity, change of impact function id, changes of mdd, and paa impact. In addition to this, attribute the risk transfer cover and attachment will be included if the information is available. By using measure class, it is possible to apply the measures in specific regions which is the measure only apply on the exposure in that specific region and the nearest centroid of hazard will be modified. Events which have greater impact exceedance frequency will give zero intensity by the hazard frequency cut off. In the measure class there is the measure sets this sets are a collection of measure and have metadata tag to store the data information. The measure data defined by the excel format and directly on CLIMADA Python then the measure can be exported using write raster function.

<u>Hazard</u>: the CLIMADA tool focus mainly on climate and weather-related hazards but the tool can be applied for all hazard type. The hazard package characterized by the following attributes: tag hazard, intensity units, centroids (encode the intensity), event id, event name, date, frequency, origin, intensity, and fraction. Tag hazard used to store data source information. In general, the input data of hazard require three main sheets (hazard centroids, intensity, and frequency). The centroids store the hazard intensity which include geographic coordinate, and centroids ID. The intensity contains the centroids ID and geographic coordinate to link with centroids and intensity value for each point. Frequency includes event name, event ID, origin (the source of the hazard can be historical or probabilistic event), frequency of events (1/RP), date for the event in ordinal format of Python library. The hazard package model the hazard based on event based probabilistic method, firstly it obtained the historical event then by using the historical event generate probabilistic events and store in the centroids. The hazard defined into four ways the first method is to read the hazard file provided by the user in different format (Raster, Excel, MATLAB, Vector, Hdf5). The second method is to define the hazard by filling the value one by one for every event.

The third method is defining the hazard by using Tropical cyclones class. This method used TC tracks class to collect the historical tracks from IBTrACS dataset. Historical events are obtained by attribute data and get track function the tracks identify based on the basin with year range and the name or ID of tracks. By using the historical tracks CLIMADA allow to create synthetic or probabilistic tracks. The synthetic tracks generate randomly with calc random walk function and interpolate equal time step. The Tropical cyclones class convert the tracks into TC hazard by following the Holland method which implies the circular wind field sum for each centroid in 1-minute sustained peak gusts (Holland, 2008). The centroid calculated based on the boundary limit and the TC hazard constructed by the tracks and centroids. It is possible to construct the TC hazard without given centroids. For future year risk the tool has an option to implement the climate change scenarios into TC hazard. The scenario implements by set up the climate scenario (Global projections of intense tropical cyclone activity for late twenty-first century) (Knutson et al., 2015). In addition to this the user can make videos for the TC hazard in CLIMADA.

The Engine packages from the actual calculation modules of the CLIMADA tool. There are tools for impact assessment and for cost benefit analysis of mitigation and adaptation alternatives class which interact the defined class in the hazard and entity (Aznar-Siguan & Bresch, 2019). The impact class applied the calc method to compute the potential impacts of the hazard on related exposures and impact functions. The result of the impact store in risk assessment metrics. Before computing the impact, the exposures and impact functions need to be set then the impact will be calculated for every exposure point and every hazard events. The output of the impact calculations are expected annual impact (EAI), exceedance frequency curve, average annual impact (AAI). Further metrics can extract using the impact attribute like the annual expected impact of category or region and annual expected impact of category or region over its total value. The result will present in numerical value, graphs, and maps format. In addition to this by fixing exposure and impact function it is possible to make videos which shows the exposures hit by the hazard.
The calculation metrics of CLIMADA for impact, expected annual impact, average annual impact, and exceedance frequency curve adopted from (Cardona et al., 2012).

- The direct impact (loss) calculates by multiplying the value of asset with the impact function. The impact calculated for all exposure, and every event. The event can be historical or probabilistic event Equation (1) shows how CLIMADA calculate the impact. The exposure calculated by setting the nearest centroid points for each exposure.

$$\chi_{ij} = val_j \, f_{imp}\left(h_{ij} \middle| \gamma_j\right) \quad (1)$$

Where:

- x_{ij} → impact due to event i at location j
- val_j → the value of exposure at j
- f_{imp} → impact function (vulnerability)
- h_{ij} → hazard intensity due to event i and location j
- y_j → parameters of exposure j that characterize its vulnerability

Different risk metrics computed by using the impact (loss) result, which is the expected annual impact, average annual impact, probable maximum impact, and exceedance frequency curve.

- The expected annual impact of the exposed asset is computed by multiplying the impact with the frequency of the events and sum the multiplied impact. The frequency weighted impact result depends on the hazard assessment, but the impact (loss) depends on the exposure and impact function. The equation used to calculate the EAI is presented below.

$$EAI_j = \sum_{i=1}^{N_{ev}} \chi_{ij} F(E_i) \quad (2)$$

Where:

- **EAI_j** → Expected Annual Impact at exposure j.
- **E_i** → Events
- **N_{ev}** → Total number of events
- **X_{ij}** → Impact
- **F** → Frequency

- The average annual impact is simply adding the EAI of all exposures. The equation seen below.

$$AAI = \sum_{i=1}^{N_{exp}} EAI_j \quad (3)$$

Where:

- **N_{exp}** → Number of exposures

- Exceedance frequency curve relates the return period of each hazard to estimate the impact, the curve computed for a given hazard set by using calculate frequency curve command. For tropical cyclone hazard which is generated by using IBTrACS in CLIMADA calculate the exceedance frequency curve based on the number of tracks and assign the largest return period for the higher damaging event

CostBenefit analysis: adaptation options appraisal class calculate the present value of the measure cost, risk today, risk in the future and cost benefit ratio. The cost benefit analysis compares the cost and benefits of the proposed measure in monetary value for specific period or justification of the cost of risk reduction measures (HPN, 2017). The class calculate the benefit of measure today and to the future based on the annual expected damage with no measures and with measures. The mitigation or adaptation measure used to mitigate the negative impact caused by climate and non-climate related hazards (Strom, 2019). In addition to improve the decisions by decision makers CLIMADA associated with Economic of Climate Adaptation (ECA) methodology. ECA is an open-source methodology which helps to develop, plan, and finance the adaptation measures (Souvignet et al., 2016).

Add-ons: connect CLIMADA tool with external data source (OpenStreetMap and Google Earth Engine API routines). The OSM data mainly used to prepare the exposure and the GEE used to produce hazard map. Any dataset available in the two external data sources can accessed by load the required packages in CLIMADA python. The user needs to use Python script to connect with the external data sources there are different examples in CLIMADA wiki https://climadapython.readthedocs.io/en/v1.5.1/index.html#.

2.4.2. RiskChanges

RiskChange aim to analyses multi-hazard risk in risk prone area, the tool have Python based version for scientist https://pypi.org/project/RiskChanges/ and Graphical User Interface for non-technical users http://riskchanges.org/. The tool includes several major features: multi-hazard, multiple assets, vulnerability database, multi-user, compare risk and spatial analysis. The multi-hazard feature performs the risk assessment for multiple natural and manmade hazards. Multiple assets feature allows to analyse the risk of multiple asset type with different spatial characteristic. The vulnerability database feature, give an access to the user to use and share physical vulnerability curve. The multiuser feature has the capacity to perform the risk assessment by multiple users, who can access the tool at the same time and the input data can be provided by different users for the same project. Compare risk feature conducts a comparison between current risk and future risk also different planning alternatives can be compared using this feature. And by using the spatial analysis feature the user can analyse the risk spatially through the web-based map interface. The tool does not produce the hazard maps, elements-at-risk maps, risk reduction alternatives and future scenarios itself, as the tool only uses the existing input data.

In general, the tool has three main components to conduct the multi-hazard risk assessment: data management, analysis, and visualization component.

a) Data management

The data management focuses on the input data preparation of elements-at-risk, hazard maps, vulnerability curves, administrative units, risk reduction alternatives and future scenarios. The data management performs different functions on the input data mainly matching projections, classify hazard maps, project vector and raster maps, checks projections, checks unique types, and links vulnerability to hazard. The match projection class will check the projection system of the given hazard and elements at risk data and converts them if they have different projection system. The data management uses the base and step size to classify the hazard intensity maps. The hazard data required to identify the model can be either a susceptibility map with classes or an intensity map, with given units of intensity. The data management will allow to convert and check the projection system of vector and raster data into any EPSG number. The Check unique types of class give the unique type of values (building occupancy type, number of floors, construction type and can be anything which can have unique id) for any column of the elements at risk data. The link vulnerability class is used to link the vulnerability file for different type of elements at risk.

- <u>Elements-at-risk</u>

Building footprints, land parcels, linear feature (road, railway, powerline) and point data are the elements-at-risk that can be included in the tool. The input data can be uploaded into two ways: user input and OGC service or database connection. The user input file needs to be in shapefile format and any other format. In the interface (Figure 3) the user is required to define the name of the elements-at-risk (e.g., building footprint), type, representative year of the elements-at-risk, risk reduction alternative and future scenarios can be selected if the data are prepared before. Finally, the user is also required to indicate the file to be uploaded and the tool recommended to use abbreviations name for all elements (building footprint as BF). After uploading the input data, the tool has an option to indicate the value of elements-at-risk metrics (average, standard deviation, minimum and maximum), unit of the elements-at-risk, which is for monetary the currency, for population the total, daytime, and night time population. In addition to this, there is an option to indicate the metrics and units of geometry (metrics can be area, length) and (unit can be in m^2, km^2, m, and km).

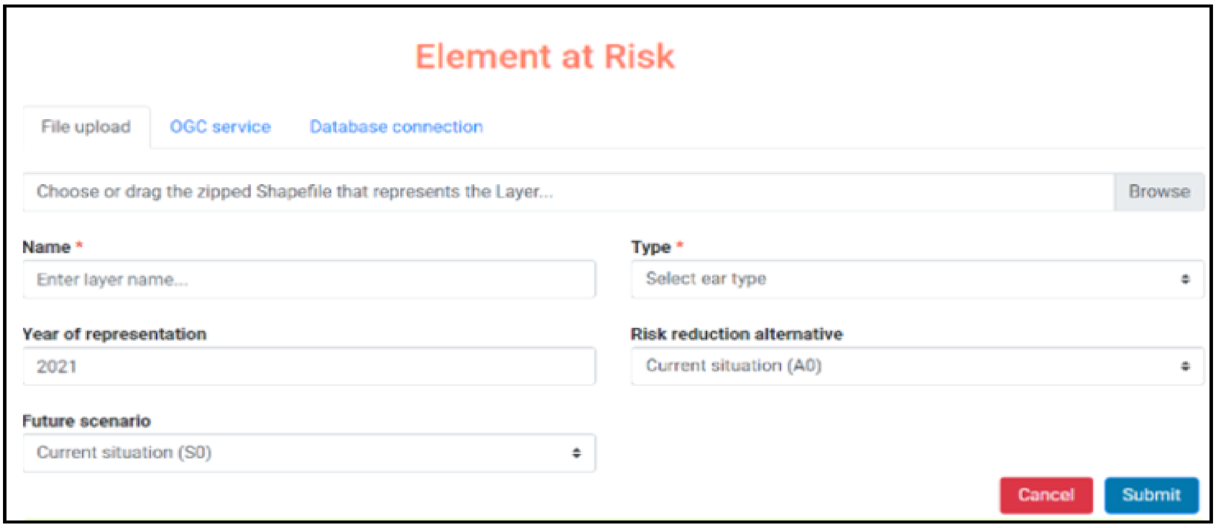


Figure 3:Interface for elements-at-risk, Source from RiskChanges GUI

After defining and uploading the file the system understand which columns are for what classes of elements-at-risk and the user can link the vulnerability functions for the classes.

- <u>Hazard maps</u>

The tool considers all types of hazards which includes natural and manmade hazards. Similar to the elements-at-risk there are two options to upload the data (user input and OGC), but the file should be in

Geotif format. The user is required to define different information related to the hazard in the system. Which includes the name of the hazard, type, return period, future or current year, spatial probability, risk reduction alternative and future scenarios. For the return period the tool has an option to choose the average, standard deviation, minimum and maximum of the return period. Currently for modelled hazard intensity the spatial probability is represented by 1 for all location, for the susceptibility map the spatial probability is linked with the number of susceptibility classes and the data can be uploaded using a csv file. For the future, the developers plan to include the spatial probability in terms of a map in Geotif format. The hazard intensity is classified by the data management by setting the base intensity value and the step size of the hazard intensity. The base is the starting point of the classification, and the step size is the interval between the classes. The step size can be smaller or larger based on the user requirements. In addition to this the risk reduction alternative and future scenarios need to be defined before in the data management like elements-at-risk.

- Vulnerability curves

Figure 4 shows the structure of the vulnerability curve database and the available information included in the vulnerability database. When the vulnerability curve is linked with the modelled hazard intensity the curves include intensity (from> to) and for susceptibility hazard it will be linked to susceptibility classes (e.g., from very low to low). The average column indicates the mean damage degree of the elements-at-risk, and the standard deviation is optional. The classification of hazard is standardized, so the increment of the intensity is standardized based on the hazard increment. The vulnerability database includes different information to be defined and used by the users which are the type of the elements-at-risk (e.g., building footprint), elements-at-risk class, hazard type, intensity type, source of vulnerability, and region for which the curve is valid. For building footprints, the elements-at-risk class has classification information for building construction type and occupancy type. In addition to this, the future year scenario or alternatives are not incorporated in the database because the system considers that the vulnerability curves of the predefined elements-at-risk would not be changed. If they change in future scenarios another vulnerability curve can be selected.

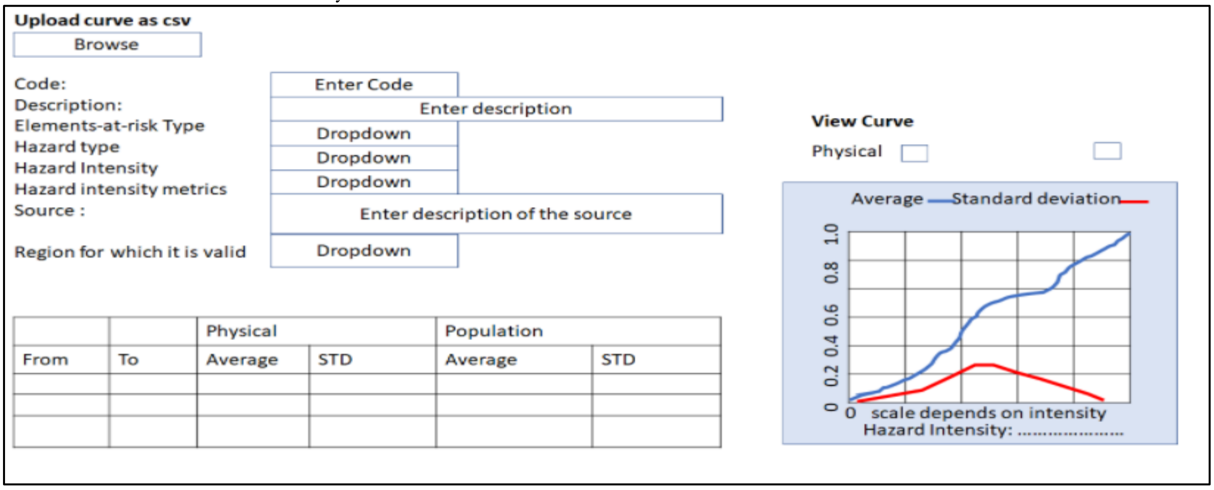


Figure 4: The interface of the vulnerability curve, Source from RiskChanges GUI

- Administrative units

The administrative unit map needs to have a name, description, and related shapefile. The administrative unit level is divided into four classes which are national level, state/province level, district level and smaller administrative unit level. The input data should be uploaded as shapefiles of polygons. The polygons are required by the system to aggregate the exposure, losses, and risk. For instance, if 60% of a land parcel is located in one administrative unit and 40% of the land parcel fall in the other admin unit, then RiskChanges will calculate the loss and risk based on their relative proportion.

- Risk reduction alternatives

The risk reduction alternative implemented by changing the different aspect of hazard, elements-at-risk, and vulnerability. The user required to define the name of the alternative (which can be for example engineering, ecological and relocation), a description of the alternatives and what is changed (hazard, elements-at-risk, and vulnerability) and upload the file. The system will understand if the elements-at-risk change then new data should be uploaded and used otherwise the existing elements-at-risk can be used in the analysis, the same is true for the hazard and vulnerability. In addition to this, the tool allow to upload the pdf format for additional description of the alternatives.

- Future scenarios

Similar method and contents are used in the future scenarios like risk reduction alternative but the changes in the hazard would be the frequency or intensity, the elements-at-risk can be changed in number, type and value, and the vulnerability of the exposed elements-at-risk change.

b) Analysis

The analysis component used to compute the analysis of the exposure, loss, risk, and cost benefit analysis; the overall methods used to compute the analysis in the tool is presented as follow:

- Exposure analysis

The Exposure function calculate the exposure with and without aggregation per administrative unit. The calculation is done in the system by using the elements at risk (EAR) shapefile, classified hazard, and unique identification key in EAR. RiskChanges perform the exposure for different combination of elements-at-risk, hazard, future scenarios, and year, return period and alternatives. The combination can be one elements-at-risk for different hazard also the reverse is possible. The output of the exposure will give the percentage of exposure per hazard classes. The example can be one building can be exposed to in different hazard classes, for example 30 % of the house exposed to 1.5m flood and 70 % to 0.4m flood. This is especially relevant for large land parcels or long linear objects. This will help to minimize underestimation and overestimation which leads to approximate loss and risk results to the reality.

- Loss analysis

The Loss function computes the loss using the calculated exposure data, EAR unique ID, cost column, linked vulnerability column, and spatial probability of the hazard. The equation used to compute the loss in RiskChanges shown in equation (4).

Compute Loss = %exposure*total cost*vulnerability*Spatial Probability (4)

The loss can be aggregated to the administration unit and different combination of hazard and elements-at-risk is possible in the system. The loss report will be for single asset or in the administrative level.

- Risk assessment

The RiskChanges calculate the single and multi-hazard risk. The risk calculation takes over after calculating the losses. For the computation of single hazard risk assessment, the tool requires the combination of the loss files and if the user want to calculate the risk for administrative units the user should also provide the aggregation layer. The RiskChanges follows Dutch method to compute the annual risk of the single hazard the equation used to calculate the single hazard risk illustrated.

$$risk = \frac{1}{T_1} * S_{1+} \left(\frac{1}{T_2} - \frac{1}{T_1}\right) * \frac{S_1+S_2}{2} + \left(\frac{1}{T_3} - \frac{1}{T_2}\right)) * \frac{S_2+S_3}{2} + \left(\frac{1}{T_4} - \frac{1}{T_3}\right)) * \frac{S_3+S_4}{2} + \left(\frac{1}{T_5} - \frac{1}{T_4}\right) * \frac{S_5+S_4}{2} \quad (5)$$

Where:

- $T_1, T_2 \ldots \rightarrow$ Return period.
- $S_1, S_2 \ldots \rightarrow$ Losses

The RiskChanges calculates the multi-hazard risk and to compute it requires two input files, the risk combination file and hazard interaction file which includes the type of interaction and their probability. For both files, the RiskChanges has a template in csv format. The multi-hazard risk can be computed with and without aggregation, the difference is to include the aggregation the user only required to add the admin unit data. During the multi-hazard risk calculation, the RiskChanges has a limiting factor to exclude the exceedance amount of risk value (the risk must be equal or less than the original value of the elements-at-risk). Table 3 describe how the RiskChanges include the hazard interaction in the multi-hazard risk assessment.

Table 3: Method used to calculate hazard interactions in RiskChanges

Hazard interaction	Hazard type A	Hazard type B	Total Loss	Explanation
Independent events	Loss A	Loss B	Loss A + Loss B	Losses can be added up if the events are truly independent
Compounding events	Loss A	Loss B	Loss A + (total value- Loss A+ Loss B)	The loss of B should be calculated when A has occurred. If calculated before this equation is an approximation
Coupled events	Loss A	Loss B	Max (Loss A, Loss B)	The hazard should be calculated together ideally and therefore also the loss. If this is not possible, this is an approximation
Dominos events	Loss A	Loss B	Loss A + Loss B	If the elements-at-risk are not located in the same area
			Max (Loss A, Loss B)	If located in the same area
Conditional events	Loss A	Loss B	Loss A + Loss B	The hazard B can only be calculated after A has occurred. Otherwise, possible scenarios are used beforehand

Source Van Westen 2020

- Cost benefit analysis

The RiskChanges is able to compare the risk reduction alternatives by analysing the cost benefit ratio. The analysis required the cost of alternatives, investment period, benefits, lifetime of the investment and discount rate. The system calculates the Net Present Value, Benefit Cost Ratio and Internal Rate of Return. The analysis can be done for current and future risk.

c) Visualization

As we discuss earlier the RiskChanges has a Python based and a Graphical User Interface (GUI), the visualization of the GUI includes maps, graphs, and tables for all combination (exposure, loss, risk, risk reduction alternatives, future scenarios) but the Python based method do not have any visualization method only the user run the procedures and get the result in shapefile, raster, and csv format.

3. STUDY AREA AND DATA

This chapter focus on the study area and the data used to implement the flood and wind loss assessment by using CLIMADA and RiskChanges tools in this research. Different input data were used and pre-processed to reach the data requirements of the tools. The building database prepared by classify the occupancy type, construction type, roof type and roof shape of the buildings using visual inspection and conditional statement. In addition to this, the value of the buildings are estimated using real estate price and area of the buildings.

3.1. Study area

This research uses the island country of Dominica in the eastern Caribbean Sea of the Lesser Antilles as case study to conduct case study-based comparison of CLIMADA and RiskChanges tools. According to the Wold Population Review (2020) the country's total population is 71,986 and the island subdivided into 10 administrative regions or parish. The island covers 750km^2, and the capital is Roseau. From the total area of the island 488km^2 covered by forest and 50km^2 area covered by arable land. The climate of Dominica island is a tropical climate which is hot and humid throughout the year, with 250 to 400mm rainfall per month during wet season (June to October) and in this season cyclones and hurricane contribute intensive amount of rainfall (World Bank Group, 2021). The topography of the island is very rugged and steep slope mountains including several active volcanoes that have not erupted in the past 23 years(Britannica, 2018; CHARIM, 2014). The average elevation of Dominica island is 724m, with highest elevation point (1447m in Morne Diablotins) and lowest elevation point (0m in Caribbean Sea). The dominant rugged terrain and the steep topography lead the physical development and human settlements concentrate along the coastline (148km) which makes the country highly vulnerable to several natural hazards (Jetten, 2016).

The Dominica island have an extensive history of natural disasters, mostly tropical cyclones, flooding, landslide, mud flow, volcanic eruption, earthquake, and tsunami. In Dominica island the natural disaster caused higher impact on the country economy. From the island disaster history, the most devastating events were occurred in 1979 hurricane David, 2015 storm Erika and 2017 hurricane Maria. Hurricane David caused for 44.65 million damage and 40 fatalities. 2015 tropical storm Erica affected 10% of the population and caused 30 fatalities and 482 million economic damage (GFDRR, 2015c).

During hurricane Maria 90% of the population and more than 90% of the buildings were affected (ACAPS, 2018). The hurricane Maria hit the island on September 18, 2017, the storm changed from category 1 into category 5 within 24 hours. 452mm of rainfall recorded at Canfield Airport and the wind speed reach 74.60m/s this intensive winds stay for more than 3 hours in the island which trigger landslide and flash flood (NHC, 2019).The effects of hurricane Maria were devastating and caused for 30 fatality, 34 missing, 1862 displaced, affected 66,926 people (PDNA, 2017). The economic damage reaches 1.37 billion USD. Table 4 show the hurricane Maria damage in public and private within different sectors. The housing sector has a lot of damage compared to the other sectors; the second highly affected sector was the infrastructure. The tourism sector which is related to the hotel had moderately damage. The damage in the sectors shows not only the loss caused by the building it also includes the equipment, infrastructure for operators, landscape, common space, furniture, and other materials loss. Figure 5 shows the location of Dominica island including the hurricane Maria track and different level of damaged building caused by this event reported by building damage assessment.

Table 4: PDNA reported loss per sectors.

Sectors	Public	Private	Total
	Loss in USD (Million)		
Housing	-	353.98	353.98
Education	48.8	25.18	73.98
Health	10.79	0.15	10.94
Cultural	5.07	-	5.07
Infrastructure	143.5	38.66	182.16
Ports and airports	18.89	-	18.89
Water and sanitation	24	-	24
Electricity	33.18	-	33.18
Telecommunications	0.37	47.37	47.74
Agriculture	37.75	16.62	54.37
Forestry	29.72		29.72
Fisheries	0.57	1.85	2.42
Commerce/Microbusiness	-	70.4	70.4
Tourism	-	20.15	20.15
Total	352.64	574.36	927

Source: PDNA (2017).

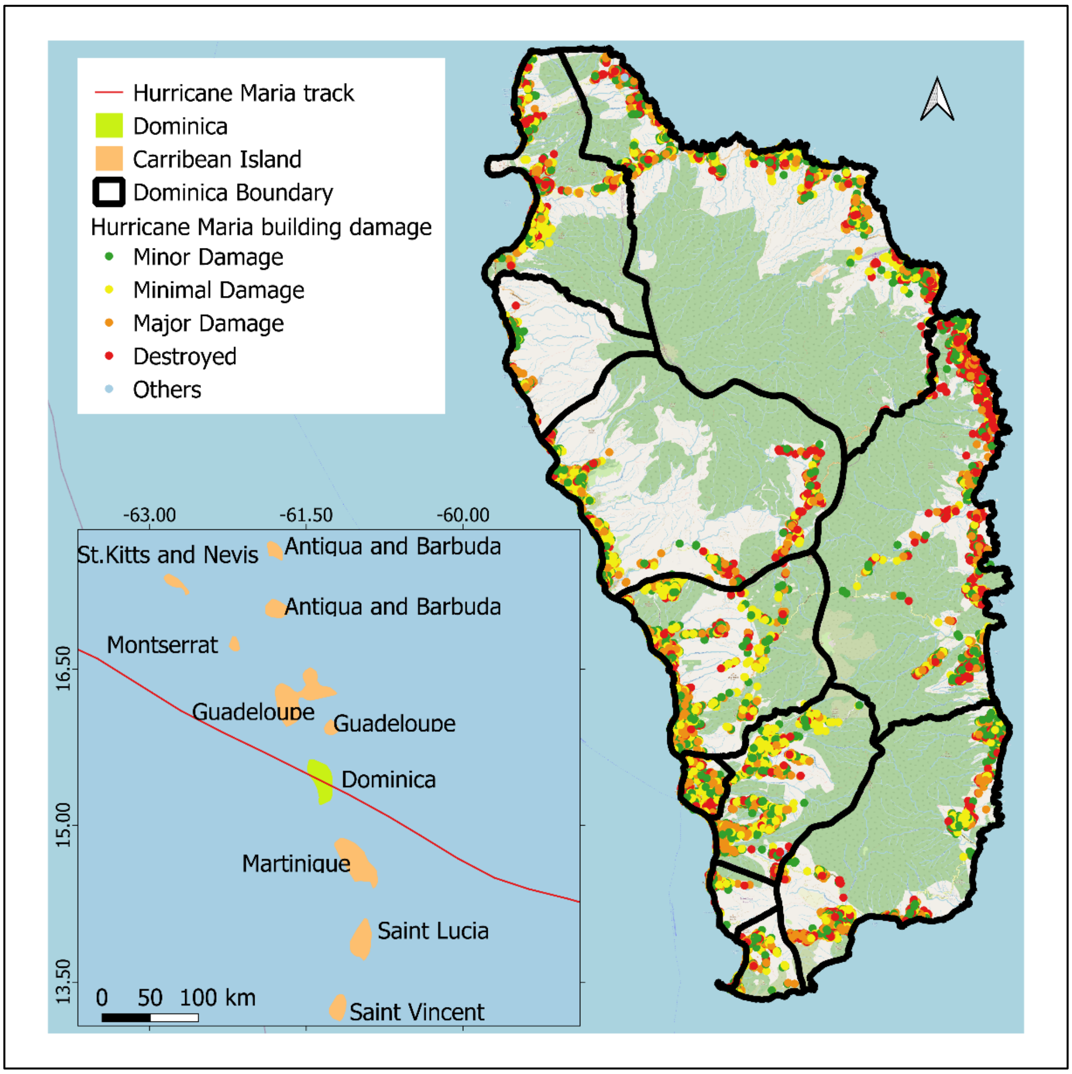


Figure 5: Study area location map with building damage by hurricane Maria 2017

3.2. Data processing and analysis

To conduct the multi-hazard risk assessment using CLIMADA and RiskChanges tools we compiled different datasets related to hazards, elements-at-risk, and vulnerability. Also, the damage data will be presented. This section presents the data used in this research, and the process used to prepare and analysis the input data.

3.2.1. Damage data

After hurricane Maria hit the island the Ministry of Housing supported by UNDP and the World Bank carried out a comprehensive building damage assessment (BDA) from November 2017 to January 2018 in Dominica island (UNDP, 2018). The structural damage census was collected using tablets with applications for capturing data. The data was collected by a group of thirty volunteers and students with different backgrounds. The UNDP provided training related to disaster preparedness and monitoring of reconstruction activity and Geographic Information System (GIS) before the census for two days (Dominica News Online, 2018). According to UNDP (2018) the structural damage census collected information for 29000 building, out of which 25,477 buildings were houses, 2916 commercial buildings, 840 public buildings and 195 other buildings. The degree of damage was categorized into four level and the assessment applied colours for each category of damage.

- Red for destroyed buildings.
- Orange for buildings of which the roof or wall were severely damaged.
- Yellow buildings where the roof had 25% - 75% damage.
- Green for buildings with roof damage less than 25%

The analysed data was given to the Government of Dominica and international partners to support the reconstruction planning and evidence-based decision-making. Unfortunately, detailed information on the method used to assess the BDA, and the result of the damage was not available. We only obtained a point file of damage points with associated damaged information.

The BDA database has different errors related to the location of the damaged buildings and the attribute information (the name of Parish was not correct for many buildings). Due to the inaccuracy of the GPS used the location of the surveyed buildings did not match with the building footprints (see Figure 6). Although the BDA assessment covered the whole island many buildings were not included in the analysis. This, unknown location of the BDA buildings made it difficult to identify the exact location of the buildings.

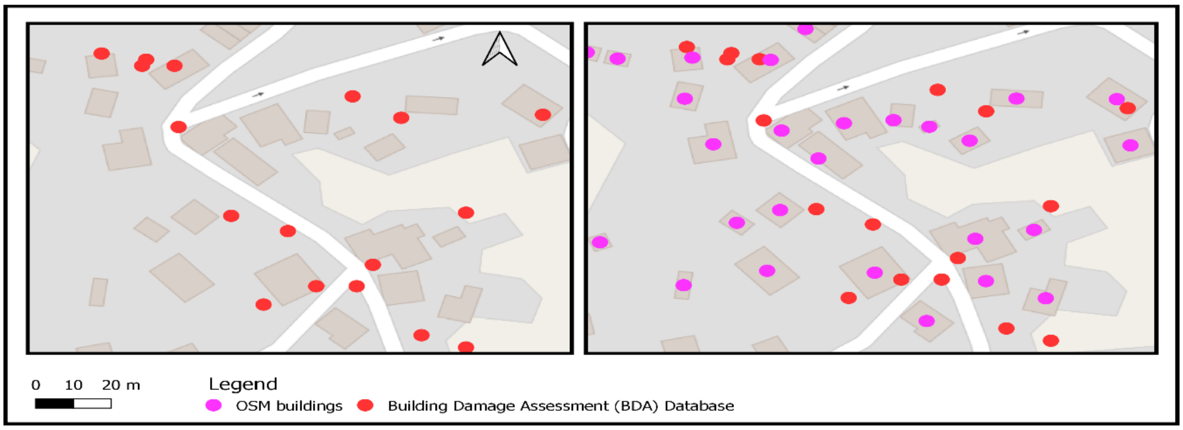


Figure 6: BDA assessment building versus OSM buildings location

In addition to the BDA the Government of the Commonwealth of Dominica requested a Post Disaster Needs Assessment (PDNA) on October 9, 2017. The PDNA was conducted with technical and financial support from World Bank, GFDRR, UN, EU, CDB, and ECCB. The government selected the most critical target sectors for the PDNA: health, transport, tourism, agriculture, housing, commerce, and industry; employment, livelihoods, and social protection, education; water and sanitation; telecommunications and energy (PDNA, 2017). The PDNA assessed the following components:

- Physical and socio-economic aspects of damages and losses
- The overall impact on macro-economic and human development.
- Recovery needs, priorities, and cost for a resilient recovery strategy.

The PDNA data was collected from October 17 to October 27, 2017. The data were gathered from the government and the damage assessment of buildings was based on the BDA. The report indicates that the damage assessment was related to the total or partial damages of the assets. The loss assessment was related to the productive sectors which decreased the output of the products. In our study the PDNA report was used to validate of the loss result and classify the OSM buildings based on the occupancy type.

3.2.2. Building data

The study focusses on building losses caused by the 2017 hurricane Maria disaster, and other elements-at-risk were not included during this study. Because the aim of the study was the validation of the loss results which are generated by the CLIMADA and RiskChanges tools with the PDNA reported loss. The PDNA reported loss shows that the damage and losses of the buildings counted more than 67% of the total damage and the report included detailed loss result on the buildings. Specially the loss on the residential buildings was higher than the other occupancy types, as in this sector the loss was more than 90% of the buildings. In addition to this the number of the residential buildings are higher than the other. Therefore, in this study the loss estimation conducted for all buildings and the residential buildings loss validated with the PDNA reported loss.

The existing building footprint map does not have metadata and required attribute information for buildings to carry out the loss estimation, such as information the occupancy type, construction type, roof type, roof shape and number of floors. Therefore, the pre-processing and analysis of buildings is required. To prepare the required building database the OSM buildings database used.

Since it is not known whether the building represents the time period before Maria, time period for which the OSM buildings were portraying the right situation was carefully checked by using Google Earth historical imagery of the time slider. It was discovered that the OSM buildings represented the situation before the hurricane Maria and even the situation before the tropical storm Erika, which occurred in 2015. Figure 7-A shows the examples of the buildings in 2014 and new buildings that were constructed after hurricane Maria. Figure 7-B shows an example of buildings in the OSM database that were destroyed during storm Erika, but still in the database.

Figure 7: A: Temporal scale of OSM buildings B Destroyed buildings by storm Erika.

The 2014 OSM buildings database contains 38557 buildings. We do not have another building database that shows the situation after tropical storm Erika and before hurricane Maria. This is important because it will not make it possible to validate the exact damage of hurricane Maria with this building data. The buildings were classified into eight occupancy groups: residential, commercial, industrial, governmental institutes, hospitals, schools, churches, and other building types. In addition to the occupancy type the construction type, roof type and roof shapes were classified. Figure 8 shows the method used to classify the buildings by four categories.
Two methods were used to classify the OSM buildings. The first method was through intensive visual inspection using Google Earth and BDA data. The second method is the use of conditional statements using the area of the building and distance from the main road. For a total of 3744 buildings the occupancy type was identified visually using the images from Google Earth and the nearest building classification of BDA. For the other 34813 buildings conditional statements were used to classify them. Only residential, commercial, and industrial occupancy types were considered in the conditional statement because it was difficult to identify the other occupancy types using only the criteria of the area and distance to the main road. For hospitals and medical centres, the CHARIM Geonode dataset was used in addition to the visual inspection which contained the location of 53 health centres.

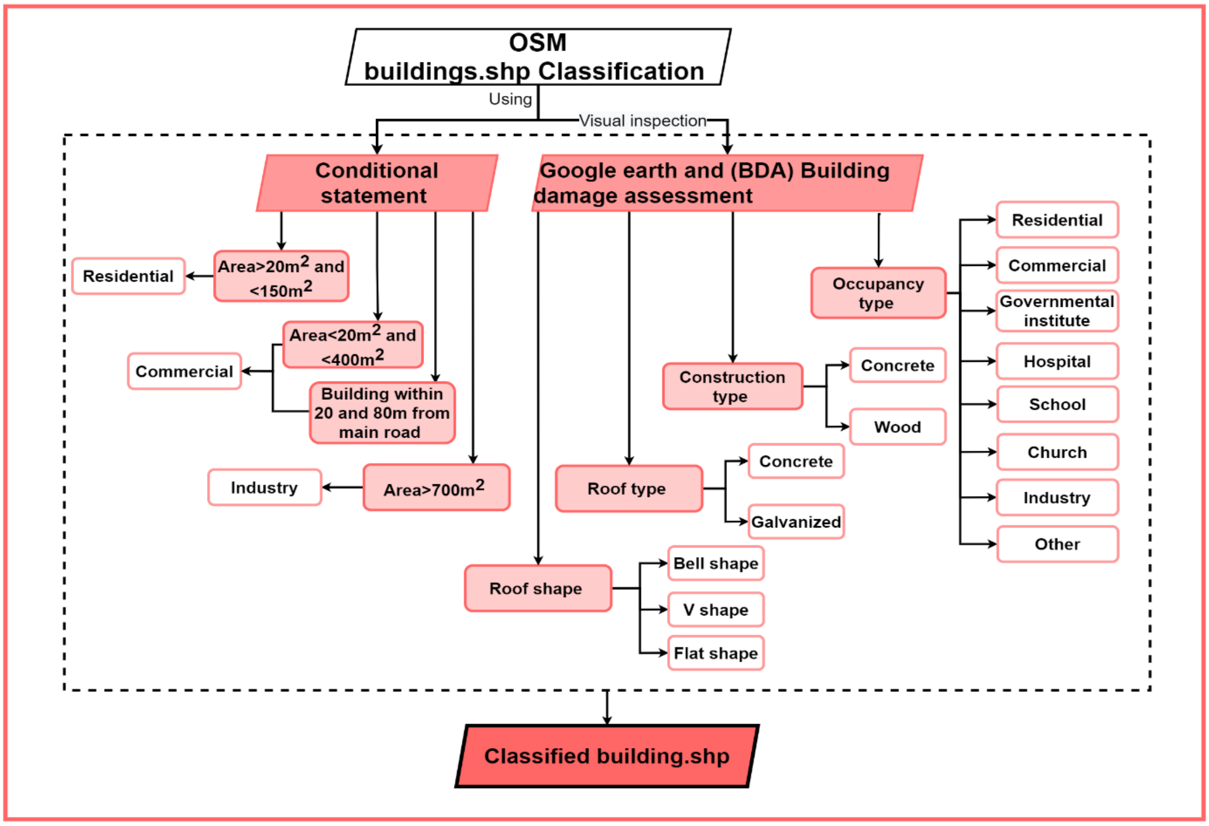


Figure 8: Method used to classify the OSM buildings.
The area condition used to identify the occupancy type of residential and industrial buildings are >20, <150 >700m², respectively. Most of the residential buildings had an area ranging between 20m² up to 150m². The average residential building in Dominica has a relatively large footprint area. Buildings with a footprint area larger than 700m² were classified as industrial. Building with a footprint area <400m² were classified as commercial buildings using both the area and distance to the main road (see Figure 8). The distance from the main road was used, as many commercial buildings are near to the main road because of their accessibility. For Roseau, the capital city of Dominica we assumed that the commercial buildings could be within 80m from the main road, based on several examples checked through visual inspection. For other part of the island a distance of 20m from the main roads was considered for the classification as

commercial buildings, as the concentration of commercial buildings outside of the capital is much lower and mostly consists of roadside shops.

Table 5: Buildings classifications based on four categories.

Occupancy type	Construction type	Roof type	Roof shape
Residential	Concrete	Galvanized	Bell shape
Commercial	Wood	Concrete	V shape
Industrial			Flat shape
Governmental institutes			
Hospitals			
Churches			
Schools			
Others			

The occupancy types of the buildings were classified by considering the PDNA critical sectors. According to Cuny (n.d.) the construction types, roof types and roof shapes were classified (see Table 5) because those type of buildings are dominated in Dominica island. In addition to this the examples of building occupancy types included in the commercial, school, church, hospital, governmental institutes, and other buildings presented in Table 6.

Table 6: Examples of building occupancy types included in the six classes of occupancy.

Building category	Commercial	Schools	Churches	Hospitals	Governmental institutes	Other
List	Hotel, bar, lodge, bakery, store, bank, insurance, pharmacy	Premier, secondary, college, and university	Church, mosque	Hospital, health center, and clinic	Town council, police station, library, post office, museum, broadcast station, prison house, court, Hydroelectric Station, water and sewerage institute, national credit cooperation, computer center, public toilet	Stadium, park, tourist site, airport, social center, embassy, shelter, football field

The classified OSM buildings result (Table 7) shows that 80.7% of the buildings were classified as residential buildings, 16.92% were commercial buildings and 2.38% of the buildings were classified in the other occupancy types. The number of commercial buildings is too high this might be due to the classification criteria. We used two criteria (area and distance to main road) this increased the probability of buildings to be classified as commercial buildings. The number of residential buildings is very similar to the PDNA reported number of buildings. Figure 9 shows the spatial distribution of the classified buildings over the island.

Table 7: Building classification result

Building category	Visually inspecte from Google Ear	Using conditional statement based on area and main road	Total number of buildings	Percentage
Residential	1412	29701	31113	80.70
Commercial	1426	5100	6526	16.92
Schools	194	194	194	0.50
Churches	130	130	130	0.34
Hospitals	106	106	106	0.27
Industrial	127	49	176	0.46
Governmental institutes	183	183	183	0.47
Other	129	129	129	0.34
Total	3744	35592	38557	100

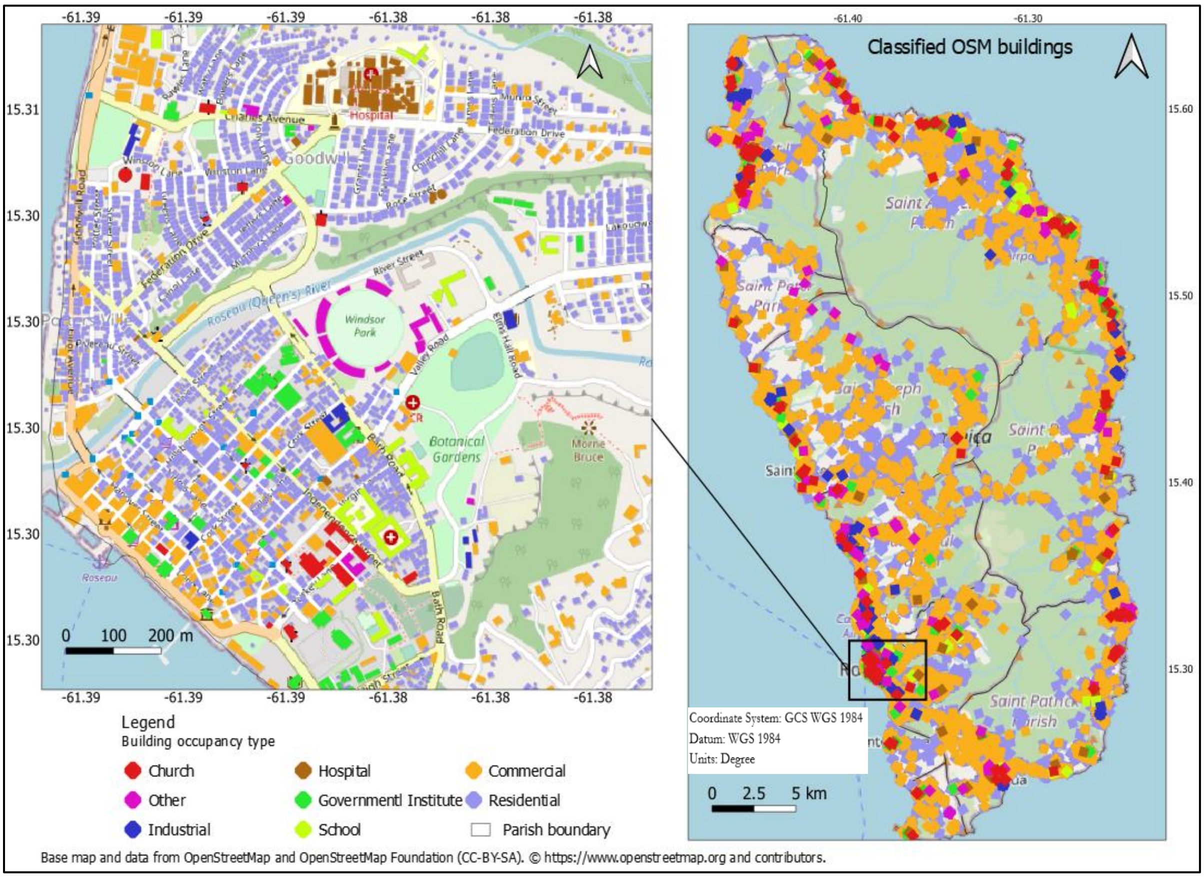


Figure 9: Distribution of classified buildings

For evaluation the construction type, roof type and roof shape class for the OSM buildings an intensive visual inspection in Google Earth was done. Identifying the roof shape and type of buildings was much easier than their construction type using vertical images. Therefore, also oblique photos were consulted. In general, concrete building with galvanized roof and V shape buildings are more dominated than the other combination of building types. Table 8 shows the possible combination of building type with their corresponding number of buildings. The type of buildings included in the roof type and shape classification categories see Figure 10 and Table 9 (number of classified buildings).

Table 8: Possible combination of buildings to select vulnerability functions.

Building type	Number of buildings
Concrete building with flat shape roof and concrete roof type	2886
Concrete building with bell shape roof and galvanized roof type	10857
Concrete building with V shape roof and galvanized roof type	12559
Wooden building with bell shape roof and galvanized roof type	634
Wooden building with V shape roof and galvanized roof type	11621

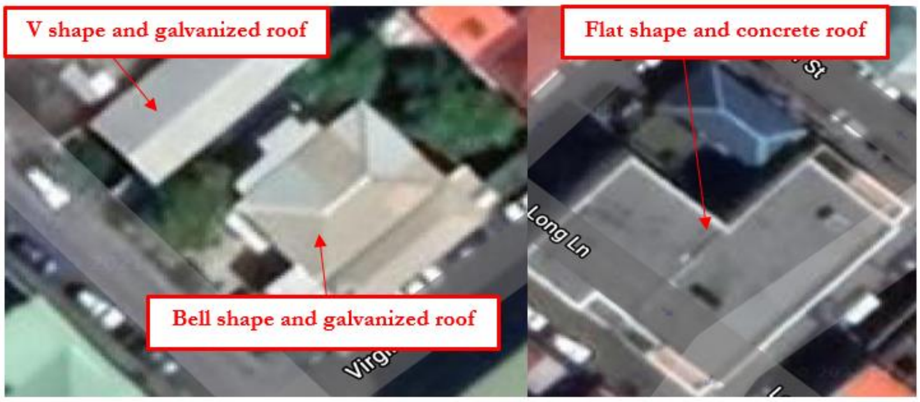


Figure 10: Type of roof shape included in the classification.

Table 9: Number of buildings classified in the three categories.

Construction type		Roof type		Roof shape		
Concrete	Wood	Galvanized	Concrete	Bell	Flat	V
26302	12255	35664	2893	11484	2893	24180

The building values were estimated using real estate prices and the footprint area of the buildings. Figure 11 shows the detailed steps used to estimate the value of the buildings. The real estate price collected by the community level for residential and commercial buildings. At least four building prices per community were collected to identify the average values. Then 10% of the average value was deducted to get the approximate building value in 2017. After that the area of the buildings was used as guidance to determine the replacement value as indicated in Figure 11. The average area of the buildings for which the real estate values was obtained and the area per m^2 was calculated. Then for each community the value of each residential and commercial buildings was obtained by multiplying the area with the value per m^2 obtained from the real-estate samples. For schools, hospitals, churches, governmental institutes, industrial buildings, and other building types the values were estimated by the area and the average value of the buildings from the real estate price (see Figure 11).

3.2.3. Vulnerability function

The most suitable vulnerability functions for flood and windstorms for the different types of buildings were selected from literature, which included the Global Flood Vulnerability Function database; Minimal Building Flood Fragility and Loss Function Portfolio at the Community Level; and Global Assessment Report on Disaster Risk Reduction (Huizinga et al., 2017; Nofal & van de Lindt, 2020; UNISDR, 2011).The functions were selected by occupancy type of the building or the combination of different building characteristics (Table 8). In this case we select the functions based on the building occupancy type because the PDNA report used these categories as well. Therefore, to validate the loss assessment results we used a similar classification. But the building construction type, roof type and shape helped to identify the most representative vulnerability functions.

a) Flood vulnerability function for buildings

Seven flood vulnerability functions were used. The respective functions for buildings in Central and South America were selected for residential, commercial, and industrial buildings from the Global Flood Vulnerability Function database (see Figure 12). For schools, hospitals, governmental institutes, churches, and other building types we used the functions from Minimal Building Flood Fragility and Loss Function Portfolio at the Community Level. Similar vulnerability functions were used for governmental institutes and other building types. The portfolio data included several types of building vulnerability functions.

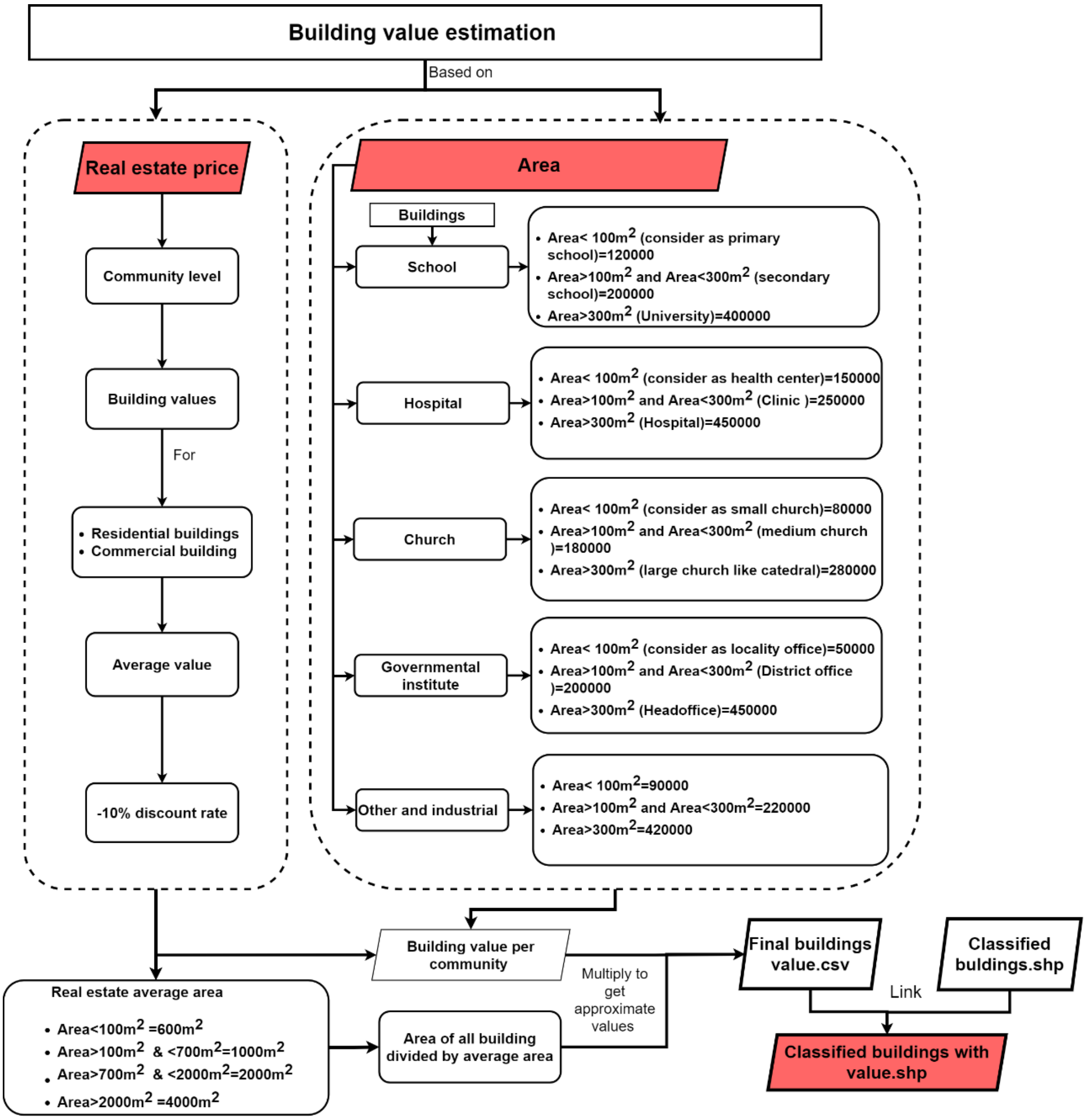


Figure 11: Method used to estimate the building value.

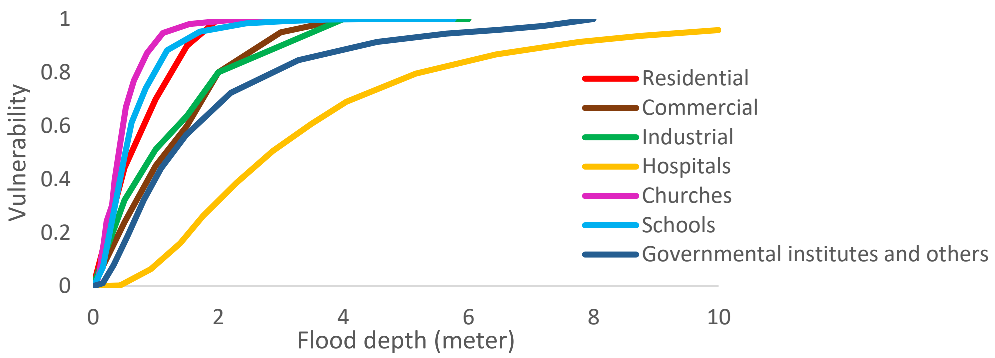


Figure 12: Flood vulnerability function, Source from Global Flood Vulnerability Function database and Minimal Building Flood Fragility and Loss Functions Portfolio

b) Wind vulnerability function for buildings

Six wind vulnerability functions were used from the Global Assessment report on Disaster Risk reduction (UNISDR, 2011).To analyze the windstorm loss assessment in Dominica island. To select the vulnerability functions, we considered that the commercial and church buildings are more vulnerable than the other type of buildings. Commercial buildings often used larger glass window for display purposes which increased their vulnerability. Like commercial buildings the church buildings vulnerability is higher and the damage of church building in the history of Dominica island was high. Figure 13 and Table 10 shows the selected vulnerability functions with the corresponsive building type and the order of vulnerability.

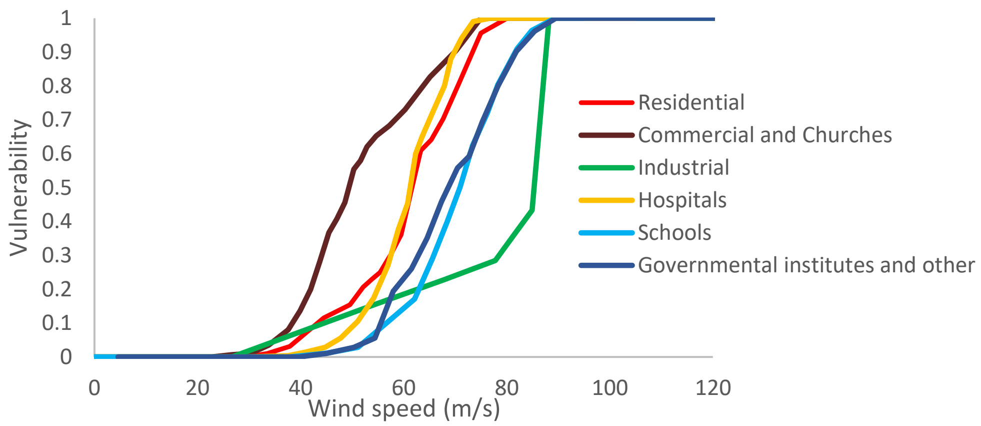


Figure 13: Wind vulnerability functions, Source from Global Assessment Report on disaster risk reduction (GAR)

Table 10: Selected wind vulnerability functions based on the building occupancy type.

Selected vulnerability functions	Building occupancy type
W1_P wood, light frame building with poor quality level	Commercial and churches
(W1_M) wood, light frame building with medium quality level	Residential
W2 -M Wood, Commercial and Industrial with medium quality level	Industrial
C4L- L reinforced concrete frames and concrete shear wall with low quality level	Schools
C4L -P Reinforced Concrete Frames and Concrete Shear Walls with poor quality level	Hospital
C4L -M Reinforced Concrete Frames and Concrete Shear Walls with medium quality level	Governmental institute and other buildings

3.3. Hazard data

The flood extent map for the 2017 hurricane Maria was prepared by Van Den Bout (2020) using physically-based model of OpenLISEM hazard. Depending on the contents and physical parameters the model used to produce the dynamic changes in the flow behaviour and internal forces at any spatio-temporal location. The input dataset include topography, channels, surface, subsurface, boundary conditions and seismic data. The flood map produced with the interaction of rainfall runoff, soil water, fluctuations, slope stability, water and sediment flow, entrainment, inundation, and sediment deposition.
The flood maps previously produced for the CHARIM project by Jetten (2016) were using the old version of OpenLISEM and the SRTM Global elevation data. The quality of topography data highly affects the result of the food maps, and the recent flood map was made by changing the topography data with the mixed 2018 LIDAR DTM and SRTM data. The LIDAR elevation data have 0.5m lateral resolution which cover the two thirds of Dominica and the data was provided by World Bank. The central area of the island was the location of the missing part because this area continuously covered by clouds which makes difficult to fly and captured the information. So, the 30m SRTM Global elevation data was mixed with LIDAR data to fill the gap. The result shows similar pattern with the previous flood maps but there is an improvement on the extent and behaviour of flat area. One of the advantages of the multi-hazard modelling is considering the complex multi-hazard interactions and one of the disadvantages is the number of input parameters required which increases the uncertainty of the output. During this study, the flood map model by including the sediments and integrated with the landslide map. The input data and the parameters values set by Van Den Bout and the modelling process for the whole island took more than five days. Figure 14 shows the hazard intensity maps for flooding.

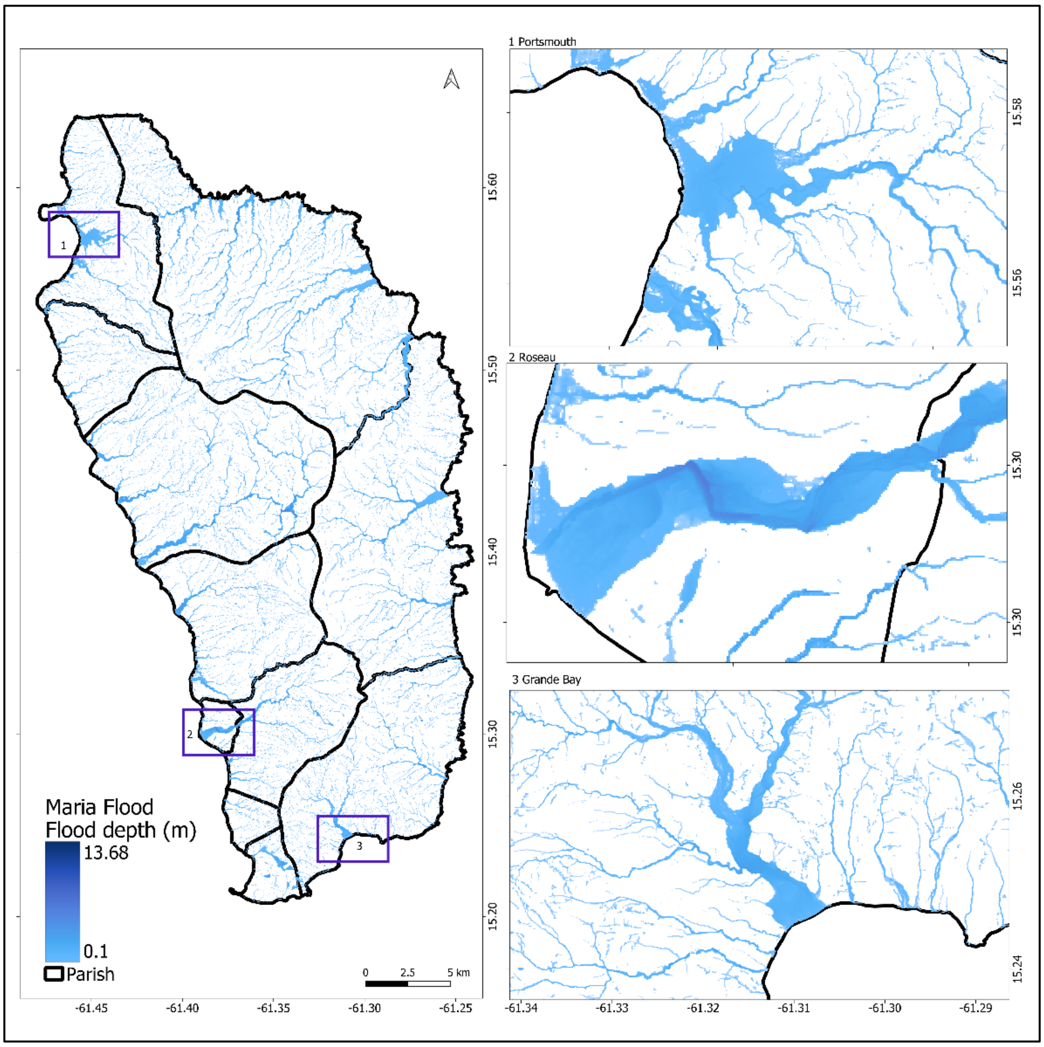


Figure 14: 2017 Hurricane Maria Flood, Source: from Van Den Bout

The 2017 Hurricane Maria windstorm hazard map was prepared in CLIMADA by using the IBTrACS historical track. The method used to prepare the map discuss in CLIMADA input data preparation. Figure 15 shows the intensity of windstorm.

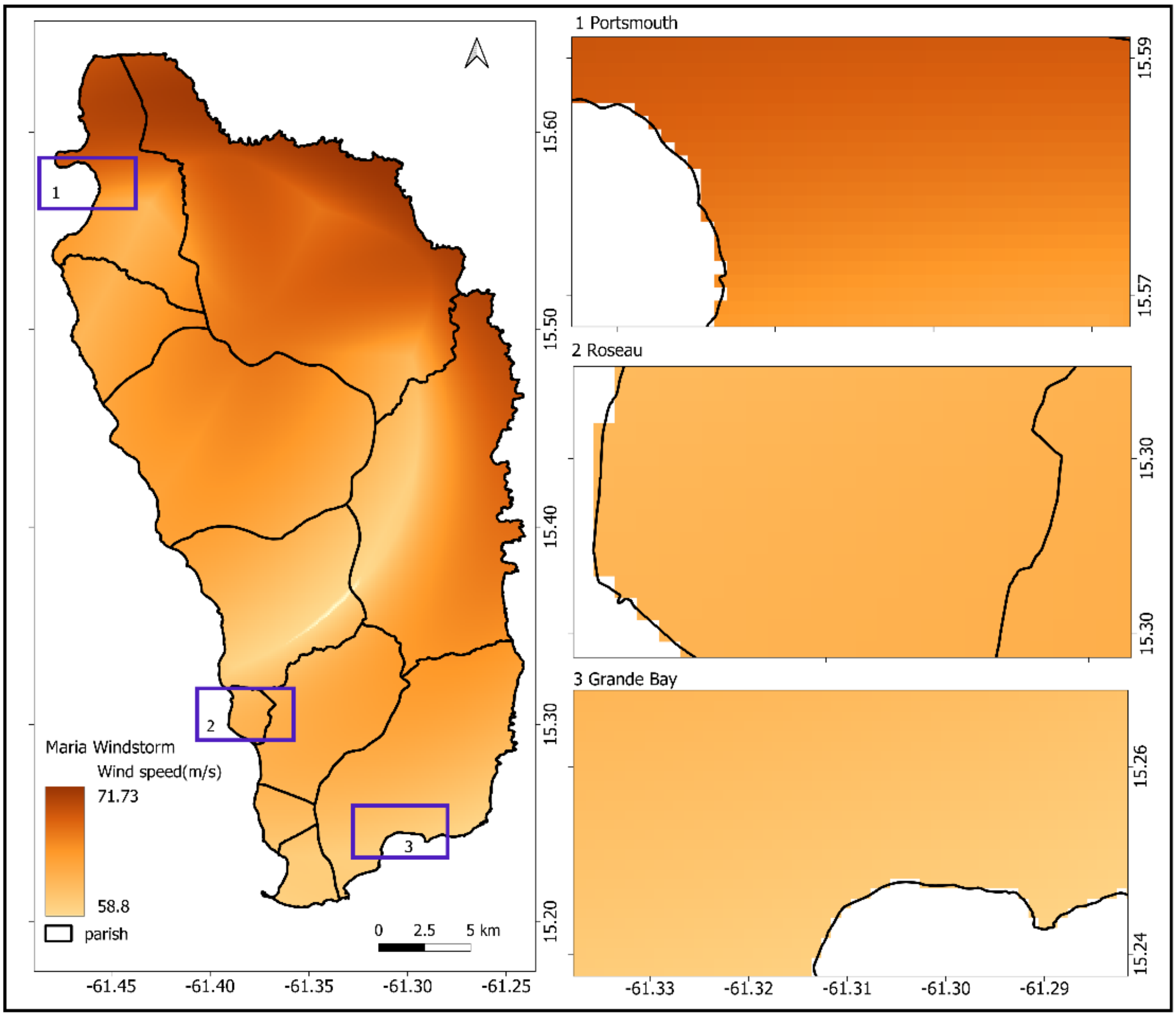


Figure 15: 2017 Hurricane Maria Windstorm map

4. METHODOLOGY

The buildings loss assessment for flood and windstorm hazard during hurricane Maria in Dominica was carried out using both CLIMADA and RiskChanges. The data presented in the previous section (hazards, buildings, and vulnerability functions) were used to prepare the input data of the tools. The methods used to compute the loss assessment and the comparison between the tools are presented in this section. The overall method used in this research is illustrated in Figure 16.

4.1. Using the CLIMADA tool

The input data required by CLIMADA presented in Figure 17 and discuss as follow.

4.1.1. Intensity, centroids, and frequency

The input data for the CLIMADA tool was prepared based on the specific data requirement. CLIMADA requires hazard data per cell represented by its centroids. To encode the hazard intensity in the centroids we generated 38557 points from the OSM buildings footprints. The reason for selecting the building footprint was to get the most representative intensities for each building. The flood hazard map has 10m resolution (100m² area per pixel). The OSM buildings data shows that the area of 69% buildings are less than 100m² and 92% less than 200m². Therefore, the generated centroid points from the building footprint represent the actual exposure of hazard intensity for each building. The flood hazard intensity was extracted by the centroid points.

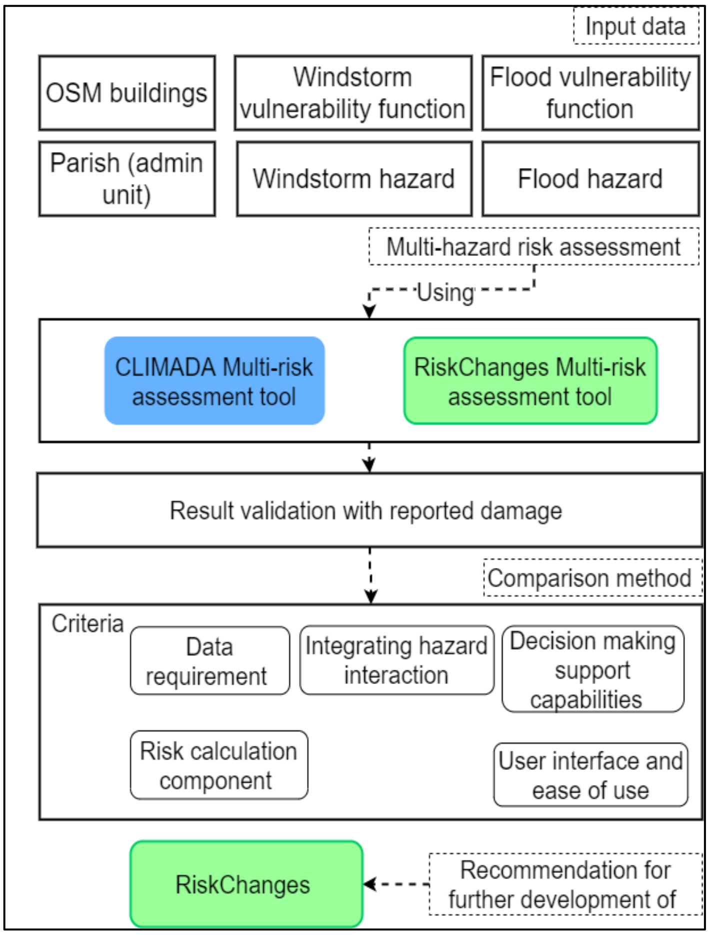


Figure 16:Overall methodology of the study

To extract the intensity of windstorm, the first step was to prepare the intensity map. The windstorm hazard map was produced in CLIMADA using the IBTrACS dataset https://www.ncdc.noaa.gov/ibtracs/ as shown in Figure 18. From the online IBTrACS historical track database the 2017 hurricane Maria track was imported by the CLIMADA hazard package of TCTracks. The IBTrACS data spatial and temporal resolution is 10km and 3 hours. The tracks in IBTrACS provided by different agencies, nearly real time data for basins provided by the agencies. The tracks position interpolated to 3 hours using splines interpolation method and non-positional interpolation which is wind speed and pressure interpolate linearly (IBTrACS, 2019). The quantitative uncertainty level in the North Atlantic basin from 2000 to now is 3.60m/s. After importing the track in CLIMAD we interpolate in one-hour timestep. The interpolation was made directly in CLIMADA by using TCTrack equal timestep function. The function uses the timestep (in float) and the land parameter (in Boolean) to interpolate the tracks. The interpolation was made to make the windstorm intensity near to the reality. Because when we use the original track the windstorm minimum and maximum intensity was 55 and 61m/s. According to NHC (2019) a category 5 nearly 74.60m/s maximum

wind speed hit Dominica. The one-hour timestep interpolated windstorm maximum intensity is 71.73m/s. Then the centroid points were constructed in the CLIMADA centroids by setting the boundary of Dominica and resolution. Through these 104835 centroid points were constructed with 100m resolution. Finally, the 2017 hurricane Maria windstorm intensity computed from the historical track properties and centroid points using Holland (2008) method which computed 1 minute sustained peak gusts in each centroid as sum of circular wind field. The windstorm intensity can be constructed without given centroids in CLIMADA using the Global centroids.
In this assessment the frequency of the hazards was not considered because the aim of the study is to validate the calculated loss result with the PDNA reported loss which caused by 2017 hurricane Maria event.

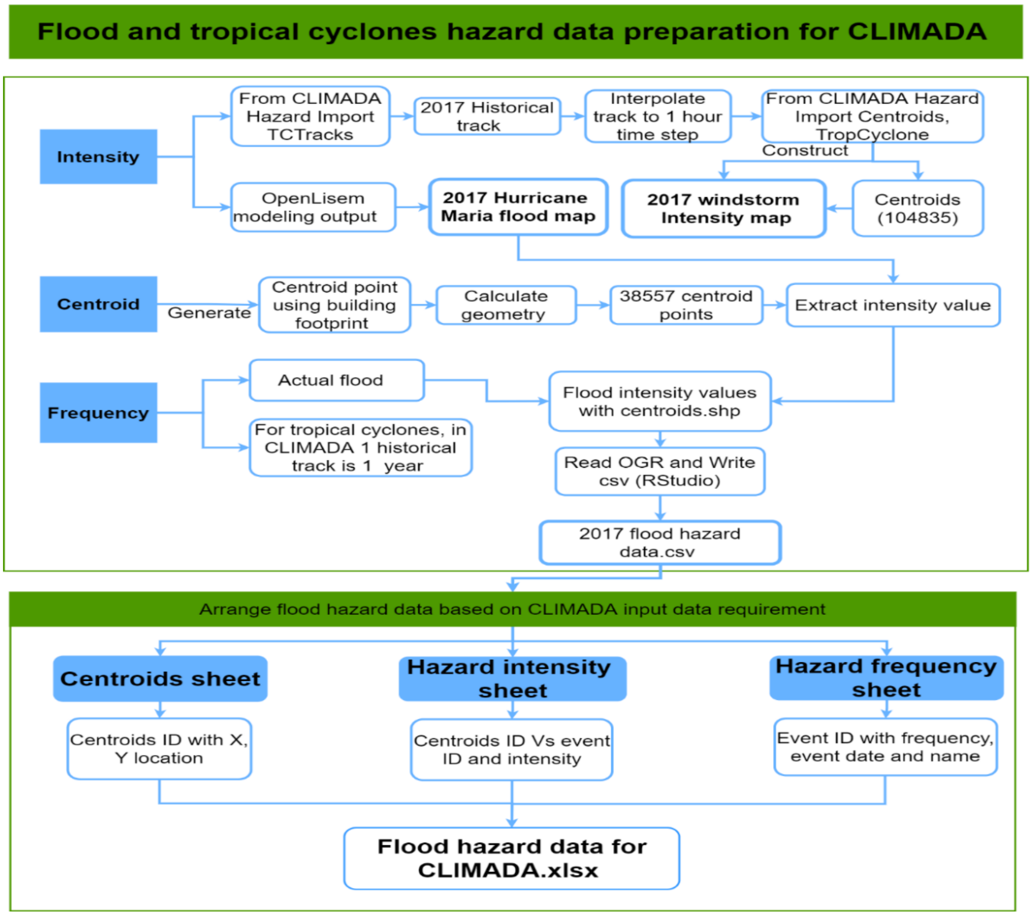


Figure 17: Hazard data preparation based on CLIMADA requirement.

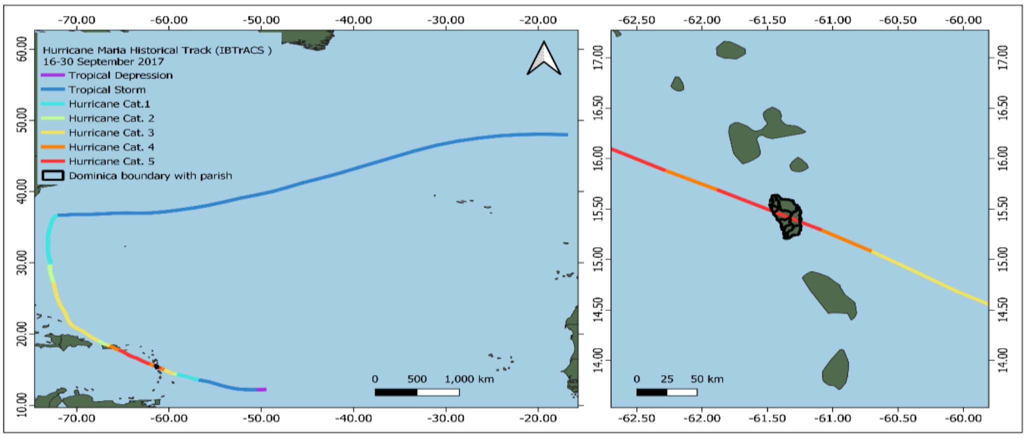


Figure 18: 2017 Hurricane Maria Cyclone Track

4.1.2. Entity

Figure 19 shows the different steps taken to prepare the entity excel file for flood and windstorm hazard. The entity file was prepared and arranged using the classified OSM building data and the vulnerability functions. The entity file contains two Excel sheets which are the asset and impact functions sheet. This includes important (building value, x y coordinate, damage function ID, and value units) and optional variables (category ID for each occupancy type and their region ID) in addition to important variables. The optional variables are included to aggregate the buildings losses per occupancy type and administrative unit. To link the impact function with the asset the function ID is stored in a column as well.

The impact function sheet includes the intensity of the hazard, MDD, PAA, hazard ID, impact function ID, name, and unit. For flood hazard the PAA value is assumed as 1 which means when the flood occurs the spatial probability that the asset will be exposed is 1. For windstorm, the PAA value increases based on the intensity of the wind speed. Assuming that the spatial probability of wind exposure is varied by topography, elevation, height of building etc., and that with higher wind speed a larger percentage of the buildings is actually exposed. As Dominica is a mountainous island with a complex topography this increased the complexity of the spatial probability. Representing the PAA is a single value might not be appropriate, but the systems does not permit the use of spatial variables PAA values. Finally, the impact function and asset sheets are linked and contain the required information to analyse the loss assessment in CLIMADA.

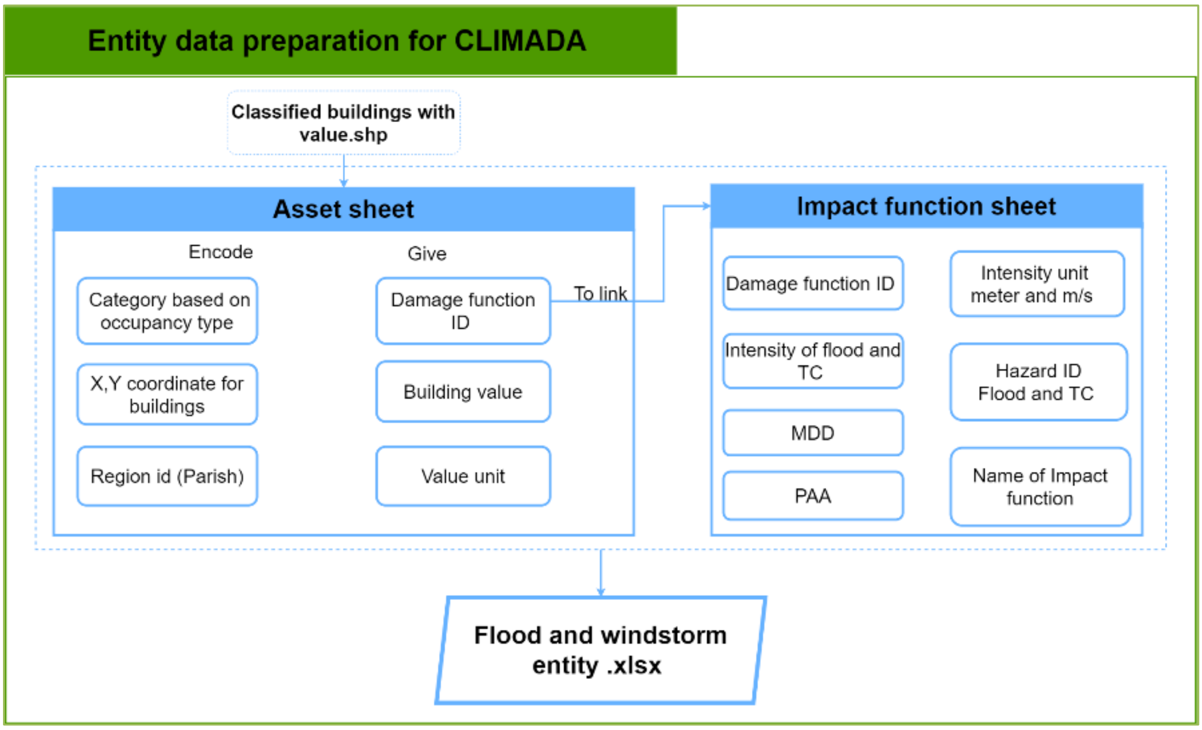


Figure 19: Entity data preparation based on the CLIMADA requirement.

4.1.3. Flood and windstorm loss assessment using CLIMADA tool.

After preparing the data the CLIMADA tool was used to analyse the flood and windstorm loss assessment that occurred in 2017. The main method using the three CLIMADA packages is illustrated in Figure 20. To access the packages, we install the CLIMADA environment in Jupyter notebook using Pip installer. Then the functions that are available in the CLIMADA packages are accessible to execute the loss assessment.

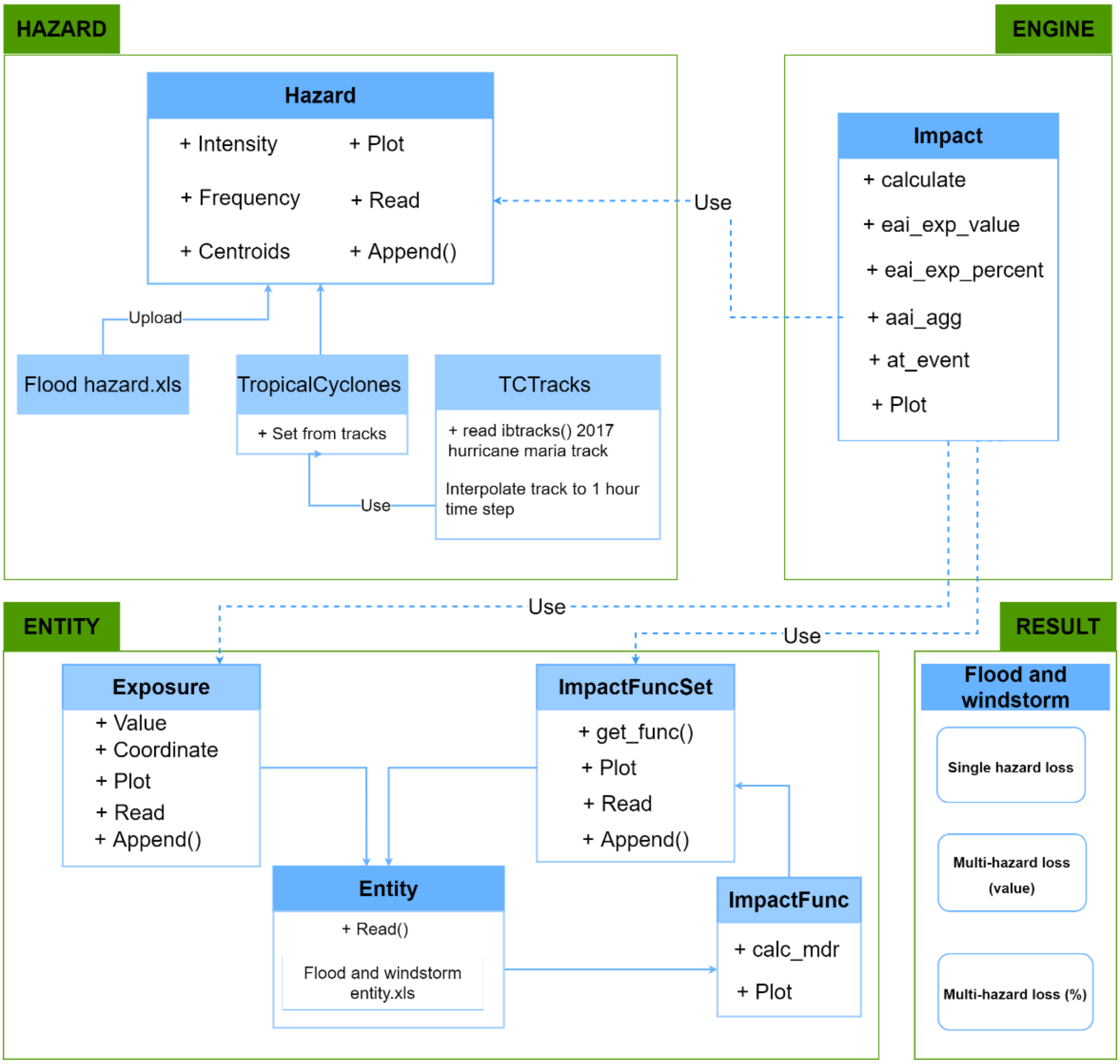


Figure 20: The main method used to assess the loss in CLIMADA.

The prepared flood hazard Excel data was loaded using CLIMADA hazard. Then the hazard type set and plotted in this way the CLIMADA engine know the proper file to calculate the flood loss.
The flood and windstorm entity Excel files are read using the CLIMADA entity. From the entity file the exposure and impact function information is collected. The CLIMADA exposure calculates the exposed value for flooding and windstorm using the building value, x y location of the building and the hazard maps. The windstorm hazard data was prepared in CLIMADA, so we do not need to upload any file. The calculated exposed value is plotted, and the data used to set the exposure checked by using the check method in the tool. The data are checked to verify if the values are well set, and the assigned values are corrected. Then the impact functions were read from the entity file using CLIMADA impact function set. The MDR calculated by multiplying the MDD and PAA on the fly. The impact functions with calculated MDR results of all available functions in the two-entity file was plotted. The exposure is computed, and impact functions were defined and analysed separately for flood hazard and windstorm. In addition to this the value and other included variables were visualized. Some statistics information extracted which are the number of buildings, mean and total value of each occupancy. In addition to this the defined impact functions ID in the Excel sheet is printed out to check the given functions ID for the buildings are corrected. Figure 21 shows an example how the CLIMADA plot the impact functions. The method used to analyse the flood and windstorm loss in Jupyter notebook is found in annex 1.

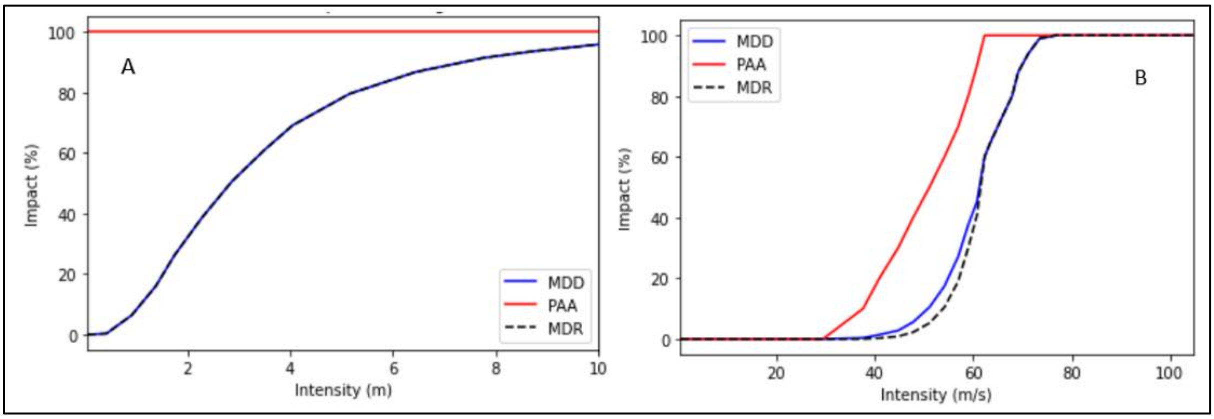


Figure 21: The vulnerability functions used to estimate the loss. A shows selected flood vulnerability function for hospitals and B shows the windstorm vulnerability function for hospitals buildings.

Finally, the impact of flood and windstorm hazard is computed using CLIMADA engine. The impact of flood and windstorm hazard were calculated by interacting the defined data in the hazard, exposure, and impact functions. In this case the expected annual impact and average annual impact is equal to the impact result, and the exceedance frequency curves were not plotted because we only analysed the Maria flood and windstorm loss.

Multi-hazard loss calculated in CLIMADA, first run single loss assessment one by one then combined simply by adding up the impact of flood and wind.

4.1.4. Flood and wind hazard risk assessment using RiskChange tool

The flood and windstorm hazard loss assessment were also conducted using the RiskChange tool. To use all the functions available in the tool we install the package using the Pip installer in Jupyter notebook.

The package imported and added the RiskChange package before analysing the exposure and loss. The steps used to analyse the flood and windstorm can be seen in Figure 22. The prepared data of OSM building, vulnerability functions, and hazard data are used in this analysis.

The RiskChange tool directly uses the prepared elements-at risk shapefile and the hazards raster dataset. The elements-at-risk shapefile required to have the type of buildings with unique ID which is the vulnerability functions linked with this ID, and the value of the buildings. Therefore, the buildings shapefile was prepared based on these requirements. The only data preparation needed was for vulnerability functions therefore we prepared the vulnerability functions based on the tool input data requirement. For each vulnerability function a separate csv file prepared which contains average vulnerability value, hazard intensity from to, and ID. The other required parameters are the spatial probability, base, and step size we test the loss result by changing the value of the parameters.

After installing the tool and preparing the required data we started the analysis by checking the projection system of the building shapefile. The building shapefile was in EPSG 4326, which we changed to the EPSG 32620 by using project vector functions in the data management part of the tool. Then the flood and windstorm hazard data were reprojected by using match projection functions. The hazard data should be classified in order to combine the hazard with elements-at-risk and create separate sub-units with different intensity levels (e.g., relevant when using large land parcels input). Similar to the spatial probability parameter we use different step size and base for the hazards.

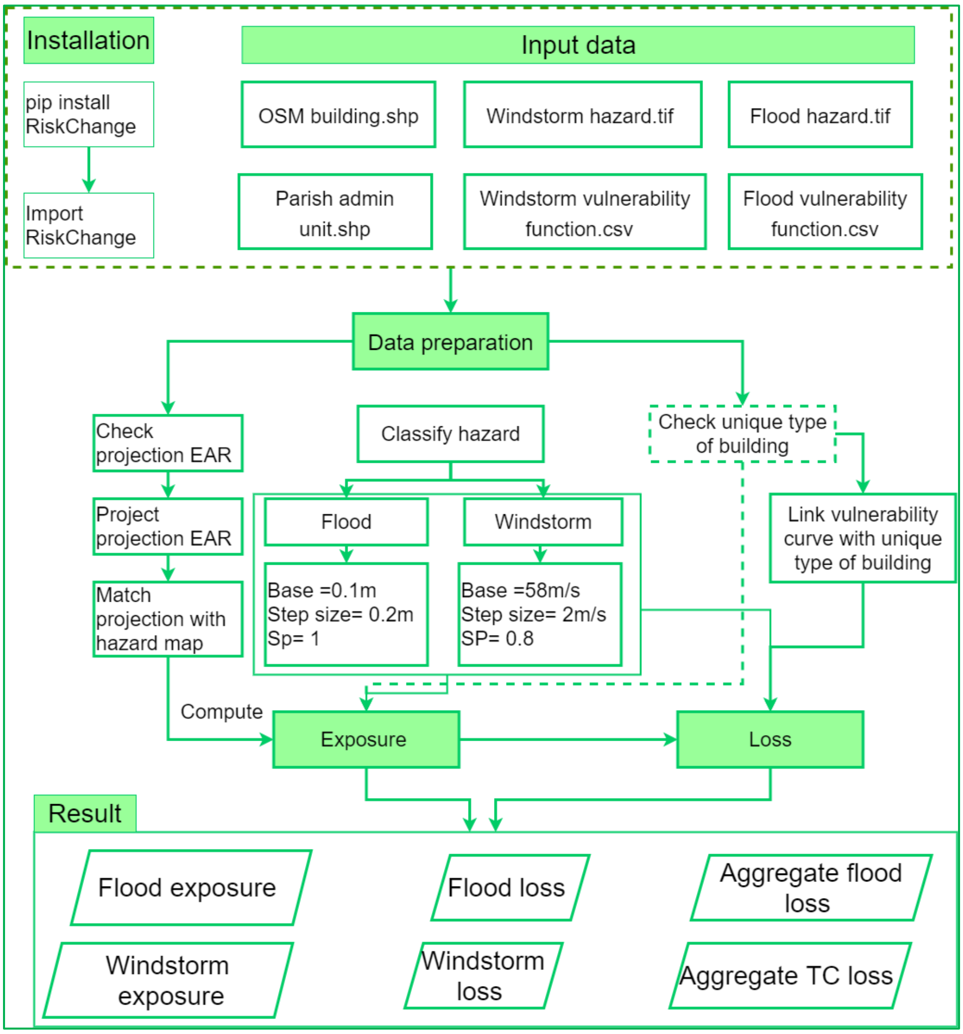


Figure 22: The main method used to analyse the loss in RiskChanges.

The loss calculations were done for the twelve trials by changing the spatial probability, step size and base parameter values. For the result interpretation and comparison of calculated loss with the PDNA reported loss we select trial five from the trials. Therefore, in trial five we use a 0.1m as the base (lowest relevant intensity value used) which is the starting point of the classification and a 0.2m interval for the step size, to divide the water depth in classes of 20cm for flood hazard. For the windstorm hazard the wind speed we used 58m/s base and a step size of 2m/s (see Table 18). The unique ID building type is used to link with the vulnerability curves. In this case we use the eight types of occupancy classes for buildings. For all types, the vulnerability functions were linked with the building data. The exposure was computed by defining the linked building file, reclassified and projected hazard data, unique ID, the output file name, and format. The exposure result data format has two options csv and shapefile we use both type of format to analyse the result. After calculating the exposure, the next module calculated the losses. The loss was estimated by using the exposure output, unique ID, the cost column of the building, vulnerability directory and column, hazard type, step size, base, hazard unit, vulnerability unit, spatial probability, output file name and format. As we discuss earlier in chapter 2 the loss calculated using the Dutch method. The aggregated loss was computed by using the loss aggregation function and the administrative units (called Parish in Dominica).

Finally, the two loss results combined by simply add the loss and exclude the exceeded value from the total loss.

4.1.5. Comparison of calculated loss with the PDNA reported loss.

The results from the CLIMADA and RiskChange were validated using PDNA (PDNA, 2017). The damage was reported for different sectors. In this research we used the damage report for the social sector which included housing, education, health, and culture. In this study we focus on the housing sector the assessment the impact of flood and windstorm damage generated from CLIMADA and RiskChanges were compared with the PDNA results.

4.1.6. Comparison between the CLIMADA and RiskChanges tool

The comparison method is based on five criteria which are formulated by using literature reviews, as discussed in chapter 2. Figure 23 shows the criteria used to compare the tools.

a) Data requirement

Multi-hazard risk assessment tools are very data intensive, and they have strong requirements regarding hazard maps. Elements-at-risk data and vulnerability function, in order to produce exposure, loss and risk results. This criterion considers the different characteristics of the tools such as: the number of formats and types of data supported by the tools, the scale of the analysis (i.e., local, regional, and global level), the degree of data uncertainty that affects the result, how data demanding the tools are to analyse the risk component and the interoperability of the tools with other datasets.

b) Integrating hazard interaction

Integrating the hazard interaction in multi-hazard risk assessment is crucial because hazard interaction increases the intensity of the hazard, exposure of elements-at-risk, and the vulnerability of exposed elements-at-risk (Barrantes, 2018). This criterion addresses the integration of hazard interactions within the methodology of the tools and how this affects the resulting loss and risk calculation.

c) Risk components

This criterion describes and identifies four components that can help to understand the logic behind the tools: the description of the risk components in the tool (hazard, elements-at-risk, and vulnerability), detail of elements-at-risk, the type of loss and risk calculation, and the calculation of uncertainty. By using these criteria, we investigate if the tool addresses all risk components, has the ability to produce hazard maps, can calculate separate exposure and loss results, includes a vulnerability database, and the method used for loss estimation, and risk assessment.

We also identify the detail of the elements at risk characterization. This allows to explore in which level of detail attribute information is used in the tools. Depending on the method used in the tools, the loss and risk result differ (i.e., probabilistic, or event-based) therefore we identify the method used to calculate the loss and risk. We also explore the role of parameters used in the loss and risk calculation, such as spatial probability. Finally, we evaluate whether and in which way the uncertainty of the risk components is incorporated into the loss and risk calculation.

d) Decision making support.

This criterium evaluates how the tools can be used as decision support tools to support decision about risk reduction planning. This criterion is important to choose the tools based on the stakeholder objective and needs. These criteria help to find out the type of decision-making support system for the tools.

e) User friendliness

The criteria are used to identify if the tool is user-friendly and if/how decision-maker can use the tool without expert support. We include different measurements to know the ability of the tools system and package. Those are installation, interface language, the architecture of the tools, available documentation, and visualization option.

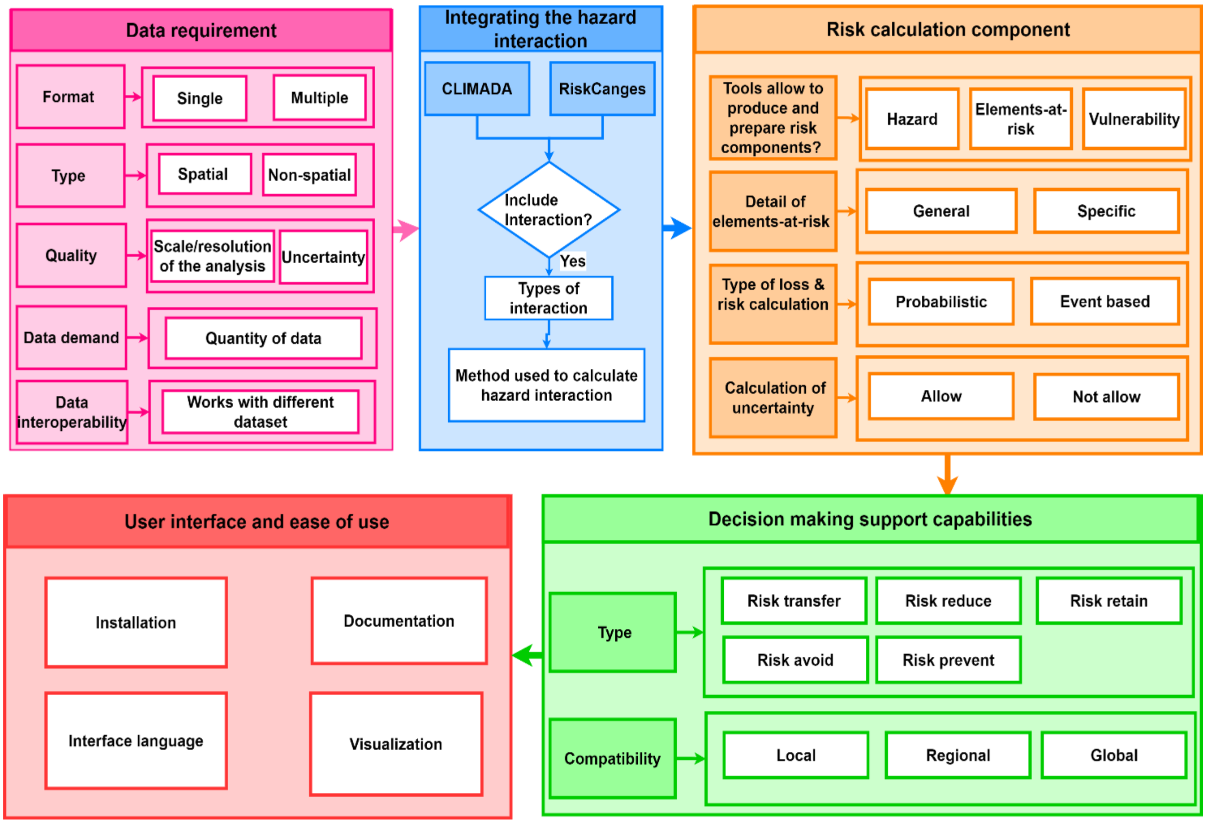


Figure 23: Comparison criteria

5. LOSS RESULTS

This chapter discusses the flood and windstorm loss results obtained through the CLIMADA and RiskChanges tools. First, the loss assessment results are illustrated and discussed based on the output of the tools and compared with the losses reported in the PDNA study.

5.1. CLIMADA result

5.1.1. Buildings exposure to flood and wind (using CLIMADA)

The results of flood exposure for buildings in Dominica are shown in Figure 24. For all the 38557 buildings centroids the flood level was obtained. The result shows that 83% of the buildings was not exposed to flood and 17% exposed to different levels of water depth.

2068 buildings were exposed to 0.1 to 0.5m flood, 2338 from 0.5 to 2m, from 2 to 5m, 1748, and 497 buildings were exposed to greater than 5m flood (see Figure 24). The buildings which are exposed to higher flood levels are located near to Roseau, Layou, and Warner rivers. The flood exposure results shows that more than 80% of the buildings were residential buildings, 18% commercial buildings and 2% combination of different types of buildings. The flood extent and depth are higher in the capital city of the island as shown in Figure 25 where a wide range of flood depth extents across the centre of the city. The main reason is the flood map overestimates the flooding in the city centre.

Although the modelled wind intensity map shows different wind speeds, the variation of the intensity within the island is quite small. This is partly due to the fact that the hurricane passed straight over the island, thus affected most of the island throughout its passage. But also, because the modelling tool does not take the difference in topography into account, which is a major shortcoming for a mountainous island like Dominica. The wind speed on the map varies between 59 and 72m/s, which is all in the highest windspeed category. For the island 104835 centroid points were generated automatically in CLIMADA and linked IBTrACS was used to produce the wind intensity map. For all buildings, the nearest centroid value was assigned. The result indicates that all buildings are exposed to wind and all buildings are experienced the effects of extreme wind speed. More than 94% of the buildings were impacted by wind speed between 60 to 72m/s and 6% of the buildings to lower speeds.
From all types of building the commercial buildings were highly exposed to extreme wind, 94% of the commercial buildings face more than 63m/s wind speed. After commercial building the second highly exposed building type is residential buildings 79% or 24675 buildings are exposed to more than 62m/s wind speed. Figure 24 shows the building exposure for wind and the number of buildings with the exposed wind speed. 6651 buildings were exposed to both flood and windstorm hazards.

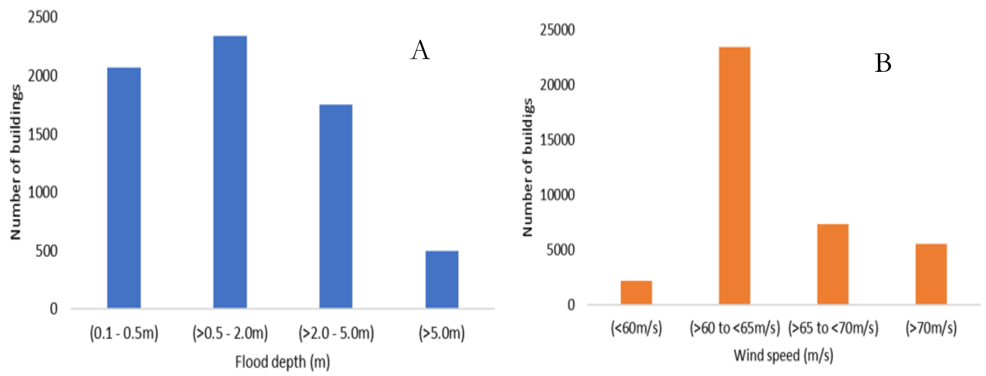


Figure 24: Flood (A) and windstorm (B) exposure.

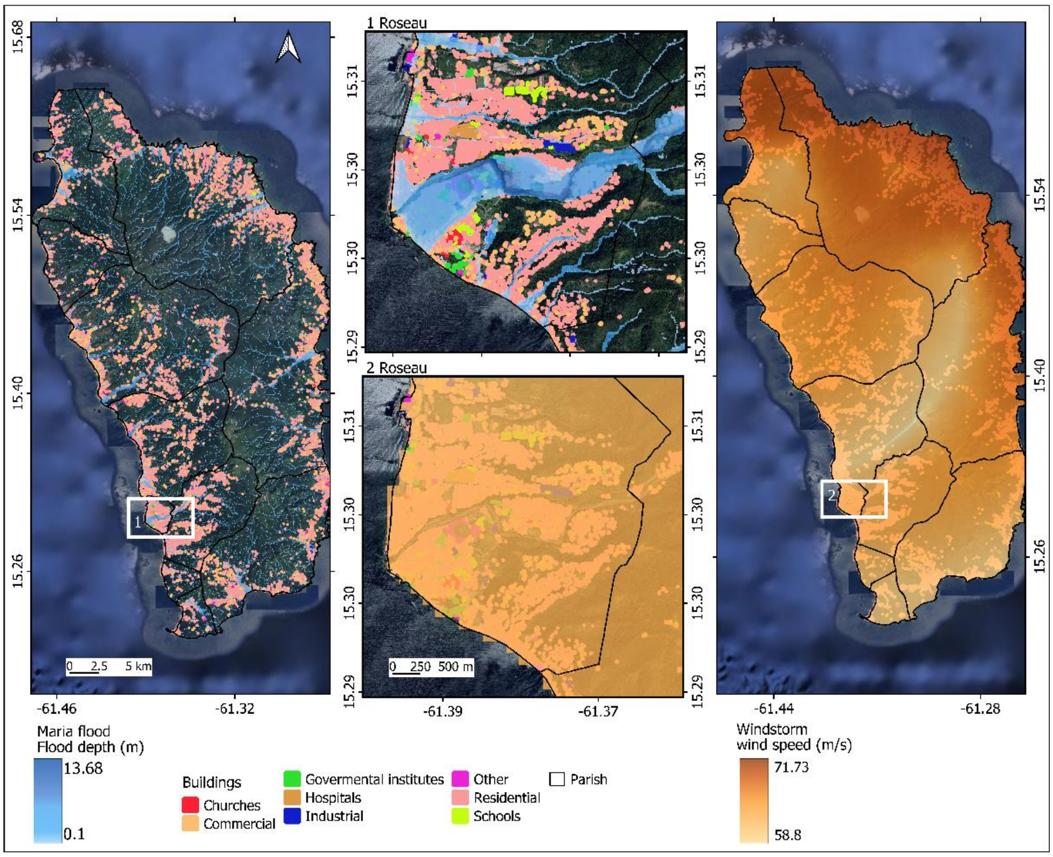


Figure 25: Flood and wind exposure in CLIMADA

5.1.2. Flood and windstorm related building losses (using CLIMADA)

The calculated loss results shows that the total impact of all buildings is 821 million USD caused by both flood and windstorm hazard. The analysis result shows that the impact of windstorm is much higher than the flooding, as it affected many more buildings. Table 11 shows the losses for the individual hazard types and the percentage. When we look at the residential buildings 12 % of the total building values are losses by flooding and 64% by wind. Flooding and wind highly affected the commercial, religious, and residential buildings. The highest impact by flooding measured was for the industrial buildings but the wind impact on the industrial building is the lower from all types of building because of the vulnerability curve which is selected for these buildings. The flooding had a low impact on hospital buildings, as they almost not exposed.

Table 11: Flood and wind loss result for all occupancy type in CLIMADA

Building type	Wind loss (USD)	Wind loss (%)	Flood loss (USD)	Flood loss (%)
Residential	3.03E+08	63.70	5.76E+07	12.06
Commercial	3.43E+08	80.78	5.23E+07	12.31
Industrial	1.57E+06	5.70	9.64E+06	34.98
Hospital	1.11E+07	68.61	2.21E+05	1.36
Church	1.12E+07	80.91	1.63E+06	11.79
School	5.51E+06	13.02	4.74E+06	11.19
Governmental institute	3.31E+06	21.23	3.82E+06	24.52
Other	6.88E+06	24.37	5.29E+06	18.73

CLIMADA computed the impact of multi hazard loss by simply adding up the losses without considering the interaction of the hazard. We converted the single hazard loss into the multi-hazard loss by summing the flood and wind losses and found 821 million USD loss for both hazards. The direct result by adding up the wind and flood losses is that the loss values. For those buildings where the combined damage was more than the total building damage, the total building damage was taken instead of the summation of the flood and wind damage. This lowers the damage to 756 million USD. Out of a total of 38577 buildings 13975 buildings were considered to be completely destroyed. The combined losses per occupancy type seen in Table 12. The flood and wind losses were added because the wind affects the roof and flood affects the structure of the buildings.

Table 12: Combined losses

Building type	Combined loss (USD)	Combined loss (%)
Residential	3.33E+08	70
Commercial	3.61E+08	85
Industrial	1.09E+07	40
Hospitals	1.12E+07	69
Churches	1.16E+07	84
Schools	9.90E+06	23
Governmental institutes	7.03E+06	45
Other	1.19E+07	42

The impact per building is different from building to building due to the value, exposure, PAA and degree of vulnerability.

Figure 26 shows the combined and adjusted windstorm and flood loss per building. In general, the combined loss results in USD have a variation (ranging from 167-920107) throughout the island which depends on the buildings estimated price. The highest loss (red colour) concentrated on the northern, northeast, and western parts. The lowest loss per building dominates the southern part of the Island. The buildings loss ranging from 167 up to 12690 USD are mainly residential buildings whereas the commercial buildings have a loss between 12690 to 20208 USD. The governmental institute, and hospital buildings have a loss more than 12690 USD. The losses per building in Portsmouth and Roseau city is higher compared to Grande Bay. There are many buildings located in Roseau which makes the losses much higher in the city than the other Parishes. In the Grande Bay the buildings loss are low which is the range between 167 to 5085 USD and the highest building loss follows the main road these buildings were commercial buildings.

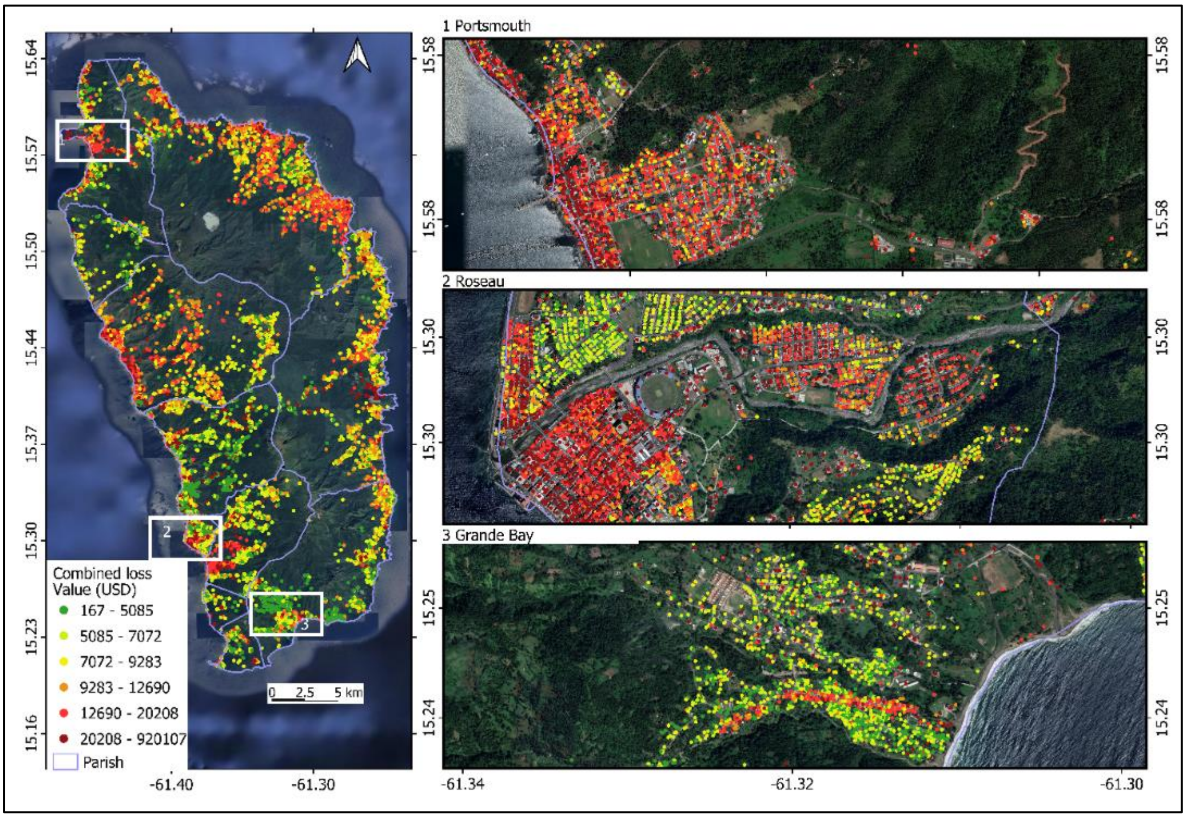


Figure 26:Flood and wind loss in value

The loss in different administrative units (Parish) was calculated and illustrated in Figure 27. Which shows the loss in USD and number of impacted buildings per Parish. The percentage of losses from the total in Saint Andrew, David, George, John, Joseph, Luke, Mark, Patrick, Peter, and Paul is 75%, 70%, 71%, 77%, 72%, 75%, 63%, 59%, 72%, and 80%, respectively. According to the result the highest loss was measured in Saint Peter, John, Luke, and Andrew. The loss increased when the number of buildings increased. compared to whole parish three of them have larger number of buildings.

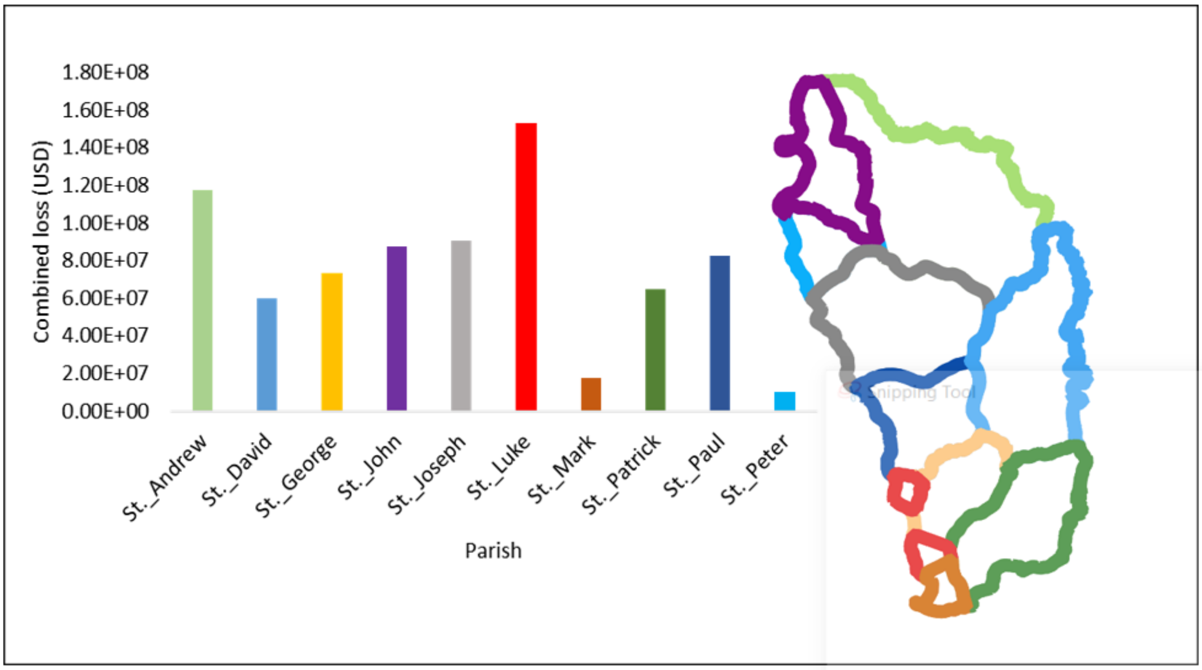


Figure 27: Loss per Parish using CLIMADA.

To identify the degree of building damage we classify the loss into four groups based on the percentage of the loss per buildings. In addition to this, to compare the calculated loss result with the reported loss in the PDNA, the classification used in the report was followed (ranging from slightly damaged to completely destroyed). Tabe 13 shows the percentage of loss per class with the number of buildings. In the third and fourth class the losses ae higher than the first two classes.

Table 13: Degree of loss per class

Loss class	Total building loss (USD)	Number of building
(<20% loss)	6.30E+06	337
(>20% and <45% loss)	3.15E+07	4596
(>45% and <70% loss)	1.35E+08	13214
(>70% loss)	5.83E+08	20410
Total	7.56E+08	38557

Figure 28 shows the spatial distribution of the classes over the island. Many of the buildings in the northeaster and the eastern parts have more than 70% loss. Major cities of the island also experienced diferent level of losses. For instance, in some parts of Roseau, the loss falls in the first two classes, but large part of the area has buildings with more than 70% losses. Also, in Portsmouth almost all buildings have a loss more than 45%. This is primarily caused by the high influence of the wind vulnerability curves used and the high wind speed levels that did not consider topographic variation. In addition to this, the southwest part (yellow colour) which is located near to the capital city the losses are less than 45% because the wind intensity in this location was low. In Grande Bay many buildings have a loss below 45%.

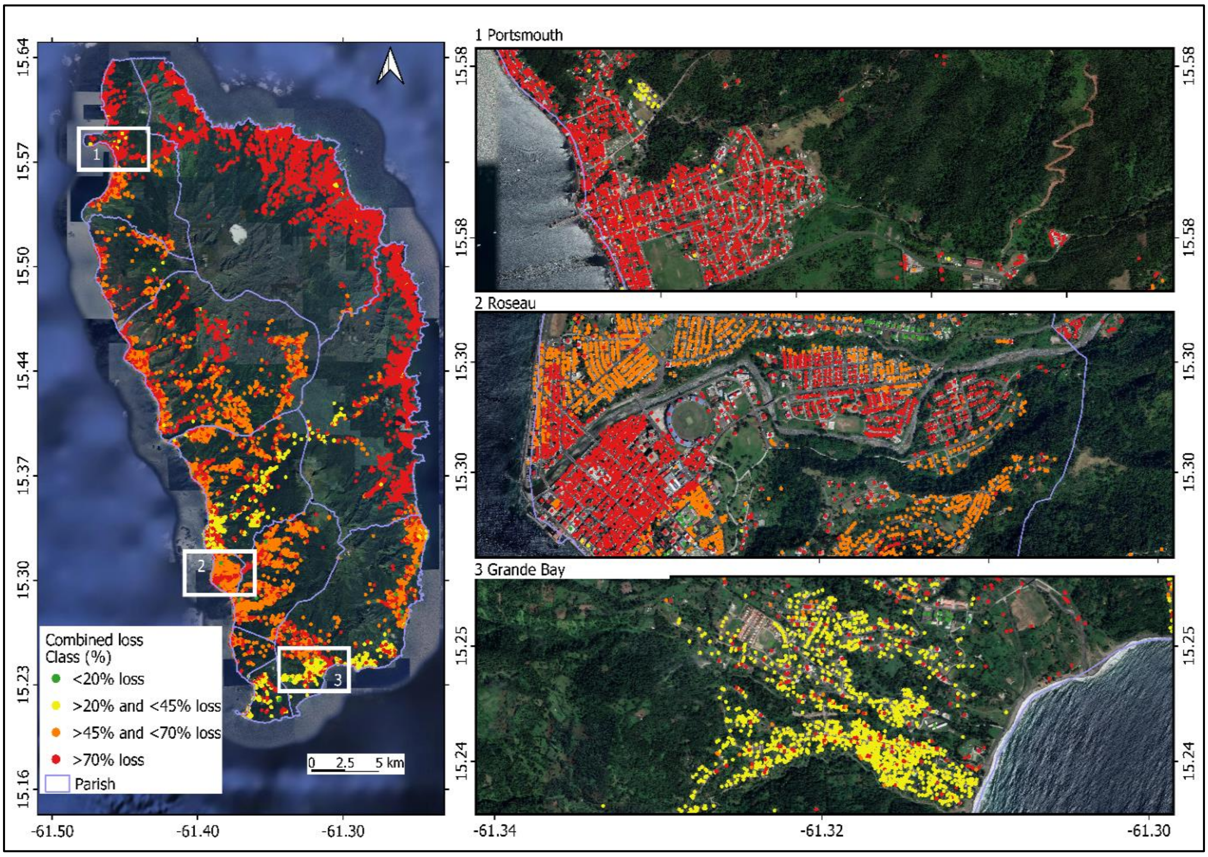


Figure 28: Combined flood and wind losses in percentage of the total building value

5.1.3. Comparison of calculated loss result (CLIMADA) in the residential buildings with PDNA reported loss.

The classified loss results from CLIMADA shows a similar pattern as the reported loss from the PDNA in terms of loss value. The reported loss in the PDNA study was assessed for 31348 residential buildings, from which 4700 buildings were reported as destroyed, for 23500 buildings different level of damaged occurred and for 3135 buildings no damage identified. In our study of the total of 38557 we classified 31113 as residential buildings. Out of these no buildings has less than 20% damage, 4405 had damage between 20% to 45%, 13107 had damage between 45% up to 70 % and 13601 building were more than 70%. To compare the number of damaged residential buildings we merge the damage into three groups: less than 20%, greater than 20% to 70% and greater than 70% damage. Because in the report the number of buildings only for three classes. Therefore, we consider less than 20 % damages with no damage, the second group (>20% to <70%) with different level of damage and greater than 70% as completely damage. Then in the first group the reported losses have 4814 damaged buildings but in the calculated loss no damaged buildings recorded, for the second group the calculated damaged buildings are lower than the reported loss by 5988, and the final group result shows the calculated damaged buildings are greater than the reported by 890 buildings. When we come to the loss results related to monetary value of the four classes shows more or less similar results, but the PDNA reported loss conducted for all hazards occurred during hurricane Maria: flooding, landslide, windstorm, debris flow, and storm surge. But in this case, we only use the flood and windstorm impact on the buildings and even if the results are aligned with the reported loss, the losses are overestimated (Figure 29 illustrate the comparison of the results). The reasons are related to the uncertainty of vulnerability functions, estimated building value, hazards, spatial probability, and methods used to calculate the losses.

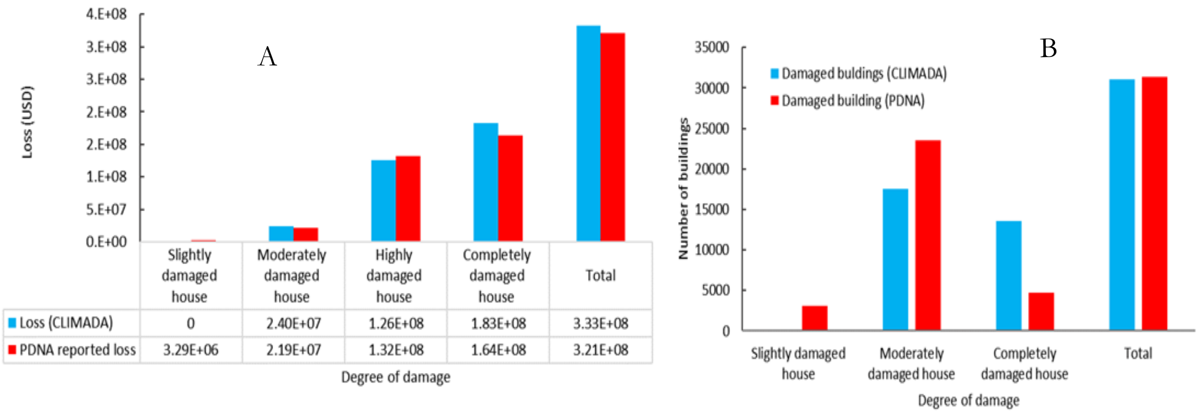


Figure 29: Comparison of calculated loss with PDNA reported loss in terms of value (A) and number of buildings (B).

5.2. RiskChange results

Before illustrating the main results, to calculate the exposure and losses in RiskChanges three parameter values are needed for the spatial probability, step size of the hazard intensity classes and base value of the hazard intensity. We selected a spatial probability of 0.8 for the wind hazard, assuming that 80% of the exposed buildings would actually experience the modelled wind speed. This is an assumption that accounts for the unknown shielding effect of the topography. For flooding we consider a spatial probability of 1, which means that all modelled flood areas during the event would have also experienced flooding. The step size and base values for the hazard intensity classification are selected by looking at the starting and ending intensity value. The combined loss calculated using similar method with CLIMADA.

5.2.1. Buildings exposure to flood and wind (using RiskChange)

The flood exposure was calculated using the reclassified hazard and building information. The hazard was classifying into 71 groups with considering the base equal to 0.1m and step size 0.2. The classification of the hazard was made to make a better estimation of the losses, and a better link to the vulnerability tables.

The exposure result shows that in total 6651 buildings were exposed in 71 flood hazard classes. RiskChanges calculate the exposure when the exposed asset exposed to greater than the base of the hazard, therefore 6651 buildings were exposed larger than the base (0.1m) of the flood hazard. The RiskChanges allows to calculate how many of the building are exposed to which level of flooding. The exposure result from RiskChanges and CLIMADA tools are similar. The only difference is the method used to calculate the exposure and the system calculates different exposure for one building. This can be used to differentiate the damage to different parts of large buildings, or in the case of land parcels.
The wind exposure calculated using the reclassified wind hazard and the building information (base 58 and step size 2). We use the wind hazard map generated in CLIMADA. The RiskChanges calculate the percentage of exposed elements-at-risk for 7 hazard classes. The result of exposure using RiskChanges are similar with CLIMADA. Figure 30 and Table 14 shows the number of buildings exposed to flood and windstorm hazard.

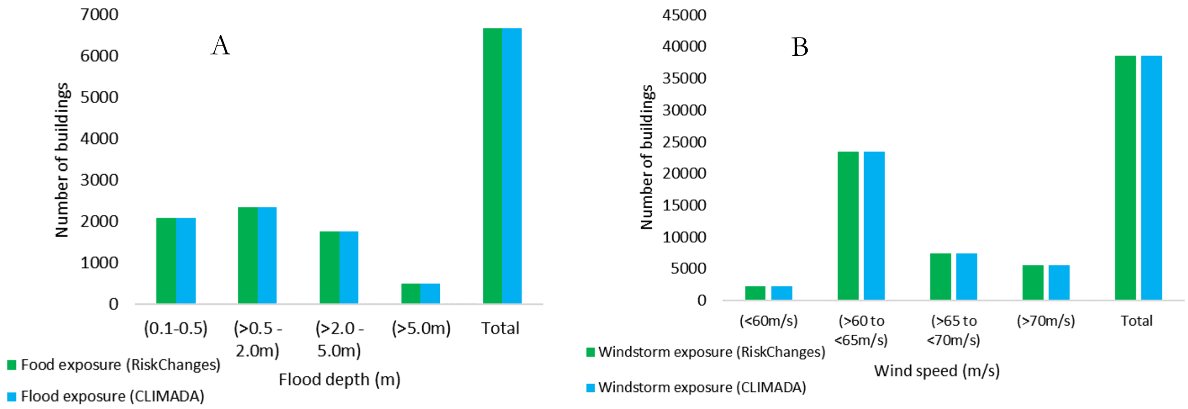


Figure 30: Flood (A) and windstorm (B) exposures using CLIMADA and RiskChanges.

Table 14: Number of building exposed to flood and windstorm.

Flood depth	Number of exposed buildings	Wind speed	Number of exposed buildings
(0.1-0.5 m)	2068	(<60m/s)	2221
(>0.5 - 2.0m)	2338	(>60 to <65m/s)	23431
(>2.0 - 5.0m)	1748	(>65 to <70m/s)	7369
(>5.0m)	497	(>70m/s)	5536

5.2.2. 5.3.1. Flood and windstorm losses on building (using RiskChange)

The building loss for windstorm and flood calculated with RiskChanges was 826 million USD. When we compare this result with CLIMADA, more or less similar and there is insignificant difference (5 million USD). Table 15 shows the loss result from RiskChanges and CLIMADA, the losses in residential, commercial, hospitals, and religious buildings caused by windstorm in CLIMADA was higher than RiskChanges. For industrial, schools, governmental institutes, and other buildings the loss was higher in RiskChanges. The flood loss result of all types of buildings were higher in RiskChanges compared to CLIMADA. The main reasons for these differences were the loss calculation methods which is related to the spatial probability, vulnerability functions and hazard intensity. The first reason is RiskChange use similar spatial probability value and CLIMADA link the spatial probability with the vulnerability functions which means when the vulnerability increases the spatial probability (PAA) also increase. Secondly, RiskChanges use the average value of vulnerability function, but CLIMADA directly use the provided function and calculate the MDR by multiplying the MDD and PAA value, most of the time the MDD and MDR has comparable value. Finally, the hazard intensity considers in two different ways:

RiskChanges use the intensity value by classifying the hazard intensity into several classes, the class range can be very small, and the system assign maximum intensity value for each class, in CLIMADA the hazard intensity assigns by taking the nearest centroid point. Therefore, those reason has a lot of uncertainty and effect on the loss results.

Table 15: Single hazard Loss result for all occupancy type in RiskChanges (values in Italic are those from CLIMADA)

Building type	Wind loss (USD)	Wind loss (%)	Flood loss (USD)	Flood loss (%)
Residential	2.53E+08 *3.03E+08*	53 *64*	8.11E+07 *5.76E+07*	17 *12*
Commercial	3.40E+08 *3.43E+08*	80 *81*	7.14E+07 *5.23E+07*	17 *12*
Industrial	1.90E+06 *1.57E+06*	7 *6*	1.13E+07 *9.64E+06*	41 *35*
Hospital	9.51E+06 *1.11E+07*	59 *69*	3.36E+05 *2.21E+05*	2 *1*
Church	1.10E+07 *1.12E+07*	80 *81*	2.06E+06 *1.63E+06*	15 *12*
School	1.15E+07 *5.51E+06*	27 *13*	6.62E+06 *4.74E+06*	16 *11*
Governmental institute	3.78E+06 *3.31E+06*	24 *21*	6.75E+06 *3.82E+06*	43 *25*
Other	7.58E+06 *6.88E+06*	27 *24*	8.31E+06 *5.29E+06*	29 *19*

The RiskChanges tool considers the multi-hazard interaction during the risk assessment phases and uses the loss results per element-at-risk which are the combined based on the hazard interaction type. In this study only the losses during hurricane Maria in 2017 were computed in order to validate the loss results with actual damage data. Therefore, we applied a similar method like CLIMADA to convert the single hazard loss into multi-hazard loss by summing the flood and wind loss at the building level and using the total building value if the combination was higher than the building value. For 6483 buildings the combined losses were higher than the building value, and when we corrected for this the final building loss was 749 million USD. When we compare the combined loss result with CLIMADA, the loss per occupancy type of buildings is very similar. Some difference observed in industrial, schools, governmental institutes, and other buildings, the losses are slightly higher in RiskChanges but Residential, and hospitals buildings have a higher loss in CLIMADA. In addition to this commercial, and religious buildings have similar results in both tools (Table 16). The combined loss by flood and wind per building shows in Figure 31, the loss is very similar with CLIAMADA in terms of the distribution and pattern of the building loss with their correspondence building value.

Table 16: multi-hazard loss result for all occupancy type in RiskChanges (values in Italic are those from CLIMADA)

Building type	Combined loss (USD)	Combined loss (%)
Residential	3.07E+08 *3.33E+08*	64 *70*
Commercial	3.67E+08 *3.61E+08*	86 *85*
Industrial	1.29E+07 *1.09E+07*	47 *40*
Hospitals	9.76E+06 *1.12E+07*	60 69

Churches	1.17 E+07 *1.16 E+07*	85 *84*
Schools	1.72E+07 *9.09E+06*	41 *23*
Governmental institutes	9.70E+06 *7.03E+06*	62 *45*
Other	1.44E+07 *1.19E+07*	51 *42*

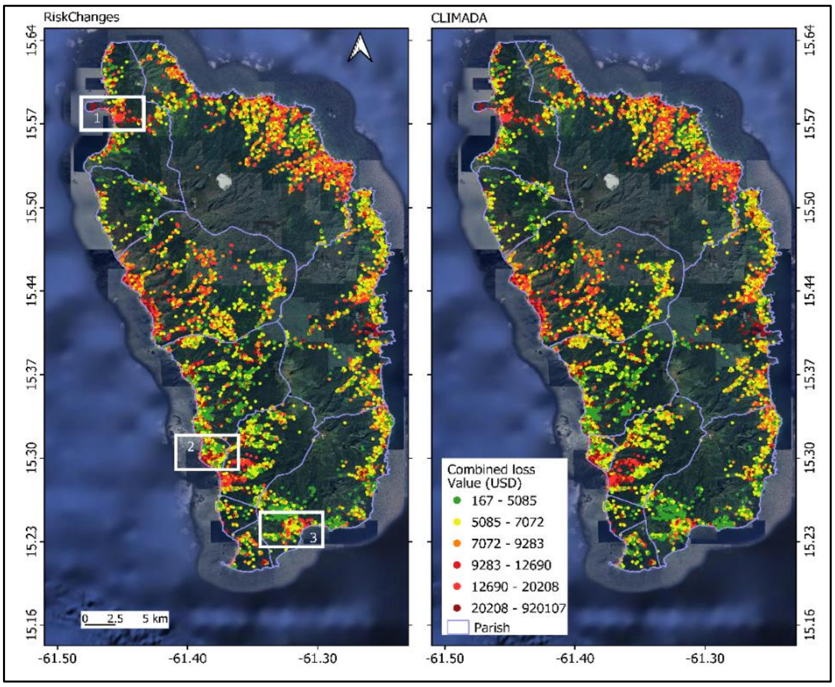


Figure 31: Combined loss in value using RiskChanges and CLIMADA.

As shown in Figure 32 the map indicates the similarity of the loss result from both tools with minor difference observed in the cities (Portsmouth, Roseau and Grand Bay).

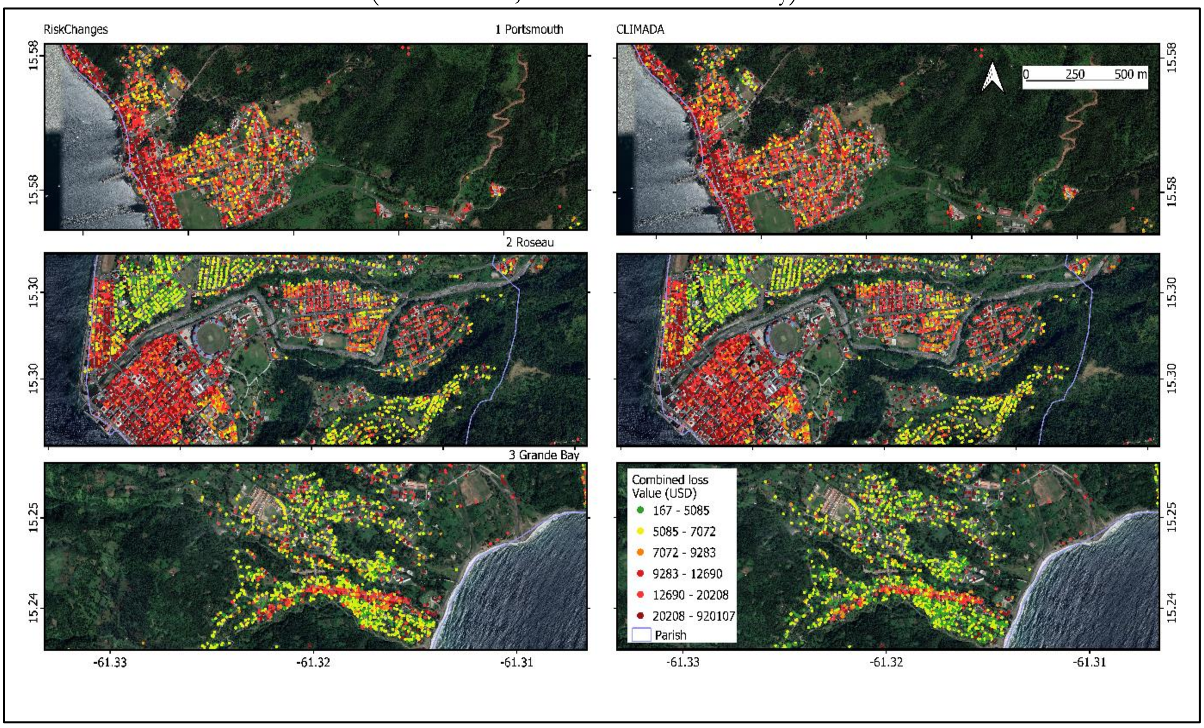


Figure 32: Comparison of building loss in the three cities

The loss result per Parish in RiskChanges and CLIMADA shows similar results. St. Peter, John, Luke, and Andrew have higher loss compared to the other Parish. In St. Peter Parish 960 buildings exist in the building database of which 80% were damaged. Figure 33 shows loss per Parish using RiskChanges and CLIMADA.

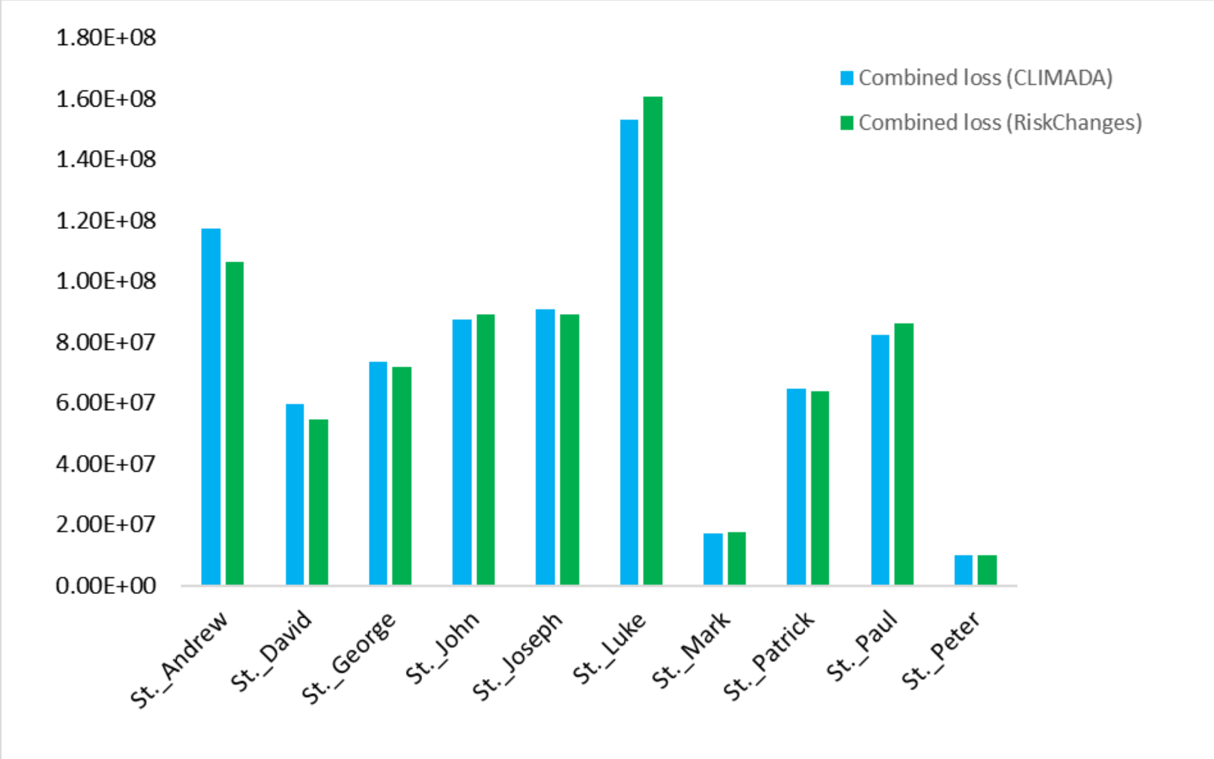


Figure 33: Loss per parish in RiskChanges and CLIMADA

The classified loss results for all buildings are shown in Table 17. The RiskChanges loss in the four classes also have similar pattern with the CLIMADA result. The large difference only occurred in the last class which is the loss greater than 70%, the RiskChanges result in this class is lower than the CLIMADA. The number of damaged buildings in the first two classes are very similar in the tools but in the third class the numbers of buildings are increased in RiskChanges and in the last class the number of buildings decreased. This difference clearly shown in the Figure 34 and the map shows the loss of the four classes. The differences are in northern, northwest, northeast and eastern parts of the island (see also Figure 35 (1)). The variations are observed in class three and four, and this variation is because of the spatial probability of the wind speed used in the tools. The other parts of the island show similar patterns in the percentage of loss class. For instance, in Roseau and Grande Bay shows similar results (Figure 35(2&3)).

Table 17: Degree of loss in RiskChanges(as compared with thos from CLIMADA in italics)

Loss class	Total building loss (USD)	Number of building
(<20% loss)	3.67E+06 *6.30E+06*	215 *337*
(>20% and <45% loss)	3.15E+07 *3.87E+07*	5011 *4596*
(>45% and <70% loss)	1.42E+08 *1.35E+08*	15445 *13214*
(>70% loss)	5.66E+08 *5.83E+08*	17886 *20410*
Total	7.50E+08 *7.56E+08*	38557 *38557*

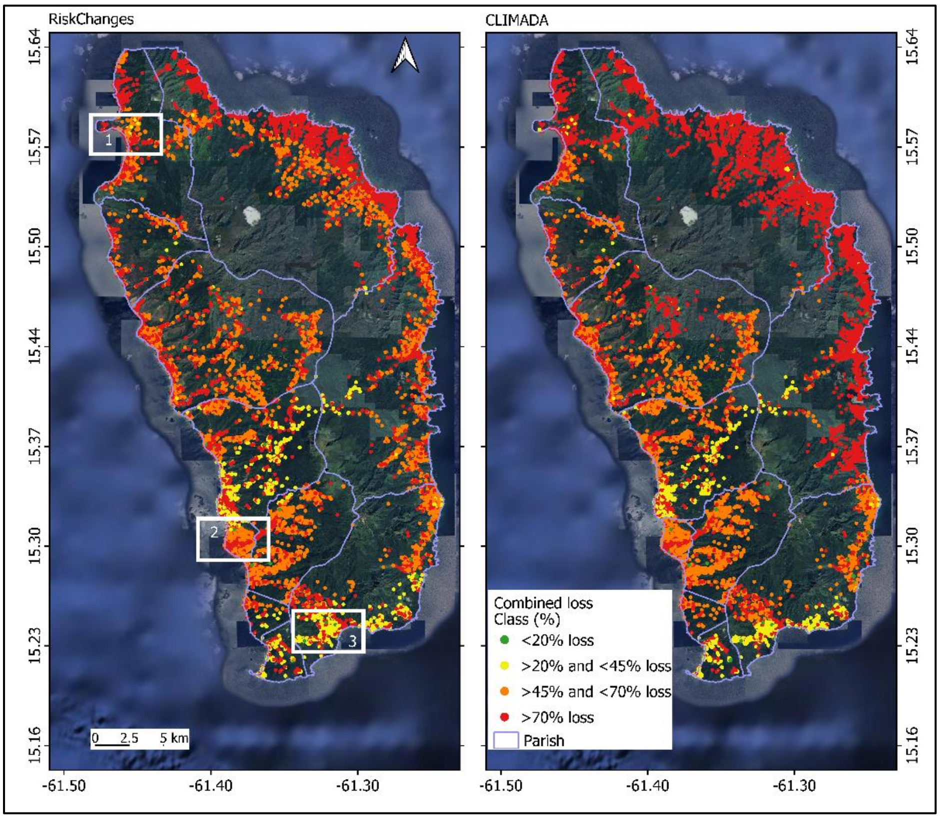


Figure 34 : Flood and wind loss percent in RiskChanges

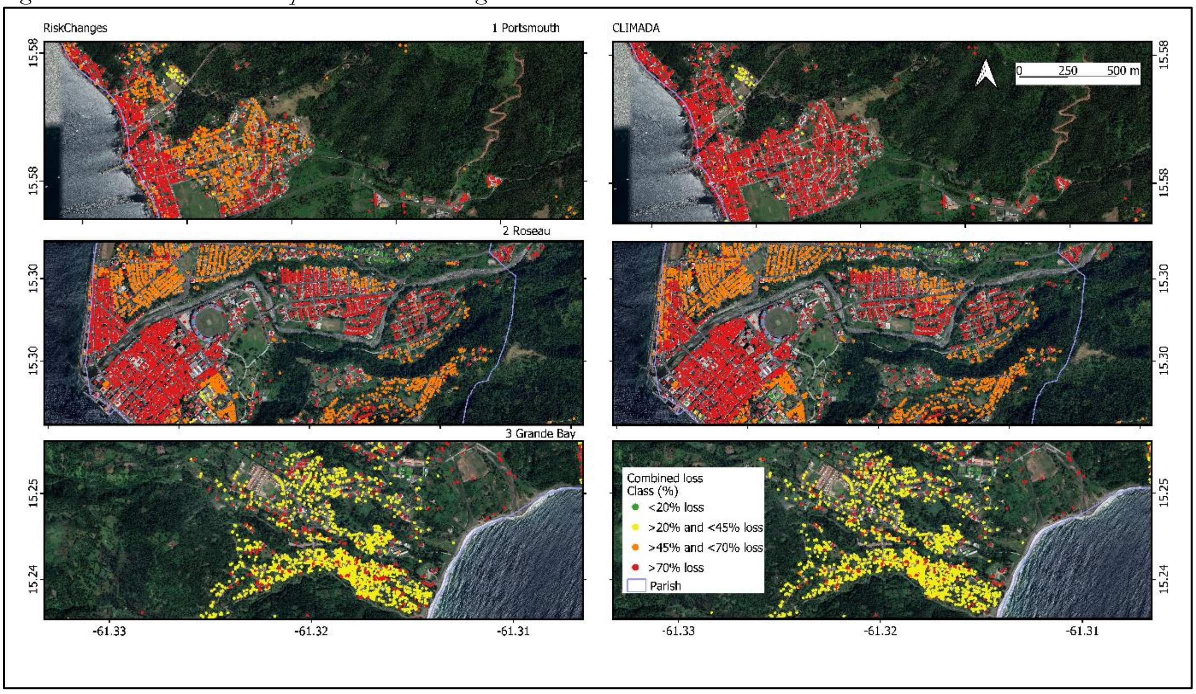


Figure 35: The loss classes in the RiskChanges and CLIMADA within different cities

5.2.3. Comparison of calculated loss result (RiskChanges) in the residential buildings with PDNA reported loss.

We tested different combinations of spatial probability, step size and base in the RiskChanges tool (Table 18). The spatial probability and base have a major impact on the loss assessment, this is because the spatial probability indicated how the hazards translate to the vulnerability and multiplied with the exposed value, and base ignore the hazard intensity value. When the spatial probability increased the loss increase (Figure 36) and the number of damaged building increase in the moderately and completely damaged class. But the increase in the base reduces the loss estimation and the number of damaged buildings decreased because the base excludes the building that fall under the specified base value (Figure 37). Minor changes occurred when we increase the step size which is the ranging between the hazard class also increased and RiskChanges take the maximum intensity value, this leads an increase in the loss estimation (Figure 38).

Table 18: Parameter values for the trials

	Flood			Wind		
	Spatial probability	Base value	Step size	Spatial probability	Base value	Step size
Changing the Spatial probability (Sp)						
Trial Sp1	0.4	0.1m	0.2m	0.4	58m/s	2m/s
Trial Sp2	0.6	0.1m	0.2m	0.6	58m/s	2m/s
Trial Sp3	0.8	0.1m	0.2m	0.8	58m/s	2m/s
Trial Sp4	1	0.1m	0.2m	1	58m/s	2m/s
Changing the Base value (B)						
Trial B1	1	0.1m	0.2m	0.8	58m/s	2m/s
Trial B2	1	0.2m	0.2m	0.8	60m/s	2m/s
Trial B3	1	0.4m	0.2m	0.8	62m/s	2m/s
Trial B4	1	0.6m	0.2m	0.8	64m/s	2m/s
Changing the Step size (Ss)						
Trial Ss1	1	0.1m	0.1m	0.8	58m/s	2m/s
Trial Ss2	1	0.1m	0.4m	0.8	58m/s	4m/s
Trial Ss3	1	0.1m	0.6m	0.8	58m/s	8m/s
Trial Ss4	1	0.1m	0.8m	0.8	58m/s	10m/s

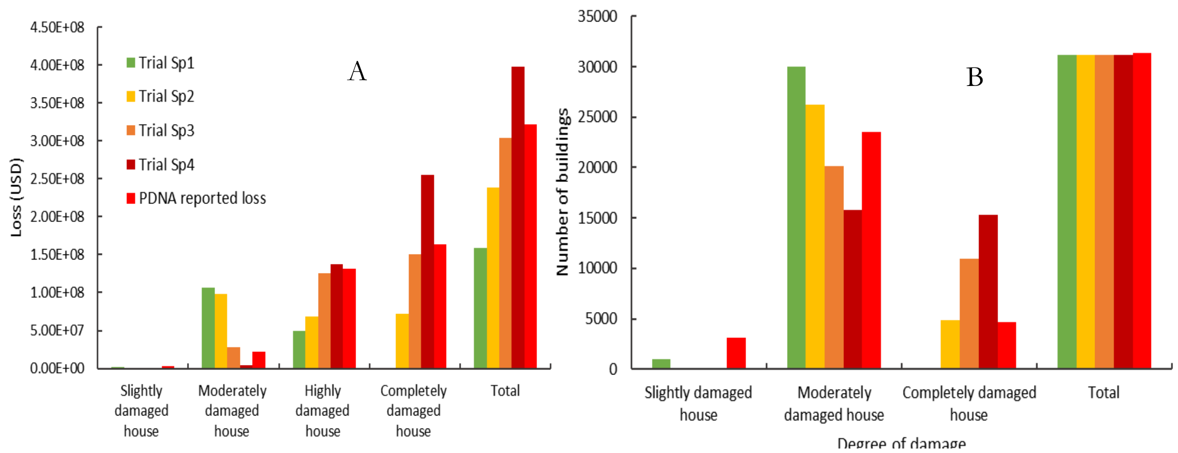


Figure 36: Estimation of losses by changing the spatial probability, (A) indicate loss in terms of value and (B) loss in terms of number of buildings.

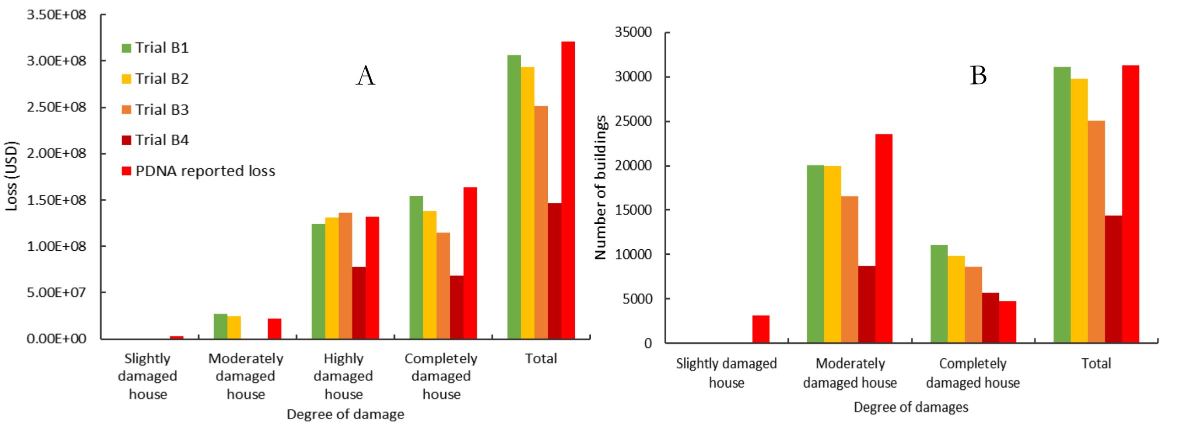


Figure 37: Estimation of losses by changing the base value, (A) indicate loss in terms of value and (B) loss in terms of number of buildings.

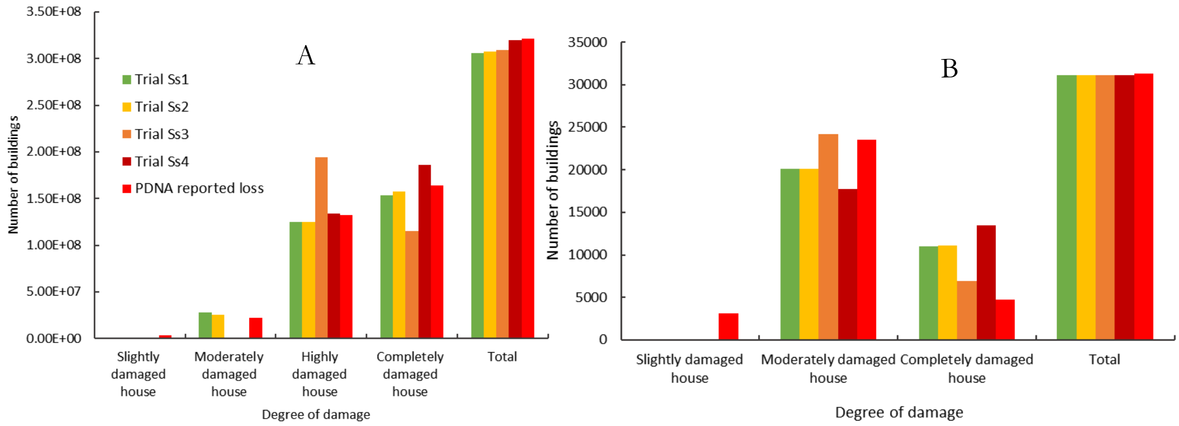
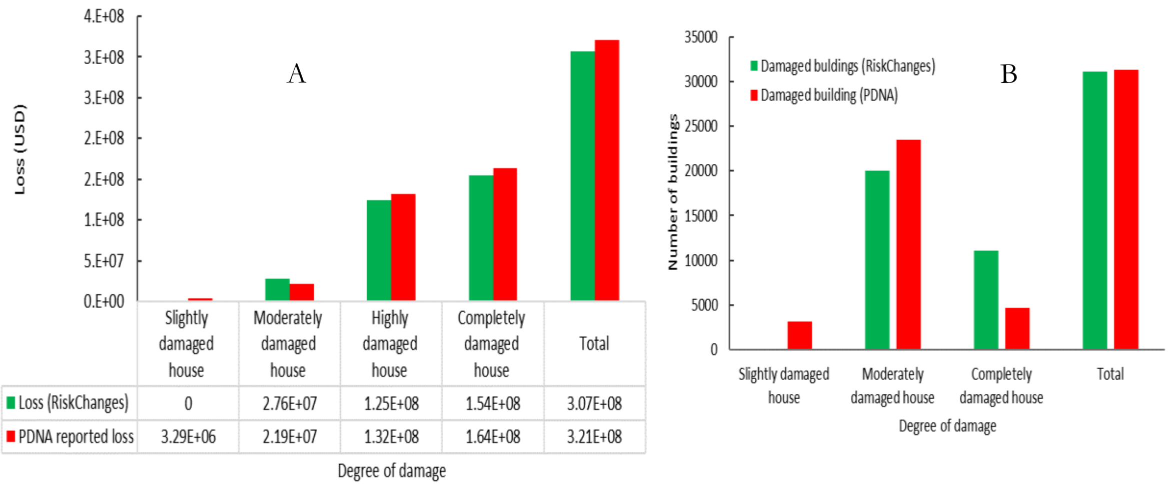


Figure 38: Estimation of losses by changing the step size, (A) indicate loss in terms of value and (B) loss in terms of number of buildings.

After testing different parameter values of spatial probability, base, and step size we select the most optimal parameter value (Trial B1) that align with our assumptions. The comparison between the calculated loss in RiskChanges with PDNA reported loss was made.

The classified loss result in RiskChanges is very similar with the PDNA reported loss. only the first class did not have damaged buildings, but the reported loss result shows 3.2 million USD losses and 3135 buildings damaged observed. The other classes are very similar with PDNA, even if the reported loss included additional hazard impacts on the loss assessment. The number of damaged buildings specially in the moderately damaged house class are highly match with the reported loss Figure 39 shows the comparison of the losses with the PDNA values.



	Slightly damaged house	Moderately damaged house	Highly damaged house	Completely damaged house	Total
Loss (RiskChanges)	0	2.76E+07	1.25E+08	1.54E+08	3.07E+08
PDNA reported loss	3.29E+06	2.19E+07	1.32E+08	1.64E+08	3.21E+08

Figure 39: Comparison of calculated loss in RiskChanges with PDNA reported loss in terms of loss value(A) and number of buildings (B).

5.3. Flood and wind loss result comparison between CLIMADA and Riskchanges

The flood and wind hazard loss result in CLIMADA and RiskChanges shows the same patter for all type of buildings. The flood loss in RiskChanges is higher than the CLIMADA and the loss difference highly observed in residential and commercial buildings. Because CLIMADA uses the nearest centroid point from flood map and RiskChanges considers all flood levels to which building footprints are exposed. The loss caused by the wind in CLIMADA is slightly higher than the RiskChanges results. Mainly the wind loss in the residential buildings is larger in the CLIMADA and for all the other buildings have similar loss to the RiskChanges. The reason is the spatial probability used in the tools. Figure 40 shows the flood and wind loss result using CLIMADA and RiskChanges.

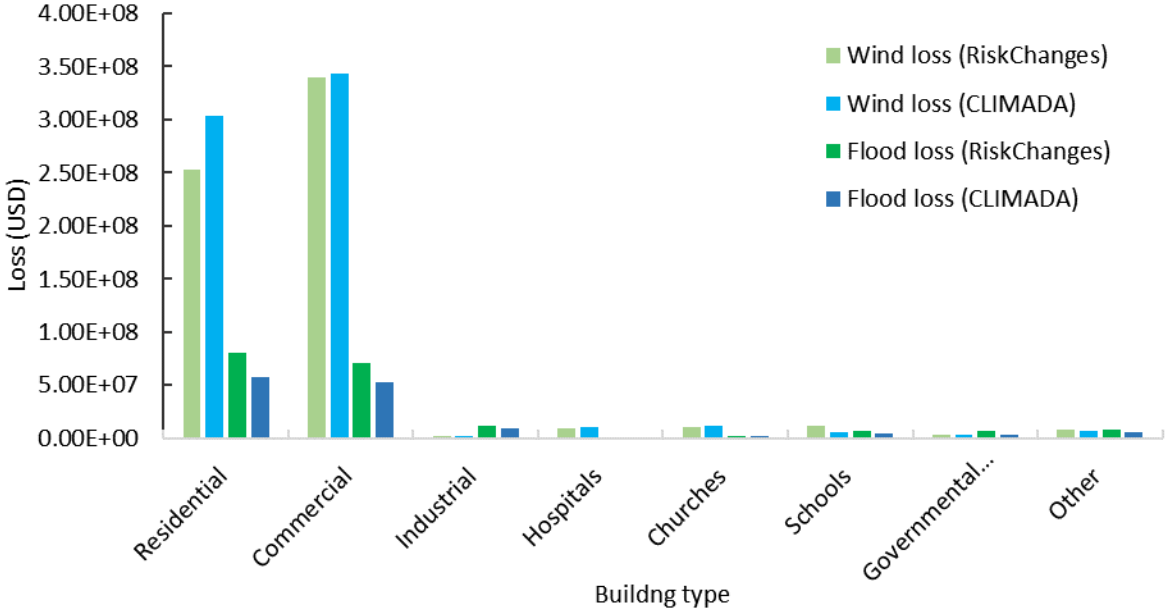
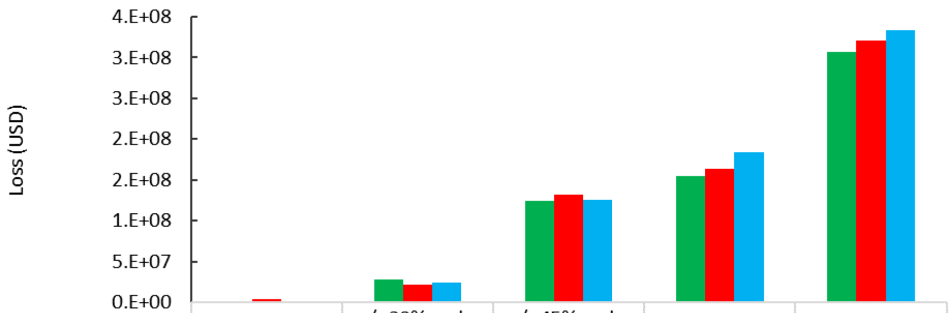


Figure 40: Wind and flood impact using CLIMADA and RiskChanges.

The multi-hazard loss results using CLIMADA and RiskChanges are similar in the total value and the distribution of the loss in the classes. The loss result from both tools shows linear loss result regarding the loss classes (Figure 41). In addition to this the total loss of all buildings in CLIMADA is 756 million USD and in RiskChanges 749 million USD. The PDNA report has also similar with RiskChanges and CLIMADA.



	(<20% loss)	(>20% and <45%)	(>45% and <70%)	(>70%)	Total
Loss (RiskChanges)	0	2.76E+07	1.25E+08	1.54E+08	3.07E+08
PDNA reported loss	3.29E+06	2.19E+07	1.32E+08	1.64E+08	3.21E+08
Loss (CLIMADA)	0	2.40E+07	1.26E+08	1.83E+08	3.33E+08

Degree of damage

Figure 41 : Comparison of flood and wind hazard loss result using CLIMADA and RiskChanges and PDNA reported loss

5.4. Comparision based on the criteria

5.4.1. Data requirements

CLIMADA uses multiple types of input data formats such as Excel, raster, vector, Hdf5, and Mat file format for the exposure, hazard, and vulnerability functions where as RiskChanges uses raster file format (GEOTIF) for the hazard data, shapefiles for elements-at-risk, and csv file format for vulnerability functions. Both use spatial and non-spatial data; CLIMADA uses the spatial data for the hazard, elements-at-risk, and future scenarios the RiskChanges use also the same spatial information in addition to that it includes the adaptation or mitigation measures spatially. The adaptation measure included in the CLIMADA using non-spatial data which is by defining the effects of the measures on the hazard, exposure and vulnerability functions the method will reduce the hazard, exposure, and vulnerability functions by the defined amount of the measures and the tool also use non-spatial data for vulnerability functions. Like CLIMADA the RiskChange use the non-spatial data for vulnerability.

The spatial probability in RiskChanges is simply define similar value for all exposure. In CLIMADA the percentage asset affected (PAA) defined by users without any dataset but the user has a choice to differentiate the PAA per exposure and vulnerability functions. The scale of the analysis for CLIMADA is from global to local scale the aim of the tool is provided good method and data in the global scale, however it is possible to implement the analysis in the local scale if the datasets are good enough. The RiskChanges develop to analyse the effects of risk reduction planning alternatives in local scale. To compute the risk in CLIMADA the tool needs additional information's rather than the hazard, exposure, and vulnerability which are the centroid points, and PAA. The RiskChanges do not need additional data or information out of the three components, but the user needs to prepare separate csv file for individual vulnerability function, and to classify the hazard the user must define the base and step size of the hazard. CLIMADA and RiskChanges have ability to work with different dataset one of the examples is this study, the tools are tested by the Dominica island datasets.
The projection system used by CLIMADA and RiskChanges are limited to World Geographic Coordinate System (WGS) with EPSG code.

5.4.2. Integrating hazard interactions

CLIMADA does not include the hazard interactions in the risk assessment, but the RiskChanges include the hazard interactions in the risk assessment for all types of interactions the type of interactions and method used to calculate the effects of the interaction shows in the Table 3.

5.4.3. Risk components

CLIMADA allows to access open data by using the web APIs from the World Bank, Natural Earth, NASA and NOAA for the hazard, future scenarios, and exposure. For instance, the LitPop, and BlackMarble night light data for economic exposures, the IBTrACS for wind hazard RCP scenarios of climate change impact for future risk. In addition to this the user can access the calibrated tropical cyclones vulnerability functions. In the RiskChanges have vulnerability database the user can access the function used by the other users. The Python version of RiskChanges used the hazard, elements-at-risk, and future scenarios as input data there are no options to create the dataset using the tools and to access the open data, but the GUI version of RiskChanges has an option to directly access data though Web Feature Service (WFS) and links to GeoNodes.
CLIMADA and RiskChanges do not have limitation on the detail of elements-at-risk the user can define the data in very specific detail information. The CLIMADA calculate the risk in event based probabilistic method, but it is possible to compute with a deterministic approach. The RiskChanges calculate the risk in deterministic and semi probabilistic approach. Both tools do not incorporate the uncertainty management in the risk assessments.

5.4.4. Decision making support.

CLIMADA is implementing the risk transfer type of decision-making support to help the insurance sectors. The tool allows to compute the effects of risk transfer with and without measures, cost benefit ratio per measure and the combined measure effect of net present value.

The RiskChange aim to help the local government and support the spatial planning. The tool allows to analyse the cost benefit including Benefit-Cost Ratio, Net Present Value, and internal Rate of Return. In addition to this there is an option to make score for the risk reduction alternatives which is the multi-criteria decision-making support to identify the highest benefit reduction alternatives by using user defined, standardized, and weighted indicators.

5.4.5. The tools can manage easily with limited knowledge.

The interface language of the tools is English, and the installation of the tools is similar by simply install the dependency environment on the preferable platform can be anaconda or Jupyter notebook. For CLIMADA several documentations are available mainly the manual, tutorials, CLIMADA web pages, Git hub and the developers are willing to help the users. To implement the tool at least basic knowledge of python is needed without this skill it is difficult to use the tools by only using the available documentations. In CLIMADA it is possible to visualize the analysis result within the interface whereas in Python version of RiskChanges it is not possible to visualize in the interface but in the GUI version there are a lot of options to visualize the result. For the visualization there is an option on the Geo- eye, but it is currently under development. Due to the development the RiskChanges do not have any documentations, but the developers are willing to help the user.

6. DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

6.1. Discussion

This chapter discuss the overall findings of the study based on the research questions with the limitation of the data and the methods used in the CLIMADA and RiskChanges.

6.1.1. How data demanding are these models, and what are their input data requirements?

Many of risk assessment tools uses a set of input data and have their own input data. The example can be RISKSCAPE (Thomas et al., 2020), CAPRA (CAPRA, 2017), HAZUS tools (Cutrell et al., 2018) in general the tools use the hazard layer, asset, vulnerability function and aggregation layers as an input. All of them have different input data requirements. Like the other tools the CLIMADA and RiskChanges have data requirements.

The aim of the study was conducting the multi-hazard risk assessment using the two tools, but the strange result from the flood hazard maps did not allowed to compute the risk assessment. Six different flood maps were prepared for 5, 10-, and 50- years return period, Erika and Maria flood event using OpenLISEM flood hazard model (see Figure 42). According to the result the smaller return period flood hazard is high in intensity and larger in the extent than the longer return periods. Erika and Maria flood event modelled using the observed rainfall data from Canfield airport rainfall station, but the other flood maps were prepared using the synthetic storm Grenada. The modelled flood hazard data is improved a lot from the previous flood map because we use the improved DEM which is mixed with LIDAR data. In addition to this determining the flood hazard return periods with this uncertainty are difficult to make the risk assessment. Therefore, we decided to make the loss assessment caused by Hurricane Maria in 2017. This event selected because the damage occurred during this event is assessed by the government of the Commonwealth of Dominica with technical support from World Bank so, the event allows to compare the results with the reported damage.

The quality of the input data determines the loss result and one of the input data is the OSM building. The OSM building data is represent the actual situation before Hurricane maria. The OSM building does not incorporate the complete attribute information such as occupancy and construction type. Identifying the exact historical period of the OSM building is difficult due to sequential updating. The building value estimated using the real estate price because there is no official record of the building price in Dominica. According to (Street Directory, 2021) the real estate price is fair in Dominica island most of the houses constructed in the larger area. The price depends on area, quality of construction and the location. In our database more than 68% of the buildings have a surface area < less than 100 m^2 the approximate value estimated by considering the real estate price and area of the buildings (if the area is lower and the estimated price of the building also lower). Still the estimated building value did not fully express the actual building value this may influence the loss results. Beside the hazard and building data the vulnerability functions are very important for calculating the loses the losses and the uncertainty in vulnerability has a large influence on the result. Vulnerability functions are difficult to obtain and are often not representative for the situation in particular study area (GRMI, 2012). In this study the buildings are classified based on the occupancy, construction, roof type and roof shape. It is hard to find vulnerability function that based on the classification of buildings.

We forced only to use the occupancy type of the buildings to select the representative vulnerability function. Using the most representative vulnerability functions for the building require additional field survey which is not possible in the study. Another option was using the damage assessment dataset this data contains the degree of damage that occurs in the building but there is a problem related to the exact location of the building. The building location is unknown so we could not use the information to determine the vulnerability functions. Finally, from the literature the most representative functions are selected based on the occupancy type of the building. The uncertainty from the vulnerability functions also has a lot of impact on the calculation of the loss.

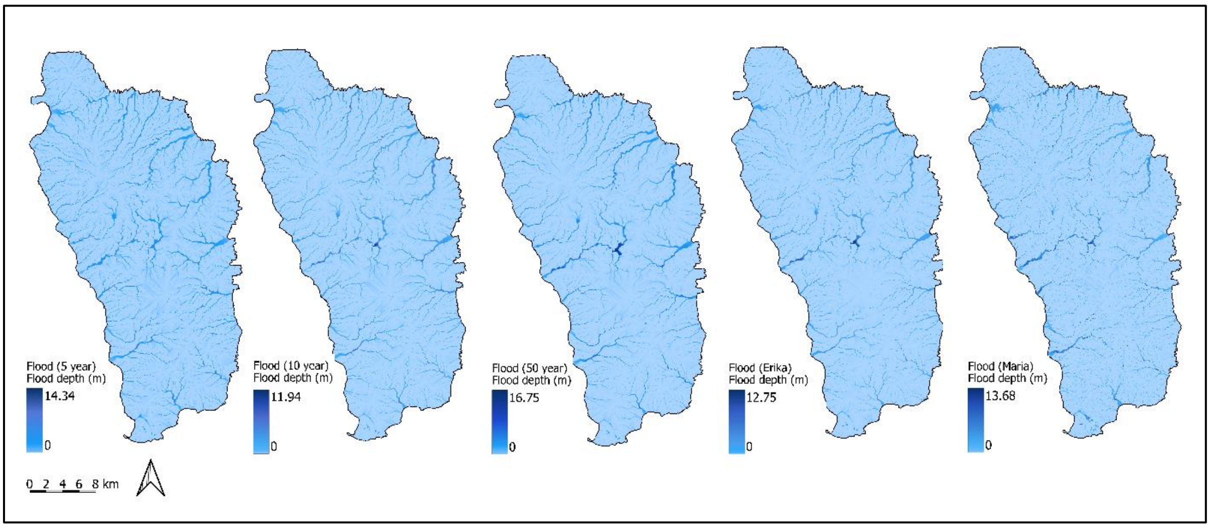


Figure 42: Flood hazard map for different return period

6.1.2. How are the hazard interactions considered in the hazard and risk assessment component?

Almost all multi-hazard risk assessment tools do not consider the hazard interactions or many of them consider the multi-hazard risk by simply adding the single hazard risk (Gill & Malamud, 2016). In CLIMADA the hazard interactions are not considered but the RiskChanges considers the type of hazard interaction in the risk assessment. The RiskChanges calculate the hazard interactions as follow:
Independent hazard interactions: the losses are added by setting the limiting factors up to the maximum value. Compounding hazard interactions are calculated by summation of the first hazard event loss with the second hazard loss and subtract from the total value then add the subtracted value with the first hazard loss. Coupled hazard interactions: it takes the maximum loss from the hazards up to the maximum value. Cascading or dominos hazard interactions: summing the losses by considering the probability of the hazards. Conditional hazard interactions: it takes the maximum by calculating the first hazard loss which is the triggering plus the second hazard loss and multiply by the probability the event triggered by the first hazard.

6.1.3. How are elements-at-risk characterized? At what level of detail and which attributes? Does it incorporate vulnerability?

The elements-at-risk represent any object/person/activity that may be exposed to a hazard in a particular area. It can be buildings, land parcels, agricultural fields, roads, (UNDRR, 2016). The elements-at-risk are characterized in numerous ways depending on their types (Merz et al., 2010). The risk assessment tools have standard to characterize the details of the elements-at-risk. CLIMADA and RiskChanges have a flexibility in using every level of detail information of the elements-at-risk. To compute the risk in CLIMADA and RiskChanges the value, geographic location, and ID of vulnerability functions attributes are mandatory. The RiskChanges has a vulnerability function data base that stores the user's vulnerability function, and the data base is available for all users. CLIMADA has vulnerability functions for tropical cyclones, but it has a general vulnerability function.

6.1.4. How are the risk components (hazard, elements-at-risk, and vulnerability) considered in the model?

Most risk assessment tools use the hazard, elements-at-risk, and vulnerability functions as an input. But few tools incorporate the link to a database with existing data, or options to produce the hazard, elements-at-risk, and vulnerability functions. For instance, the CAPRA tool has a vulnerability functions database that provide to use the existing functions, create, and visualize(Cardona et al., 2012). The RiskChanges has similar feature for the vulnerability functions, but the tool considers the hazard and elements-at-risk only as an input because of the aim of the RiskChanges to support the decision makers by using the existing datasets. CLIMADA consider the risk components in different ways: the first is simply as an input data and the second way is generate the hazard, exposure, and future scenario data from open data source. However nearly all the data are in global level with coarse resolution. For the local scale risk assessment, it is not good enough to use in the global scale. When we compare the exposure value using classified building data with the CLIMADA BlackMarble economic exposure in Roseau (Figure 43) generalize the exposure value for the larger part of the city and the estimated value is very high because the spatial resolution of the data is 5km the city covered by within few numbers of pixels.

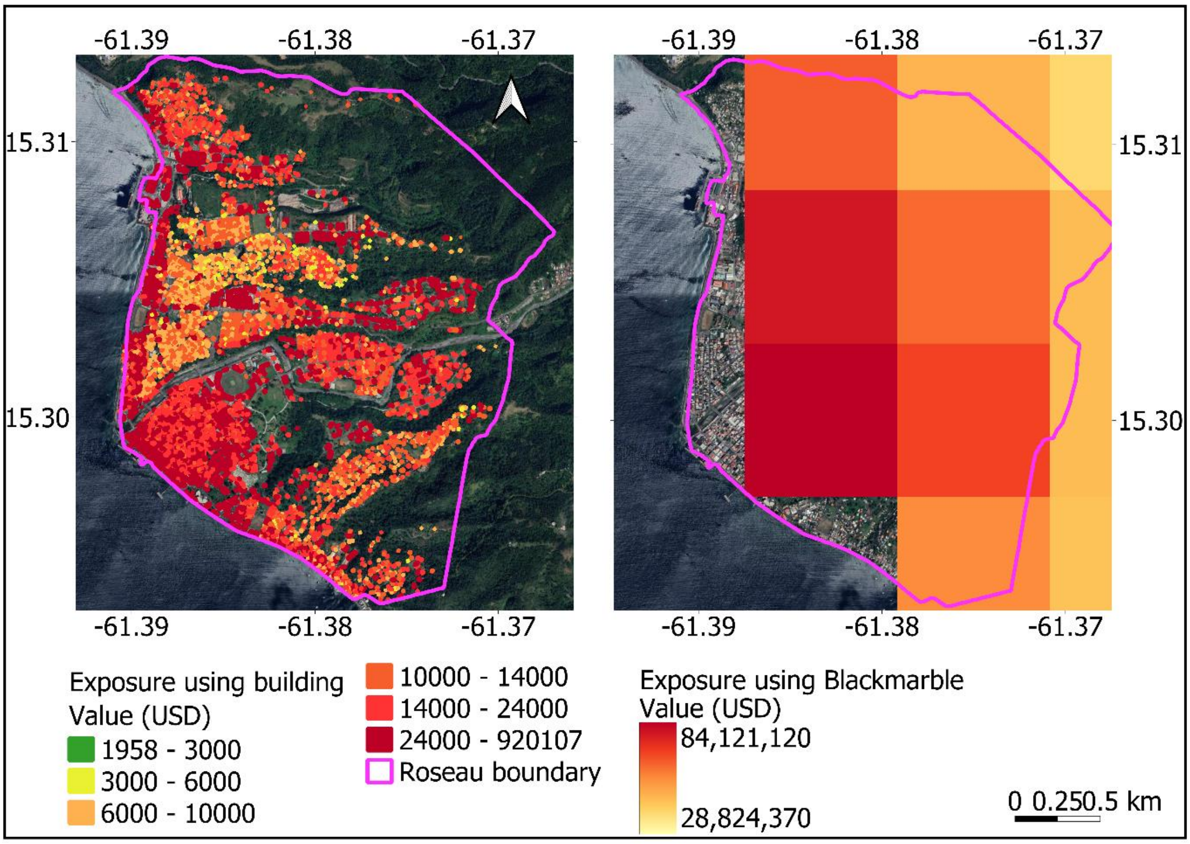


Figure 43: Comparison between BlackMarble and building exposure result.

6.1.5. Which type of losses are calculated, and which risk calculation is carried out?

Deterministic and probabilistic methods are used to calculate the loss and risk, many of the probabilistic tools developed are proprietary tools used commercially (GFDRR, 2015a). The RISKSCAPE tool, which is now no longer available, can be an example from deterministic approach (Reese et al., 2007) and CAPRA, which is still available but no longer supported, an example of the probabilistic approach (CAPRA, 2017). When we look at CLIMADA it implements probabilistic approach to calculate the loss and risk whereas the RiskChanges use semi probabilistic method.

CLIMADA calculate the loss by multiplying the mean damage ratio with exposed value then multiply the impact by the frequency of the hazard. During the calculation of loss, the PAA has larger uncertainty because it is based on an assumption and expect estimation. For instance, in this study, we applied a PAA value of 1 for flood by assuming when the flood occurs the probability getting the flood for all buildings are equal and for windstorm, we assume that when the intensity of the wind speed increases the PAA also increase to consider the unknown topographic effect. The PAA does not vary, as it is not possible to determine this since the PAA is linked to the vulnerability function, to option the MDR, in order to calculate loss. The risk in CLIMADA calculated by simply summing the expected annual impact of the event this indicate that when the number of hazard event increased the risk also increase.

The loss calculation using RiskChanges is by multiplying the exposure, value and spatial probability. The calculation depends on the base, step size and spatial probability parameters. Those parameters have a lot of impact on the loss result because RiskChanges classifies the hazard using the base and the step size when the step size increased the average hazard intensity also increased this cause to overestimate the exposure of the elements-at-risk. When the average hazard intensity increased the degree of vulnerability also increased. That is why when the step size increases the loss also increase but the base has revers impact compared to the step size. The base is to tell the model to ignore the hazard intensity values until the base value as no damage will occur, so when you exclude relevant hazard intensities (ass was the case in Trail B3 and B4 of Figure 37) this decreases the reported loss, because a part of the losses are ignored. The spatial probability has a much higher impact on the loss results, than the step-size and base level. The spatial probability in RiskChanges is comparable with the PAA in CLIMADA, in representing the fraction of element-at-risk that would be affected giving a certain hazard class. It is meant to account for hazard maps that do not have intensity values but only susceptibility classes (e.g., for landslide susceptibility where the spatial probability would then indicate the expected landslide density within the susceptibility classes), or when the modelled hazard intensity has a large uncertainty due to oversimplification (as was the case for the wind hazard where the topography was not considered for the modelled wind speed). When superior impact on the loss result. Because when we apply the spatial probability 1 the exposure value and vulnerability value directly determine the loss but by using the spatial probability of 0.7 the loss would be 70% less. Using the same spatial probability for all exposed value has a lot of impact on the loss result. Those factors are increased the uncertainty of the loss result. The single hazard risk calculates by aggregating the losses and for multi-hazard risk the tool computes the risk based on the interactions.

Both CLIMADA and RiskChanges have a large uncertainty due to the calculation methods, whereas both tools do not incorporate the uncertainty of the input data into the calculation, because it is difficult to quantify the uncertainty of the hazard, exposure, and vulnerability. Therefore, the uncertainty caused by input data and the calculation method in the tool increased the uncertainty of the loss result.

6.1.6. Can the result be validated using recent disasters in the study area?

Only the loss results are possible to validate because they relate to a specific even. If you do a loss estimation for a disaster for which you have reported damage information, it is possible to validate the loss assessment. It is not possible to validate the risk as it deals with all possible events that might occur in future. Few studies validated the estimate loss with the reported damage of a disaster (Astoul et al., 2013; GFDRR, 2015a). The loss result for hurricane Maria from the CLIMADA and RiskChanges tools both gives good result when we compare with the reported loss. Also, the RiskChanges loss result specifically the total losses are very similar to the reported loss. The tools have ability to compute the loss and risk assessment. Even if the method of the tools is affecting the loss result but the accuracy of the results are highly depends on the quality of the input data. The loss result for single hazard and multi-hazard loss are more or less very similar in both tools.

6.1.7. How the tools incorporate the evaluation of risk reduction alternatives?

CLIMADA and RiskChanges have a capacity to evaluate the risk reduction alternatives by conducting cost benefit analysis. During the study we test the risk reduction measure by using the CLIMADA tutorial example measures from San Salvador flood risk assessment (Nigel G et al., 2015) and Florida tropical cyclones impact (Bresch, 2017), but the implementation of measures in CLIMADA is unable to see the effects of the measures in very localized area. Because the measures implement by defining the percentage of the measures which can averts the intensity of the hazard, vulnerability, and exposure in general. But the tool can implement the measures into region level. The measures evaluated by calculating the cost benefit ratio per measures for all return periods, and net present value. The RiskChanges implement the measures in the local level focus on the planning alternatives which is mainly the engineering, ecological and relocation solutions. Evaluate the measures by conducting cost benefit analysis which can identify the net present value and internal rate of return. Implementing risk reduction option using RiskChanges do not conduct in this study because the tool is still under development and the data of the risk reduction option was not prepared.

6.1.8. Can the tools analyze changes in multi-hazard risk for specific future years under different scenarios?

Analyzing changing risk in multi-hazard risk for specific future years under different scenarios depends on the quality of the input data and capacity of the tool. Many tools do not consider the dynamics of multi-hazard risk only consider the current risk (Du et al., 2016). But the risk changes due to several reasons which is the climate change impact, population growth, urban development and any other factors change the hazard intensity, exposure, and vulnerability (GRMI, 2012). CLIMADA and RiskChanges have a capacity to analyze the changing risk using different scenarios. During this study we face difficulty to express the changing risk due the input data. The ISIMP future climate change scenarios for flooding and the RCP scenarios for wind hazard implemented in CLIMADA but the data resolutions are very coarse which is 5km (Zenodo, 2021). The data did not have any change on the island. Therefore, the input data was not good enough to express the changing risk.

6.1.9. Can the tools be applied by decision-makers with limited technical knowledge?

Many tools are not developed for other users or for non-professional users (Du et al., 2016). The authors also indicate the documentation are very poor to understand how the tools are work and testing with new data set is difficult. CLIMADA develop for the climate scientists to analyse the risk, using the tool without the knowledge of the risk science and the python skill is very difficult. However, several information's are available like manual, tutorials, studies, web page and help from developers are very help full to understand how it work. The RiskChanges develop for decision makers, but the tool is currently under development there are no official documentation how the tool work. In the coming period the developers will launch the web page, documentation, and the tool. Comparatively the RiskChanges much easier than the CLIMADA to implement the risk assessment.

6.2. Conclusions

This study examined the potential of Open-source and Python based multi-hazard risk assessment tools (i.e., CLIMADA and RiskChanges), and the validation of these tools based on a recent disaster event (hurricane Maria in Dominica) with reported damage. Based on the findings CLIMADA requires the data as a series of points (centroids), for the hazard and asset value with their geographic coordinate, linked with impact function and Percentage Asset Affected (PAA) estimations to compute the loss. The CLIMADA tool has an option to access global, coarse resolution, Open-source datasets for hazard, exposure, and future scenarios. Even though the CLIMADA tool accesses those Open-source datasets, the quality of these dataset is appropriate for global scale but not at a local scale, even not at the scale of the country of Dominica. The CLIMADA tool aim to address global scale climate related hazard risk assessment, but the scale is flexible, and it can be applied also in the local scale, if data is available. The multi-hazard risk in CLIMADA is calculated without considering the hazard interactions by simply adding the annual expected impact of the hazards.

RiskChanges also required different input datasets. The main inputs are the hazard data, elements-at-risk, and vulnerability functions. RiskChanges use the mean value of the hazard and vulnerability functions rather than the centroids. In addition to the input dataset the tool requires additional parameters which is the base, step size and spatial probability. The RiskChanges develop to help the local decision makers and the scale of the analysis is at local level. The RiskChanges has a capacity to compute the hazard interactions in the multi-hazard risk assessment and has a database for vulnerability functions.

The calculated loss calibrated with the PDNA reported loss and the result shows similar in both tools. Even if the loss results using CLIMADA and RiskChanges similar with the reported loss, the calculated losses are overestimated. Because the reported loss includes all the hazards occurred during hurricane Maria in this research, we only consider the flood and wind hazards. In addition to this the uncertainty of the input data and the parameters value increased the loss estimation.

The selected criteria were good to explore the capacity of the tools in terms of data requirement, hazard interaction, risk component, decision making support and ease of use. The comparison results using the criteria shows in both CLIMADA and RiskChanges some similarity and difference. Both the tools have the capacity in data interoperability if the input data is prepared based on the data requirements of the tools and also the tools have a challenge to better incorporate the uncertainty management in the loss and risk assessment. In addition to this the tools have difficulty to express the spatial probability (PAA)of the hazard which have the higher impact on the loss results. The spatial probability values given by assumptions of the expert. Setting the spatial probability with different value lead an increased or decreased on the estimation of the loss result. Additionally, the quality of the results in the tools completely depends on the quality of the input data. Mainly getting an appropriate vulnerability functions that can express the characteristics of the classified building was very difficult and estimating the building price without detail information is very complicated.

6.3. Recommendations

The study explores the capacity of CLIMADA and RiskChanges based on the data requirement, integration of hazard interaction, loss and risk calculation, decision making support and ease of use. This section provides valuable recommendation to improve the capacity of the tools. The recommendations are given as follow:

- The spatial probability of the hazard has an impact on the loss calculation, the tools include the spatial probability by giving the specific value of the expert assumption. Therefore, for the tools recommended to include option to represent the spatial probability as a map as one of the input data, in terms of spatial data (i.e., considering the spatial variation of the parameter, based on the characteristics of the study area). The spatial probability maps are difficult to generate however, as it requires the incorporation expected density of the hazard phenomena.
- Both the tools do not incorporate the uncertainty in the risk assessment it is important to include the uncertainty management in the tool (e.g., by including the average and standard deviation values of return period, hazard intensities, replacement costs, and physical vulnerabilities). It could also be done by incorporating the uncertainty in the hazard modelling component, and there are only few applications that represent the uncertainty of the modelled hazard intensities.
- In CLIMADA after running the command it is possible to visualize the output. This data visualization advantage needs to be incorporated within the python interface of the RiskChanges, but this is possible in the www.RiskChanges.org GUI.
- CLIMADA use the nearest centroid points of the hazard intensity for the elements-at-risk and this analysis will lead to underestimation or overestimate the exposure. RiskChanges use the intensity of the hazard for each elements-at-risk location for instance if one part of the building exposed 60% for one intensity value and 40% of the building exposed to another intensity value the tool assigns the vulnerability function independently. Therefore, it would be useful if the CLIMADA tool consider this potential of RiskChanges.
- RiskChanges has the capacity to calculate the effect of hazard interaction during the multi-hazard risk assessment. However, CLIMADA does not include the hazard interaction. It is good to include the hazard interaction calculation to improve the efficiency of the CLIMADA tool.
- The vulnerability function in CLIMADA incorporated using only single excel file whereas in RiskChanges the vulnerability functions the number of files linked with the elements-at-risk category (i.e., the building classified into 8 occupancies type the study use 7 vulnerability functions those functions prepared in a separate csv file to implement in the RiskChanges). Therefore, it is important to use one single csv file to reduce redundancy in preparing the other files separately.
- The documentation, manual, tutorial, and web portal of the CLIMADA tool is well organized and it is good to follow this practice in RiskChanges when it is publicly lunched. In addition to this CLIMADA is open for the user to contribute to improve the tool in GitHub and it is also important to include such practice in RiskChanges.
- CLIMADA is developed for the climate scientist community, and it is more at a professional level. It is good to make the tool more user friendly that can be used by the local decision makers.
- CLIMADA allow to access the freely available datasets in the data scarce areas, and it is good to integrate this potential within the RiskChanges.

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ANNEXS

Annex 01 Flood and windstorm loss assessment using CIMADA (Jupyter notebook)

2017 Flood and windstorm loss assessment in Dominica using CLIMADA

June 21, 2021

1 2017 Flood and windstorm loss assessment in Dominica using CLIMADA

CLIMAD tool have three module which are entity, hazard and engine: the entity module allow to calculate and import the asset, exposure, and impact function. the hazard module used to load and read the hazard centroid, intensity and frequency. engine module will calculate the impact of the hazard

SET THE EXPOSURE

flood_entity file loaded by using the CLIMADA exposure. The deductable and cover is zero because we don't have information on the insurance cover

[1]:
```
import pandas as pd
import os
os.chdir("D:\\Thesis")
from climada.entity import Exposures

ENT_FILE = 'Flood_wind_entity.xlsx' # entity file name

exp_acel = Exposures(pd.read_excel(ENT_FILE))
exp_acel.check() # check values are well set and assignes default values
exp_acel.head()  # show first 5 rows
```

```
2021-06-21 23:36:57,266 - climada - DEBUG - Loading default config file:
D:\Masters research\V1.5
CLIMADA\climada_python-1.5.1\climada_python-1.5.1\climada\conf\defaults.conf

C:\Users\fagir\anaconda3\envs\climada_env\lib\site-
packages\pandas_datareader\compat\__init__.py:7: FutureWarning:
pandas.util.testing is deprecated. Use the functions in the public API at
pandas.testing instead.
  from pandas.util.testing import assert_frame_equal

2021-06-21 23:37:05,533 - climada.entity.exposures.base - INFO - crs set to
default value: {'init': 'epsg:4326', 'no_defs': True}
2021-06-21 23:37:05,533 - climada.entity.exposures.base - INFO - tag metadata
set to default value:  File:
 Description:
```

```
2021-06-21 23:37:05,533 - climada.entity.exposures.base - INFO - ref_year
metadata set to default value: 2018
2021-06-21 23:37:05,537 - climada.entity.exposures.base - INFO - value_unit
metadata set to default value: USD
2021-06-21 23:37:05,537 - climada.entity.exposures.base - INFO - meta metadata
set to default value: None
2021-06-21 23:37:05,537 - climada.entity.exposures.base - INFO - centr_ not set.
2021-06-21 23:37:05,537 - climada.entity.exposures.base - INFO - category_id not
set.
2021-06-21 23:37:05,537 - climada.entity.exposures.base - INFO - geometry not
set.
```

[1]:

```
   category  latitude  latitude.1  longitude     value  deductible  cover  \
0         6   15.2979     15.2979   -61.3840  599135.0         0.0    0.0
1         6   15.3123     15.3123   -61.3447  122578.0         0.0    0.0
2         6   15.2972     15.2972   -61.3866  348860.0         0.0    0.0
3         6   15.3096     15.3096   -61.3784  538793.0         0.0    0.0
4         6   15.3096     15.3096   -61.3786  527118.0         0.0    0.0

   if_FL  if_TC Value_unit  region_id
0      6      6        USD          6
1      6      6        USD          3
2      6      6        USD          6
3      6      6        USD          6
4      6      6        USD          6
```

[2]:

```
# some statistics
print('Number of houses, mean, total and standard deviation value of  buildings:
 ↪ \n')
print(exp_acel[['category', 'value']].groupby('category').agg(['count', 'mean',␣
 ↪'sum', 'std']))
```

```
Number of houses, mean, total and standard deviation value of  buildings:

          value
          count           mean           sum            std
category
1         31113   15334.109195  4.770901e+08   10632.251739
2          6526   65111.419143  4.249171e+08   76239.601663
3           176  156606.756364  2.756279e+07  157288.295943
4           106  152942.885849  1.621195e+07  120689.608943
5           130  106177.598615  1.380309e+07  108462.707203
6           194  218291.117010  4.234848e+07  204281.712546
7           183   85146.726557  1.558185e+07  118902.971016
8           129  218799.818682  2.822518e+07  192958.621785
```

[3]:

```
print(exp_acel[['category', 'if_FL']].groupby('category').agg(['unique']))
```

```
          if_FL
```

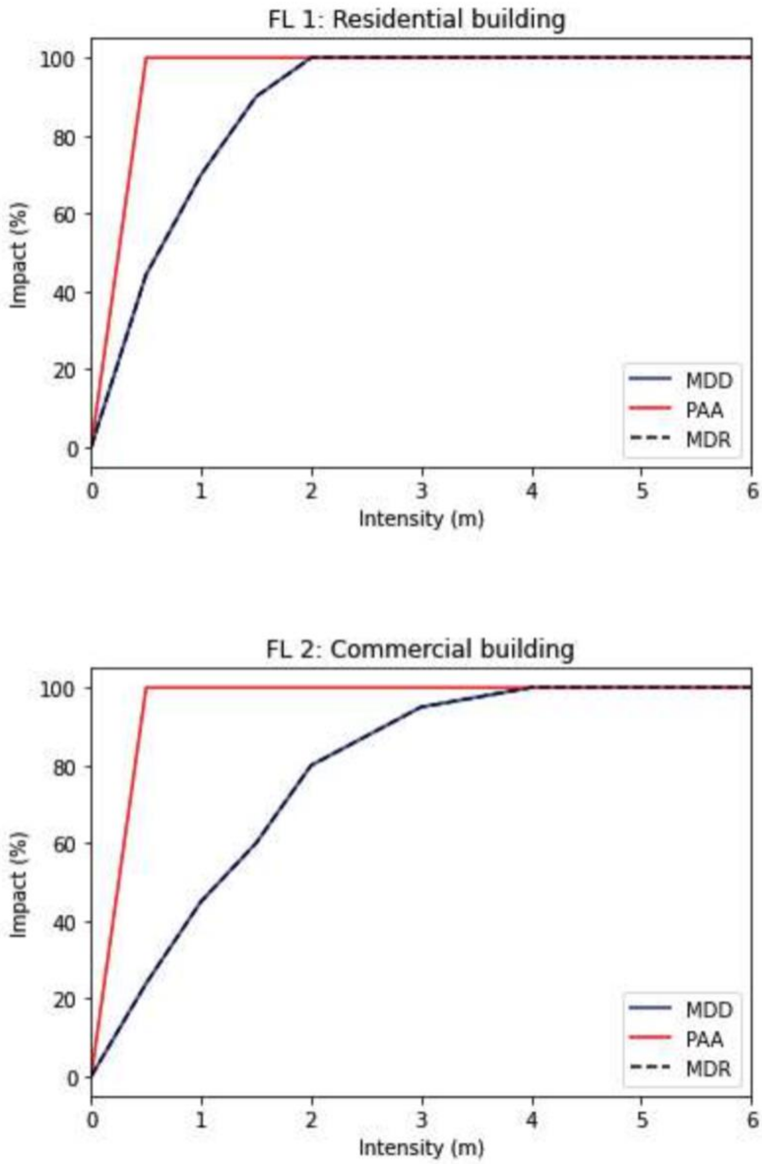
```
         unique
category
1           [1]
2           [2]
3           [3]
4           [4]
5           [5]
6           [6]
7           [7]
8           [7]
```

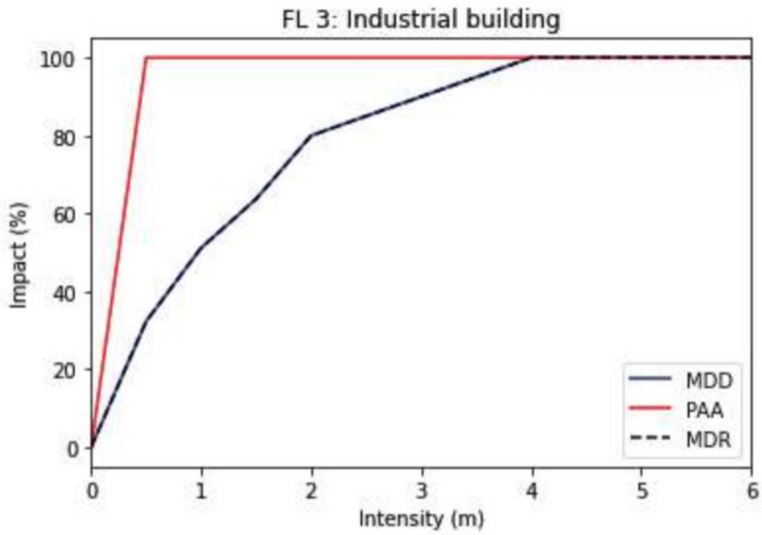
SET FLOOD IMPACT FUNCTION

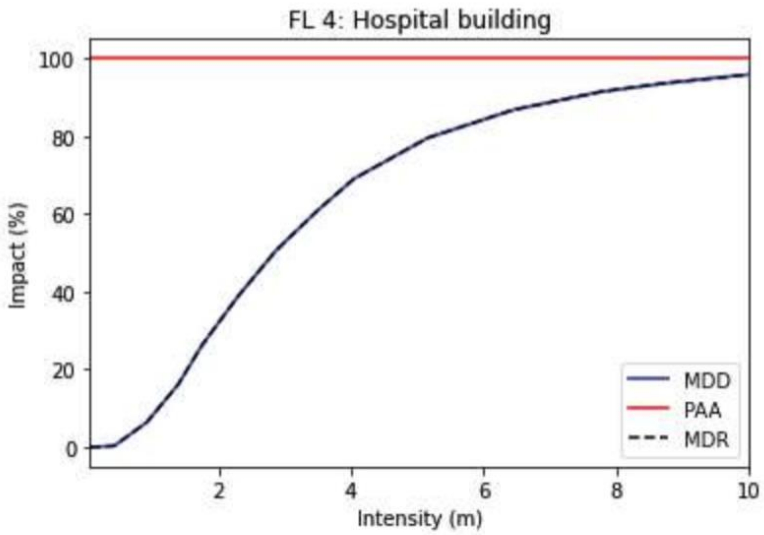
[4]:
```
from climada.entity import ImpactFuncSet

if_acel = ImpactFuncSet()
if_acel.read_excel(ENT_FILE)
if_acel.check()

print('MDD: mean damage ratio; PAA: percentage of afected assets; MDR = PAA*MDD:
 ↪ mean damage ratio:')
if_acel.get_func('FL', 1).plot() # plot flood function 1
if_acel.get_func('FL', 2).plot() # plot flood function 2
if_acel.get_func('FL', 3).plot() # plot flood function 3
if_acel.get_func('FL', 4).plot() # plot flood function 4
if_acel.get_func('FL', 5).plot() # plot flood function 5
if_acel.get_func('FL', 6).plot() # plot flood function 6
if_acel.get_func('FL', 7).plot() # plot flood function 7
```

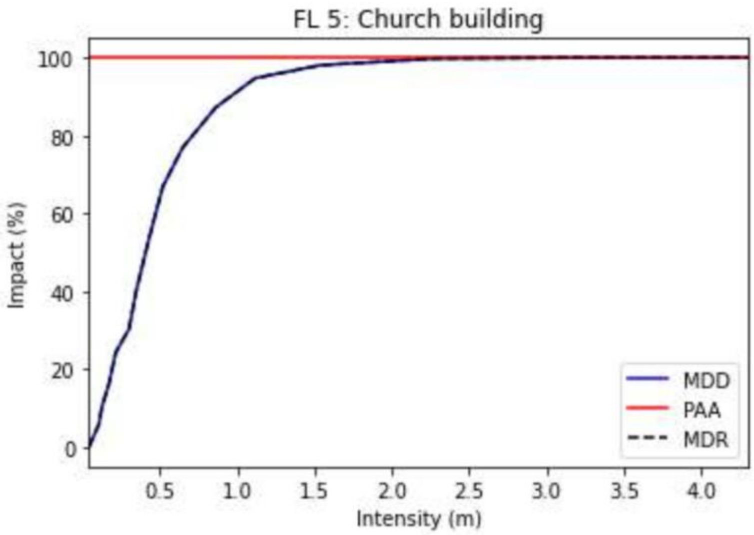
```
2021-06-21 23:37:24,186 - climada.entity.impact_funcs.base - WARNING - For
intensity = 0, mdd != 0 or paa != 0. Consider shifting the origin of the
intensity scale. In impact.calc the impact is always null at intensity = 0.
MDD: mean damage ratio; PAA: percentage of afected assets; MDR = PAA*MDD: mean
damage ratio:
```

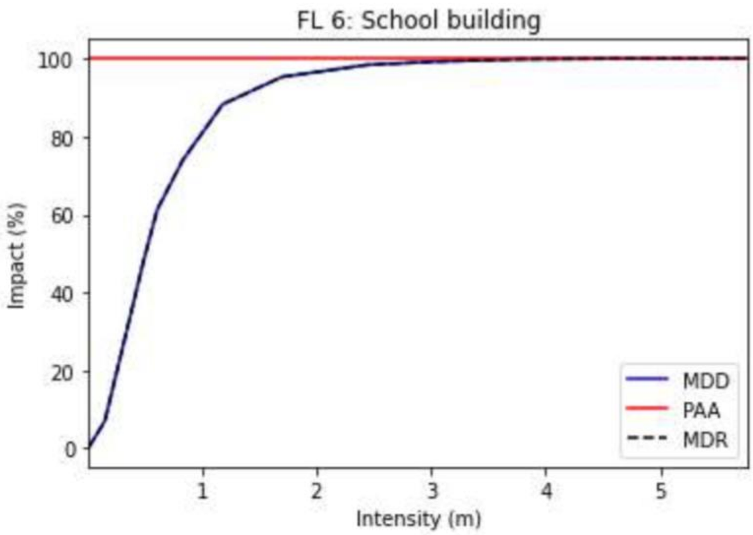
[4]:
```
<matplotlib.axes._subplots.AxesSubplot at 0x232d00d3148>
```

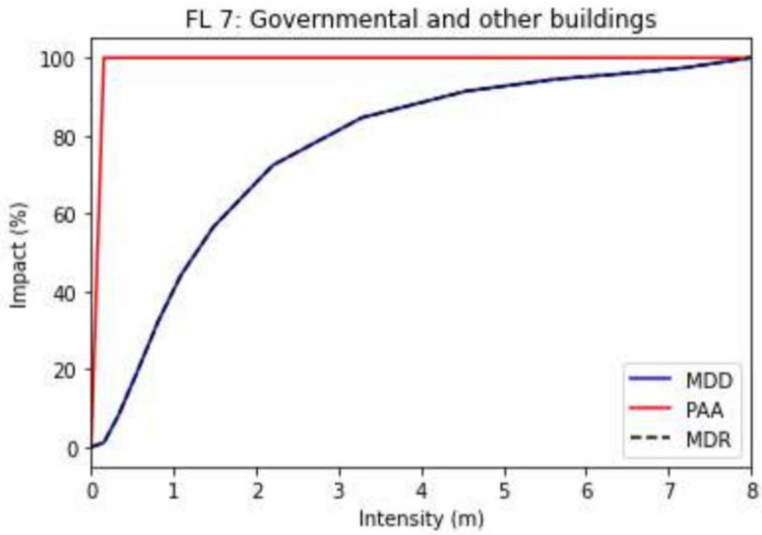

FL 1: Residential building
Impact (%)
Intensity (m)
MDD
PAA
MDR
FL 2: Commercial building
Impact (%)
Intensity (m)
MDD
PAA
MDR


FL 3: Industrial building
Impact (%)
Intensity (m)
MDD
PAA
MDR


FL 4: Hospital building
Impact (%)
Intensity (m)
MDD
PAA
MDR


FL 5: Church building
Impact (%)
Intensity (m)
MDD
PAA
MDR


FL 6: School building
Impact (%)
Intensity (m)
MDD
PAA
MDR



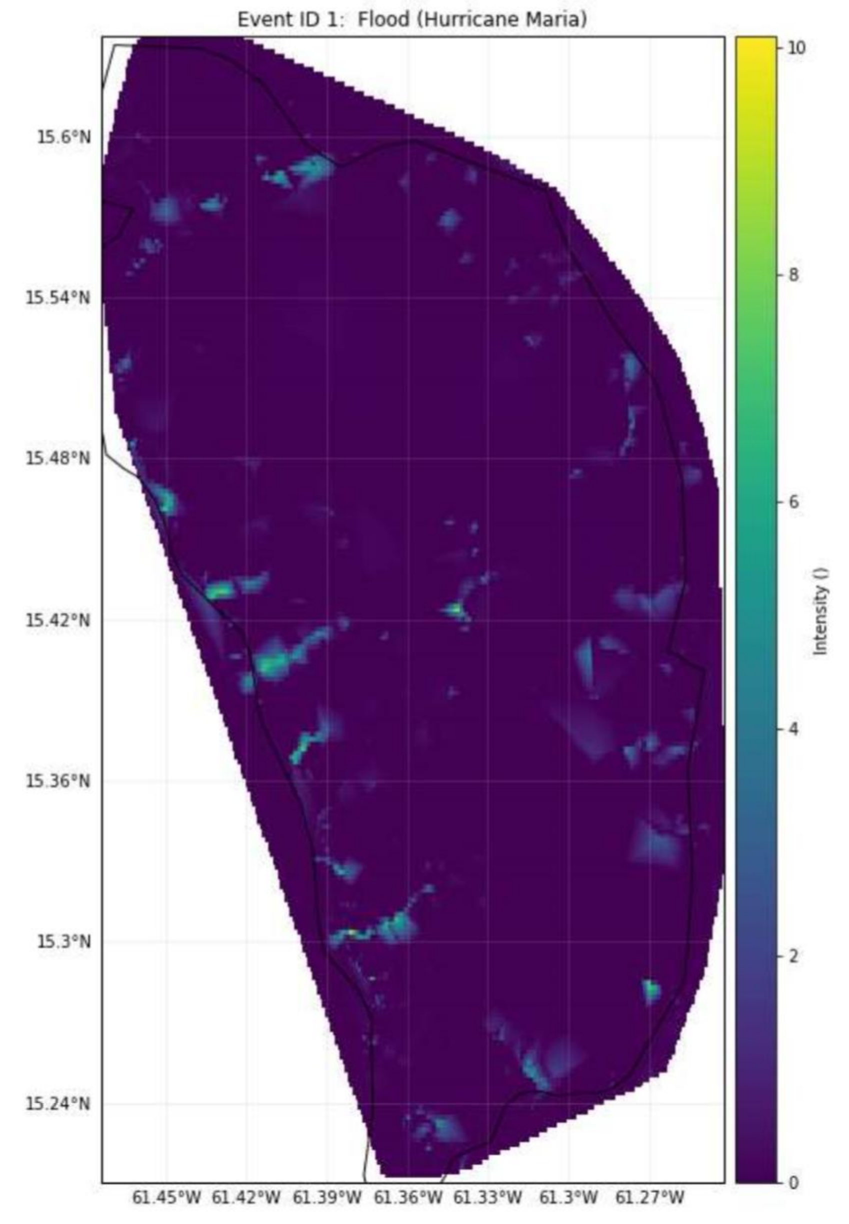
SET THE FLOOD HAZARD

[5]:
```
from climada.hazard import Hazard
import os
os.chdir("D:\\Thesis")
HAZ_FILE = 'Flood_hazard.xlsx'
haz_acel = Hazard('FL')      # set hazard typeD:
haz_acel.read_excel(HAZ_FILE) # load file
```

```
2021-06-21 23:37:34,903 - climada.hazard.base - INFO - Reading Flood_hazard.xlsx
2021-06-21 23:37:34,905 - climada.hazard.centroids.centr - INFO - Reading
Flood_hazard.xlsx
```

[6]:
```
# plot every event
for ev_name in haz_acel.event_name:
    haz_acel.plot_intensity(ev_name)
```

```
D:\Masters research\V1.5
CLIMADA\climada_python-1.5.1\climada_python-1.5.1\climada\util\plot.py:314:
UserWarning: Tight layout not applied. The left and right margins cannot be made
large enough to accommodate all axes decorations.
  fig.tight_layout()
C:\Users\fagir\anaconda3\envs\climada_env\lib\site-
packages\cartopy\mpl\feature_artist.py:225: MatplotlibDeprecationWarning: Using
a string of single character colors as a color sequence is deprecated. Use an
```


Event ID 1: Flood (Hurricane Maria)
15.6°N
15.54°N
15.48°N
15.42°N
15.36°N
15.3°N
15.24°N
61.45°W
61.42°W
61.39°W
61.36°W
61.33°W
61.3°W
61.27°W
Intensity ()
0
2
4
6
8
10

COMUPUTING FLOOD IMPACT

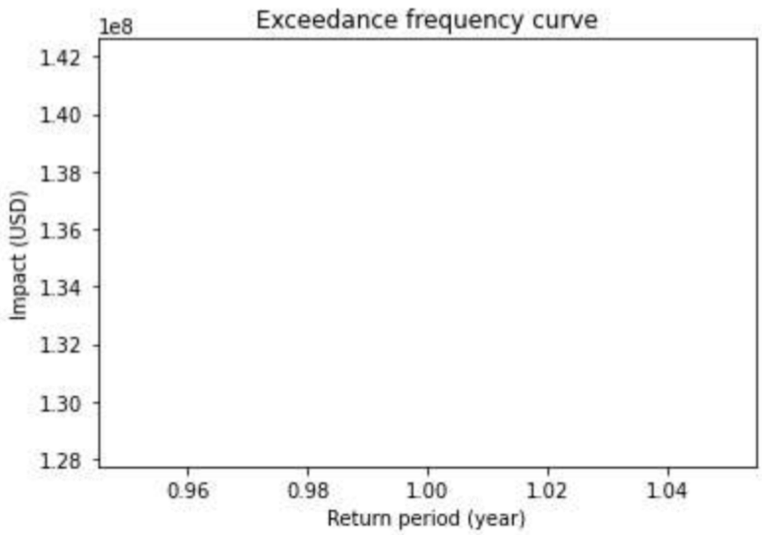
```
[7]: from climada.engine import Impact

     imp_flood = Impact()
     imp_flood.calc(exp_acel, if_acel, haz_acel) # compute hazard's impact over␣
      ↪exposure
```

```
2021-06-21 23:37:56,166 - climada.entity.exposures.base - INFO - Matching 38557
exposures with 38557 centroids.
2021-06-21 23:38:03,010 - climada.engine.impact - INFO - Calculating damage for
38557 assets (>0) and 1 events.
```

```
[8]: print('Annual expected impact of flooding: {:.3e} USD'.format(imp_flood.
      ↪aai_agg)) # get average annual impact
     imp_flood.calc_freq_curve().plot()
```

```
Annual expected impact of flooding: 1.352e+08 USD
```

```
[8]: <matplotlib.axes._subplots.AxesSubplot at 0x232d1953548>
```



It is possible to compute the annual expected impact for one point

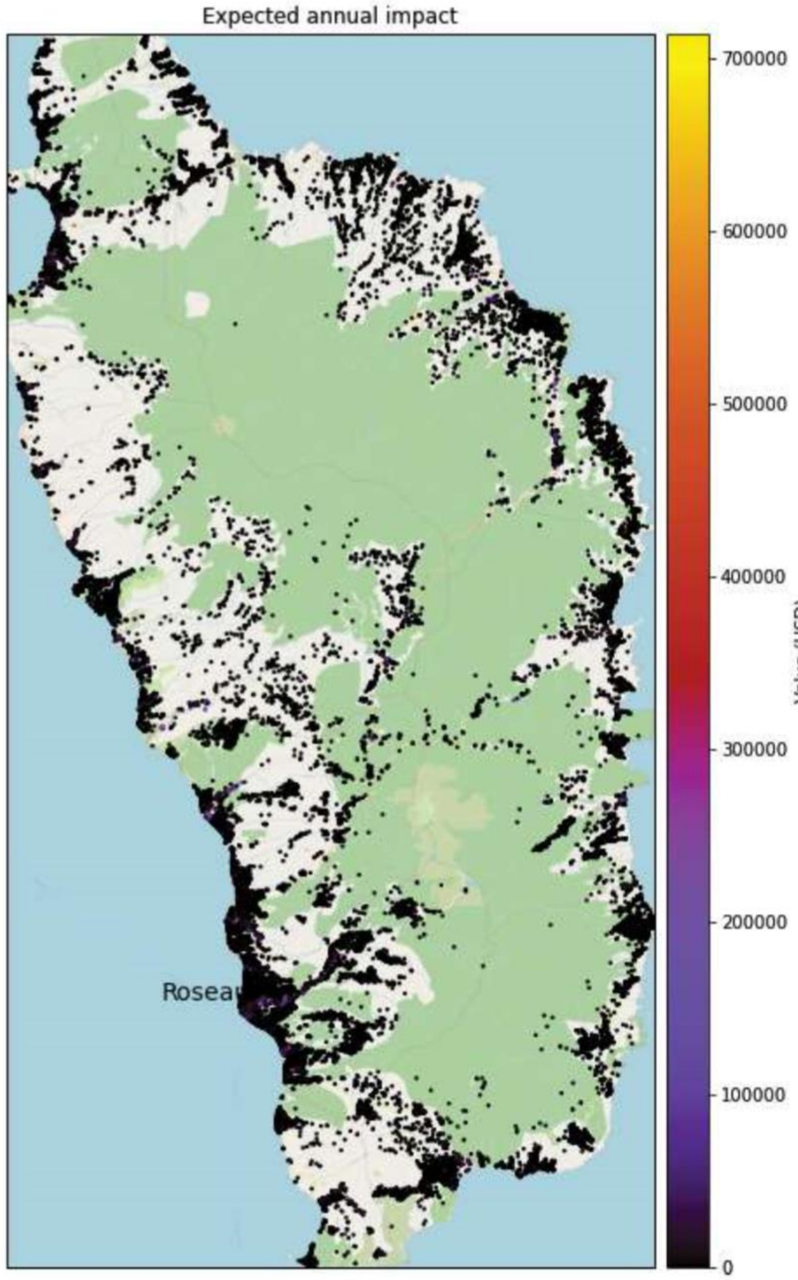
[9]:
```
point_idx = 6740
point_lat = exp_acel.latitude.values[point_idx]
point_lon = exp_acel.longitude.values[point_idx]
point_eai = imp_flood.eai_exp[point_idx]
print('Annual expected impact in {:.4f}° N {:.4f}° W is {:.0f} USD.'.
 ↪format(point_lat, point_lon, point_eai))
```

```
Annual expected impact in 15.2985° N -61.3879° W is 25021 USD.
```

[10]:
```
import contextily as ctx # map the expected annual impact per building
imp_flood.plot_basemap_eai_exposure(url=ctx.sources.OSM_C, zoom=15, s=2,␣
 ↪cmap='gnuplot')
```

```
2021-06-21 23:38:15,528 - climada.util.coordinates - INFO - Setting geometry
points.

C:\Users\fagir\anaconda3\envs\climada_env\lib\site-
packages\ipykernel_launcher.py:2: FutureWarning: The "contextily.tile_providers"
module is deprecated and will be removed in contextily v1.1. Please use
"contextily.providers" instead.


C:\Users\fagir\anaconda3\envs\climada_env\lib\site-
packages\pyproj\crs\crs.py:53: FutureWarning: '+init=<authority>:<code>' syntax
is deprecated. '<authority>:<code>' is the preferred initialization method. When
making the change, be mindful of axis order changes:
https://pyproj4.github.io/pyproj/stable/gotchas.html#axis-order-changes-in-
proj-6
  return _prepare_from_string(" ".join(pjargs))

2021-06-21 23:38:18,837 - climada.entity.exposures.base - INFO - Setting
latitude and longitude attributes.

D:\Masters research\V1.5
CLIMADA\climada_python-1.5.1\climada_python-1.5.1\climada\util\plot.py:314:
UserWarning: Tight layout not applied. The left and right margins cannot be made
large enough to accommodate all axes decorations.
  fig.tight_layout()
C:\Users\fagir\anaconda3\envs\climada_env\lib\site-
packages\pyproj\crs\crs.py:53: FutureWarning: '+init=<authority>:<code>' syntax
is deprecated. '<authority>:<code>' is the preferred initialization method. When
making the change, be mindful of axis order changes:
https://pyproj4.github.io/pyproj/stable/gotchas.html#axis-order-changes-in-
proj-6
  return _prepare_from_string(" ".join(pjargs))

2021-06-21 23:39:31,792 - climada.entity.exposures.base - INFO - Setting
latitude and longitude attributes.
```

[10]:
```
<cartopy.mpl.geoaxes.GeoAxesSubplot at 0x232d042c708>
```


Expected annual impact
Value (USD)
700000
600000
500000
400000
300000
200000
100000
0
Rosea

[12]:
```
imp_flood.write_csv('D:\\Thesis/flood_impact_CLIMADA.csv')
```

```
2021-06-21 23:39:57,341 - climada.engine.impact - INFO - Writing
D:\Thesis/flood_impact_CLIMADA.csv
```

Additional statistic value can be extracted. In this case impact per building type and administrative unit

[13]:
```
eai_res = imp_flood.eai_exp[exp_acel[exp_acel.category==1].index].sum()
print('Annual expected impact of Residential buildings: {:.3e} USD.'.
 ↪format(eai_res))
eai_per_res = eai_res/exp_acel[exp_acel.category==1].value.sum()*100
print('Annual expected impact of Residential buildings over its total value: {:.
 ↪2f}%.'.format(eai_per_res))

eai_commer = imp_flood.eai_exp[exp_acel[exp_acel.category==2].index].sum()
print('Annual expected impact of Commercial buildings: {:.3e} USD.'.
 ↪format(eai_commer))
eai_per_commer = eai_commer/exp_acel[exp_acel.category==2].value.sum()*100
print('Annual expected impact of Commercial buildings over its total value: {:.
 ↪2f}%.'.format(eai_per_commer))

eai_indu = imp_flood.eai_exp[exp_acel[exp_acel.category==3].index].sum()
print('Annual expected impact of Industrial buildings: {:.3e} USD.'.
 ↪format(eai_indu))
eai_per_indu = eai_indu/exp_acel[exp_acel.category==3].value.sum()*100
print('Annual expected impact of Industrial buildings over its total value: {:.
 ↪2f}%.'.format(eai_per_indu))

eai_hosp = imp_flood.eai_exp[exp_acel[exp_acel.category==4].index].sum()
print('Annual expected impact of Hospital buildings: {:.3e} USD.'.
 ↪format(eai_hosp))
eai_per_hosp = eai_hosp/exp_acel[exp_acel.category==4].value.sum()*100
print('Annual expected impact of Hospital buildings over its total value: {:.
 ↪2f}%.'.format(eai_per_hosp))

eai_chur = imp_flood.eai_exp[exp_acel[exp_acel.category==5].index].sum()
print('Annual expected impact of Church buildings: {:.3e} USD.'.
 ↪format(eai_chur))
eai_per_chur = eai_chur/exp_acel[exp_acel.category==5].value.sum()*100
print('Annual expected impact of Church buildings over its total value: {:.2f}%.
 ↪'.format(eai_per_chur))

eai_schoo = imp_flood.eai_exp[exp_acel[exp_acel.category==6].index].sum()
```

```
print('Annual expected impact of School buildings: {:.3e} USD.'.
 ↪format(eai_schoo))
eai_per_schoo = eai_schoo/exp_acel[exp_acel.category==6].value.sum()*100
print('Annual expected impact of School buildings over its total value: {:.2f}%.
 ↪'.format(eai_per_schoo))

eai_GI = imp_flood.eai_exp[exp_acel[exp_acel.category==7].index].sum()
print('Annual expected impact of Governmental institutes buildings: {:.3e} USD.
 ↪'.format(eai_GI))
eai_per_GI = eai_GI/exp_acel[exp_acel.category==7].value.sum()*100
print('Annual expected impact of Governmental institutes buildings over its␣
 ↪total value: {:.2f}%.'.format(eai_per_GI))

eai_OT = imp_flood.eai_exp[exp_acel[exp_acel.category==8].index].sum()
print('Annual expected impact of other buildings: {:.3e} USD.'.format(eai_OT))
eai_per_OT = eai_OT/exp_acel[exp_acel.category==8].value.sum()*100
print('Annual expected impact of other buildings over its total value: {:.2f}%.
 ↪'.format(eai_per_OT))
```

```
Annual expected impact of Residential buildings: 5.755e+07 USD.
Annual expected impact of Residential buildings over its total value: 12.06%.
Annual expected impact of Commercial buildings: 5.229e+07 USD.
Annual expected impact of Commercial buildings over its total value: 12.31%.
Annual expected impact of Industrial buildings: 9.641e+06 USD.
Annual expected impact of Industrial buildings over its total value: 34.98%.
Annual expected impact of Hospital buildings: 2.210e+05 USD.
Annual expected impact of Hospital buildings over its total value: 1.36%.
Annual expected impact of Church buildings: 1.627e+06 USD.
Annual expected impact of Church buildings over its total value: 11.79%.
Annual expected impact of School buildings: 4.741e+06 USD.
Annual expected impact of School buildings over its total value: 11.19%.
Annual expected impact of Governmental institutes buildings: 3.820e+06 USD.
Annual expected impact of Governmental institutes buildings over its total
value: 24.52%.
Annual expected impact of other buildings: 5.286e+06 USD.
Annual expected impact of other buildings over its total value: 18.73%.
```

Example how to extract the impact in administrative unit

[14]:
```
eai_region = imp_flood.eai_exp[exp_acel[exp_acel.region_id==1].index].sum()
print('Annual expected impact of St.Andrew parish: {:.3e} USD.'.
 ↪format(eai_region))
eai_per_concrete = eai_region/exp_acel[exp_acel.region_id==1].value.sum()*100
print('Annual expected impact of St.Andrew parish over its total value: {:.2f}%.
 ↪'.format(eai_per_concrete))
```

```
Annual expected impact of St.Andrew parish: 7.279e+06 USD.
Annual expected impact of St.Andrew parish over its total value: 5.12%.
```

2 Windstorm impact assessment

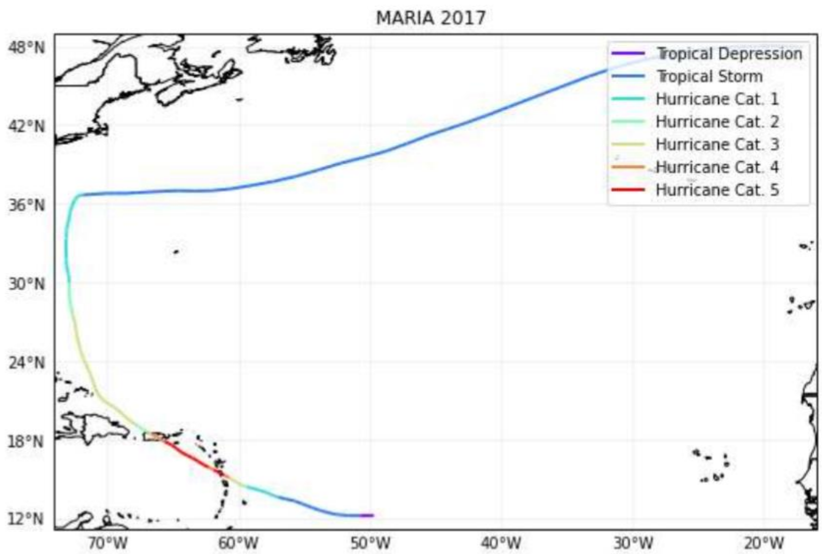
Get the 2017 hurricane Maria track from IBTrACS

[15]:
```
from climada.hazard import TCTracks
tr_maria = TCTracks()
tr_maria.read_ibtracs_netcdf(provider='usa', storm_id='2017260N12310') #2017 TC␣
↪track
ax = tr_maria.plot()
ax.set_title('MARIA 2017 ') # set title
```

```
D:\Masters research\V1.5
CLIMADA\climada_python-1.5.1\climada_python-1.5.1\climada\util\plot.py:314:
UserWarning: Tight layout not applied. The left and right margins cannot be made
large enough to accommodate all axes decorations.
  fig.tight_layout()
```

[15]:
```
Text(0.5, 1.0, 'MARIA 2017 ')
```

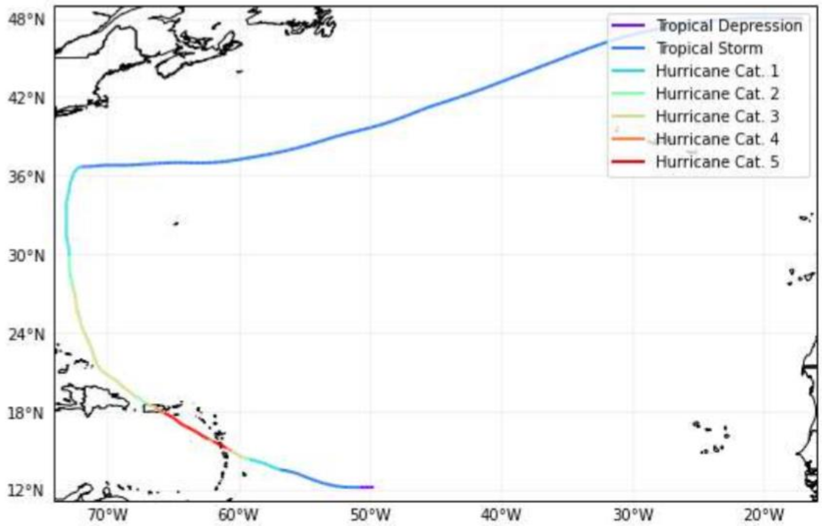
```
C:\Users\fagir\anaconda3\envs\climada_env\lib\site-
packages\cartopy\mpl\feature_artist.py:225: MatplotlibDeprecationWarning: Using
a string of single character colors as a color sequence is deprecated. Use an
explicit list instead.
  **dict(style))
```



```
[16]: tr_maria.equal_timestep(time_step_h=1) # interpolate properties to 1 hour time␣
      ↪step
      tr_maria.plot()
```

```
2021-06-21 23:40:22,988 - climada.hazard.tc_tracks - INFO - Interpolating 1
tracks to 1h time steps.
```

```
[16]: <cartopy.mpl.geoaxes.GeoAxesSubplot at 0x232d02bc848>
```




```
[17]: help(TCTracks.equal_timestep) #how CLIMADA interpolate the track
```

```
Help on function equal_timestep in module climada.hazard.tc_tracks:

equal_timestep(self, time_step_h=1, land_params=False)
    Generate interpolated track values to time steps of min_time_step.
    Parameters:
        time_step_h (float, optional): time step in hours to which to
            interpolate. Default: 1.
        land_params (bool, optional): compute on_land and dist_since_lf at
            each node. Default: False.
```

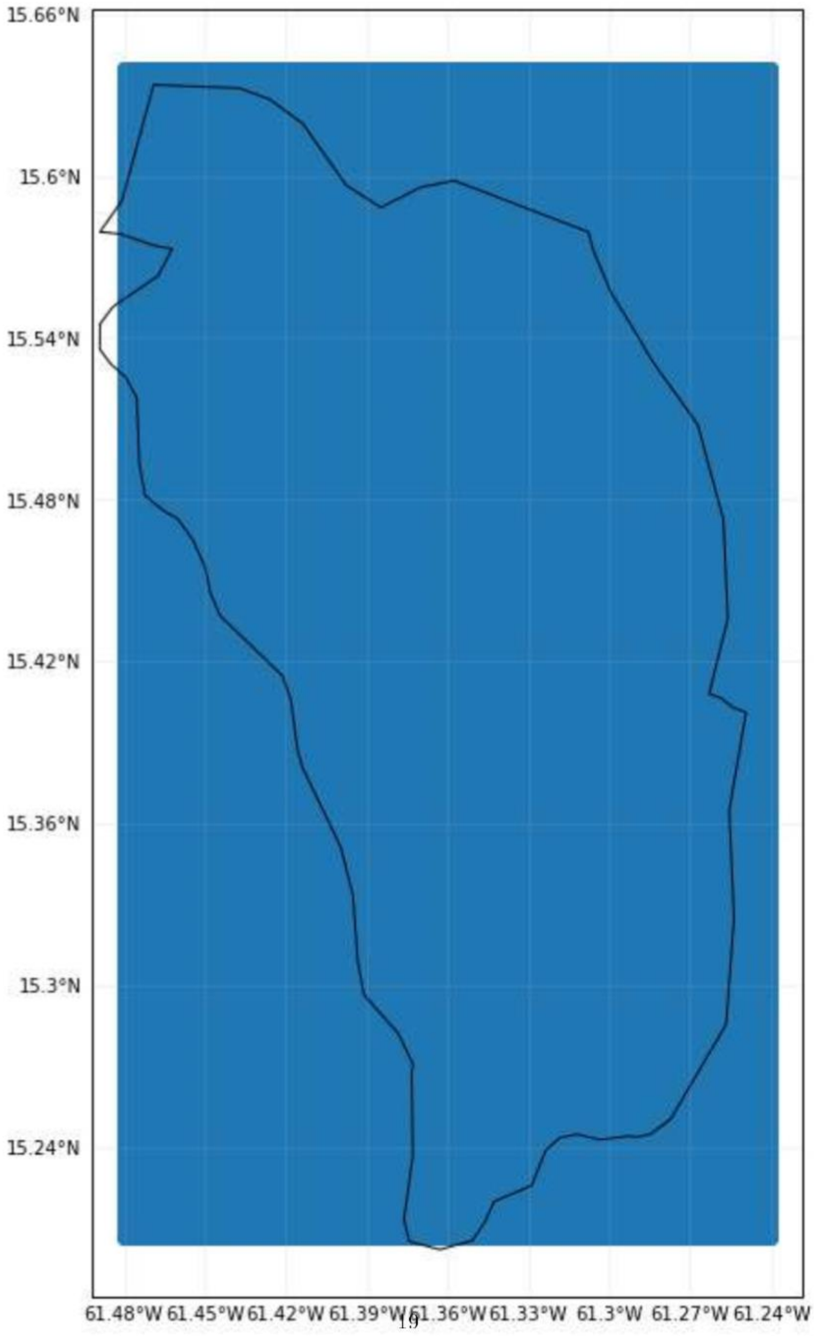
```
[18]: tr_maria.get_track('2017260N12310') # metadata information of the track
```

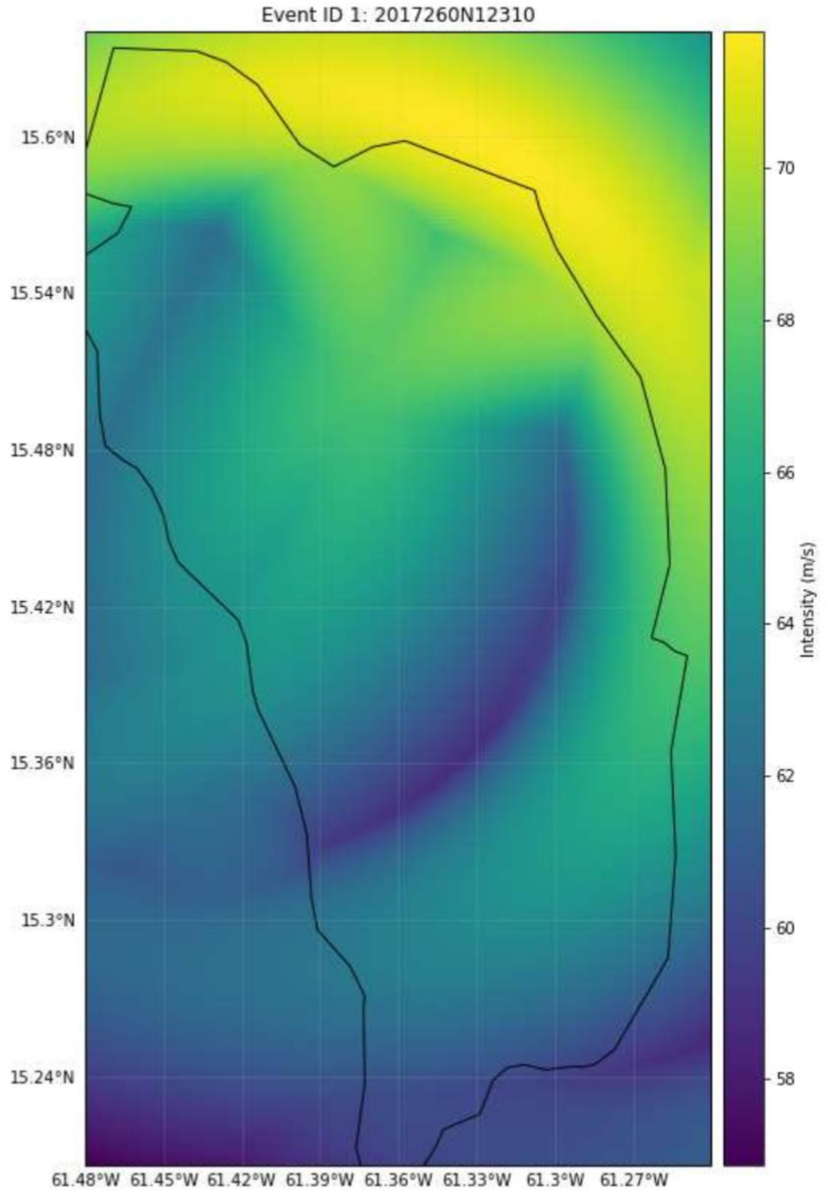
[18]:
```
<xarray.Dataset>
Dimensions:                (time: 385)
Coordinates:
  * time                   (time) datetime64[ns] 2017-09-16T12:00:00 …
2017-10-02T12:00:00
    lon                    (time) float64 -49.7 -50.06 -50.41 … -17.85 -17.0
    lat                    (time) float64 12.2 12.19 12.19 … 48.04 48.03 48.0
Data variables:
    time_step              (time) float64 1.0 1.0 1.0 1.0 … 1.0 1.0 1.0 1.0
    radius_max_wind        (time) float64 40.0 40.0 40.0 … 90.0 90.0 90.0
    radius_oci             (time) float64 150.0 150.0 150.0 … 150.0 150.0
    max_sustained_wind     (time) float64 30.0 31.67 33.33 … 33.33 31.67 30.0
    central_pressure       (time) float64 1.006e+03 1.006e+03 … 1.016e+03
    environmental_pressure (time) float64 1.012e+03 1.012e+03 … 1.016e+03
Attributes:
    max_sustained_wind_unit:  kn
    central_pressure_unit:    mb
    name:                     MARIA
    sid:                      2017260N12310
    orig_event_flag:          True
    data_provider:            usa
    basin:                    NA
    id_no:                    2017260012310.0
    category:                 5
```

Constructing centroide points and intensity map for windstorm

[19]:
```python
from climada.hazard import Centroids, TropCyclone

# construct centroids
min_lat, max_lat, min_lon, max_lon = 15.206251, 15.640139, -61.480141, -61.
↪240139
cent = Centroids()
cent.set_raster_from_pnt_bounds((min_lon, min_lat, max_lon, max_lat), res=0.001)
cent.check()
cent.plot()
#

# construct windstorm for Maria track
tc_m = TropCyclone()

tc_m.set_from_tracks(tr_maria, centroids=cent)
tc_m.check()
tc_m.plot_intensity('2017260N12310')
```

```
2021-06-21 23:40:39,225 - climada.hazard.centroids.centr - INFO - Convert
centroids to GeoSeries of Point shapes.

C:\Users\fagir\anaconda3\envs\climada_env\lib\site-
```


15.66°N
15.6°N
15.54°N
15.48°N
15.42°N
15.36°N
15.3°N
15.24°N
61.48°W 61.45°W 61.42°W 61.39°W 61.36°W 61.33°W 61.3°W 61.27°W 61.24°W
19



Event ID 1: 2017260N12310
15.6°N
15.54°N
15.48°N
15.42°N
15.36°N
15.3°N
15.24°N
61.48°W 61.45°W 61.42°W 61.39°W 61.36°W 61.33°W 61.3°W 61.27°W
70
68
66
64
62
60
58
Intensity (m/s)

SET WINDSTORM IMPACT FUNCTION

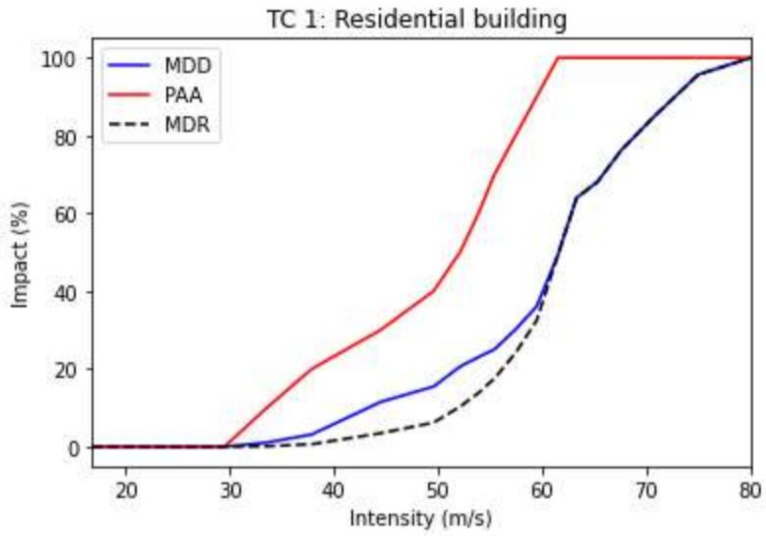
[20]:
```
print(exp_acel[['category', 'if_TC']].groupby('category').agg(['unique']))
```

```
          if_TC
         unique
category
1           [1]
2           [2]
3           [3]
4           [4]
5           [2]
6           [6]
7           [7]
8           [7]
```

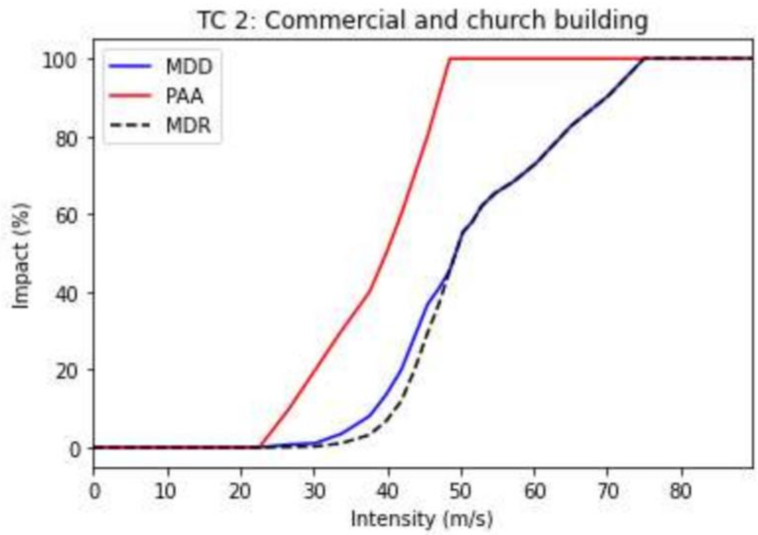
[21]:
```
from climada.entity import ImpactFuncSet

if_Wind = ImpactFuncSet()
if_Wind.read_excel(ENT_FILE)
if_Wind.check()

print('MDD: mean damage ratio; PAA: percentage of afected assets; MDR = PAA*MDD:
↪ mean damage ratio:')
if_Wind.get_func('TC', 1).plot() # plot function 1
if_Wind.get_func('TC', 2).plot() # plot function 2
if_Wind.get_func('TC', 3).plot() # plot function 3
if_Wind.get_func('TC', 4).plot() # plot function 4
if_Wind.get_func('TC', 6).plot() # plot function 6
if_Wind.get_func('TC', 7).plot() # plot function 7
```

```
2021-06-21 23:41:47,243 - climada.entity.impact_funcs.base - WARNING - For
intensity = 0, mdd != 0 or paa != 0. Consider shifting the origin of the
intensity scale. In impact.calc the impact is always null at intensity = 0.
MDD: mean damage ratio; PAA: percentage of afected assets; MDR = PAA*MDD: mean
damage ratio:
```

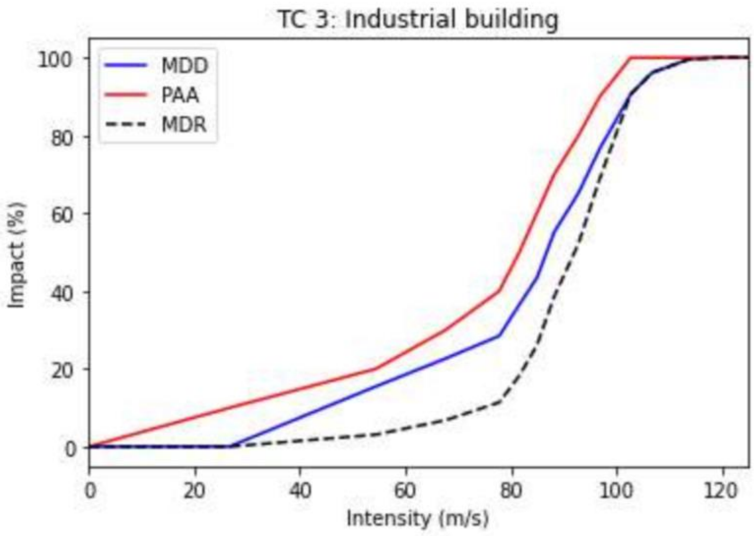
[21]:
```
<matplotlib.axes._subplots.AxesSubplot at 0x23282363548>
```

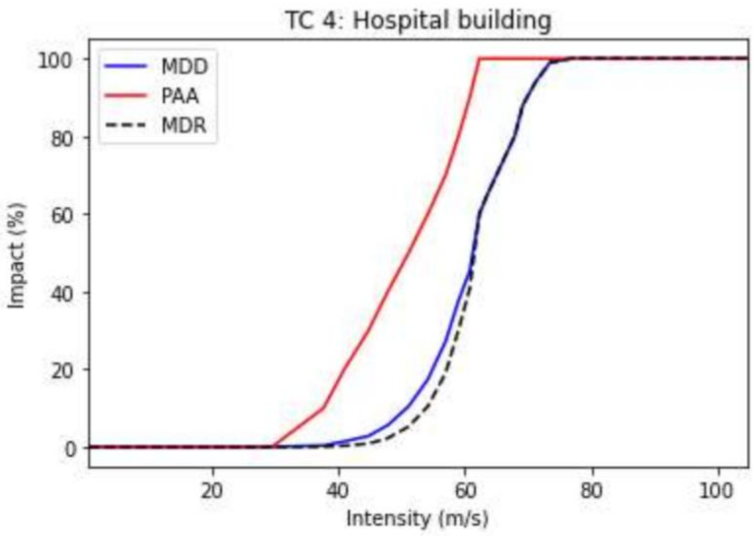


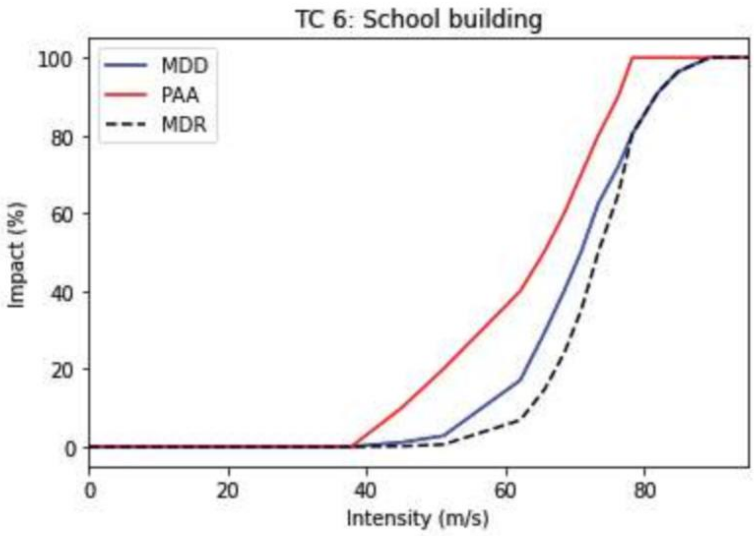
TC 1: Residential building
MDD
PAA
MDR
Impact (%)
Intensity (m/s)

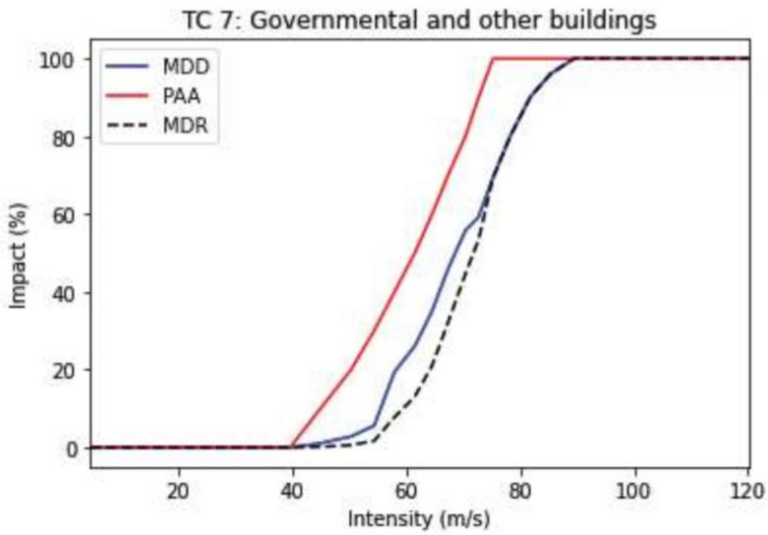


TC 2: Commercial and church building
MDD
PAA
MDR
Impact (%)
Intensity (m/s)


TC 3: Industrial building
MDD
PAA
MDR
Impact (%)
Intensity (m/s)
0
20
40
60
80
100
120


TC 4: Hospital building
MDD
PAA
MDR
Impact (%)
Intensity (m/s)
0
20
40
60
80
100


TC 6: School building
MDD
PAA
MDR
Impact (%)
Intensity (m/s)


TC 7: Governmental and other buildings
MDD
PAA
MDR
Impact (%)
Intensity (m/s)

COMPUTE WINDSTORM IMPACT, same process was done like flood impact

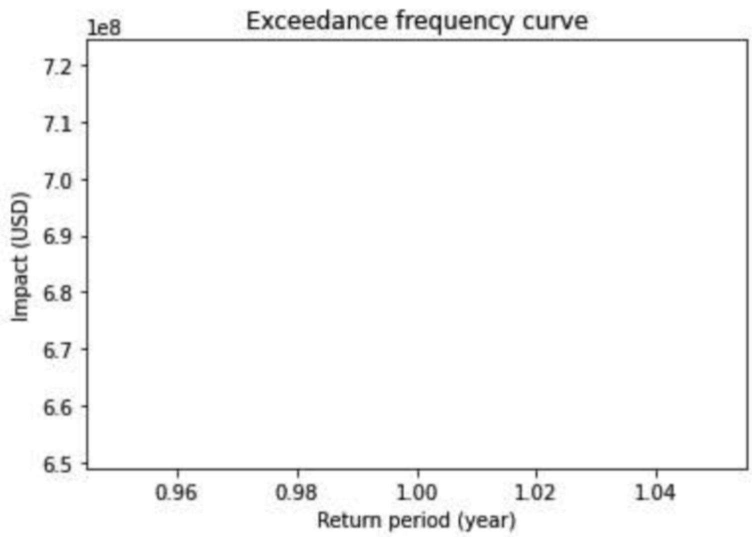
[22]:
```
from climada.engine import Impact

imp_wind = Impact()
imp_wind.calc(exp_acel, if_Wind,tc_m) # compute hazard's impact over exposure
```

```
2021-06-21 23:41:53,997 - climada.entity.exposures.base - INFO - Matching 38557
exposures with 104835 centroids.
2021-06-21 23:41:54,005 - climada.engine.impact - INFO - Calculating damage for
38557 assets (>0) and 1 events.
```

[23]:
```
print('Annual expected impact of TC: {:.3e} USD'.format(imp_wind.aai_agg)) #␣
↪get average annual impact
imp_wind.calc_freq_curve().plot()
```

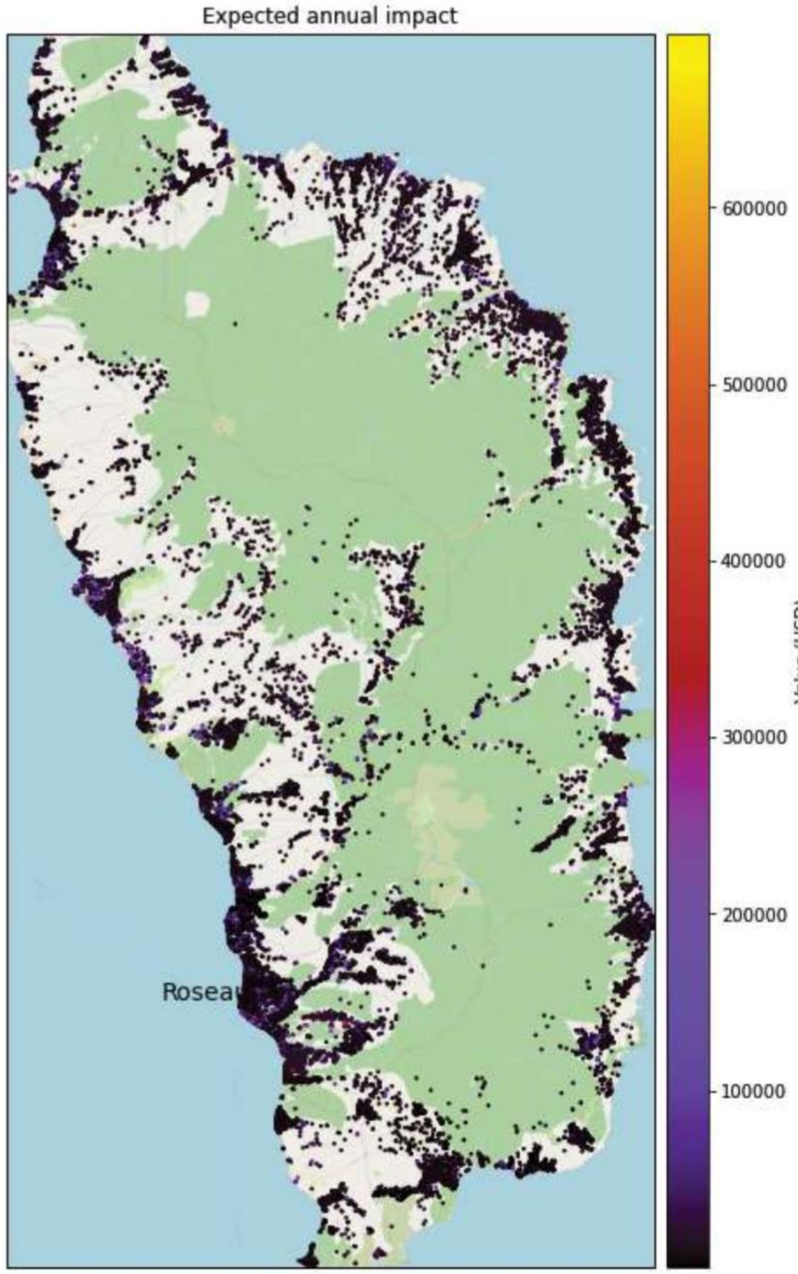
```
Annual expected impact of TC: 6.867e+08 USD
```

[23]: `<matplotlib.axes._subplots.AxesSubplot at 0x23282349a48>`



[24]:
```
import contextily as ctx # map the expected annual impact per building
imp_wind.plot_basemap_eai_exposure(url=ctx.sources.OSM_C, zoom=15, s=2,␣
↪cmap='gnuplot')
```

```
2021-06-21 23:42:00,182 - climada.util.coordinates - INFO - Setting geometry
```


Expected annual impact
Roseau
600000
500000
400000
300000
200000
100000
Value (USD)

```
[25]: imp_wind.write_csv('D:\\Thesis/wind_impact_CLIMADA.csv')
```

```
2021-06-21 23:42:19,905 - climada.engine.impact - INFO - Writing
D:\Thesis/wind_impact_CLIMADA.csv
```

```
[26]: eai_TC_res = imp_wind.eai_exp[exp_acel[exp_acel.category==1].index].sum()
print('TC Annual expected impact of Residential buildings: {:.3e} USD.'.
 ↪format(eai_TC_res))
eai_TC_per_res = eai_TC_res/exp_acel[exp_acel.category==1].value.sum()*100
print('TC Annual expected impact of Residential buildings over its total value:␣
 ↪{:.2f}%.'.format(eai_TC_per_res))

eai_TC_commer = imp_wind.eai_exp[exp_acel[exp_acel.category==2].index].sum()
print('TC Annual expected impact of Commercial buildings: {:.3e} USD.'.
 ↪format(eai_TC_commer))
eai_TC_per_commer = eai_TC_commer/exp_acel[exp_acel.category==2].value.sum()*100
print('TC Annual expected impact of Commercial buildings over its total value:␣
 ↪{:.2f}%.'.format(eai_TC_per_commer))

eai_TC_indu = imp_wind.eai_exp[exp_acel[exp_acel.category==3].index].sum()
print('TC Annual expected impact of Industrial buildings: {:.3e} USD.'.
 ↪format(eai_TC_indu))
eai_TC_per_indu = eai_TC_indu/exp_acel[exp_acel.category==3].value.sum()*100
print('TC Annual expected impact of Industrial buildings over its total value:␣
 ↪{:.2f}%.'.format(eai_TC_per_indu))

eai_TC_hosp = imp_wind.eai_exp[exp_acel[exp_acel.category==4].index].sum()
print('TC Annual expected impact of Hospital buildings: {:.3e} USD.'.
 ↪format(eai_TC_hosp))
eai_TC_per_hosp = eai_TC_hosp/exp_acel[exp_acel.category==4].value.sum()*100
print('TC Annual expected impact of Hospital buildings over its total value: {:.
 ↪2f}%.'.format(eai_TC_per_hosp))

eai_TC_chur = imp_wind.eai_exp[exp_acel[exp_acel.category==5].index].sum()
print('TC Annual expected impact of Church buildings: {:.3e} USD.'.
 ↪format(eai_TC_chur))
eai_TC_per_chur = eai_TC_chur/exp_acel[exp_acel.category==5].value.sum()*100
print('TC Annual expected impact of Church buildings over its total value: {:.
 ↪2f}%.'.format(eai_TC_per_chur))

eai_TC_schoo = imp_wind.eai_exp[exp_acel[exp_acel.category==6].index].sum()
print('TC Annual expected impact of School buildings: {:.3e} USD.'.
 ↪format(eai_TC_schoo))
eai_TC_per_schoo = eai_TC_schoo/exp_acel[exp_acel.category==6].value.sum()*100
```

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```
print('TC Annual expected impact of School buildings over its total value: {:.
 ↪2f}%.'.format(eai_TC_per_schoo))

eai_TC_GI = imp_wind.eai_exp[exp_acel[exp_acel.category==7].index].sum()
print('TC Annual expected impact of Governmental institutes buildings: {:.3e}␣
 ↪USD.'.format(eai_TC_GI))
eai_TC_per_GI = eai_TC_GI/exp_acel[exp_acel.category==7].value.sum()*100
print('TC Annual expected impact of Governmental institutes buildings over its␣
 ↪total value: {:.2f}%.'.format(eai_TC_per_GI))

eai_TC_OT = imp_wind.eai_exp[exp_acel[exp_acel.category==8].index].sum()
print('TC Annual expected impact of other buildings: {:.3e} USD.'.
 ↪format(eai_TC_OT))
eai_TC_per_OT = eai_TC_OT/exp_acel[exp_acel.category==8].value.sum()*100
print('TC Annual expected impact of other buildings over its total value: {:.
 ↪2f}%.'.format(eai_TC_per_OT))
```

```
TC Annual expected impact of Residential buildings: 3.039e+08 USD.
TC Annual expected impact of Residential buildings over its total value: 63.70%.
TC Annual expected impact of Commercial buildings: 3.432e+08 USD.
TC Annual expected impact of Commercial buildings over its total value: 80.78%.
TC Annual expected impact of Industrial buildings: 1.571e+06 USD.
TC Annual expected impact of Industrial buildings over its total value: 5.70%.
TC Annual expected impact of Hospital buildings: 1.112e+07 USD.
TC Annual expected impact of Hospital buildings over its total value: 68.61%.
TC Annual expected impact of Church buildings: 1.117e+07 USD.
TC Annual expected impact of Church buildings over its total value: 80.91%.
TC Annual expected impact of School buildings: 5.512e+06 USD.
TC Annual expected impact of School buildings over its total value: 13.02%.
TC Annual expected impact of Governmental institutes buildings: 3.308e+06 USD.
TC Annual expected impact of Governmental institutes buildings over its total
value: 21.23%.
TC Annual expected impact of other buildings: 6.878e+06 USD.
TC Annual expected impact of other buildings over its total value: 24.37%.
```

Combining the two impact together

[27]:
```
Multi_hazard_loss=imp_wind.aai_agg + imp_flood.aai_agg
print(Multi_hazard_loss)
```

```
821881447.5892339
```

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