EVALUATING HURRICANE RECOVERY IN DOMINICA

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ABSTRACT

Disasters cause significant economic and human life losses and may affect both the natural and built-up environment for a longer period. The modifications of the local environmental conditions may also lead to the occurrence of further hazardous processes, characterising the situation as a multi-hazard scenario, which was the case in Dominica where Hurricane Maria hit the island on September 2017, while the country was still recovering from Tropical Storm Erika, which had happened two years earlier. With the rapid development of the internet and the growing engagement of the general population in collecting and sharing geographical information, evaluating post-disaster recovery can make use of the application of Volunteered Geographic Information (VGI) and images/videos from Unmanned Aerial Vehicles (UAV).

The main goal of this research was to analyse multi-hazard risk conditions using UAV- and VGI- derived data in the post-disaster recovery of Dominica after Hurricane Maria. The steps toward achieving this goal are made by four primary contributions. First, the effects of the main manifestations of Hurricane Maria were assessed (high-speed winds, intense rainfall and extreme waves), identifying the hazard relationships in a framework that considered two-time steps: during and after the event. Secondly, a damage database collected by volunteers after Hurricane Maria was examined, depicting how VGI derived data, integrated with UAV images, can contribute to assessing the effects of the hurricane. Thirdly, pre-Maria hazards maps were validated with the actual damage data from Hurricane Maria. Finally, different recovery scenarios were analysed, and the possible influence on risk components was evaluated.

Results indicate the utility of the hazard relationship framework in assessing how damages to the vegetation and excess sedimentation on river channels can influence the occurrence of further hazardous processes, demonstrating that exposure of the EaR increased due to changes in the built-up environment. The analysis and use of a building database obtained during fieldwork linked with VGI derived data suggest the need for an update of the wind and flood hazard maps in order to better reflect the hazard as a basis for spatial planning. Most importantly, the results show the usefulness and limitations of VGI-derived data along with UAV images to support planners for monitoring and making strategic decisions where efforts should be invested to decrease exposure and vulnerability of elements-at-risk (EaR) with information of the effects on the built-up and natural environment.

Keywords: multi-hazard, hazard interactions, post-disaster recovery, VGI.

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LIST OF ABBREVIATION

BBB – Build Back Better

BDA – Building Damage Assessment

DRM – Disaster Risk Management

DRR – Disaster Risk Reduction

EaR – Elements-at-risk

EWS – Early-Warning System

GIS – Geographic Information System

NDVI – Normalized Difference Vegetation Index

OAM – OpenAerialMap

OSM – OpenStreetMap

SMCE – Spatial Multi-Criteria Evaluation

TS – Tropical Storm

UAV – Unmanned Aerial Vehicles

UNDP – United Nations Development Program

USAID - United States Agency for International Development

VGI – Volunteered Geographic Information

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1. INTRODUCTION

1.1. Background

Natural hazards are potentially damaging phenomena that may cause property damage, loss of life, impacts on the natural and built-up environment and disrupt services, affecting the society and economy (UNISDR, 2009). These events can have major effects on the well-being of the population and make significant changes in the landscape (Lanzano et al., 2016). They can be grouped into weather, climate or atmospheric processes, biological hazards, or geophysical hazards (Islam & Ryan, 2016).

When there is an overlap of a hazard with a vulnerable society, a disaster may happen, an event that can affect a significant number of lives, the local economy and social aspects. It disrupts a community's structure and functionality, causes physical damage, environmental impacts, and since the community might not be able to cope with its resources, it can require outside help to start the recovery process (UNISDR, 2009). Due to the impacts of such an event, the hazards can change, and the affected elements-at-risk (EaR) may present different vulnerability than before, which might make them more susceptible to hazards.

Regarding vulnerability, UNISDR (2009) defines it as the features of a community or system that make it prone to losses. A significant characteristic of vulnerability is its dynamicity. It is a property of an EaR, and it is modified according to exposure and the event. In addition, there are multiple aspects of it, like physical, economic, social and environmental. The physical vulnerability can be defined as the probability of damage to an EaR (physical structure or object) that is exposed to a given intensity of a hazard (van Westen & Greiving, 2017). When analysing from the physical vulnerability perspective, disasters can affect infrastructures and disrupt essential societal functions, like energy and water supply (Eidsvig et al., 2017). The damage to physical structures also causes distress in social and economic aspects. For instance, affecting the environment and the landscape can disturb food sources and jeopardise regular societal activities (Frigerio & De Amicis, 2016).

Disaster management can be seen as a cycle, with actions that relate to each other, happening before and after the event: mitigation, preparation, response and recovery. These four concepts overlap in their characteristics, with features that are used before or after an event (Coppola, 2015). As for recovery, it is marked as a complex process with different definitions in the literature. There are controversies about the starting and ending point and what aspects are involved in it. Recent literature sees it as a dynamic process that incorporates mitigation strategies to reduce further risks (Ruiter, 2011). Yet, recovery is considered to be the least understood phase of the disaster management cycle due to the involvement of numerous and different stakeholders and the overlap of several roles during the phases (Chang, 2010). Overall, it is seen as a process to restore the affected community to a state of pre-disaster, applying disaster risk measures and reinstating the distressed population back to normality (Coppola, 2015).

The process of disaster risk management (DRM) is nowadays supported by new technologies and systems used to provide further insights. Volunteered Geographic Information (VGI) has had a significant role in assisting in disaster situations, especially in less developed countries. It is defined as the engagement of groups of people in the collection of geographic information, shared in a collective environment. Most of the times these groups have no qualifications and are unexperienced, being volunteers in a campaign or a system that collects geographical data (Goodchild, 2007). Due to the constant growth and connectivity of mobile gadgets, VGI can offer rapid information in assisting disaster management (See et al., 2016) by creating campaigns to map damage in a community or providing data on road network, for instance. Successful applications of VGI have been helping researchers and planners to draw better strategies for urban environments. The OpenStreetMap (OSM) project, for example, is responsible for offering geospatial data that has been used to assess the exposure of EaR. However, VGI systems may suffer from untrained volunteers, which may put data quality in perspective (Arsanjani et al., 2015) with problems such as logical consistency, completeness, positional and attribute accuracy that must be appropriately addressed.

Unmanned aerial vehicles (UAV) has been widely used for DRM purposes. It consists of remotely piloted aircrafts coupled with sensors that can provide quality spatial data and images (Gevaert et al., 2018) at high temporal resolution and spatial scale. The technology has been extensively popularised, and its lower costs nowadays have made it accessible to the population to acquire and share the data in online environments (Johnson et al., 2017). It can be used to investigate multi-hazard environments, perform damage mapping and land cover characterisation, amongst others (Ventura et al., 2017). For instance, Rollason et al. (2018) made use of UAV footage provided by a private citizen to produce an extensive database on the occurrence of a flooding hazard event in 2015 in Corbridge, England, using the results for mitigation measures to be applied.

Hazards are often considered independent and isolated phenomena, a problematic approach since they interact with the environment, and might modify local conditions leading to other hazards being more likely to occur. A disaster can change aspects of the environment by increasing the exposure of soils, reducing vegetation and altering hydrological processes. These actions can create consequential hazards, e.g. unvegetated soil may have decreased stability and be more susceptible to the occurrence of landslides. Such hazards can be activated by volcanic eruptions, earthquakes or hydro-meteorological threats, like extreme rainfall events (Chen et al., 2016) and due to the circumstances, they may be triggered by less rainfall. Hence, understanding a multi-hazard scenario is crucial to model new hazards and comprehend the interactions in a post-disaster situation.

Multi-hazard approaches have been widely used to assess hazards, where the system should be viewed holistically, comprehending its interactions and consequential events along with vulnerability and exposure of the EaR (Gill & Malamud, 2016). These interactions are often related not only to the environment but also to social aspects, requiring the consideration of natural and anthropogenic processes and the relations they may have (Sullivan-Wiley & Short Gianotti, 2017). It is also worth noticing that multi-hazard approaches are already encouraged to be used, for instance by The Sendai Framework of Disaster Risk Reduction (2015-2030) (UNISDR, 2015). Moreover, the United Nations Office for Disaster Reduction (UNISDR) & (WMO) (2012) affirmed that cases of good practice with the use of this approach are a reality leading to mitigation of hydrological hazards in Bangladesh, Japan and China.

Despite the attention that multi-hazard approaches have been receiving, there are still many challenges involved. Evaluating the changing situation when hazards occur sequentially is one of them. When the conditions change (e.g. vegetation, land cover, terrain) the susceptibility to hazards also changes, as well as the vulnerability for the affected EaR. Thus, if a structure is affected by a type of hazard, it may be more vulnerable to be affected by a second hazard, unless it is repaired or rebuilt. That makes it difficult to assess the situation using the same data as before, e.g. using vulnerability curves as for undamaged buildings. One more challenge is the difficulty of comparability between different processes. Hazards differ according to their nature, intensity, frequency and interaction with EaR. Hence, they present different units of reference for measurement of the impacts, such as depth of water for flooding events or mass movement units for landslides. There are some proposed methods to overcome such challenges, one of them being the classification of hazards using a qualitative approach that defines thresholds for intensity and frequency allowing to outline hazard classes. Nevertheless, different sources may use different methods of classification, and it can become problematic when comparing such data (Kappes et al., 2012).

One more significant challenge is that they are mostly addressed as multi-layer single events, i.e. when several different hazards are investigated independently. While they should be treated as a whole, it is essential to analyse their relationships, all the connections and consequent threats that a primary hazard may have (Gill et al., 2016). As an example, a landslide can trigger a flooding event, that can be catalysed by urbanisation processes. These processes can modify the land surface and affect soil properties, which can trigger other hazards. The non-identification of these interactions may lead to exposure of elements to unnecessary risks.

1.2. Research problem

The recovery phase after a disaster is a process that demands time, effort and resources from stakeholders, ideally involving the application of concepts and ideas that reduce further risks, such as build back better (BBB) strategies, which integrates disaster risk reduction (DRR) procedures to restore and increase the resilience of communities and physical infrastructures. Many areas in the world have a high susceptibility to hazards, as is the case of islands in the Caribbean, which in 2017 were hit by Hurricanes Harvey, Irma and Maria. These areas are frequently affected by hazardous events that may result in disasters, and the success, quality and speed of recovery depend on factors such as the capacity of the country, the level of resources, outside support, the impact of the past event, the time between two successive events, the temporal probability of the next event, amongst others. Communities need time to recover, as well as the environment to have the same level of protection as before, and if a next event happens soon, it may intensify the situation.

A post-disaster situation can also be aggravated if analysed from a limited perspective, such as not considering the relationships that a hazard may have, a common approach when assessing multiple hazards. Besides, the degree of changes that a hazardous event may cause involves social, economic, physical and environmental aspects to be investigated. For instance, disturbance in the built-up environment can impact greatly on social and economic features by influencing their relations (Carpenter, 2012). Comprehension of the interactions between the disaster and the changes that occurred in the area is fundamental for spatial planning actions.

Characterising the post-disaster situation is already a necessity to avoid losses as well as identifying susceptibilities. A post-disaster situation demands investigation and analysis of the changes in the environment, rapid data collection and an analysis of the risks, actions that can help to improve and create a more resilient community. These actions also depend on the level of capacity and resources of the location. In addition, issues such as changing vulnerability of structures, different characteristics of the hazards, unknown cause-effect relations between hazards and changes induced by primary hazards (which can create favourable conditions for a sequential hazard) play significant roles as challenges to overcome. It is also essential to consider the coping capacity of the society and individuals, how they dealt with past events, and how the government is working in the present time. Therefore, performing a multi-hazard approach in a post-disaster situation is vital not only to comprehend and identify the relationship between hazards or the effects of changed environment but to obtain information on where efforts and resources should be invested, to help communities deal with forthcoming events. Moreover, limited country capacity, resources and rapidly changing environments require specific data acquisition methods.

The purpose of this research is to analyse the role of UAV images and VGI-derived data in the recovery of a post-disaster situation, by comprehension of multi-hazards on the island of Dominica. It is expected that the research will generate information to implement future recovery actions better, improve the quality of reconstruction planning, offer information for DRM procedures to be more efficient and provide an estimation of different recovery scenarios on the island.

1.3. Objectives and Research Questions

1.3.1. Main Objective

To analyse changing multi-hazard risk conditions using data from Unmanned Aerial Vehicles (UAV) and Volunteered Geographic Information (VGI) in a post-hurricane recovery situation.

1.3.2. Specific Objectives and Research Questions

The main objective is supported by the following specific objectives and research questions:

1. To develop a conceptual framework of the relationships between hazards in the study area in space and time.
    i. What are the interactions between hazards during and after a major hurricane in a Caribbean island setting?
    ii. How do changes in the built-up areas, sediments and land cover influence the relationships between hazards?
2. To identify the potential usability of data from Unmanned Aerial Vehicles (UAV) and Volunteered Geographic Information (VGI) in a multi-hazard post-disaster recovery context.
    i. How to integrate VGI derived data to assess, monitor and support the process of post-disaster recovery?
    ii. What are the advantages and disadvantages of using VGI derived data in a post-disaster context?
    iii. How can UAV images be integrated with VGI derived data to assess recovery in post-disaster scenarios?
3. To analyse how hazards, elements-at-risk (EaR) and physical vulnerability have changed as a consequence of a disaster event.
    i. How do EaR and their exposure change in a post-disaster multi-hazard environment, and what are the influencing factors?
    ii. How reliable are pre-disaster hazard maps, and how do they need to be updated after a major disaster?
    iii. How does physical vulnerability change after a major hurricane?
4. To evaluate different recovery scenarios in a small Caribbean island context.
    i. What are the possible recovery scenarios for the study area?
    ii. How do the risk components change for these scenarios, and which scenario is best from a risk reduction point-of-view?

1.4. Thesis Structure

This research is organised into six chapters. In **chapter 01** the research background, study area, context and motivation are presented, followed by the research objectives and questions. **Chapter 02** discusses hazard interactions and a conceptual framework of hazards relationships in the study area is portrayed and analysed. In **chapter 03** the analysis of the Building Damage Assessment (BDA) database is debated illustrating the structure, problems encountered, limitations and data analysis. **Chapter 04** examines pre-event hazard maps displaying and evaluating the conditions of the study area before and after the event. Further data are combined to evaluate the reliability of these maps. **Chapter 05** studies how changed environment conditions influence on possible recovery scenarios, also investigating how risk components change during recovery scenarios. Lastly, **Chapter 06** depicts a comprehensive discussion and conclusion of the research, providing a critical examination of the results, its findings, limitations, and presenting recommendations.

1.5. Study Area

This research focuses on the area of Dominica, an island located in the Lesser Antilles archipelago in the Caribbean Sea, between the islands of Guadeloupe and Martinique, with approximately 750 km^2 of area and a population of about 73.162 inhabitants in 2015 (United Nations, 2017).

Dominica has steep and rugged terrain, which represents a challenge to the development of human settlements and agriculture. While the topography of the south part of the island is dominated by a chain of mountains, the northern half of the island is determined by the cone of Morne Diablotin, the highest point with 1.447 meters of elevation, and Morne Au Diable with 861 meters high. As the peaks of its mountains are close to the sea, there is an orographic influence on climate and the development of Dominica. Due to this influence, some parts of the island can receive up to 2.500 mm of rainfall per year (Benson et al., 2001).

The island has a dry season that goes from February to June and a wet season from July to December with variation in rainfall because of the orographic effects. During the wet season, there is heavy rainfall of short duration periods. Regarding its physical characteristics, the geology of the island is complex, the soils are erodible, and the island has a dense forest cover. Main river valleys are located in the centre, where flat areas are mostly restricted. Along the coast are flatter and moderately steep slopes. It is also where agricultural activities are established and where the majority of the population lives (Shriar, 1991).

The high amount of rainfall has the potential to cause damages due to flooding. The problem is dependent not only by the amount of rainfall but also of slope steepness, size and shape of the basin, the degree of urbanisation process and characteristics of soils. Furthermore, such factors can also have influences on landslides hazards. Debris flows are the most common type of landslide in Dominica, with the potential to cause significant economic losses, disturb agricultural activities and cause human life losses (Shriar, 1991).

Dominica is hazard-prone, suffering from earthquakes, volcanic activities, droughts, landslides and is frequently hit by hurricanes and storms, which can also trigger other hazards. The last major event was Hurricane Maria, which occurred in September 2017, causing the death of 64 people and more than one billion dollars in total damages (Hu & Smith, 2018). Figure 1.1 displays an overview of the islands of the Caribbean with the path of Hurricane Maria and the location of Dominica along with the built-up area and relevant cities further discussed.

Figure 1.2 portrays the southern part of Dominica depicting the inventory of landslides, debris flows and floods occurred due to Hurricane Maria. Such inventory was created using Pléiades satellite images with 0.5 meters resolution, obtained between September and October 2017. Further Digital Globe Images were also utilized, and the images were interpreted in order to map landslides as polygons, as well as classifying them in types (Van Westen, Zhang and Van den Bout, 2018).

Additionally, an overview of the major disaster events occurred on the island for the past 55 years is shown in Table 1.1, based on the The Emergency Events Database - EM-DAT (2018).

Figure 1.1: Location map depicting Dominica and relevant cities. The bottom left figure illustrates the islands of the Caribbean along with the path of Hurricane Maria and the trajectory dates. The indication of figures on the map depicts the location of later discussed areas on this research.

Source: CHARIM (2018); National Hurricane Center – NHC (2019).

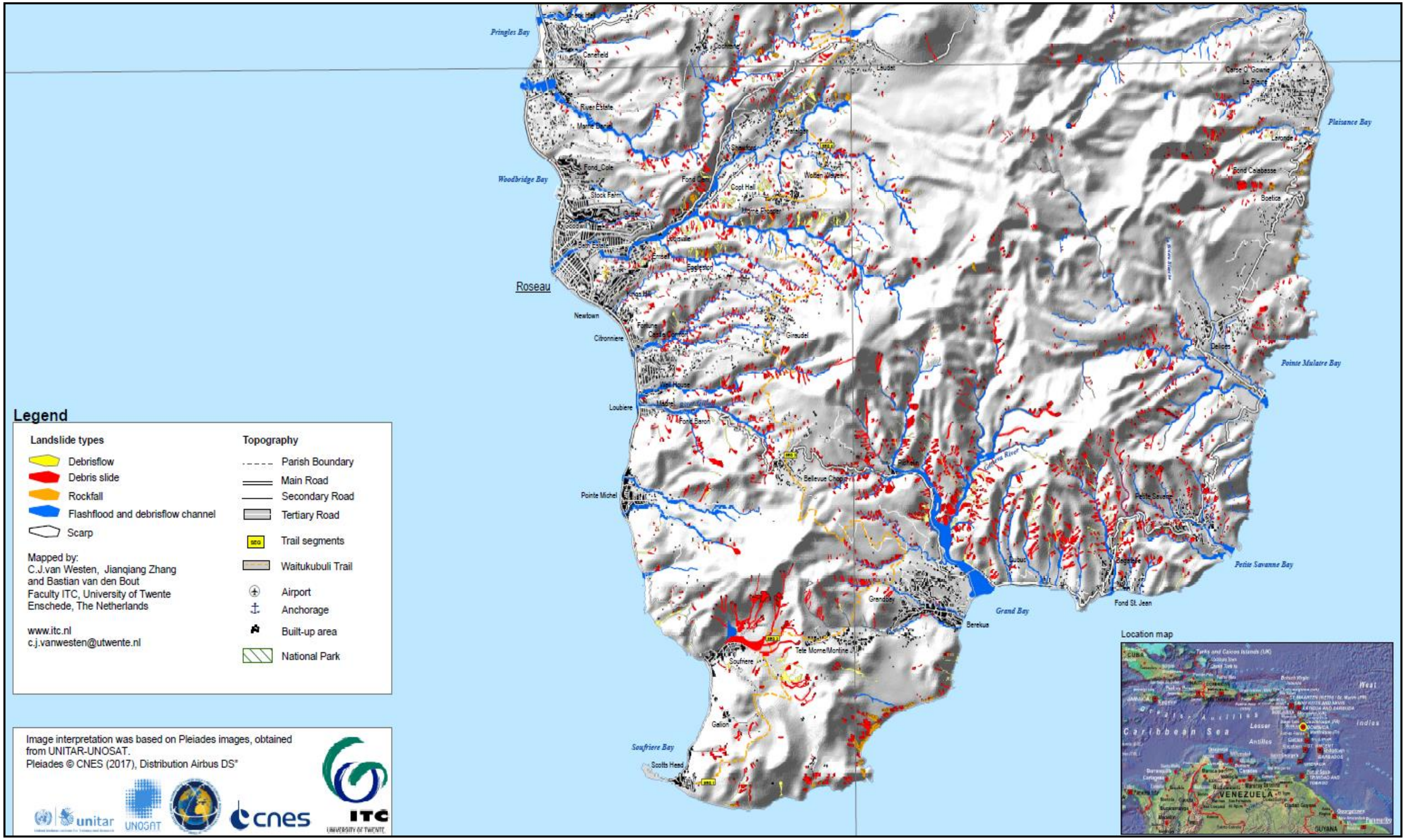


Figure 1.2: Map of hazardous processes triggered by hurricane Maria in Dominica. Only southern part of the island is shown.

Source: (Van Westen, Zhang and Van den Bout, 2018).

Table 1.1: Information about the major disaster events in Dominica.

Year	Disaster	Total deaths	Total People affected	Total damage and losses (US$)
1930	Storm	2000	Unknown	Unknown
1963	Hurricane Edith	Unknown	Unknown	2.6 million
1979	Hurricane David	40	70.000	44.650 million
1984	Hurricane Klaus	2	10.000	2 million
1989	Hurricane Hugo	0	710	20 million
1995	Hurricane Marylin	2	5.001	195 million
1995	Hurricane Luis			
1999	Hurricane Lenny	0	715	Unknown
2004	Earthquake	0	100	Unknown
2007	Hurricane Dean	2	7.530	20 million
2011	Hurricane Ophelia	0	240	Unknown
2015	Tropical Storm Erika	30	28.594	482.8 million
2017	Hurricane Maria	64	71.393	1.4 billion

Source: The Emergency Events Database - EM_DAT (2018).

Hurricane Maria and David are depicted amongst the most significant events on the island. Although, data presented for the events illustrate a lack of consistency in, for instance, total people affected. No remarks on the criteria used to define what is affected were discussed. Therefore, even though the database displays a significant quantity of information, such dataset must be taken into account with regards. Data might be presented incomplete or outdated and depict results that do not represent reality. As Guha-Sapir & Below (2002) discussed, demand for data has increased in light of disaster events, and quality is often sacrificed in exchange of speed in acquiring information. Arbitrary criteria of the collection, difficulty in obtaining quality historical data records and dependability in damage reports are amongst the aspects that may increase problems with datasets. It is recommended that obtention of data should follow a clear methodology to improve the reliability of the database and a further dataset to be used complementing the information provided.

1.6. Data

This section provides information on the content and data utilised during this research and its obtention.

1.6.1. Building Damage Assessment (BDA) Database

In the months succeeding Hurricane Maria, a comprehensive building damage assessment (BDA) was performed for the whole island of Dominica. The work was done in cooperation with the Ministry of Housing supported by the United Nations Development Program (UNDP) and led by the World Bank, lasting from November 2017 to January 2018. Thirty teams worked with over 100 assessors from different backgrounds varying from technical to engineering staff, including volunteers and students. The training occurred for two days, where methodology was the focus of the first day while the second day emphasised on disaster preparedness and monitoring of reconstruction activities. Participants received information on geographic information system (GIS), components of damage assessment and disaster preparedness. The data was mainly collected through the use of tablets and paper forms (Dominica News Online, 2018). Annex 01 include pictures of the training. Buildings were classified in five different categories for damage level by using a system where colours were assigned for each type of damage, as can be seen in Table 1.2. The goal of the BDA was to comprehend what was the level of destruction and damage to buildings on the island after a significant event, so it can be used to improve the response of forthcoming events (United Nations Development Program - UNDP, 2018).

Further information regarding the BDA and its methodology was requested to the Government of the Commonwealth of Dominica and the UNDP but not successfully obtained. The only material available are reports with a general overview, information collected during fieldwork and website reports from the assessment.

Table 1.2: Damage classification from the BDA.

DAMAGE CLASSIFICATION		
Colour	**Classification**	**Description**
Green	Minimal Damage	Roof with less than 25% damage.
Yellow	Minor Damage	Roof with more than 25% damage.
Orange	Major Damage	Roof totally damaged as well as walls.
Red	Destroyed	Building completely destroyed.
	Others	The building lacks information.

Source: United Nations Development Program - UNDP (2018).

The category stated as "others" embodies damage points that lack information in one or more features such as building occupancy, size of the building, insurance status, repair status, roof damage, walls damage, floor damage and/or ceiling damage. For further analysis, the category "others" is referred to as "no information".

The BDA database consists of a shapefile with 29.434 damaged building points surveyed through the island. Some areas like Petite Savanne and Dubuc were not mapped as they were marked to be "special disaster areas", which is discussed further in Chapter 3. The damage points provide information that encircles from damage status, insurance status, name of the community, coordinates, occupants of the building, type of use of the building, amongst others. Annex 02 shows the information provided in the database and used to obtain the results of this research.

A pilot exercise for a second building damage assessment (BDA 2.0) was performed from December 6th to 9th, 2018 in Roseau. The training consisted of two days and it was a partnership from the Ministry of Housing and Lands with the UNDP, assessing more than 200 buildings in the community of Newtown. It involved forty people, including technical staff from the Physical Planning Division, the Ministry of Housing and Lands and Dominica State College students, where the participants were divided into ten groups, making use of an application-software on their phones to survey and assess the conditions of houses. Since the first BDA was performed, the UNDP has made upgrades in the activity of damage assessment and the BDA 2.0 can be considered as a progressed version, correcting mistakes from the first BDA (UNDP Barbados and the OECS, 2019).

1.6.2. Data Collected in Field (Recovery Database)

A point file database was constructed representing 212 buildings mapped one year after the event by the author during fieldwork in October 2018. Damage was assessed taking into account an adaptation of the EMS-98 classification of masonry damage (Grünthal, 1998). It is important to note that the recovery database provides a limited amount of data and serves as a validation of the landslide and flood inventory, hazards maps and the BDA, verifying the accuracy of such data. The classes and its descriptions can be visualised in Table 1.3.

Table 1.3: Damage classification applied to the data collected in fieldwork.

DAMAGE CLASSIFICATION	
Classification	**Description**
No damage	No apparent structural damage can be seen.
Slight damage	Some cracks and pieces of the structure can be spotted.
Moderate damage	Cracks and partial collapse/detachment of pieces of the structure are spotted.
Substantial damage	Large cracks, roofs tiles detached, failures and partial collapse/detachment of pieces of the structure are easily spotted.
Very heavy damage	Serious failures of structure, partial collapse of roofs and floors, large cracks and pieces detached of the structure can be instantly spotted.
Destruction	Structure near or totally collapsed/destroyed.

Source: Adapted from Grünthal (1998).

ArcMap was used to create a feature class to organise and describe attributes and spatial reference for the features. Attribute fields were created encompassing fields as the name of the area, code of the building (FID), hazard (flooding, debris flows, debris slides, wind and coastal), number of stories, amongst others displayed in Annex 03.

The second step was to display the shapefile with building footprint using the software ArcMap. The editor tool was used to create point files on the space depicting the location of the mapped buildings in the field. These points were linked to the building footprints according to their code numbers (FID). After creating a point, the attribute table was filled with the information collected in fieldwork. Hazard attributes, repair and abandonment status were given binary fields, where 0 represents a false statement (hazard not present on the area, not repaired and not abandoned, respectively) and 1 depicts a true statement (hazard present on the area, repaired and abandoned, respectively).

Since classification from both databases uses different methods, for the analysis of the recovery database an equivalence had to be made. A comparison between the description and patterns of damage classes was performed for the recovery database along with the damage classes from the BDA. Table 1.4 illustrates the damage classes equivalence.

Table 1.4: Equivalence of damage classification for both databases.

DAMAGE CLASSES EQUIVALENCE		
BDA	**Recovery Database**	**Description**
	0 - No damage	No apparent structural damage.
Minimal damage	1 - Slight damage	Slight general damage can be seen or roof with less than 25% damage.
Minor damage	2 - Moderate damage	Some apparent structural damage can be seen or roof with damage between 25% and 49%.
Major damage	3 - Substantial damage	Moderate to heavy structural apparent damage can be seen or roof and walls totally damaged.
	4 - Very heavy damage	
Destroyed	5 - Destruction	Structure near or totally collapsed.
Others		Building lacks information.

Source: Adapted from (United Nations Development Program - UNDP, 2018) and (Grünthal, 1998).

1.6.3. Other Datasets

Each dataset presented is used in different parts of the research and some are used to complement, examine and validate information already established by other datasets. Table 1.5 depicts geospatial data, inventories, hazard maps, satellite images and UAV images from different sources. Likewise, reports on damage assessment, development plans, post-disaster needs assessment and summary reports for after the event also are demonstrated.

Table 1.5: Further datasets used in the research.

DATA	DESCRIPTION
Boundaries	Vector map (polygon) covering the boundary of Dominica and its parishes.
Roads map	Vector map (lines) covering the island with roads network.
Buildings footprint	Vector map (polygon) covering the island with buildings footprints. Obtained from OpenStreetMap representing the situation in 2015.
Landslide and flooding inventories (hazards inventories) – ITC	Landslide and flood inventory made after the event by analysis of high-resolution satellite images. The events were triggered by Hurricane Maria, and the inventory covers the island. Produced by ITC between October and December 2017.
Landslide inventory map – ITC	Landslide inventory map covering the island (data from 1987, 1990, 2007, 2014, 2015). Produced by ITC in 2016.
Landslide susceptibility map	Raster map covering the island with three classes (Low, moderate and high landslide density). Generated using a Spatial Multi-Criteria Evaluation in 2016 based on landslide inventories from 1987, 1990, 2007, 2014 and 2015 by ITC.
Flood hazard map	Raster map covering the island with five classes (no flood, low, moderate, high and very high flood hazard) produced by ITC, 2016.
Wind hazard map	Vector map (polygon) covering the island with five classes (very high, high, moderate, low and very low hazard). Produced by the United States Agency for International Development - USAID.
Satellite images	High-resolution Pleiades images, panchromatic (0.5m pixel size) and multispectral (2m pixel size) covering the island. Retrieved between September and October 2017.
Unmanned Aerial Vehicles (UAV) images pre Hurricane Maria	High-resolution UAV images covering partially thirty areas of Dominica. Retrieved on August 2017, before Hurricane Maria. No information by whom it was retrieved from.
Unmanned Aerial Vehicles (UAV) images - RescUAV / Global Medic	High-resolution UAV images covering partially ten areas of Dominica. Retrieved in October 2017 by RescUAV / Global Medic.
Unmanned Aerial Vehicles (UAV) images - Aerial Dominica	High-resolution UAV images depicting some areas of Dominica by Aerial Dominica YouTube channel. Images retrieved with a DJI Mavic Pro in 2017.
Unmanned Aerial Vehicles (UAV) images - One year after Hurricane Maria	High-resolution UAV images covering part of the area of Pichelin. Retrieved in October 2018 by private citizens when in fieldwork in Dominica.
Report - Dominica	Guide to Dominica's Housing Standards, 2018.
Report - Dominica	Dominica National Physical Development Plan, 2016.
Report - Dominica	Post-Disaster Need Assessment Hurricane Maria, September 18, 2017.
Report - Dominica	Summary Report - Hurricanes Irma and Maria: One year on

Moreover, Dominica was one of the target countries of a project which aimed for the support and generation of risk information to sustain projects and planning programs, the Caribbean Handbook of Risk Management (CHARIM, 2018). Thus, further datasets obtained and generated during the project, as well as information retrieved from the CHARIM database were used in the research to achieve the results discussed.

2. HAZARD RELATIONSHIPS

This chapter aims to demonstrate a comprehensive analysis of the relationships between hazards in a multi-hazard post-disaster situation. A conceptual framework is built and depicted to investigate the influence of hazards interactions on the environment and built-up areas.

2.1. Multi-hazard Scenarios

Damages to the built-up and natural environment can be exacerbated due to other hazards occurring sequentially or as a consequence of a primary hazard. Besides them, anthropogenic activities have a significant role by impacting the biophysical environment and natural resources and these processes can lead to disaster events. Assessing hazards requires comprehension of the hazard scenario which is defined by magnitude/intensity/frequency relationship of the event (van Westen et al., 2017) and hazard identification, that occurs by determining key characteristics. Table 2.1 exemplifies the main components to be defined for hazard identification.

Table 2.1: Key components of hazard identification given a flooding example.

Flooding Hazard	
Components	**Explanation / Examples**
Triggering factors	Precipitation, landslides.
Spatial occurrence	Location: spatial features. E.g. topography, hydrology, degree of urbanisation; Dimension: areal extension. E.g. river floods can inundate large areas.
Duration	Definition of starting and ending points. E.g. flash floods: few hours or less.
Time of onset	Predictability of the hazard. E.g. heavy rainfall shows signs of the possibility of flooding events.
Frequency / Magnitude	Frequency indicates the number of times a hazard occurs in a specific period. Magnitude indicates the extent of the event or energy released. E.g. flash floods present smaller frequency and higher magnitude.
Intensity	Indicates the different effects occurred in a physical space. E.g. if heavy rainfall exceeds a threshold it may cause flooding. Some hazards have no exclusive intensity defined. E.g. landslides.
Interactions	The influence of the event in the natural and built-up environment. E.g. flooding triggering landslides.

Source: Adapted from van Westen et al. (2011).

Identification leads to the classification of hazards in categories that can be subjective and happen in many ways, with more or fewer sorts depending on hazard features. This research will contemplate the classification of hazard types used by the International Disaster Database EM-DAT (Guha-Sapir et al., 2016) and the Integrated Research on Disaster Risk – IRDR (Integrated Research on Disaster Risk - IRDR, 2014), which lodges a full range of threats classified in two main groups: natural and technological hazards. They also present sub-groups that vary according to the type of hazard, e.g. geophysical, hydrological, meteorological, industrial accident, amongst others. Each sub-group presents different types of hazards, which in its turn, can also be classified in multiple different generic sets of other hazards. For instance, the hydrological sub-group has landslides as a type that can be categorised in debris flows, rockfall, mudflow, amongst others. Several sub-types of hazards can be derived depending on the key components.

The relevance of the hazard is an important aspect to be studied. Greiving et al. (2007) discourse about it by considering the spatial planning aspect. Spatially relevant hazards are linked to areas that are already prone to certain types of hazards. That means that hazards can be predicted to occur in determined areas, allowing planners to consider specific characteristics of such hazard. For example, storm surges affect the coasts up to a certain elevation, known by the stakeholders who will be able to apply better-localized risk reduction strategies. Spatially non-relevant hazards may occur anywhere and the spatial planning aspect does not have as much influence for mitigation as other factors. For instance, earthquakes may affect large areas where the resistance of the buildings is a substantial aspect to be considered rather than spatial planning.

Return period is also a relevant aspect to be considered in planning strategies. It is characterised as the probability in which events can be expected to happen. It is rather difficult to assess and also changes over time (van Westen et al., 2017). Authorities may also plan their mitigation approaches based on return period as studied by Dittes et al. (2018). Their work assessed the state of flood protection systems under the light of climate change, addressing questions related to mitigation planning, such as if the protection is adequate for the actual and future demands and how the frequency of events influence on protection criteria. These features indicate that there are many issues to be addressed in spatial planning that it needs to be coordinated in a way that considers numerous aspects of hazards.

It is important to develop a database of historical hazards events in a specific area and to identify secondary hazards that may occur. The follow-up step is to initiate reporting and making a profile of the characteristics of a hazard, where it is described in its local context, area where it occurs, historical background, exposure of EaR and its vulnerabilities, possible consequences and probability of occurrence so that risk can be assessed and DRR strategies can be successfully implemented.

2.1.1. Hazard Interactions

Gill & Malamud (2017) define interaction as the possible effects that a process or phenomena may have on another process or phenomena, either being natural or anthropogenic. When a hazardous event happens, it may influence many other processes by relating to the environment and initiating chain events, when one hazard might be the cause of another one (Liu et al., 2016). These interactions may occur due to characteristics of the natural or built-up environment and can be the cause of multi-hazards situations. A rather important aspect is that the impacts of a disaster might also chain other main or secondary impacts. Such chain may have an influence on regular societal functions and activities, disturbing displacement of people, transport of goods or impacting food supply, for instance.

In multi-hazard conditions, the hazardous processes should not be treated as independent phenomena's since it can misrepresent management priorities. Instead, a thorough analysis of the area regarding all the hazards it has, how these hazards may influence other processes and who/what can be affected shall help to create strategies that can reduce risks for the society and environment. Following this line, multi-hazard assessment has been widely used nowadays, focusing on the idea of the non-independency of natural hazards and considering the influence that one hazard may have in the environment. To outline the importance of such assessment, Gill & Malamud (2014) presented an overview of hazard interactions by analysing four case studies that presented different types of hazard and its relationships. The case studies vary from 1792 until 2010 and show that in all circumstances one main event had interactions that affected the probability of a secondary hazard happening. In its turn, the secondary hazard may have also affected the probability of another hazard and so on, therefore, creating a network of hazards interactions.

When assessing multi-hazard situations, it is essential to understand the origin, location and if they can change the conditions for the occurrence of other hazards. While classifying interaction types is a step to understanding the influence that a hazard may present on another, identifying and analysing how hazards interact with each other is still a challenge. There are some aspects (of environmental or anthropogenic origins) that impact how a hazard may manifest itself and how it can have an effect in other hazardous processes. Factors such as topography, climate, geology, vegetation, urbanisation, deforestation and many others have a significant role when talking about the occurrence of hazardous events, but cannot be held entirely responsible for starting/activating other events by themselves. For that, an event such as a meteorological (e.g. storm that triggers landslides) or geophysical (e.g. earthquake that generates a tsunami) is generally the triggering factor that will create scenarios where one hazard communicates with the environment and influences another one (van Westen et al., 2017).

Many ways of describing relations between hazards exist in literature, and there is not a unique terminology. Some examples are authors such as Gill et al. (2016), the European Commission (2010) and Pippo et al. (2008) referring to the relationships as interactions, while Delmonaco et al. (2007) called them cascading effects but use the term domino effects as well. The relationships between hazards considered in this thesis are the ones studied by van Westen et al. (2017), who presented a four classification type when analysing the interactions in multi-hazard conditions. They vary from independent events, coupled events, changing conditions events and domino hazards. Figure 2.1 presents schematic examples of these relationships.

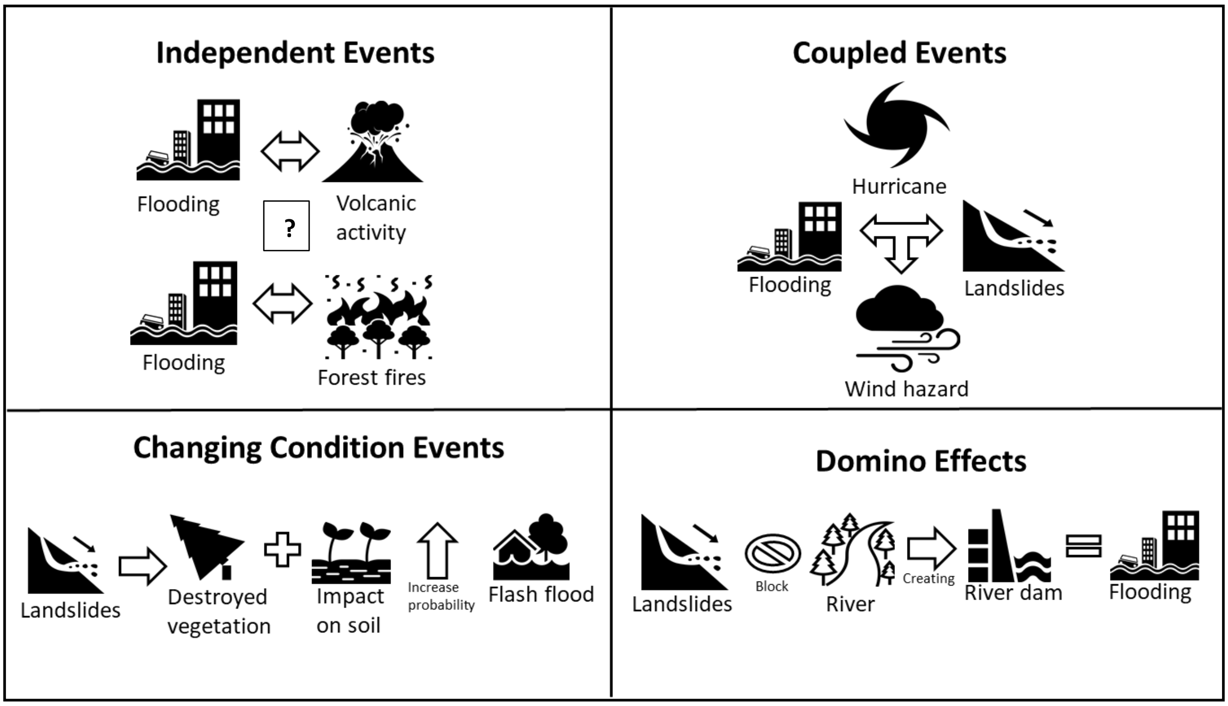


Figure 2.1: Examples of hazard relationships categorised according to a four type interaction classification.
Source of the icons: The Noum Project (2018).

Independent events are hazards that manifest in independent ways and relate to different triggers to be activated. Although, even if two hazards can be considered independent, both create conditions that can trigger another hazard. For instance, earthquake activities may trigger a landslide which can act as a dam and cause flooding. In such cases, both hazards cannot be considered completely independent. Assessing the situation must be done considering different hazard types and risk can be analysed for each independent hazard, adding the losses.

Coupled events happen when different types of hazards are triggered by the same event. Studying coupled events should be done considering the maximum scenario of the risks from the hazards, and when analysing the situation, one must ponder the spatial extent of the hazards since they will overlap. Thus, hazard modelling should be performed together. Risk should be assessed by using combined hazards, but making it clear that the intensities are different for each hazard, therefore, using different vulnerability-intensity curves.

Changing condition events are relations where one hazard changes environmental aspects, influencing the conditions that can make the area more susceptible to other hazards, but not triggering them. This relation makes it clear that there are constant changes in conditions from areas susceptible to hazards, and further processes may alter them according to the event. Assessing changing conditions situations may be complex due to how hazards will interact amongst themselves, and it is challenging to be done before the hazard altered the condition since it can be unpredictable. It is suggested a constant update of the multi-hazard risk assessment for every event.

The last relationship is called domino effects (or cascading hazards) and occurs when one hazard is the cause of another hazard. Since hazards may be chained and occurring in sequence, this type of relationship is difficult to analyse, also depending on the area and its characteristics (van Westen et al., 2017).

2.2. Hazard Relationships During Hurricane Maria

This section addresses the conceptual framework of hazard relationships, which was based on literature review and fieldwork assessments. It is disaster and country-specific. Therefore, it reports how Hurricane Maria was manifested on the island, the consequent hazards and the outcomes brought to the built-up and environment areas. It categorises the relationships between hazards and how their interactions impacted the country. The framework is divided into two sections, first displaying the interactions of the hazards during the event and secondly how the consequences of the event manifest in a post-disaster situation.

Identifying the hazards present on the island was the first step to start the framework. Literature review on high-speed winds, storm surges and intense rainfall and how they influence soil and vegetation were examined. Hazard inventory along with fieldwork information were used to identify and validate which hazards affected the island, how and what type of damage they produced.

During the event, impacts on the soil and vegetation have significant effects on hydrological processes and soil stability, which triggered further actions that led to hazardous processes such as flooding and landslides. These impacts were further investigated, assessing their effects in changing the conditions of the environment for other hazardous processes. The post-disaster situation was similarly constructed. According to the outcomes of the hazards during the event, fieldwork information along with UAV and satellite images were utilised to assess the conditions of the riverbeds and channels and confirm their circumstances. By the end of the process, a cycle is formed, and the characteristics that lead to this situation are examined.

Analysing the relationship between hazards took into account the four type classification presented by van Westen et al. (2017). A classification was assigned according to the influences of hazards and their potential of changing the conditions for the occurrence of other processes. A matrix was created depicting all the possible relationships between the presented hazards on the island of Dominica.

Hurricane Maria manifested itself with high-speed winds, intense rainfall and extreme waves near the coast. These hazards had a high impact on the environment and built-up area, creating conditions that changed the exposure of EaR. Furthermore, when interacting with the environment, these hazards influenced other processes, originating chain events that resulted in a multi-hazard environment.

Figure 2.2 presents the conceptual framework of the relationships between hazards during Hurricane Maria. It is divided into three branches, according to each manifestation, which also interacts amongst themselves.

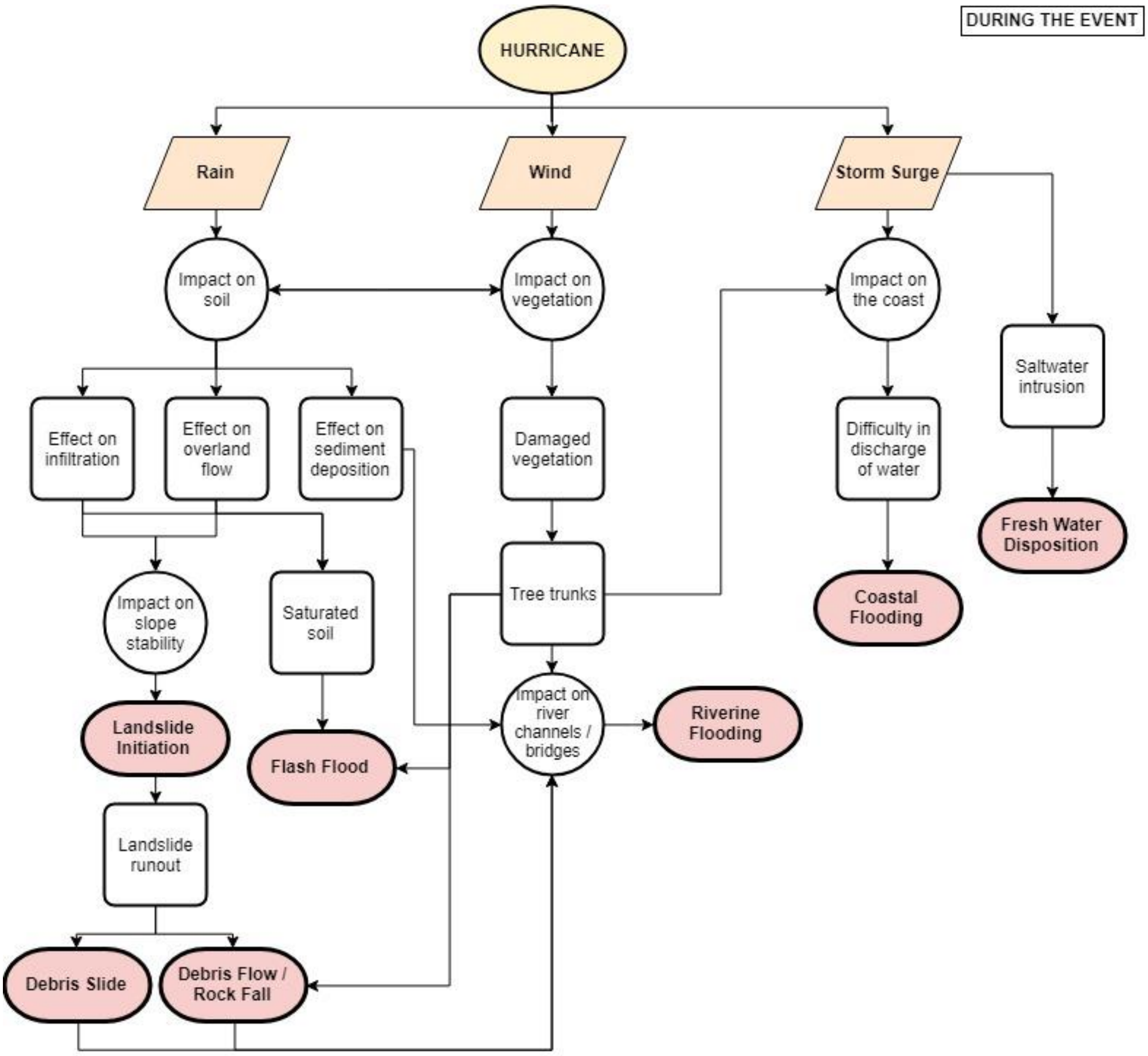


Figure 2.2: Conceptual framework of the relationship between hazards occurring during Hurricane Maria.

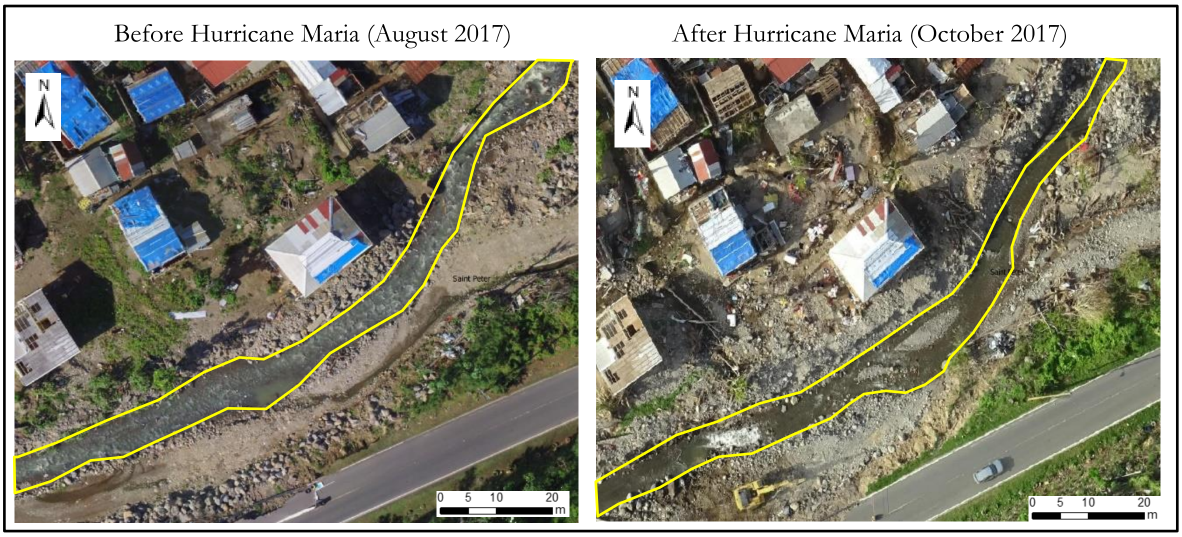
High-speed winds along with intense rainfall had a substantial effect on vegetation and, consequently, on the soil. Throughout the island, a significant part of the vegetation was destroyed causing widespread forestry damage with stripped forests and fallen trees. Hu et al. (2018) performed a study in Dominica adopting a normalised difference vegetation index (NDVI), an indicator that can be utilised to assess the living state of green vegetation of a determined area. The results presented show that NDVI value dropped from 0.91 to 0.69 after the passage of Hurricane Maria in 2017, displaying severe loss of green area on the island. The low value also matched with the statement from the Post-Disaster Needs Assessment report from Hurricane Maria (Government of the Commonwealth of Dominica, 2017), which showed that forest resources were damaged with approximately 80% to 90% of environmental resources being affected. The post-event situation presented values that range from 0.68, in October 2017, to 0.83 in November 2017, showing signs of temporal vegetation recovery.

The absence of green areas disturbed hydrological processes and soil water balance, impacting directly on soil properties. Such disturbances occurred by interfering on the amount of water intercepted by canopy, an increase of water flow on the surface and rapid saturation of the soil (Khalili Moghadam et al., 2015). In the case of Dominica, due to heavy precipitation, saturated soils impeded the continuation of infiltration processes, which affected the overland flow. With less vegetation, canopy interception diminished, reducing the protection against raindrop impact and increasing land degradation processes (Tsiko et al., 2012). Along with it, the catchment shape influenced directly on the occurrence of flash floods (Grillakis et al., 2016) on the island.

With less green cover the amount of plant roots diminished, reducing shear strength, forces that act on the slope to maintain it in place (Chok et al., 2015). As examined, the literature demonstrates a relationship between plant roots and shear strength, showing an increase in values of the forces on *in situ* soil blocks reinforced with plant roots (Wu, 2013; Kekuatan et al., 2011; Wu & Watson, 1998). The reduction of shear strength values contributed to decreasing the stability of the slopes (Kristo et al., 2017) of affected areas, causing slope failure and initiating landslide processes as seen in the first branch of the framework.

The second branch discusses mainly flooding. As intense rainfall and high-speed winds destroyed a significant part of vegetation, trees were stripped and fell, being dragged into river channels and bridges, obstructing rivers courses. Along with it, the process of sediment transportation by the rivers, sediment detachment due to rainfall, and landslide processes contributed significantly for increased sediment deposition on the river beds and channels of Dominica. These aspects permitted less space for the water to run and increased flood risks.

Flooding events with extreme intensity can also contributed to changes in the dynamics of a river (Dai & Lu, 2010). In Dominica, the Colihaut River could be observed to have suffered from excessive sedimentation, which affected its natural course after Hurricane Maria, as can be seen in Figure 2.3. The images depict Colihaut River in the periods of August and October 2017.


Before Hurricane Maria (August 2017)

After Hurricane Maria (October 2017)

Figure 2.3: UAV images illustrating the conditions of Colihaut River in the region of Colihaut, parish St. Peter, before and after Hurricane Maria.

Source: UAV images RescUAV / Global Medic (2017).

Figure 2.3 shows that the river morphology has changed due to severe sediment deposition, which might modify exposure to hazards, affecting EaR that were not affected before. When in fieldwork, activities of dredging were being done to remove the excess of sediments in some areas of Dominica.

The third branch discusses storm surges, impacting mainly the coast. Due to it, saltwater intrusion can be pushed into riverine environments by the forces of winds and waves, and present effects that manifest in long-term on the population, such as loss of soil fertility and affect the disposition of freshwater (Rajan & Saud, 2018). The event also caused a rise in sea level, where the water was being pushed in direction to coastal areas, congesting the discharge of the river mouth to the sea, already impacted by destroyed vegetation (mostly tree trunks) and causing a retreat of the water and, eventually, flooding the coast.

2.3. Post-Maria Hazard Relationships

The second section of the framework illustrated in Figure 2.4 demonstrates the set-up in a post-disaster situation, where the consequences of the first section are taken into account. A significant portion is clarified during the first section since the processes are similar and the changing variable is the time. The time frame illustrated for the post-disaster framework is mid-term after Hurricane Maria, where no temporal recovery of vegetation occurred significantly and no mitigation measures have been implemented.

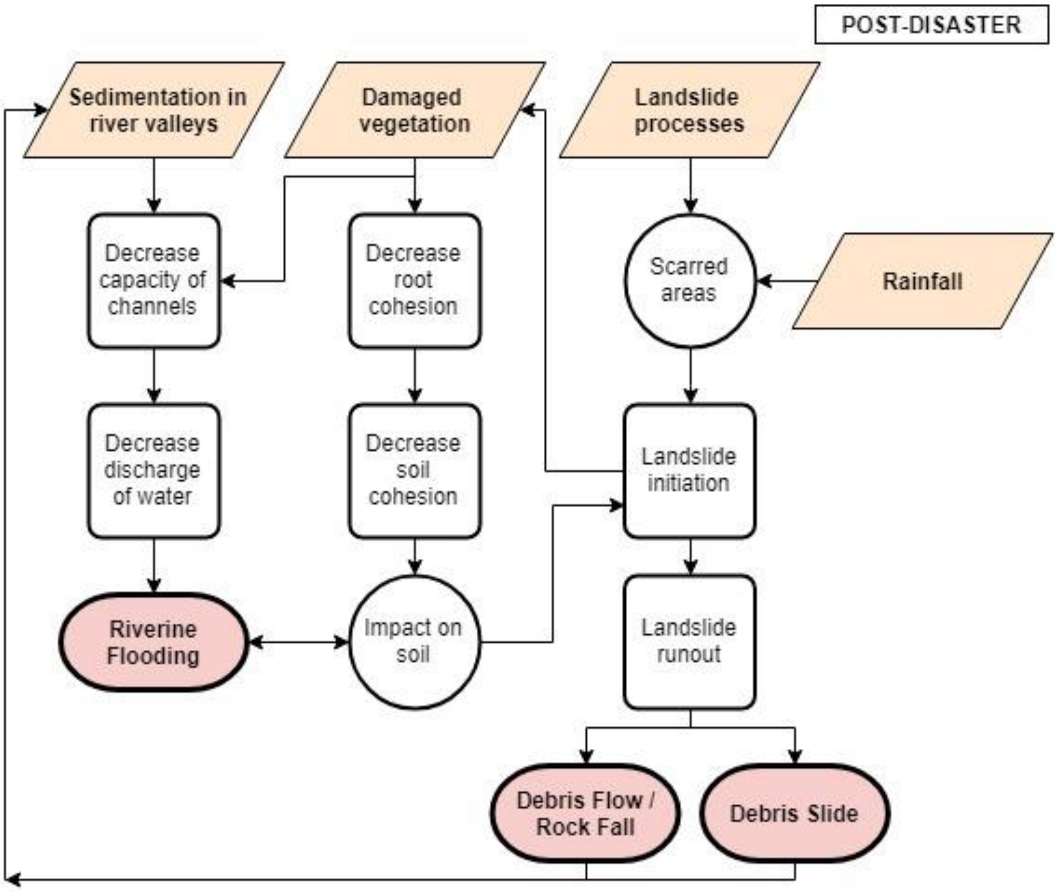


Figure 2.4: Conceptual framework of the relationship between hazards occurring in a post-disaster scenario for Dominica.

Due to sediment deposition processes rivers decreased their capacity of holding water. Damaged vegetation (tree trunks) further intensified blocking effects on river channels, increasing flow resistance (Solari & Oorschot, 2015). Such factors directly related to the occurrence of flooding events. Furthermore, the mixture of sealed areas from the urban environment with possible damming of rivers due to landslides contributed to increasing the likelihood of flooding hazards.

Rainfall events on disturbed soil and scarred areas from landslides processes also contributed to increasing the probability of new hazard initiations. Such factors put the system in a loop, affecting the soil and vegetation and influencing the occurrence of other hazardous processes. These actions can become a cycle when not properly addressed.

Long-term effects must take into consideration temporal recovery from vegetation and mitigation measures applied on areas at risk. In areas where no mitigation measures are applied, sediment deposition will continue to increase on the river valleys and the vegetation may be destroyed by hazardous processes, continuing creating conditions for further processes. An important aspect to be considered is how long will it take before a next major event hits the island. Caribbean islands are depicted to present high vulnerability to the effects of climate change (Taylor et al., 2018), proved to influence on the intensity and frequency of extreme events (Field et al., 2012). Therefore, impacts may be greater if no measures are implemented after the last event.

2.3.1. Summary: Hazard Relationships in Dominica

The conceptual framework illustrates several hazards in the same area and the different factors that might trigger another event to happen, characterising a multi-hazard situation. These hazards were categorised according to their relationships, presented in Table 2.2.

Table 2.2: Relationships between hazardous processes occurring in Dominica during Hurricane Maria. The table should be read horizontally, starting from the left.

	Storm	Wind hazard	Storm surge	Landslides	Debris flow	Flooding
Storm		Coupled Events	Coupled Events	Coupled Events	Coupled Events	Coupled Events
Wind hazard	Coupled Events		Domino	Changing Conditions	Changing Conditions	Changing Conditions
Storm surge	Coupled Events	Coupled Events		Independent	Independent	Domino
Landslides	Coupled Events	Coupled Events	Coupled Events	Changing Conditions	Changing Conditions	Changing Conditions / Domino
Debris flow	Coupled Events	Coupled Events	Coupled Events	Changing Conditions	Changing Conditions	Changing Conditions / Domino
Flooding	Coupled Events	Coupled Events	Coupled Events	Changing Conditions	Changing Conditions	Changing Conditions

The hazards were analysed in terms of their outcomes and effects on the environment, resulting in a classification for each relationship, being independent events, coupled events, changing conditions or domino effects. As discussed, the relationships are dependent on the characteristics of the multi-hazard environment, triggering factors, the environment, the impact interactions and the timeframe analysed. Different relationships can occur depending on the situation during or after an event. Table 2.2 was created considering relationships occurring during Hurricane Maria. Then, for instance, wind hazard and flooding events would be considered couple events in this situation because they have the same triggering event (Hurricane Maria) and might affect the same area. In different circumstances, they could be considered independent events.

3. ANALYSING A BUILDING DAMAGE DATABASE

This chapter analyses the information from a building damage database that was collected by volunteers after Hurricane Maria, depicting the methods utilised to extract information, and examining how such data contribute in post-disaster recovery.

3.1. Volunteered Geographic Information (VGI)

Current technology and the rapid development of the internet allow for deeper interactions between population and partly replace what used to be a function reserved for official agencies: the creation of geographical information. Smartphones, tablets and notebooks are the main gadgets used to participate in such activities. Goodchild (2007) proposed that humans are like networks of sensors that can observe, compile and interpret information of their surroundings, gathered with local knowledge and mobility. They offer data that must be filtered, but sufficient to grant local context. In this sense, VGI can be seen as an advantageous use of such network.

Different reasons have been driving the increasing engagement of private citizens, often with little to no qualification, on the field of crowdsourcing. As See et al. (2016) analysed, researchers with limited resources may use this advent to obtain data necessary that otherwise would take longer or would not be possible to be attained. Such desire to contribute and produce new geographical information by private citizens can also be inspired by the simple need to share information, by georeferencing photos online or allowing close relatives to check one's location by an application on the smartphone.

Further motivations include contributing to a cooperative cause, like mapping areas in OSM, or informing the situation of a place where a disaster occurred. These systems have been essential inputs in the scientific community, allowing scientists, planners and governmental agencies to trace better strategies for the development of cities. However, the constant and rapid growth of VGI puts into perspective the question if the information provided by private citizens have sufficient standards to be used for scientific purposes.

3.1.1. Quality of the Information

There are concerns regarding the quality of the information that is collected using VGI (See et al., 2013), such as the quality of the French OSM Dataset (Girres & Touya, 2010), comparing the quality of crowdsourced data shared by experts and non-experts (See et al., 2013), and measuring data completeness in OSM (Hecht et al., 2013). Since the approaches of how one may proceed when contributing to a VGI dataset varies from person to person, there is a risk of not following a standardised method. This brings significant data problems, which can be classified in different quality problems, such as attribute accuracy, spatial accuracy, logical consistency, completeness and currency. These are addressed in VGI to ensure quality and uncertainty problems (Arsanjani et al., 2015).

Fan et al. (2014) assessed the quality of building footprint data in OSM for the city of Munich, Germany, indicating high completeness and semantic accuracy (i.e. measuring the correspondences between buildings in the real world and in the system) but lacking attribute accuracy. Haklay (2008) investigated the quality of OSM information, depicting results that attested for the accuracy of the system. The author claims that OSM quality can be comparable to authoritative data where information is complete, also expressing reasonable positional accuracy in his results. Although, data is dependent on a well-organised group of participants and inconsistency of the information can remain a problem.

Goodchild & Li (2012) discussed and presented three alternative approaches to ensure information quality in crowdsourced data, mostly used in traditional mapping agencies. The first approach involves having others to validate and correct people's mistakes, relying on the knowledge and accuracy of, what is expected, local acquaintances. The reliance on this approach works better on important geographic facts and problems with disagreement of features in areas may create what the author called "tag wars", where different people repeatedly change the information because they do not agree with it.

The second approach refers to a social method, relying on groups of selected individuals trusted to act as moderators of data inputs. An example is OSM, which works with two different categories of contributors: regular users and the Data Working Group, responsible for assuring the correctness of information. Such hierarchical structures are applied to traditional mapping agencies, counting on experience and qualifications to be led to higher positions.

The last one is called the geographical approach and leans on a comparison between the allegedly correct geographical information along with a comprehensive geographic knowledge of the area. This approach rests primarily on the first law of geography, that says that everything is related to everything else, but nearby things are more related than distant ones (Tobler, 1970). For instance, if a restaurant is georeferenced in an area, the geographical context implies that this area is not classified as an industrial land use type or that this building lies in a recreational park. If such advent happens, it can be rejected from the dataset and classified as a mislocation. Yet, implementing such feature with reasonable accuracy in a VGI system remains a challenge, being time and resources consuming.

3.1.2. VGI Applied to Disaster Risk Management (DRM)

Disaster management is frequently represented as a four-component cycle: mitigation, preparedness, response and recovery. These components include features like risk identification and analysis, capacity building, monitoring, early warning, reconstruction, amongst others, distributed in the phases of the components (Coppola, 2015). Different types of information and data are required according to each component to plan strategies, analyse losses or investigate dangerous areas. The data are generally provided by official agencies and institutions related to disaster management. However, this pattern has been changing with the increasing field of VGI (Poser & Dransch, 2010).

The application of crowdsourced data for DRM is already a reality. In disaster scenarios, crowdsourced data can provide information to be worked for strategies to mitigate or reduce losses and damages caused to properties. Kerle & Hoffman (2013) discuss collaborative damage mapping and the role of cognitive systems, analysing how users can improve their contributions to VGI systems and the challenges in existing methods for emergency response. Schelhorn et al. (2014) explored how OSM data can be used to identify EaR. Yan et al. (2017) examined the use of social media data in monitoring and assessing post-disaster tourism recovery. McCallum et al. (2016) investigated the role of VGI in flood disaster risk reduction and how the scenario has been changing with the growth and popularisation of mobile connected technology. The study treats the difficulty to obtain community-level information in order to draw better strategies for future interventions, especially in less developed countries where there are substantial data deficiency and less capacity for disaster risk monitoring. Overall, VGI data has been demonstrating its worth and advantages, showing utility in supporting disaster management. In contrast, quality control is the main obstacle for its usage, requiring constant filtration and validation to be used operationally.

3.2. Unmanned Aerial Vehicle (UAV) Applied to Disaster Risk Management (DRM)

UAVs are remotely controlled aircraft systems that have been increasingly used for the collection of geospatial data. When equipped with a camera, they can provide high-resolution imagery that can be utilised to monitor changes in the environment (Gevaert et al., 2018) and due to the popularisation of such technology, acquisition of images at high temporal and spatial scale is becoming affordable. The applications vary from mapping areas to obtain information for the creation of detailed elevation models, attaining footages for disaster risk management purposes, acquiring video footages of public events or even transportation and logistics.

The technology has the potential to fill gaps when referring to remote sensing. It also allows the integration with other systems, such as for VGI purposes. Johnson et al. (2017) analysed the challenges and developments of volunteered drone imagery, screening the potential use of UAV image collection allied with the role that citizens have in collecting geographical information for the conception of a shared user-generated imagery library. An example given is the industrial oil spill disaster occurred in the Gulf of Mexico, 2010, where homemade aerial imagery integrated with VGI systems assisted in the coverage of impacted sites. Another example is the open source platform OpenAerialMap (OAM), which offers aerial imagery that can be hosted by the population and integrated with OSM to be used for the creation of geospatial information for disaster management resolutions. Annex 04 illustrates examples of aerial imagery for Dominica obtained from OAM platform.

In a post-disaster scenario, the usage of UAV on the evaluation of the terrain before and after the disaster can provide significant information on measuring the impacts on the environment (Johnson et al., 2017). For instance, Clapuyt et al. (2016) investigated the suitability of the use of UAV for monitoring remotely and poorly accessible areas, pointing out the importance for the study of mass movements and the monitoring of fluvial environments. Gonçalves & Henriques (2015) made use of high-resolution imageries, provided by UAV to examine coastal topography changes, highlighting the advantages of using such technology.

Recently, UAVs have been used for monitoring and inspecting buildings regarding assessing damages and deformations, by implementing algorithms that allow for the automatic extraction of such needed information (Vacca et al., 2017). Such features have been assisting when tracing strategies for planning better constructions that are more resilient towards hazardous events. There are, however, concerns regarding the operation of such technology that might affect the quality of the product. Weather conditions, the autonomy of the battery and weight of the UAV might be limiting factors that can influence the result. Besides, when performing an aerial campaign, one must be aware of privacy considerations, airspace flight restrictions and licence and registration for the equipment, aspects that vary according to each country (López et al., 2017).

3.3. Methodology Applied on the Databases

This section presents information on the use of building damage data collected with the help of volunteers, as well as the necessary actions to make them operational.

3.3.1. Extraction of Information from the BDA Database

The BDA database, explained in section 1.6.1, was the dataset used to provide quantitative analyses and results further discussed. The software ArcMap was used to analyse the dataset. Since the database contains information on several features, spatial selection queries were utilised by combining attributes conditions to extract results. Then, composite conditions were written making use of Boolean operators to select attributes where the condition holds. For instance, to retrieve tuples where buildings are destroyed from parish St.

Paul and that do not belong to the commercial type, a spatial selection was performed with the following condition: "Parish" = 'St. Paul' AND "TagLabel" = 'Destroyed' AND NOT "PrivateStr" = 'Commercial'.

The next step was to prepare the data for further analysis. An overlay of the damage points to an existing base where they could be connected with the information from the buildings on the island was made. A shapefile with building footprints derived from OSM was used so that damage points could be linked with the buildings. Such connection allows for certifying that damage points relate to buildings and to quantify the number of damaged buildings existent. The BDA database contained many errors that prohibited, in most of the cases, to directly link the damage points with the building footprint. Therefore extensive editing was carried in order to move the building points so that they overlapped the building footprint. Figure 3.1 provides an example of an area of the database before and after linking damage points to the building footprint.

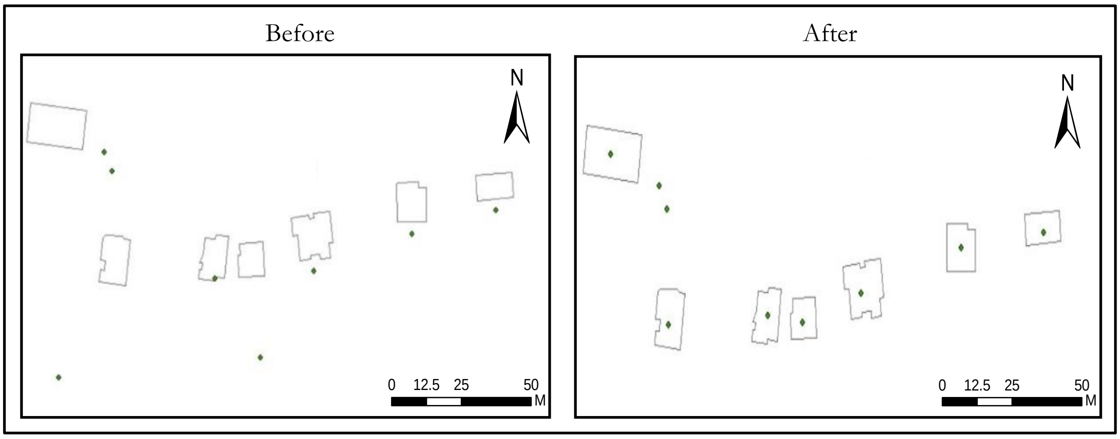


Figure 3.1: Before and after linking damage points to the building footprint. The left figure shows the building footprint with the original damage points distributed on the space. The right figure shows the points tied to the building footprint after edition.

Since the BDA is composed of 29.434 damage points for the entire island, only a limited number of buildings were connected to the building footprints due to time restriction and to focus on the areas where damage was the highest. Five parishes were chosen to complete the process of edition. They are: St. George, St. Luke, St. Mark, St. Patrick and St. Peter. By the end, a total of 13.301 damage points were connected to the building footprints, totalizing 45.10% of the points in the BDA.

In order to represent the certainty with which the points matched the building footprints, an additional field was created, ranging from 0 to 1, where 0 represents a false statement (uncertain that the damage point belongs to the corresponding building), and 1 denotes a true statement (certain the damage point belongs to the corresponding building). The criteria used to assign such values followed two sequential steps. In the first step if the point did not match the requirement, the value assigned would be 0, uncertain. If the point matched the first requirement, the second step was, then, analysed. If it matched the second requirement, value 1 would be assigned, otherwise, value 0 was given. The requirements are as follow:

1. Proximity from the damage point to the building footprint: an analysis of the closeness of the point to the footprint was first made. Since a point can be linked to more than one footprint, representing computational problems, a visual interpretation was performed for the 13.001 points. Points that were until 30 meters far from the footprint were accepted and analysed on the second step;
2. Validation with the size of the building: after confirmation of the first step, the second step was to validate the building footprint with the attributes of the points. Since building size is a feature assessed in the BDA, a visual interpretation of the feature of the building footprint and a comparison with the attribute on the BDA was made to assign the final value of certainty. If the

building matched with the approximate attribute size on the database, certain value (1) was appointed. If not, the uncertain value (0) was allocated.

Since the database did not contain information on the specific hazards types, it was necessary to edit it to include attributes that could later provide information on what type of hazard produced the damage and where. The first operation performed was to modify the database's attribute table and add six fields representing the hazards identified on the conceptual framework: flooding, debris flows, debris slides, rock fall, wind hazard and coastal hazard. The fields created have numerical attributes that range from 0 to 2. These were designed to describe if a building was affected by a specific type of hazard, where 0 represents that the element does not belong to the set of hazard (false statement), 1 represents that the element belongs to the set of hazard (true statement) and 2 represents the uncertainty if the element is a member of the set of hazard. To assign values to the hazards fields, two requirements were analysed, as follows:

1. Overlay the landslide and flood inventory of Hurricane Maria (see Figure 1.2) with the building footprint and BDA to cross information on where such hazards had an impact. The map showed information on flooding, debris flows, debris slides and rock fall. Coastal hazard was analysed during fieldwork and added to the attributes. Wind hazard was also investigated in fieldwork and added to the attributes. Hazards field were then assigned the value of 1 if the hazard overlaid an area with damage points, 2 if it was uncertain they overlaid an area with damage points and 0 if not;

2. Validation with field information: during fieldwork performed in Dominica, an investigation of the areas with the landslide and flood inventory map was done. The data was collected for the construction of the recovery database and it could be noticed that some areas were not fully mapped within the landslide and flood inventory. These areas were noted and received value 2 when assigning values for the hazards field, representing uncertain areas. Other cases where the value assigned was 2, were when no hazard was mapped in an area but according to the BDA buildings were damaged.

3.4. Analysis of the Building Damage Assessment (BDA) Database

A total of 29.434 buildings were assessed in the BDA, verifying degree of damage, occupancy, repair status, type of infrastructure, amongst others described in Annex 02. About 28.51% of the buildings were classified as having minor damage followed by 26.97% with minimal damage and 25.53% with major damage. The percentage of destroyed buildings was as high as 18.44% of the total number of buildings, and finally 0.55% was classified as "others".

Table 3.1 shows further information on the number of buildings affected by parish as well as their degree of damage. As for the values of damages and losses, Table 3.2 displays the summary from Tropical Storm (TS) Erika and Hurricane Maria for Dominica.

Table 3.1: Summary of damaged buildings by damage class and per parish.

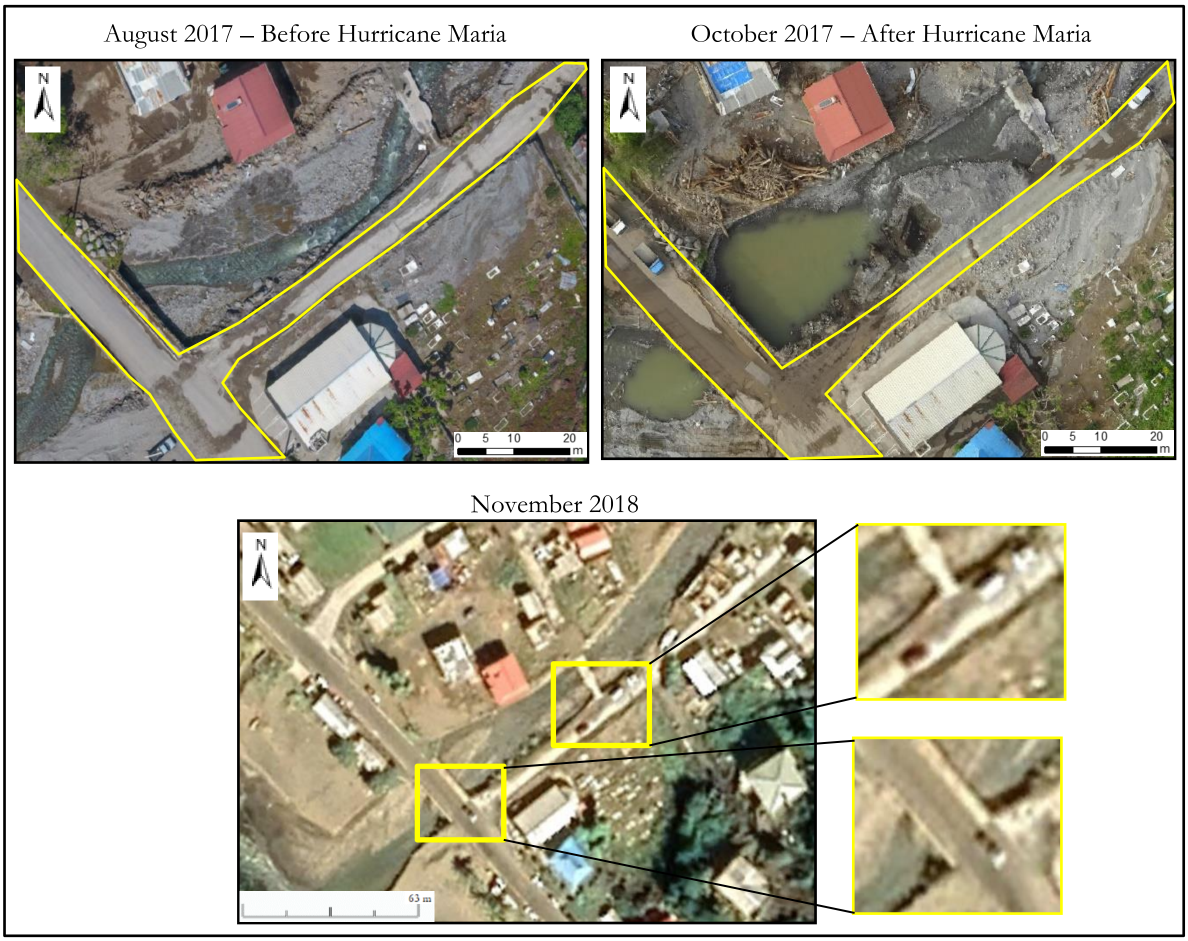
Damage	**Entire country**	**Parishes**									
		St. Andrew	St. David	St. George	St. John	St. Joseph	St. Luke	St. Mark	St. Patrick	St. Paul	St. Peter
Minimal	7943	1056	420	2295	811	1011	215	283	572	1162	118
Minor	8392	1318	634	2358	559	867	254	247	908	997	250
Major	7516	1124	563	1953	616	647	151	352	794	995	321
Destroyed	5428	911	1107	926	506	361	106	153	821	381	156
No-information	155	20	15	41	24	17	13	14	4	7	0
Total	**29434**	**4429**	**2739**	**7573**	**2516**	**2903**	**739**	**1049**	**3099**	**3542**	**845**

Table 3.2: Summary of damage and losses from TS Erika and Hurricane Maria for Dominica in million.

	Sectors	**Subsectors**	**Damage (US$) (M)**	**Loss (US$) (M)**	**Total (M)**
TS Erika	**Productive**	Agriculture, fisheries and forestry	42.46	4.87	47.33
		Tourism	19.48	11.7	31.18
		Industry and Commerce	9.13	0.56	9.69
	Infrastructure	Water and Sanitation	17.14	2.38	19.52
		Air and Sea Ports	14.9	0.08	14.98
		Roads and Bridges	239.25	48.28	287.53
		Electricity	2.19	0.33	2.52
		Telecommunications	10	0	10
	Social	Housing	44.53	9.61	54.15
		Education	3.55	0.45	4
		Health	0.64	1.3	1.94
Hurricane Maria	**Productive**	Agriculture	55.27	124.37	179.64
		Fisheries	2.41	0.5	2.91
		Forestry	29.72		29.72
		Commerce and Micro Business	70.4	6.85	77.25
		Tourism	20.15	70.77	90.92
	Infrastructure	Water and Sanitation	24	39.73	63.73
		Airport and Port	18.89	3.26	22.15
		Transport	182.15	52.62	234.77
		Electricity	33.18	32.94	66.12
		Telecommunications	47.74	8.31	56.05
	Social	Housing	353.96	28.5	382.46
		Education	73.98	3.21	77.19
		Health	10.9	6.95	17.85
		Culture	5.07	2.91	7.98

Source: (Government of the Commonwealth of Dominica, 2015) and (Government of the Commonwealth of Dominica, 2017).

The damage was large in the social and infrastructure sectors. Roads were extensively covered by debris during the event, impeding connections amongst communities and disturbing societal functions. Figure 3.2 illustrates a road and bridge in the area of Coulibistrie, parish St. Joseph, before and after Hurricane Maria, an area that suffered from severe floods and sediment deposition, which helped in clogging the river channels and changing conditions for further hazardous processes.



August 2017 – Before Hurricane Maria

October 2017 – After Hurricane Maria

November 2018

Figure 3.2: Images depicting the conditions of the roads and bridge in Coulibistrie before and after Hurricane Maria. Bottom figure illustrates the conditions of the transport infrastructure in November 2018.

Source: UAV images RescUAV / Global Medic (2017); Google Earth (2019).

As displayed in Figure 3.2, the top left image shows transport infrastructure that was still in recovery from TS Erika and was hit by Hurricane Maria. The top right image illustrates the same area one month after Hurricane Maria, where the street is barely visible, covered with debris and sediments and the bridge was damaged by flooding. When in fieldwork, it could be noticed the streets were cleared and infrastructure was still in the recovery process. The bottom figure displays the same area one year after Hurricane Maria to show how recovery is taking place. Although the image does not have the same resolution as the previous ones, it was used to verify elements that could indicate recovery of the function related to transport infrastructures, such as cars travelling on the roads and bridge. Furthermore, Figure 3.3 depicts the conditions of roads and streets in two different places one month after Hurricane Maria to depict how the process of recovery started and clearance of the roads occurred.

Figure 3.3: The left figure shows the centre of Roseau where the streets were cleared. The right figure depicts an area of Pointe Michel where houses are surrounded by debris, but the streets have been cleared out.
Source: UAV images RescUAV / Global Medic (2017).

A general analysis of the state of the roads after the event shows that accessibility of some areas was restored within one month, with roads being cleared and having its regular functions reinstated, signifying the start of the recovery process after the event. As stated in the UNDP report (United Nations Development Program - UNDP, 2018) the clearing of the connections was a priority to guarantee safety and accessibility for the population, ease the access to remote areas and reinstate regular daily activities.

The housing subsector suffered a total of 29.22% of damages and losses during Hurricane Maria compared to 11.2% from TS Erika, as depicted in Table 3.2. Out of the total of 29.434 buildings, 26.588 are regular homes and houses that share commercial activities. From these, 26.509 buildings suffered damages in their structures. The remarkable difference between the values can be first clarified by the intensity of the events. Hurricane Maria presented winds reaching a speed of 274 km/h against 85 km/h from TS Erika, having a significant impact in the built-up areas. Furthermore, assessment from TS Erika considered a limited area of the island when studying the impacts since damages were more localised compared to Hurricane Maria (Government of the Commonwealth of Dominica, 2015).

A secondary factor influencing the damage values in the housing subsector were building standard guides. The Guide to Dominica's Housing Standards (Government of the Commonwealth of Dominica, 2018), is a document with the purpose of being a reference for standard housing that can sustain weather and seismic events, released after Hurricane Maria, in 2018. The guide is an update of an already existing, but outdated, building code document that offered procedures for safe constructions. According to the staff of the Physical Planning Division the guide has been widely reinforced by the Government of Dominica, but the information could not be verified during fieldwork. Figure 3.4 presents an overview of buildings in the regions of Pointe Michel and Soufriere where buildings that appeared to have followed previous versions of the guide suffered less damage through Hurricane Maria.

An important feature to be considered when applying the guide is the changing vulnerability aspect. Such guide can also be seen as a measure to reduce physical vulnerability for wind hazard and it is likely that houses, where the updated guide is applied, will suffer less damage to such hazard compared to the ones where it is not applied in case of a next hurricane. For instance, the houses depicted in Figure 3.4 that present good roof conditions, reduced their physical vulnerability when addressing improvements that allow the building to withstand high-speed winds. However, that does not mean these houses have low vulnerability to flooding events, for instance, if no measures were applied to avoid damages from such hazard.

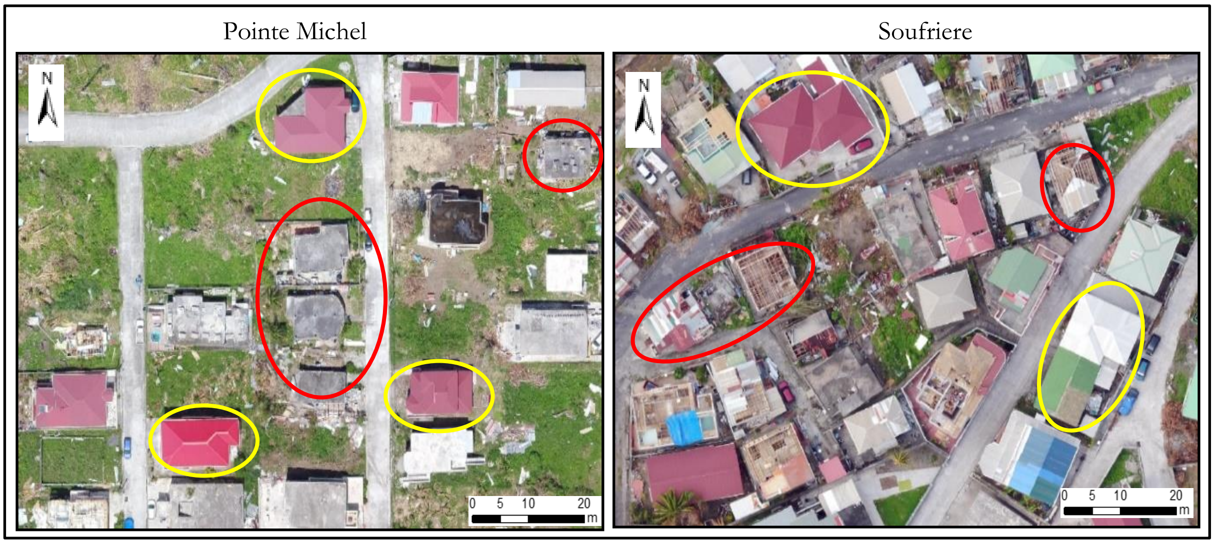


Figure 3.4: Damage pattern to buildings in two locations of Dominica. The figures depict a comparison of the situation between damaged houses and houses with little to no damage. Red circles indicate buildings with construction design that suffered more damage. Yellow circles depict buildings with little to no damage and possible better construction design.

Source: UAV images RescUAV / Global Medic (2017).

In the regions depicted in Figure 3.4, buildings with roof appearing to be in good conditions suffered less damage compared to the ones where the guide was, supposedly, not followed. As stated by Thouret et al. (2014), features such as type of material, maintenance and repair status are aspects directly related with physical vulnerability and such buildings, by following the guidelines proposed, may have decreased their physical vulnerability. For instance, the yellow circles in Figure 3.4 portray roofs that show signs of better design and materials and appear to be in the right maintenance conditions. Evidence of damages such as debris is less distributed around these buildings. In contrast, buildings circled in red seem to have suffered more damages and are surrounded by more debris.

3.4.1. Damage According to Building Use

The building damage resulting from the BDA was also analysed according to the building use. The event caused substantial damage to services such as electricity, telecommunications, and the health care system. Assessing the state of buildings serves as indicators that can express how societal functions were affected and how recovery is taking place.

The analysis took into consideration basic societal functions, including education, health care, public works, social structure and economy (SJPH, 2014). Figure 3.5 depicts the degree of damages for six categories of buildings. Repair status assists as an indicator of how recovery is taking place after three months of the event, with buildings being fixed and its functions being restored. Furthermore, repair status also indicates how physical vulnerability may change according to the conditions of the buildings. If a next event happens shortly after and no repairs or build back better strategies were implemented, the physical vulnerability of the EaR will be increased depending on the hazard. For instance, houses affected by wind hazard during TS Erika and that were not repaired before Hurricane Maria suffered more damages. Aspects such as design, materials, inadequate protection measures and lack of public information can potentially change vulnerability values.

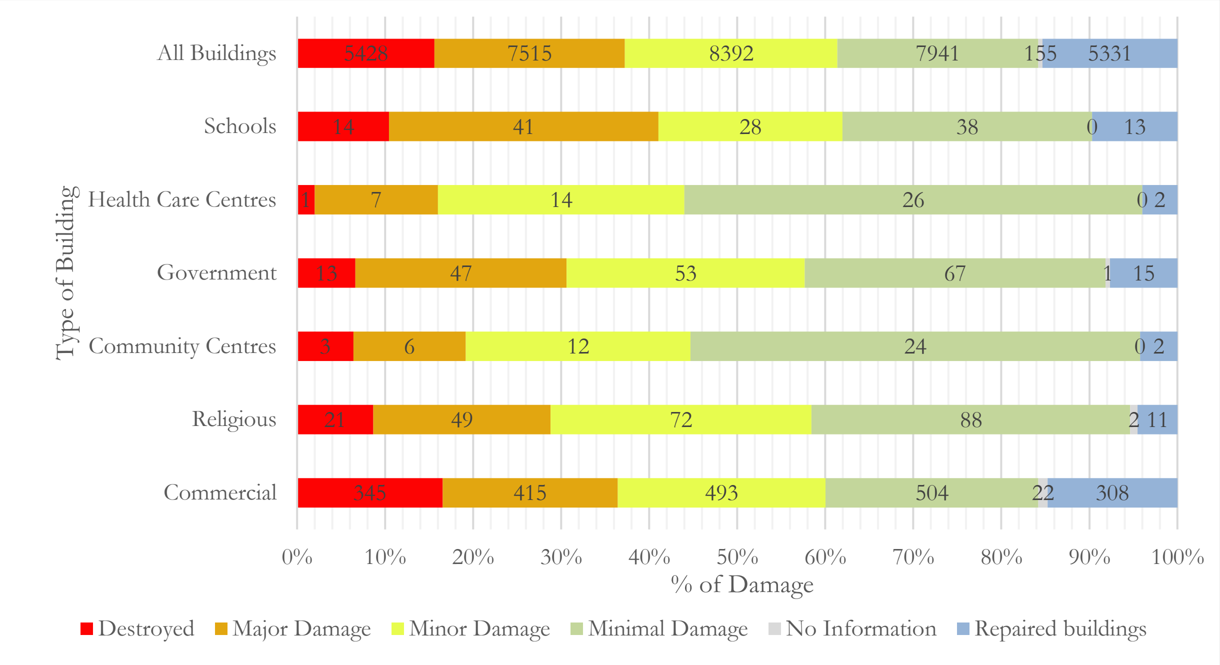


Figure 3.5: Percentage of damage according to the type of building. The numbers inside each bar indicate the number of buildings affected.

Commercial buildings were significantly affected, having the higher number of destroyed buildings. Overall, 17% of the buildings showed signs of being repaired after Hurricane Maria, pointing to a quick start of the recovery process of the activity in a short period. Health care centres suffered mostly minimal damage. Relocation of facilities far from flood risk areas as well as an upgrade of the hospital are long-term actions to be implemented after TS Erika (Government of the Commonwealth of Dominica, 2015), but was not done yet. Repair status showed that only two buildings were being repaired within three months, indicating the recovery of the function was compromised. However, according to the Post-Disaster Needs Assessment Hurricane Maria, the hospital and health centres were emphasized on the recovery needs.

As for school buildings, repair status indicates that only 10% were being repaired within three months. Such percentage may provide an indication that recovery was still slow for this function and a decrease in learning outcomes in short to mid-term might have happened. The Post-Disaster Needs Assessment (Government of the Commonwealth of Dominica, 2017) corroborate such aspect showing that education was interrupted with approximately 95% of the student population not having access to schools until November 2017, almost two months after the event. However, according to the Post-Disaster Needs Assessment recovery strategies prioritised the education sector, rebuilding and repairing schools with minor damage to guarantee continuity of the activities. When in fieldwork, it could be observed schools being repaired.

3.4.2. Analysing Damage Patterns Related to Hazards

Five parishes were chosen for analysing the relation between building damage hazard type, which required the exact position of the damaged building and the linkage with building footprints. This was described in the section on data preparation, and the dataset represented 45% of the buildings on the island. Building footprints were overlaid with the landslide and flood inventory triggered by Hurricane Maria (Van Westen, Zhang and Van den Bout, 2018). Table 3.3 was created to illustrate the number of buildings affected by each hazard type identified in the conceptual framework. The matrix shows buildings that were hit or probably hit by hazards. The number of buildings damaged was assessed by both the BDA and by the building footprint since there are differences in the total number from both databases. The building footprint has 38.534 buildings in comparison to 29.434 from the BDA.

Table 3.3: Matrix of the number of affected buildings by damage classification x hazards inventories. The number outside the brackets represents damaged buildings considering only damage points from the BDA. The number in brackets is the number of buildings affected considering only the building footprint.

HAZARD PARISH	Flooding	Debris Flow	Debris Slide	Rock Fall	Wind Hazard	Coastal Hazard
Total of 5 Parishes	**756 (825)**	**19 (41)**	**25 (83)**	**1 (2)**	**5140**	**374**
Minimal damage	140	6	7	0	1292	74
Minor damage	228	5	4	0	1576	121
Major damage	208	6	3	0	1372	104
Destroyed	177	2	11	1	889	72
Others	3	0	0	0	11	3
St. George	**192**	**2**	**5**	**0**	**2528**	**32**
Minimal damage	23	0	1	0	770	1
Minor damage	51	0	0	0	787	7
Major damage	85	2	1	0	655	15
Destroyed	33	0	3	0	311	9
Others	0	0	0	0	5	0
St. Luke	**191**	**1**	**0**	**0**	**351**	**169**
Minimal damage	47	0	0	0	109	36
Minor damage	66	1	0	0	128	63
Major damage	41	0	0	0	67	44
Destroyed	34	0	0	0	43	24
Others	3	0	0	0	4	0
St. Mark	**5**	**7**	**8**	**0**	**425**	**98**
Minimal damage	1	3	1	0	100	24
Minor damage	3	1	2	0	104	25
Major damage	1	2	2	0	151	24
Destroyed	0	1	3	0	70	25
Others	0	0	0	0	0	0
St. Patrick	**233**	**9**	**12**	**1**	**1536**	**25**
Minimal damage	58	3	5	0	272	6
Minor damage	67	3	2	0	471	6
Major damage	39	2	0	0	389	9
Destroyed	69	1	5	1	402	3
Others	0	0	0	0	2	1
St. Peter	**135**	**0**	**0**	**0**	**300**	**50**
Minimal damage	11	0	0	0	41	7
Minor damage	41	0	0	0	86	20
Major damage	42	0	0	0	110	12
Destroyed	41	0	0	0	63	11
Others	0	0	0	0	0	0

Wind and coastal hazard were not mapped in the landslide and flood inventory from Maria. Fieldwork information served as a basis to obtain the number of affected buildings for these hazards. Buildings close to areas where a pattern of coastal damages was observed were considered when assessing the number of damaged buildings. Buildings damaged by wind hazard were considered by analysing areas where no hazards were mapped on the inventories but the BDA still reported that the building was damaged. Then, the assumption is that wind hazard had a significant impact on the area. There is, however, uncertainty in the number of buildings affected by wind and coastal hazards due to this factor.

Table 3.3 shows that landslide processes did not have a very direct contribution to the building damage. Although, during fieldwork, it could be verified that the number of buildings damaged by debris flows was significantly higher than analysed. As consulted in the recovery database a total of 77 buildings (out of 212 investigated) were affected by debris flow compared to only 19 analysed in Table 3.3. For instance, the area of Dubuc was mainly affected by debris flows and flooding, but the inventory mostly shows flooding as the main hazard occurred in the area. Figure 3.6 portrays information on the area of Dubuc together with the landslide and flood inventory and the recovery database.

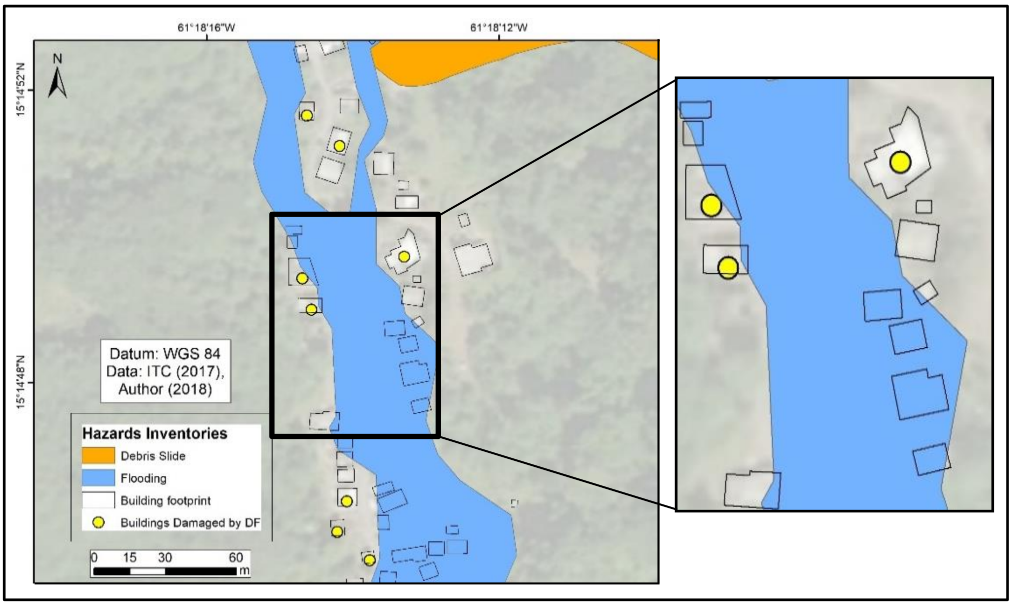


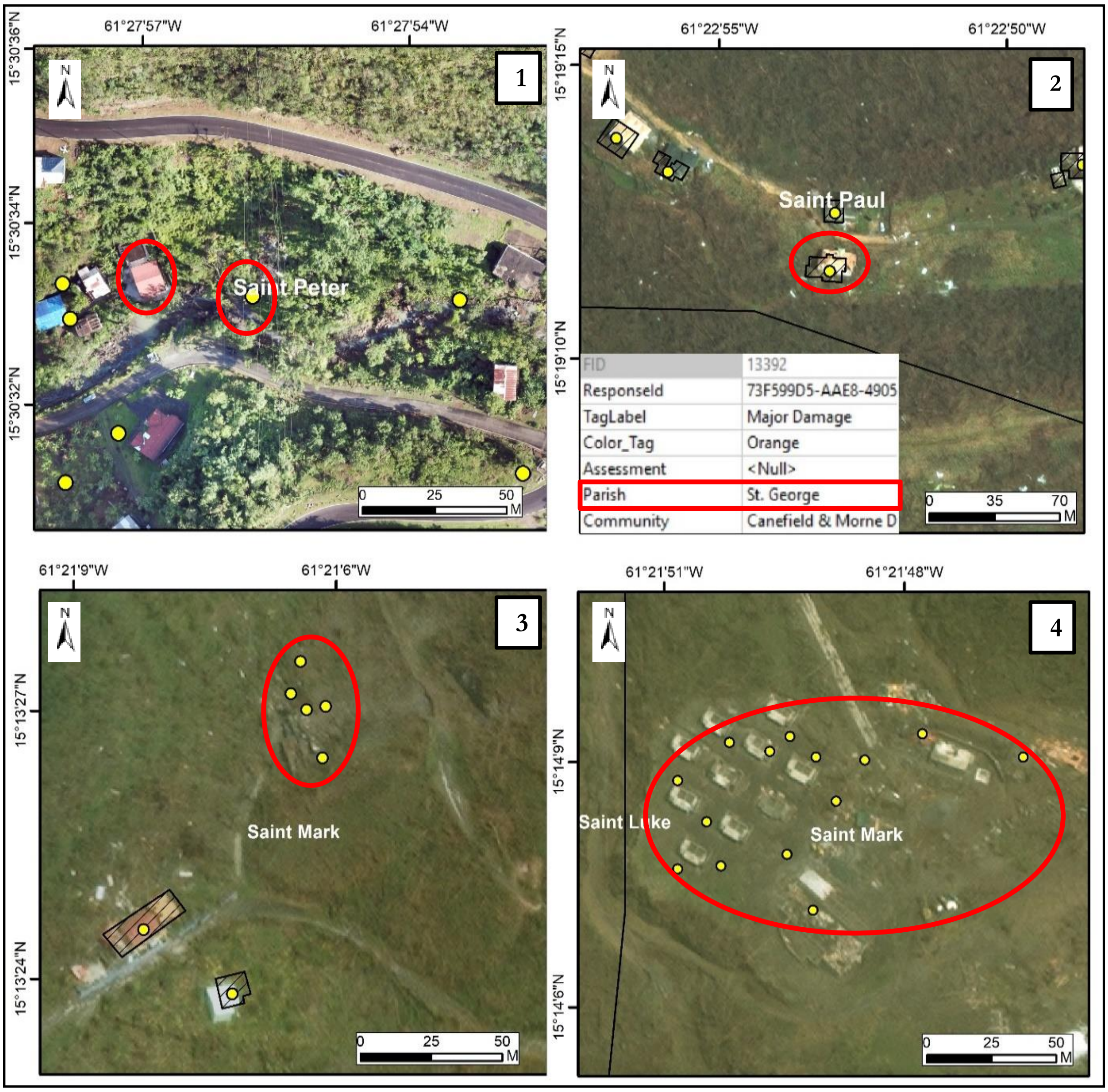
Figure 3.6: The area of Dubuc overlaid with the hazard inventory, building footprint and recovery database. The figure show buildings damaged by debris flow (DF) verified on the recovery database but the hazard inventory depict them as mostly affected by flooding.

Figure 3.6 illustrates that buildings were mostly affected by flooding. The hypothesis is that it is challenging to identify and separate flooding and debris flow from satellite images (Pierson, 2005), and polygons mapped by flooding could also have been affected by debris flows. Therefore, the landslide and flood inventory may not have properly distinguished between these hazards for most areas, depicting in many cases that buildings were affected mostly by one hazard type. Consequently, category flooding had an increase in its number and landslides processes had a decrease.

Wind hazard was expected to be the one with the highest number of buildings affected amongst hazard types, responsible for around 81% of damaged buildings on the BDA. Some areas, although, had more damage than others due to physical and environmental features that offered some safety against it. Pointe Michel, for instance, is surrounded by hills that offer natural protection. Hence, vulnerability of buildings for this hazard decreases and less damage is expected in the area, the opposite of parish St. George. Flooding also represented a major hazard for all parishes, with 11% of representation amongst the hazards described.

3.5. Errors

During data preparation, it was noticed that many building damage points were not properly mapped and errors such as positional and attribute accuracy were common amongst the 29.434 points mapped. As discussed in section 1.6.1, mapping occurred with the use of a tablet (with inbuild GPS) and paper forms, which could have led to errors varying from human to machine mistakes. Aspects such as satellite positioning, 3D positioning, space segment errors or even due to the receiver's equipment or environment could be related to the errors (ITC, 2012). Figure 3.7 illustrates some of these errors.



FID	13392
ResponseId	73F599D5-AAE8-4905
TagLabel	Major Damage
Color_Tag	Orange
Assessment	<Null>
Parish	St. George
Community	Canefield & Morne D

Figure 3.7: Different type of errors found on the BDA. Frame 01 illustrates positional error. Frame 02 shows attribute accuracy error. Frame 03 displays damage points where there are no buildings. Frame 04 illustrates possible error from the building footprint data, where no building footprint exists on the area.

The first error encountered was of positional nature. When performing data preparation it was observed that some damage points were mapped where no building existed. Several points were found with these errors, some with over 10 kilometres distance from the nearest building. The solution for these errors was to create a certainty field that would tell if the point belonged to the nearest building or not based on attributes from the BDA and the building footprint. Figure 3.7 frame 01 displays this error.

The second error met was the attribute accuracy, affecting nominal data. During analysis, some points presented different parishes' names from where they belonged. The error generally happened close to the borders of the parishes, where boundaries are difficult to be visualised. Even though, some points were found that were misclassified with parishes that are not adjacent to each other. The errors can be attributed to human faults and were fixed manually. Figure 3.7 frame 02 shows a damage point with the attribute parish described as St. George when the point is located in parish St. Paul.

The third error found was the non-existence of buildings where damage points were mapped. In this case, damage points were assigned to non-existent houses when checked in satellite images. Building footprints could also not be found on the location. Human error is possible in this case and a second hypothesis is that the error falls in the systematic error category from positional accuracy, due to malfunctioning of instruments, leading to a dislocation of the point. Since the satellite image used to examine the image from this error is dated from after Hurricane Maria (retrieved between September and October 2017), the supposition of outdated satellite images not depicting the buildings can be discarded. Figure 3.7 frame 03 illustrates five damage points from the BDA where there are no actual buildings depicted on the satellite image.

The fourth error discovered was the non-existence of building footprints in locations where there are damaged buildings recorded. For this error, damage points were mapped on a site where no building footprints existed, not even within a certain distance. Satellite images (retrieved between September and October 2017) prove there are buildings in the location. It is likely that this error is from the building footprint, being a location that was not mapped since damage point was performed between November 2017 and January 2018. Figure 3.7 frame 04 depicts an area showing damage points where there are buildings, but no building footprint mapped.

Another specific type of error found was that some areas were not mapped at all. The assumption is that since it is stated that post-disaster redevelopment or new development of areas identified as "special disaster areas" (i.e. special areas due to constant risk from natural hazards) is discouraged, no building mapping occurred in the area. An example is the area of Petite Savanne, a community that was hit by TS Erika, and where a great number of houses are abandoned. According to the Physical Planning Division, the population of the area was supposed to be relocated to a new settlement being constructed in Bellevue Chopin, west area from Petite Savanne, where houses were being built to accommodate disaster affected population.

Furthermore, the number of buildings affected based on the BDA data differs significantly compared to the number of buildings affected in the building footprint. A supposition is that since the creation and update of the building footprint in Dominica, the built-up environment has changed, and some buildings might not have been there when the BDA was mapped, causing a difference in the number of buildings of each dataset. Therefore, considering such aspect and also that the BDA did not mapped some areas of the island, the number depicted on the BDA could be indicated as an underrepresentation of the actual number of buildings in the island.

4. VALIDATING PRE-EVENT HAZARD MAPS

A major disaster such as Hurricane Maria also is the "proof of the pudding" with respect to the hazard maps that are made for the various hazard types. This chapter addresses the analysis of how these hazard maps were validated by comparing them with the actual damage, either mapped through the building damage assessment (BDA) or the mapping of landslides, floods and debris flow.

4.1. Validating the Wind Hazard Map

In order to predict the spatial variation of wind speeds, it is important to have a reliable wind hazard map. There is a wind hazard map generated for Dominica in a multi-hazard study from 2006 carried out by the United States Agency for International Development (USAID). A numerical modelling of hurricane motion served as a base for the methodology, which considered procedures for calculating wind loads with information on topography, surface roughness and wind speeds. Then, the wind hazard map was created based on a GIS generalisation of these actions at an appropriate scale (USAID, 2006).

The existing wind hazard map contains five classes varying from very low, low, moderate, high and very high wind speeds. Wind data was consulted for the island of Dominica through the Global Wind Atlas (2019), pointing out that higher speed winds occur mostly on the west and south part of the island, with values above 7.50 m/s. The methodology used on the Global Wind Atlas is based on a downscaling process from topographic, orographic and surface roughness dataset. A generalization method is also used to achieve the results.

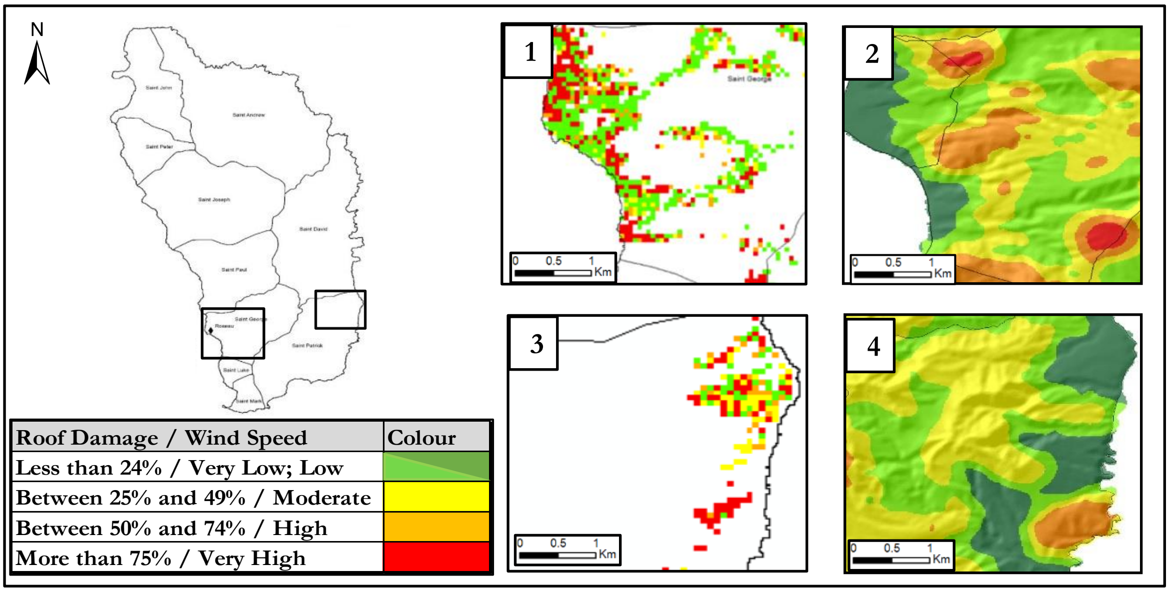
Many variables have a role in wind hazard building damage patterns, but literature confirms that structural roof failure is usually the first sign (Mehta et al., 1983; Kopp et al., 2017). Based on it, a correlation between wind speeds and building damage classes was done to examine the likeness of damage occurring related to the wind hazard map. It is important to notice that natural variability also has a significant role when assessing damage patterns.

Validation of the existing hazard map made use of roof damage as an approach to compare with wind hazard on the island. Roof damage is classified in four classes on the BDA: less than 24%, between 25% and 49%, between 50% and 74% and more than 75% damage. A quantitative analysis of the number of damaged buildings correlating roof damage class with wind speeds was also performed by spatially joining information from the BDA with the wind hazard map. Table 4.1 illustrates the equivalence of roof damage with wind speeds and the amount of damaged building to each combination of the classes. Colours were assigned to ease the process of validating the hazard and relate to the existing colours of the wind hazard map.

Table 4.1: Correlation between damage class with wind speeds and the number of the damaged buildings.

Damage Class / Wind Speeds	Very low	Low	Moderate	High	Very High
Less than 24%	4627	3947	970	350	4
Between 25% and 49%	1887	1602	406	125	0
Between 50% and 74%	1654	1465	477	156	0
More than 75%	4203	4949	1703	430	4

Additionally, to explain the influence of wind hazard, a map depicting roof damage was created and compared to the wind hazard map. Figure 4.1 depicts parts of these maps for the areas of Roseau and La Plaine and compare the influence of wind before and after Hurricane Maria.



Roof Damage / Wind Speed	Colour
Less than 24% / Very Low; Low	🟩
Between 25% and 49% / Moderate	🟨
Between 50% and 74% / High	🟧
More than 75% / Very High	🟥

Figure 4.1: Two areas are depicted in the images: the area surrounding Roseau, parish St. George (frames 1 and 2) and the area surrounding of La Plaine, parish St. Patrick (frames 3 and 4). The images represent a comparison between the roof damage map (frames 1 and 3) and the wind hazard map (frames 2 and 4). The legend is common to both maps since it is a correlation between roof damage and wind speed.
Source: (USAID, 2006); United Nations Development Program - UNDP (2018).

Validation of the wind hazard map took into account an analysis of both maps and the number of damaged buildings, as depicted in Table 4.1. When analysing frame 01 in Figure 4.1, it is established that the area of Roseau is a mix of "less than 24%" and "more than 75%" of roof damage. When considering the equivalence made between both classifications depicted in the legend, the class "more than 75%" damage correlates to "very high" wind speeds, which is not accurately represented in the wind hazard map. The same example is applied to the area of La Plaine, where the southeast part of the area is mainly composed of the class "more than 75%" of roof damage (frame 03), while frame 04 is mainly composed of "very low" and "high" wind speeds. Furthermore, Table 4.1 illustrates that 4.203 buildings with "more than 75%" damage to the roof are depicted as "very low" wind speed class, which does not represent reality. Meanwhile, only 4 buildings in the "very high" wind speed class sustain "more than 75%" damage to the roof, illustrating that the wind hazard map does not correlate well with the roof damage map.

Most areas of Dominica do not present a built-up environment. Therefore, validation of the wind hazard for the entire island is limited to the such areas. Analysing the rain forest damage, which was significantly high during Hurricane Maria, would also be a suitable validation method. Although, it would require a much more detailed assessment of forest damage over the island, which is not available.

When validating the wind hazard map, a point to be considered is that direction of hurricanes and tropical storms hitting the Caribbean are generally from the east to the north-west. Considering such information the variability in damage patterns between the wind hazard and roof damage map related to wind direction can be diminished. Further information of the directional aspect for hurricanes in the Caribbean can be seen in Annex 05, depicting a hurricane tracking chart with the events that occurred in 2017. Nevertheless, even when considering natural variability for the creation of the wind hazard map, most of the areas do not present correlation with the roof damage as observed during Hurricane Maria. An updated wind hazard map is suggested. Both wind hazard and roof damage maps are shown in Annex 06.

4.2. Validating the Flood Hazard Map

A second map that can be validated after the occurrence of Hurricane Maria is the flood hazard map. The map was created considering records on daily rainfall to determine the rainfall depth for 5, 20 and 50 years. Then, design events were made to simulate flood dynamics using a modelling software. A model dataset based on a DEM was built. Such DEM was available in 5-meter resolution, being resampled to 20 meters to the creation of the hazard map. Main rivers were digitised and had to be corrected because they did not coincide with the DEM. A building map for Roseau and a shapefile of the road map were utilized, as well as a digitized soil map and land cover map (Jetten, 2016).

An analysis of the flood hazard map was made along with the flood inventory (see Figure 1.2) to check the degree of correlation. Figure 4.2 illustrates part of the flood hazard map overlaid with the flood inventory. The flood hazard map depicts five classes that demonstrate the return periods, varying from 5, 10, 20 and 50 years return. It translates into low, moderate, high and very high flood, respectively. The flood inventory only depicts the occurrence or not of flooding on the island. Thus, validation on the areas depicted as flooded on the inventory compared to the flood hazard map can be made.

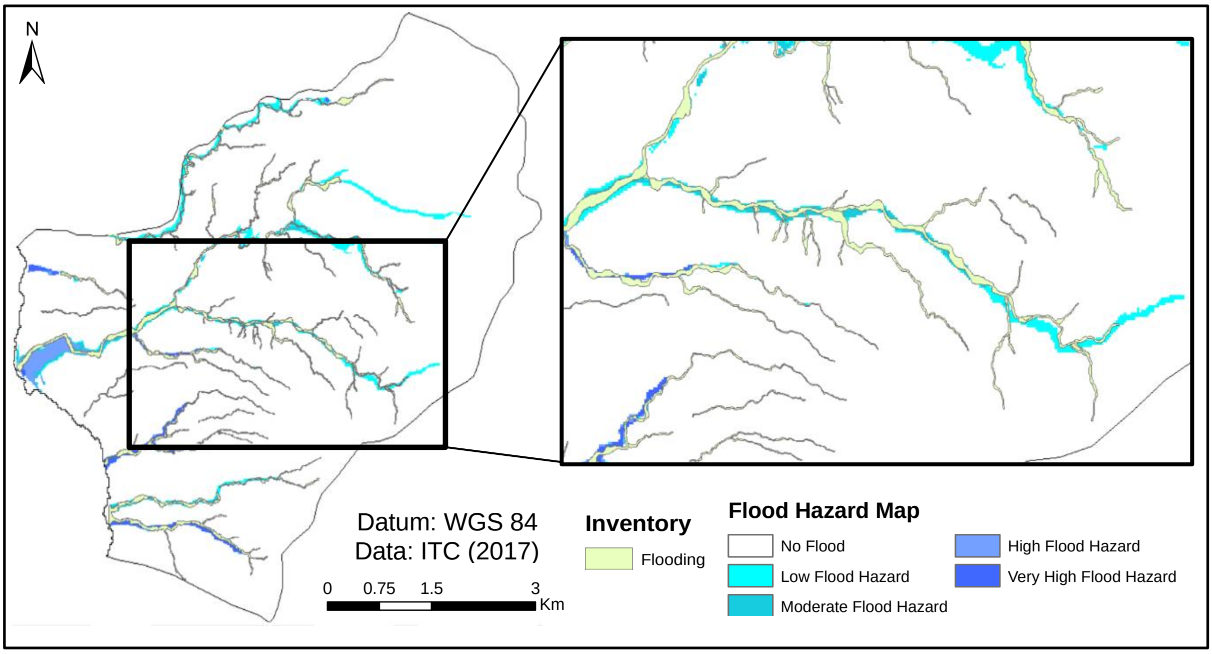


Figure 4.2: Overlay of the flood hazard map and the flood inventory in parish St. George. The zoomed frame shows the central area of parish St. George and how the inventory correlates with the flood hazard map.

The studied areas of St. George, St. Luke, St. Mark, St. Patrick and St. Peter present good visual overlays overall, depicting areas that were in fact flooded. Nevertheless, the situation is not the same for other parts of the island. The northeast part of parish St. David and the east and northeast part of St. Andrew, for instance, are represented in the flood hazard map but did not experience a flood according to the Maria process inventories. The same condition happens on the contrary to some other spots. Annex 07 displays the entire map of Dominica created to show the flood hazard and the flood inventory where such aspects can be seen.

Verification of the overlay was made through a quantitative analysis of the area modelled in the hazard map compared to the area observed to be flooded. The software ILWIS was used to obtain the results. Only flood and debris flows processes from the landslide and flood inventory from Maria were considered. The inclusion of debris flows processes when considering the analysis of flooded areas is explained in section 3.4.2. To obtain the results, first, the area for each class from the flood hazard map was calculated and a cross operation with the flood inventory was performed, obtaining the area flooded in each hazard class. Then, an attribute map was created depicting flooded areas from the inventory. A cross operation was made between the flood hazard map and the attribute map to extract information on the area modelled and flooded, as well as the area not modelled and flooded. The results can be seen in Table 4.2 and Table 4.3.

Table 4.2: Area flooded (inventory) correlated by each hazard class (flood hazard map).

Hazard Map	**Area Flooded (Inventory) (km^2)**
No Flood	8.5
Low Flood	2.4
Moderate Flood	1.3
High Flood	0.81
Very High Flood	2.5
Total (km^2)	**15.51**

Table 4.3: Information on areas modelled (flood hazard map) and flooded.

	Flood Hazard Map
Area modelled and flooded (km^2)	7.01
Area modelled and not flooded (km^2)	38.52
Total (km^2)	**45.53**

	Flood Inventory
Area modelled and flooded (km^2)	7.01
Area not modelled and flooded (km^2)	8.5
Total (km^2)	**15.51**

The results indicate that the area modelled as “no flood” and flooded (inventory) represents the largest area from the classes on the hazard map, with 8.5 km^2, already indicating an insufficient reflection from the flood hazard map. Moreover, the total modelled area is 45.53 km^2, but only 7.01 km^2 was actually flooded (inventory), which also indicate an underrepresentation of the flood inventory. Such underrepresentation can be seen in Figure 4.2 and is further discussed in this chapter.

Furthermore, during fieldwork in Dominica, in discussion with the population and examination of the structures, it was noted that some of the buildings had sustained flooding damages but were not mapped on the inventory. The centre of Roseau, along the Roseau River, is one area where it could be verified from marks on buildings that suggested they were damaged by the last event. A visual image interpretation from high-resolution satellite images was also made and it was difficult to recognize urban areas that were flooded.

To provide more reliable results, a correction of the flood inventory was made for the areas where it was noted to be inaccurate based on observations in the field. Figure 4.3 shows two maps of the centre of Roseau with flooding events overlaying the building footprint and the modelled flood area.

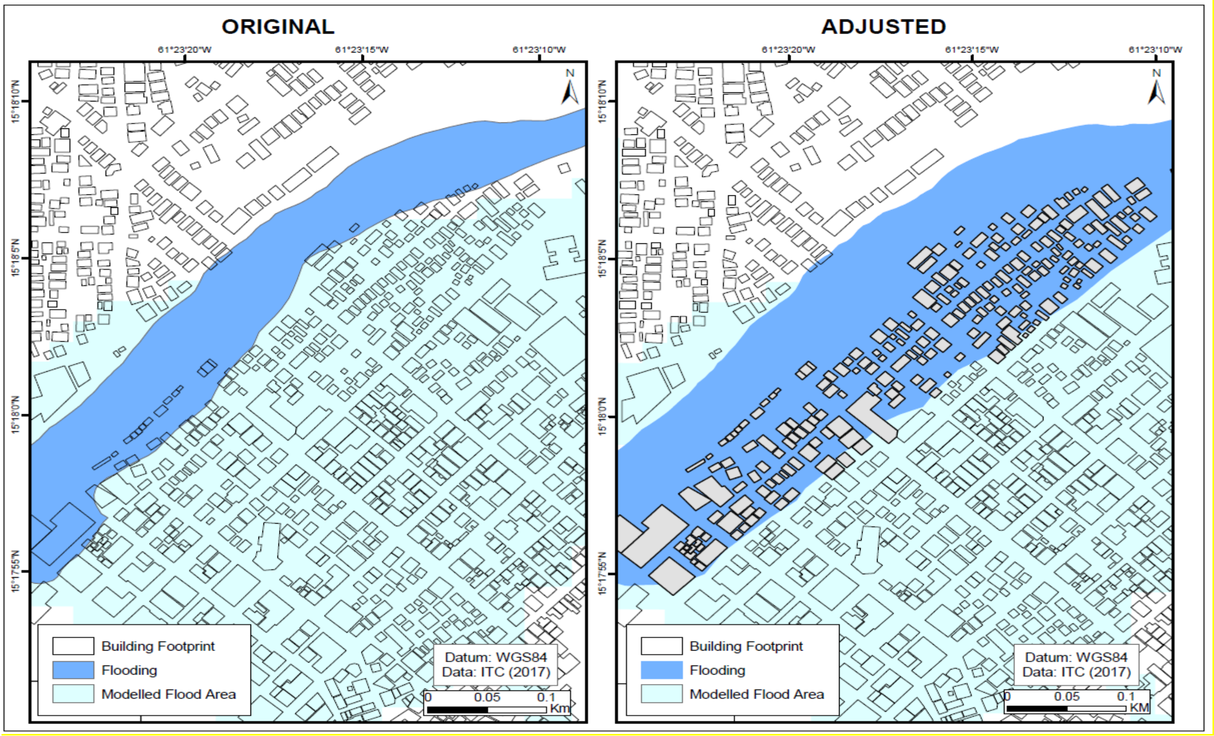


Figure 4.3: The left map depicts the original flood inventory and the right map shows the adjusted flood inventory, where more buildings are affected. Both overlaid the building footprint and the modelled flood area. Buildings in grey indicate the EaR affected that were not counted in the original flood inventory.

As can be seen in Figure 4.3, the flooded area was underrepresented, depicting only 46 affected buildings on the original dataset compared to 237 buildings on the adjusted map. The second point of corroboration is the modelled area that depicts an area modelled as flooded. Hence, the flood inventory can be seen as an underrepresentation of the hazardous process occurred during Maria. To support the adjustment of the flood inventory, satellite and UAV images were examined displaying sediments filling the streets. As stated by Dai et al. (2010), the deposit of sediments is a process often accompanied by flooding events, supporting the hypothesis that the area depicted in Figure 4.3 suffered from flooding. Annex 08 shows UAV images provided by private citizens depicting the area of Roseau City Centre affected by flooding.

4.3. Validating the Landslide Hazard Map

As for the landslide category, a susceptibility map along with the landslide inventory were used to check the degree of accuracy of where landslides happened and the landslide free areas. The process of validation of a landslide susceptibility map is dependent on factors such as input data, model, study area, amongst others (van Westen et al., 2017). The analysis validated the susceptibility map with the landslides that were triggered during Hurricane Maria.

The susceptibility map was created by analysing causal landslides factors using statistical modelling with Weights of Evidence (WOE), which shows how strong evidence support a hypothesis. In this case, the importance of the factor classes such as slope direction, elevation, slope steepness, amongst others was tested for the creation of the final susceptibility map. Relevant causal factors were determined through a contrast factor to measure the importance of the factors causing landslide occurrence. They were utilized for the final susceptibility map that was created using Spatial Multi-Criteria Evaluation (SMCE), a knowledge-driven method. In the SMCE, a criteria tree was used to combine and order the factor maps according to the expert knowledge, resulting in the final susceptibility map (van Westen, 2016). The accuracy of the susceptibility map was checked according to the areas depicted in the susceptibility classes and the occurrence of landslide processes after Hurricane Maria. Figure 4.4 illustrates the area of Bagatelle and Petite Savanne depicting the susceptibility map and the landslide inventory from Maria.

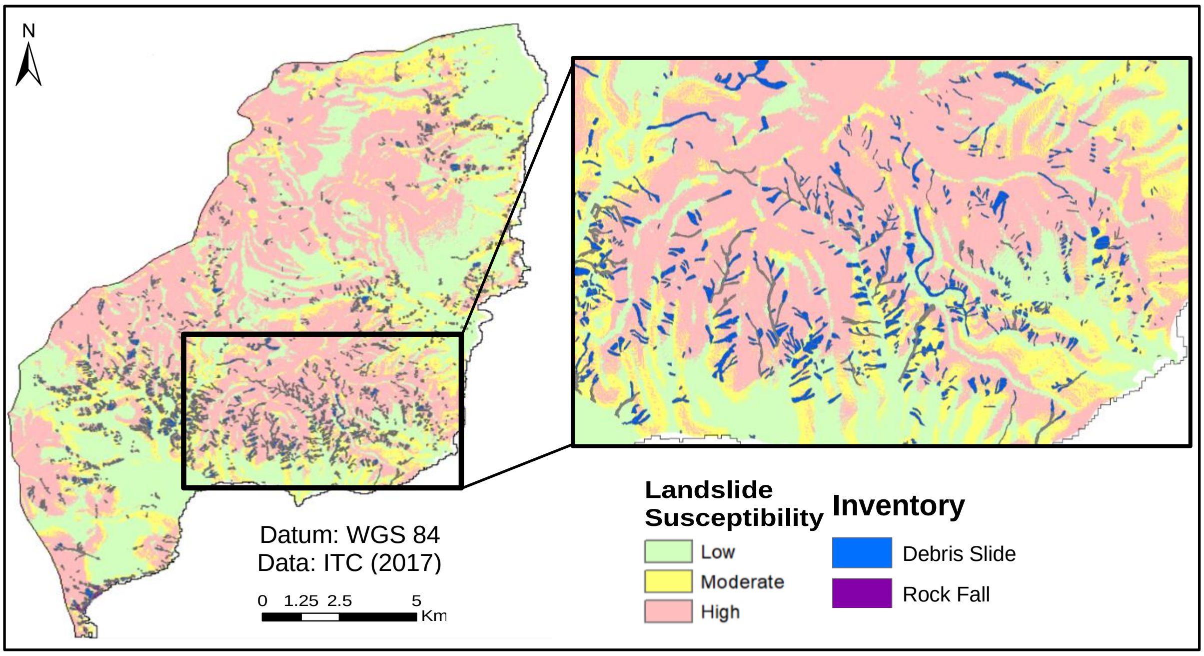


Figure 4.4: Parish St. Patrick with the landslide susceptibility map overlaid with the landslide inventory. The zoomed frame in the areas of Bagatelle and Petite Savanne shows debris flows, debris slides and rock fall processes relating to the susceptibility map.

Validation of the landslide hazard map was made through a quantitative analysis to obtain their characteristics related to susceptibility classes. The landslide inventory from Maria was overlaid with the susceptibility map using the software ILWIS. Landslide processes were separated on the software so that the data could be rasterized and an attribute map created. The map depicted information of only landslide processes, excluding debris flows processes since there is difficulty in identifying and separating them from flood processes, as explained in section 3.4.2. Then, a cross operation was performed between the susceptibility map and the attribute map, providing the information depicted in Table 4.4.

Table 4.4: Landslide information related to Maria inventory and the susceptibility map.

	Low	**Moderate**	**High**	**Total**
Number of Landslides	2574	2618	3731	**8923**
Area Susceptibility Classes (km^2)	402.76	156.95	189.45	**749.16**
Percentage of the Map (Susceptibility)	53.76%	20.95%	25.29%	**100.00%**
Area Landslides (km^2)	1.84	2.37	3.58	**7.79**
Percentage of Landslides	23.62%	30.42%	45.96%	**100.00%**
Density (%)	0.457%	1.510%	1.890%	
Number landslides / km^2	6.39	16.68	19.69	**11.91**

Low susceptibility class should depict mostly landslide free areas or, when not, have very low density values. Such class present the smaller number of landslides per km^2 compared to the other classes. The area of landslides is also the smaller, 1.84 km^2. Even though the number of landslides in the class is smaller, it might still be comparable with the number of landslides in the moderate class. However, the susceptibility area is more than two times larger than in moderate, which influences the number of landslides per km^2, giving a final density of 0.457%. The moderate susceptibility class is presented as a zone where landslides are likely to occur, but not with a substantial density, an intermediate zone as illustrated in Table 4.4. As for the high susceptibility class, it is depicted with the highest density, 1.89%, and percentage of landslides, 45.96%, as expected. Such aspects can also be seen in Figure 4.4, showing that most of the landslide processes are contained in the high susceptibility class. These characteristics provide an indication of the reliability of the landslide susceptibility map.

Additionally, it is also important to observe what landslide susceptibility classes represent for spatial planning. An analysis to show the number of buildings located in each class, according to the BDA, was carried out to verify if the number of buildings in each class corresponds to reality. The results are shown in Table 4.5, indicating the number of buildings for five parishes and with certainty that the buildings are linked to the building footprint. Such parishes were chosen as explained in section 3.3.1.

Table 4.5: Buildings exposed to different susceptibility classes for five parishes.

Parish	**Landslide susceptibility classes**		
	Low	**Moderate**	**High**
All five parishes	4916	487	18
St. George	2335	298	10
St. Luke	334	17	0
St. Mark	398	43	4
St. Patrick	1601	83	3
St. Peter	248	46	1

Low susceptibility class should represent no restrictions to planners as for landslides occurring in the areas and the higher number of buildings fall into this class. It is still suggested to check such areas for further hazardous processes. In Dominica, a significant part of the west and east coasts present areas of such class intercalated with moderate susceptibility areas. Intermediate areas, such as the case of moderate class, can be problematic and may be falsely depicted as secure areas. Further detailed studies on landslides are advised. The high susceptibility areas present restrictions with respect to spatial planning and should be avoided for the development of residential areas (van Westen, 2016). In Dominica, such areas are mostly present in the south and northwest parts of the island.

4.4. Summary

The hazard maps were investigated to verify if the information they present reflect on the reality by comparing with the datasets used in this research. A summary of the validation is further presented.

- Validation of the wind hazard map was limited to the built-up area, where damage to the roofs was analysed and compared to the hazard. Even considering natural variability on the wind hazard map, it does not represent, in most of the areas, correlation with the damage caused by Hurricane Maria. An updated version is suggested;
- The flood hazard map was analysed along with the flood inventory, considering flood and debris flows processes. The results indicated that a significant part of the hazard map depicted as “no flood hazard” was actually flooded, according to the inventory. Furthermore, the flood inventory also does not represent the entire process occurred in Dominica. An update of the flood hazard map and the flood inventory are advised to better support planning and mitigation strategies;
- The landslide hazard was verified according to the susceptibility map overlaid with the landslide inventory from Maria. Overall, it depicts a good representation of the reality, where the highest number of landslides occurred in the high susceptibility areas. However, the illustration of runout is suggested.

5. RECOVERY SCENARIOS

This chapter discusses post-disaster recovery and evaluates some of the possible recovery scenarios on the island after Hurricane Maria. It presents and investigates four scenarios: abandonment, government relocation, individual relocation and protective measures. The influences of the scenarios on the risk components are examined and depicted as an overview at the end of the chapter.

5.1. Definition of Post-Disaster Recovery

The term recovery has many definitions according to the literature. Early publications, from 50 years ago, defined it as an ordered and predictable process occurring in linear manners and having the emphasis on the physical reconstruction aspects of the cities, encompassing reconstruction of public infrastructures, buildings and houses relating to the recovery of urban functions, focusing on the return to normality (Haas et al., 1977). Subsequent studies have contested the idea behind this definition. Rodríguez et al. (2007) claimed that recovery is a process that demands the recognition of an extensive amount of factors, such as past disaster experience, access to resources, social status of the population, race and others. Rather, it is an uncertain, complex and difficult process moulded by pre and post-disaster circumstances, that involves aspects of rebuilding, restoring and reshaping social, economic, natural and physical environment. Moreover, Miles & Chang (2003) also discuss the early conceptions of recovery, contesting them with studies that show the influence of social aspects, decision-making processes and conflicts amid groups with different interests. In their work, the term is used as the process of returning to a pre-disaster condition, a perspective often taken by the population affected by a disaster.

A point that must be observed is that trying to restore the community to the condition as before the disaster, implies in replicating former hazard vulnerability. Disaster recovery must be a process that incorporates mitigation measures and strategies that can protect communities from forthcoming events. Interventions on the hazard source, community protection works and BBB practices (UNISDR, 2015) are actions that can reduce the likelihood of events, mitigate impacts and limit EaR exposure to hazards.

Recent definitions of recovery have emphasised the impacts of disasters in the social, economic, natural and physical environment besides incorporating strategies to reduce further risks. Coppola (2015b) defines it as a phase that starts after the immediate response and may take months or years. It revolves in returning the lives of the affected population to normality considering the consequences of the disaster. Lindell (2013) describes disaster recovery as having three interrelated meanings. The first involves restoring community activities to normality such as they were before the event. The second encompasses stabilising the conditions to make communities return to its usual routines. The last is when the community reaches the objective to return to regular habits. Mitigation activities are also integrated into the concept. In its turn, the UNISDR (2009) explicitly incorporate concepts that involve mitigation procedures, encouraging measures such as build back better principles and retrofitting (improvement of current structures to make them more resistant to hazard's effects). It defines recovery as *"restoring or improving of livelihoods and health, as well as economic, physical, social, cultural and environmental assets, systems and activities, of a disaster - affected community or society, aligning with the principles of sustainable development and "build back better", to avoid or reduce future disaster risk"* (UNISDR, 2016).

A significant aspect of recovery is the functional restoration of regular social activities. Urban settings are a complex web of interactions with different groups or layers, going from infrastructures to business activities that influence on social and economic aspects of an urban centre (Bettencourt & West, 2010). In the urban environment, the interactions occurring in the layers fuel the functionality of the system, in what can be related to urban functions. The term is generally related to the operational characteristic of the land, as in the provision of goods and services depend on the land function (Foerstnow, 2017). Although, achieving functional recovery is a more challenging task than physical recovery (Dong, 2012). For instance, hospitals may have their necessary infrastructure rebuilt, allowing them to operate again. Its functionality, though, might not yet be fully restored due to lack of personnel or supplies. Functional and physical recovery will be completed once the hospital is fully rebuilt and restored with supplies and employees

Literature occasionally divided the recovery process into stages or phases, sometimes with a given temporal length. This aspect was criticised due to the dynamicity of the process, with no clear termination point. Dividing it may oversimplify how it happens, masking the real course of recovery (Brown et al., 2015). Nowadays, it is accepted that disaster recovery comprises multiple actions that are implemented during and after the process of recovery. Different aspects of communities have different time length to recover. Hence, Lindell (2013) suggests a four function approach when considering disaster recovery, containing distinct activities in each of it that can occur concurrently or at different times. Table 5.1 illustrates an overview of these functions.

Table 5.1: Disaster recovery functions.

Disaster Assessment	
Rapid assessment	Victims' needs assessments
Preliminary damage assessment	"Lessons learned"
Site assessment	
Short-term Recovery	
Impact area security	Emergency demolition
Temporary shelter/housing	Repair permitting
Infrastructure restoration	Donations management
Debris management	Disaster assistance
Long-term Reconstruction	
Hazard source control and area protection	Infrastructure resilience
Land use practices	Historic preservation
Building construction practices	Environmental recovery
Public health / mental health recovery	Disaster memorialization
Economic development	
Recovery Management	
Agency notification and mobilisation	Public information
Mobilisation of recovery facilities and equipment	Recovery legal authority and financing
Internal direction and control	Administrative and logistical support
External coordination	Documentation

Source: Lindell (2013).

Disaster assessment is recommended to be part of the emergency response phase since it is the function responsible for assessing the effects of the disaster. Short-term recovery emphasises guaranteeing the immediate security of the areas affected, establishing the circumstances in which the process of recovery can start for households and business (Lindell, 2013). A considerable challenge in this function is the provision of shelters and temporary housing for the population affected. Anderson (2012) demonstrates that the hasty development of short-term recovery function may bring undesirable effects, such as people settling in inadequate areas, which influences the quality of the recovery process. Ruiter (2011) also points out that incorporating mitigation measures may affect the speed of recovery negatively in exchange for an increase in quality.

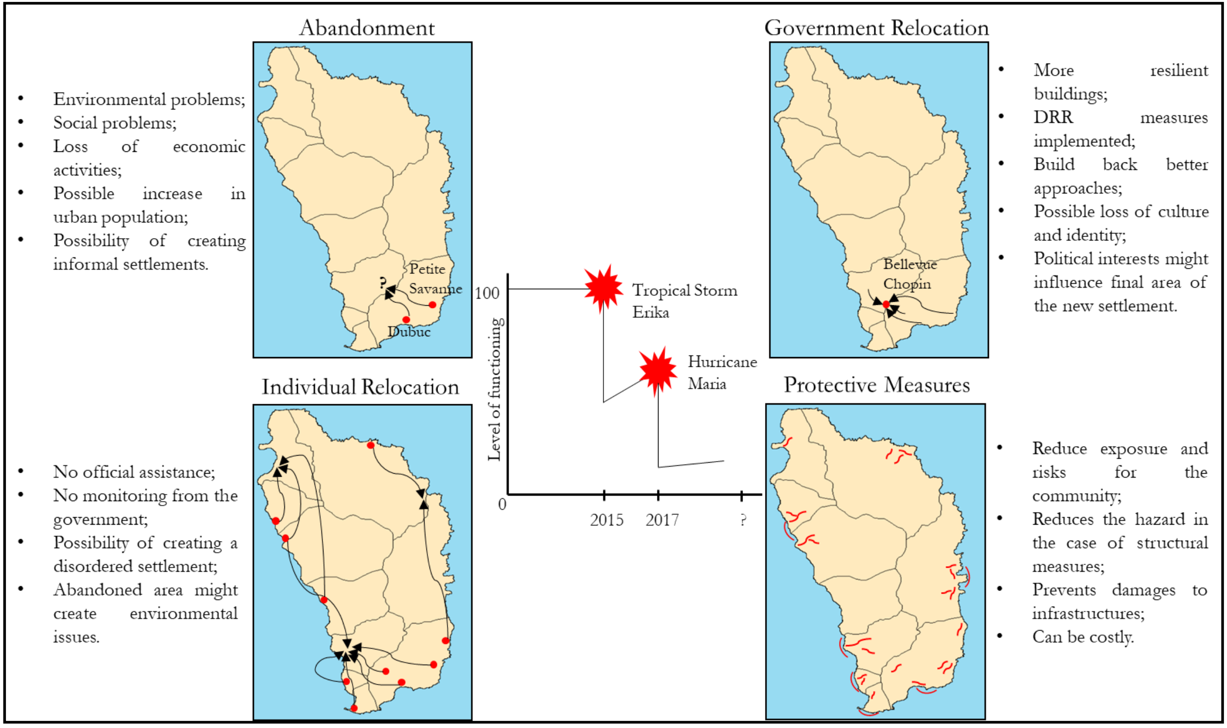
Short-term recovery is the precursor of the long-term recovery function. The last is responsible for managing the reconstruction of the affected area, as well as the economic and political impacts. It is highly dependent on planning strategies and the implementation of adequate policies. Lastly, recovery management is accountable for the management and monitoring of the previous functions, ensuring proper coordination and resources to achieve the respective processes (Lindell, 2013).

5.1.1. Importance of Stakeholders in the Recovery Process

Stakeholder involvement in recovery environments varies according to the context of the disaster. A current challenge is managing different groups and organisations with distinct experiences and logistics after the event occurred. In cases where external help is necessary, it becomes even more difficult, since the local government has to supervise how the resources provided by other countries are to be distributed, while it is still trying to recover from the disaster (Meduri, 2016). To maximise their influence on the environment, different groups must be identified by disaster management. For instance, stakeholders connected to the construction sector can have a significant part in reconstruction and structural mitigation measures, while researchers and scientists can benefit from recovery information acquired in the field (Mojtahedi & Oo, 2012). Furthermore, stakeholders involved in planning play a unique role in retrieving knowledge from previous stakeholders and former scenarios to apply in the recovery of the affected community (Sheykhmousa, 2018).

5.2. Methodology Applied to Construct the Recovery Scenarios

The construction of the recovery scenarios was done based on an integration of the information retrieved during fieldwork, literature review, the datasets and results obtained for this research. Most important were discussions with the staff of the Physical Planning Division of Dominica. The analysis considers how planning alternatives and associated effects influence the recovery of the environment and built-up areas related to natural hazards and disaster events. Four scenarios were conceptualised and presented in Figure 5.1, which also depicts how the functioning of a community works when several events hit the place.



- Environmental problems;
- Social problems;
- Loss of economic activities;
- Possible increase in urban population;
- Possibility of creating informal settlements.

- More resilient buildings;
- DRR measures implemented;
- Build back better approaches;
- Possible loss of culture and identity;
- Political interests might influence final area of the new settlement.

- No official assistance;
- No monitoring from the government;
- Possibility of creating a disordered settlement;
- Abandoned area might create environmental issues.

- Reduce exposure and risks for the community;
- Reduces the hazard in the case of structural measures;
- Prevents damages to infrastructures;
- Can be costly.

Figure 5.1: Schematic representation of the scenarios analysed.

- Abandonment: this took into account areas visited during fieldwork and evaluated in the comprehensive building damage assessment. Additionally, the National Physical Development Plan (Government of the Commonwealth of Dominica, 2016) provided information on areas at risk marked for resettlement that could also be potentially identified as abandoned areas. Spatial analysis on the BDA using the software ArcMap was utilised to execute queries and obtain the number of destroyed buildings;

- Governmental relocation and individual relocation: both relocation scenarios were discussed according to the guidelines from Dominica's National Physical Development Plan and considering areas tagged for relocation after TS Erika. As in the abandonment scenario, the BDA was utilised to retrieve valuable information for the edification of the scenario;

- Protecting communities: as for the protective measures scenario, a limited number of procedures were investigated and discussed considering their potential feasibility on the island. Literature review, the conceptual framework, the hazards inventories and the results obtained were utilized to achieve in which ways and how this scenario would affect EaR on the island.

5.3. Abandonment Scenario

The term abandonment can be interpreted as the act of leaving or withdrawing from a place due to reasons that escape one's control. In Dominica, the abandonment scenario reflects on which areas were the most impacted to the point that desertion could or already happened.

The construction of this scenario takes into account the abandonment of sites due to hazardous events affecting the place, the estimation whether similar events will also occur and considering past events, e.g. Hurricane Maria (2017) and TS Erika (2015). The National Physical Development Plan (Government of the Commonwealth of Dominica, 2016) states that after TS Erika, some settlements were identified as "special disaster areas", locations where there is an on-going risk from natural hazards. In these areas, acknowledged for partial or full resettlement, new development or redevelopment are not to be encouraged, and post-disaster redevelopment is not permitted. Nine areas were recognised as "special disaster areas" after TS Erika: Bath Estate, Campbell, Coulibistrie, Dubuc, Good Hope, Petite Savanne, Petite Soufriere, Pichelin and San Saveur. The scenario was edified taking into account such areas.

According to governmental guidelines, the nine "special disaster areas" were supposed to be resettled, and the population should be relocated following phased approaches. Since resettlement was supposed to occur, some of these areas were expected to be abandoned. Although, during the fieldwork, it could be observed that these areas were not entirely abandoned, like Pichelin, impacted by both last events. Four of these areas were analysed in terms of the number of buildings and occupation after Hurricane Maria, depicted in Table 5.2.

Table 5.2: Comparison between the number of affected buildings and the number of occupied buildings by "special disaster areas" assessed through the BDA.

	Bath Estate	**Dubuc**	**Petite Savanne**	**Pichelin**
Number of Buildings (building footprint)	352	67	332	202
Number of Buildings Assessed (BDA) and linked to the building footprint with certainty	158	0	0	57
Number of Occupied Buildings (BDA)	129	No Information	No Information	57

The areas analysed were chosen based on data preparation, as explained in section 3.3.1. The areas of Dubuc and Petite Savanne were not assessed by the BDA because they were intensely affected by TS Erika, having several buildings destroyed. Therefore, no information on building occupancy could be extracted. The hypothesis is that individual relocation occurred and most of the population moved to what they consider to be safer areas. Furthermore, according to the staff from the Physical Planning Division, the population from Petite Savanne was supposed to be relocated to a new settlement in Bellevue Chopin, but the new resettlement area was still under construction. Nonetheless, partial occupation was still a reality in these areas, inspected during fieldwork. The area of Bath Estate and Pichelin were still significantly occupied, with over 80% of the buildings assessed on the BDA and also investigated during fieldwork.

The recovery database also shows a significant number of occupied buildings for Pichelin and Petite Savanne, with over half of the buildings assessed as occupied. As for Bath Estate, it is a settlement localised in Roseau and not likely to be abandoned. Therefore, even marked to be resettled, government control for such area is difficult to occur. These characteristics indicate that prioritising such areas for resettlement had little effect on the population. To exemplify the occupancy of Pichelin, Figure 5.2 depicts two UAV images provided by private citizens and taken in October 2018, showing the condition of houses.

Figure 5.2: UAV images of the area of Pichelin depicting indications of building occupancy. Yellow circles indicate signs of houses with good conditions, with roofs repaired after Hurricane Maria.

Figure 5.2 shows signs of repaired houses indicating that a part of Pichelin did not abandon the area. Not abandoning houses in risky areas can be explained by social, economic and cultural relations, the major aspects that may impede individuals from leaving such areas. As Wardak et al. (2012) pointed out there is often a significant value of the land or house for the individual living on the site. Figure 5.3 exemplifies a case where the house was not abandoned, even being in an area at risk.

The family was living between the areas of Pichelin and Grand Bay, significantly affected by flood and debris flow processes. The house was not heavily affected by Hurricane Maria but presented structural damages. They decided to stay since it is where part of their economic income takes place and due to the significant value of the place for them.

Figure 5.3: Example of family in a house between the areas of Pichelin and Grand Bay.
Source: (van Westen, 2018).

In such situations, knowledge of the exposed dangers is a factor habitually ignored in exchange of maintaining local needs, culture and the feeling of financial security from an already established economic activity in the community. The number of occupied buildings in the areas analysed (see Table 5.2) is one variable that can substantiate such supposition. Furthermore, an analysis of the recovery database on the number of buildings still occupied in Petite Savanne depicts that from 23 buildings evaluated only three were abandoned. It is important to observe that the area of Petite Savanne presents poor quality road connections, where roads are covered with sediments and debris and the bridge that connects two areas in the region has collapsed. Even though, the area is partially occupied. Figure 5.4 shows the conditions of the roads in the area.

Figure 5.4: Road conditions in the area of Petite Savanne. The area has difficult accessibility and public connection infrastructures are in poor quality.

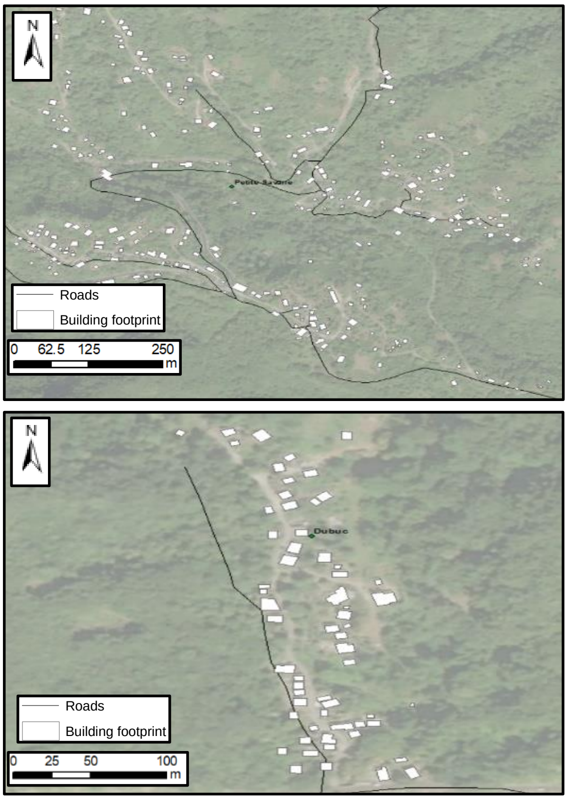
Another significant outcome of the scenario is the role of the abandoned areas for the government. Besides having to assume the economic burdens, some have commercial purposes, e.g. agricultural fields, that provide subsidies for locals and represent the income of numerous families. As stated by Rico et al. (2008), the abandonment of such areas has cultural and economic consequences for the population and the government.

Abandoned areas may often not have the proper management regarding impacts on the environment, which can change conditions for other hazardous events to happen explained in the hazard relationship framework. That can be the case for areas such as Dubuc or Petite Savanne, where no public transport infrastructure were repaired. In such cases, road connection are compromised, impacting people who still live there. Tourism can also have a significant role in this scenario. When investigating the state of buildings in Dominica, encountering abandoned structures that were not occupied through the whole year was a reoccurring situation. These buildings were identified as family houses from Dominicans who do not live on the island but visit during specific periods of the year. These buildings were not quantified on the recovery database but the majority visualised were not repaired after Hurricane Maria. It is important to observe that this people are often not in risk and may not want to abandon the area, which may create further governmental problems. Furthermore, the population may face other hazards since the consequences of an abandoned land may turn into a cycle for the impacts on the environment, as discussed in the conceptual framework.

5.4. Relocation Scenarios

Abandonment is habitually followed up by relocation, planned or individual. Several drivers may put in motion the necessity of displacement of a community. In the case of Dominica, the main reasons for relocation involve the protection of affected population where the community can no longer function by themselves since they were affected by a disaster that impacted public infrastructure on the community (e.g. roads) or because they are threatened by constant hazardous events. The process of relocation can occur as an individual act or a planned action by the government.

In a multi-hazard situation, as is the case of Dominica, the relocation process after TS Erika was strategised to focus on nine "special disaster areas", already discussed in the abandonment scenario. Since the areas of Petite Savanne and Dubuc had no information on buildings assessed on the BDA, it is assumed they were prioritised on the resettlement process after TS Erika and most of the population was displaced to other settlements. This supposition can be investigated through the recovery database, where fieldwork information was investigated to check the occupation of such areas. Figure 5.5 depicts data for Petite Savanne and Dubuc retrieved from the recovery database.



Petite Savanne

- 23 buildings were examined;
- 20 occupied;
- Most of the buildings were hit by flooding and wind hazard processes;
- Physical conditions corresponded with abandoned buildings and precarious road infrastructure;
- 10 buildings marked as repaired.

Dubuc

- 19 buildings examined;
- 1 occupied;
- Most of the buildings were hit by flooding and debris flow processes;
- Physical conditions corresponded with abandoned buildings;
- No building had been marked as repaired.

Figure 5.5: Overview of the areas of Petite Savanne and Dubuc depicting information regarding occupation and infrastructure of the areas investigated through the recovery database.

The area of Petite Savanne had difficult accessibility and most of the buildings could not be examined closely. While only a limited number of buildings could be investigated for the recovery database, they still offer an indication if the process of relocation for these areas was effective. The data show that a great number of buildings in the area of Petite Savanne was still occupied, while Dubuc only had one. Most of the houses in Dubuc were abandoned, indicating that relocation in the last area was more positive than in Petite Savanne. Nevertheless, these numbers must be interpreted with caution, since the number of buildings in such areas are higher and only a limited number of structures were mapped for the recovery database. Moreover, it is difficult to estimate if the population was relocated as an individual or planned action.

The individual relocation revolves in people relocating themselves in other communities or sites where, generally, the population do not expect government assistance for displacement or new housing. Reasons for the process might also include deciding when to leave the area based on the perceived risk they have from the surroundings, affected societal functions, damaged housing and environment. This process is likely to happen without official monitoring of the new community or environment they are inserted on (Ferris, 2011). In Dominica, individual relocation could be identified when in discussion with population and the staff from the Physical Planning Division occurring in Roseau from the areas of Pichelin, Coulibistrie, Scotts Head and Petite Savanne. Since there is no official organization, quantification of the process is challenging and disordered settlements are to be expected as problems that can occur, having direct impacts on the environment (Devi et al., 2017) and possibly changing conditions for other hazards to happen.

A new resettlement area was still under construction in Bellevue Chopin one year after Hurricane Maria, comprising 340 residential units (Housing Dominica, 2019). The area was analysed to assess the potential of housing the affected population of Bath Estate, Dubuc, Petite Savanne and Pichelin. The areas of Bath Estate and Pichelin represent a total of 186 households to be displaced (see Table 5.2). The area of Dubuc and Petite Savanne were not assessed on the BDA. Therefore, the number of occupied houses for these areas was analysed through the recovery database. In both areas, a total of 21 houses were still occupied when the database was constructed. It is important to note that the recovery database provides a limited amount of information and the number can be considered underestimated. The outcome is positive to lodge the disaster-affected communities under this situation. Furthermore, the Government of Dominica already relocated 38 from the 340 residential units to families from Petite Savanne in the beginning of 2019 and the final transfer is estimated to occur in March 2019. The families in need to be displaced from the "special disaster areas" are given such houses with no costs. Other housing projects are still in development aiming at the construction of resilient buildings, such as in Roseau, Portsmouth and La Plaine (Housing Dominica, 2019). Figure 5.6 illustrates the new settlement in Bellevue Chopin where families are already being relocated.

Figure 5.6: The left picture illustrates the new settlement in Bellevue Chopin still under construction. The right figure depicts an example of the design of a house constructed in the new settlement.

As for the individual relocation, it revolves in people relocating themselves in other communities or sites where, generally, the population do not expect government assistance for displacement or new housing. Reasons for the process might also include deciding when to leave the area based on the perceived risk they have from the surroundings, affected societal functions, damaged housing and environment. This process is likely to happen without official monitoring of the new community or environment they are inserted on (Ferris, 2011). In Dominica, individual relocation could be identified when in discussion with population and the staff from the Physical Planning Division occurring in Roseau from the areas of Pichelin, Coulibistrie, Scotts Head and Petite Savanne. Since there is no official organization, quantification of the process is challenging and disordered settlements are to be expected as problems that can occur, having direct impacts on the environment (Devi et al., 2017) and possibly changing conditions for other hazards to happen.

With limitations in funding and large international debt, the support of national development and housing projects has been made effective through a programme of *"citizenship by investment"*. In this case, recovery and restoration efforts are made in a partnership between the government along with investors that build new settlements that will shelter disaster affected population or transport infrastructure in exchange of economic benefits and tax-related incentives on the island. That is the case of the new settlement in Bellevue Chopin, which is being constructed in a partnership with investors from other countries. The programme has been a reality in Dominica and even though it assists developing sectors in need, some impacts may arise from it, such as schemes related to benefits in tax regimes that can be risky and vulnerable realities in view of tax transparency and tax evasion (Scherrer & Thirion, 2018).

Further problems that may arise in Dominica are from political and economic interests that have great roles when choosing such sites (Lindegaard, 2017). Issues with land tenure may arise from such actions, where the land can be held for different purposes that might affect how organised a settlement is. Squatting on public or private lands, for instance, may bring disordered settlements, where no appropriate infrastructure is available (Croix, 2002), influencing on the quality of life of the new and the already established population.

5.5. Protective Measures Scenario

The last scenario analysed considers protecting existing settlements, even when they are located in hazardous places such as close to the sea, or on narrow valley floors of the river coming out of the steep mountains. One of the options is to focus on the further construction of protective measures to guarantee the safety of communities in areas at risk for new hazards. Two measures that could potentially mitigate damages and reduce risks are analysed, which may have an effect on the hazard or in the vulnerability of the EaR.

The development of early warning system (EWS) is a mitigation measure that consists of alert arrangements organised for an area with the aim of preparing local population for a rapid response in case a hazardous event happens. Strengthening EWS in Dominica is a recovery strategy described in the National Physical Development Plan (Government of the Commonwealth of Dominica, 2016). Such systems can act on the whole island, giving people time to escape of risky areas in case of hurricanes and tropical storms, as was studied by Collins & Kapucu (2008), who analysed the use of EWS in providing information for the population, showing the importance of the system alerting for tornado activities. Although, specific warnings for processes such as landslides, debris flows and flash floods are considered difficult, since these may happen very fast and different monitoring strategies need to be taken into account. Figure 5.7 depicts a simple scheme from regions of Dominica where EWS could be applied to prevent flood damages.

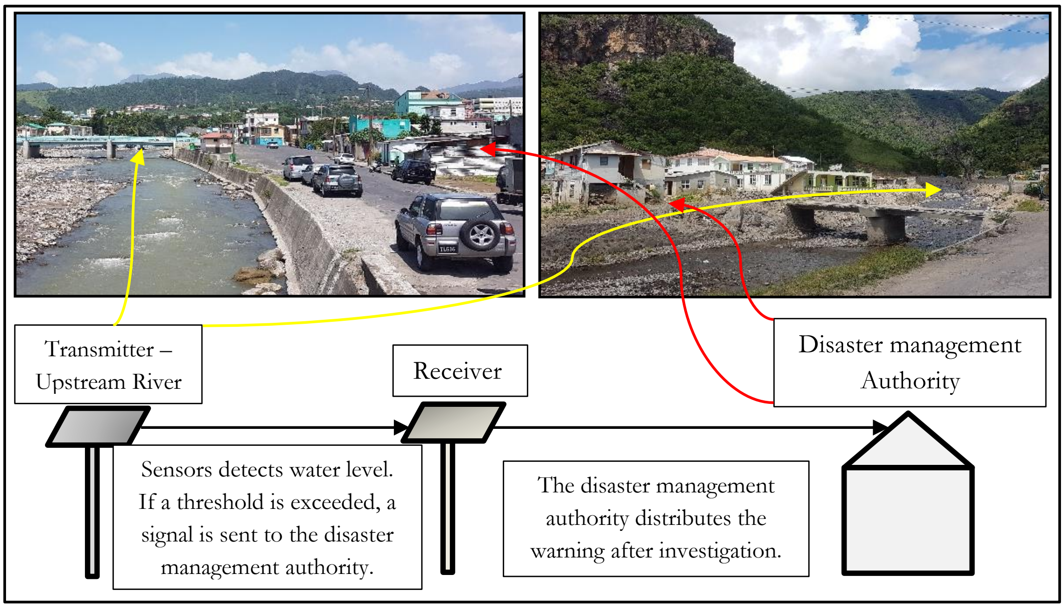


Figure 5.7: EWS applied to two regions of Dominica.

As for the quantification of cost-effectiveness for EWS, it is problematic and relative (Rogers & Tsirkunov, 2010). An important factor is the proper characterisation of the hazards. Dominica presents a multi-hazard situation, and different types of monitoring must take place. As an example, the region of Soufriere was highly impacted by flooding, debris flows and debris slides. A proper EWS would require a set of monitoring systems evaluating the conditions of rivers, slopes, rainfall, amongst other features, to be installed in the area, demanding a high number of personnel and operation schemes. Such aspects can increase the cost for implementation of the system. Moreover, such costs have a direct relation to the frequency of events and the damage associated with it, and the cost-effectiveness is calculated according to the value spent for the system compared to the value of associated damages of an event (Rogers et al., 2010). Therefore, spatial planning is very important when implementing EWS.

A second mitigation measure examined is the removal of sediments from the river valleys that were deposited by debris flows and flash floods during Hurricane Maria. This is also referred to as dredging. It is the act of clearing the bottom and sides of a river, reservoir or harbour from accumulated materials (Jeong et al., 2016), and can also be used for deepening watercourses and conceptualising artificial channels. As discoursed in the conceptual framework, sediment deposition over time can change the morphology of rivers, besides contributing greatly for increasing the river bed and disturbing river flow, which is one of the factors that can intensify the risk of flooding. Due to a multi-hazard situation, the sediment deposition of river channels in Dominica was high, with landslides processes contributing along with the natural process of river transportation (C. Y. Chen, 2009), consequently increasing the risk for flooding events. Considering such factor, along with the shape of the catchment and conditions of rivers, some areas of Dominica presented higher probability for flooding events, e.g. Pichelin. Figure 5.8 illustrates the region of Pichelin one month and one year after Hurricane Maria depicting the process of sedimentation and dredging activities.

Figure 5.8: UAV images depicting the same area of Pichelin. The left figure shows the situation one month after Maria. The right figure illustrates the situation one year after Maria.

Source: UAV images RescUAV / Global Medic (2017).

The area of Pichelin suffered severe sediment deposition on the river valleys, permitting less space for water to run and changing conditions for further hazardous processes. During fieldwork, it could be noted that river valleys had a significant amount of sediments that were being dredged, not only in Pichelin but also in areas such as Coulibistrie and Castle Comfort.

A concern from the population is that the level of the dredging in the area of Pichelin might not be enough to prevent flooding in the next event. Furthermore, dredging may not be a solution for all flooding problems.

Widening river channels allowing more water storage and flow in the river may also increase flood risk downstream (Scottish Environment Protection Agency, 2010). The activity also demands long-term maintenance and is time requiring. Besides, dredged material may accumulate pollutants that need to be disposed properly so it does not impact negatively other areas. Such aspects can increase the costs of dredging (Jeong et al., 2016).

The protective measures scenario considers a limited number of procedures and many more exist to mitigate risks for the community. Landslide mitigation measures may use embankments alongside roads and boulder barriers composed of metal nets as a way of preventing damages to infrastructures and roads; coastal defences, such as seawall, should be improved in the areas of Pointe Michel, Soufriere and Scotts Head to protect houses and public infrastructures; bridges should be reinforced or better designed to prevent damages during flood events; the Guide to Dominica's Housing Standards should be further applied to constructions so that buildings are more resistant to wind damage; river embankments should be made larger where rivers run through settlements, for instance, Roseau. Besides these measures, spatial planning has a significant role in mitigating multi-hazards.

The Physical Planning Division of Dominica exercises the use of existing tools to propose and optimize physical infrastructures, influencing the cities to reduce vulnerability to threats. As spatial planning is directly connected to increasing urban resilience, the development of further methods to determine the safety of an area for reconstruction should be made a priority for Dominica, since the island is hazard prone and effects of climate change have been shifting the frequency of extreme events (Field et al., 2012).

5.6. Summary

It is important to acknowledge that this research considered a limited number of scenarios. Situations where the buildings are built back in the same location but not better and not considering strategies to reduce the risk is also a scenario that can potentially change risk as well. In such case, it infers in repeating the previous hazard vulnerability and a forthcoming event will likely cause as much damage as the first event. Not only buildings, but public infrastructure should also take advantage of BBB as an approach to diminish vulnerability and increase resilience. Another important scenario is considering the influence of damaged vegetation in the long term. Since Hurricane Maria damaged a significantly large part of forests and green areas, loss of vegetation protection might cause Dominica to face landslide and flood hazards in the future, where processes may be triggered with lower rainfall thresholds due to reduced slope stability and the fact that many tree trunks might be carried to river channels. Cascading events may also happen, producing more losses and damages to the communities.

As for the scenarios considered, a comparison between the four set-ups is presented in Table 5.3. Remarking points and the conceptual risk regarding each situation is provided.

Table 5.3: Remarks and risk comparison between different analysed scenarios.

	Abandonment	**Government Relocation**	**Individual relocation**	**Protective Measures**
REMARKS	Loss of land with economic purposes; environmental issues on the abandoned area; social problems.	Settlements constructed to be resilient; disaster risk measures implemented; political interests on choosing sites.	No official monitoring; risk of creation of informal settlements; increasing risk of social problems.	Requires constant monitoring; can be costly; reduce risks.
RISK	**DECREASES**	**DECREASES**	**DEPENDS**	**DECREASES**
Hazards	**Remains the same** Hazards remain high in the coming years until vegetation regrowth.	**Remains the same** Hazards do not affect the relation sites, given that new settlements will have mitigation and risk reduction measures.	**Depends** Depends on the selected location to live.	**Decreases** In the case of structural mitigation measures.
Exposure of EaR (built-up areas)	**Reduces** Fewer buildings exposed.	**Reduces** Value of EaR might increase.	**Depends** Depends on the selected location to live.	**Decreases** If hazard is reduced, also exposure reduces.
Exposure EaR (people)	**No more EaR** People left the area in the case of total abandonment.	**Depends** Depends on the amount of people to be relocated.	**Depends** Depends on the selected location to live.	**Decreases** The amount of EaR can decrease due to EWS.
Physical Vulnerability of EaR	**Increases** Buildings already damaged.	**Decreases** Build back better: lower vulnerability.	**Depends** Depends on the type of new construction.	**Temporal decrease** Depending on the protective measure.

Table 5.3 conceptualises risk for the scenarios. The given classes are estimations of how it can behave in the face of each situation since they have different particularities that change the variables. Individual relocation, for instance, considers factors such as the new location of living, knowledge regarding the new location's hazards, and what type of construction will accommodate individuals. Thus, risk changes depending on the decisions of such citizens. Furthermore, when quantifying risk, it must be acknowledged that parameters vary spatially and temporally. For instance, flooding can have different return periods, each with a different spatial extent and varying in intensity, which impacts on the value of risk (van Westen et al., 2011). As for protective measures, depending on which one to be applied an influence on the hazard or the physical vulnerability can occur, decreasing the risk. For instance, dredging activities will influence the hazard, also decreasing exposure of EaR (built-up areas) depending on the hazard. In the case of reinforcing building structures, there will be an influence on physical vulnerability, diminishing its value. Therefore, it will be dependent on the measure to be applied. Hence, the risk will decrease in three scenarios analysed where two depicts measures that can benefit the population: government relocation and protective measures.

6. DISCUSSION AND CONCLUSION

This chapter discusses the main findings of this research, considering and reflecting over the limitations of data and methods applied to obtain the results. Integration between the results is made to discuss the remarks and the influences on a multi-hazard situation.

6.1. Framework of Hazard Interactions

The developed conceptual framework of hazard interaction can be used to foresee and assess impacts on specific areas and support strategic measures for DRR. It is country-specific, but its application can be refined to a parallel situation as for other islands in the Caribbean in terms of effects on the natural environment. A generalisation of the processes can be done by attributing that impacts on the soil and vegetation may bring similar collateral effects, but the dynamics of the built-up environment will differ, which might require significant adjustment of the framework. Nevertheless, variables such as the intensity of the event triggering hazards and mitigation measures applied to the location need to be taken into account when adapting the framework.

A further question to be addressed is modelling hazard interactions, which was not in the scope of this research. Risk studies often make use of evaluating each hazard independently so that losses can be calculated. However, not considering that such hazards may have overlaps and interact with the environment may be an underestimation of the total risk, disregarding chain effects, for instance. An integrated approach that considers the occurrence of several types of hazards is necessary in the case of multi-hazard environments, such as Dominica. The OpenLISEM model is already used to integrate the occurrence of hazards and comprehend the behaviour of processes occurring on land surface, predicting the changing aspects and dynamics of processes. It is important to observe that models do not lead straight to the hazard, but it allows the obtention of further information about the situation, which can be used to apply DRR measures.

The framework considers the effects of the hazards without further mitigation measures, which might provide uncertainty in further outcomes, specifically in the post-disaster situation. Sediment deposition, damaged vegetation and disturbed soil properties are depicted without having interference, illustrating a worst possible scenario and acting as a cycle where hazards tend to get worse. As could be seen in the field and reported by officials, mitigation strategies are in motion, even though they are not enough. Furthermore, it is important to observe that the relationships between hazards differ according to different periods after the event. Short-term, mid-term and long-term interactions need to consider the outcomes and consequences of the event, having different relationships.

Also rather important are the potential effects of climate change on hazards and extreme events. Due to the size, topography and climate dependent economic activities, the islands of the Caribbean present increased vulnerability to climate change (Taylor et al., 2018). Such influence can impact the intensity, frequency, duration and spatial extent of events (Field et al., 2012), and might have influenced on the level of the sea, worsened rainfall events and storms, producing the damages seen after Hurricane Maria. Since the frequency of extreme events might be altered, the recovery of the natural and man-made environment is also dependent on the timing between successive events, being jeopardised and causing more damages if two hurricanes occur in a small period of time.

6.2. Recovery Process of Build-up Structures and Societal Functions

Dominica was in the recovery process from TS Erika when Hurricane Maria hit the island and the built-up area in some parts was not totally repaired. Post-disaster recovery is generally urged to be a fast process by the population, which might rapidly bring the level of functionality of the community to the normality but may ignore strategies that reduce the risk. It is a process highly dependent on the country's resources, capacity and social features. Still, even though restoring communities to normality is a priority, a perspective often engaged is returning the community to what it was before a disaster (Ruiter, 2011), a mistaken perception that often prioritizes speed over quality of the recovery process, exposing the community to the same vulnerability level as before. Such aspects of recovery are schematically illustrated in Figure 6.1.

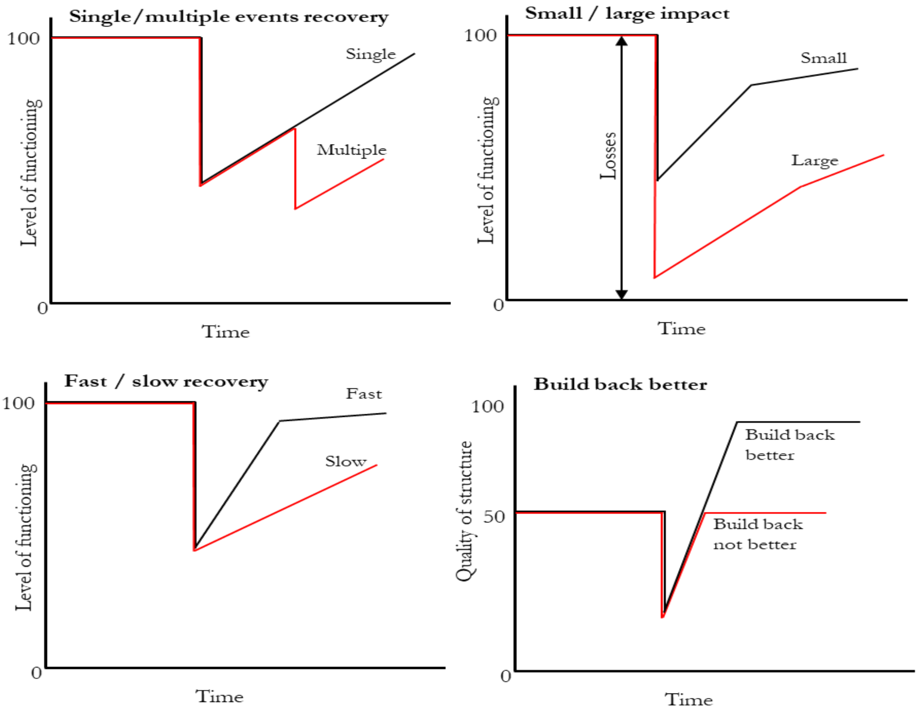


Figure 6.1: Different aspects of the recovery process.

Since Dominica faces financial limitations, the population often starts the recovery process of their communities by themselves and may not implement measures that reduce risks. Furthermore, locations as Petite Savanne and Dubuc were marked to be resettled and had no further investments on public infrastructures from the government, as observed during fieldwork. Such places, where no adjustments or improvement were performed to mitigate adverse effects and were only superficially restored to previous conditions suffered significantly from the impacts of the event.

A further aspect to be examined is the application of BBB practices to enhance the resilience of communities through procedures that improve the physical conditions of the buildings. In Dominica, the use of building code guides showed to be useful in preventing damages in some areas. Still, an updated version was only released in 2018, focusing on damages produced from hurricanes and earthquakes. The updated version is being reinforced by the government, which could not be verified during fieldwork, but the application of the guidelines should reduce physical vulnerability for some hazards and damages in case of the next event.

The damage produced by the last event mostly affected the physical structure of housing and transport subsectors. Great differences in values of damage and losses between Hurricane Maria and TS Erika are recorded. Such differences can be first explained due to the intensity of the events. Hurricane Maria sustained three times more speed winds than TS Erika. Apart from it, public investments could explain why transport subsector was less affected during Hurricane Maria than TS Erika. Still, the island was in recovery from TS Erika when Hurricane Maria occurred, which worsened the situation, making the recovery process slower. As for the housing subsector, such differences can also be explained by the physical vulnerability of the EaR. Buildings hit by the previous event and not repaired had increased vulnerability, presenting losses that could have been avoided in case of a quality process of recovery had been in course.

The damage produced on the physical structures also affected regular societal functions. It is known that reaching functional recovery is depicted to be a more difficult task than achieving physical recovery (Dong, 2012). Hence, basic societal functions were analysed to illustrate how they were influenced by the event. The results depict that the conditions of structures had a direct impact on the functioning of society, as expected. However, only a limited number of basic functions were analysed and upon reflection on the results, damaged structures might not always be the reason for disrupted societal functions. Lack of personnel and government funding can also be portrayed as motives for preventing the regular functionality of schools or hospitals, for instance. Therefore, further investigation of the impacts on societal functions is suggested.

Analysing the recovery aspects was made through datasets varying from the BDA, the recovery database, hazard inventories and further geospatial data acquired from the CHARIM project. In the BDA, damage points were mapped with GPS and errors were often found, such as positional and attribute accuracy. Thus, an edition process had to be carried out to provide more reliability for the analysis. Still, there is still uncertainty with respect to the number of destroyed buildings in the event since no building footprint was used to link the damage points to an existing building. The suggestion is that an improvement on the methodology of collection of data should be done when carrying out building damage assessment. The survey should be made using a building footprint map, as available in OSM, so that errors and uncertainties can be reduced and the number of buildings damaged by different processes can be extracted with higher reliability. Recording damages due to different hazard types should also be considered so that risk reduction measures can be better applied to determined areas.

6.3. Pre-event Hazard Maps

The hazard maps were validated based on damage information obtained from the datasets, as well as the inventory of process mapped from Hurricane Maria. As for the inventory, upon further analysis it could be observed limitations on the database. The inventory was made by analysing high-resolution satellite images from after Hurricane Maria and might not represent the real condition. It could be noted, for instance, that the dataset underestimated the level of flooding in some urban areas. Such limitation can influence when analysing the reflection of the hazard map compared to the real event.

The wind hazard map reflected on natural variability by considering information on topography, surface roughness and wind speeds. Duration of the event and directional changes were not considered for the creation of the map. Nonetheless, the National Hurricane Center – NHC (2019) shows that direction of hurricanes and tropical storms hitting the Caribbean are from the east to the north-west, as depicted by Annex 05. Therefore, damages due to wind direction variability can be diminished considering the hazard map was created for a situation where the event occurred in the same direction. A limitation from this analysis is that it could be done only for the built-up area, mostly on the coast, covering a small part of the island. The reliability of the map in the central part of the island could not be established due to lack of survey of damaged vegetation. Results indicated no correlation with the damage caused by Hurricane Maria. It is suggested an update on the wind hazard map.

The flood hazard map illustrated areas that are not depicted in the inventory, which could have further implications on spatial planning. The results show significant flooded area occurring in parts where the hazard map was modelled as “no flood”. Along with the underrepresentation from the flood inventory, an update for both hazard map and inventory is suggested since the area not modelled and flooded represents 8.5 km^2 from 15.51 km^2 from the flood inventory.

The areas not depicted on the flood inventory and depicted on the hazard map might be related to the intensity since the hazard map shows classes that illustrate different return periods, but the flood inventory only represents the flooded areas. A second reason for differences in both maps could be due to the quality of the DEM used for the creation of the flood hazard map. A low-quality data might not properly represent the river valleys, affecting the final quality of the hazard map, while the Hurricane Maria flood inventory was made from image interpretation and follows the river valleys better.

The landslide susceptibility map, overall, provides a good indication of the reflection of landslide processes in Dominica. An analysis on the number of buildings located in low, moderate and high susceptibility classes depicted that, as expected, the highest number is located in the low class, which has the lowest density of landslides. However, it is important to note that landslides occur on steeper slopes where there are no buildings. Their travel distance might cause significant damages and affect the built-up area located in low susceptibility classes. Moreover, sediments merged in the valleys with the runoff might produce debris flows, affecting more buildings. Therefore, it is suggested that runout is indicated in the hazard map so that a better representation of the potential damages can be depicted.

6.4. Recovery Scenarios

The construction of the recovery scenarios was limited to four situations. Further reflection on the results indicate that the lack of data on areas of Dominica restricts significantly the analysis. For instance, the areas of Dubuc and Petite Savanne were not assessed on the BDA, limiting the analysis to the recovery database, which had a reduced amount of buildings assessed. Areas marked to be resettled were, in most cases, still significantly occupied, indicating the influence of economic, social and cultural aspects in relocation processes. Even though, the abandonment status was evaluated to verify and compare with the conditions depicted from the National Physical Development Plan (Government of the Commonwealth of Dominica, 2016). Results showed that, even under poor quality transport infrastructure for some regions, there were still a significant number of people living in such areas, which relates to social, economic and cultural aspects.

Relocation scenarios are also mainly illustrated by the planned action from the government, with little information on individual relocation. There is a lack of clear guidelines on where to build and information from the government to determine whether an area is safe to be constructed or not. Therefore, individual relocation presents itself as a difficult aspect to be evaluated quantitatively. As for the last scenario, only two measures are portrayed, which limits the scope in terms of mitigation measures to be applied on the island and their influence on the hazards and/or vulnerability of the EaR. Many more protective measures can be further applied, such as embankments alongside roads and reinforcement of bridges to avoid flooding damages.

A limiting aspect of the thesis related to the conception of the scenario was the construction of the recovery database. It assessed 212 building spread on different parts of the island. Some communities had difficult accessibility, which restricted the number of buildings examined. Others had spaced buildings that did not allow examination of a significant number of buildings. Still, the methodology for assessing a damage database such as this needs improvement. Instead of collecting sparse data on several areas, a number of communities should be chosen so that a substantial number of buildings can be evaluated and provide valuable insights as to evaluating the recovery of such areas.

The conception of scenarios is presented as a useful tool for addressing uncertainties, but it should not be reflected as precise predictions since there are many implicit factors influencing the situation that were not accounted for. Instead, it should be addressed as reasonable future settings (Malek & Boerboom, 2015), depicting probable effects that could have distinct outcomes over time.

6.5. Final Remarks and Recommendations

This research presented information towards understanding how post-disaster situations can be further comprehended by making use of technologies widely available for the population nowadays. The integrated use of UAV images along with VGI derived data allowed for private citizens to become substantial sources of geographic information, assisting indirectly on strategic planning for hazard-prone areas. Overall, the results show that integrating both data in the assessment of post-disaster recovery situations can provide useful insights and analysis, but challenges regarding data quality and the methodology chosen remain significant obstacles to explore the maximum potential of such systems in DRM.

A range of problems could be identified from the current approach of using VGI derived data to assess multi-hazard situations. The results show that potential lack of clear rules for the collection of data translates into mistakes in the database, influencing the outcomes. The chosen methodology also needs to be revised for a better understanding of the work to be done. For instance, not using an existing map where damage points could be linked to the buildings was one of the major issues from the VGI database and had a significant effect on the certainty of the number of damaged buildings assessed.

Moreover, the capabilities to perform and understand the methodologies and instructions of mapping from the volunteers need to be verified. The building damage assessment (BDA) made use of volunteers with different backgrounds, where a two days training was given to provide enough information on the topics of damage assessment, GIS and disaster preparedness. However, it is unclear if the instructions provided had an unambiguous and intelligible definition of the attributes to be mapped, especially for the damage classification. Being able to differentiate between similar damage categories, e.g. minimal and minor damage, requires comprehensive instructions and many issues related could be noted during analysis of the BDA.

A further aspect to be examined is evaluating the transparency from communication tools and how user-friendly the mapping software was. Communication must be done simply and easily to understand, providing plain explanation on the use of attributes, symbology and colour codes. The software should be convenient and easy to be learned, facilitating the collection and storage of data (Kerle et al., 2013). These aspects were already acknowledged by the organisers of the BDA and a second version of the damage assessment, named BDA 2.0, was made in December 2018, in Roseau, Dominica. An upgrade of the application used for damage assessment was made, and corrections on the methodology were addressed. Since it is a pilot exercise, further results should be seen in the future.

The results found and discussed on this research have potential use for spatial planning departments and policymakers, who can benefit from the information for proper development of DRR strategies, drawing approaches that will improve resilience and guide proper development of Dominica.

The framework of hazard interactions contributes to a comprehensive analysis of the influences of the natural and built-up environment and could be utilised as a tool to identify areas at risk on the island, foresee and reduce vulnerability to the threats presented. The analysis of the building damage assessment has potential use to identify areas heavily affected during Hurricane Maria and reflect on the vulnerability and recovery of such areas present. As for the validation of the hazard maps, it reflects on the reliability of such tools to provide information that helps the population to be aware of the risks in a specific area. Verifying the reliability of such maps helps planners to know where resources should be invested and the use of an outdated hazard map may illustrate an inadequate use of such resources. Furthermore, the comprehension of the post-disaster situation through recovery scenarios can address uncertainties and provide evidence to identify where possible efforts should be applied to improve public infrastructure and increase the resilience of communities. Risk will be decreased for three of the scenarios analysed, where two also depicts possible benefits for the population.

Finally, this research provides insights on proposed measures for upcoming studies. Some actions are recommended for obtaining better results and can also be subsidies for future works. They are:

- Application of preconditions for building damage assessment should be made, such as sufficient guidance for the volunteers and application of a user-friendly mapping software;
- Improvement of the rules and methodology applied for building damage assessment (BDA) that can reduce the number of errors in the database;
- Further completion of the correction of the BDA for the entire island that allows a comprehensive analysis of the damage assessment for all parishes;
- The inclusion of coastal processes in the inventory of hazards;
- Update of the landslide and flood inventory from Hurricane Maria allowing for better reflection on the real conditions of the event on the island;
- Update of the hazard maps permitting spatial planning to be more effective;
- Development of a tool to determine whether a specific location is safe for reconstruction to be used by the Physical Planning Division;
- Improvement of methodologies for the creation of a primary database of damage assessment during fieldwork;
- Further consideration of different recovery scenarios which will depict additional settings for recovery possibilities for Dominica.

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ANNEXES

Annex 01 – Training received to perform the BDA after Hurricane Maria, 2017.

Source: Dominica News Online (2018).

Annex 02 - Relevant information analysed on the BDA.

BUILDING DAMAGE ASSESSMENT	
Information	**Description**
FID	Identifier of the object.
Shape	Type of shapefile.
Responseld	Code assigned for each object by the organizers.
TagLabel	Classification of damage of the building.
Color_Tag	Colour classification according to the damage of the building.
Assessment	Date of assessment (all values are null).
Parish	Administrative region.
Community	Community attributed to the damage point.
Latitude	Coordinates from the damage point (latitude).
Longitude	Coordinates from the damage point (longitude).
BuildingOc	Type of occupation of the building (leased, owned, rented, vacant).
Public_Pri	Type of building (public or private).
StructureU	Type of use of structure (public or private).
PrivateStr	Type of use of private building.
PublicStru	Type of use of public building.
PublicSt_1	Type of private use of public building.
Insurance	Information on availability of insurance.
RepairsDon	Information on whether repairs were done.
LandTitle	Information on the availability of land title.
LandTitle_	Information on the type of land title.
OccupantsA	Information on whether there are occupants in the building.
Owner_avai	Information on whether the owner lives on the building.
Primary_Oc	Full name of the primary occupant of the building.
PrimaryOcc	The family name of the primary occupant of the building.
PrimaryO_1	First name of the primary occupant of the building.
PrimaryO_2	Gender of the primary occupant of the building.
PrimaryO_3	Age of the primary occupant of the building.
Secondary	Information of a second occupant of the building.
SecondaryO	The family name of the second occupant of the building
Secondar_1	First name of the second occupant of the building.
Secondar_2	Gender of the second occupant of the building.
Secondar_3	Age of the second occupant of the building.
Count_of_A	The number of adults in the building.
Count_of_W	The number of women in the building.
Count_of_M	The number of men in the building.
Count_of_C	The number of children in the building.
Count_of_G	The number of girls in the building.
Count_of_B	The number of boys in the building.
Count_of_E	The number of elderly in the building.
Count_of_D	The number of disabled people in the building.
BuildingSI	Size of the building assessed.
Height	The height of the building.
Width	The width of the building.
Length	The length of the building.

Nb_Floors	The number of floors of the building.
Main_Damag	Information on whether the roof was damaged.
Main_Dam_1	Information on whether the walls were damaged.
Main_Dam_2	Information on whether the structure was damaged.
Main_Dam_3	Information on whether the services (water, electricity, etc) were affected.
Main_Dam_4	Information on other damage.
RoofDamage	Percentage of damage to the roof.
Walls_Dama	Percentage of damage to the walls.
Floor_Dama	Percentage of damage to the floor.
Ceiling_Da	Percentage of damage to the ceiling.

Source: United Nations Development Program - UNDP (2018).

Annex 03 - Relevant information analysed on the recovery database.

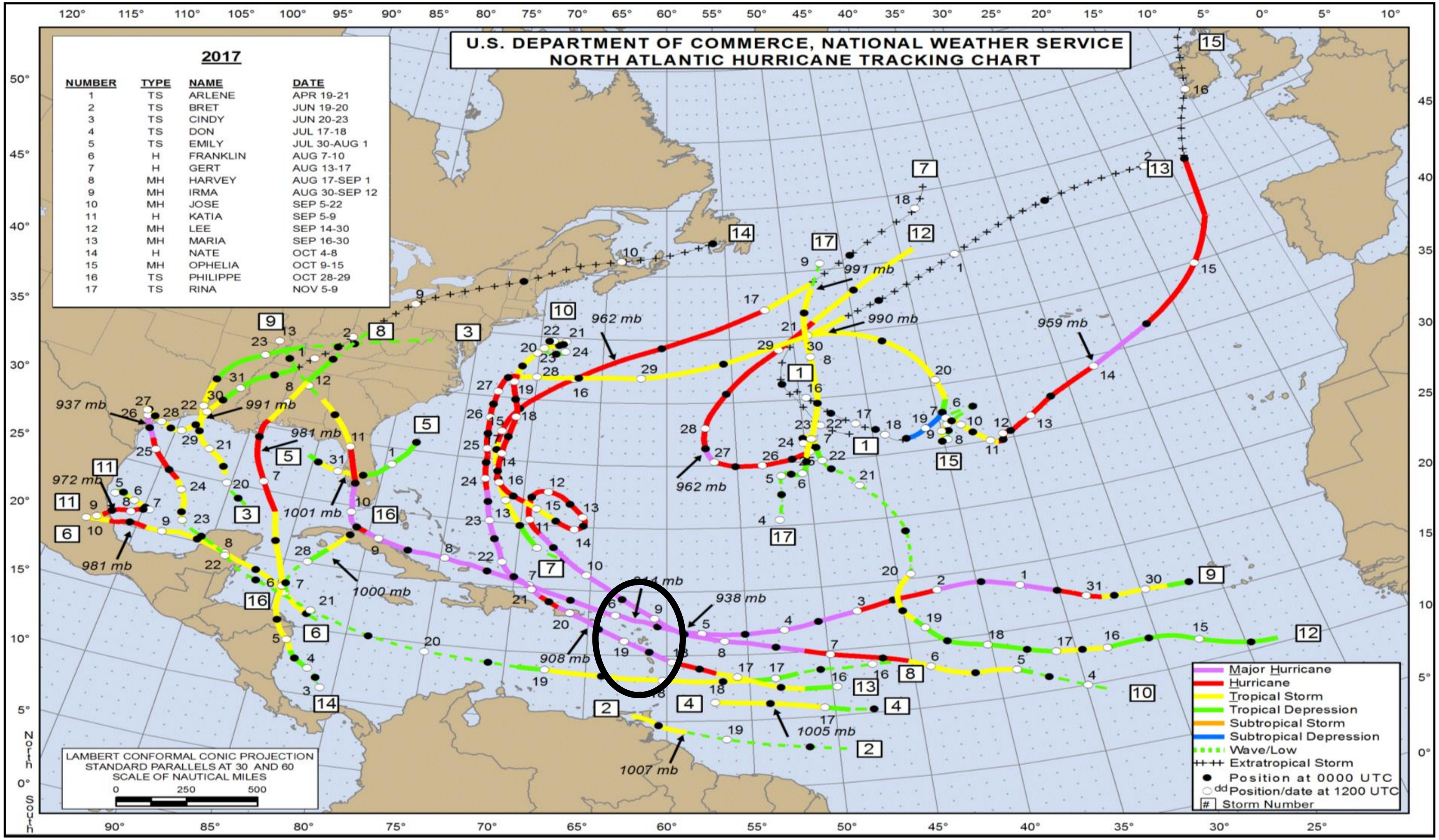
BUILDING DAMAGE ASSESSMENT	
Information	**Description**
Name_area	The name of the community/city/settlement attributed to the point.
FID	OSM Code attributed to the point.
Flooding	Binary field assessing the existence of flooding hazard or not.
Debrisflow	Binary field assessing the existence of debris flows hazard or not.
Landslide	Binary field assessing the existence of landslide hazard or not.
Wind	Binary field assessing the existence of wind hazard or not.
Cosatal	Binary field assessing the existence of coastal hazard or not.
Number_stories	The number of stories attributed to the building.
Type_occupancy_IBC2018	Occupancy classification attributed to the point according to the IBC 2018.
Type_construction	Type of construction material attributed to the building.
Repair_status	Information on whether repairs were made on the building.
Damage_class	Information regarding the damage class attributed to the point.
Abandonment_status	Information on whether the building was abandoned.

Annex 04 – UAV images of Dominica obtained from the OAM platform.

Image 01: Image depicting part of the area of Soufriere, took in October 2017.
Source: RescUAV / Global Medic (2017).

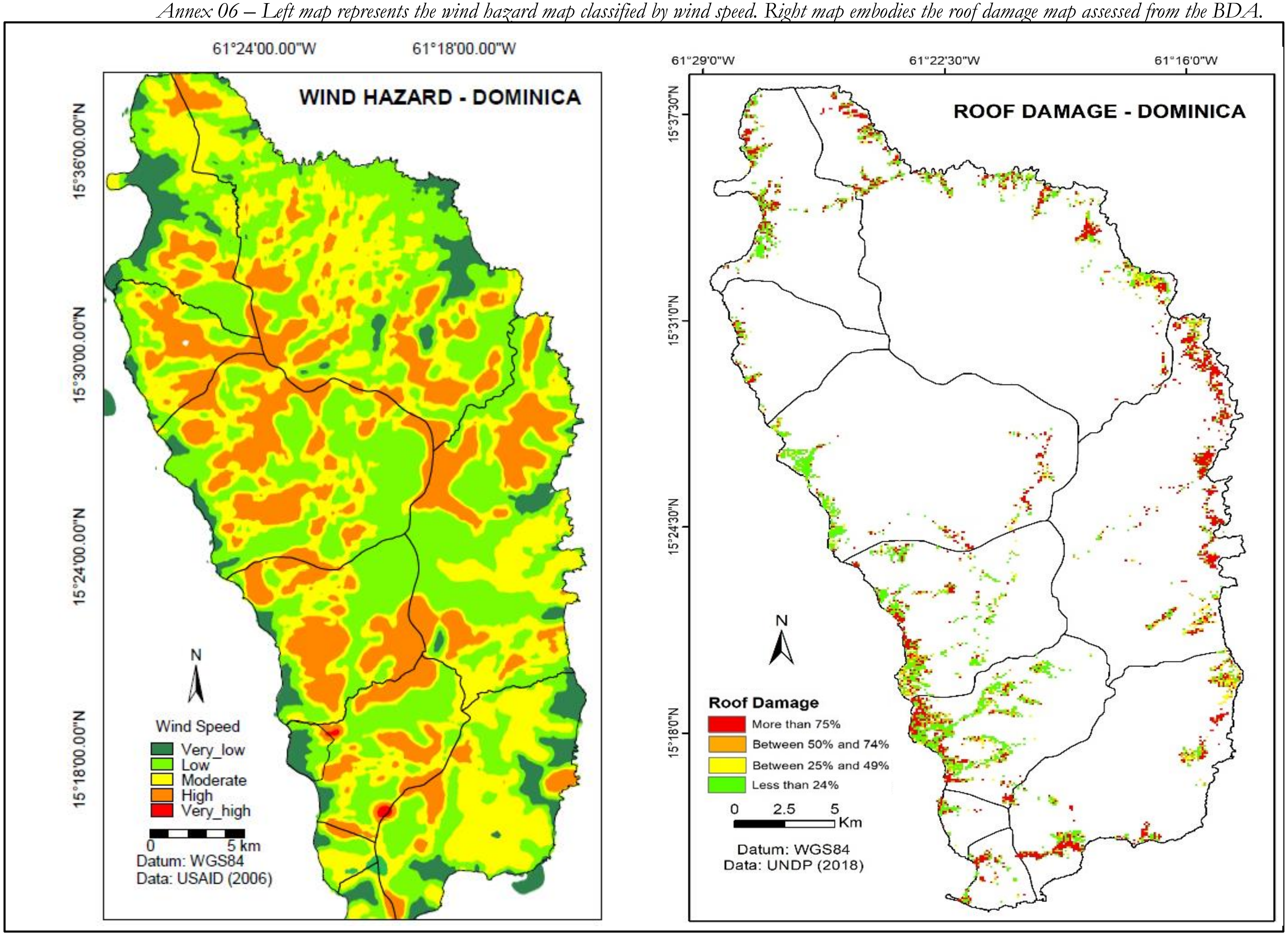
Image 02: Image depicting part of the area of La Plaine, took in February 2018.
Source: RescUAV / Global Medic (2017).

Annex 05 – Hurricane trajectory depicting the North Atlantic ocean. The dark circle indicates the islands of the Caribbean illustrating that the events come from the east and go to the north-west direction.

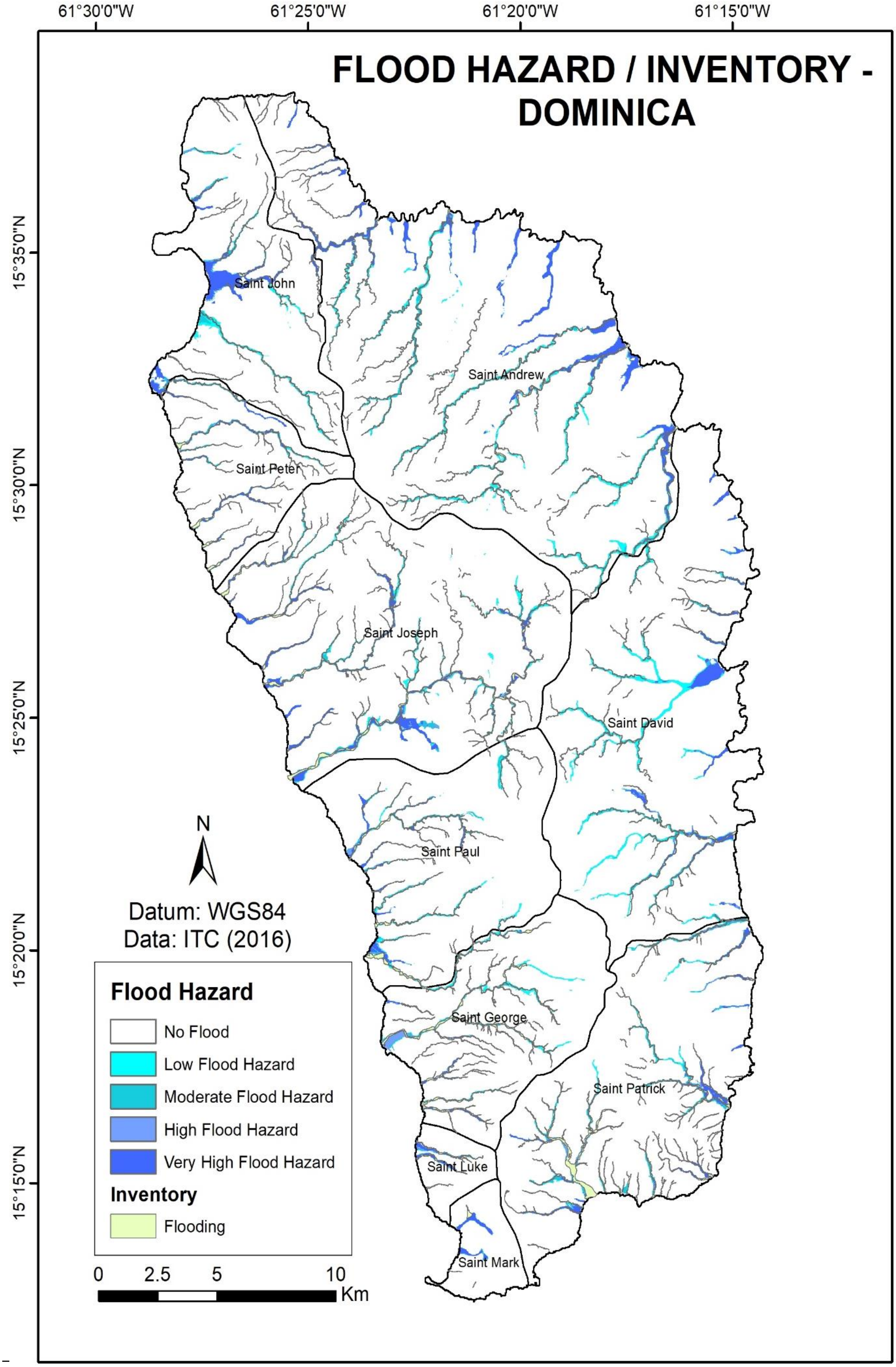


Source: National Hurricane Center – NHC (2019).

Annex 06 – Left map represents the wind hazard map classified by wind speed. Right map embodies the roof damage map assessed from the BDA.



Annex 07 – Flood hazard overlaid with the hazards inventory depicting flooding areas in Dominica.



Annex 08 – UAV images from Roseau Centre taken two weeks after Hurricane Maria.

Image 01: Part of the area affected by flooding that was not mapped on the inventory. Sediment deposition can be seen along the streets with damaged buildings.
Source: Aerial Dominica (2017).

Image 02: Sediment deposition on the banks of Roseau River showing evidences of flooding. This area was further considered when adjusting the flooding events inventory.
Source: Aerial Dominica (2017).