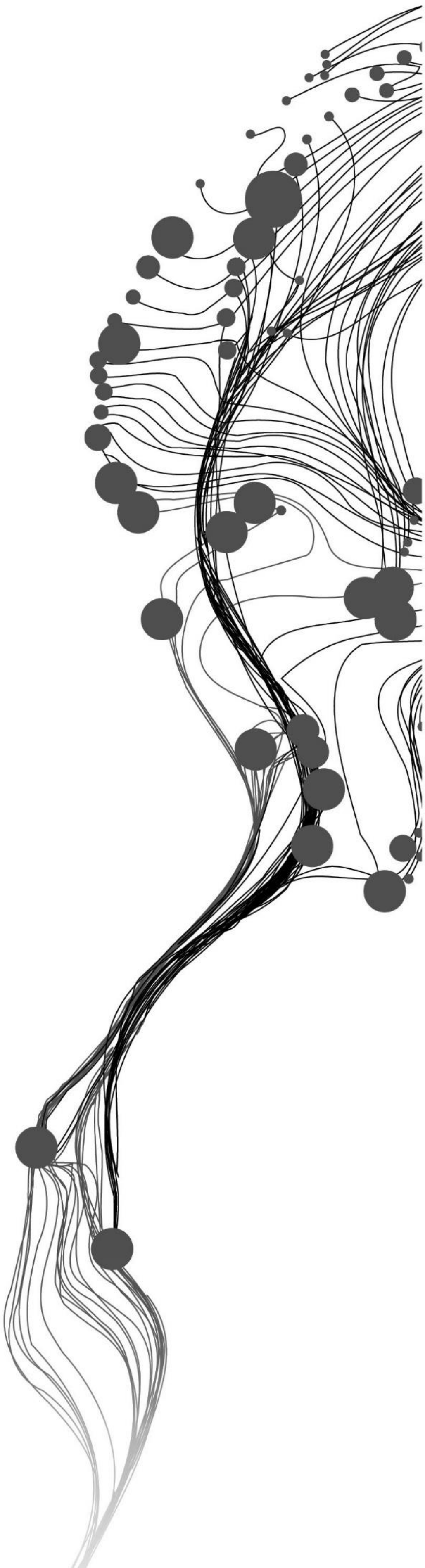
NATIONAL SCALE LANDSLIDE HAZARD ASSESSMENT ALONG THE ROAD CORRIDORS OF DOMINICA AND SAINT LUCIA

JOVANI YIFRU
March, 2015

SUPERVISORS:
Dr. C.J. van Westen
Dr. H.R.G.K. Hack



NATIONAL SCALE LANDSLIDE HAZARD ASSESSMENT ALONG THE ROAD CORRIDORS OF DOMINICA AND SAINT LUCIA

JOVANI YIFRU
Enschede, The Netherlands, March, 2015

Thesis submitted to the Faculty of Geo-Information Science and Earth Observation of the University of Twente in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation.
Specialization: Applied Earth Sciences (Natural Hazards and Disaster Risk Management)

SUPERVISORS:
Dr. C.J. van Westen
Dr. H.R.G.K. Hack

THESIS ASSESSMENT BOARD:
Prof.Dr. V.G Jetten (Chair)
Dr. L.P.H. (Rens) van Beek (External Examiner, Universiteit Utrecht)

ABSTRACT

The Caribbean Islands of Dominica and Saint Lucia are characterized by their intense heavy rainfall and steep slopes which give rise to frequent landslide occurrences. This has affected their limited road network greatly in the past causing road damage and impeding vehicular traffic. In this research, the landslide susceptibility of different sections of the major roads of Dominica and Saint Lucia are analysed by characterizing them by their topography, geology and soil type. Unlike Dominica, some efforts have been made in Saint Lucia to manage the landslides triggered by rainfall focusing on road related landslides and, here, the methods utilized in Saint Lucia are assessed for their applicability in Dominica.

Historical landslide records together with image interpretation and field mapping are used to generate a multi temporal road related landslide database for storm events that hit the Islands. The distribution of the landslides of this events on the different roads sections are assessed with respect to landslide density per kilometre of the road sections. Then instability factors, slope, soil and geology, of the road sections are examined in relationship to landslide frequency and distribution. The storm events return periods are treated with respect to their daily rainfall amount using generalized extreme value distribution model. Finally, the landslide susceptibility of the major roads are analysed with spatial multi criteria evaluation (SMCE) based on the available input factor maps: landslide points, slope angle, soil, geology, drainage and land use.

Through this work, the road sections with high landslide susceptibility are identified. Besides, the relation of the landslide occurrences with the triggering rainfall amounts and their return periods are provided. This can help in determining the sections that need further investigation for implementing landslide mitigation measures. Also, the results can be used to identify possible blockage site of the roads due to landslides during storm events.

ACKNOWLEDGEMENTS

I would like to express my very great appreciation to my supervisors Dr. C.J. van Westen and Dr. H.R.G.K. Hack. For guiding me through my thesis. Their valuable remarks and critical comments were always helpful to come up with a good solution. Thank you for your persistent questions and most especially for imparting your wisdom and knowledge during my fieldwork and analysis stage.

Deep gratitude is to all Caribbean group (staff and student) for their support and encouragement. Special thanks for Drs. N.C. Kingma for her guidance during my field work.

Also, I would like to thank the staff members of the ministry of works and infrastructure in Dominica and Saint Lucia for helping me through my data collection process.

Thank you to my classmates in AES for making the class enjoyable to my friends for making my life in the Netherlands so fantastic.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

1.1. Background

Landslides are part of the normal geomorphic cycles of landscape development and they become hazardous when they interfere with human activities. Landslide hazards are potentially dangerous phenomena which affect humans and their physical environment. Globally, landslides cause billions of dollars in damages and thousands of deaths and injuries each year which in the process cause damage to economy, natural ecosystems and infrastructures. Between 2002 and 2011, about 197 landslide occurrences are reported worldwide which took 9823 people lives and caused 1.9 billion US dollar damage (IFRC, 2012). This figure is a large underestimation as only large scale landslide disasters are included in the analysis. This is also reflected by the CRED database (CRED, 2014).

Landslide hazard assessment incorporates the prediction of where the landslides will occur, how frequent they might occur and how large the failure will be, with indications of spatial, temporal and size probability respectively (Guzzetti et al., 1999). Landslides are the result of spatial-temporal conjunction of several factors. These factors can be grouped into two i.e. quasi-static variables like geology, slope geometry and drainage pattern which contribute to landslide susceptibility of the area; and dynamic variables like rainfall and earthquakes which trigger the landslides (Anderson & Holcombe, 2013; Dai & Lee, 2001).

A detailed landslide inventory mapping is the key for every landslide hazard assessment. The inventory maps can be prepared using methods like historical archive studies, interviews, detailed geomorphologic fieldwork, and mapping from remote sensing data and topographic maps (Van Westen et al., 2012). In spite of technological advancements in the last two decades, visual image interpretation using stereoscopic aerial photography remains the most common and effective method for landslide mapping (Guzzetti et al., 2012). The recent advancement in remote sensing, which presented high resolution imagery both from aerial and satellite sources, has made the visual image interpretation a lot easier than before.

GIS based landslide susceptibility analysis (spatial probability) approaches that allow better structuring and comparison of the various factors and their components are standard practice and very common (Castellanos Abella & Van Westen, 2008). Generally, the approaches for spatial probability can be classified as geomorphologic (expert dependent), statistical and physically-based modeling approaches (Suzen & Doyuran, 2004). The statistical approaches have an advantage of assessing spatial probability of landslides in an objective way, without the need for detailed geotechnical information. However, they depend very much on the quality of the inventories, thematic maps of contributing factors, and knowledge of the persons involved in the mapping. Among the statistical methods, the use of bivariate and multivariate methods are wide spread (Nandi & Shakoor, 2010; Suzen & Doyuran, 2004).

To address the temporal probability of occurrence of landslides two main approaches are widely used: slope stability analysis and statistical analysis of past landslide events (Aleotti & Chowdhury, 1999; Lopez Saez et al., 2012; Tien Bui et al., 2012). The first approach which requires intensive assessment of the current slope condition is less suitable for large area studies. The second approach, on the other hand, requires a complete record of past landslides spanning a long enough time period. Since it is difficult to acquire such data for all existing landslides on a regional or national scale, (Jaiswal & van Westen, 2009) suggest the use of empirical methods that estimate the rainfall thresholds obtained by studying rainfall conditions that have resulted in landslides.

The landslide risk associated to road lines could vary from direct risk of damaging the road itself, vehicles and people to indirect risk of blocking the road line which in consequence disrupts socio-economic activity of the area and beyond (Jaiswal et al., 2010). To assess these risks and plan for appropriate risk mitigation measures, it is vitally important to have a comprehensive landslide susceptibility and hazard map of the road corridors. Dai & Lee (2001) emphasizes the importance of considering the effect of man-made features while analyzing landslide susceptibility. The same triggering event may result in a large differences in number of landslides between natural slope and modified slope. Therefore, it is crucial to study the landslide hazard and susceptibility of the road sections separately from natural terrain.

Dominica and St. Lucia, which are windward Caribbean islands, are known for frequent landslide and flash flood occurrences caused by the combined effect of the steep topography, geology and climate of the areas. The steep slopes prevalent in these islands together with the materials underlying the slopes provide a favorable condition for landslide creation (DeGraff, 1985, 1987). Because these slopes are close to failure, their stability is likely to be affected by small triggering effect and cause landslides. Based on past landslides that occurred until 1987, Dominica and St. Lucia have 1.2 and 0.7 landslide occurrences per square kilometer respectively (UWI, 1999). The main triggering factor for the landslides is rainfall. Anderson et al. (2011) point out besides the rainfall, human activity is the second major element that contribute to the landslide occurrences on the Islands. Most of the landslides are related to these human activities like road construction which disturb the natural slope characteristic and increase their probability of failure.

1.2. Research Problem

Road networks play a crucial role in the development of a country. The economies of Dominica and St. Lucia are heavily dependent on the tourism industry, an industry for which road infrastructure plays a significant role in transporting tourists from the major hotel areas and cruise ship landing places to other tourist attractions on the islands. However, the Islands are not benefiting from their road networks as they should because of frequent landslide and flash flood occurrences along the major roads. In addition, the islands generally have very limited road networks that generally circle the island along the coasts with relatively few connecting roads across the island. Blocking of a road therefore has important consequences as there are no or limited alternatives. For instance, Dominica has an airport located on the other side of the island, as compared to the capital, which is accessible only by one road. This road was recently upgraded, and it is now of good quality except for a number of stretches on the center of the island where active landslides take place, which threaten the road.

Dominica and St. Lucia have lost a considerable amount of money due to damaged and destroyed roads by landslides. In Dominica, more than 462,000 dollar was spent between 1983 and 1987 for road maintenance and clearance caused by landslides (UWI, 1999). The case of St Lucia is also similar. As noted by Holcombe & Anderson (2010), the impact of landslides on developing countries like Dominica and St. Lucia becomes clear when landslide costs are expressed as a proportion of the gross domestic product per unit area of a country. According to them, this measurement shows that central and South America and Caribbean take 40% of the global economic losses. For such nation, damage caused by landslide disaster has a considerable impact on the economy, which could hinder development or even cause recession

In recent years, the major rainfall events that triggered landslide occurrences in St. Lucia and/or Dominica were: September 2006, Hurricane Dean august 2007, October 2008, Hurricane Tomas 2010, April 2013 and

December 2013 (Anderson & Holcombe, 2013). During Hurricane Tomas, 5 persons were reported dead in St. Lucia and numerous homes, commercial buildings and vehicles were severely damaged or swept away by mudslides and floods. On April 2013 in Dominica, as a result of the heavy rainfall there was a major road subsidence due to washout of a road culvert near Pond Casse which caused the death of two persons and closing of the road for long period. The December 2013 event occurred on Christmas eve, and damaged several houses and infrastructures in both islands and killed six people in St. Lucia and affected 183 people in Dominica (ReliefWeb, 2013). These events have triggered a strong desire in both Islands to upgrade the road networks by mitigating the problems in the existing roads which in the process will facilitate the communication and reduce the landslide risks. To achieve this goal, it is necessary to assess the associated landslide risks and implement effective risk reduction measures. Nevertheless, the available landslide inventory maps are outdated, they only cover events up to 2006, and are very incomplete. This is especially the case for Dominica. In Dominica, the landslide hazard, with respect to space, time and size, is not known for the road sections. Besides, no study has been done to identify the root causes of the landslides occurring along the road corridors. In Saint Lucia, on the other hand, attempts have been made to manage landslide risks. In 2013, Saint Lucia was said to be a success story by World Bank, within the Caribbean region, for its efforts in managing landslides triggered by rainfall (SNO, 2013).

Previously, several attempts have been made by the governments of Dominica and St. Lucia and international organizations to develop landslide inventory maps. Even though these attempts have presented a useful and interesting contribution to the landslide study of the area, they have gaps and limitations in their landslide inventories. The limitations and gaps include (but are not limited to): incomplete or inaccurate inventories; scarcity of inventory data for inaccessible areas; inventories overlook coastal events; and inventories without accurate temporal data that do not allow correlations between events and triggering factors. With regard to road related landslides of the Islands, the work of Anderson (1983) and Holcombe et al., (2011) can be mentioned which focuses on the relationship of stability of road cuts with their slope and material property. The work done by Mott MacDonald (2013) has also studied the road related landslides of Saint Lucia in detail, by considering two landslide events: hurricane Allen and hurricane Tomas.

1.3. Research Objectives and questions

1.3.1. Research Objectives

The main objective is to carry out a comprehensive landslide hazard assessment for the major roads of Dominica and St. Lucia based on image interpretation, field investigation and historical landslide records and generate a national road-related landslide database that can be used by the ministries of public work in risk mitigation.

Sub-objectives

- To generate multi temporal landslide inventory maps along the road network using image interpretation, fieldwork, existing landslide inventories and historical landslide records
- To subdivide the road network in segments and characterize these segments in terms of topography, geology, geomorphology and the road earthwork type (road cut or fill)
- To characterize landslide events in terms of landslide type, volume and date of occurrence using road maintenance and clearance records, interviews, newspaper records etc. and relate them to the triggering factors (rainfall characteristics)
- To determine the spatial and temporal probability of landslide occurrence along the road corridors using statistical analysis models.

- To evaluate whether the landslide situation in the two islands are different and investigate the reasons for that, and to apply methods that have been developed for one country with more data (saint Lucia) to the other country (Dominica).

1.3.2. Research Questions

Questions related to the 1st sub-objective

- What specific information related to past landslides could be extracted through visual image interpretation? Can road related landslides be mapped from these images?
- Are there historical records on road maintenance from which landslide dates, locations and volumes could be obtained? Which landslide information can be extracted from historical records?
- Is it possible to identify the activity of the landslides from field investigation and interviews with people from the public works department?
- How are the landslides distributed in time and space along the road corridors?
- Is there a major difference between the two Islands? If so in which way?

Questions related to the 2nd sub-objective

- How many road segments with similar characteristics can be derived for the whole road network?
- Which attributes are used for the subdivision of the road segments? Is it possible to do this only based on landslide occurrences, and which factors can be effectively used in subdividing the segments?
- Is there enough information to characterize the road segments with respect to landslide frequency and volume? Which segments exhibit more landslides and what is it's indication of the factors contribution for landside creation?

Questions related to the 3rd sub-objective

- What are the major landslide events that occurred on the study areas in the past and how many of these are related to rainfall triggers?
- Can the size-frequency distribution of the landslides be determined based on field investigation and historical records?

Questions related to the 4th sub-objective

- How to assess the spatial probability of landslides along the road?
- How good is the data for applying a Poisson distribution model for landslide temporal probability modelling based on past landslide triggering events?
- Can Gumbel frequency analysis be used for characterizing the number of landslides per unit length of the road, based on past occurrences?
- Which method is best suited to predict size probability of landslides based on the available input data?

Questions related to the 5th sub-objective

- How different are the two Islands in landslide occurrences along the major roads?
- How do the storm events that caused landslides in the two islands relate?

- How can the methods developed in Saint Lucia to study the landslide along the roads be used in Dominica?

1.4. Methodology

Figure 1.1 below shows the flowchart of the methodology used.

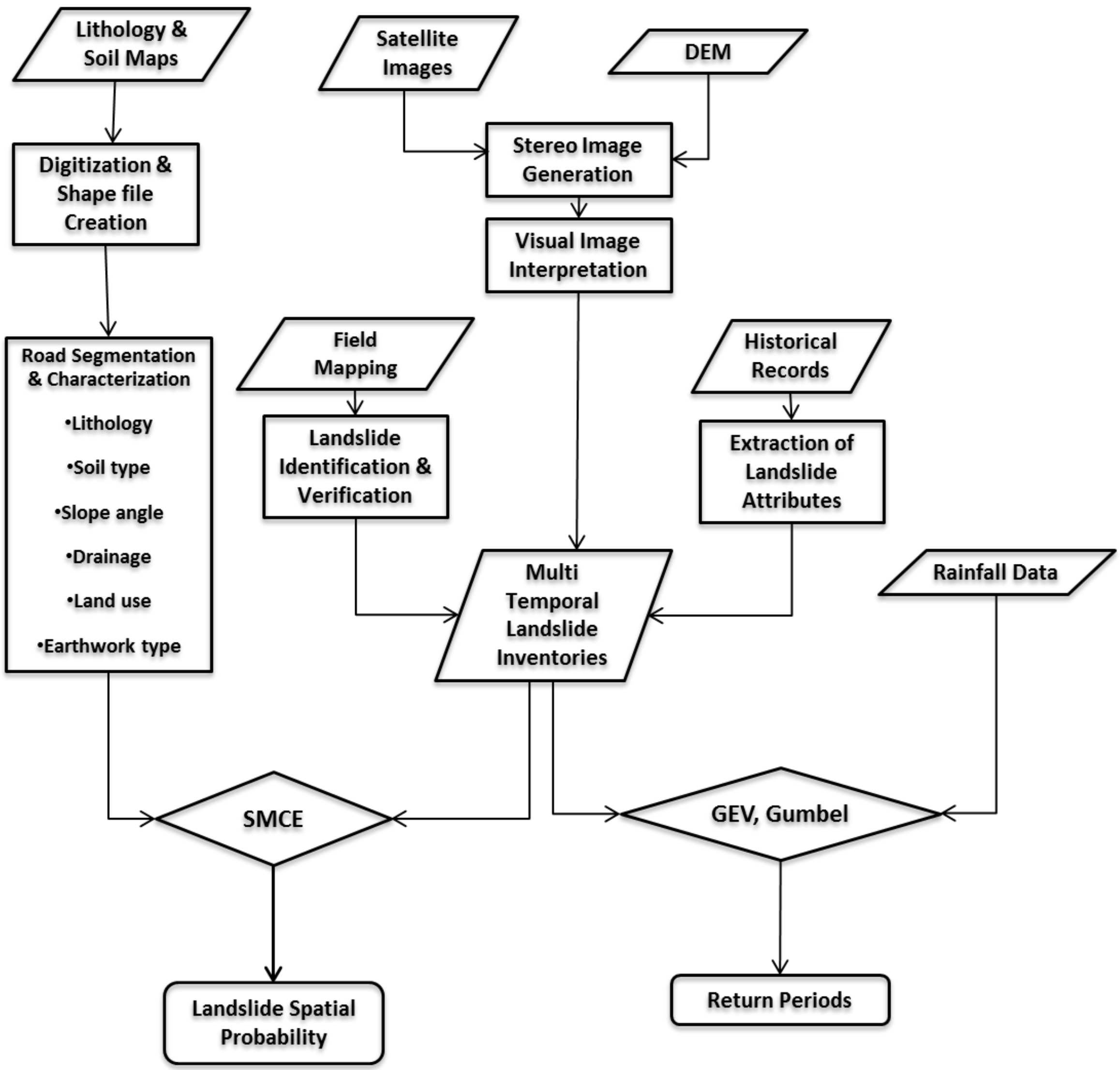


Figure 1.1. Flowchart of the methodology used in this research

The generation of the landslide inventories along the road network was mainly based on historical records collected from road maintenance and clearance reports after landslide events. To support and verify the information obtained through historical records, visual image interpretation was also performed. The image interpretation was done using stereo image obtained by combining high resolution imagery with a digital elevation model. Accordingly, multi-temporal landslide inventory maps along the major roads were prepared. Based on the inventories, landslide densities per kilometer length in each major road sections were calculated for different storm events. To analyze the temporal probability, the return periods of the rainfall amounts of the storm events that caused landslides were modelled using generalized extreme value distribution method and Gumbel method. Finally, the landslide susceptibility analysis was made using spatial multi criteria evaluation. All the methods used in this study are discussed in detail in Chapter 4.

1.5. Thesis Structure

This thesis is structured as follows

- Chapter 1 introduces the thesis by explaining why the research should be carried out and stating the objectives of this research
- Chapter 2 is literature review describing Landslide hazard and the factors influencing the phenomena together with the methods of assessment
- Chapter 3 examines the study areas by providing descriptions of the geology, soil and previous landslide studies
- Chapter 4 presents the data used and the methodology in which the landslide inventory is constructed and the spatial and temporal factors are assessed
- Chapter 5 provides the results of the analysis and the discussion including the landslide susceptibility map of the roads and the rainfall return periods of the historical events
- Chapter 6 concludes this research by discussing the key aspects of the research and describing the objectives met and by indicating potential paths for future research

2. LITERATURE REVIEW

2.1. Landslide Inventory and Mapping

The term "landslide" comprises almost all varieties of mass movements on slopes, including some, such as rock-falls, topples, and debris flows, that involve little or no true sliding (Varnes, 1984). Landslides are generally isolated natural processes, which individually may not be of very large in size but can occur with a high frequency in an area (van Westen et al., 2012). Aleotti & Chowdhury (1999) list four fundamental assumptions that are made for landslide mapping:

- Landslides will always occur in the same geological, geomorphological, hydro-geological and climatic conditions as in the past;
- The main conditions that cause land sliding are controlled by identifiable physical factors;
- The degree of hazard can be evaluated; and
- All types of slope failures can be identified and classified.

Landslide inventory mapping can be done using different techniques. Selection of a specific technique depends on the purpose of the inventory, the extent of the study area, the scale of the base maps, the scale, resolution and characteristics of the available imagery, the skills and experience of the investigators, and the resources available to complete the work (Guzzetti et al., 2012). Some of the difficulties related to landslide mapping include: the discontinuous nature of slope failures in space and time; the difficulty of identifying the causes, the triggering factors and the cause-effect relationships; and the lack of complete historical data concerning the frequency of these geomorphologic processes (Aleotti & Chowdhury, 1999). Some of the landslide inventory techniques include: historical archive studies, interviews, detailed geomorphologic fieldwork, and mapping from remote sensing data and topographic maps (van Westen et al., 2012). Each of the mentioned techniques has its advantages and disadvantages.

Depending on the extent of investigation, a landslide inventory contains the location, classification, volume, run-out distance, date of occurrence and other relevant characteristics of the landslides (van Westen et al., 2012). The inventory maps can either be event inventories that show landslides triggered by a single event (like earthquake, rainstorm, or snowmelt) or can be historical inventories that show the cumulative effects of many events over a period of hundreds or thousands of years. Guzzetti (2003) propose the following recommendations for the preparation and use of landslide inventories maps:

- When preparing landslide inventory maps use consistent and reproducible methods. Analyze the relationships between the lithological and the landslide types and distribution.
- Prepare inventory maps after each landslide triggering event, covering the whole area affected by the event and discuss the landslides triggered by extreme events using frequency-size distribution.
- Keep a record of the landslides and of the landslide events that have occurred in historical times which could be used to prepare multi temporal inventory maps. Analyze the spatial relationships between landslides of different events and types.
- Determine the quality of the inventory maps in regard to their completeness, resolution and reliability. Discuss the techniques, methods and tools used to complete the inventory, including type of stereoscope, type and scale of aerial photographs and base maps, and level of experience of the investigators.

2.2. Geomorphological Field Mapping

Geomorphological field mapping is on the ground mapping of existing landslides in areas of known slope instability, which comprises plotting of both visible landslide features and the possible locations of historical landslides. While mapping landslides on the field, Anderson & Holcombe (2013) suggests to include identification of the topography and other preparatory factors likely to be associated with both existing and future slope failures. Detecting landslides on field could be a difficult task and often requires experienced person, particularly old landslides. The difficulties may arise from one or more of the following causes (Guzzetti et al., 2012): the size of the landslide too large to be seen completely in the field; the investigator unable to see all parts of the landslide with the same detail from his/her viewpoint; and old landslides partially or totally covered by forest, or have been partly dismantled by other landslides, erosion process, and human actions including agriculture and forest practices.

2.3. Visual Image Interpretation

Visual interpretation, with and without on screen digitizing of both two and three dimensional data, has been commonly used in the past and is still an effective method of landslide mapping (Joyce et al., 2009). For visual image interpretation, it is essential to have a stereoscopic imagery of high to very high resolution. Identifying landslides using this technique requires experience, training, a systematic methodology, and well defined interpretation criteria. There are no standard rules for image interpretation, the person doing the interpretation identify and classify based on experience and analysis of a set of characteristics that are visible on the image. These include: shape, size, photographic color, tone, mottling, texture, pattern of objects, site topography and setting (Guzzetti et al., 2012).

Despite significant technological innovation, aerial photographs remains the most common inputs for landslide interpretation and landslide map preparation. The use of remote sensing in the study of landslides was not fully exploited until recently, with a limited number of researchers making a full use of multispectral images for landslide identification and detection and identification (Metternicht et al., 2005). In recent years, however; very high resolution satellite imagery has become the best option for landslide mapping. Particularly, in areas where the availability of aerial photograph is low, or when the objective is to integrate a landslide inventory with other digital data for regional landslide hazard assessment, the use of satellite images is a viable option (Nichol et al., 2006; van Westen et al., 2008). Very high resolution images can provide similar and complementary landslide information on landslides than aerial photographs, including information on landslides that leave only faint signs. It is also possible to create a 3D view of the terrain by combining the satellite images with DEMs for a better detection of landslides (Guzzetti et al., 2012).

2.4. Slope Instability Factors

Many landslide hazard assessment schemes employ the concept of superimposing and integrating spatial information or maps, showing individually the factors thought important in assessing slope stability. Commonly these include: topography, geology, soils, hydrology, geomorphology, land use and anthropogenic factors. The selection of slope instability factors relevant for landslide susceptibility analysis depends on the type of landslides, the type of terrain and the availability of existing data and recourses. Different analysis methods use different types of data, although they share also common ones, such as slope gradient, soil and rock types, and land use types (Corominas et al., 2013; van Westen et al., 2008; Varnes, 1984).

Slope angle

Slope angle is one of the key determinants and most important parameter in slope stability analysis. Because the slope angle is directly related to the landslides and it is frequently used in preparing landslide susceptibility maps (Pourghasemi et al., 2012). Slopes with a higher slope angle exhibit a greater shear stress acting upon soil and rock masses in the slope. The relationship between slope angle and slope stability, however; is not straight forward, since the shear strength of the slope is determined by other variables like material strength, water table height, and the influence of loading and vegetation (Anderson & Holcombe, 2013). Thus, shallow slopes with deep, weak soils can be less stable than steeper slopes comprised of shallower soils or exposed bedrock.

Slope Material

Landslides are greatly controlled by the material properties of the slope. Since different lithology and soil units have different landslide susceptibility values, they are very important in providing data for susceptibility mapping. In assessing the influence of slope material on stability, three broad characteristics need to be determined (Anderson & Holcombe, 2013):

- The depth and location (strata) of different material types in the slope
- The shear strength of the materials
- The hydrological properties of the materials

In tropical areas like Dominica and St. Lucia, rock weathers rapidly due to the high temperature and humidity; this can result in the formation of deep soils over weakened bedrock. In general the greater the weathering from rock to soil, the weaker the material. The strength of residual soils can vary greatly depending on its parent material (composition). The lithology and soil type of Dominica and Saint Lucia are discussed in section 3.

2.5. Landslide Triggering Factors

Landslides tend to have a direct relationship of spatial distribution with the mechanisms which triggered them. Rainfall and earthquake are considered to be the main triggering factors of landslide and each triggering factor corresponds to different model of spatial distribution.

Earthquake

Earth quake is one of the triggering factors of landslides. Some of the most damaging landslides recorded in history have been triggered by seismic shock. Particularly susceptible materials for earthquake triggered landslides are those with a loose or open structure such as loess, volcanic ash on steep slopes, saturated sands of low density, fine grained sensitive deposits of clay or rock flour, and cliffs or fractured rock or ice (Varnes, 1984). Hack et al., (2007) suggests that earthquake triggers the failure, but is almost never the cause of the failure. According to these authors, weathering, erosion and sedimentation that reduce the strength of the slope material or changes the geometry of the slope, together with manmade influences like road cuts or agricultural use, are normally the cause for slope failure during an earthquake. Spatial distribution of landslides induced by earth quake tend to adjust to an ellipse shape with its long axis roughly following the fault that generates the earth quake (Gonzalez-dıez et al., 1999; Palmquist & Bible, 1980). For Dominica and Saint Lucia, however, earth quake triggered landslides are not that significant. Since 1870, only three landslide occurrences are reported that were triggered by seismic event and all of them were in Saint Lucia.

Rainfall

Rainfall is the other main triggering factor which contribute to most of the landslides occurred in the past in different parts of the world. Landslides triggered by rainfall occur in most mountainous landscape. Some of these landslides occur suddenly and travel many kilometers at high speed. Many attempts have been made by different authors, to formalize and quantify the relationship between landslide occurrence and rainfall variables in the past (Dai & Lee, 2001; Finlay et al., 1997; Grelle et al., 2013; Jaiswal & van Westen, 2009; Lee et al., 2013; Lu et al., 2013; Miller et al., 2009). Rainfall promotes slope failure through an increase in the amount of water stored in the rock body which increases fluid pressure with a consequent decrease in effective pressure and shear strength. An increase in precipitation operates through the infiltration linkage to directly increase water storage with a rise in a water table which ultimately could cause a slope failure. Rainfall also affects slope erosion and river incision which results in increased relief, hill slope gradient and slope failure (Palmquist & Bible, 1980). Spatial distribution of movements triggered by rainfall appear to be located all over the basin, on the upper part of hill slopes, older and younger terraces, as well as valley floors and older landslide deposits (Gonzalez-dıez et al., 1999).

2.6. Landslide Hazard Assessment

Landslide hazard can be defined as the probability of landslide occurrence within a specified period of time and within a given area of potentially damaging phenomena (Varnes, 1984). Guzzett et al., (1999) rephrase this definition to include the magnitude of the expected landslide in terms of its area, volume and velocity or momentum. They suggest that landslide hazard assessment should incorporate the prediction of where the landslides will occur, how frequent they might occur and how large the failure will be, with indications of spatial, temporal and size probability respectively.

Landslide hazard assessment methods can broadly be classified into qualitative and quantitative methods. Qualitative methods are subjective and portray the hazard zoning in descriptive qualitative terms. These methods are highly dependent on the person who is doing the landslide investigation. Quantitative methods, on the other hand, produce numerical estimates probabilities of the occurrence of landslide phenomena in any hazard zone. Guzzetti et al., (1999) regroup the most important methods into five main categories namely:

- geomorphological hazard mapping;
- heuristic or index based methods;
- analysis of landslide inventories;
- functional, statistically based models;
- Geotechnical or physically based models.

Geomorphological hazard mapping is a qualitative, direct method. This method allows a rapid assessment of stability in a given area, taking into consideration a very large number of factors. It has also an advantage of that it can successfully be used at any scale, and if necessary, adapted to specific local requirements. Aleotti & Chowdhury (1999) summarizes the main disadvantages of field geomorphological analysis method as: i) the subjectivity in the selection of both the data and the rules that govern the stability of slopes or the hazard of instability. This fact makes it difficult to compare landslide hazard maps produced by different investigators or experts; ii) use of implicit rather than explicit rules hinders the critical analysis of results and makes it difficult to update the assessment as new data become available; iii) lengthy field surveys are required.

The heuristic or index based approach is an indirect mostly qualitative method. The method is based on the a priori knowledge of all causes and instability factors of land sliding in the area under investigation, that relies on how well and how much the person doing the investigation understands the geomorphological processes acting upon the terrain. Instability factors are ranked and weighted which is proportional to their assumed or expected relative contribution in causing mass movements. This method has an advantage that it considerably reduces the problem of the hidden rules and enables total automation of the operations through appropriate use of geographical information systems. It also enables the standardization of data management techniques from acquisition through to final analysis. Nevertheless, it has major disadvantage that it involves lengthy operations, particularly where large areas are concerned. Subjectivity in attributing weighted values to each parameter and to the different factors; and difficulty of extrapolating a model developed for a particular area to other areas are also the disadvantages of this method (Aleotti & Chowdhury, 1999; Guzzetti et al., 1999).

Analysis of landslide inventories method is an indirect quantitative method. In this method, possible future landslide failure patterns are predicted using past and present landslide distribution inventories. The inventory maps of the past and present landslides are prepared first showing the number or density of landslides over each landslide mapping units (Guzzetti et al., 1999).

Statistical analysis methods are also indirect and quantitative approaches. These analysis methods are based on the functional relationships between the factors causing the slope failures and the past and present landslides distribution. The major advantage of these methods is that it is possible to validate the importance of each instability factor and decide on the final input maps in an interactive manner. However, they strongly depend upon the quality and quantity of the data collected (landslide inventories and thematic maps of the instability factors). The analysis method can be either bivariate or multivariate. In bivarite analysis each individual instability factor is compared with the landslide distribution map. In the multivariate statistical model, unlike the bivariate model, all instability factors are treated together and their interaction as independent variable is compared with landslide density as dependent variable. These analysis techniques require a prolonged effort to collect enough landslide information on the study area (Aleotti & Chowdhury, 1999; Guzzetti et al., 1999; Nandi & Shakoor, 2010; Suzen & Doyuran, 2004; van Westen et al., 2008).

Geotechnical models are process based approaches which depend upon the understanding of physical laws controlling slope instability. Geotechnical models can either be deterministic or probabilistic approaches. These approaches have been widely employed in civil engineering and engineering geology for landslide analysis, especially after the introduction of geographic information systems. A deterministic approach was traditionally considered sufficient for both homogeneous and non-homogeneous slopes. In this approach factor of safety for each slope section is calculated based on an appropriate geotechnical model and on the physical mechanical parameters. Accuracy and reliability is improved as detailed knowledge of the area of application increases. Calculating the safety factor requires geometrical data, data on the shear strength parameters and information on pore water pressure. However, this conventional approach doesn't take into consideration the variability of geotechnical material parameters such as porosity, permeability and shear strength. Probabilistic approaches take the parameter variability into account (Aleotti & Chowdhury, 1999; Guzzetti et al., 1999; Xie et al., 2004).

2.7. Spatial Multi Criteria Evaluation (SMCE)

Multi criteria evaluation is a decision analysis that uses a set of systematic procedures for analyzing complex decision problem. The basic strategy is to divide the decision problem into small, understandable parts, analyze each of them, and integrate the parts in a logical manner to produce a meaningful solution

(Pourghasemi et al., 2012). To solve spatial based problems like landslides, GIS based spatial multi criteria evaluation (SMCE) have been used by different researchers (Abella & Van Westen, 2007; Pourghasemi et al., 2012; Pourghasemi et al., 2013). SMCE is a semi quantitative analysis method. It follows a procedure aimed at identifying and comparing of solutions to spatial problem, based on the combinations of multiple factors that can be at least partially represented by maps.

The SMCE application available in ILWIS GIS software assists and guides users in doing multi criteria evaluation in spatial manner. It is an ideal tool for group decision making which are combined and weighted with respect to the overall goal. The criteria may be of two types: factors and constraints. A constraint in SMCE is a criteria that determines in the calculation which areas should be considered, it is Boolean in character and serves to discard undesired areas from consideration. Factor on the other hand, is a criteria that contributes to a certain degree to the output. A factor could be either a benefit or a cost that contributes positively or negatively to the output respectively. The model can be used for landslide hazard assessment, by formulating a criteria tree where the landslide contributing factors are grouped standardized and weighted. The contributing factors are weighted by means of direct, pair-wise and rank ordering comparison and the output is composite index map which indicates the realization of the model implemented (Pourghasemi et al., 2012).

3. STUDY AREA

The study areas of this research are The Caribbean Islands of Dominica and Saint Lucia. In this section, these study areas are discussed. Description about their geology, soil and landslide occurrences are given. Figure 3.1 shows the geographic location of the study areas.

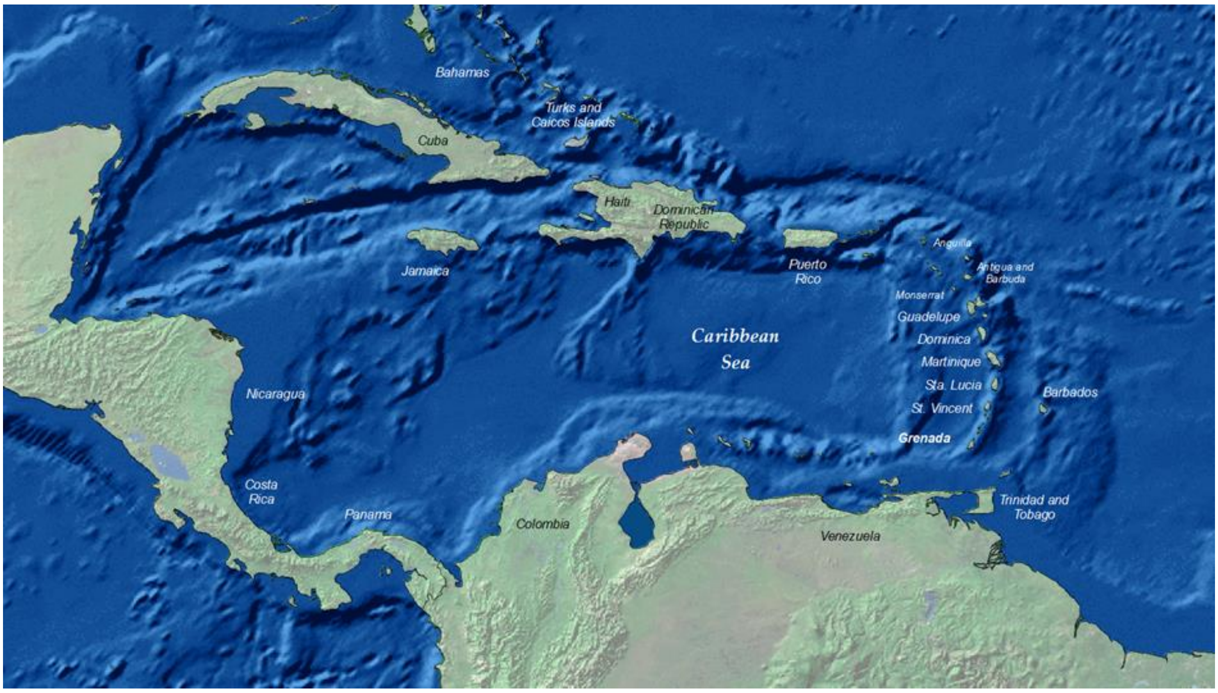


Figure 3.1. Geographic location of the study areas, Dominica and Saint Lucia.

3.1. Dominica

Dominica is one of the windward islands of Caribbean Sea located at 15o 25' N, 61o 20' W coordinates. The 752 square kilometre island of Dominica has a series of peaks and connecting ridges which runs the length of the island, the highest peak being 1,447 meters at the centre of the island. According to the 2014 census the population of the island is estimated to be around 72,301. The island is among the wettest in Caribbean, its annual rainfall ranging from 1000 mm to 10,000 mm in different parts of the island. Dominica has a total road network of 812 km subdivided into three categories: main roads (336km), feeder roads (350km) and secondary/village roads (126km) (IMF, 2006).

3.1.1. Geology

The geology of Dominica is predominantly volcanic bedrock composed mainly of Andesitic to Dacitic material erupted from at least ten volcanic centres, mainly during the Pleistocene (Reading, 1991). The bedrock is a mixture mainly of the minerals Plagioclase and Biotite with some Hornblende, Quartz, and Pyroxene. On a north-south trend through the central part of the island, Young Lava Domes of Mornes Diabltin, Trois Pitons, Micrtin, and Patates are aligned. Ignimbrite rocks deposited by hot ash fall and Nuee Ardantes are found at the outside surface of the plugged vents. Nearly vertical cliffs of fine grained and hard rock, resulted from these deposits, can be seen in some parts of the island. Two sedimentary bedrock units, consolidated limestone consisting of coral, shells and limey mud and unconsolidated alluvium, are the only significantly different bedrocks found on the island (Degraff, 1987). Figure 3.2 shows the geologic map of Dominica.

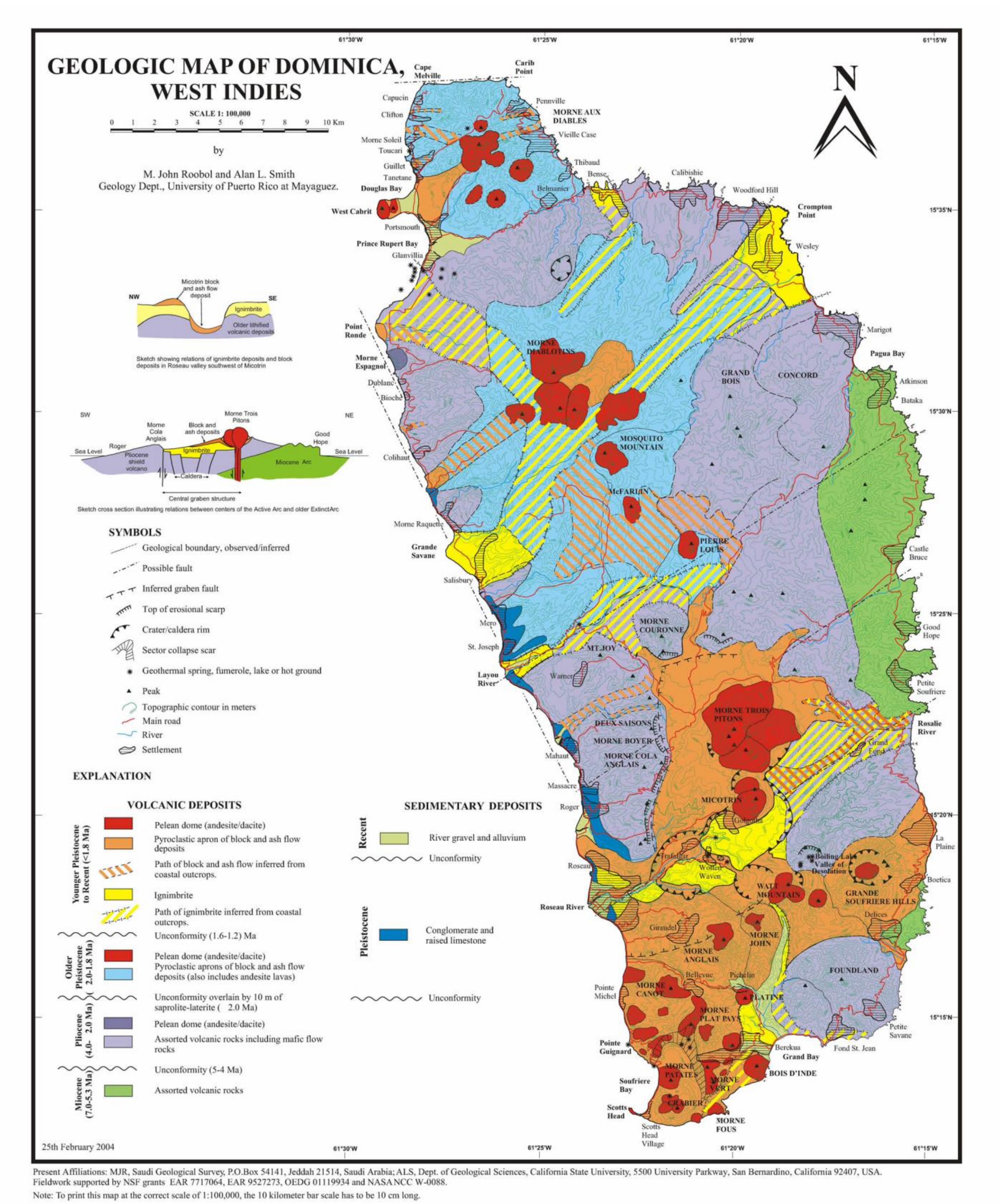


Figure 3.2. Geologic map of Dominica. Source: (Atlas of Dominica, 2011)

3.1.2. Soils

Mr. David Lang completed the major work on the classification of Dominica's soils over 40 years ago. He studied the basic soil characteristics and capabilities crucial for land use planning and agricultural development. Soils in Dominica are mostly residual soils, formed by the process of chemical weathering of rock. The climatic conditions of the island, especially warm temperatures and abundant rainfall, enhance the weathering process. Weathering of volcanic rocks changes their mineral composition and physical character. The andesitic bedrock on Dominica weathers to form clay and other secondary minerals (Degraff, 1987). The engineering properties of these soils are often very different from that of transported and re-deposited soils. Their unique properties are a response to the combination of environmental conditions found in the tropics; climate (especially rainfall and temperature regimes), parent material, water movement (drainage conditions), topography (e.g., slope length and gradient), vegetation and age (i.e., degree of weathering) are generally considered the most relevant factors (Reading, 1991; Rouse, 1990). Figure 3.3 shows the Lang's (1967) soil classification of Dominica based on degree of weathering.

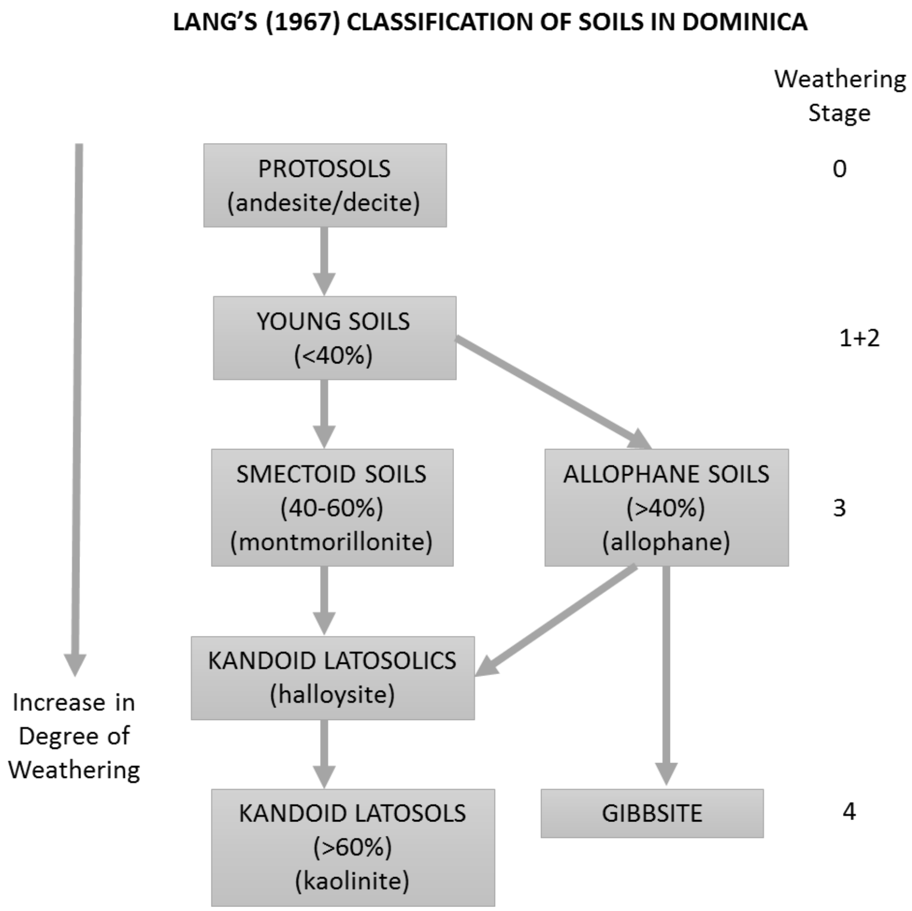


Figure 3.3. Lang's (1967) classification of Soils in Dominica. Figures in brackets are the proportion of minerals weathered to matrix size. Source: (Rouse et al., 1986)

Four distinct soil types are important in Dominica, these are: smectoid soils, kandoid soils, allophane latosolics and allophane podzolics. Rouse et al., (1986) investigated the properties of these soil types and it is summarized below.

- Smectoid soils (motmorillonite-rich): these soils occur in the highly seasonal parts of the island (annual rainfall below 2100 mm) where leaching is low, interrupted and incomplete. The montmorillonite content, together with an occasional cemented silica pan makes these soils impermeable when wet. Compared with the other soils of Dominica, smectoid soils have high subsoil dry unit weights and low porosities that ranges from 12.1 to 17.8 kN/m3 and from 0.36 to 0,61 respectively.
- Kandoid soils (mostly latosolics) (Kaolin/halloysite-rich): these soils typify areas receiving rainfall between 2100 mm and 3750 mm annually and a shorter duration of dry season, leaching is moderately intense and uninterrupted. Kandoid soils take a longer time to mature than smectoid and allophane soils, they are only found in older volcanic areas i.e. in the north and east part of the island. They have much lower subsoil dry unit weights (5.9 - 9.5 kN/m3) than smectoid and as a result their porosities are much higher (0.66 - 0.79).
- Allophane latosolics (allophane-rich): in areas with high annual rainfall greater than 3750 mm and no dry season, where leaching is intense and constant, allophane soils predominate. With continued leaching even the silica may be removed to form gibbsite, but because of the youthfulness of the relief and the effectiveness of the slope erosion, allophane latosolic soils tend to persist and indeed cover large parts of the island interior. Generally, these soils have very low subsoil dry unit weights and extremely low topsoil dry unit weights, 5.5 - 10 kN/m3 and 1.9 - 4.1 kN/m3 respectively. As a result, their subsoil porosities are very high (0.66 -0.81) and top soil porosities even higher (0.86-0.93).
- Allophane podzolics (allophane-rich): in the wettest areas with annual rainfall greater than 7000 mm, where leaching is extremely high, a peculiar variant of allophane is found. The allophane podzolics are characterized by deep litter and organic humic Ah horizons, a bleached highly leached subsoil, and a subsoil pan formed by accumulation of a complex of organic matter and amorphous sesquioxides. Their dry unit weights and porosities are higher than for allophane latosolics.

Figure 3.4 below, shows the soil map of Dominica.

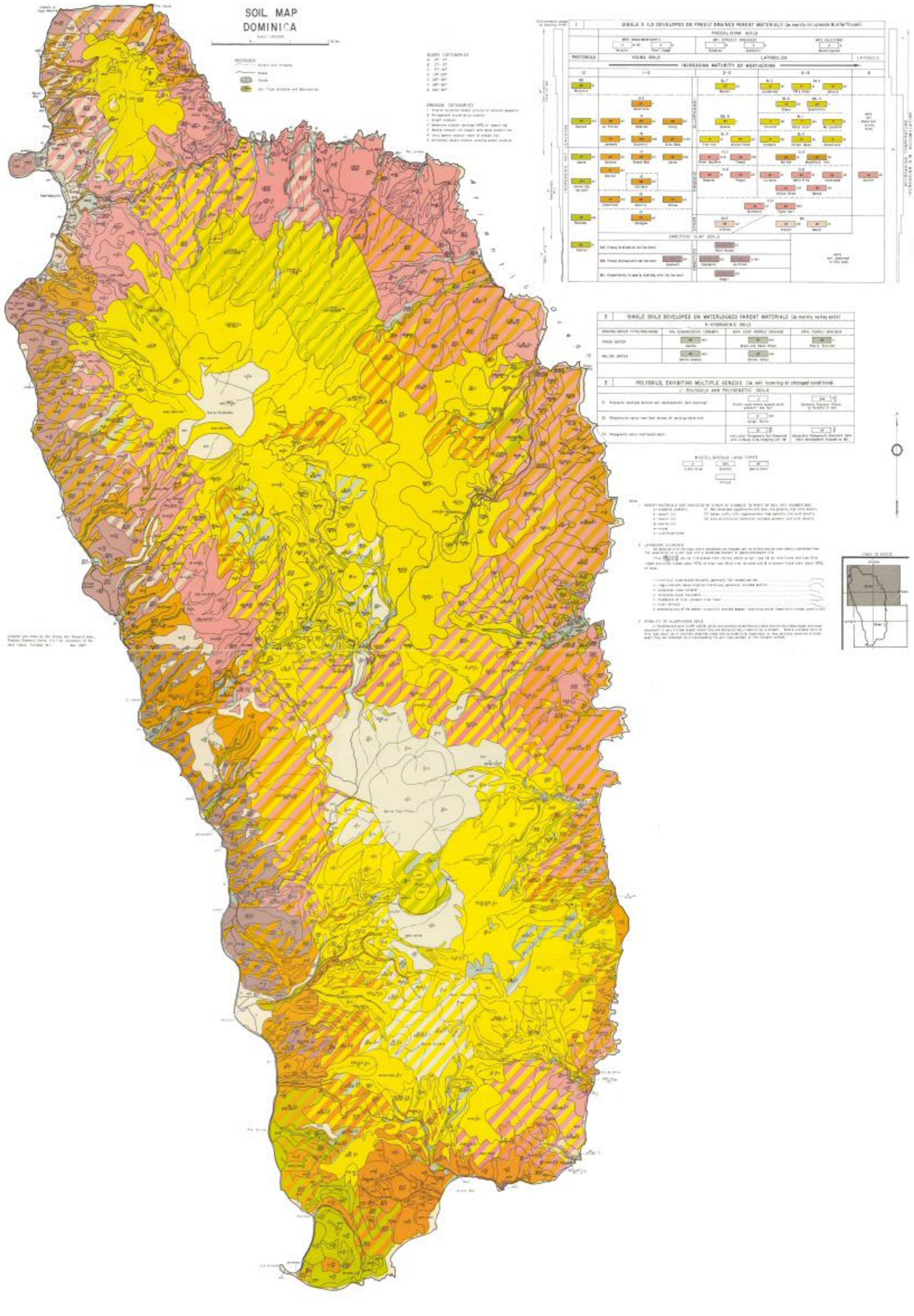


Figure 3.4. Soil map of Dominica. Source: (Andereck, 2007)

3.1.3. Landslides

The geology of Dominica coupled with its topography make the country very susceptible for landslides. In the past the country has encountered a lot of landslide events and almost all of them are related to high rainfall events. Between the period May and December, the country experiences its highest precipitation of the year and most of the disaster events occurred during this period. The disaster events occurred in Dominica since 1806 are provided in Appendix I. Hurricane David, which occurred on August 29/1979, can be considered as the biggest disaster event occurred in the last 40 years. The whole island was hit by the hurricane and suffered a considerable damage. Due to this event 42 persons were reported dead, around 2000 people were injured and 78% of the population was rendered homeless by housing destruction. Almost all the roads and most of the bridges were also damaged by this event. Many roads were blocked by landslides and road communication between the different parts of the country was greatly altered. The preliminary cost estimate for rehabilitation and reconstruction of the roads was estimated to be 82 million east Caribbean dollar, which is about 30 million us dollar with today's exchange rate. The map below (figure 3.5) shows the roads which were totally damaged and needed replacement and roads blocked by landslides and needed clearance (ECFLA, 1979).

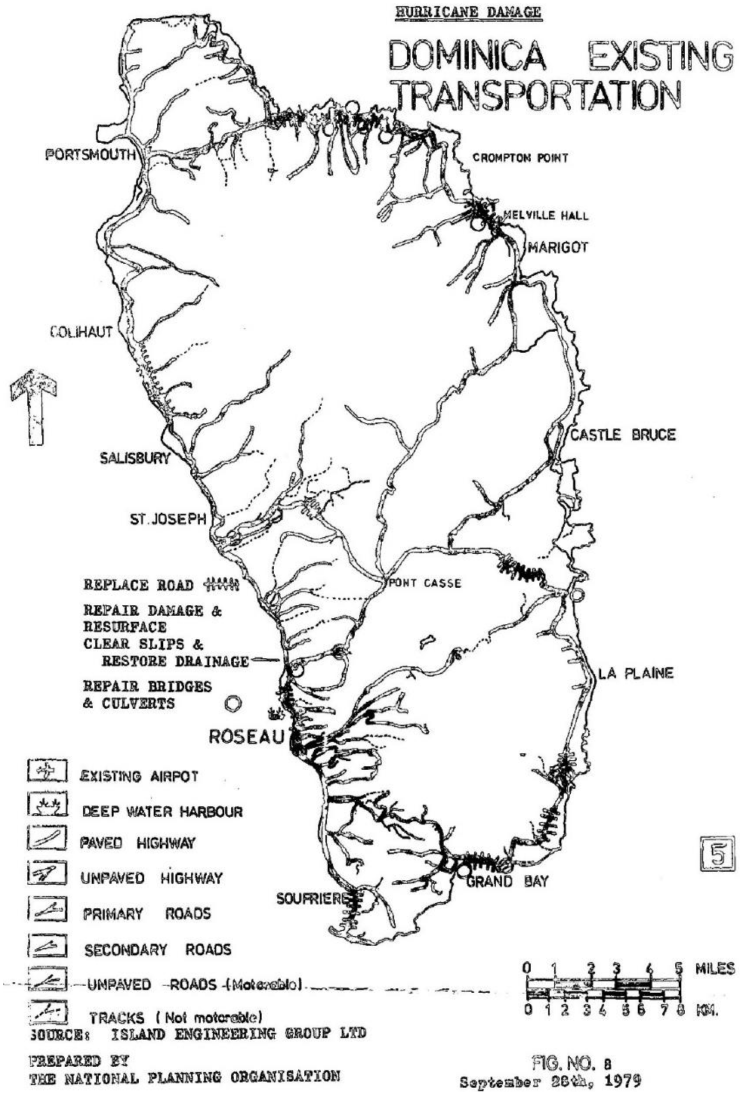


Figure 3.5. The road damage caused by hurricane David, Dominica. Source: (ECFLA, 1979)

3.2. Saint Lucia

Saint Lucia also belongs to the windward islands of the Caribbean Sea and is located at 13° 54' N and 61° 00' W coordinates. The island covers 616 square kilometre area. Steep slopes are common in much of the island. The central ridge exhibits the steepest terrain with the north and south ends being flatter (the highest point is 950 meters). According to the 2010 census, Saint Lucia has a total population of 174,000. The annual rainfall ranges from 1500 mm along the coastal fringe to over 3800mm in the mountainous interiors. In 2000, there was an estimated total road network of 910 km of which 150km were main roads and 127 km were secondary roads (Ed, 2002).

3.2.1. Geology

Saint Lucia is made up almost totally of volcanic origin, presenting andesite, dacite and basalt rock formations resulted from the tertiary or late quaternarty age volcanism. Sedimentary beds occur but are of small extent. Beds of mixed sedimentary and volcanic origin are common; they have good bedding and stratification such as tuffs, agglomerate tuffs and conglomerates (DeGraff, 1985; OAS, 1986). Newman, 1965 (as cited in Lindsay et al., 2002) divide the volcanic centres in Saint Lucia into three categories based on age and geographic distribution. These groups are the Northern, Central and Sothern series, from oldest to youngest. Lindsay et al., (2002) revised this sub division, owing to the confusion that the original grouping made like: several of the centres within the northern series are actually located in the south and several centres that were grouped as the youngest southern series correlate more to the older northern series. The revised grouping of Lindsay et al., (2002):

- Eroded basalt and andesite centres (a revision of the Northern series of Newman, 1965): these centres are the oldest rocks on the islands which are located in the northern and southern most parts of the island. The age dates for the centres in the north and south range from 18 to 5 and 10.1 to 5.2 Ma (millions of years) respectively. Except some shallow seismicity and cold fumarolic activity associated with some of the southern centres, the eroded centres are unlikely to erupt again.
- Dissected andesite centres (called the Central series by Newman, 1965): these centres are younger than the eroded dominantly basaltic centres of the north and south, in which their age dates range from 10.4 to 2.8 Ma. Dissected andesite centres are located mainly at the central and eastern part of Saint Lucia. These group of centres are also unlikely to erupt again in the future.
- Soufriere volcanic centre (a revision of the Southern series of Newman, 1965): Soufriere volcanic centre is the youngest volcanic activity in Saint, located at the south western part of the island. It has a series of different volcanic vents and vigorous high temperature geothermal field. The oldest dated rocks of this centre are 5 to 6 million years old. Soufriere volcanic centre is still active, but it is uncertain to say when the last eruption occurred in the island.

Figure 3.6 below shows the geological map of Saint Lucia.

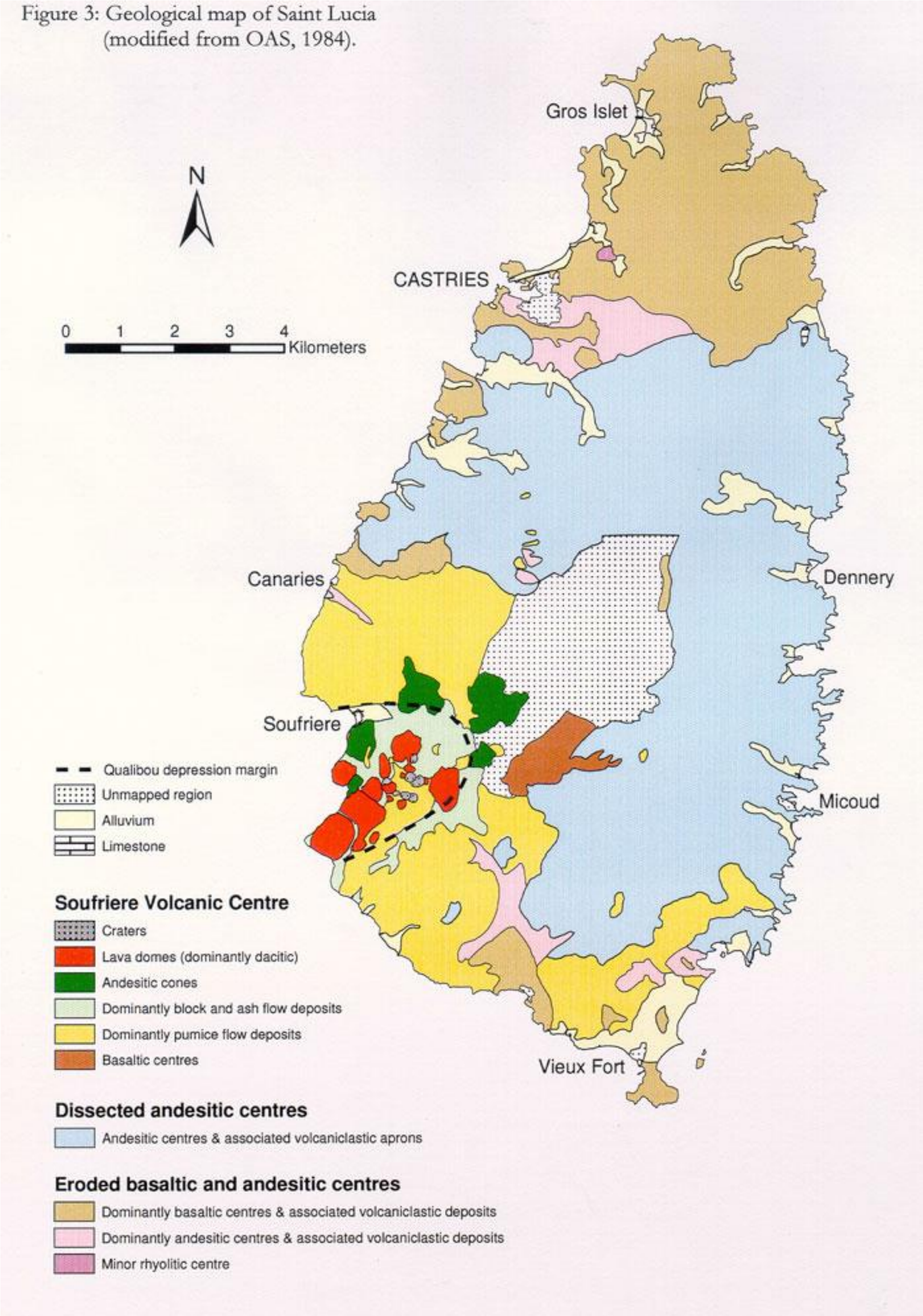


Figure 3.6. Geological map of Saint Lucia

3.2.2. Soils

The mineralogy of and weathering characteristics of the volcanic bedrock generally produces fine grained soils often containing high proportions of clay. Due to the widely varying rainfall pattern on the island, the parent materials are subject to different amount of leaching. This together with steep topography of the island and dacitic ash showers, contribute to the differentiation of the soil types. In areas with heavy rainfall and little or no dry season, the soils are of latosols or latosolic. The clay of these soils is usually kaolinitic but in special conditions allophane and illite may also exist. In areas with several months of dry season, the soils are of expanding clays of the montmorillonitic type (OAS, 1986). Under the unified soil classification used by engineers and geologists, the soils of Saint Lucia would be fine grained soils such as silty clays, clayey silts, silty clays-inorganic and sandy clays, or inorganic clays of medium plasticity (DeGraff, 1985). In the available soil map of Saint Lucia the classification is made based on parent material and the classes are: agglomerate soils, alluvial soils, clay soils, colluvial soils, miscellaneous soils and volcanic soils. The soil map of Saint Lucia is shown in the figure 3.7 below.

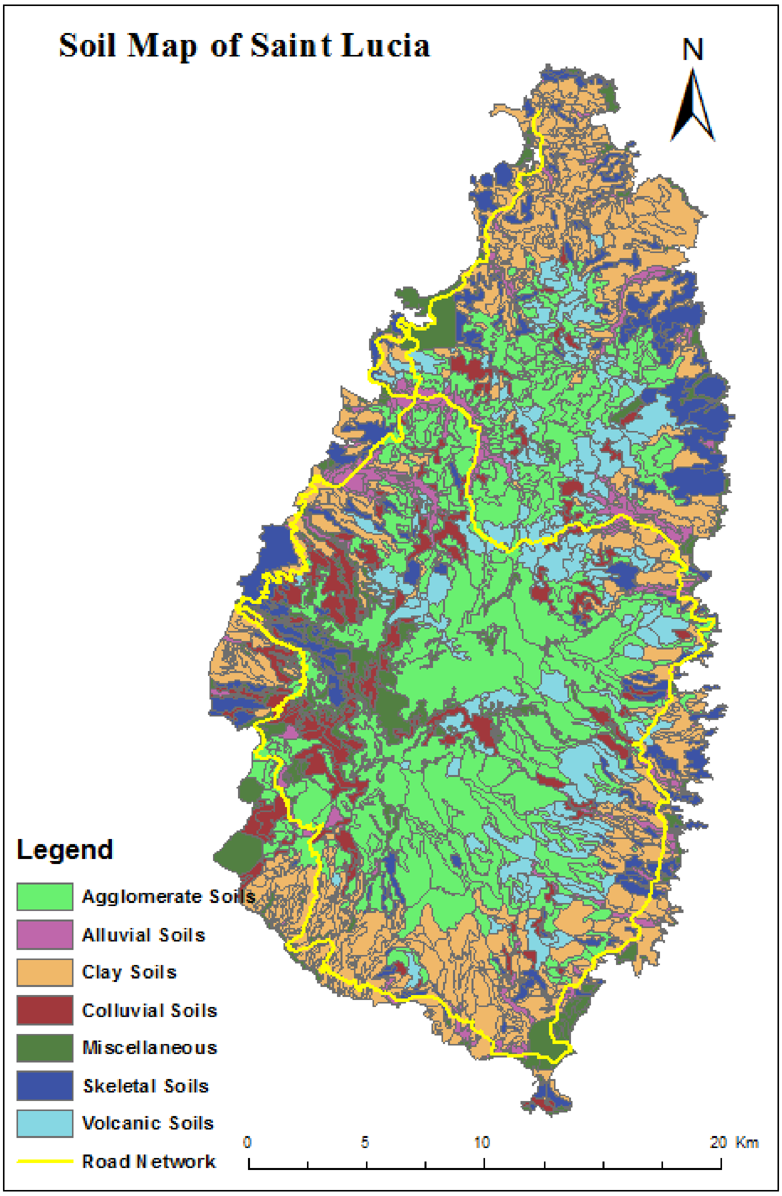


Figure 3.7. Soil map of Saint Lucia

3.2.3. Landslides

Owing to the country's mountainous topography, volcanic geological formation and heavy rainfall St. Lucia is affected by frequent flooding and landslides. Like Dominica, Saint Lucia exhibits the highest precipitation of the year from May to December, as a result most of the disaster events occurred in the past are concentrated in this period. Just in the last five years the country was hit by two big disaster events, Hurricane Tomas and the 2013 Christmas eve trough. The Christmas eve trough in 2013, occurred on December 24/2013. This disaster event caused the death of 6 persons and displaced 550. A total of 99.88 million us dollar damage was reported from different sectors of the country due to the disaster. 72% of this damage was sustained by transportation infrastructure sector (GSL & WB, 2014). Figure 3.8 shows the landslide inventory map along the major roads of Saint Lucia, which was prepared by Mott MacDonald (2013). The inventory mainly contain landslides occurred during hurricane Allen (August, 1980) and hurricane Tomas (October, 2010). The Disaster events of Saint Lucia since 1870's are provided in Appendix II.

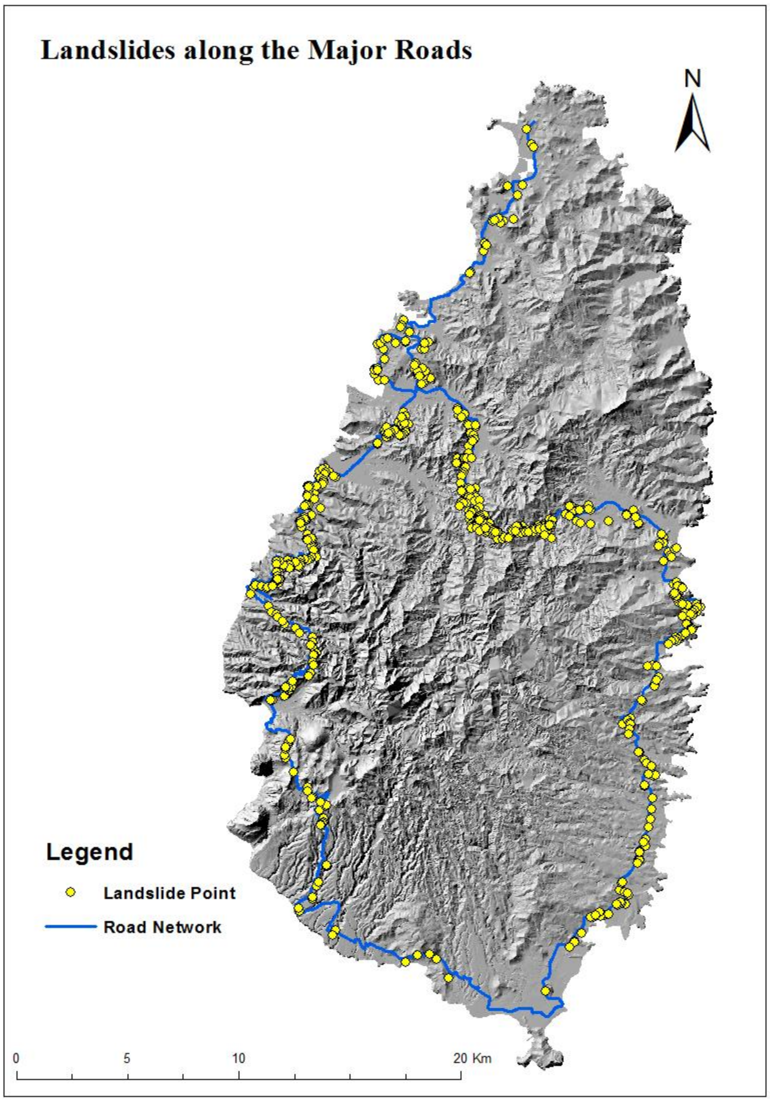


Figure 3.8. Landslides along the Major roads of Saint Lucia. Source: (Mott MacDonald, 2013)

Hurricane Tomas was the worst one that struck the country on October 31/2010. The fact that the country experienced a drought period longer than usual made the event to cause severe damage due to flood and landslides throughout the country. Statistically, the wave of the wind occurred in this event was a 1:15 year event. Whereas the return period of the rainfall was in order of 180 years. The disaster killed seven persons and injured 36. The total cost of the damage was estimated to be 336.2 million us dollar which accounts for 43.4% of St. Lucia's GDP. The road infrastructure has suffered badly as result of landslide action (mass slope movement), river bed erosion and river sedimentation occurred in the event. According to the ministry of works of Saint Lucia estimation, the transportation subsector has incurred a total damage of 100 million East Caribbean dollar, around 37.2 million US dollar with today's exchange rate (ECLAC, 2011).

During fieldwork, some of the road sections affected by hurricane Tomas was visited. Road sections around Canneries, Soufriere and Dennery regions were mostly affected by this event. The extent of the landslides and their effect was still visible. For instance, four embankment failures were occurred in Dennery region that washed away almost half lane of the road in each failure spots. The failures occurred with 500 meter intervals on average and now the road is being reconstructed (figure 3.8. top right). In addition, the rock falls occurred in Soufriere region during this event were quite considerable. The falling rocks were on average 1 to 1.5 m3 in size. Even though, there was no property damage, the road was closed for some time until it was cleared of the rocks. Figure 3.8 bottom left, shows some of the cleared rocks along this section of the road. The landslides occurred in Canneries were relatively fewer, but they were big in size. This road section was also closed for some time due to this slides. Figure 3.9 top left shows one of the big slides occurred in this region, this slide was also reactivated during the charismas eve event (2013).

Figure 3.9. Pictures showing landslides along the major roads of Saint Lucia, Hurricane Tomas

4. DATA AND METHODS

The study area of this research are the major roads of Dominica and Saint Lucia, which cover 310 and 146 km length roads respectively. The research is mainly focused on the use of historical landslide records to analyse the spatial and temporal probability of landslides along road corridors. For this, road maintenance and clearance reports, previous landslide inventory maps, damage assessment reports from storm events and technical and non-technical reports related to landslides were collected. Prior to the field work and even after that, visual image interpretation was carried out to identify the landslide prone areas and verify the historical records obtained from different organizations of the islands. The images were processed using ArcMap 10.2.2 and Erdas Imagine 2014 for correct geo-referencing. The images were then combined with digital elevation models, using ILWIS 3.4, to generate stereo-images. The stereo image interpretation and digitizing process was also performed using this software. In addition, daily rain fall records of the past 30 years and more period, depending on the availability, were collected from different rainfall stations of the countries. Based on the available data, generation of road related inventory maps together with the characterization of the road sections and landslide density calculation were done. The spatial probability was analysed using spatial multi criteria evaluation (SMCE) method. The temporal probability was approached by analysing the rainfall data using generalized extreme value distribution method.

4.1. Data Collection

The initial step in this thesis involved obtaining and assessing necessary data for the project. Previous landslide studies on both Islands were thoroughly investigated. In March of 2014, a field work was conducted for 15 days in each of the islands. The field work was done in two phases i.e. field visit of the landslide areas, and gathering historical records on landslides and other essential information for the study. During the second phase, contacts were established in governmental and local agencies, specifically with ministry of works, infrastructure, metrology and disaster management offices that were eager to exchange data.

Various data layers were used in this study they include:

- A very high resolution Pleiades images consisting of panchromatic band with 0.5 and multi spectral bands with 2 meters resolution for both islands covering the whole area,
- Digital elevation model with 50 meter resolution for Saint Lucia
- Contour map with 2.5 meters interval for Saint Lucia and with 10 meters interval for Dominica
- Road network shape file including major and minor roads for both islands
- Geology vector map with lithological description for Saint Lucia and in pdf format for Dominica
- Soil vector maps with soil type and other characteristics for both islands
- Landslide inventory maps from 1985, 1995 and 2010 for Saint Lucia from 1987 for Dominica
- Daily rainfall data from two stations for Dominica and 19 stations for Saint Lucia.

In the following sections the data collected during the fieldwork are discussed in detail

4.1.1. Rainfall Data

Saint Lucia

Rainfall records from 19 stations were obtained for Saint Lucia. All the stations have records on daily and hourly basis. Since the daily rainfall data contain longer period records than the hourly, the hourly records were not taken into consideration. The daily rainfall records are available for a period ranging from 26 to 51 years on different stations. For the purpose of this study, the stations with the longest record period (51 years) were considered. Nine stations have 51 years record (1955 - 2005), these stations are: Barre De L'Isle, Barthe, George V. Park, Mahaut, Mamiku, Patience, Soucis, Troumasse and Union Agr satation. Nevertheless, all of these stations have missing data in the middle, five of them even 25 % and more missing data. For instance, Mahaut station has 9512 missing data i.e. more than 50 % of the expected 18628 records for 51 years. It was, therefore, decided to consider only stations with fewer missing data for the analysis. The stations with fewer missing data are: Union, Barre De L'Isle, Barthe and Union. Out of these stations, Barthe and Barre De L'Isle were chosen for the final analysis, considering there spatial representation. Barthe is located in the south west of the island and it is in proximity to the Soufriere region, with road sections affected by frequent landslide occurrences. Barre De L'Isle is located in the middle of the island, which is also in proximity to the other landslide susceptible road section i.e. Barre De L'isle section of the east coast road. Figure 4.1 below shows the geographical location of the stations on the island.

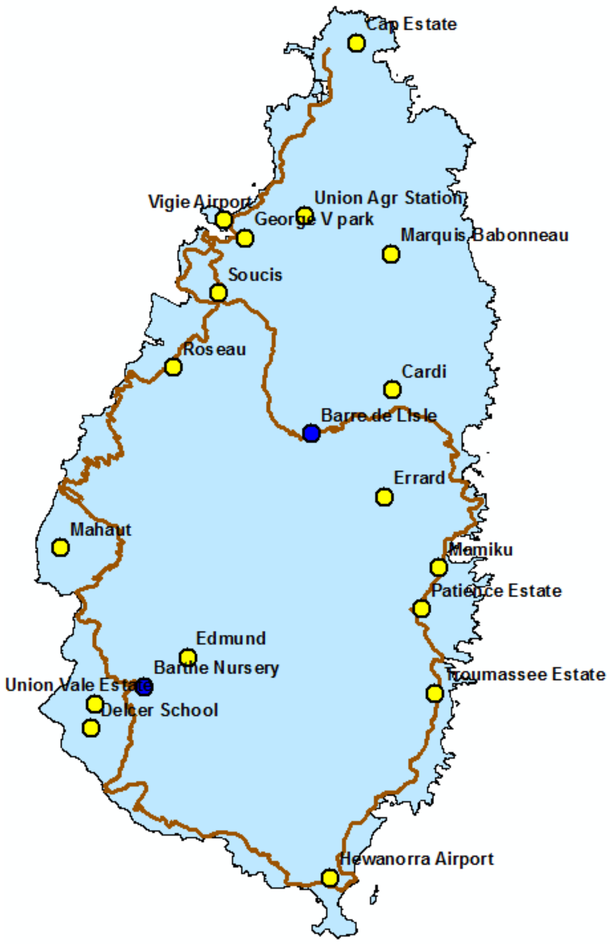


Figure 4.1. Rainfall Stations of Saint Lucia. The stations with blue dots are used for the analysis.

Dominica

For Dominica, rainfall records were available for only two stations namely: Canefield airport and Melville airport. Compared to Saint Lucia, the records also cover relatively shorter periods. Canefield airport station is located in the south west part of Dominica, at 15.1 N and 61.24 W coordinates. Records of 31 years, from 1982 to 2013, were available for this station. Melville airport station, on the other hand, has 39 years record that spans from 1974 to 2013. The station is located at 15.32 N and 61.18 W coordinates, north east part of the island. In terms of gaps, except few unreadable values which could be a data entering problem, there were no major gaps.

4.1.2. Landslide Data

Saint Lucia

The first field work of this study was done on St. Lucia. During office visits, it was found that there has been a recent study on landslides along the road. The work was done by Mott MacDonald (2013) in a large project which was carried out for the Ministry of Infrastructure of Saint Lucia. In the study they focused on the collection of previous works and analysed geology and seismicity, hazard assessment, vulnerability analysis, risk assessment and finally slope stability measures for selected road sections.

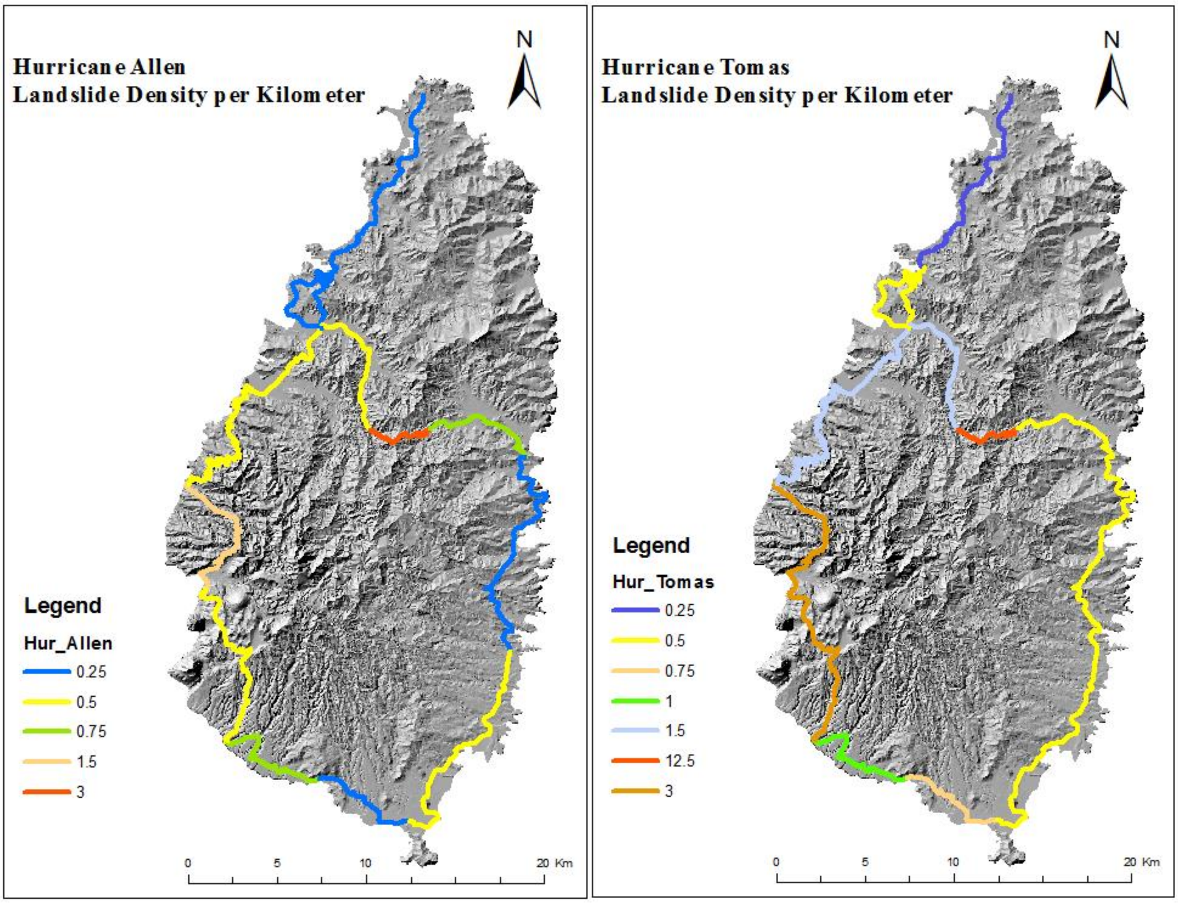


Figure 4.2. The results of the study by Mott MacDonald (2013) on landslide density per kilometre road. Post hurricane Allen (left) and post hurricane Tomas (right).

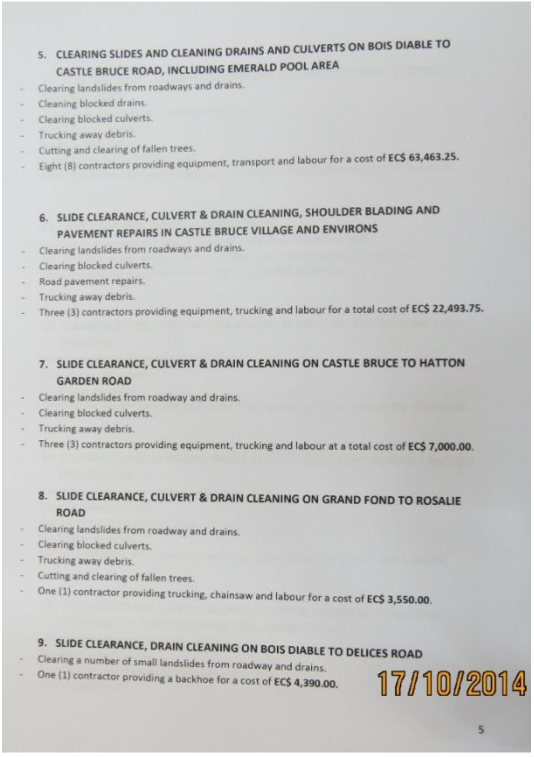
To assess the landslide hazard they used density analysis taking two storm events namely hurricane Allen and Tomas that occurred on August 3, 1980 and October 31, 2010 respectively. The landslide inventories they used for these storm events were the works of Degraff after hurricane Allen (1980) and Rogers after Tomas (2010). During their analysis stage, they selected the landslides which they considered that directly affect the primary roads and made a different landslide datasets for both events. Then they totalled the number of landslide occurrences along a defined road section for each of the datasets and calculated a density per km of road section as shown in the figure 4.2 above. Road sections were defined based on the land morphology and locations of main towns. They supported the landslide inventories by field visit and verifying the landslide location and characteristics.

Other than the Mott MacDonald work, some road clearance and maintenance records from other landslide events like the Christmas eve event (2013) were obtained. However, this records luck workable spatial reference and the number of landslides occurred were not mentioned. Therefore, it was difficult to include them in the study. The field work was concluded by visiting major landslide prone areas along the road. The focus of the field visit was given to Dennery and Souffrier road sections that are affected by frequent landslides.

Dominica

Dominica, on the contrary to Saint Lucia, has limited landslide inventories, only has the latest available inventory that covered the whole area made by Degraff (1987). There is also a work done by Andereck (2007). However, his work only focused on some parts of the island: Grand Fond, Petite Soufriere and Mourne Jaune. Assisted by an engineer from the ministry of works of Dominica, most of the road sections which are affected by frequent landslides were visited during fieldwork. Some of the landslides occurred along the road in previous storm events were identified by taking GPS points and notes on their characteristics. In most of the road sections, however, the areas adjacent to the road are covered with thick vegetation and it was impossible to see or identify landslides on those sections.

Road maintenance and clearance reports were obtained from the Ministry of Works for five rainfall events: September 3/2009 (tropical storm Erica), October 31/2010 (Hurricane Tomas), September 28/2011 (tropical storm Ophelia), November 28/2011, and April 17-25/2013. The reports don't have any spatial references for the landslide locations, they only have the road sections starting and end point where landslide clearance had been done and the amount of money spent for clearance (figure 4.3). To locate those areas and prepare them as geo-spatial dataset, the available high resolution images and thematic maps of the island were used.



5. **CLEARING SLIDES AND CLEANING DRAINS AND CULVERTS ON BOIS DIABLE TO CASTLE BRUCE ROAD, INCLUDING EMERALD POOL AREA**
- Clearing landslides from roadways and drains.
- Cleaning blocked drains.
- Clearing blocked culverts.
- Trucking away debris.
- Cutting and clearing of fallen trees.
- Eight (8) contractors providing equipment, transport and labour for a cost of **EC$ 63,463.25.**

6. **SLIDE CLEARANCE, CULVERT & DRAIN CLEANING, SHOULDER BLADING AND PAVEMENT REPAIRS IN CASTLE BRUCE VILLAGE AND ENVIRONS**
- Clearing landslides from roadways and drains.
- Clearing blocked culverts.
- Road pavement repairs.
- Trucking away debris.
- Three (3) contractors providing equipment, trucking and labour for a total cost of **EC$ 22,493.75.**

7. **SLIDE CLEARANCE, CULVERT & DRAIN CLEANING ON CASTLE BRUCE TO HATTON GARDEN ROAD**
- Clearing landslides from roadway and drains.
- Clearing blocked culverts.
- Trucking away debris.
- Three (3) contractors providing equipment, trucking and labour at a total cost of **EC$ 7,000.00.**

8. **SLIDE CLEARANCE, CULVERT & DRAIN CLEANING ON GRAND FOND TO ROSALIE ROAD**
- Clearing landslides from roadway and drains.
- Clearing blocked culverts.
- Trucking away debris.
- Cutting and clearing of fallen trees.
- One (1) contractor providing trucking, chainsaw and labour for a cost of **EC$ 3,550.00.**

9. **SLIDE CLEARANCE, DRAIN CLEANING ON BOIS DIABLE TO DELICES ROAD**
- Clearing a number of small landslides from roadway and drains.
- One (1) contractor providing a backhoe for a cost of **EC$ 4,390.00.**

17/10/2014

5

Figure 4.3. Example of landslide clearance reports obtained from ministry of works of Dominica

The reports from April 2013 and September 2011 have accompanying pictures of the landslides at the time of their occurrence. An attempt was made to relate these pictures with the pictures taken during fieldwork and locate them by their GPS point. Some of them were easy to relate because their scars were still visible during the fieldwork (Figure 4.4). But for the others, which were vegetated during the field work period, personal judgment had to be taken in looking for some signatures to relate the pictures as shown in Figure 4.5.

Figure 4.4 Relating the Landslide pictures, left from the report and right taken during field work. Which are very similar and easy to relate.

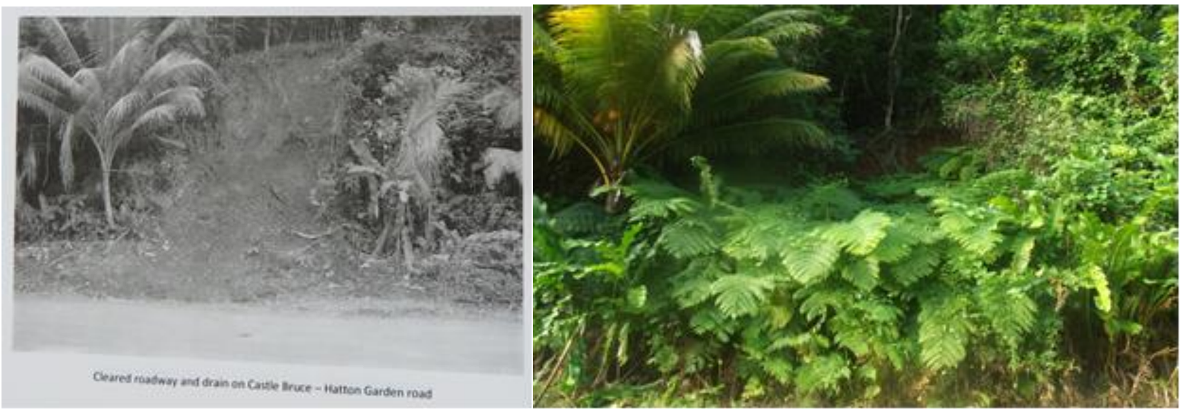


Figure 4.5. Relating the Landslide pictures, left from the report and right taken during field work. Difficult one, I relate them considering the small tree on the left side and tree roots at the top of the scar.

The other three events don't have accompanying pictures; therefore, the information was extracted by taking the road sections starting and end point and the number of landslides occurred in that section together with the clearance cost. In some instants the number of landslides on the sections were not mentioned, only the clearance cost. For such cases, first the average clearance cost per landslide was calculated taking all the five events then estimation was made for the number of slides of those sections without information by dividing their total clearance cost with the average value. Finally a geo-spatial data base for each storm events showing the number of landslides in different road sections of the island were made (Table 4.1).

Table 4.1. Example of landslide data base prepared for each storm events

Road segment	Starting point	Ending point	Length	Sep 2011 no of slides	Sep 2011 clearing cost	Sep 2011 slide description
s001	Pont Casse	Bois Diable	4509.74	1	10573	Landslide, cost include road repair
s002	Castle Bruce	Bois Diable	9314.67	1	13407	Landslide, cost include road repair
s003	Castle Bruce	Petite Soufriere	8583.14	15	496087	Numerous slides some major, cost include repair
s004	Hatton Garden	Castle Bruce	19935.64	10	134079	Several small slides
s006	Bois Diable	Rosalie	8267.5	4	42294	Landslide, cost include road repair
s006	Grand fond	Rosalie	2031.44	6	234642	small landslides, Cost includes realignment of z road

4.1.3. Road Database for Dominica

Other than the maintenance and clearance reports, a road data base was also obtained from ministry of works of Dominica. They prepared the road database in 2009 but upgrading of the database has been done every time there is change on the road sections. The road database has information on the entire road network of the country. Among other things, the kind of information obtained from the database include: drainage type and width both in the left and right side of the road, adjacent ground whether it is cutting or valley or flat, and land use of the area around the road section. These information are available on average with a 1km interval. Here also the road sections are indicated only by their starting and end point.

To transform the road database into a geospatial dataset high resolution imagery together with location and road network map of Dominica were used. First, the names and location of junction points of the road network were identified using the location map. Then, these points were digitized on the road network map using the high resolution image as a reference. The points were then correlated to the starting and end point information of the road sections provided in the database. After this, the road network was further segmented into 1km interval segments from the starting to end point of each road sections. Finally all the information from the database on each individual road segments were transferred to the respective road segments in road network map. There were some segments with missing data, and it was treated by referring to the images and neighbouring segments. Table 4.2 below, shows the geospatial road database prepared.

Table 4.2. Part of the geospatial road database prepared for Dominica

Road seg	*Starting point*	*Ending point*	*Length Km*	*Drainage type left*	*Drainage type right*	*Drainage widht left*	*drainage width right*	*Adjecent ground left*	*Adjecent ground right*	*Landuse type*
s042	Loubiere	White river Delices								
s042a	Petite Savane	White river Delices	7.4							
s042a1			2	Earth	Earth	0.34	0.6	Valley	Cutting	Forest
s042a2			1	Earth	No_drainage	0.34	?	Cutting	Valley	Forest
s042a3			1	Concrete_lin	No_drainage	0.34	?	Cutting	Valley	Forest
s042a4			0.4	Earth	Earth	1	0.6	Flat	Flat	Empty_lot
s042a5			1	Earth	Earth	1	0.6	Flat	Cutting	Empty_lot
s042a6			1	Kerb	Earth	0.14	0.6	Flat	Flat	Residential
s042a7			1	Earth	Earth	0.14	0.6	Cutting	Valley	Residential
s042b	Bagatelle	Petite Savane	5.4							
s042b1			1	Concrete_lin	No_drainage	0.14	?	Cutting	Valley	Residential
s042b2			1	Earth	Earth	1	0.6	Cutting	Valley	Empty_lot
s042b3			1	Earth	Earth	0.34	0.6	Valley	Cutting	Forest
s042b4			1	Earth	Earth	0.34	0.6	Cutting	Valley	Forest
s042b5			1.4	Earth	Earth	0.14	0.6	Cutting	Valley	Residential
s042c	Grand bay	Bagatelle	3.9							
s042c1			1	Earth	No_drainage	1	?	Flat	Flat	Empty_lot
s042c2			1	Concrete_lin	No_drainage	1	?	Cutting	Valley	Empty_lot
s042c3			1	Earth	No_drainage	1	?	Flat	Flat	Empty_lot

4.2. Data Analysis

4.2.1. Segmentation and Characterization of the Road

Road segmentation and characterization refers to subdividing the entire road network into smaller segments that possess the same spatial characteristics. The road segmentation was developed based on the road database obtained during fieldwork. The database was converted into a geo-spatial dataset, by entering all the information available in the database into the road shape file. As explained above in section 4.1.3, the shape file has attributes: adjacent ground terrain left and right (whether it is a cut slope, valley or flat), drainage type left and right, and adjacent ground land use. The information from the database were available per one kilometre segment of the road. Due to this, further segmentation of the roads was not possible, instead the 1km segments were used as a basis to extract the lithology, soil type and slope angle of the road segments.

The lithology, soil type and slope angle of the one kilometre road segments were extracted from the available geology map, soil map and digital elevation model (DEM) respectively. For this purpose buffer maps along the road network were prepared taking 50m buffer distances on both sides. For each road segment the upslope side buffer was identified based on the information obtained from the road database and image interpretation. Then, for each road segment the upslope side was selected and the other side was deleted from the buffer map. The buffer map was then crossed with the factor maps. Finally, the geology, soil type and slope angle were assigned for road segments, taking the predominant value (weighted by area) of each of the segment from the crossed tables.

4.2.2. Landslide Density

The landslide density is expressed as the number of landslides per one kilometre section of the road. For Saint Lucia, the landslide densities made by Mott MacDonald (2013) were directly used. They calculated two landslide densities after Hurricane Allen and Hurricane Tomas, and the method they used is explained briefly in the section 4.1.2.

For Dominica, the landslide inventories of the five storm events, prepared using the road maintenance and clearance reports, and the road database were used. For this analysis ILWIS 3.4 was used. First the information on the number of slides per road sections from the landslide inventories were joined to the road database. Then, the length of all road sections were calculated by excluding the sub-sections where the terrain is flat in both sides. The flat sub-sections were identified based on the high resolution images and the information obtained from the road database. Finally, the number of landslides per kilometre (landslide density) was calculated for each road section by dividing the number of slides by the length of the road section. This was done for all the five storm events separately.

4.2.3. Rainfall Analysis

To analyse the distribution of extreme events of rainfall and calculate their return periods, Generalized Extreme Value (GEV) and Gumbel distribution models were used. As mentioned in section 3, for Saint Lucia the available two stations data with 31 and 39 years record and for Dominica the selected two stations with 51 years record with fewer gaps were used for the analysis. All these stations were analysed separately and return period of extreme events were calculated for each. First, annual daily maximum value of each recoding period was calculated for all the stations that were considered. This gave 51 records for both selected stations of Dominica and 31 and 39 records for Cane field and Melville stations of Saint Lucia respectively. Then each records were fitted to GEV and Gumbel models using RStudio.

RStudio has an extreme value analysis package called "extRemes" (Gilleland, 2015). Two functions contained in this package were used for the analysis namely: Fit an Extreme Value Distribution to Data (fevd) and Likelihood-ratio Test (lr.test). The FEVD function can be used to fit the data into GEV distribution model or Gumbel distribution model. As an output, it gives different set of plots such as: QQ and QQ2 plots of the empirical quantiles against model quantiles, histogram of the data against the model density, return period plot of the return period against the rainfall with 95 percent confidence intervals, etc. The LR test function tests the likelihood ratio of two model fits and indicates which model has a greater fit.

4.2.4. Spatial Probability

The spatial probability analysis was performed using spatial multi criteria evaluation (SMCE). To formulate the criteria tree, the attributes of the characterized road segment map were used as spatial factors. Because the characterized road segment maps of the two islands don’t contain the same attributes, the criteria trees were prepared in different ways.

Saint Lucia

Here, the spatial factors used for the criteria tree were: number of landslides, slope angle, erosion, geology and soil. The number of landslides factors represent the landslide points counted in each road segments. The landslide points were extracted from the landslide inventory made by (Mott MacDonald, 2013). The values of the number of landslide factor range from 0 to 14 and it was standardized as benefit using maximum value. The slope angle factor represents the upslope of the road segments and its values range from 0 to 49. This factor was also standardized as benefit using maximum value. The erosion factor represents the extent of erosion of the ground adjacent to the road segment, which was extracted from erosion map of island. It was classified qualitatively as: no apparent erosion, slight erosion, moderate erosion, severe erosion, very severe erosion and extremely severe erosion. These classes were given values between 0 and 1 for the standardization of the factor, no apparent erosion being 0 and extremely severe erosion being 1. The geology and soil factors were standardized based on the landslide density within each geologic unit and soil type unit respectively, which is discussed in section 5. The units were first ranked starting with the highest landslide density and then they were given values between 0 and 1 for the standardization.

Other than the spatial factors mentioned above, flat section attribute was used as spatial constraint. This spatial constraint discard the flat section from the analysis by giving a value 0 in the final output. The weighing of the spatial factors was given using direct method. The highest weight is given to the landslide factor (0.5), followed by slope factor which is 0.25. Geology and soil together as material, are given 0.17 weight. Out of this, 60% of the weight is for soil and 40% is for geology. Finally the remaining 0.08 weight was given to erosion. Figure 4.6 below shows the SMCE criteria tree of Saint Lucia.

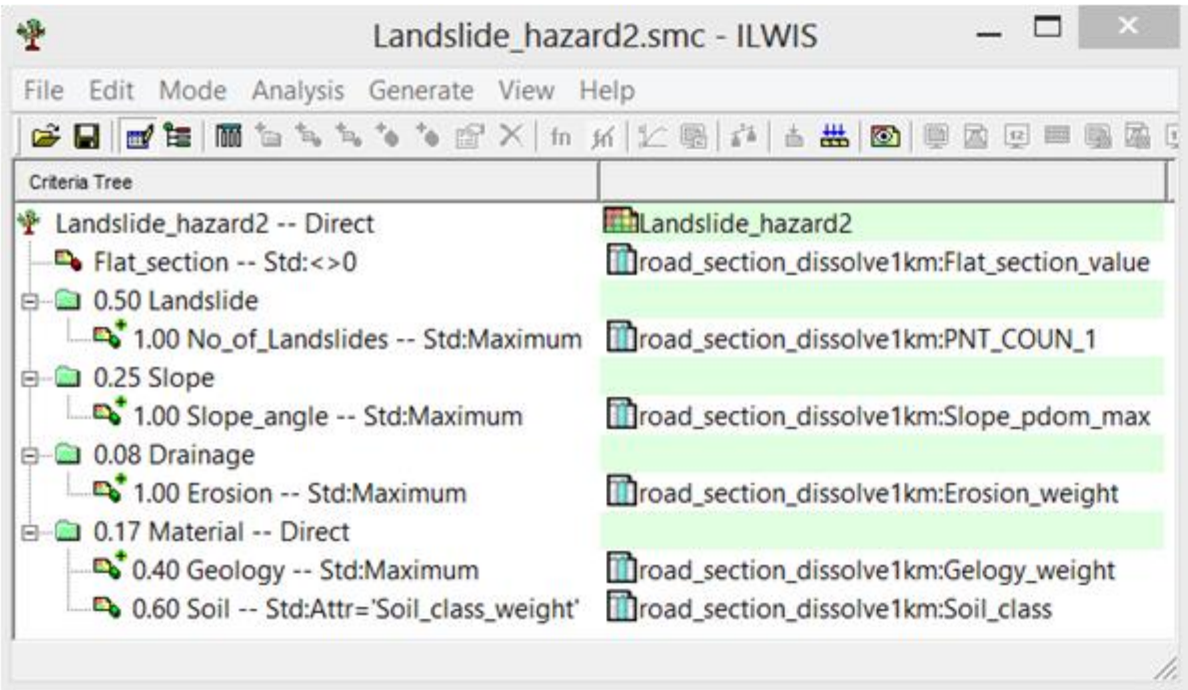


Figure 4.6. Spatial multi criteria tree for Saint Lucia

Dominica

The criteria tree for Dominica was prepared using slope, drainage, material and land use attributes as spatial factors. Under the slope factor, slope type of adjacent ground left and right and slope angle were included.

The slope angle was given 80% weight of slope factor and it's standardized the same way as done for Saint Lucia. The slope type of adjacent ground indicates whether the road segment is cut, valley or flat section, and it takes the remaining 20% weight of the slope factor. It was standardized using pair wise comparison as: cutting is strongly more important than valley and very strongly more important than flat, and valley is moderately more important than flat. In the drainage spatial factor, side ditch type left and right were included. The side ditch has 4 types namely: concrete lined rectangular, concrete lined V drain, kerb and no drainage. And it was standardized pair wise, giving the highest importance for no drainage and the lowest for concrete lined rectangular and V drain. The material spatial factor (geology and soil) is treated in similar way as Saint Lucia. The last spatial factor, land use type beside the road segment, has four types: residential, commercial, forest, agricultural and empty lot. This factor is standardized by rank ordering, giving the 1st rank for empty lot and the last for residential and commercial.

Here also one attribute was used as constraint to exclude the flat sections from the analysis. In weighing of the spatial factors, which was done by direct method, the highest weight was given for slope which is 0.6. Material was given the next higher weight of 0.3. Drainage and land use took equal weight of 0.05. Figure 4.7 below shows the SMCE criteria tree of Dominica.

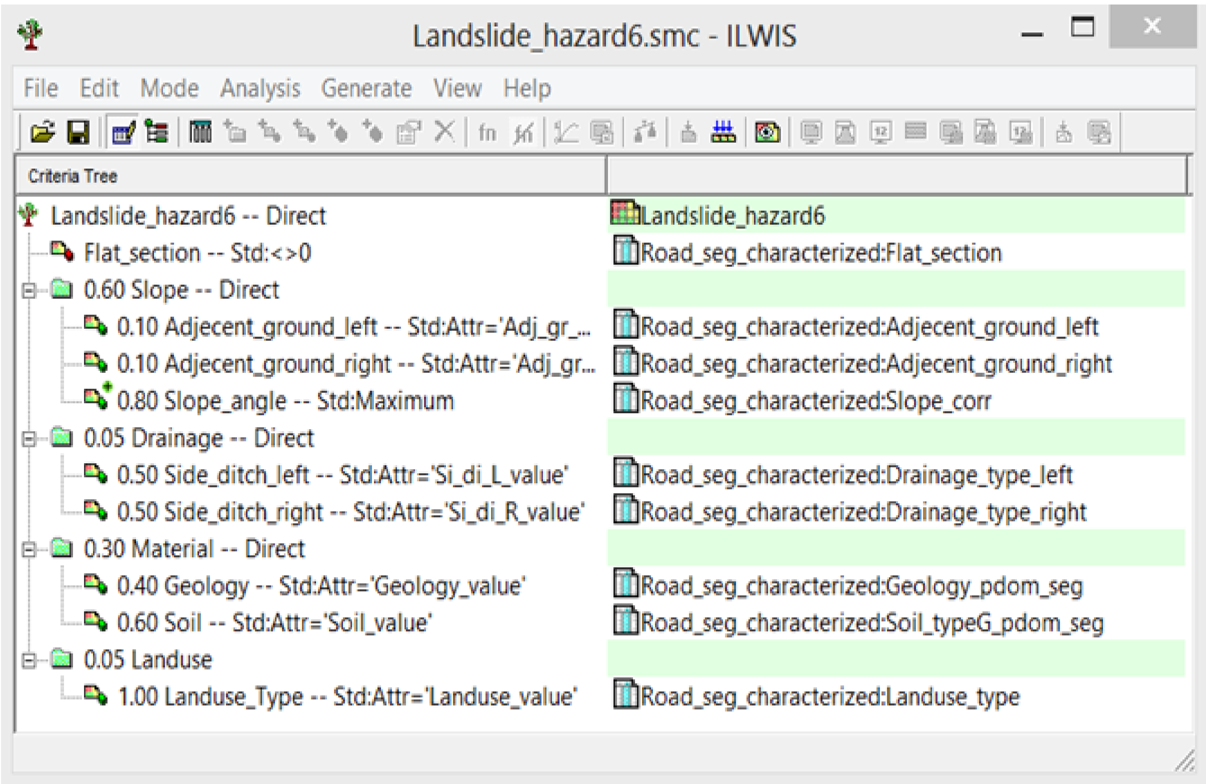


Figure 4.7. Spatial multi criteria tree for Dominica

5. RESULTS

The results obtained based on the applied methodology described in the previous chapter are presented in this chapter. First, landslide frequency and density distribution within each geological and soil units of the two islands are presented. This is followed by the results of landslide density analysis of the road sections of Dominica for the studied five storm events. Then, the rainfall return period analysis results for both Islands are presented. Finally, the results of the spatial probability analysis along the major roads of the Islands are provided.

5.1. Landslide Frequency and Density within Each Slope Class

5.1.1. Dominica

The slope angles of the adjacent ground to the major roads vary from 0 to 51 degrees. To analyse the landslide distribution, the slope angles were classified into 6 classes: 0 – 2, 2 – 5, 5 – 10, 10 – 20, 20 – 30 and over 30 degrees. Table 5.1 below shows the results obtained from the landslide distribution analysis within each classes.

Table 5.1. Landslide Distribution within each slope class, Dominica

Slope Class	Segment length (km)	No of Landslide	Landslide density per Km	% of total length of the road	% of total no of Landslides
0-2 degrees	83.77	14	0.17	27%	6%
2-5 degrees	3.60	3	0.81	1%	1%
5-10 degrees	53.69	46	0.86	17%	18%
10-20 degrees	79.37	63	0.80	26%	25%
20-30 degrees	69.89	88	1.26	22%	35%
Over 30 degrees	20.34	35	1.71	7%	14%
Grand Total	**310.66**	**249**	**0.80**	**100%**	**100%**

The results revealed that the highest landslide frequency was registered in slope class 20 – 30 and 10 – 20 degrees, with 88 and 63 landslides respectively. Whereas, slope classes 2 – 5 and 0 – 2 have the lowest landslide frequency, 3 and 14 landslides respectively. Based on the landslide distribution result, however, the highest landslide density per kilometre was obtained in slope class over 30 degrees. This class has recorded 1.71 landslides per kilometre, followed by slope class 20 – 30 degrees with 1.26 landslide density per kilometre. As expected the lowest landslide distribution was obtained in slope class 0 – 2 degrees, with 0.17 landslide density. The results seem to have a direct relation with an increase of slope angle except for slope class 10 – 20 degrees, which recorded landslides density less than slope classes 2 – 5 and 5 – 10 degrees.

5.1.2. Saint Lucia

In Saint Lucia, the slope angles vary from 0 to 48 degrees and they were classified in the same way as for Dominica. Table 5.2 below shows the results obtained from the landslide distribution analysis within each classes.

Table 5.2. Landslide Distribution within each slope class, Saint Lucia

Slope Class	Segment length (km)	No of Landslide	Landslide density per Km	% of total length of the road	% of total no of Landslides
0-2 degrees	33.30	26	0.78	23%	5%
2-5 degrees	5.87	14	2.38	4%	2%
5-10 degrees	12.93	39	3.02	9%	7%
10-20 degrees	28.14	154	5.47	19%	27%
20-30 degrees	38.39	214	5.57	26%	38%
Over 30 degrees	27.65	123	4.45	19%	22%
Total	**146.28**	**570.00**	**3.90**	**100%**	**100%**

The highest landside frequency was obtained in slope class 20 – 30 degrees with 214 landslide, followed by slope class 10 – 20 degrees with 154 landslides. While the lowest landslide frequency was recorded in slope class 2 – 5 and 0 – 2, with 14 and 26 landslides. In slope class over 30 degrees, 123 landslides were recorder which is lower than what is recorded in slope classes 10 – 20 and 20 – 30. The results from landslide density per kilometre also show the same hierarchy except for the lower classes. Even though 0 – 2 class has higher landslide frequency than the 2 – 5 slope class, its landslide distribution was the lowest with 0.78 landslides per kilometre. The 2 – 5 slope class has 2.38 landslide density per kilometre. The highest was registered in 20 – 30 slope class with 5.57 landslides per kilometre.

5.2. Landslide Frequency and Density within Each Geological Units

5.2.1. Dominica

Table 5.3 shows the total length and landslides recorded within each geological unit of Dominica. The analysis is made based on the geologic map of Dominica, which mainly focuses on the time periods of the geologic units but with some description of type of rocks. According to the results obtained, the dominant lithology is the Pliocene (Assorted Volcanic rocks including Mafic flow), with a total length of 101.69 km and with 78 landslides. Miocene (assorted volcanic rocks) and Older Pleistocene (Pyroclastic aprons of block and ash flow also includes andesite lavas) also exhibit a considerable number of landslides, 62 and 42 landslides respectively. The lowest landslide frequency is recorded within Younger Pleistocene (Ignimbrites), only 6 failures.

The analysis of the landslide frequency revealed that, although the highest frequency is recorded in Pliocene (Assorted Volcanic rocks including Mafic flow), the density distribution is not the highest. The computation of the number of landslides per kilometre length of the road for each lithological unit revealed that Pliocene (Assorted Volcanic rocks including Mafic flow) has 0.77 landslides per kilometre. The highest landslide density is obtained within Older Pleistocene (Pyroclastic aprons of block and ash flow also includes andesite lavas) with 1.12 landslides per kilometre length of the road and the lowest within Younger Pleistocene (Ignimbrites) with 0.54 Landslide per kilometre. High densities are also recorded within Older Pleistocene

(Pyroclastic aprons of block and ash flow also includes andesite lavas) and Recent (River Gravel and Alluvium), 1.02 and 0.9 landslides per kilometre respectively.

Table 5.3. Landslide frequency and density within each geological units of Dominica

Lithology type	Segment length (km)	No of Landslide	Landslide density per Km	% of total length of the road	% of total no of Landslides
Older Pleistocene, Pyroclastic aprons of block and ash flow also includes andesite lavas	37.54	42	1.12	12%	17%
Pleistocene, Conglomerate and raised limestone	13.91	9	0.65	4%	4%
Recent, River Gravel and Alluvium	14.42	13	0.90	5%	5%
Pliocene, Assorted Volcanic rocks including Mafic flow	101.69	78	0.77	33%	31%
Miocene, assorted volcanic rocks	60.77	62	1.02	20%	25%
Younger Pleistocene, pyroclastic apron of block and ash flow	71.30	39	0.55	23%	16%
Younger Pleistocene, Ignimbrites	11.04	6	0.54	4%	2%
Total	*310.66*	*249*	*0.80*	*100%*	*100%*

Thus the frequency distribution of the landslides in each lithological unit does not correlate with density distribution. The landslide density distribution suggests that the lithological unit most susceptible for landslide is Older Pleistocene (Pyroclastic aprons of block and ash flow also includes andesite lavas), whereas Younger Pleistocene (Ignimbrites) and Younger Pleistocene (pyroclastic apron of block and ash flow) are the least susceptible. The lithological unit of Miocene (assorted volcanic rocks) have also high degree of susceptibility to landslides.

5.2.2. Saint Lucia

Table 5.4 shows the road length covered by each geologic unit of Saint Lucia and the landslides occurred within that unit. The analysis is made based on the geologic amp of Saint Lucia. Compared to Dominica, this map has relatively good description of the geologic units. The results show that most of the landslide occurrences (75%) are concentrated in the central series. In the southern and northern series 14% and 7% of the landslides are recorded respectively. And in the recent deposits only 4% are recorded. Considering the geological description of the units, Andesite ash altered and Andesite Agglomerate of the central series have exhibited the highest number of landslide failures, 209 and 114 failures respectively. Compared to these two geologic units, the landslide occurrences in the other units are very low, 46 and below occurrences in each of the units. The lowest landslide frequency is recorded in the Dark Andesite Cones geologic unit of the southern series with one failure only.

From the analysis of the density distribution, it is observed that all the geological units in the central series have high landslide density per kilometre, ranging from 5.10 to 11.91 and on average 6.86. Like the landslide frequency, the landslide density distribution is also highest in the andesite ash altered geologic unit of the central series. The results showed that, it has 11.91 landslide density per kilometre length of the road. The second highest landslide density per kilometre is obtained in the Andesite Porphyritic geologic unit of the central series with 7.34 landslides per kilometre. The lowest landslide density is calculated within the southern series geological units, Dark Andesite Cones and Belfond Pumice flow tuff which have 0.50 and 0.33 landslide density per kilometre respectively.

Table 5.4. Landslide frequency and density within each geological units of Saint Lucia

Series	Geology	Seg. length (km)	No of Landslides	Landslide density per Km	% of total length of the road	% of total no of slides
Central	*Altered Andesite Porphyritic*	4.30	22	5.12	3%	4%
	Andesite Agglomerate	19.15	114	5.95	13%	20%
	Andesite Ash Altered	17.54	209	11.91	12%	37%
	Andesite Porphyritic	3.68	27	7.34	3%	5%
	Mudflow	6.08	31	5.10	4%	5%
	Agglomerate Tuffs, Tuffs	4.53	26	5.74	3%	5%
Northern	*Andesite*	5.19	14	2.70	4%	2%
	Basalt, Agglomerate	6.43	16	2.49	4%	3%
	Basalt, Andesite, Agglomerate, Tuff	6.51	9	1.38	4%	2%
Southern	*Andesite Agglomerate*	13.41	46	3.43	9%	8%
	Andesite Pumice Flows Tuff	1.79	3	1.68	1%	1%
	Belfond Pumice Fall	1.94	5	2.57	1%	1%
	Belfond Pumice Flow Tuff	12.03	4	0.33	8%	1%
	Dark Andesite Cones	1.98	1	0.50	1%	0%
	Piton Agglomerate	4.46	14	3.14	3%	2%
	Porphyritic Basalt	2.33	5	2.15	2%	1%
Recent	*Alluvial, Beach & Terrace*	30.26	20	0.66	21%	4%
Urban*(not mapped)*	*Unclassified*	4.67	4	0.86	3%	1%
Total		*146.28*	*570*	*3.90*	*100%*	*100%*

The above results suggest that, in general the central series geologic units are more susceptible for landslides than the other geologic units. And andesite ash altered is the most susceptible unit followed by andesite porphyritic unit. The least landslide susceptible geological units are Dark Andesite Cones and Belfond Pumice flow tuff units of southern series and alluvial, beach and terrace units of recent deposits.

5.3. Landslide Frequency and Density within Each Soil Types

5.3.1. Dominica

As shown in table 5.5 below, among the five major soil types of Dominica Kandoid soil type has the highest landslide frequency with 105 failure occurrences which is 42% of the total recorded landslides. The Young soil type has also high frequency with 89 landslide failures, followed by Allophanoid soil type with 41 failures. The lowest landslide frequencies are registered in Protosols and Smectoid clay soils with 3 and 11 respectively. The analysis on the landslide density distribution also revealed the same relation of landslide failures with the soil types except for Protoslos. Even though Protoslos soil type has the lowest landslide frequency, it is the second highest in the computation of the landslide density per kilometre with 1.17

density, the highest being Kandoid soil with 1.19 density. Accordingly, the lowest density is recorded in Smectoid clay soils (0.23 failures per kilometre).

Table 5.5. Landslide frequency and density within each soil types of Dominica

Soil_type	Segment length (km)	No of Landslide	Landslide density per Km	% of total length of the road	% of total no of Landslides
Allophanoid	70.59	41	0.58	23%	16%
Kandoid	88.18	105	1.19	28%	42%
Protosols	2.57	3	1.17	1%	1%
Smectoid Clay Soils	47.46	11	0.23	15%	4%
Young Soils	101.86	89	0.87	33%	36%
Total	*310.66*	*249*	*0.80*	*100%*	*100%*

5.3.2. Saint Lucia

In Saint Lucia the soils are classified into 7 main soil classes namely: Agglomerate, Alluvial, Clay, Colluvial, Skeletal, Volcanic and Miscellaneous. Considering the landslide frequency within each soil type, the Agglomerate soils are dominant with 161 landslides followed by Clay soils which have 153 landslide failures. The least landslide frequency is recorded in Alluvial soils with only 7 failures. The density distribution, however, revealed that the Volcanic soil class has the highest landslide density per kilometer. Although the landslide frequency obtained in the Volcanic soil class is 84 which is 15% of the total failures and almost half the frequency of Agglomerate and Clay soils, it has 11.19 landslide density per kilometer which is considerably high when compared to the second and third highly dense soil classes, Agglomerate (7.95) and Skeletal (6.29). Table 5.6 shows the summary of the results.

Table 5.6 Landslide frequency and density within each soil types of Saint Lucia

Soil class	Segment length (km)	No of Landslide	Landslide density per Km	% of total length of the road	% of total no of Landslides
Agglomerate soils	20.26	161	7.95	14%	28%
Alluvial soils	21.39	7	0.33	15%	1%
Clay soils	55.66	153	2.75	38%	27%
Colluvial soils	8.38	51	6.08	6%	9%
Miscellaneous	19.89	31	1.56	14%	5%
Skeletal soils	13.20	83	6.29	9%	15%
Volcanic soils	7.50	84	11.19	5%	15%
Total	*146.28*	*570*	*3.90*	*100%*	*100%*

5.4. Landslide Density

Landslide density for Saint Lucia was analyzed by Mott MacDonald (2013) for hurricane Allen that occurred in August 1980 and hurricane Tomas occurred in October 2010 and the results are presented in section

4.1.2. Here, landslide density analysis results of Dominica are presented. The analysis is made for five storm events: September 2009, October 2010, September 2011, November 2011 and April 2013. And the number of landslides reported on these events were 27, 20, 84, 74 and 44 respectively. The maps of these five events showing the number of landslides occurred in different major road sections of Dominica are provided in appendix A.3. In each of the events, the number of landslide occurrences reported in different road sections of Dominica were quite different, so are the results obtained from the landslide density analysis. The results are presented below (figure 5.1 and table 5.7) by providing the road sections map accompanied by table showing the landslide density in each of the road sections on the respective storm events.

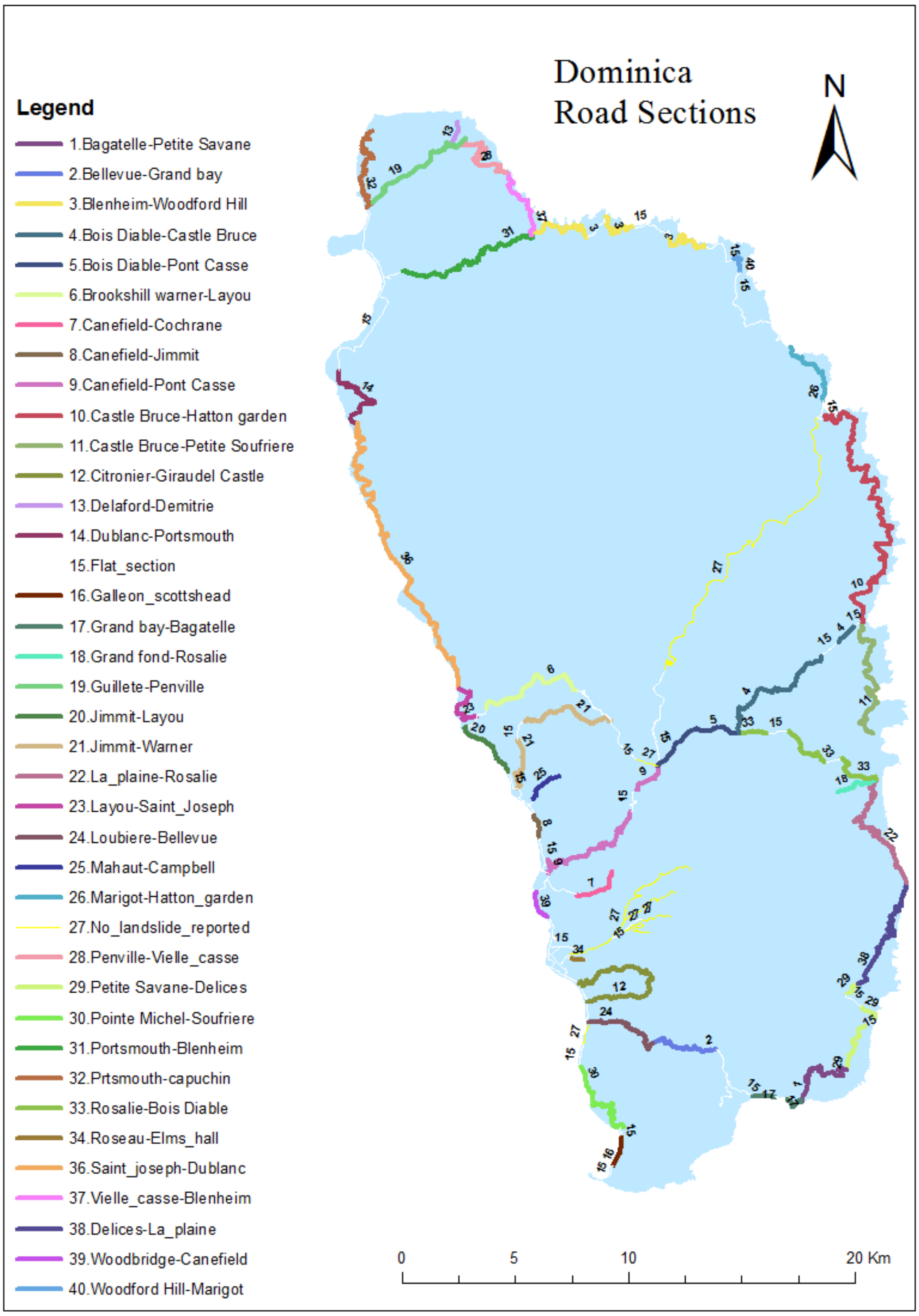


Figure 5.1. Map of the road sections of the major road network of Dominica

Table 5.7. Landslide density per kilometer length of the road for the five landslide events

Road Section	**Sept. 2009**	**Oct. 2010**	**Sept. 2011**	**Nov. 2011**	**April 2013**	**Average**
Bagatelle – Petite Savane	0	0.19	0.77	0.38	0.96	*0.46*
Bellevue – Grand bay	0	0	0.12	0.37	0.12	*0.12*
Blenheim – Woodford Hill	0	0	0.36	0.27	0	*0.12*
Bois Diable - Castle Bruce	0.51	0	0.13	0.76	0.38	*0.36*
Bois Diable - Pont Casse	0	0	0.22	0	0	*0.04*
Brookshill warner - Layou	0	0.35	0	0	0.71	*0.21*
Canefield - Cochrane	0	0	1.71	0	0.43	*0.43*
Canefield - Jimmit	0.84	0	0	0	0	*0.17*
Canefield – Pont Casse	0.09	0	0	0	0	*0.02*
Castle Bruce - Hatton garden	0	0.15	0.51	0.26	0.15	*0.21*
Castle Bruce - Petite Soufriere	0	0	1.75	0.82	0.58	*0.63*
Citronier - Giraudel Castle	0	0	0.10	0	0	*0.02*
Delaford - Demitrie	0	0	0.85	0	0	*0.17*
Dublanc - Portsmouth	0	0	0	0	1.05	*0.21*
Galleon_scottshead	0	0	0.74	1.47	0	*0.44*
Grand bay - Bagatelle	0.95	0.48	0.48	0.95	0.95	*0.76*
Grand fond - Rosalie	0	0.49	2.95	0	0.49	*0.79*
Guillete - Penville	0	0	0	1.25	0	*0.25*
Jimmit - Layou	0.65	0.33	0	0	0	*0.20*
Jimmit - Warner	0	0.26	0	0	0.13	*0.08*
La plaine - Rosalie	0	0.22	0.89	0.22	0	*0.27*
Layou - Saint Joseph	0.92	0	0.31	0	0.31	*0.31*
Loubiere - Bellevue	0	0	0.12	0.37	0.12	*0.12*
Mahaut - Campbell	0	0.54	0.54	0	0	*0.22*
Marigot - Hatton garden	0	0	0.25	0	0	*0.05*
Penville - Vielle_casse	0	0	0.89	0	0.18	*0.21*
Petite Savane - Delices	0	0.20	0	0.60	0.40	*0.24*
Pointe Michel - Soufriere	1.02	0.34	0.68	0.34	0	*0.48*
Portsmouth - Blenheim	0	0	0.23	1.26	0.11	*0.32*
Prtsmouth - capuchin	0	0	0	0	0.31	*0.06*
Rosalie - Bois_Diable	0.46	0	0.61	1.84	0.15	*0.61*
Roseau - Elms_hall	0	3.77	5.66	0	0	*1.89*
Saint joseph - Dublanc	0	0	0	0	0.12	*0.02*
Vielle casse - Blenheim	0	0	0.69	1.15	0.69	*0.50*
Delices - La plaine	0	0.13	0.26	0.13	0	*0.10*
Woodbridge - Canefield	3.73	0	0	0	0	*0.75*
Woodford Hill - Marigot	0	0	0.36	0.27	0	*0.12*

5.5. Analysis of Rainfall Return Periods

5.5.1. Dominica

The two rainfall stations of Dominica, Melville and Cane field, are analyzed separately. For Melville 40 years and for Cane field 32 years period rainfall records are considered. From the records it is observed that, Melville station encounter more rainfall than Cane field station both in rainfall amount and number of rainy days. Figure 5.2 shows the annual daily maximum rainfall and annual rainy days of each recording period in the two stations. The known landslide occurrence events are also indicated in the map. As can be seen from the figure, in all recording periods the annual rainy days are greater at Melville Station. In addition, with the exception of some years, the annual daily maximum rainfall amounts at Melville are more intense. Within the recording periods, Melville station has registered on average 157.1mm annual daily maxima rainfall amount, the maximum being 422.3mm. Whereas, at Cane field station these values become 120.2mm and 287.3mm respectively.

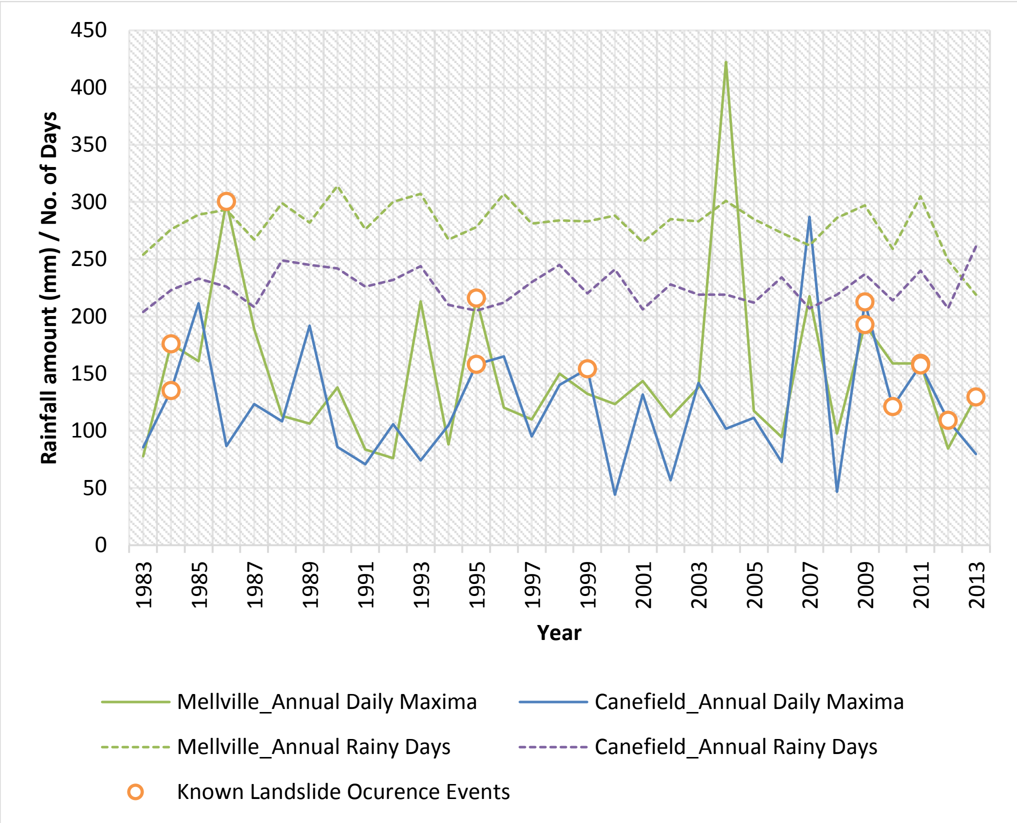


Figure 5.2. Annual daily maxima rainfall amount and annual rainy days for two rainfall stations of Dominica

To calculate the rainfall return period, the annual daily maxima values from each recording period were taken, which resulted with 40 records for Melville station and 32 records for Cane field station. These records were tested to fit into Generalized Extreme Value (GEV) distribution model and Gumbel distribution model. The fitted models showed that GEV distribution model is a better fit for both stations. The GEV model has 5.11 and 4.17 likelihood ratio over the Gumbel model for Melville and Cane field stations respectively. Besides, three and more records fall out of the 95% confidence limit in the case of Gumbel model; while, the GEV model contained all the records. Figure5.3 show the GEV fitted models of the two stations.

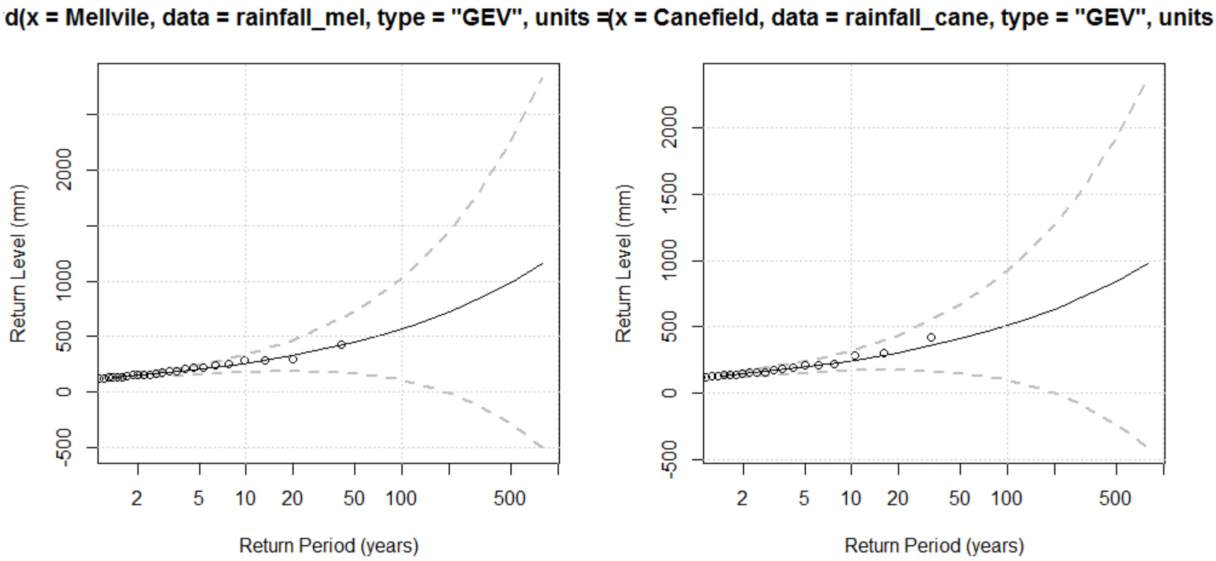


Figure 5.3. Rainfall return periods of the two stations of Dominica modeled using GEV distribution method. Mellville (left) and Cane field (right)

Accordingly, the rainfall amount for different return periods were computed using the GEV distribution model. Table 5.8 below shows the estimated rainfall amounts together with the 95% lower and upper confidence limit. Up to 20 years return period, the results obtained are somewhat similar. However, in return period 50 years and above the Melville estimation shows higher amounts than Cane field. The reason for this is that, the annual daily maxima values of Melville are relatively greater than Cane field. Moreover, Melville has 40 records which means that more extreme values to be considered. Generally, return period calculations give a good estimation for a period two times the rainfall recording period. Therefore, the results obtained here are as good up to 50 years return period. After that, the upper and lower confidence limits get considerably wide range. For instance, the 95% lower confidence limit of the 200 year return period even goes to negative value for Melville station.

Table 5.8. Estimated rainfall amount for different rainfall return periods, Dominica

Return Period	**Mellvile**			**Canefield**			**Average Estimate**
	95% Lower Limit	Estimate	95% Upper Limit	95% Lower Limit	Estimate	95% Upper limit	
2-year	115	133	152	113	132	152	133
5-year	158	196	234	152	191	230	194
10-year	181	253	326	172	243	314	248
20-year	190	324	459	178	306	434	315
50-year	166	446	726	153	410	667	428
100-year	107	567	1027	99	511	922	539
200-year	-7	720	1447	1	635	1269	678

Rainfall Return Periods for the Five Landslide Events of Dominica

The rainfall amounts registered in the two stations for the five landslide events are quite different except for tropical storm Erica (September 2009). During tropical storm Erica extreme daily rainfall values are recorded in both stations, 192.6mm at Melville and 212.7mm at Cane field. During the other landslide events, however, only one of the two stations has registered extreme values. For example, during hurricane Ophelia (September 2011) the daily rainfall amount registered at Cane field was 157.4mm while at Melville it was 30.2mm. Therefore, for these events only the daily rainfall amounts, from either of the two stations, which have likely caused the landslides are considered. Accordingly, the return period of the landslide events were calculated using their respective station model as shown in table 5.9 below.

Table 5.9. Rainfall return period of the five landslide events of Dominica

Landslide Event	**No of Landslides Reported**	**Daily Rainfall amount (mm)**		**Estimated Return Period (years)**	
		Mellvile	Canefield	Mellvile	Canefield
Erica (Sep. 4/2009)	27	192.6	212.7	5	7
Tomas (Oct. 31/2010)	20		121.2		<2
Ophelia (Sep. 28/2011)	84		157.4		3
November 28/2011	74	158.9		3	
April 21/2013	44	129.4		2	

The results obtained revealed that, almost all of the landslide events are relatively of short return periods. The longest return period found was from tropical storm Erica, which is 5 to 7 years considering both stations estimation. Hurricane Tomas, on the other hand, is the shortest with return period less than 2 years, but still the rainfall amount falls within the 95% lower confidence limit of the 2 years return period. The results also revealed that the number of landslides reported in each events are comparative with their rainfall return periods except for tropical storm Erica. Figure 5.4 below shows the landslides number versus the return period plot. Although, tropical storm Erica has the highest rainfall amount of all the five events, the reported landslides were relatively few (only 28 landslides). In contrast, on the 3 years return period events, hurricane Ophelia and November 2011, 84 and 74 landslides are reported respectively. The reason for this could probably be a problem of reporting, for some events all landslides are reported properly and for others only major slides are given emphasis. Unfortunately, there are no indications in the reports to confirm this assumption.

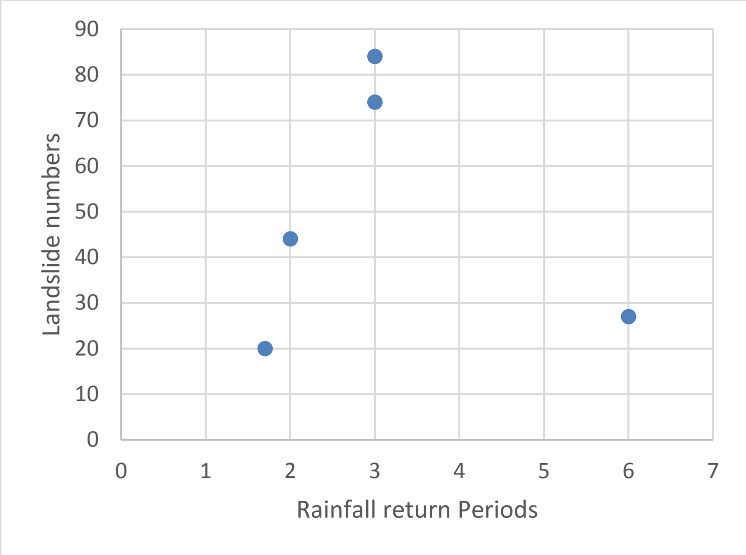


Figure 5.4. The number of landslides versus the return period of the five storm events, Dominica

5.5.2. Saint Lucia

As Explained in section 4.1.1, only two stations Barre De L'Isle and Barthe were considered in Saint Lucia for the analysis. The analysis was made taking the annual daily maxima for each record period, which resulted to 51 records for each station. Figure 5.5 shows the annual daily maximum rainfall of each recording period in the two stations together with the known landslide occurrence events. The records show that the rainfall in both Barre De L'Isle and Barthe stations are almost similar, with maximum annual daily maxima of 464.8 mm and 482.6mm and average annual daily maxima of 121.7 mm and 124.7 mm respectively.

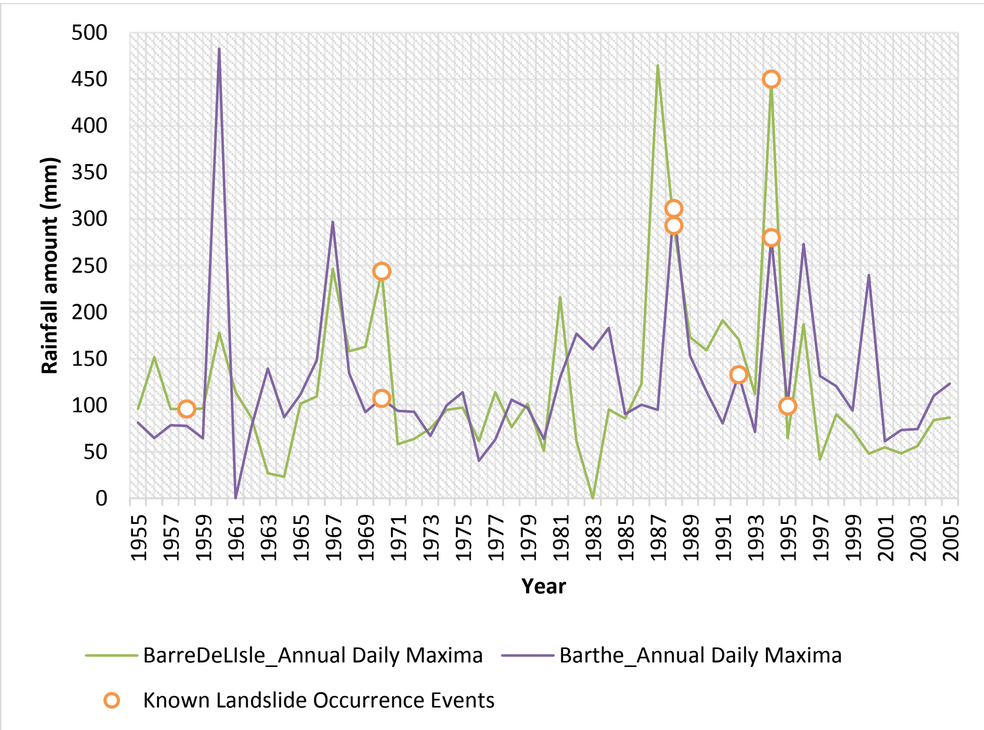


Figure 5.5. Annual daily maxima rainfall amount for two rainfall stations of Saint Lucia

To analyze the frequency magnitude distribution of the records, generalized extreme value distribution (GEV) and Gumbel distribution models were tested. It was found that the GEV model gives a better fit than the Gumbel model. The GEV model has a 4.1989 likelihood ratio for Barre De L'Isle and 2.5367 likelihood ratio for Barthe over the Gumbel model. In addition, the Gumbel distribution shows four and more fitted values falling out of the 95 % confidence limit for both stations. On the other hand, the GEV model has only one fitted value for Barre De L'Isle and two for Barthe that fall out of the 95 % confidence limit. The fitted plot of the two stations using the GEV model are shown in figure 5.6 below.

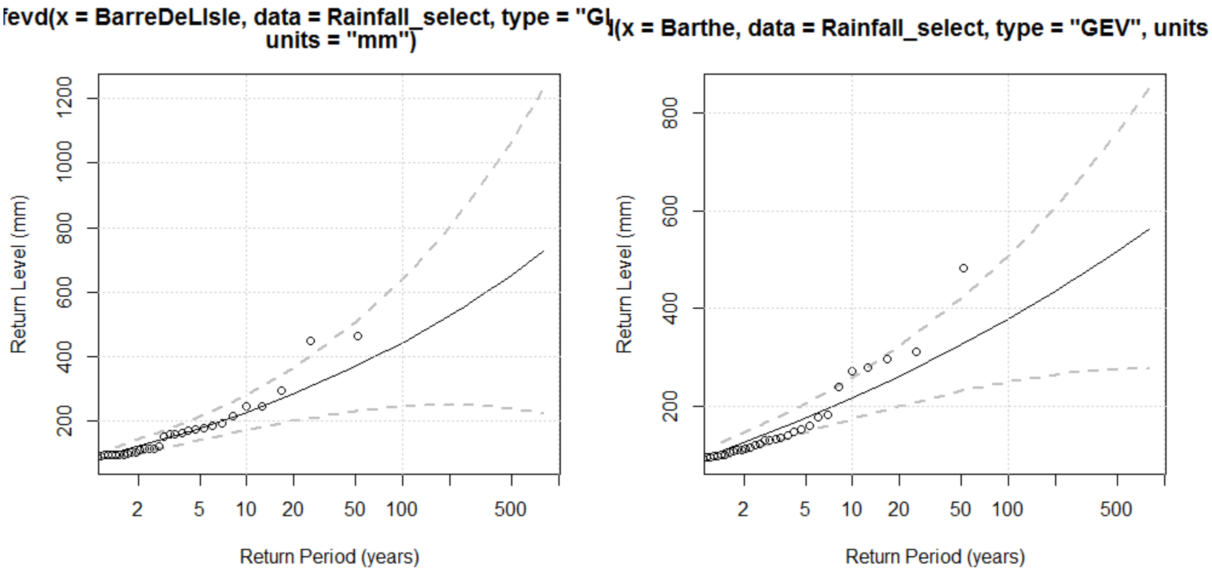


Figure 5.6. Rainfall return periods of the two stations of Saint Lucia modeled using GEV distribution method. BarreDeLisle (left) and Barthe (right)

Accordingly, the GEV model was used to calculate the rainfall amount for different return periods of the two stations. Table 5.10 shows the estimated rainfall amount of the return periods with 95% lower and upper confidence limit.

Table 5.10. Estimated rainfall amount for different rainfall return periods, Saint Lucia

Return Period	**BarreDeLIsle**			**Barthe**			**Average Estimate**
	95% Lower Limit	Estimate	95% Upper Limit	95% Lower Limit	Estimate	95% Upper limit	
2-year	82	100	119	92	109	125	105
5-year	136	169	202	142	169	197	169
10-year	171	223	275	173	214	255	218
20-year	200	281	362	200	260	320	271
50-year	230	368	505	231	325	420	347
100-year	245	442	640	250	379	507	411
200-year	250	526	802	265	436	607	481

Rainfall Return Periods for Hurricane Allen and Hurricane Tomas, Saint Lucia

Hurricane Allen was occurred in August 4, 1980. On both Barre DeLisle and Barthe, there was no rainfall record for this event. Out of the 19 stations, the only stations with the record of this event were Patience, Marquis, Cap and Union vale. On these stations daily rainfall amounts ranging from 82.7 to 111.8 mm were recorded. On Mott MacDonald (2013), they have mentioned a maximum daily rainfall amount record of 127 mm for this event. Therefore, for estimating the rainfall return period of this event, an average daily rainfall amount of 101 mm was taken. Hurricane Tomas was occurred on October 30, 2010. According to Mott MacDonald (2013), 9 stations were functional on the day of this event and they have recorded daily rainfall amounts between 358 and 593 mm, with an average of 499 mm. Thus, the average rainfall amount was taken to estimate the return period of this event.

Based on the calculation of the return periods, hurricane Allen has a 2 years return period. During this event, the maximum landslide density per kilometer length, calculated by Mott MacDonald (2013), was 3 in BareDelisle road section. Based on their landslide density calculation, around 70 landslides were occurred along the major roads during this event. Hurricane Tomas on the other hand, was a big event and the estimation shows that this event has around 200 years return period. Mott MacDonald (2013) and ECLAC (2011) have also analyzed the return period of this event, and their result conforms to this estimation(they estimated 200 and 180 years return period respectively). In terms of landslide occurrence, the calculated maximum landslide density per kilometer during hurricane Tomas was 12.5, also in BarreDelisle road section. Based on the density calculation, hurricane Tomas has caused around 216 landslides along the major roads of Saint Lucia, which is exceptionally very high number to occur in one event.

5.6. Landslide Spatial Probablity

In this section the results obtained on the landslide susceptibility analysis of the major roads of Dominica and Saint Lucia are presented. The susceptibility is analyzed using spatial multi criteria evaluation (SMCE).

For Dominica, as explained in section 4.2.5, four spatial factors were used to analyze the landslide susceptibility of the major roads i.e. slope, drainage, material and land use. Whereas, for Saint Lucia, landslide, slope, drainage and material were used as a spatial factor. The analysis was made considering one kilometer road segments with the same spatial characteristics. The results obtained from the SMCE show that the road segments have landslide susceptibility scores ranging from 0 to 0.75 for Dominica and 0 to 0.83 for Saint Lucia, representing road segments from the lowest to the highest susceptibility. To check the validity of the analysis result of Dominica, prediction rate calculation was made. The prediction rate was done using 214 new landslide points along the major roads, 71 of these landslides were mapped during field work and the remaining were obtained from landslide inventory dataset of the whole country prepared by Cees van Westen (taking only the landslides that affect the roads). However, for Saint Lucia, there were no new landslide points to be used for the prediction. Therefore, the landslide points that were used as a spatial factor in the SMCE analysis are used to check the success rate of the analysis.

Figure 5.7 shows the prediction rate graph of the susceptibility analysis of Dominica. As the graph shows, about 60% of the landslides are located in 30% of the road segments with high susceptibility scores. Considering the quality and quantity of the data used for the analysis, it is believed that the prediction rate is satisfactory. Figure 5.8 shows the success rate graph of the susceptibility analysis of Saint Lucia. The graph shows that around 80% of the landslides are located in 30% of the road segments with high susceptibility scores.

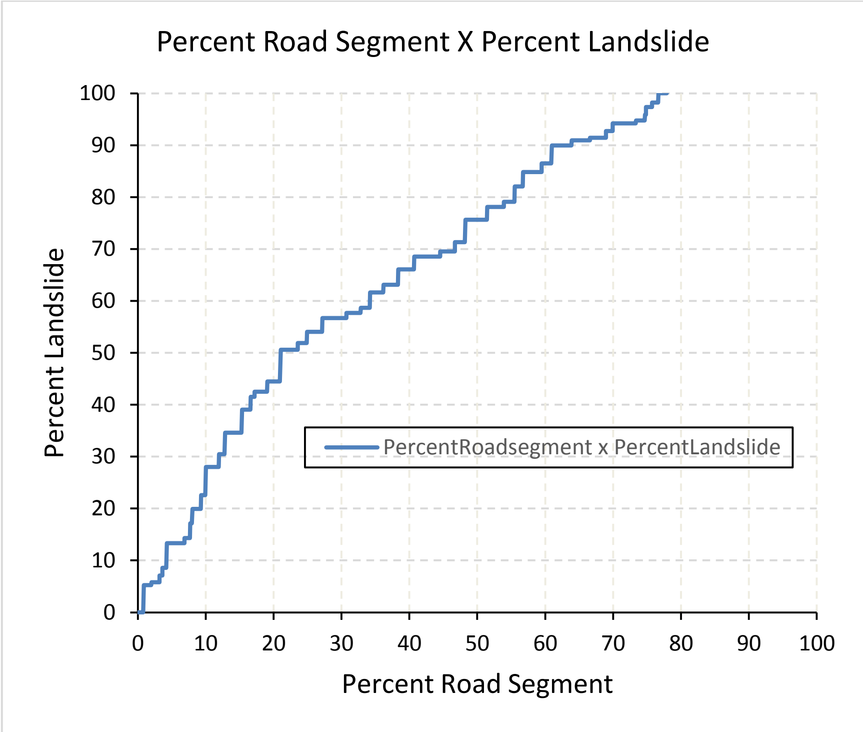


Figure 5.7. Prediction rate of the susceptibility analysis of Dominica

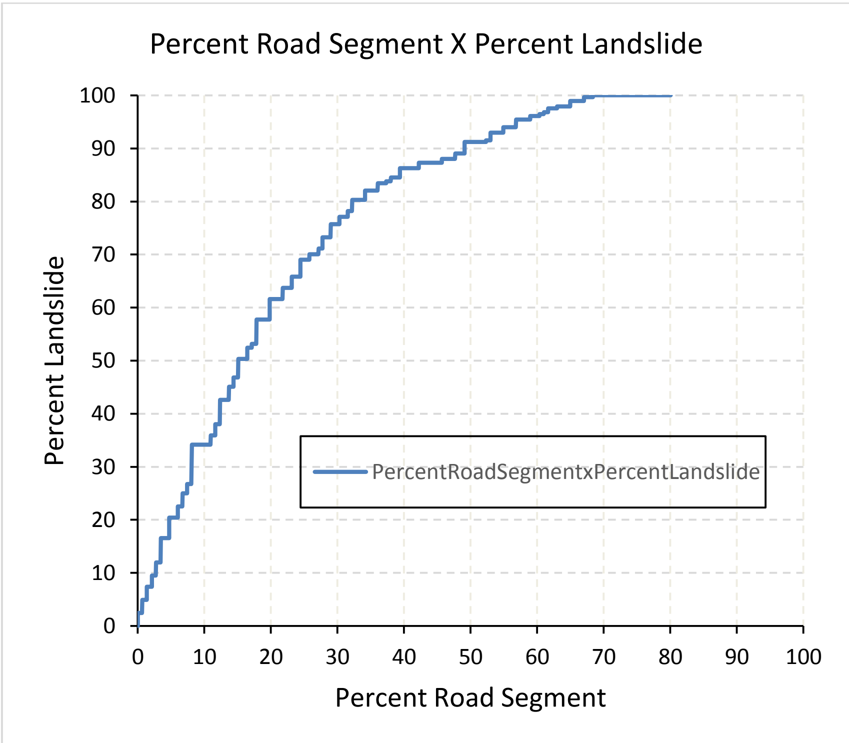


Figure 5.8. Success rate of the susceptibility analysis of Saint Lucia

Based on the prediction rate result for Dominica and success rate result for Saint Lucia, the susceptibility maps were then classified into three classes of susceptibility level i.e. high, moderate and low. The boundaries of these classes are determined by considering the percentage of the landslides. For Dominica, it was assumed that 60% of the landslides are located within high, the next 30% within moderate and the remaining 10% within low susceptibility class of the road segments. Whereas, for Saint Lucia, it was assumed that 80% of the landslides are located in the high, the next 15% in the moderate and the remaining 5% in the low susceptibility class of the road segments. The reason for using a different boundaries was that, in case of Saint Lucia the landslides were used as a spatial factor; therefore, the high susceptibility class should contain most of the landslides. With this classification, in both Islands, 40% of the major road segments fall in the low, 30% in the moderate and the remaining 30% in high susceptibility zones. The landslide susceptibility maps along the major roads are shown in the figure 5.9 (Dominica) and figure 5.10 (Saint Lucia). In the maps, known previous landslide locations of both Islands are also indicated with black dots.

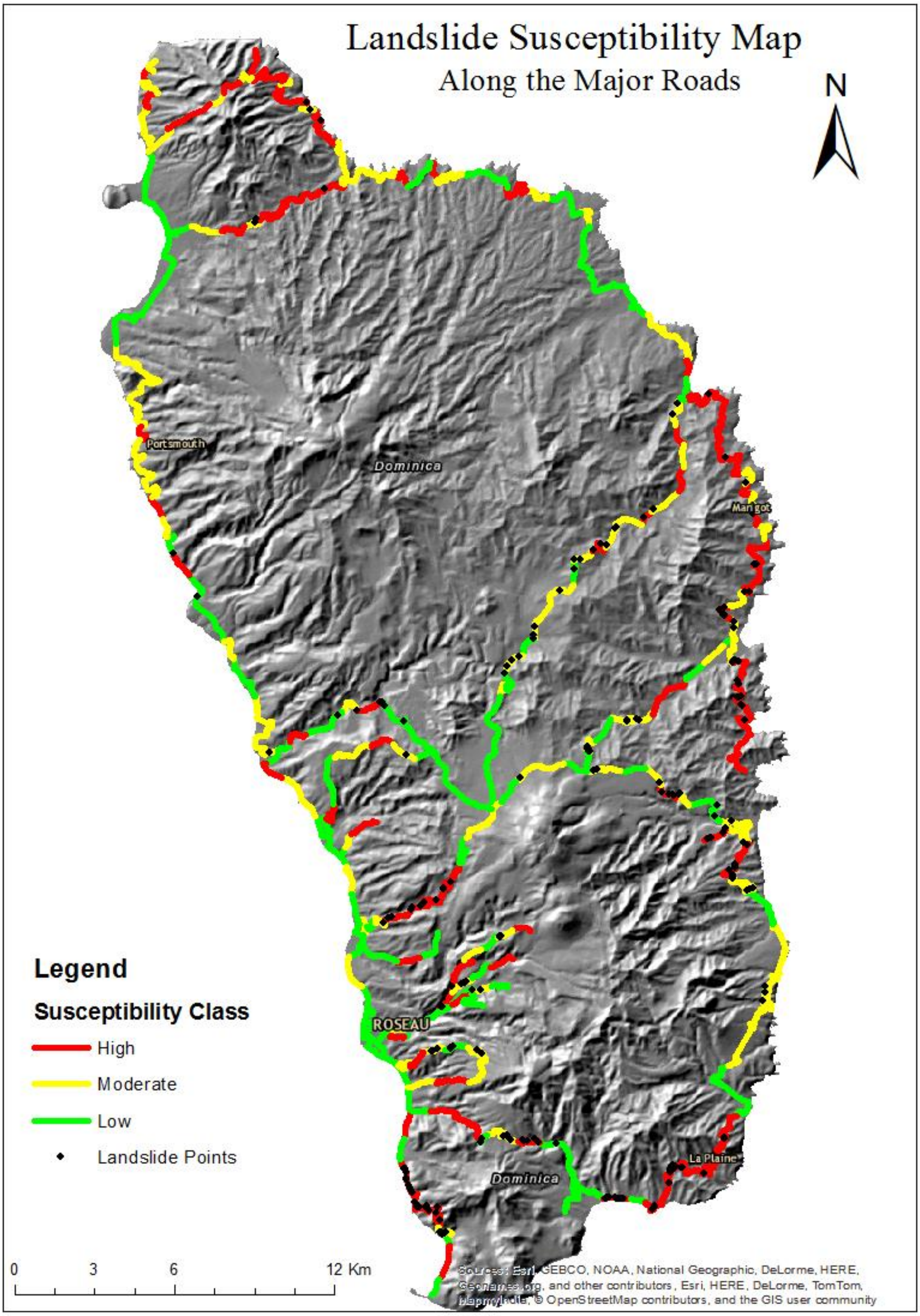


Figure 5.9. Landslide suceptiblity map along the major roads of Dominica

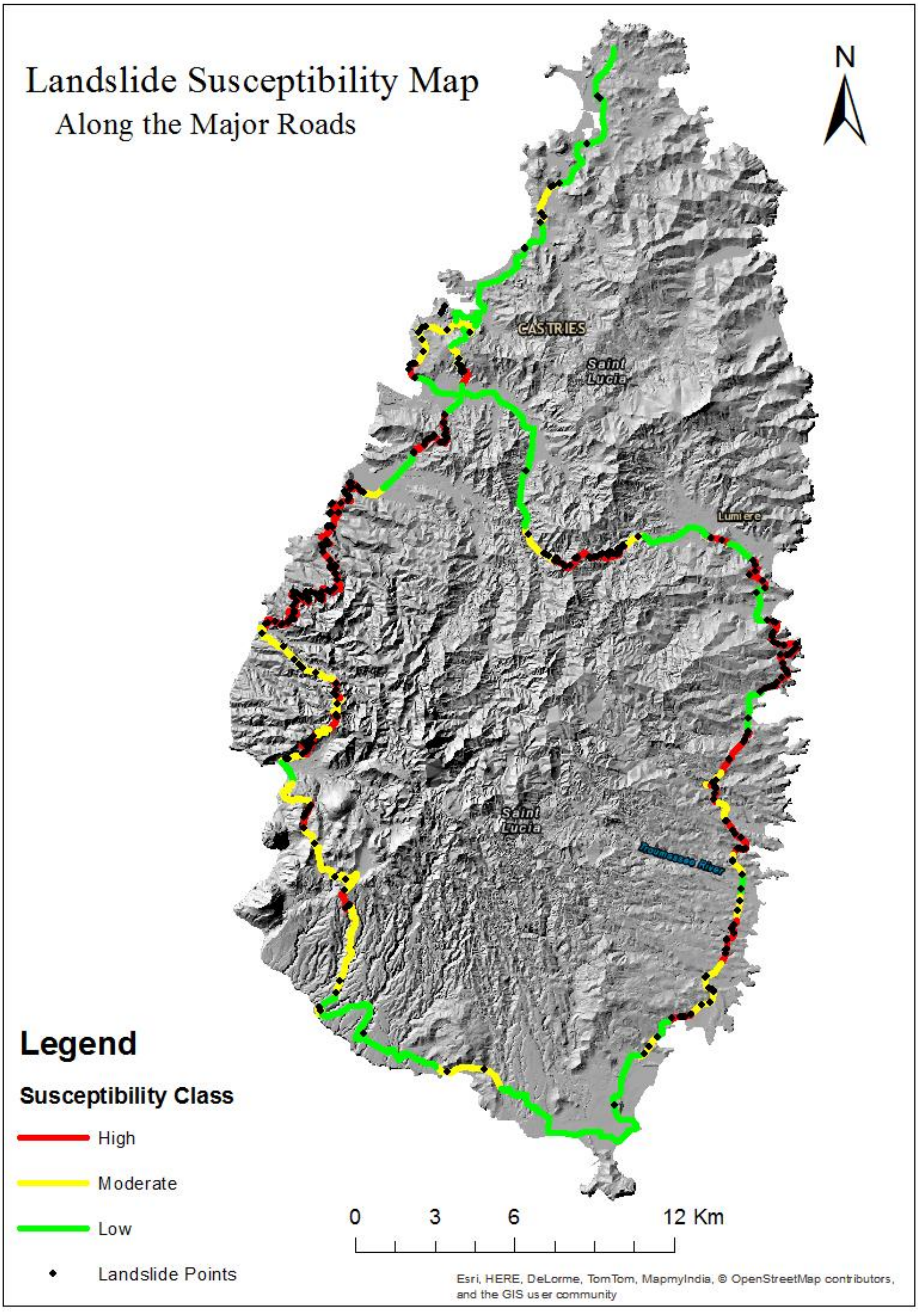


Figure 5.10. Landslide suceptiblity map along the major roads of Saint Lucia

6. DISCUSSION AND CONCLUSION

In this section the key aspects of the results found in this research are discussed. Comparison of the results found for the two islands is also discussed here. Finally, conclusion and recommendations for future studies are provided.

6.1. Discussion

6.1.1. Slope Instability Factors

The accuracy of any landslide hazard assessment is dependent on the quality and accuracy of the input variables. Slope, geology and soil were among the variables used in this study to analyze the landslide susceptibility of the road sections and they are discussed below.

Slope

In both Islands, the highest upslope angles obtained along the road section were around 50 degrees. However, during the field work period, slopes steeper than 50 degrees were observed in most part of the road sections. This problem may have arisen from the quality of the digital elevation models used for generating the slope angles. Especially for Dominica, the available digital elevation model was extracted from a contour map and the quality is very poor. Due to this the results obtained may have some inaccuracies. For, instance in Saint Lucia the highest landslide distribution was obtained in 20 – 30 degrees (table 5.2). The 'over 30 degrees' slope class, however, has lower landslide distribution than the 10 – 20 and 20 – 30 degrees slope classes. In case of Dominica the highest landslide distribution was obtained in "over 30 degrees' slope class. Here also the slope class 10 – 20 degrees has registered lower landslide density than 5 – 10 and 2 – 5 degrees (figure 5.1). The reason for these occurrences could be the excavation methods used for construction the roads. Because during field work, it was observed that most of the slides occurring along the roads are manmade slides caused by poor cut slope design. However, to assess this effect enough information were not obtained, which calls for further investigation. The work by Mott MacDonald (2013) has studied the slopes of Saint Lucia for selected landslide prone sites by focusing on landslide remedial design and landslide management. And similar investigation for Dominica would have a greater impact on mitigating the Landslide hazard.

Geology

The geology maps used for in this study for the two islands have different classification of lithology, which makes it difficult to compare the results obtained. In terms of quality, the map used for Saint Lucia was better because it has a better description of the rock types. However, for Dominica, the classification was more focused in the time periods of the geologic units. The results from table 5.3 show that, in Dominica, the Older Pleistocene (Pyroclastic aprons of block and ash flow also includes andesite lavas) geological unit has the highest landslide distribution, which suggests that this unit is highly susceptible for landslides. This result has some similarity to the result obtained in Saint Lucia. In Saint Lucia the highest landslide distribution was obtained in the andesite ash altered geological unit followed by andesite porphyritic unit (table 5.4). In both Islands the highly susceptible geologic units contain Andesite rock type.

Soil

Here also the soil maps of the two islands used for the analysis have different classification of soil types. The Dominica soil maps follows Lang's (1967) soil classification which was based on the mineral composition of the soils. Based on the results from table 5.5, it can be inferred that Kandoid and Protoslos soils have higher susceptibility for landslides than the other soil types. The susceptibility hierarchy then goes down to Young soils, Allophanoid and Smectoid clay soils in decreasing order. This, however, doesn't correlate to the degree of the weathering of the soils (the greater the weathering from rock to soil the weaker the material), except for Kandoid. According to Lang's, 1967 soils classification of Dominica (as cited in Rouse et al., 1986), Kandoid soils are at the last stage of the degree of weathering, while Protosols have the lowest degree of weathering than the other soils (see figure 3.3). In Saint Lucia, on the other hand, the classification of the soils is made based on the parent material. The density distribution analysis result from table 5.6 suggests that, the volcanic soil class is the most prone soil class for landslide failures. Alluvial soil class on the other hand is the list susceptible soil type. The other soil classes have moderate to high landslide susceptibility in order of: miscellaneous soil class, clay soils, colluvial soils, skeletal soils and agglomerate soils.

6.1.2. Landslide Density

The results from figure 5.1 and table 5.7 show that, on some of the road sections there are frequent landslide occurrences. For instance, the road section from Grand bay to Bagatelle landslides occurrences are reported in all the five storm events. Road sections, Bagatelle – Petite Savane, Bois Diable – Castle Bruce, Castle Bruce – Hatton garden, Point Michel – Soufriere and Rosalie – Bois Diable, have encountered landslides in four out of the five storm events. On the other hand, some road sections like Bois Diable – Pont Casse and Canefield to Pont Casse have a rare landslide occurrences, only in one of the storm events they encountered landslides. Of course, it should be noted that there are road sections with no reported landslide in all of the events (yellow line segment on the map). Considering each individual storm events, the highest number of landslides was reported in the September 2011 event with 84 landslides and these landslides were somehow distributed on most of the road sections (landslides were occurred in 26 road sections). The storm event that affected limited number of road sections was the September 2009, only 9 road section have encountered landslides. The remaining three events have affected number of road sections ranging from 13 to 20.

In terms of Landslide density, the highest density was obtained in Roseau – Elms hall road section for September 2011 and October 2010 events, with 5.66 and 3.77 landslides per kilometer respectively. The next highest was recorded in WoodBridge – Canefield road section with 3.73 landslides per kilometer for September 2009 event. These Road sections, however, encountered landslides only on the specified storm events, no landslides were reported on the other events. The road section from Grand fond to Rosalie has also encountered high landslide density during September 2011 event, 2.95 landslides per kilometer. This road section has also encountered landslides on October 2010 and April 2013 events; although, the landslides densities obtained were not that high. Therefore, based on the results obtained it can be said that road sections, Roseau – Elms hall, Grand fond – Rosalie, Grand bay – Bagatelle, Woodbridge – Canefield, Castle Bruce – Petite Soufriere and Rosalie – Bois Diable, are relatively more susceptible to Landslides than the other road sections. The reason for this could be the steep slope and/or moderate to high weathered material characteristics of the road sections. During the field work some of these road sections were visited. As observed there, Grand bay to Bagatelle and Woodbridge to Canefield possess a steep slope cut slopes (>70) with moderately weathered rock material on most of their parts, and these parts are frequently affected by rock falls (figure below). Whereas, Castle Bruce to Petite Soufriere and Rosalie to Bois Diable have a considerable high cut slope (between 45 and 60 degrees) with highly weathered clay material on most of their parts, which make them Landslide prone areas even with minor storm events (figure Below).

Figure 5.4.2. Road sections from Grand bay to Bagatelle (left) and from Castle Bruce to Petite Soufriere (right).

Among the landslide events considered in this study, only hurricane Tomas (October 2010) is shared by both Countries. However, the impacts it caused in the two islands were quite different. This event has caused around 216 landslides along the road sections of Saint Lucia and the highest landslide density recorded was 12.5 landslides per kilometer BaareDeLisle road section. Whereas, in Dominica it only caused 20 landslides and the highest landslide density was 3.77. In fact, the rainfall amounts registered in the two islands during this event have also a big difference, daily rainfall of 121 in Dominica and 499mm in Saint Lucia.

A comparable landslide event between the two islands was observed between the September 2011 (hurricane Ophelia) and November 2011 events of Dominica and hurricane Allen of Saint Lucia. During hurricane Allen about 70 landslides were occurred along the major roads of Saint Lucia and the two events of Dominica have caused 84 and 74 landslides respectively. In terms of landslide density, for hurricane Allen the highest was 2.75 and for the two events of Dominica 5.77 and 1.84

Rainfall Return Periods

In the rainfall analysis results of the two islands (figure 52 and 5.5), it was observed that there are some extreme daily rainfall amount records and not all have caused landslides or no reports were made. For instance, the rainfall event recorded at Melville station of Dominica on September 13, 2014 was exceptionally very high, 422.3 daily rainfall. This event is related to hurricane Jeanne, which was the deadliest hurricane for other places like Puerto Rico and Dominican Republic. However, no disaster or damage reports were found for Dominica. In addition, the rainfall amount registered at Cane field station on August 17, 2010 was also relatively very high, 287mm daily rainfall. This event is related to hurricane Dean which caused flash flooding in the Island, but no landslides were reported on that event. On the other hand, for hurricane David that occurred in August 30, 1979 and caused many landslides all over the Island, no rainfall data was recorded on both stations. In case of Saint Lucia, on March 1960 at Barthe station and on May 1987 and September 1994 at BarreDeLisle station, exceptionally high rainfall amounts were recorded, 450mm and above daily rainfall. The latter one is related to tropical storm Debby that caused more than 400 landslides, shallow debris flow in the upper areas, debris and rock slides along roads. For the 1960 and 1987 events, however, no documented or reported hurricane or storm events were found. There were hurricane Abby in 1960 and hurricane Emily in 1987; nevertheless, they occurred in July and May months respectively, which are far from the mentioned rainfall events.

6.2. Conclusion

The preparation of the multi temporal landslide inventory maps along the road was performed using road maintenance reports made during landslide events. This task was supported using image interpretation before and after field work. During field work mapping of landslide locations was also integrated. For Dominica, road maintenance reports from five landslide events were obtained. From these reports the location and number of landslides occurred in the events were extracted. Even though, it was not possible to get the exact locations of the landslides, the whereabouts of the landslides in terms of the road sections junction points were extracted. The maintenance reports obtained in Saint Lucia were somehow generalized in that, the reports only focused on cost of the clearance and maintenance and they are barely indicative of the locations of the landslides. Therefore, the inventory maps used for Saint Lucia were taken from previous studies which were extracted from island wide inventory maps after two big storm events. For this reason the exact locations of the landslides are known in both events. It was observed from the inventory maps that Saint Lucia has more landslide density than Dominica. This could arise from the fact that the storm events in Saint Lucia are more intense and the country was hit by strong storm event in recent years (hurricane Tomas, 2010). For Dominica, the biggest landslide event goes back to 1979 (hurricane David) and no information on the landslide density or even the amount of rainfall recorded on that event is obtained, which makes it difficult to compare it with the other events. With regard to size, the landslides along the roads of both islands are small to medium size but in comparison Saint Lucia has bigger slides than Dominica (as observed during field work). Nevertheless to give a statistical comparison, no information was found from the maintenance reports. From the analysis it was observed that the islands are prone to landslides even by storm events with two years and three years return periods. Evidently in Dominica only one year was skipped without a reported landslide from 2009 to 2013 and some sections of the road encounter landslides in every of storm events. This indicates that the road sections require a better attention in investigating the main causes and finding long-lasting solution to mitigate the problem than just clearing the roads every time a storm event comes.

LIST OF REFERENCES

Abella, E. A. C., & Van Westen, C. J. (2007). Generation of a landslide risk index map for Cuba using spatial multi-criteria evaluation. *Landslides*, *4*(4), 311–325. doi:10.1007/s10346-007-0087-y

Aleotti, P., & Chowdhury, R. (1999). Landslide hazard assessment: summary review and new perspectives. *Bulletin of Engineering Geology and the Environment*, *58*(1), 21–44. doi:10.1007/s100640050066

Andereck, Z. D. (2007). *Mapping Vulnerability of Infrastructure to Destruction by Slope Failures on the Island of Dominica , WI : A Case Study of Grand Fond , Petite Soufriere , and Mourne Jaune*. Doctoral Dissertation, Miami University.

Anderson, M. G. (1983). Road-cut slope topography and stability relationships in St Lucia, West Indies. *Applied Geography*, *3*(2), 105–114. doi:10.1016/0143-6228(83)90033-4

Anderson, M. G., & Holcombe, E. (2013). *Community-Based Landslide Risk Reduction-Managing Disasters in Small Steps*. The World Bank, Washington, DC. doi:10.1596/978-0-8213-9456-4

Anderson, M. G., Holcombe, E., Blake, J. R., Ghesquire, F., Holm-Nielsen, N., & Fisseha, T. (2011). Reducing landslide risk in communities: Evidence from the Eastern Caribbean. *Applied Geography*, *31*(2), 590–599. doi:10.1016/j.apgeog.2010.11.001

Atlas of Dominica. (2011). Maps of Dominica. Retrieved February 18, 2015, from http://www.hoeckmann.de/karten/amerika-nord/dominica/index-en.htm

Castellanos Abella, E. A., & Van Westen, C. J. (2008). Qualitative landslide susceptibility assessment by multicriteria analysis: A case study from San Antonio del Sur, Guantánamo, Cuba. *Geomorphology*, *94*(3-4), 453–466. doi:10.1016/j.geomorph.2006.10.038

Corominas, J., van Westen, C., Frattini, P., Cascini, L., Malet, J.-P., Fotopoulou, S., Catani, F., Van Den Eeckhaut, M., Mavrouli, O. Agliardi, F., Pitilakis, K., Winter, M.G., Pastor, M., Ferlisi, S., Tofani, V., Hervas, J., Smith, J. T. (2013). Recommendations for the quantitative analysis of landslide risk. *Bulletin of Engineering Geology and the Environment*, *73*(2), 209–263. doi:10.1007/s10064-013-0538-8

CRED. (2014). The International Disaster Database. Retrieved February 18, 2015, from http://www.emdat.be/database

Dai, F.C., & Lee, C.F. (2001). Frequency–volume relation and prediction of rainfall-induced landslides. *Engineering Geology*, *59*(3-4), 253–266. doi:10.1016/S0013-7952(00)00077-6

DeGraff, J. V. (1985). *Landslide Hazard on St. Lucia, West Indies - Final Report. Organization of American States, washington D.C.* (pp. 21).

Degraff, J. V. (1987). *Landslide Hazard on Dominica, West Indies - Final Report. Organisation of American States Washington, D.C.* (pp. 27).

ECFLA, Economic commission for Latin America, Office for the Caribbean. (1979). *Report on Effect of Hurricane "David" on the Island of Dominica*. CEPAL/CARIB ,1979. (pp. 62).

ECLAC, Economic Commission for Latin America and the Caribbean. (2011). *Saint Lucia, Macro Socio-Economic and Environmental Assessment of the Damage and Losses Caused by Hurricane Tomas: A Geo-Environmental Disaster Towards Resilience* (pp. 183). doi:10.1016/B978-1-85166-661-4.50049-9

Ed, 2002 10th. (2002). *South America, Central America and the Carribean 2002, Regional Surveys of the World* (pp. 930). Psychology Press. Retrieved from http://books.google.com/books?id=o9ODxqsr-dIC&pgis=1

Finlay, P. J., Fell, R., & Maguire, P. K. (1997). The relationship between the probability of landslide occurrence and rainfall. *Can Geotech J*, 34(6), 811-824.

Gilleland, E. (2015). *Extreme Vallue Analysis, Functions for performing extreme value Analysis, Package 'extRemes'* (pp. 115). From http://www.assessment.ucar.edu/toolkit/.

Gonzalez-dıez, A., Remondo, J., Ramon Diaz de Teran, J., & Cendrero, A. (1999). A methodological approach for the analysis of the temporal occurrence and triggering factors of landslides. *Geomorphology*, *30*, 95–113.

Grelle, G., Soriano, M., Revellino, P., Guerriero, L., Anderson, M. G., Diambra, A., Fiorillo, F., Esposito, L., Diadato, N., Guadagno, F. M. (2013). Space–time prediction of rainfall-induced shallow landslides through a combined probabilistic/deterministic approach, optimized for initial water table conditions. *Bulletin of Engineering Geology and the Environment*. doi:10.1007/s10064-013-0546-8

GSL, Government of Saint Lucia, & WB, World Bank. (2014). *Saint Lucia, Joint Rapid Damage and Needs Assessment, Flood Event of December 24-25, 2013* (pp. 66).

Guzzetti, F. (2003). Landslide hazard assessment and risk evaluation: limits and prospectives. *Proceeding of the 4th EGS Plinius Conference held at Mallorca, Spain. October 2002.*

Guzzetti, F., Carrara, A., Cardinali, M., & Reichenbach, P. (1999). Landslide hazard evaluation: a review of current techniques and their application in a multi-scale study, Central Italy. *Geomorphology*, *31*(1-4), 181–216. doi:10.1016/S0169-555X(99)00078-1

Guzzetti, F., Mondini, A. C., Cardinali, M., Fiorucci, F., Santangelo, M., & Chang, K.-T. (2012). Landslide inventory maps: New tools for an old problem. *Earth-Science Reviews*, *112*(1-2), 42–66. doi:10.1016/j.earscirev.2012.02.001

Hack, R., Alkema, D., Kruse, G. a. M., Leenders, N., & Luzi, L. (2007). Influence of earthquakes on the stability of slopes. *Engineering Geology*, *91*(1), 4–15. doi:10.1016/j.enggeo.2006.12.016

Holcombe, E., & Anderson, M. (2010). Tackling landslide risk: Helping land use policy to reflect unplanned housing realities in the Eastern Caribbean. *Land Use Policy*, *27*(3), 798–800. doi:10.1016/j.landusepol.2009.10.013

Holcombe, E., Smith, S., Wright, E., & Anderson, M. G. (2011). *An integrated approach for evaluating the effectiveness of landslide risk reduction in unplanned communities in the Caribbean*. *Natural Hazards*, 61, 351–385. doi:10.1007/s11069-011-9920-7

IFRC, International Federation of Red Cross and Red Crescent Societies. (2012). *World Disasters Report 2012, Focus on forced migration and displacemen*. Retrieved from http://www.ifrcmedia.org/assets/pages/wdr2012/resources/1216800-WDR-2012-EN-FULL.pdf

IMF, International Monetary Fund. (2006). *Dominica: Poverty Reduction Strategy Paper - Preparation Status Report* (pp. 35). International Monetary Fund. Retrieved from http://books.google.com/books?id=sM2-SF-rPwcC&pgis=1

Jaiswal, P., & van Westen, C. J. (2009). Estimating temporal probability for landslide initiation along transportation routes based on rainfall thresholds. *Geomorphology*, *112*(1-2), 96–105. doi:10.1016/j.geomorph.2009.05.008

Jaiswal, P., van Westen, C. J., & Jetten, V. (2010). Quantitative assessment of direct and indirect landslide risk along transportation lines in southern India. *Natural Hazards and Earth System Science*, *10*(6), 1253–1267. doi:10.5194/nhess-10-1253-2010

Joyce, K. E., Belliss, S. E., Samsonov, S. V., McNeill, S. J., & Glassey, P. J. (2009). A review of the status of satellite remote sensing and image processing techniques for mapping natural hazards and disasters. *Progress in Physical Geography*, *33*(2), 183–207. doi:10.1177/0309133309339563

Lee, D.-H., Lai, M.-H., Wu, J.-H., Chi, Y.-Y., Ko, W.-T., & Lee, B.-L. (2013). Slope management criteria for Alishan Highway based on database of heavy rainfall-induced slope failures. *Engineering Geology*, *162*, 97–107. doi:10.1016/j.enggeo.2013.04.012

Lindsay, J., David, J., Shepherd, J., & Ephraim, J. (2002). *Volcanic Hazard Assessment for Saint Lucia , Lesser Antilles*. Seismic Research Centere, University of West Indies, St. Augustine, Trinidad and Tobago.

Lopez Saez, J., Corona, C., Stoffel, M., Schoeneich, P., & Berger, F. (2012). Probability maps of landslide reactivation derived from tree-ring records: Pra Bellon landslide, southern French Alps. *Geomorphology*, *138*(1), 189–202. doi:10.1016/j.geomorph.2011.08.034

Lu, N., Wayllace, A., & Oh, S. (2013). Infiltration-induced seasonally reactivated instability of a highway embankment near the Eisenhower Tunnel, Colorado, USA. *Engineering Geology*, *162*, 22–32. doi:10.1016/j.enggeo.2013.05.002

Metternicht, G., Hurni, L., & Gogu, R. (2005). Remote sensing of landslides: An analysis of the potential contribution to geo-spatial systems for hazard assessment in mountainous environments. *Remote Sensing of Environment*, *98*(2-3), 284–303. doi:10.1016/j.rse.2005.08.004

Miller, S., Brewer, T., & Harris, N. (2009). Rainfall thresholding and susceptibility assessment of rainfall-induced landslides: application to landslide management in St Thomas, Jamaica. *Bulletin of Engineering Geology and the Environment*, *68*(4), 539–550. doi:10.1007/s10064-009-0232-z

Mott MacDonald. (2013). *Landslide Risk Assessment for Saint Lucia's Primary Road Network, Hurricane Tomas Rehabilitation and Reconstruction Final Feasibility Report, September 2013* (p. 258). Government of Saint Lucia, Castries.

Nandi, A., & Shakoor, A. (2010). A GIS-based landslide susceptibility evaluation using bivariate and multivariate statistical analyses. *Engineering Geology*, *110*(1-2), 11–20. doi:10.1016/j.enggeo.2009.10.001

Nichol, J. E., Shaker, A., & Wong, M.-S. (2006). Application of high-resolution stereo satellite images to detailed landslide hazard assessment. *Geomorphology*, *76*(1-2), 68–75. doi:10.1016/j.geomorph.2005.10.001

OAS, Organization of American States. (1986). Saint Lucia Resources and Agricultural developent Project - Studies and proposlas for the implementation of a land regestration programme. Retrieved January 23, 2015, from https://www.oas.org/dsd/publications/Unit/oea36e/begin.htm#Contents

Palmquist, R. C., & Bible, G. (1980). Conceptual Modelling of Landslide Distribution in Time and Space. *Internatiional Association Of Engineering Geology*, *21*, 178–186.

Pourghasemi, H. R., Moradi, H. R., Fatemi Aghda, S. M., Gokceoglu, C., & Pradhan, B. (2013). GIS-based landslide susceptibility mapping with probabilistic likelihood ratio and spatial multi-criteria evaluation models (North of Tehran, Iran). *Arabian Journal of Geosciences*, *7*(5), 1857–1878. doi:10.1007/s12517-012-0825-x

Pourghasemi, H. R., Pradhan, B., Gokceoglu, C., & Moezzi, K. D. (2012). Landslide Susceptiblity Mapping using a Spatial Multi Criteria Evaluation Model at Haraz Watershed, Iran. *In: Pradhan B, Buchroithner M (eds) Terrigenous Mass Movements. Springer, Berlin*, pp 23–49. doi:10.1007/978-3-642-25495-6

Reading, A. J. (1991). Stability of tropical residual soils from Dominica, West Indies. *Engineering Geology*, *31*, 27–44.

ReliefWeb. (2013). Situation Report #1 - Dominica Flash Flooding and Landslides, April 17- 25, 2013 - Dominica | ReliefWeb. Retrieved August 06, 2014, from http://reliefweb.int/report/dominica/situation-report-1-dominica-flash-flooding-and-landslides-april-17-25-2013

Rouse, C. (1990). The mechanics of small tropical flowslides in Dominica, West Indies. *Engineering Geology*, *29*(3), 227–239. doi:10.1016/0013-7952(90)90052-3

Rouse, W. C., Reading, A. J., & Walsh, R. P. D. (1986). Volcanic Soil Properties in Dominica, West Indies. *Engineering Geology, 23, 1- 28.*

SNO, Saint Lucia News Online. (2013). St. Lucia a "success story" for managing risk of landslides, says World Bank | St. Lucia News Online. Retrieved February 14, 2015, from http://www.stlucianewsonline.com/st-lucia-a-success-story-for-managing-risk-of-landslides-says-world-bank/

Suzen, M. L., & Doyuran, V. (2004). A comparison of the GIS based landslide susceptibility assessment methods: multivariate versus bivariate. *Environmental Geology*, *45*(5), 665–679. doi:10.1007/s00254-003-0917-8

Tien Bui, D., Pradhan, B., Lofman, O., Revhaug, I., & Dick, Ø. B. (2012). Regional prediction of landslide hazard using probability analysis of intense rainfall in the Hoa Binh province, Vietnam. *Natural Hazards*, *66*(2), 707–730. doi:10.1007/s11069-012-0510-0

UWI, University of West Indies. (1999). Natural Hazards and Disasters: Landslides. Retrieved July 27, 2014, from http://www.mona.uwi.edu/uds/Landslides.html

Van Westen, C. J., Castellanos, E., & Kuriakose, S. L. (2008). Spatial data for landslide susceptibility, hazard, and vulnerability assessment: An overview. *Engineering Geology*, *102*(3-4), 112–131. doi:10.1016/j.enggeo.2008.03.010

Van Westen, C. J., Jaiswal, P., Ghosh, S., Martha, T. R., & Kuriakose, S. L. (2012). Landslide Inventory, Hazard and Risk Assessment in India. *In: Pradhan B, Buchroithner M (eds) Terrigenous Mass Movements. Springer, Berlin*, pp 239-282 . doi:10.1007/978-3-642-25495-6

Varnes, D. J. (1984). Landslide hazard zonation: A review of principles and practice. UNESCO Press, Paris (1984) 63 pp.

Xie, M., Esaki, T., & Zhou, G. (2004). GIS-Based Probabilistic Mapping of Landslide Hazard Using a Three-Dimensional Deterministic Model. *Natural Hazards*, *33*(2), 265–282. doi:10.1023/B:NHAZ.0000037036.01850.0d

APPENDIX I. DISASTER EVENTS OF DOMINICA SINCE 1806.

Year	Day	Events	Notes	Information available
1806	09/09/1806	Hurricane	Landslides and Flooding	
1813	23/07/1813	Hurricane	Flooding	
1813	25/08/1813	Hurricane	Flooding	
1834	10/09/1834	Hurricane	NI	
1834	20/09/1834	Hurricane	Landslides and Flooding	
1851	NI	Hurricane	NI	
1916	28-8-1916	Hurricane	Landslides and Flooding	
1920	NI	NI	Landslides and Flooding	
1921	NI	Hurricane	NI	
1924	NI	Hurricane	NI	
1926	24-7-1926	Hurricane	Landslides and Flooding	
1928	12-9-1928	Hurricane	NI	
1930	1-9-1930	Hurricane	Landslides and Flooding	
1948	NI	Tropical Storms	Landslides and Flooding	
1949	set-49	Tropical Storms	NI	
1960	NI	NI	Landslide Bellevue Chopin	
1963	28-9-1963	Hurricane Edith	Landslides and Flooding	
1966	jun-66	Tropical Storms	Landslides and Flooding	
1970	20-8-1970	Hurricane Dorothy	Landslides and Flooding	
1977	NI	NI	Landslide (Bagatelle)	
1979	29-8-1979	Hurricane David (Cat. 5)	Landslides and flooding	
1980	NI	Hurricanes Frederick & Allen (Cat. 1)	NI	
1983	NI	NI	Landslide Bellevue Chopin	
1984	NI	NI	Landslides	
1984	6-11-1984	Hurricane Klaus	Debris Down	
1986	11-11-1986	Several days of heavy rainfall	Landslide Good Hope	
1986	12-11-1986	Several days of heavy rainfall	Landslide Castle Bruce	
1988	NI	Hurricane Gilbert	Landslides' Mathieu and Layou River	
1989	NI	Hurricane Hugo	NI	
1995	25-8-1995	Hurricane Luis	NI	
1995	4-9-1995	Hurricane Iris	Large landslides Mathieu River	
1995	16-9-1995	Hurricane Marilyn (Cat. 1)	Flooding	
1997	18-11-1997	NI	Debris Flow Mathieu River	Location known
1997	25-11-1997	NI	Landslides Mathieu River	
1997	28-11-1997	NI	Landslides Mathieu River	
1999	apr-99	Hurricane Lenny	Landslides in the north	
2003	NI	NI	Carholm landslide	
2003	9-12-2003	NI	Landslide Bellevue Chopin	Location known

2004	nov-04	NI	Series of Landslides’	
2004	21-11-2004	earthquake	NI	
2007	NI	NI	Landslide Campbell	Location known
2007	NI	NI	Landslide Bellevue Chopin	Location known
2007	20/07/2007	Hurricane Dean (Cat. 2)	Flash Flooding	
2008	okt-08	Hurricane Omar	NI	
2009	jul-09	NI	Flooding	
2009	Sep-3rd & 4th	Tropical storm Erika	Landslides	Along roads
2010	24-5-2010	Heavy rains Overnight	Saint Sauver Slide	Location known
2010	Oct 30&31	Hurricane Tomas	Landslides	Along roads
2011	28-7-2011	NI	Miracle Lake Flooding	
2011	29-7-2011	NI	Landslide Soufriere	Location known
2011	sep-28	Storm Ophelia	Landslides	Along roads
2011	Nov-28	NI	landslides	Along roads
2012	29-8-2012	Tropical Storm Isaac	landslides’	
2013	apr-13	NI	Landslides	Along roads
2013	5-9-2013	NI	Landslide Morne Prosper	Location known
2013	24-12-2013	Christmas Eve trough	landsides and Flooding	

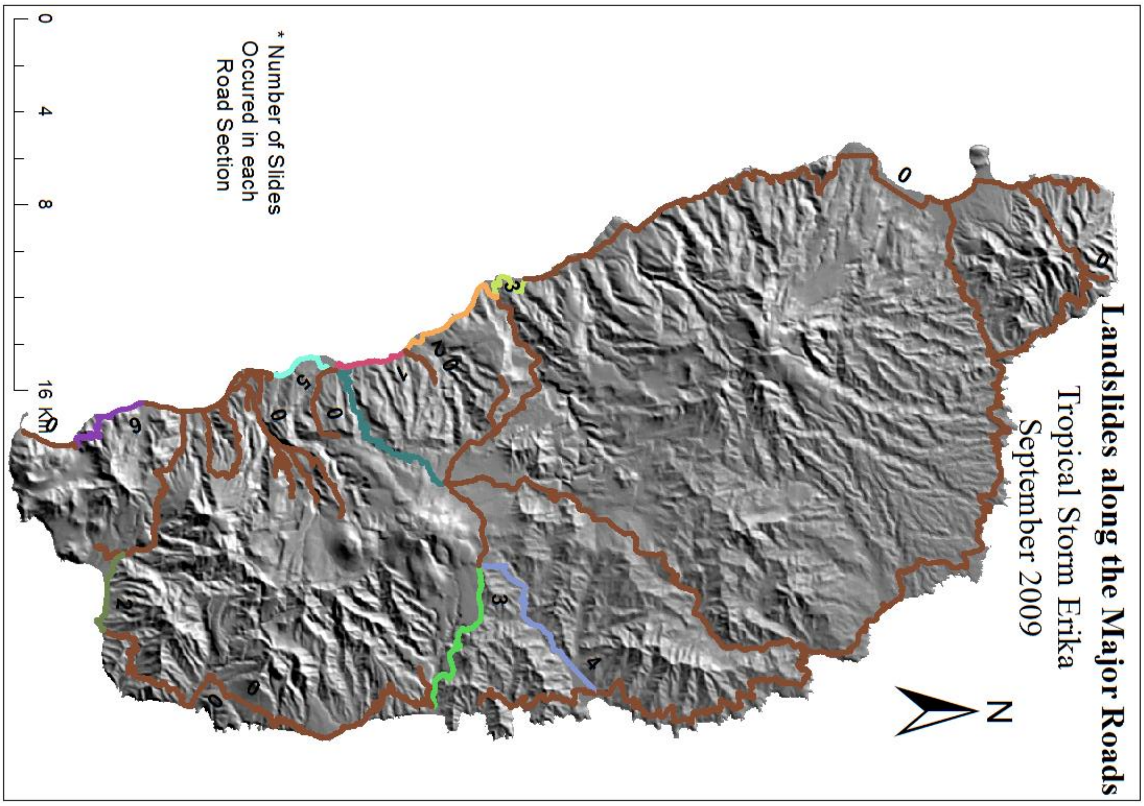
APPENDIX II. DISASTER EVENTS OF SAINT LUCIA SINCE 1870'S.

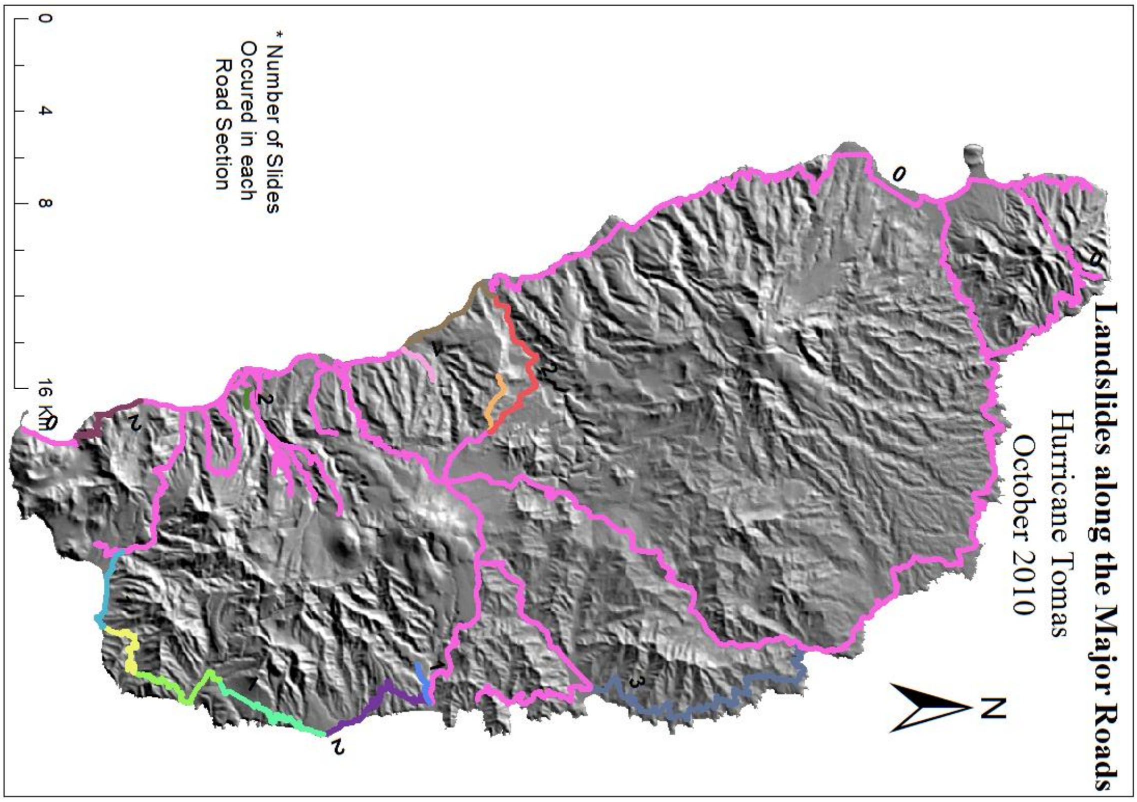
Year	Day	Events	Notes	Information available
1872	09-20/09/1872	Hurricane	NI	
1875	08-18/09/1875	Hurricane	NI	
1876	01/11/1876	Hurricane	NI	
1879	09-16/10/1879	Tropical Storm	NI	
1880	15-20-08/1880	Hurricane	NI	
1886	15-27/08/1886	Hurricane	NI	
1887	08/08/1887	Tropical Storm	NI	
1887	11-22/09/1887	Hurricane	NI	
1888	01-08/11/1888	Tropical Storm	NI	
1891	18-25/08/1891	Hurricane	NI	
1894	11-20/10/1894	Tropical Storm	Landslides and Flooding	
1895	22-30/08/1895	Hurricane	NI	
1896	11/09/1896	Tropical Storm	Landslides and Flooding	
1898	05-20/09/1898	Hurricane	NI	
1901	04-13/07/1901	Hurricane	NI	
1903	06-16/08/1903	Hurricane	NI	
1916	10-22/07/1916	Hurricane	NI	
1916	12-20/08/1916	Hurricane	NI	
1916	06-15/10/1916	Tropical Storm	NI	
1917	20-30/09/1917	Hurricane	NI	
1918	09-14/09/1918	Tropical Storm	NI	
1921	10-9-1921	Tropical Storm	Landslides and Flooding	
1924	16-18/08/1924	Hurricane	NI	
1928	19-9-1928	Tropical Storm	Landslides and Flooding	
1931	10-21/08/1931	Tropical Storm	NI	
1938	21-11-1938	Tropical Storm	Landslides and Flooding	
1938	22-11-1938	Tropical Storm	Landslides Ravine Crebiche and Flooding	
1939	7-1-1939	Tropical Storm	Landslides Ravine Poisson and flooding	
1940	7-8-1940	Tropical Storm	Landslides and Flooding	
1941	23-30/09/1941	Hurricane	NI	
1942	21-31/08/1942	Hurricane	NI	
1942	15-22/09/1942	Tropical Storm	NI	
1943	11-18/10/1943	Hurricane	NI	
1948	1-9-1948	Tropical Storm	NI	
1949	3-9-1949	Tropical Storm	NI	
1951	5-9-1951	Hurricane Dog	NI	
1954	12-12-1954	Tropical Storm	Landslides Ravine Poisson and Flooding	
1958	4-7-1958	Tropical Storm	Landslides and Flooding	
1958	6-9-1958	Hurricane Ella	NI	
1960	10-7-1960	Hurricane Abbey	NI	

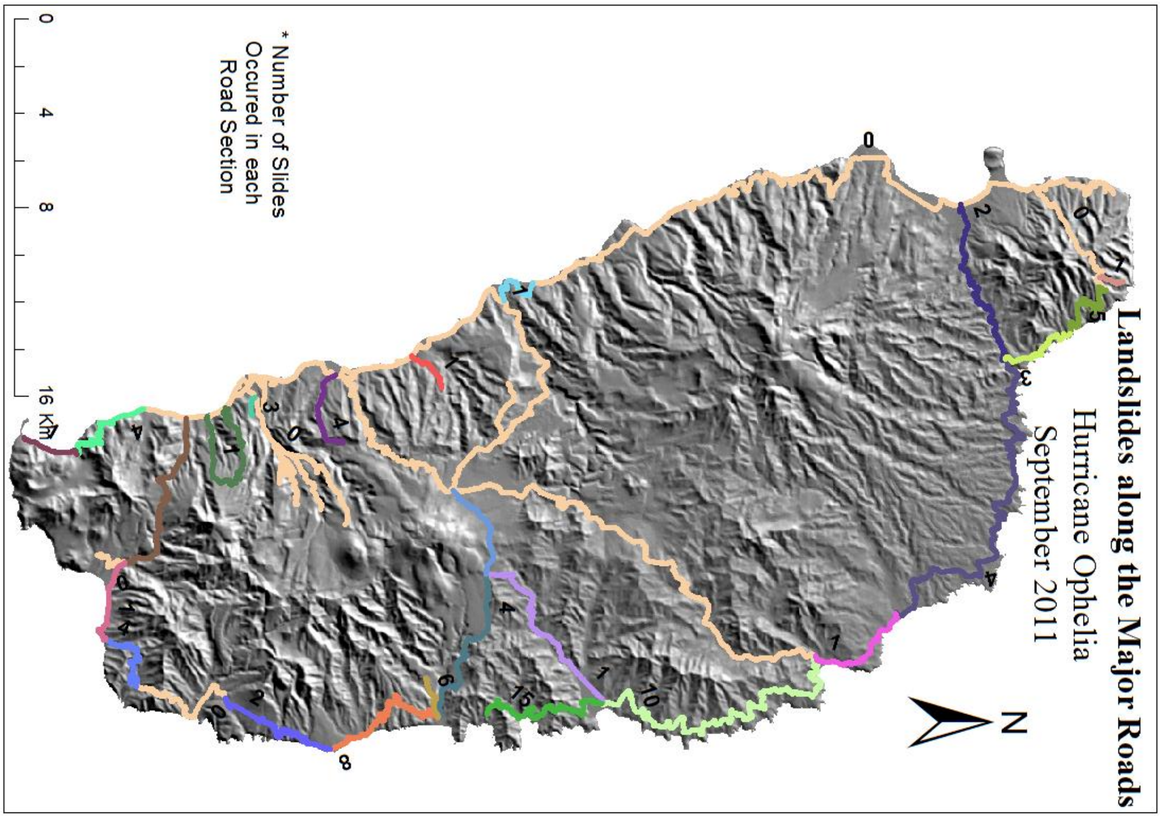
1963	24-9-1963	Hurricane Edith	NI	
1965	27-9-1965	Hurricane Betsy	NI	
1965	25-10-1965	Tropical Storm	Landslides and Flooding	
1966	jun-66	Tropical Storm	Landslides and Flooding	
1966	27-30/09/1966	Tropical Storm Judith	NI	
1967	8-9-1967	Hurricane Beulah	NI	
1967	26-9-1967	Tropical Storm Edith	NI	
1969	25-27/07/1969	Tropical Depression	NI	
1970	17-23/08/1970	Tropical Storm Dorothy	NI	
1970	2-10-1970	Tropical Depression	Landslides and Flooding	
1971	18-25/08/1971	Tropical Storm Chole	NI	
1976	03-12/10/1976	Tropical Depression	NI	
1979	19-24/06/1979	Tropical Storm Ana	NI	
1980	3-8-1980	Hurricane Allen	Widespread landslides particular Barre de l'isle	
1981	nov-81	Storm	Landslides	
1983	23-7-1983	Storm	NI	
1984	24-26/07/1984	Tropical Depression	NI	
1988	11-9-1988	Tropical Storm Gilbert	Landslide	
1990	6-11-1990	NI	Landslides More du Don	
1992	29-11-1992	NI	Landslides	
1993	14-17/08/1993	Tropical Storm Cindy	NI	
1994	09/09/1994	Tropical Storm Debby	More than 400 Landslides shallow debris flow in the upper areas, debris and rock slides along roads	Mapped by Cassandra Rogers
1995	26-08-1995	Hurricane Iris	Landslides Millet Primary school,	
1998	Sep-1998	Earthquake and incessant rain	Landslides Boguis	
1999	7-10-1999	Seismic Event	soil creep and slow gravitational movement and Flooding	
2001	14-22/08/2001	Tropical Storm Chantal	NI	
2001	04-09/10/2001	Tropical Storm Jerry and Hurricane Iris	NI	
2003	07-17/07/2003	Hurricane Claudette	NI	
2004	03-14/08/2004	Tropical Storm Bonnie	NI	
2004	26-9-2004	Seismic Event	Landslides Tapion	

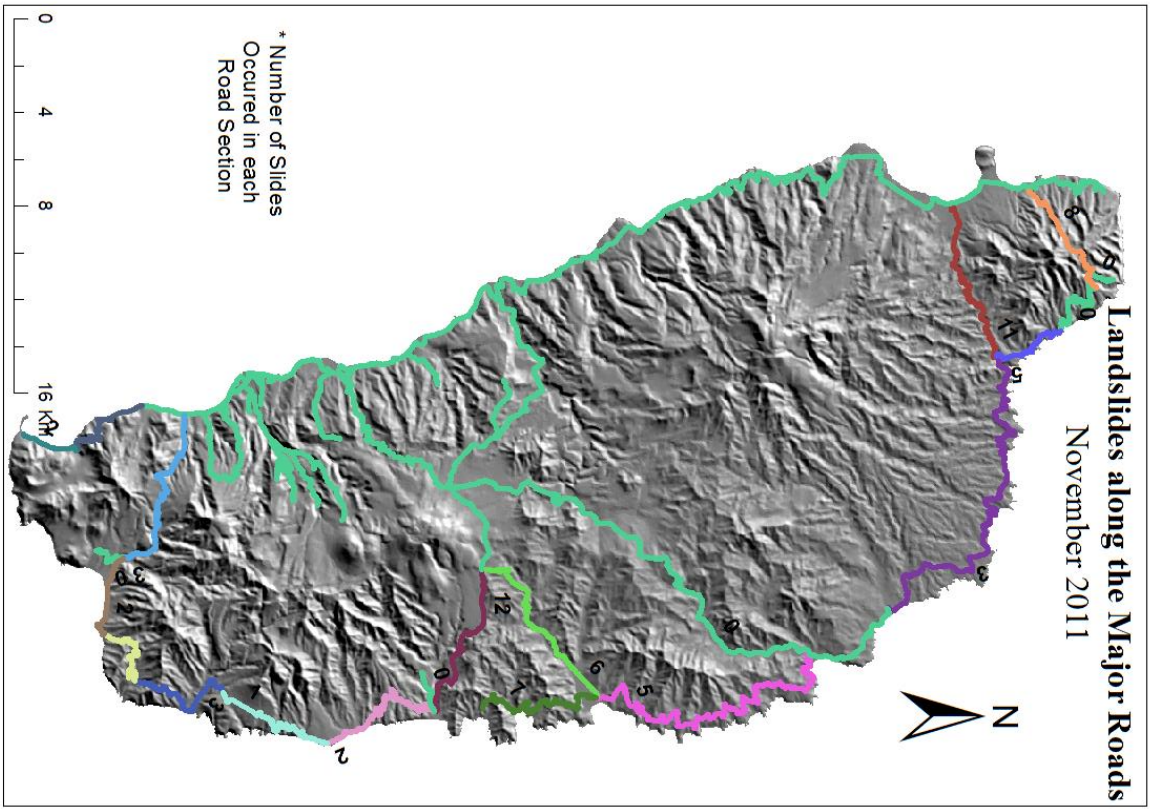
2005	1-7-2005	Heavy rainfall prior to the failure	Landslide Windjammer Landing Beach Resort
2007	13-23/08/2007	Hurricane Dean	NI
2010	30-31/10/2010	Hurricane Tomas	Many landsides Colombette, Fond St Jacques, along the Barre De L'ile, Millet and on the hills east and south of Castries
2004	26-9-2004	Seismic Event	landslides' Tapion
2005	1-7-2005	Heavy rainfall prior to the failure	Landslide Windjammer Landing Beach Resort
2007	13-23/08/2007	Hurricane Dean	NI
2010	30-31/10/2010	Hurricane Tomas	Many landslides' Colombette, Fond St Jacques, along the Barre De L'ile, Millet and on the hills east and south of Castries
2013	24-12-2013	Christmas Eve trough	Several landslides along the roads

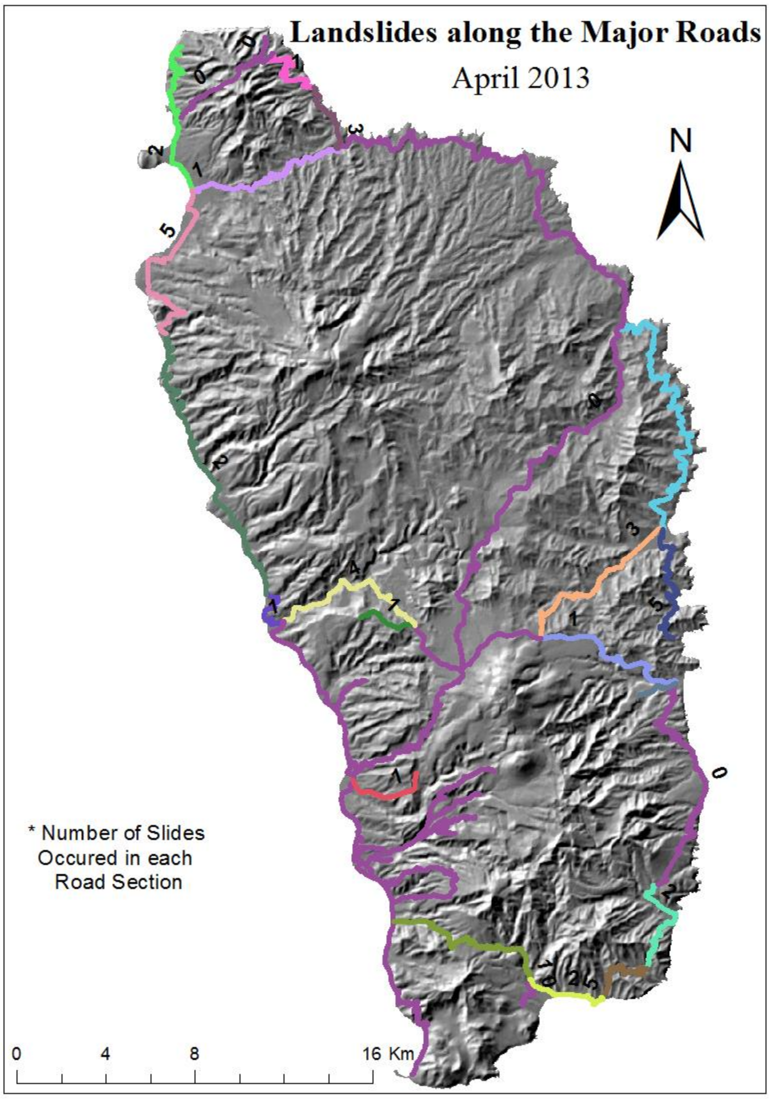
APPENDIX III. LANDSLIDE INVENTORY MAPS ALONG THE ROAD FOR THE FIVE DISASTER EVENTS, DOMINICA






Landslides along the Major Roads
Hurricane Ophelia
September 2011
N
* Number of Slides
Occured in each
Road Section
0 4 8 16 km


Landslides along the Major Roads
November 2011
N
* Number of Slides
Occured in each
Road Section
0 4 8 16 km


Landslides along the Major Roads
April 2013
N
* Number of Slides
Occured in each
Road Section
0
4
8
16 Km