NATIONAL SCALE LANDSLIDE SUSCEPTIBILITY ASSESSMENT FOR DOMINICA AND SAINT VINCENT

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March, 2015

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ABSTRACT

The windward Caribbean island countries are of volcanic origin, have deep tropical storms, and are exposed to high intensity rainfall events, including tropical storms and Hurricanes. This makes these countries highly susceptible to landslides. These countries are also relatively small in size and in population, and often lack the expertise to generate landslide inventory and susceptibility maps. Therefore both the historical inventories as well as the spatial factors that should be used for landslide susceptibility assessment are far from complete.

This research addresses the problem of generating national landslide susceptibility maps in such data poor tropical island environments, with a focus on the islands of Dominica and Saint Vincent. . Due to their similar topography and geological origin, a comparison between their results will be useful to understand how the differences in land use/cover influence the landslide occurrence (type and magnitude), and landslide susceptibility. Very extensive multi-temporal image interpretation was carried out to generate landslide inventories, and to corroborate existing inventories. The difference in the quality of the Digital Elevation Models available for the two countries made a large difference in terms of the landslide inventory. For Dominica image interpretation was carried out using very high resolution Pleiades images from 2014, and Google Earth images from different periods. For Saint Vincent it was also possible to digitize historical landslide occurrences using a hillshading image derived from a LIDAR-DEM. The landslide inventories were checked in the field and a database was developed of landslide inventories for different triggering events. Unfortuantely it was not possible to generate these inventories for more than 2 different events per countries. Existing spatial data about environmental factors (topography, geomorphology, geology, and soils) were homogenized and new thematic data layers were prepared for the drainage network, geomorphology and land cover.

Landslide susceptibility assessment was carried out in two steps. First the importance of the various causal factors was analyzed using statistical modelling with Weights of Evidence (WOE) Analysis. This was done in an iterative process, and new factors were generated and tested. The final landslide susceptibility maps were generated using Spatial Multi-Criteria Evaluation (SMCE), where the weights form the statistical analysis were used as a basis, but were modified when considered appropriate. Also the effect of different weighting between the factor maps was evaluated. The quality of the resulting landslide susceptibility maps was tested using success rate curves, which were also used to classify the final susceptibility maps.

The comparison of the resulting landslide susceptibility maps of the two countries revealed that despite the differences on the DEM quality used, the slope angle is the most important factor related to the landslide initiation susceptibility for both islands, and that the quality of the landslide inventory plays an important rol on the modelling as could be seen on the validation process when using the point landslide inventory and polygn landslide inventory to produce success rates gage different results.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

1.1. Justification

The Caribbean and Latin-America are some of the most disaster-prone regions in the world, ranking second after Asia in terms of total disaster occurrences. The Caribbean region has the highest proportion of population affected by disasters (Walling, Douglas, Mason, & Chevannes-Creary, 2010). The disasters are mainly hydro-meteorological, due to the location within the hurricane belt, which exposes the small islands to extreme wind conditions and torrential rains, caused by Atlantic hurricanes and tropical weather systems.

For Dominica and Saint Vincent, two of the Caribbean islands, the natural hazards are even worse due to their location along the boundaries of tectonic plates. The steep terrain due to their volcanic origin, the recent volcanic activity resulting in areas with recent pyroclastic soils, and hydrothermally altered rocks, the presence of thick volcanic deposits and regolith and land-cover changes due to several land-use practices makes Dominica and Saint Vincent extremely susceptible for landslides triggered by rainfall (Jones, Bisek, & Ornstein, 2011).

Dominica and Saint Vincent have had big economic losses due to rehabilitation of damaged and destroyed infrastructure due to tropical storms and hurricanes that generated flooding and landslides; According to DeGraff et all, (1989), the main infrastructure affected is the roads; and the average annual cost of landslide repairing and maintenance of roads in small islands as St Vincent, St Lucia, and Dominica is around $115,000 to $121,000 in normal years.

More recently, after Tropical Storm Ofelia (September 2011), A grant of $3,501,322.59 were needed in order to support with the repairing and maintenance of road infrastructure. Finally, 2,016 thousand dollars were spent under an immediate response rehabilitation loan from the Caribbean Development Bank (CDB). It was used to undertake emergency works and clean-up operations following a trough system which caused flash flooding, landslides, rockslides in the southern part of Dominica on December 24, 2013. (http://dominicanewsonline.com/news/homepage/news/economy-development/31-million-spent-infrastructure-january-june-pm-skerrit/)

In Dominica, from 1925 to 1986, at least 25 fatalities were registered due to 5 separate events (GFDRR, 2010a). As an example the Bagatelle landslide caused 12 casualties on 21/09/1977. In 1997, two landslide dams were formed and breached one after the other, finally a huge debris flow formed a large dam which blocked the Matthieu river creating a lake behind the dam. After 14 years, on July 2011, the dam from the debris flow failed and flooded Layou valley downstream (James & De Graff, 2012). In Saint Vincent, in 2008, heavy rainfalls triggered 25 landslides (GFDRR, 2010b).

In May of 2010, heavy rains triggered a landslide in San Sauver in Dominica (CDEMA, 2010). In the end of July and the beginning of August 2011, the tropical storm Emily hit Saint Vincent, triggering several landslides that blocked roads in 7 places in the windward side of the island and 2 places in the leeward side of the island (CDEMA, 2011). On 9 and 10 of July of 2013, the tropical storm Chantal generated strong winds and torrential rain in the south of Dominica that triggered landslides on the major roads (CDEMA, 2013b).

The most recent event occurred during Christmas 2013, when a Low Level Trough System impacted Dominica and Saint Vincent with a constant rainfall over a period of 24 hours. In Saint Vincent it caused 19 casualties, 3 people missing, 37 injured, 500 affected and 237 with shelter due to landslides and flooding being catalogued as a disaster of level 2 (CDEMA, 2013c). While in Dominica 35 landslides or mudslides were recorded and 24 families were affected by flashfloods (CDEMA, 2013a).

The development, urbanization, economic activities and agricultural production are restricted, by the rugged terrain in Dominica and Saint Vincent, puts a pressure on the coastal areas, where flat terrain is present. Due to limited human and financial resources, as well as lacking geospatial data for hazard and risk assessment, the lack of planning policies is allowing the expansion onto slopes prone to failure (GFDRR, 2010a; GFDRR, 2010b).

1.2. Background – Literature review

A proper National planning policy integrates vulnerability assessment and risk reduction into management and development planning (Jones et al., 2011). In this way (prediction of areas with first time failures), allows planners to understand how a natural slope with no presence of landslide in the past or present, can then be affected by landslides due to different human activities such as road cuts or land-use changes. It also helps to predict reactivation of existing landslides. Based on the assessments a proper zonation (spatial planning) of safer places to build certain constructions is possible. For example after a disaster, it facilitates to make a good selection of the right place to reconstruct a building/town.

In order to have proper national planning policies and to avoid fatalities due to landslides, a good landslide hazard assessment is needed. Landslide hazard imply knowing the probability of occurrence of a landslide within a given area (landslide susceptibility), within a specified period of time, and with a given intensity or magnitude (Guzzetti, 2003). For this, an integration of triggering factors and a landslide susceptibility assessment must be carried out.

Landslide susceptibility or spatial probability refers to the probability of a landslide occurring in an area with specific local terrain conditions (Baban & Sant, 2005). It is the likelihood of the terrain to form a landslide (slope movements), i.e., an estimate of "where" landslides are likely to occur. It is necessary to carry out a separate analysis of the propensity of the slopes to fail (initiation susceptibility) and the possible area that can be affected by the potential run-out (run-out susceptibility) or regression of landslides from their source (Fell et al., 2008). This likelihood for landslides to occur is represented in a landslide susceptibility map.

A landslide susceptibility map consists of subdivisions of the terrain in areas that have different spatial probability or likelihood to present landslides. The likelihood could be indicated either qualitatively (as high, moderate and low) or quantitatively (e.g. as the density in number per square kilometers). Landslide susceptibility maps do also include those areas where landslides happened in the past, where they could happen in the future and the run-out zones, if possible. (Jordi Corominas & Mavrouli, 2011).

To generate a proper susceptibility map, information about the following factors is needed: environmental factors, (e.g. topography/geomorphology, slopes angle, length, aspect), geology (e.g. faults, lithology), soils (e.g. geotechnical properties), hydrology, land use/cover changes, triggering factors (e.g. rainfall, hurricane, earthquake) and landslide inventories (location, time and magnitude). The landslide inventory is of particular importance because of the premise "landslides are mostly likely to occur in areas where they have already occurred in the past". Finally it would be possible to find out which factor control the initiation and presence of landslides, or in what percentage each factor contributes (van Westen, Castellanos, & Kuriakose, 2008).

A landslide inventory is the compilation of landslides in a certain place for a certain period, preferably in digital form (as points or polygons) with spatial information related to the location combined with attribute information. These attributes should ideally include information about the type of landslide, geometrical characteristics (e.g. size or volume), date of occurrence or relative age, state of activity and possible causes, in order to be able to analyze it and obtain information regarding distribution (e.g. pattern), magnitude-frequency relation, and possible causal factors.

Landslide inventory maps can be classified based on archives or geomorphological data. The geomorphological can be classified as historical, event-based, seasonal or multi-temporal depending on how many landslides events, triggering events and period of time is considered. The maps can be produced after different methods: conventional (geomorphological field mapping or visual interpretation of aerial photographs), recent (visual interpretation of satellite images, visual analysis of DEMs) and new (techniques for semi-automatic detection of landslides from DEMs, or images - Object oriented analysis) (Guzzetti et al., 2012).

There are several methods to analyze the environmental factors and to produce the landslide initiation susceptibility model (***Figure 1.*** **Error! Reference source not found.**) which can be qualitative (knowledge driven) or quantitative (data driven and physically based). To create a landslide inventoryis the first step for all of them.

Knowledge driven methods depends on the expert opinion. In the direct method, an expert interprets the susceptibility directly in the field. In the indirect method, the use of GIS is necessary in order to combine a number of factor maps (environmental factors), which can be done by an expert who assigns a particular weight to the classes of the individual factor maps and a weight to the maps themselves. Several methods can be used: Geomorphological mapping (image interpretation), direct mapping method (field), multiclass weighting method, spatial multi-criteria analysis, analytical hierarchy process (AHP), and Fuzzy logic approach (Corominas & Mavrouli, 2011).

Data driven methods are based on the assumption that conditions that have produced landslides in the past will do it again in the future. In this way, the methods evaluate statistically the combination of factors that have produced landslides in the past, and quantitative predicts areas with similar conditions that can have landslides in the future are. These methods can be bivariate statistical models (e.g. weights of evidence), Multivariate statistical models and Artificial Neural Networks (ANH). Physically based methods are based on slope stability models and they are used in local scale due to the detailed information needed (Corominas & Mavrouli, 2011).

Methods for assessing landslide runout can be classified as empirical and analytical/rational. Empirical methods are usually based on field observations and on the analysis, per type of landslide, of "the relationship between morphometric parameters (i.e. the volume of the landslide mass), characteristics of the path (i.e. local morphology, presence of obstructions) and the distance travelled by the landslide deposits". The empirical Methods can be classified as geomorphologically-based, geometrical approaches and volume change methods. Rational methods are based on the use of mathematical models of different degrees of complexity. They can be discrete or Continuum based models (Corominas & Mavrouli, 2011).

The main output of a landslide hazard assessment is a map that can be used together with an elements-at-risk map and a vulnerability map, produced on a vulnerability assessment, to produce the final risk map in a landslide risk assessment. This assessment, aims to determine the "expected degree of loss due to a landslide (specific risk) and the expected number of live lost, people injured, damage to property and disruption of economic activity (total risk)"(Guzzetti et al., 2012).

A landslide hazard map consists on the subdivision of the terrain in zones that are characterized by the expected intensity of landslides within a given period of time, or the probability of landslide occurrence. Like the susceptibility map, the landslide hazard maps also should show both the places where landslides may occur as well as the run-out zones. However, landslide hazard maps differ from landslide susceptibility maps as they would indicate for specific zones, what can be expected, with which frequency and with which intensity (Jordi Corominas & Mavrouli, 2011).

Once the risk from an area susceptible to landslides is identified, it would be possible to take measures to mitigate landslide risk to the community if it is necessary, and be able to prioritize the allocation of resources, and increase the resilience of population to disasters. There are several strategies to deal with it, which could be grouped into planning control (e.g. reducing expected elements at risk), engineering solution (e.g. prevent landslide to happen or diminish the spatial impact of it), acceptance (i.e. acceptable or unavoidable), and monitoring and/or warning systems (e.g. evacuation), (Dai, Lee, & Ngai, 2002).

However, the lack of information regarding susceptibility and hazard assessment could impeed the creation of a proper national landslide hazard mitigation plans, forcing the national governments to use most of all engineering solutions, spending a lot of money that with the proper knowledge could be used in a better way. Good planning control (e.g. new developments can be prohibited, restricted or regulated in landslide-prone areas) seem to be the most practical and cost-effective mitigation measure over a longer period (Dai et al., 2002).

1.3. Research problem

Regardless of all the environmental, social and economic problems that landslides have caused in Dominica and Saint Vincent and the Grenadines (SVG), it is still not sufficiently known which areas are more prone to landslides, their spatial and temporal distribution, their magnitude or what their triggers. That means that the landslide susceptibility and hazard, is still unknown.

Previous attempts have been made in order to provide a landslide hazard zonation for the islands. In Dominica, in 1987, (DeGraff, 1987) a national landslide hazard assessment was done through the analysis of three factors: geology, geomorphology and topography. The geomorphology was represented by a

1:25,000 landslide inventory map obtained through the interpretation of aerial photographs from 1984 at a scale of 1:20,000 that covered the whole island from north to south, except a strip on the east-central part of the island and fieldwork on the major roads. For the geology, they did not have a national map, so they took data published in articles, and integrated it with geology map of all the Caribbean islands to obtain a geology map with 12 classes. The topography was represented by 3 slope classes. No rainfall information was used, as well as any land cover/use. The final map was a landslide susceptibility map (named as landslide hazard map) obtained from the analysis of the proportion of bedrock-slope combinations subject to past landslide activity (landslide area divided by bedrock – slope area).

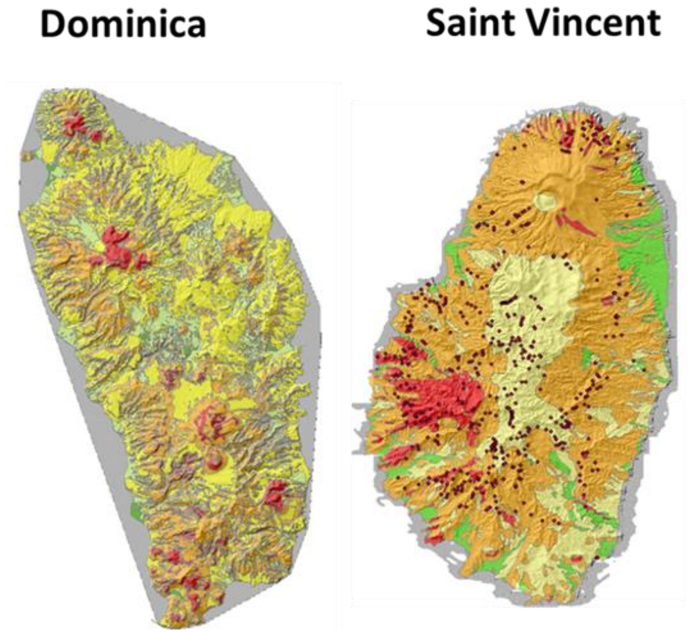


Figure 1. *Dominica: study carried out by CIPA for USAID in 2006, as part of a multi-hazard mapping project. Saint Vincent: Susceptibility map generated by DeGraff in 1988.*

The same methodology was used to generate a landslide hazard zonation in Saint Vincent in 1988, (DeGraff, 1988) For this island, the aerial photographs were from 1981 and had a complete coverage of the island except for a small cloud cover obscuring parts of Soufriere. The geology map was a map with the major bedrock types (5 classes) was used. The topography factor was a slope map with 6 classes.

In 1990, in Dominica, a new landslide inventory was made only with fieldwork that contained all landslides occurred between 1987 and 1990 (DeGraff, 1990), in order to validate the hazard zonation made in 1987, and assess the role of vegetation. They concluded that the hazard zonation was reliable. They also found that most of the landslides occurred on areas with managed vegetation (tree crops and secondary rainforest), indicating that this land-cover may reduce slope stability.

In 2003, in Saint Vincent (CDERA, 2003) an assessment of the status of hazard maps and digital maps was done. The only information about the landslide inventory made by DeGraff in 1988, is in paper. In digital format at scale 1:25,000, there are contour lines, agricultural land use, rivers, and roads. There is no adequate data on geology, soils or vegetation.

In Dominica, in 2006, a landslide hazard map, and a multi-hazard assessment was made at national level (USAID, 2006). The landslide inventory was obtained through the integration of previous work made by DeGraff in 1987 and 1990 with aerial photographs and fieldwork. The aerial photographs were from February 2 of 1992 at a scale of 1:10,000. The fieldwork was made with help of local representatives, who helped in the location of critical areas, recent and historical landslide events and to corroborate the image interpretation. For the hazard assessment they used elevation, slope angle, slope aspect, geology and soils. Finally, they combined all the factors to generate the landslide susceptibility model, which they named as hazard map.

Since any of these studies comprised an analysis of the triggering events and their relationship with landslide occurrence, it is clear that they are basic landslide susceptibility assessments; however, they leave out important factors as soils, land-cover, land use and geological structures as faults.. Due to that a real understanding of the relationship between landslide occurrence, triggering events and factor maps is still not very clear.

In order to find out those relationships, a comparison between the landslide hazard assessment of Dominica and Saint Vincent will be done; due to their same geological origin, and a similar topography, it would be easy to analyze how the differences in rainfall regime and land cover influence the landslide occurrence (type and magnitude).

1.4. Project framework

Currently, Dominica and SVG are part of a group of five beneficiary countries within a World Bank project (CHARIM: Development of a handbook for hazard, vulnerability and risk assessment for decision-making for the Caribbean) (ITC, 2013), for which ITC is the consortium leader.

The aim of this project is to build capacity of government clients in the Caribbean region. Specifically in the countries of Belize, Dominica, St. Lucia, St. Vincent and the Grenadines and Grenada. The project will generate hazard and risk information about landslides and flooding and apply this in disaster risk reduction use cases focusing on planning and infrastructure (i.e. health, education, transport and government buildings) through the development of a handbook and, hazard maps, use cases, and data management strategy.

By developing a national-level landslide hazard map for Dominica and Saint Vincent, this research will support the objective number 4 of the project related to developing nine hazard mapping studies in the five target countries.

1.5. Objectives and reseacrh questions

1.5.1. General Objective:

Generate a national-scale landslide susceptibility assessment of Dominica and Saint Vincent, focusing on the generation of multi-temporal landslide inventory maps.

1.5.2. Specific Objectives

- Generate a multi-temporal landslide inventory at national scale (1:25.000) for each island
- Analyze the available historical information of landslides occurrences and their relationship with triggering factors on each island.
- Analyze the relevant factors related to the occurrence of landslides on each island.
- Develop a landslide susceptibility model at national scale (1:25.000 – 1:100.000) for each island.
- To assess how differences in the quality of the landslide inventory influence the final susceptibility maps;
- To assess how differences in the spatial representation (as points or polygons) influence the final susceptibility map.
- To assess how different standardization methods can influence the final landslide susceptibility map.

1.6. Thesis outline

This document has the following structure:

Chapter 1: introduction

Chapter 2: Study areas

Chapter 3: Methodology

Chapter 4: Landslide inventories

Chapter 5: Anlayzing the importance of the factors.

Chapter 5: Generation of susceptibility maps

Chapter 6: Discussion and conclusions
Annex: Includes full resolution version of the maps.

2. STUDY AREAS

The study areas are Dominica and Saint Vincent, two islands of the Lesser Antilles in the Eastern Caribbean, with areas of 750 Km² and 345 Km² respectively. Their highest points Morne Diablotin peak (1,447m) and La Soufrière volcano (1,234 m) (CARIBSAVE, 2012a; CARIBSAVE, 2012b). Both islands have a volcanic origin which determines the topography, soils, forest and population distribution.

***Figure 2**. General location of the study areas.*

2.1. Urban Areas:

The islands have a relatively small population, ranging from 72,000 (Dominica) to 105,897 (Saint Vincent). Both islands have a rugged and steep terrain in the middle of the islands, with deep-cut valleys and high vertical coastal cliffs alternated with flat and wide valleys, and undulating coastal plains. Due to this, the population is concentrated mostly along the coast. Therefore the population density, (***Table 1***) is not representative for the actual settlement areas.

Due to lack of building control related to natural hazards prevention, new urbanization processes are taking place on the surrounding hills of the urban centers, which leads to building constructions on landslide prone areas. The road network is in a similar situation. Primary road networks generally follow the coastlines, passing through debris flow prone gully's areas as well as rock-fall prone cliffs (e.g. Road in Stowe area in Dominica).

***Table 1.** Relevant characteristics of the islands for the landslide susceptibility assessment.*

Characteristics	Dominica	St. Vincent and the Grenadines
Surface Area	754 km²	390 km² Saint Vincent: 342.7 km² Bequia: 17.00 km² Union Island: 7 km² Mustique: 5.70 km² The other 28 islands are smaller than 1.5 km²

Characteristics	Dominica	St. Vincent and the Grenadines
Coastline	148 km	84 km
Terrain	Rugged mountains of volcanic origin, 9 potentially active volcanos. Max. elevation: 1,447 m	Volcanic, mountainous. Max. elevation: 1,234 m
Volcanic activity	9 potentially active volcanos. Seismic swarms in South of the island	Active volcano Soufriere in the north of the island.
Economy	(Eco) tourism, bananas, other agricultural products Export: 37 M US$ Import: 220 M US$ Debt: 379 M US$ 70% of GDP	Tourism, significant clandestine marihuana trade. Export: 45 M US$ Import: 360 M US$ Debt: 533 M US$
Road network	Complex network , partly circular, partly crossing. Few very import5ant stretches	No circular network. Leeward ad windward road.
Population	72,301 (2014)	105,897 Of which > 100,000 on main island
Population density	105/km2	307 km2

2.2. Geology:

Both islands have a volcanic origin, with several volcanoes in the central part of the islands. In the case of Saint Vincent, Soufriere Volcano is considered active presenting destructive eruptions (historically recorded eruptions have occurred in 1718, 1812, 1902, 1971 and 1979), characterized by ash falls, mudflows and glowing avalanches of incandescent gas called "nuees ardentes"(Teytaud et al., 1990).

Due to their volcanic origin, the geologic units are complex, including ignimbrites, lava flows, lahar deposits, and volcanic ashes. All of them are very heterogeneous (vertical and horizontal changes) and have not been mapped in detail for any of the islands. The geologic maps are too general and do not map in detail the volcanic deposits.

As it could be seen during the fieldwork, the difference between rocks and soils is not clear in engineering terms, due to the relative degree of consolidation of the volcanic deposits, their heterogeneity and the effect of weathering. These volcanic deposits are usually very thick; they may sustain vertical road-cuts, however, after weathering processes take place such road-cuts may cause problems, as seen in Dominica **Figure 3e and 3f**).

A

B

C

D

Figure 3. *Examples of outcrops in volcanic deposits. a, b and c in Saint Vincent: d, e and f in Dominica.*

2.2.1. Saint Vincent:

The geologic map has only 9 units, differentiated according to phases of volcanic activity (age). Due to this, the units are too general, including several materials that have different degree of landslide susceptibility that cannot be differentiated on the map. These materials include pyroclastic deposits (unconsolidated), Tephra (ash deposits consolidated), scoria deposits (fragments of basaltic rock with vesicles) and lava flows, which have different characteristics as texture, cementation and strength that is not represented on the map.

2.2.2. Dominica

For Dominica, the geologic map also represent 9 units, subdivided according to its origin (volcanic or sedimentary) and to its age. Despite this, the units are very general, for example the unit in grey color on the map contains (called: Basalt to dacite lavas, pillow lavas and pyroclastic deposits), contain lavas and pyroclastic deposits, two materials that have different characteristics as texture, cementation, and strength, that makes them to present different degree of landslide susceptibility that cannot be differentiated on the map.

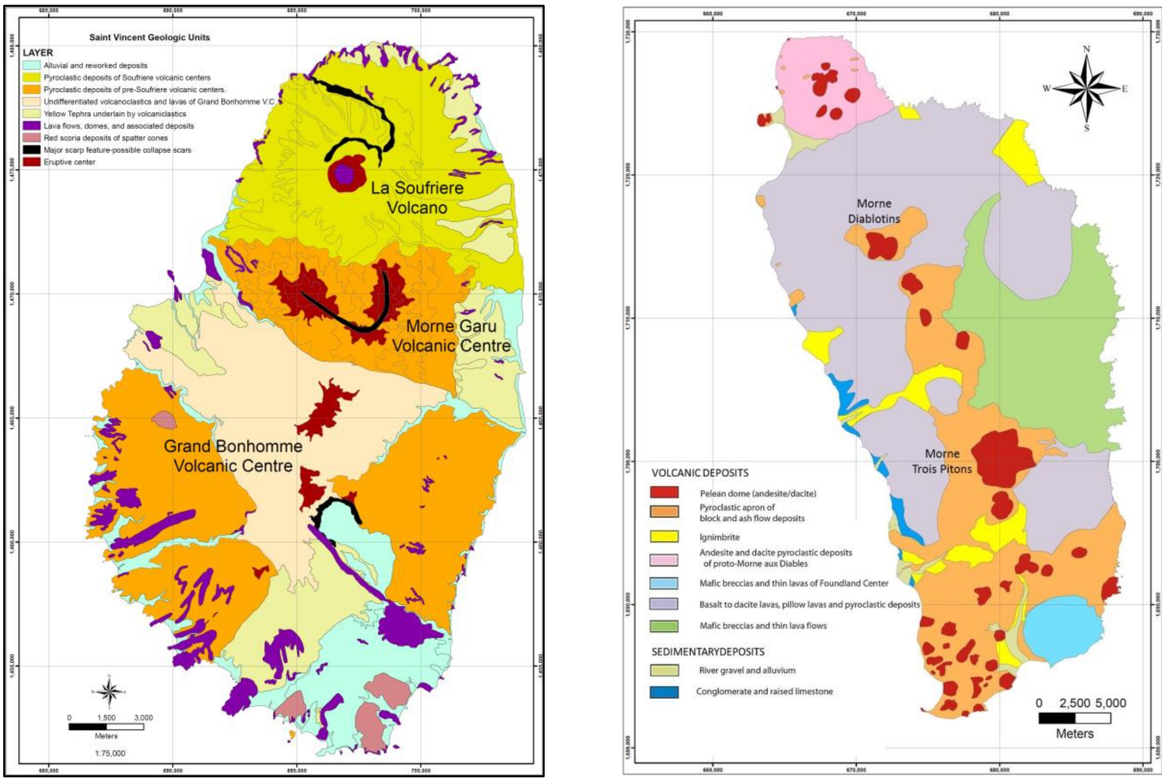


***Figure 4**. Geologic maps of Saint Vincent (Left) and Dominica (Right)*

2.3. Soils:

The soil maps are more detailed than the geologic maps, showing a large differentiation, however they are focusing on pedologic soil characteristics for agriculture purposes, which is no so useful when analyzing the information regarding landslide susceptibility.

2.3.1. Saint Vincent

For Saint Vincent, the soil information consists on a vector file that has an attribute table with information about soils type, erosion state, dominant slope, and amount of boulders.

There are 46 soil types, named according to their localization and texture (clay, loam, sand or gravel content). Despite this, there is not enough information to infer anything about slope stability; for this it would be necessary to have information regarding geotechnical properties like in-situ moisture, strength, consistency and depth.

2.3.2. Dominica

For Dominica, the soil type map consists of 17 main types. According to the report (D.M.LANG. 1967), This classification was made in order to identify agricultural fertility problems. For this the degree of weathering were estimated based on field observation data as pH, texture, structure and X-ray analysis on clay mineral content. Other factors were used as well such as parent materials, climate, plant and animal organisms, age of land and topography.

From the map, it is possible to observe that the main soil is A*llophanoid Latosolics* (Very highly permeable, low bulk density and at least 40% of matrix-clay size) occupying the middle area of the island, then on the northeast there are *Kandoid Latosolics* (High to moderate permeability, low bulk density), and on the SW there are *Young Soils* (low water holding capacity, low bulk density and no less than 60% of matrix-clay size) and *Smectoid Clay Soils* (40 to 60% of matrix-clay size).

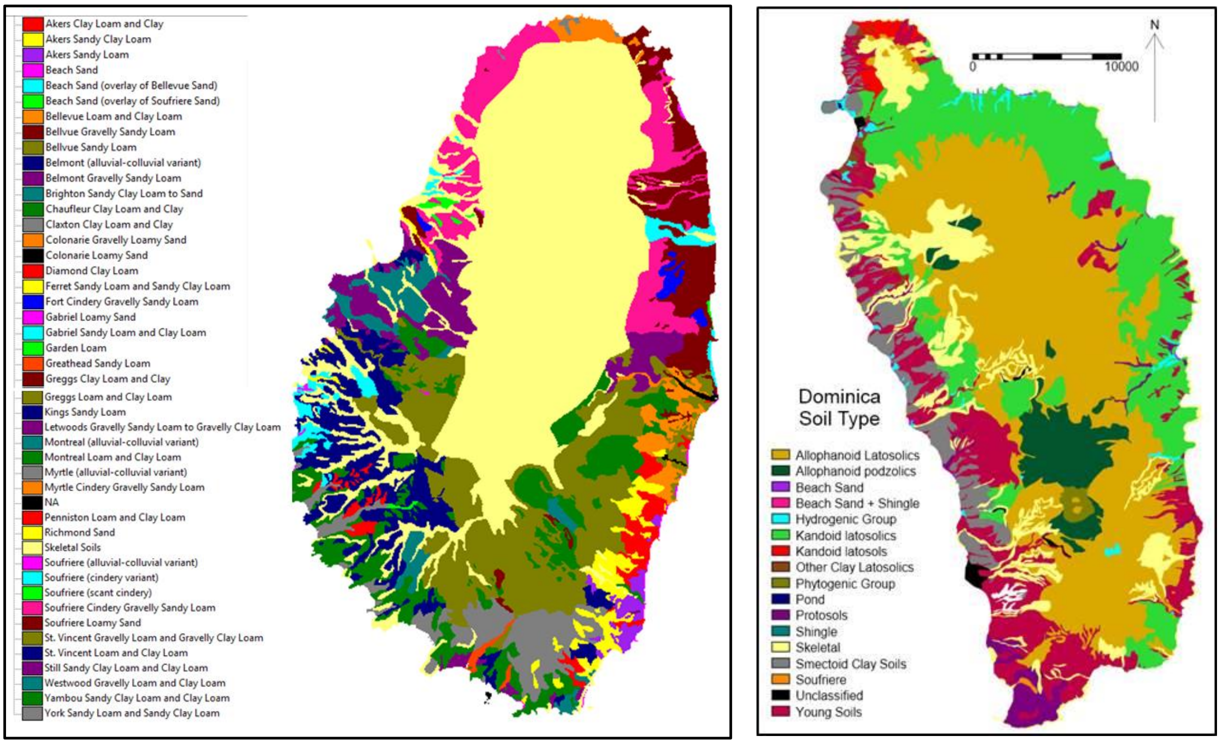


Figure 5. *Soil Texture map of Saint Vincent, and Soil Type map of Dominica*

2.4. Landcover

For both islands there is a general zonation from natural land cover consisting on forest on the middle of the islands, while the modified land covers as plantations, and buildings are in the distal part near the shoreline.

2.4.1. Saint Vincent

For Saint Vincent, there are three land-cover maps, made in three years: 2000, 2005 and 2014.

The first two maps were vector files, and the units were too general. The last map, made in 2014 by the British Geological Service, through an image classification of Pleiades images, has 16 units. It reflects the current status of the island. Because of this and the fact that it was based on the same images used for the generation of the landslide inventory, is the land-cover map that was used for the modelling.

Due to the topography, Saint Vincent has cultivation on most of the island below 305 meters, mainly banana crops, however, cultivation is extending occupying very steep slopes. On the steep parts in the center of the island also quite some illegal marihuana crops are found, which generates low public security in those areas.

2.4.2. Dominica

For Dominica, the land-use map consists of 18 units. The origin of the classification is unknown, but the boundaries of the units seem very general, which can be seen on the class agriculture, occupying a lot of area without specifying any crop types.

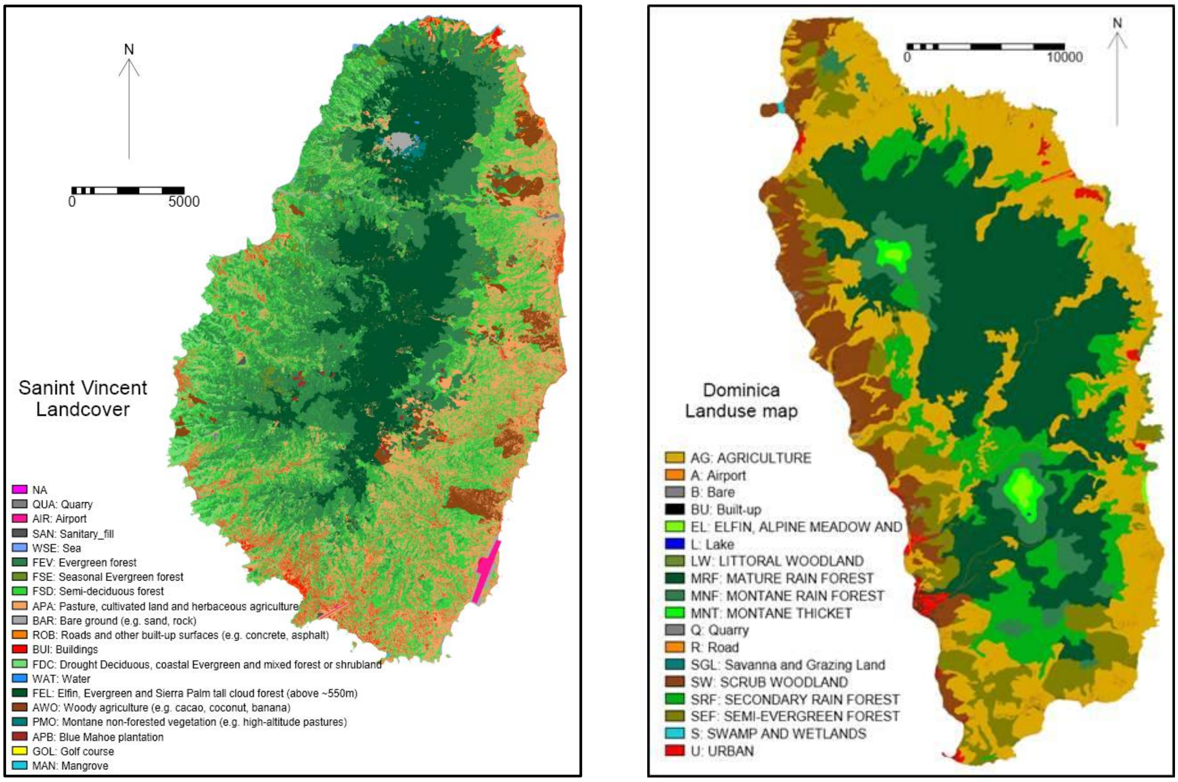


***Figure 6**. Land-cover map for Saint Vincent (left) and Dominica (right)*

2.5. Hydrometeorological hazard records:

One of the most important factors for the generation of landslides is information about triggering events. This could be earthquakes, rainfall or human activities. For both islands the earthquakes are considered not to have enough intensity to cause significant landslide problems. Human interventions are considered to be the initiating situation however rainfall is still needed to trigger the landslides. Because of this rainfall events are considered the most important landslide trigger.

Both islands have an orographic rainfall, meaning that it rains more in the mountainous areas than in the flat areas. For Dominica the rainfall is characterized by heavy rainfall events of short duration. There is a very high rainfall on the center of the island with 10,000 mm annually and just 1,200mm annually on the western side (Shiar et al., 1990). For Saint Vincent it is characterized by showery rainfall events and varies from 6604 mm to 6985 mm annually in the mountainous interior to 1778 mm to 2286 mm annually on the valleys and coastal area of the south (Government of Saint Vincent and the Grenadines, 2010).

For both islands, the rainy season is from June to December which is also the hurricane season. Dominica is located directly in the hurricane belt. Although Saint Vincent is located to the south of the main hurricane and tropical storms track, the island have been hit several times in the last decade: Tropical Storm Chantal on August 17, 2001; Tropical Storm Jerry on October, 8 2001; Tropical Storm Lily on September 23, 2002; Tropical Storm Claudette on July 8, 2003; and Hurricane Tomas on October 31, 2010. (CARIBSAVE, 2012b).

Due to this it was important to have an idea of the most important events that have affected the islands to be able to relate them with the landslide inventories. According to van Westen, (2014), 53 events have affected Dominica from 1806 to 2013 (Table 2) and 49 events have affected Dominica from 1874 to 2013 (Table 3).this databases were made mainly from newspaper records.

***Table 2.** Historical disaster events in Dominica collected from different sources (NI = No Information).(Van Westen, 2014).*

Year	Day	Events	Notes	Information available
1806	09/09/1806	Hurricane	Landslides and Flooding	
1813	23/07/1813	Hurricane	Flooding	

Year	Day	Events	Notes	Information available
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 Disaster)	
1979	29-8-1979	Hurricane David (Category 5)	Landslides	
1980	NI	Hurricanes Federick & Allen (Cat1)	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	aug-07	Hurricane Dean (Cta 2)	Flash Flooding	
2008	okt-08	Hurricane Omar	NI	
2009	jul-09	NI	Flooding	
2010	24-5-2010	Heavy rains Overnight	Saint Sauver Slide	Location known
2011	28-7-2011	NI	Miracle Lake Flooding	
2011	29-7-2011	NI	Landslide Soufriere	Location known
2011	sep-11	Storm Ophelia	NI	Inventory along roads
2012	29-8-2012	Tropical Storm Isaac	landslides'	
2013	apr-13	NI	Landslides	Inventory along roads
2013	5-9-2013	NI	Landslide Morne Prosper	Location known
2013	24-12-2013	Christmas Eve trough	landsides and Flooding	Inventory along roads, image interpreted inventory

Table 3. *Historical disaster events in Saint Vincent collected from different sources (NI = No Information). (Van Westen, 2014).*

Year	Day	Events	Notes	Information available
1874	09/09/1874	Tropical Storm	Landslides and Flooding	Heavy Rain
1876	01/01/1876	Tropical Storm	Landslides and Flooding	Heavy Rain for 2 days
1884	16/08/1884	Tropical Storm	Landslides and Flooding	NI
1886	15/08/1886	Tropical Storm	NI	NI
1887	30/07/1887	Tropical Storm	NI	NI
1887	11/09/1887	Tropical Storm	NI	NI
1895	06/09/1895	Tropical Storm	Landslides and Flooding	NI
1895	15/09/1895	Tropical Storm	Landslides and Flooding	NI
1896	28/10/1896	Tropical Storm	NI	Heavy Rain
1897	NI	Tropical Storm	Flooding	Cyclone

Year	Day	Events	Notes	Information available
1898	11/09/1898	Hurricane	NI	NI
1902	8-5-1902	Earthquakes and volcanic activity	Landslides	NI
1916	okt-16	Tropical Storm	Flooding	Heavy Rain
1955	23-9-1955	Hurricane Janet	NI	NI
1954	9-10-1954	Tropical Storm	Flooding	
1957	30-5-1957		Landslide	
1963	5-7-1963	Storm	NI	NI
1963	24-9-1963	Hurricane Edith	NI	NI
1962	1-9-1962	Heavy rain	Landslide	Heavy Rain
1962	25-6-1962	Tropical Storm	NI	NI
1967	17-9-1967	Hurricane Behulah	Landslides and Flooding	18" of rain in 12 hours
1974	13-5-1974	Heavy rains	Landslides and Flooding	heavy Rains
1974	2-10-1974	Tropical Storm	Landslides and Flooding	Heavy Rains
1977	18-10-1977	Heavy Rains	Flooding	Heavy Rains
1978	19-10-1978	NI	Landslide	NI
1980	11-8-1980	Hurricane Hallen	NI	NI
1981	1-5-1981	Tropical Storm	Landslides	NI
1986	8-9-1986	Tropical Storm Daniel	Landslides and Flooding	NI
1987	21-9-1987	Hurricane Emily	Landslides and Flooding	NI
1987	nov-87	NI	Landslides'	NI
1988	22-08-1988	Previous Heavy Rains	Rockslides	Heavy Rains
1988	22-10-1988	Heavy Rains	Landslides	Heavy Rains
1990	28-09-1990	Heavy Rains	Landslides and Flooding	Heavy Rains
1991	26-08-1991	Heavy Rains	Flooding	NI
1991	24-10-1991	Torrential Downpours	Landslides	NI
1992	21-09-1992	Heavy Rains	Flooding	NI
1995	26-08-1995	Tropical Storm Iris	Landslides and flooding	NI
1996	08-09-1996	Incessant Rain	Flooding and Landslides	NI
1998	08-01-1998	Torrential rainfall	Flooding	NI
1999	17-11-1999	Hurricane Lenny	Flooding	NI
2000	29-11-2000	Torrential Downpours	Flooding	NI
2001	4-10-2001	Tropical Depression Iris	NI	NI
2002	24-9-2002	Tropical Storm	Landslides and flooding	NI
2004	8-9-2004	Hurricane Ivan	Landslides and Flooding	NI
2004	24-11-2004	Tropical Storm	NI	NI
2005	14-7-2005	Tropical Storm	NI	NI
2010	29-10-2010	Hurricane Tomas	NI	NI
2011	11-4-2011	Tropical Storm	Landslides	NI
2013	24-25/12/2013	Tropical Storms	Flooding	Heavy Rain 200 to 300 mm in two hours

3. METHODOLOGY

For this study the methodology had two main processes: a pre-modelling and a modelling part.

In the pre-modelling it is included all the data collection and data base preparation in order to have all information needed (factor maps and landslide inventories) for the following modelling stage. At this stage the most important work consisted on the generation of several landslide inventories for both islands through fieldwork, image interpretation and digitizing old landslide inventories.

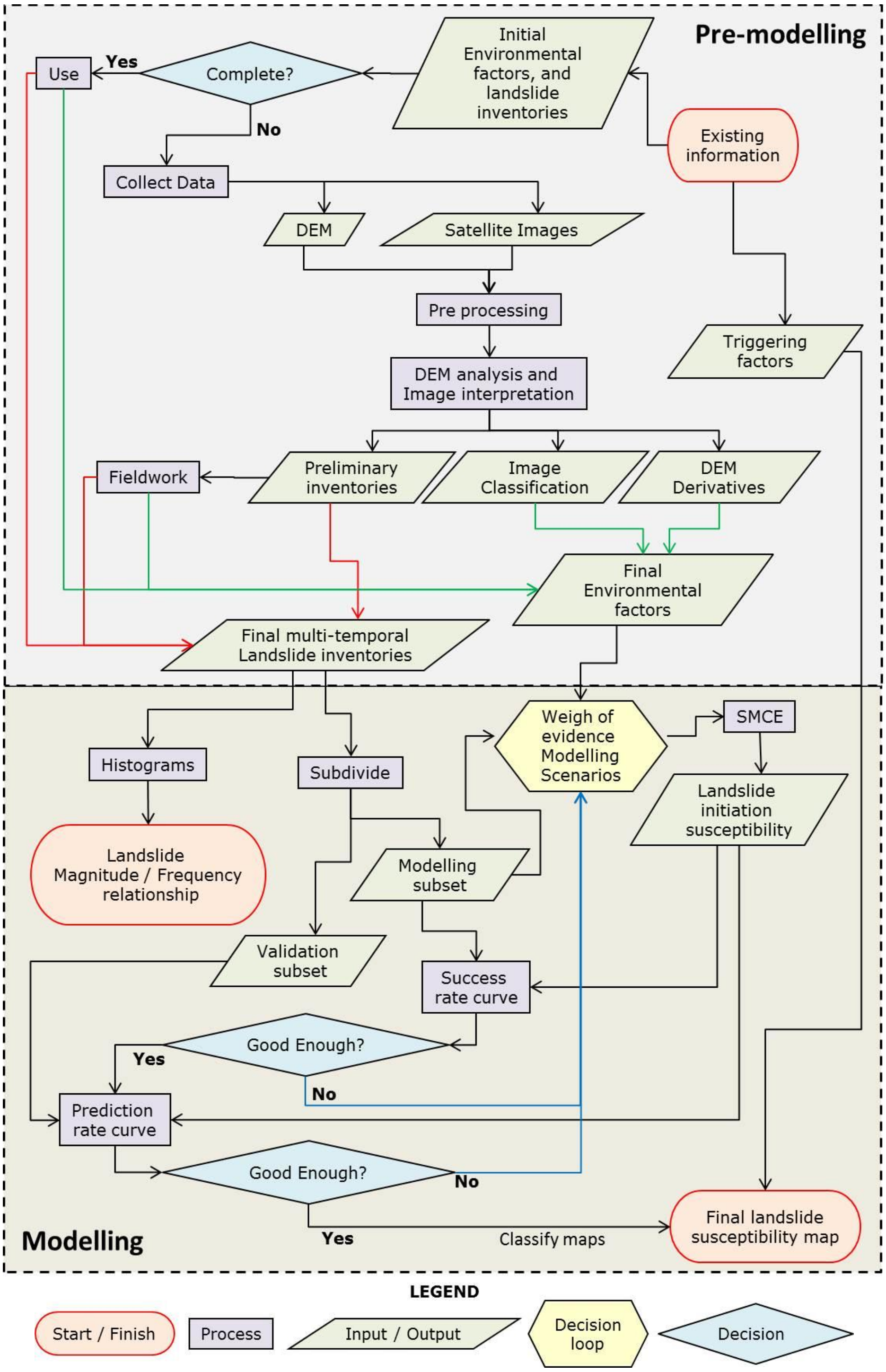


Figure 7. *Flowchart of the methodology followed.*

In the Modelling part is included the analysis of the different landslide inventories, factor maps and the construction of several scenarios in order to obtain a final landslide susceptibility map.

3.1. Review of existing information:

Availability of information (***Table 4***) regarding topography, environmental factors, satellite images and landslides inventories was assessed in order to find out what information is missing, and so, plan how to obtain it or what to do without it. The data quality of this data layers will be discussed on the chapter 5.

Table 4. *Available data before fieldwork.*

INFORMATION	DOMINICA	SAINT VINCENT
DEM	Made from contour lines every 10m	Lidar 5m pixel size with whole in the middle filled with SRTM 90m pixel size.
Hydrology	Shapefile (lines) with rivers and streams, cover the whole island	Shapefile (lines) with rivers and streams, cover the whole island
Road network	Shapefile (lines), cover the whole island	Shapefile (lines), cover the whole island
Land-use map	Shapefile (polygons). With 10 classes. Cover the whole island. 2013.	Shapefile (polygons). With 11 classes. Has a whole in the middle
Geology map	Shapefile (polygons) with 10 units. No structural information (faults, folds, etc.). Cover the whole island. Pdf, with all the information.	Pdf with 10 units corresponding to deposits. No rock units or structural information (faults, folds, etc.)
Soil map	soil types and other characteristics of the soil	Is not available
Geomorphology map	Is not available	Is not available
Landslide inventory	Made in 1987 and 1990. Pdf and Shapefile (Polygons and points), types (debris flow, rock-fall) class (scarp, deposit), status (definite). Some attribute codes are not defined	Made in 1988. pdf without attributes
Satellite images - Pleiades. 2014	Panchromatic (50cm pixel size) and multispectral (2m pixel size). February.	Panchromatic (50cm pixel size) and multispectral (2m pixel size), cloud cover in the middle. March.

3.2. Satellite Images and DEM analysis

The analysis of Digital Elevation Model and satellite images had two main objectives:

- To plan the fieldwork, it was necessary to do a preliminary analysis, in order to prioritize the places to visit (confirm the interpretation, or assess the characteristics of unusual landslides), and so save time.
- As a crucial part of the whole project, the analysis of the DEM and satellite images was used to generate several landslide inventories needed for the landslide susceptibility analysis.

For both islands it was used the Pleiades images as a basis for the image interpretation to generate the landslide inventory of all landslides caused by the so called Christmas-eve event occurred in December 2013, when several of the islands were hit by a high intensity rainfall event.

Table 5. *Available satellite images.*

Country	Satellite	Date	Type	Columns, Rows
Dominica	Downloaded from google Earth	Various covering the island, but all with very high resolution	Colour image	35120, 63354
	Digital Globe	13 FEB 2014	Cloud cover 3.6 % pixel size 2 meters	6983, 30999
	Pleiades	2014 03 08	0.5 meter panchromatic 2 meter multispectral. Covers North west part of the island	43814, 80743
	Pleiades	2014 01 17	0.5 meter panchromatic 2 meter multispectral. Covers middle part of the island	7009, 18049
	Pleiades	2014 03 08	0.5 meter panchromatic 2 meter multispectral. Covers Northwest part of the island	10921, 20183
	Pleiades	2014 01 17	0.5 meter panchromatic 2 meter multispectral. Covers east part of the island	47246, 101040
Saint Vincent	Pleiades	2014 02 23	0.5 meter panchromatic 2 meter multispectral. Covers whole island	12507, 16250

Image pre-processing consisted on the geometric correction that was done by the University of the West Indies as part of the CHARIM project. For the landslide image interpretation the procedure followed consisted of mapping the landsides as points located on their scarps. The landslide inventories generated included an attribute table that comprised the type of landslide, the certainty, and the state of activity.

The analysis of Digital Elevation Model (DEM) was done through the extraction of terrain derivatives (e.g. slope angle, slope aspect, curvature, and roughness), and through visual analysis of the hillshading image for Saint Vincent in 3D, obtaining a geomorphological (DEM based) landslide inventory for Saint Vincent.

Through the combination of the satellite images (2m pixel size) and the DEM (5m pixel size), a stereo-image was produced, which allowed to have 3D-views of the terrain that were visually interpreted to obtain a point based landslide inventory for 2014 (Pleiades based) for Saint Vincent, and a polygon based landslide inventory for both islands.

3.3. Fieldwork

The fieldwork had duration of 4 weeks from September to October 2014, 2 weeks per island. It had as objective to gather information in order to check and complement information about the landslide inventory. It consisted on:

a. On each island it was spent one week on going to several government offices, in order to compile digital and hardcopy including geospatial data, reports and all kind of background information relevant for the analysis, such as occurrence dates of rainfall events, as well as landslides.
In Saint Vincent the government offices visited were: department of forestry (of the Ministry of Agriculture, Industry, Forestry, Fisheries and rural transformation), department of Physical planning and department of Lands and surveys (of the Ministry of Housing, Informal Human Settlements, Lands and Surveys and Physical Planning), and Ministry of Transport and works.

In Dominica the Government offices visited were: physical planning division (of the Ministry of environment, Natural resources, physical planning and fisheries), Ministry of public works, Energy and Ports, and Dominica Meteorological service.

b. On each island it was spent one week on the field, During this week, it was made a the validation of the image interpretation, by going to the landslides previously identified. This stage also included going in the countries together with the road engineers in order to know the locations where landslides have occurred in the past.

3.4. Data-base peparation

All the information collected, was checked, selected, and modified in order to have it the most complete possible, in the same GIS format, and in the same coordinate system. This process included digitizing DeGraff landslide inventories, modifying the existing maps (land-cover, geology, soils) in order to improve them, and generation of new maps that could be useful on the analysis as flow accumulation, slope angle, slope aspect, elevation, stream network, stream network distance, road network distance, etc.

Finally, all DEM derivative maps as well as distance maps, had to be classified before using them in the model, to accomplish this, for each island, using the point based landslide inventories, it was analyzed how many landslides were per value of each factor map through the use of histograms.

3.5. Modelling - Landslide susceptibility assessment

In order to obtain the landslide susceptibility, it is necessary to identify the source areas or landslide initiation susceptibility and the deposit areas or landslide run-nout susceptibility.

As it was mentioned before, there are many different methods for landslide susceptibility assessment ((Fell et al., (2008); Corominas et al., (2013)). In order to select the method it is important to have in mind the size of the study area (342.7Km ^{2} for Saint Vincent and 754 Km ^{2} for Dominica), the amount of available data, the scale of analysis (input data ranging in scale between 1:25,000 and 1:50.000, and raster maps with a pixel size of 5 meters) and the experience of the susceptibility analysts.

Because of this, the use of physically-based modelling is not possible, due to the huge extension of the study area, and to the absence of parameters such as soil thickness distribution or the geotechnical and hydrological parameters required to carry out physically-based modelling. Besides for a statistical approach we require a sufficiently large landslide datasets related to different triggering events. The current landslides inventories cover a large number of years, during which the causal factors might have changed (e.g. land use/land cover).

Finally, the method selected and used consisted on generate a landslide initiation assessment. This process was done through a combination of statistical method (Weights of Evidence – WOE) and expert-based methods (Spatial multi-criteria Evaluation - SMCE). This analysis was done per type of landslide, and per landslide inventory.

3.5.1. Landslide initiation susceptibility assessment using statistical analysis – Weights of evidence (WOE)

As a first step to find out the landslide initiation susceptibility, it is necessary to understand the role of the different contributing factors or combination of them in the study area. To do so, the bi-variate statistical method Weights of evidence – WOE, (***Figure 8***) was used, on this method, each factor map as well as each landslide inventory was rasterized, and overlayed, finding the density of landslides within the area occupied by the factor and comparing it with the landslide density in the entire study area, from those comparisons, positive and negative weights ($W+i$ and $W-i$) are assigned to each of the different classes into which each factor map is classified (e.g. each geological unit within a geologic map) using the contrast factor.

$$W_i^+ = \log_e \frac{P\{B_i|S\}}{P\{B_i|\overline{S}\}}$$

and

$$W_i^- = \log_e \frac{P\{\overline{B_i}|S\}}{P\{\overline{B_i}|\overline{S}\}}$$

Contrast factor $C_w = W^+ - W^-$

Figure 8. *Weights of evidence method – WOE. Where, Bi = presence of a potential landslide conditioning factor, Bi = absence of a potential landslide conditioning factor, S = presence of a landslide, and Si = absence of a landslide.*

The general analysis was done in two steps:

1. As an exploratory tool to determine the final input data: Using all the point based landslide inventories, this procedure was done for each factor map, evaluating how important was each factor map and each landslide inventory, identifying how consistent was a landslide inventory respect to the others, what landslide inventories should not be used, or should be integrated in one (because their behavior was similar), as well as the need to combine factor maps in a new one (e.g. Geology combined with slope).
2. Then the WOE was done again using the final landslide inventories and final factor maps.

Finally the values obtained on the WOE procedure were then used as an indication of the weight that should be used on the Spatial Multi-Criteria evaluation (SMCE) for the landslide initiation susceptibility.

3.5.2. Landslide inventory subsets:

In order to assess the quality of the model, the point based landslide inventories were used to model, and the polygon based landslide inventory were used to validate the model.

3.5.3. Landslide initiation susceptibility assessment using SMCE

For implementing the analysis, the SMCE module of ILWIS was used. In this method, the expert judgment plays an important role, from the problem definition, till the weighting of the factors within a group and among groups. 5 general steps were followed:

a. **Definition of the problem**. This step consists on organizing the problem into a criteria tree, with several branches or groups, and a number of factors and/or constraints.
b. **Weighting and Standardization of the factors**. For the weights of the classes of each factor map it was used the results from the WOE analysis. All factors may be in different format (nominal, ordinal, interval etc.) and should be normalized to a range of 0-1.
c. **Weighting of the groups and the factors within each group**. To assign the weight to each factor and group of factors, the results from the WOE were used (as indication of the relative importance of each factor), together with the expert judgment, on which different criteria as quality of the maps was taken into consideration. To carry on this process, the method selected was Rank Ordering.
d. **Analysis of the resulting map.** This analysis was a cyclic procedure till the result was satisfactory. It included:
    - Analyzing where the resulting susceptibility map shows anomalies, and which contributing factors might be responsible for that.
    - Comparing the results with the existing landslide pattern.
    - Generation of some success rate curves.
    - Adjusting either the number of contributing factors, or combine some of the factors to make them more focused, or adjust the weighting of the contributing factors.
    - Generating a new version of the susceptibility map, and repeating the analysis

e. **Success rate and prediction rate:** This process consisted on the elaboration of success rate curve and a prediction rate curve. On the first one, using the same landslide inventory used in the statistical model (WOE), it is determined how well the resulting hazard map has classified the areas and explains the existing landslides. On the second one, using a different landslide inventory than the one used or modelling, it is evaluated how accurate and reliable the model was to predict areas prone to landslides.

   For the elaboration of the success rate curve, the susceptibility map (before classification) was overlaid with the landslide inventory. The percentage of the susceptibility map with values ranging from the highest to the lowest were plotted on the X-Axis, and the percentage of the number of landslides on the Y-axis. The steeper the curve is and the more it deviates from the diagonal, the better the prediction is.

f. **Scenarios:** Before deciding the final maps, several scenarios were tried as a sensitivity analysis to find out the best combination and ordering of the factor maps, and to compare how different methods of standardization can affect the results.
   - Running SMCE with all factor maps standardized as Benefit-Interval. On this standardization all values are scaled from 0 to 1.
   - Using all factor maps without grouping but using rank ordering to give the order of importance of the factor maps and using Benefit-Interval as standardization method.
   - Using only the relevant factor maps and grouping them. Using also Benefit-Interval as standardization method.
   - From the scenarios made before, select the best one and change the standardization method to Benefit-Goal. On this method all negative values will be standardized as 0 and only positive values between 0 and 1.

g. **Classification of the results**. The map obtained is classified into 3 susceptibility classes (high, moderate and low), based on the analysis of the histogram of the resulting susceptibility map.

3.6. Final document and maps.

All the process described before, were done independently for each island. After having all the results, an analysis of the results obtained for both islands will be done in order to assess if the existing differences in the different factor maps play an important role on the model. The final maps are delivered as annexes..

4. LANDSLIDE INVENTORIES

For Saint Vincent with an area of 344,492.1 km^2 it was possible to obtain four point based landslide inventories (DeGraff-1988, Pleiades image interpretation-2014, Fieldwork-2014 and DEM analysis), with a total amount of 5.259 points, having a landslide density of 1.53% (0.0153 landslides/km^2). Instead for Dominica, with an area of 752,115.1 km^2, it was possible to obtain tree point based landslide inventories (DeGraff-1987, DeGraff-1990, and Fieldwork-2014) with a total amount of 1.169 points, having a landslide density of 0.16% (0.0016 landslides/km^2).

After having all the point based landslide inventories, for each island, an integration of the point based landslide inventories were made by Cess Westen, generating a polygon based landslide inventory. On this inventory each polygon represents the whole body of the landslide from its initiation point (scarp or crown), till its deposit or foot.

Even though the landslide inventories were made for different years, (1988, 2014 for Saint Vincent, and 1987, 1990 and 2014 for Dominica), those landslide inventories are multi-temporal, including old landslides and fresh ones in the same landslide inventory, showing the progress or changes of each landslide. Because of this not event based landslide inventory was acquired.

Finally, since most of the landslide inventories had an attribute table classifying the landslides per Type, it was possible to obtain a type based landslide inventory per year.

4.1. Existing Inventories

For both islands the already existing inventories came from the work carried out by J. DeGraff from the US Forest Survey for the OAS in the late 1980's. He did detailed image interpretation of landslides using the available black and white aerial photographs. He did a differentiation among landslide types. It is important to mention that the mapping by DeGraff was not related to a specific triggering event.

For both islands, DeGraff landslide inventories were obtained as shapefiles of points and pdf. When analyzing the shapefile and comparing it with the pdf, it was noticed that some points were missing and that the points were located on the middle of each landslide. So in order to use these inventories on the landslide initiation susceptibility it had to be complemented and modified placing each point on the scarp area of the landslides.

For Dominica, the inventory of 1987 have a total of 900 landslides were interpreted by DeGraff on black and white aerial photographs from 1984 on scale 1:25.000, classified as Debris Flow (541), Debris Slide (338) and Rockfall or rockslide (20). The landslide inventory made in 1990 comprises 186 landslides unclassified (***Figure 9***).

For Saint Vincent, after digitizing DeGraff landslide inventories, based on aerial photographs from 1981 on scale 1:25000 (DeGraff, 1988), it was obtained that for Saint Vincent, there was a total of 576 landslides classified as Debris Flow (405), Debris Slide (85), Rockfall or rockslide (22), Deep-seated rockslide (64).(***Figure 9***).

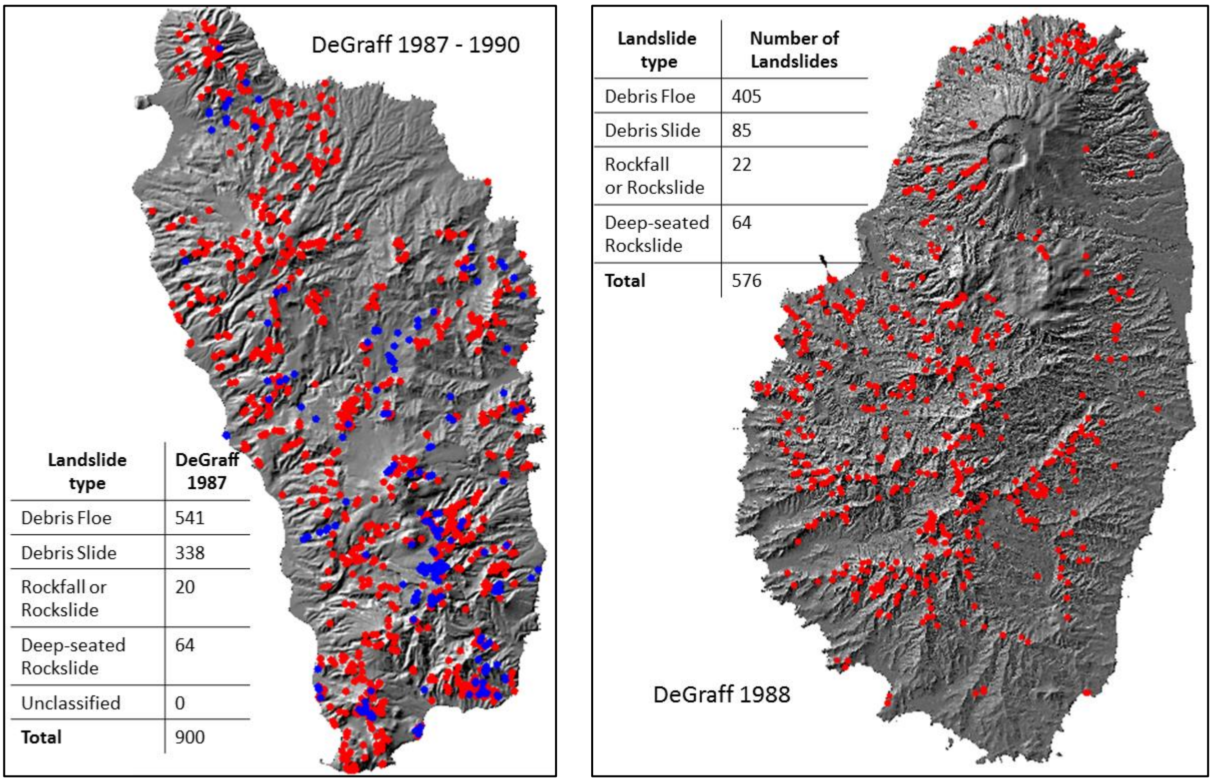


Figure 9. *DeGraff landslide inventories for both islands. For Dominica the blue points represent 1990 Landslide Inventory.*

4.2. Image interpretation landslide inventories

For both Islands, a preliminary landslide inventory based on image interpretation of very high resolution Pleiades images from 2014 was done, resulting in the creation of a shape-file of points that included an attribute table with information regarding type (Complex, Debris Flow, Earth Flow, Rockfall, Rotational Landslide, Shallow_translational_landslide, and Translational Landslide), activity (Relict, Dormant, and Active) and certainty (Low, Medium or High).

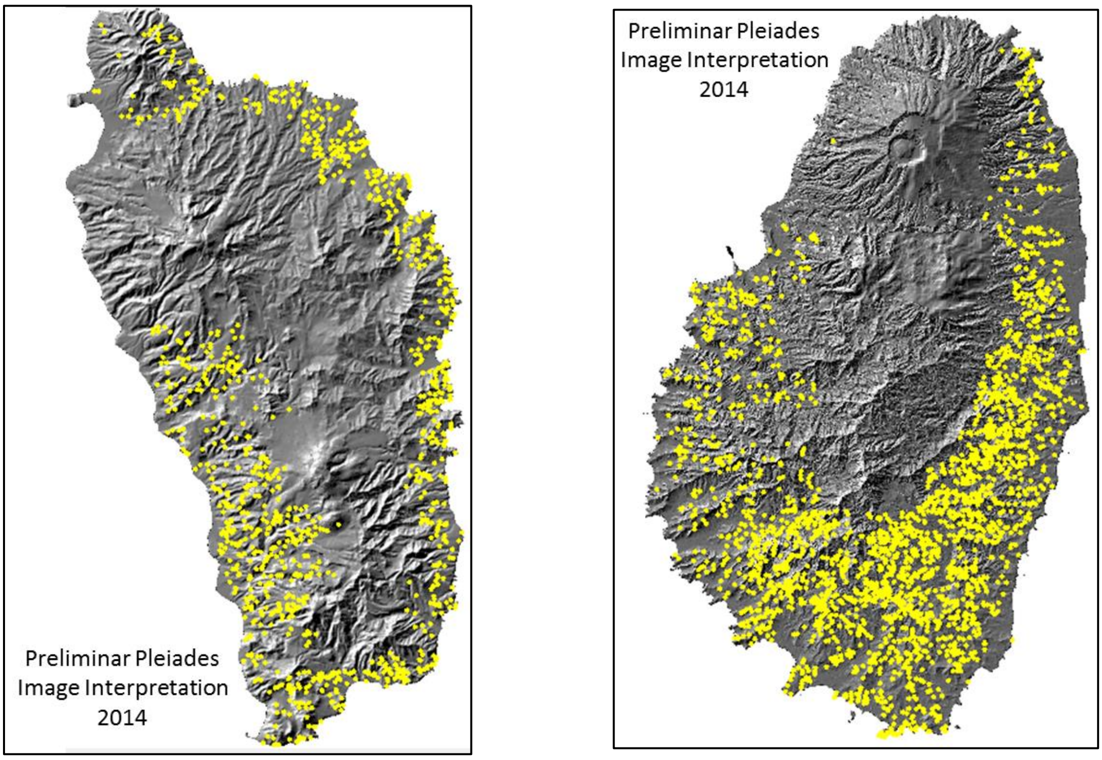


Figure 10. *Prelimiar landslide inventories based on image interpretation of very high resolution Pleiades images from 2014*

For Saint Vincent and Dominica, a total of 2,463 points and 1,088 points were found as indicators of possible landslides for each island respectively. This image interpretation was made having in mind to map only fresh landslides, based on this the main criteria to identify a possible landslide was the presence of denuded areas showing light tones, with elongated morphology in direction of the movement.

During fieldwork, it was possible to assess that most of those points, were actually land being prepared for a new crop season, as mentioned before.

Because of this, after fieldwork, a reinterpretation of the images was done, using not only vegetation criteria, but also morphology and drainage features; which combines changes in geometry, texture and color, to indicate the presence of a terrain feature typical of a landslide.

Table 6. *Main photographic characteristics used to identify landslides on the image interpretation. Modified from* (Soeters & Westen, 1996).

Terrain Features		**Relation to slope Instability**	**Photographic Characteristics**
Morphology	Concave/convex slope features	Landslide niche and associated deposit.	Concave/Convex anomalies in stereo model.
	Semicircular backscarp	Head part of slide with outcrop of failure plane.	Light-toned scarp, associated with small, slightly curved lineaments.
Vegetation	Vegetation clearances on steep scarps	Absence of vegetation on headscarp.	Light-toned elongated areas at crown of mass movement or on body.
	Irregular linear clearances along slope	Slip surface of translational slides and track of flows and avalanches.	Denuded areas showing light tones, often with linear pattern in direction of movement.
Drainage	Anomalous drainage pattern	Streams curving around frontal lobe or streams on both sides of the body.	Curved drainage pattern upstream with sedimentation or meandering in (asymmetric) valley.

For the new landslide inventory, the landslides were classified according to their Type (as it was classified by DeGraff, including shallow landslides as a new class), State of activity, and certainty. McCalpin, (1984) presents a summary of several methodologies used to classify state of activity fro landslides. From this it was selected and used the following: **Active**: those landslide seen on the image, usually fresh, where the soil moved can be recognized easily. **Recent**: those landslides recognized on the DEM, and located on the head of the catchments, where a lot of erosion is happening. **Old**: for those landslides which can be recognized from DEM but are currently totally covered by vegetation.

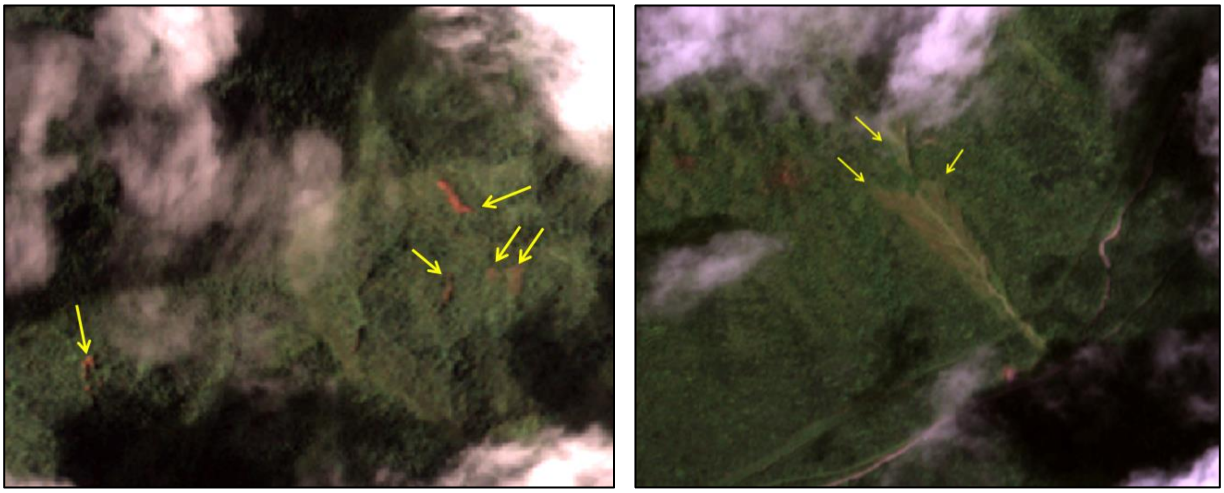


Figure 11. *Examples of Landslide image interpretation. A. Active debris flows in Saint Vincent (left) and B. Recent one in Dominica (Right) near Fresh Lake.*

The easiest landslides to identify were the most recent ones which appeared as a brown to reddish-brown against the background of the vegetation (especially within forested vegetation). Less obvious, but identifiable, landslides can be found where pioneer vegetation species are covering the landslide scar and deposit. The new vegetation typically appears a brighter (lighter) green compared to surrounding vegetation.

Figure 12*. Examples of Landslide image interpretation in Dominica. A. The yellow arrows indicate Debris Slides (Left) and B. Rockslides (Right). The red arrows show areas of Rockfall.*

Debris Flows (***Figure 11***) usually start with the arcuate scar (indicated by the yellow arrows) where movement was initiated extending downslope to the natural channel. Sometimes it is possible to observe faint lines showing fluvial erosion (***Figure 12***) of the bare soil exposed by the debris flows passage.

Occasionally there may be a small amount of deposit at the very bottom next to the channel, but it is very often transported downstream. Debris slides are usually shallow, elongated and narrow, and lack of resistant escarpments (***Figure 12***). Rockslides have a square or circle geometry and the presence of a resistant escarpment (***Figure 12*****)**.

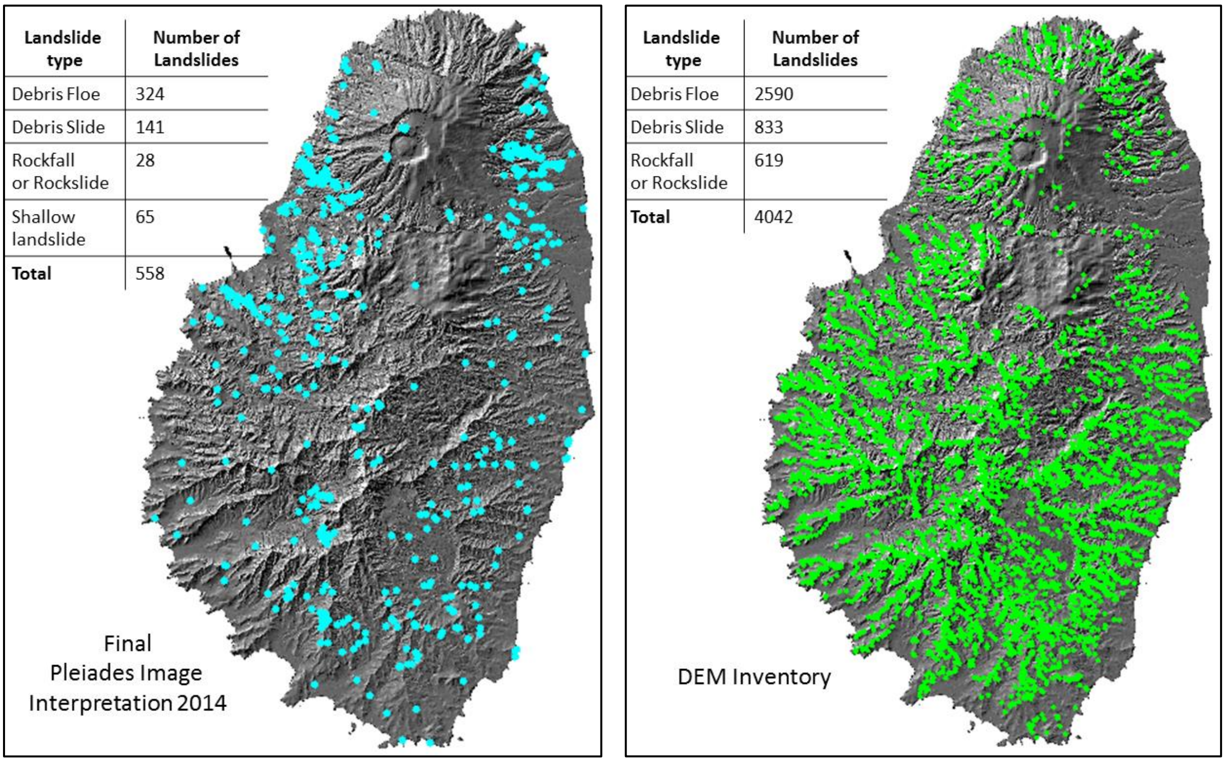


Figure 13. *Final landslide inventories based on image interpretation of very high resolution Pleiades images from 2014 and Dem based landslide inventory for Saint Vincent.*

According to Cruden & Varnes, (1996), Debris flows commonly follow pre-existing drainage ways, affecting the soils and they exist where a significant thickness of weathered soil overlies the bedrock. Debris slides affects also the soil, and sometimes the upper layer of rock, however they exist only where a thin layer of soil overlays the rock. Rosckslides are usually deep, moving a huge volume of material (rock).

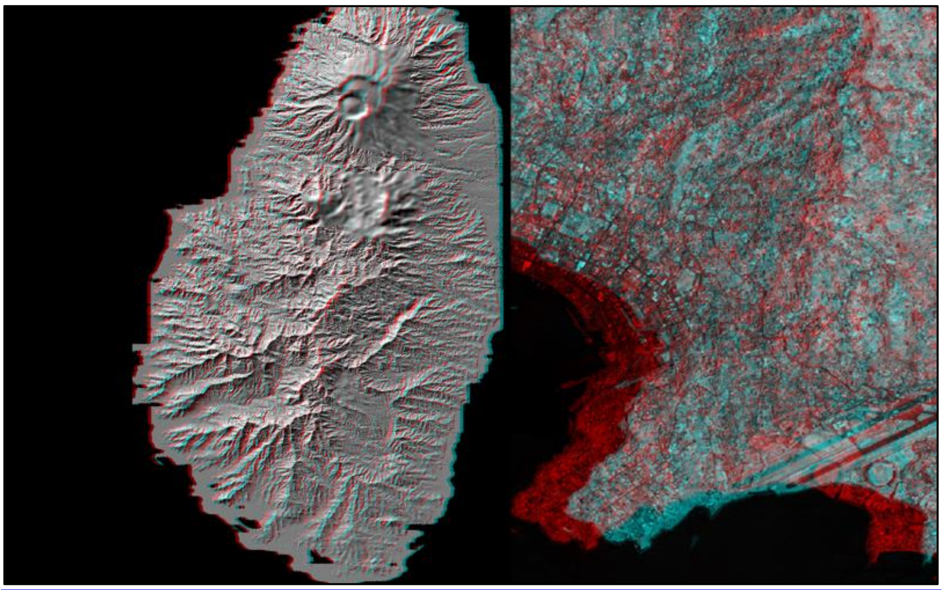


Figure 14. *Example of a stereo image for Saint Vincent, displayed as anaglyph image. Use red-green glasses for stereo viewing.*

The point based landslide inventory made for Saint Vincent resulted in a total of 558 landslides classified by Type as Debris Flow (324), Debris Slide (141), Rockslide (28) and Shallow landslide (65).

Despite the high resolution of the Pleiades mages, due to the fact that there has not been a recent major landslide triggering event in the past years, it was difficult to map out recent landslides; however, the final point based landslide inventory could be representative of the landslides caused by the 2013 Christmas Eve trough.

Due to the quality of the DEM of Saint Vincent (made from Lidar points), a geomorphological landslide inventory was made in order to get the best information for the landslide susceptibility (***Figure 13***, ***Figure 14*** and ***Figure 15***).

A total of 4042 landslides were identified, classified as Debris Flow (2590), Debris Slide (833) and Rockslide (619) (***Figure 13***).

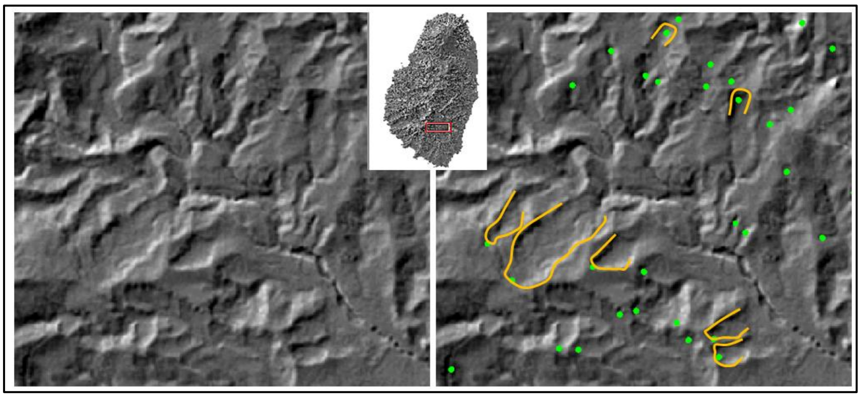


Figure 15. *Example of Landslide interpretation on the DEM Left raw image, on the right it is indicated some of the landslide points in green with some of the crowns in orange.*

4.3. Landslide mapping in the field

During fieldwork, the main method consisted in going to viewpoints, in order to have a wide range of observations of the landscape and to check the landslides mapped by DeGraff and the ones found on the image interpretation. This was combined with occasional guidance from Government officers who indicated the location and date of occurrence of some landslides.

Landslides were identified where there was a presence of hummocky and irregular slope morphology, or a change on the morphology, vegetation or drainage of a slope (***Figure 16***). We identified the basic landslides features: crown or scarp, body and deposit. Most of the landslides identified were shallow landslides affecting the top layer of soil (usually 1m thick) on steep slopes (around 60 to 80 degrees) leaving an area without vegetation corresponding to the crown of the landslide; in some places, this shallow landslides could be debris-flow or debris-slides.

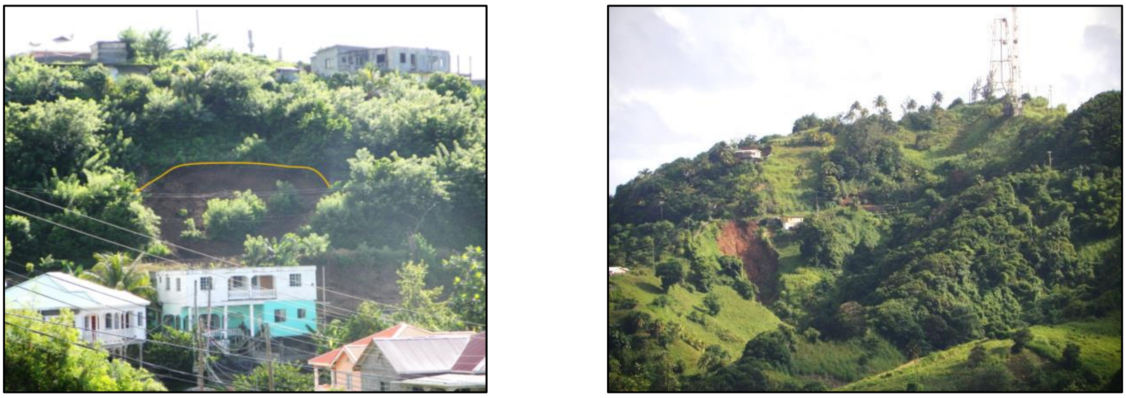


Figure 16. *Landslides in Saint Vincent. Belmont Landslide (right). It is possible to identify the changes in morphology and vegetation on the slopes.*

There were also some rare deepseated landslides, which affected the roads through displacements and subsidence, which was in the most extreme case up to 2 meters (Deux Branch area), the biggest one is located in Dominica on the Layou River (***Figure 17***.).

Figure 17. *Landslides identified on fieldwork in Dominica. Deux Branch Area (Left), and Belle Wet Area Junction (Right).*

From the observations made, landslides don't seem to be related to a specific landcover or soil type, instead, they seem to be related to the slope angle, presenting most of the landslides in the steepest slopes in the middle of the islands, besides most of the shallow landslides seem to be first time failure.

Along the road network, landslides are common (***Figure 18***), in most of the cases they were related to cutslope failures (e.g. Rockfall in Stowe area in Dominica) or embankment failures. (eg Champagne beach area in Dominica, or Belmont Landslide in Saint Vincent).

Figure 18. *Rockfall and embankment failure in Dominica - Champagne beach area (Left), and Embankment failure in Saint Vincent – Belmont Landslide (Right).*

Being in the field it became obvious that many of the points identified as landslides on the previous image interpretation, were not landslides but cropland. It is possible that the date of the satellite images matches to the time when the farmers are preparing the land to plant the seeds of the new crops, which makes easy to confuse bare soil (with elongated shapes parallel to the length of the slope) with fresh landslides, this is the case of the Arrowroot plant, which harvesting time is from October to May, and as the satellite images are from February, then most of the fields where arrowroot is cultivated will look like bare soil or fresh landslides.

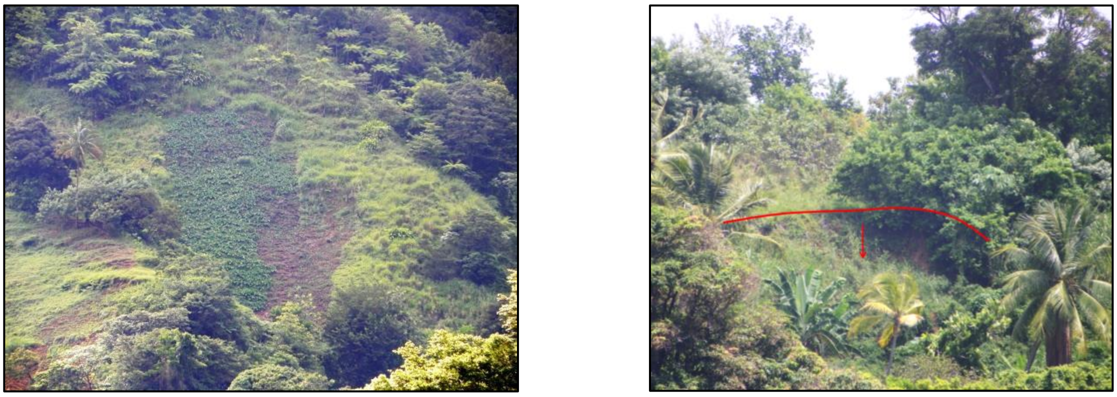


Figure 19. *On the left: Arrowroot crops on top of a possible old landslide. On the right it is possible to observe a sugar Cane crop on top of a landslide deposit.*

In other situations, there were crops on the deposit of old landslides, however the crown was identifiable on the field (***Figure 19***).

After digitizing all stations and landslides found on the field, it was possible to observe that most of the landslides are related to natural terrain, however very few of them are recognizable on satellite images or match with DeGraff landslides.

The landslides found on the field were classified as related to natural terrain (usually of big magnitude in area, or depth affecting the roads, bending them or displacing them) or to cut-slopes (this category comprises slope failures due to road-cut, house cuts, or embankment failure). In some places there were no evidence of any landslide; however there were retaining walls or gabions, those points were recorded as unstable.

From the analysis of the fieldwork inventory it is possible to observe that less than half of the landslides identified on the field were mapped by DeGraff, and were recognizable on the satellite images. Besides, from the 576 landslides mapped by DeGraff for Saint Vincent, only 9 were identified in the field and from the 900 landslides mapped by DeGraff for Dominica only 15 were identified on the field.

This has several reasons, the first one is that the fieldwork were made along the roads, and most of DeGraff inventory comprises landslides occurred in the middle of the island. Another reason is that due to the tropical weather, the vegetation grows really fast, covering completely any evidence of landslides (ie in Saint Vincent, Manning village landslide occurred in December 2013, was already completely vegetated by September 2014), actually the location of most of the DeGraff landslides identified on the field, were indicated by the government officers (ie Bagatelle or Belle-vue Landslide in Dominica). This is one of the major obstacles in the landslide inventory mapping from images. Unless the images are taken within a few months after the triggering event, it becomes very difficult to recognize them as such (***Figure 20***).

Figure 20. *Manning Village landslide (left) and Belle-vue Landslide (Right)*

In addition it is important to have in mind that most of the landslides identified on the field were too small (9m^2) to be identified on the satellite images (5m pixel size) or too shallow to be identified on the DEM.

Finally a couple of tables (***Table 7*** and ***Table 8***) with the occurrence date of some known landslides found in the field. From which is possible to observe that in Dominica there are more records of huge landslides triggered by different rainfall events, while in Saint Vincent most of the events are superficial and triggered by the Christmas Eve event.

Table 7*. Occurrence dates for some landslides found in the fieldwork in Dominica.*

Station	Type	Location	Date of occurrence
3	Landslide	Bellevue landslide	25 years ago
4	Landslide		10 years old
8	Landslide	Begatelle	40 years old, 21/09/1977, monument on the road.
12	Gully	red gully area	Terraces. previous to 2011 used to be an area prone to landslide
18	Landslide	good hope	20 years old - Shortly after 3:00 AM on November 12, 1986
22	Landslide	Salibia school	5 years ago the school was abandoned
25	Landslide	Deux branch area	road was reconstructed and is being monitored
77	Landslide	Cochrane	On road from Cochrane to main road, September 28, 2011. Hurricane Ophelia.
78	Landslide	Layou river	Huge landslide that generated the dam in Layou river and the debris flow. November 18, 1997
11a	Landslide	on the road	Deep and slow movement. Rotational. No younger than 5 years
20a	Landslide	Saint souviere	June 2010
79b	Landslide	Campbell	It was generated under hurricane Dave in 2007.

Table 8*. Occurrence dates for some landslides found in the fieldwork in Saint Vincent.*

Station	Type	Location	Date of occurrence
4	Landslide	Troumaka	December 24, 2013
5	Landslide	Belmont	2-Sep-13
64	Landslide		December 24, 2013
65	Landslide		December 24, 2013
69	Landslide		December 24, 2013

4.4. Polygon Landslide inventory

Finally, analysing the multitemporal polygon based landslide inventory made by Cees Westen, .it is important to mark that on this inventory there were included not only landslides but also flooded areas due to Debris Flow and areas that could be prone to landslides as Quarries, Cutslopes and cliffs.

For this inventory it was carried out an extensive interpretation of landslides using different sets of satellite images, and also using historical imagery from Google Earth Pro. It includes a large number of landslides that were not on the previous landslide inventories. It was also incorporated the landslides from the previous inventories and made a complete classification for all landslides. Also the mapping of coastal landslides was carried out.

For Dominica it was obtained a total of 2167 polygons, that included Debris Flow, Debris Slide, Deep-seated Rockslide, Rockslide, Rockfall-Rockslide, Debris avalanche, Earth Flow, Coastal cliff, Quarries, Roadcut with slide potential, and flooded areas due to debris flow. From those a total of 1089 landslides were identified only in 2014, and 182 only in 1990, meaning that 182 landslides occurred between 1987 and 1990, and 1,089 landslides occurred between 1990 and 2014.

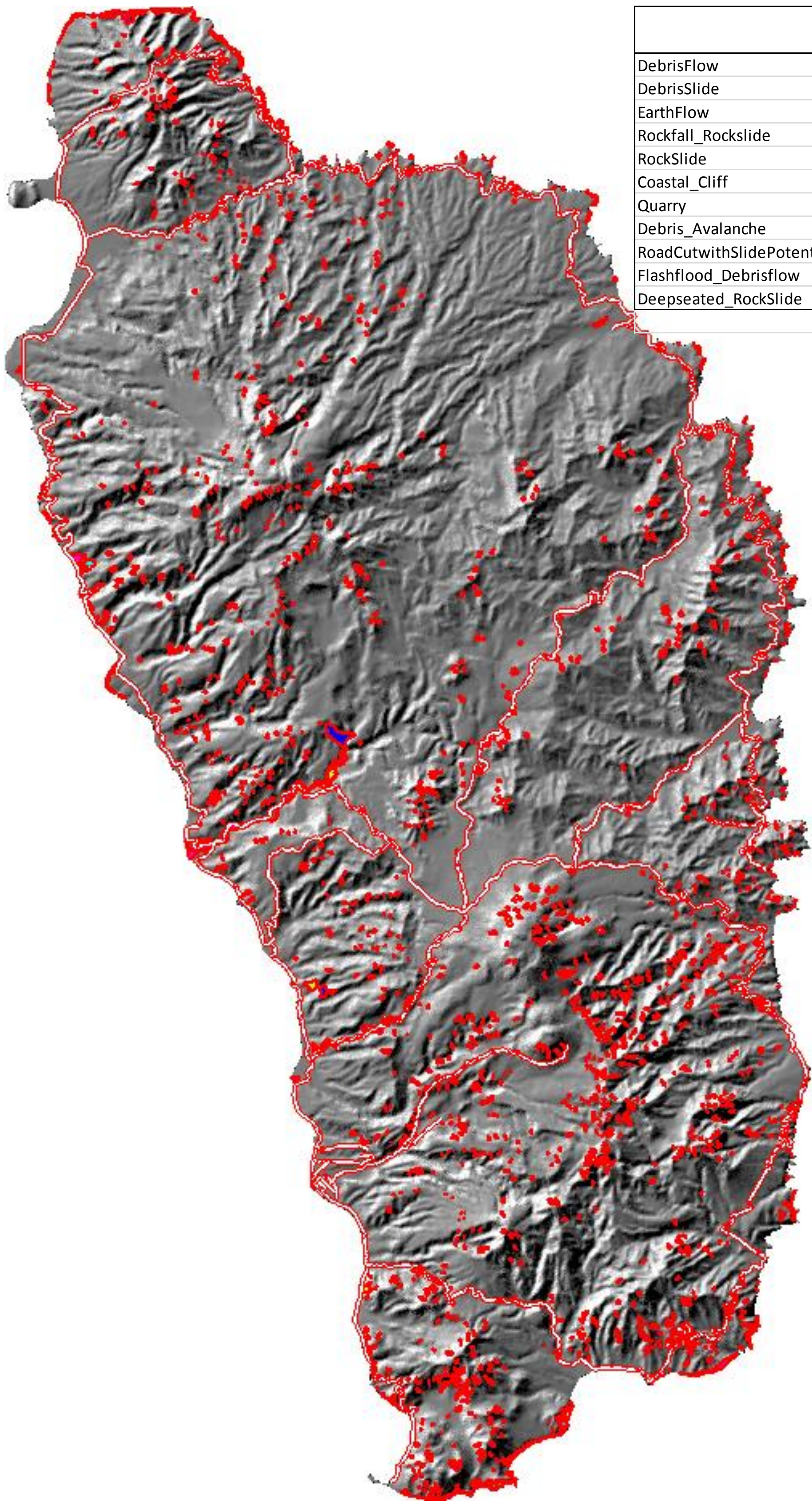
Table 9. *Polygon based landslide inventory for Dominica, showing number and area of landslides for 2014, and how many of those were present in DeGraff inventories.*

Landslide Type	Area_2014	Number_2014	Area_1987	Number_1987	Area_1990	Number_1990
Absent	0	0	7,072,319	1,274	6,235,641	1,092
Coastal_Cliff	1,047,557	48	0	0	0	0
Debris_Avalanche	386,544	76	0	0	0	0
DebrisFlow	4,127,725	663	3,264,114	483	3,232,852	489
DebrisSlide	4,147,106	1,103	1,966,817	317	1,939,669	314
Deepseated_RockSlide	533,927	7	0	0	0	0
EarthFlow	17,566	1	17,566	1	17,566	1
Flashflood_Debrisflow	477,391	1	0	0	0	0
Quarry	811,318	35	0	0	0	0
RoadCutwithSlidePotential	89,984	3	0	0	0	0
Rockfall_Rockslide	632,160	89	47,351	8	47,351	8
RockSlide	600,933	118	0	0	6,283	1
Unknown	26,769	23	545,490	87	1,434,295	265
Total	12,898,980	2,167	12,913,657	2,170	12,913,657	2,170

For Saint Vincent it was obtained a total of 1,647 polygons, including Debris Flow, Debris Slide, Deep seated rockslide, rockslide, Shallow landslide, and flooded areas due to Debris Flow. From those, a total of 1,097 were identified only in 2014 (including 17 flooded areas due to debris flow) having in mind that the 2014 landslide inventory includes the DeGraff landslide inventory, this means that at least 1,080 landslides were triggered by some event occurred between 1988 and 2014.

Table 10.*Polygon based landslide inventory for Saint Vincent, showing number and area of landslides for 2014, and how many of those were present in DeGraff inventories.*

Landslide type	Number_1988	Area_1988	Number_2014	Area_2014
Absent	1,097	5,557,070	0	0
Debris_Flow	390	822,661	1,011	2,183,004
Debris_Slide	75	155,972	383	1,173,790
Deep_seated_Rockslide	59	132,625	60	138,139
Rockslide	26	95,921	100	424,619
Shallow_landslide	0	0	61	129,904
Stream_Flood_DebrisFlow	0	0	17	2,626,295
Unknown	0	0	15	88,498
Total	550	6,764,249	1,647	6,764,249



	Area (hectares)	Number of landslides
DebrisFlow	413	663
DebrisSlide	415	1103
EarthFlow	2	1
Rockfall_Rockslide	63	89
RockSlide	60	118
Coastal_Cliff	105	48
Quarry	81	35
Debris_Avalanche	39	76
RoadCutwithSlidePotential	9	3
Flashflood_Debrisflow	48	1
Deepseated_RockSlide	53	7
	1288	2144

Figure 21. *Final Polygon based landslide inventory for Dominica.*

	Area (hectares)	Number of landslides
Debris_Flow	218	1011
Debris_Slide	117	383
Deep_seated_Rockslide	14	60
Rockslide	42	100
Shallow_landslide	13	61
Stream_Flood_DebrisFlow	263	17
	667	1632

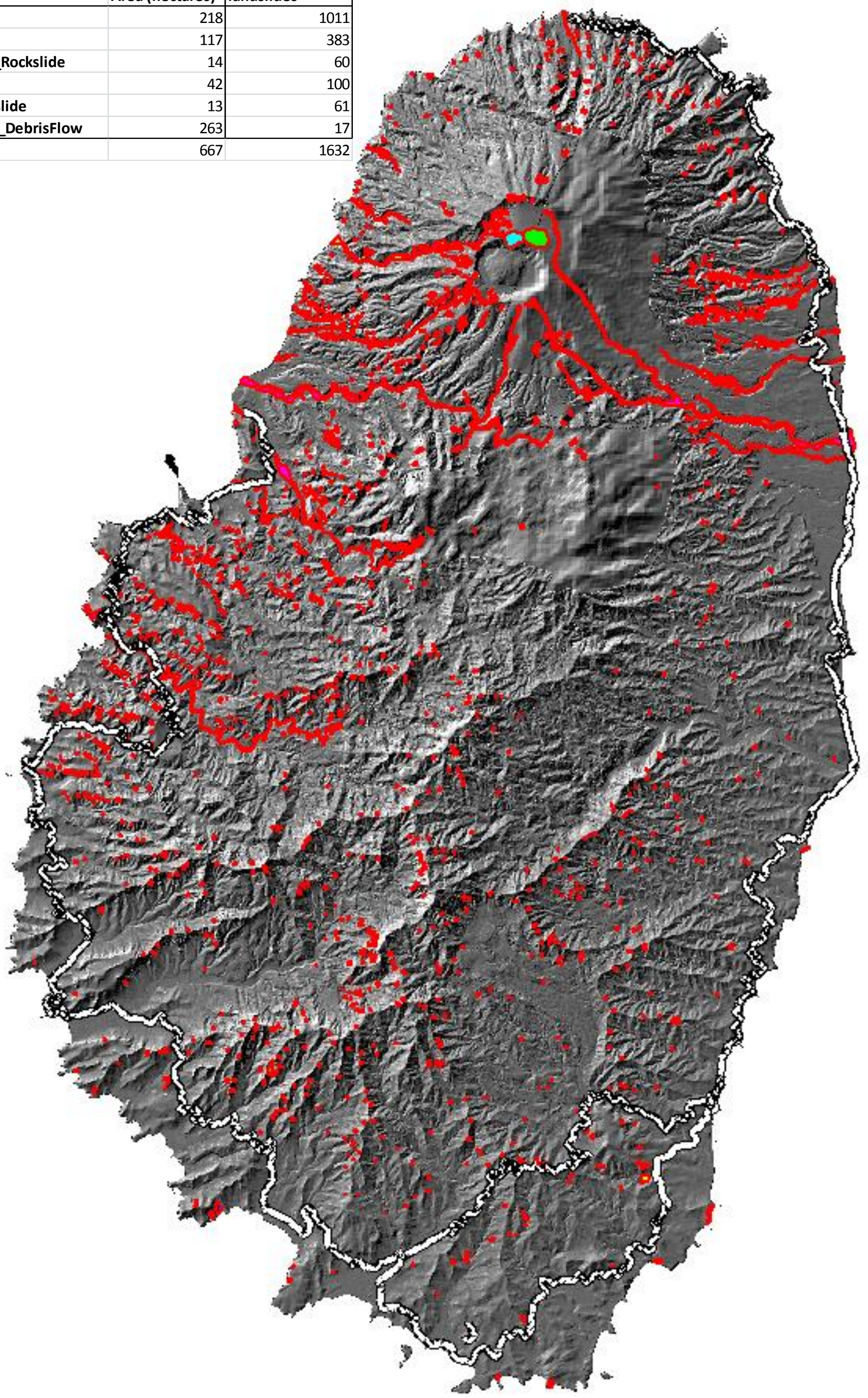


Figure 22. *Final Polygon based landslide inventory for Saint Vincent.*

5. ANALYZING THE IMPORTANCE OF THE FACTORS

In order to analyze the landslide susceptibility, the following factors were used: Dem derivatives: Slope Angle, Slope Aspect, Flow Accumulation, Elevation, Geology, Soil type, Landcover, Distance from rivers, Distance from roads, Distance from ridges and Distance from coast.

Before using all those maps in the modelling, they had to be prepared. First of all it was necessary for all the maps to cover the same area; due to this the DEM was used as a mask to produce the final maps that were going to be used. Then, it was checked the quality of them in terms of topological consistencies, and amount on units or classes to be used per factor map. All of these maps were used as class maps, for this process they had to be classified as mentioned in the methodology.

For both islands, and all main factor maps (Geology, Soils, Landcover, Elevation, Slope Angle, Slope Aspect, Flow Acumulation, Geomorphology) it was made an analysis on which it was analyzed how the contrast factor varies among landslide inventories and among landslide type. With this result it was decided what landslide inventories to use in the modelling. There was also made a weight of evidence analysis on which it was compared the weights of the factor maps and the combined factor maps with slope. The result of this analysis was used as an indication of the importance of the factor maps.

For the geology it will be explained step by step what was done for each factor map. Even though this methodology was repeated for all factor maps for both islands; in order to not be repetitive, on the description of the other factor maps it will be taken just the relevant charts or graphs to explain the main relationships found.

5.1. Geology

For Saint Vincent this maa came as a shapefile which didn't preset any problems when importing to ilwis. Instead, for Dominica the shapefile had topologic inconsistencies. When imported to Ilwis some polygons were missed. In order to fix this, it was digitized directly in Ilwis.

For Saint Vincent it was analyzed the contrast factor values per landslide type, it was found that there was no consistency among landslide inventories. As can be seen in the tables 11, 12, and 13. Some units have relatively similar values for a landslide type on all landslide inventories while others don't. For example, the unit FLD related to rockslides have a high contrast factor (2.21) on DeGraff landslide inventory, while on Pleiades have a negative value (-5.17) and on Dem inventory is an intermediate value (0.99). On the other hand The unit RSD related to Debris Slide have relatively similar values being negative in all of them; and almost the same on DeGraff and Pleiades inventories, -4.76 and -5.17 respectively.

Table 11. Contrast factor values per landslide type on DeGraff landslide inventory.

Geology	Geology	Total landslides	Debris Flow	Debris Slide	Rockslide	Deep-seated rockslide
ARD	Alluvial and reworked deposits	-2.03	-1.79	-6.93	-5.58	-2.03
ERC	Eruptive center	0.22	0.39	0.40	-4.29	-5.36
LFD	Lava flows, domes, and associated deposits	0.28	-0.30	0.00	2.21	1.40
MSC	Major scarp feature-possible collapse scars	0.46	0.00	1.83	-3.09	-4.16
PPS	Pyroclastic deposits of pre-Soufriere volcanic centers.	0.21	0.26	0.42	-1.07	-0.01
PSV	Pyroclastic deposits of Soufriere volcanic centers	-0.44	-0.32	-0.44	-0.03	-2.67
RSD	Red scoria deposits of spatter cones	-6.68	-6.32	-4.76	-3.41	-4.48
UNK	Uknown	-2.91	-2.56	-1.00	0.36	-0.71
UVL	Undifferentiated volcanoclastics and lavas of Grand Bonhomme V.C.	0.72	0.87	0.23	-0.61	0.59
YTV	Yellow Tephra underlain by volcaniclastics	-0.40	-0.83	-0.15	0.48	0.61

Table 12. Contrast factor values per landslide type on Pleiades landslide inventory.

Geology	Geology	Total landslides	Debris Flow	Debris Slide	Rockslide	Deep-seated rockslide
ARD	Alluvial and reworked deposits	-0.59	-1.06	-0.36	0.32	0.00

ERC	Eruptive center	-0.71	-0.27	-6.15	0.11	-5.38
LFD	Lava flows, domes, and associated deposits	0.23	0.24	0.20	-5.17	0.65
MSC	Major scarp feature-possible collapse scars	-6.32	-5.78	-4.95	-3.33	-4.17
PPS	Pyroclastic deposits of pre-Soufriere volcanic centers.	-0.39	-0.41	-0.76	0.03	0.11
PSV	Pyroclastic deposits of Soufriere volcanic centers	0.74	0.65	1.43	1.18	-2.69
RSD	Red scoria deposits of spatter cones	-0.93	-0.80	-5.27	-3.65	0.13
UNK	Uknown	-2.88	-2.33	-1.50	0.11	-0.73
UVL	Undifferentiated volcanoclastics and lavas of Grand Bonhomme V.C.	-0.16	0.21	-1.43	-1.61	-0.14
YTV	Yellow Tephra underlain by volcaniclastics	0.21	0.08	0.18	-1.32	1.02

Table 13. Contrast factor values per landslide type on DEM landslide inventory.

Geology	Geology	Total landslides	Debris Flow	Debris Slide	Rockslide
ARD	Alluvial and reworked deposits	-0.53	-1.02	0.09	-0.05
ERC	Eruptive center	0.13	0.42	-0.20	-3.02
LFD	Lava flows, domes, and associated deposits	0.42	0.17	0.99	0.40
MSC	Major scarp feature-possible collapse scars	-0.60	-0.68	-0.32	-0.72
PPS	Pyroclastic deposits of pre-Soufriere volcanic centers.	0.38	0.38	0.44	0.30
PSV	Pyroclastic deposits of Soufriere volcanic centers	-0.97	-0.84	-1.72	-0.80
RSD	Red scoria deposits of spatter cones	-0.55	-0.73	-0.82	0.18
UNK	Uknown	-4.86	-4.41	-3.28	-2.98
UVL	Undifferentiated volcanoclastics and lavas of Grand Bonhomme V.C.	0.14	0.34	-0.16	-0.53
YTV	Yellow Tephra underlain by volcaniclastics	0.15	0.09	-0.14	0.67

Then comparing the landslide inventories between each other, it was possible to observe that for Saint Vincent Pleiades inventory and DeGraff had a similar behavior in all units except in MSC and RSD. Reaching values above 0.80 in most of the units except ARD and UNK. For Dominica Both DeGraff inventories have similar behavior except in CRL, PIG, and RGA.

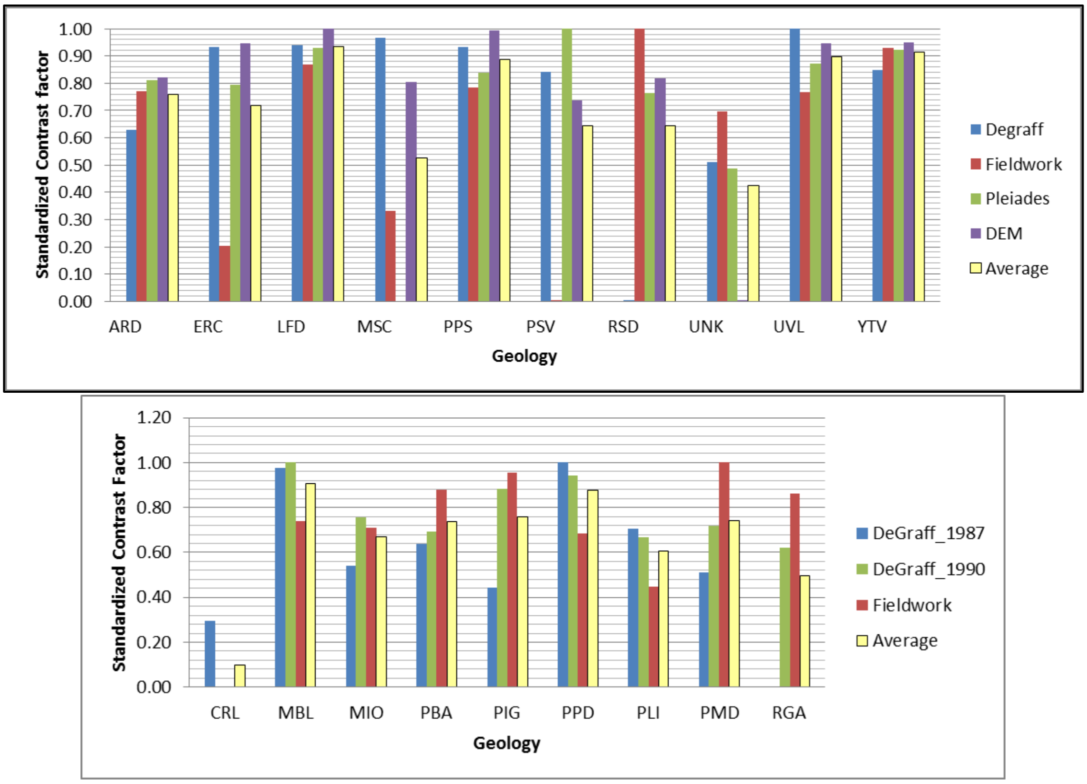


Figure 23. *Bar graph showing the contrast factor of each geologic unit for each landslide inventory. And the average contrast factor value. Saint Vincent (Above) and Dominica (Below).*

Then in order to test if combining the geology with the slope angle could improve the result, two test were performed using DeGraff and Pleiades together as one landslide inventory:

A. It was calculated how many landslides per slope class were in relation to the geologic units. The results are presented in the table

***Table 14**. Matrix showing amount of landslides combining Geologic units and slope classes for Saint Vincent*

Geologic units	Slope Classes					Grand Total
	0 - 10	10-20	20 - 30	30 - 45	> 45	
ARD	4	7	14	16	4	45
ERC		1	2	12	17	32
LFD		4	14	44	23	85
MSC		1	2	1	5	9
PPS	1	12	43	165	120	342
PSV	1	6	24	91	134	256
RSD	1			1	1	3
UVL		9	22	113	90	234
YTV		3	18	72	38	131
Grand Total	**7**	**43**	**139**	**516**	**432**	**1138**

From this table it is possible that it is indeed a relation among the units PPS and PSV with the slope classes 30 -45 and >45 degrees. So this combination of factors should have more weight than the others.

***Table 15.** Matrix showing amount of landslides combining Geologic units and slope classes for Dominica*

Dominica Geologic units		Slope Classes					Grand Total
		0 - 10	10-20	20 - 35	35 - 50	>50	
CRL	Conglomerate and raised limestone			2			2
MBL	Mafic breccias and thin lavas of Foundland Center	1	7	53	29	1	91
MIO	Miocene	6	26	68	16		116
PBA	Pleistocene apron of block and ash	3	10	95	74	11	193
PIG	Pleistocene Ignimbrites	3	7	21	6		37
PPD	Pleistocene Pelean Domes		2	77	84	8	171
PLI	Pliocene	12	47	248	129	9	445
PMD	Proto Morne aux Diables	1	6	13	11		31
RGA	River gravel and alluvium			2			2
	Grand Total	26	105	579	349	29	1088

As happened on Saint Vincent, for Dominica there is also a relationship among slope classes and geologic classes, existing a clear relation among the Pliocene (PLI) unit with the slope class 20 to 35 and 35 to 50, and in less degree the units PBA, PPD and MIO, with the slope classes 20-35 and 35-50.

B. Weight of evidence values were calculated for each geologic class and for each combination of the geologic class and slope classes.

Table 16. WOE values for the geological classes of Saint Vincent

GEOLOGICAL	WMAP	0-10	10-20	20-30	30-45	>45
ARD	-1.06	-2.59	-1.64	-0.40	0.29	0.75
ERC	-0.15	-7.46	-0.32	-1.01	-0.20	0.19
LFD	0.26	-8.80	-1.26	-0.24	0.77	1.08
MSC	-0.24	-6.04	0.38	-0.22	-1.58	0.49
PPS	-0.08	-3.46	-1.72	-0.76	0.24	1.00
PSV	0.22	-3.15	-1.36	-0.68	0.05	1.38
RSD	-1.66	-1.57	-8.69	-8.09	-0.52	2.02
UNK	-5.74	-3.47	-3.98	-3.94	-4.20	-4.11
UVL	0.33	-9.10	-0.94	-0.59	0.41	1.08
YTV	-0.07	-10.11	-2.41	-0.64	0.56	1.59

Table 17 WOE values for the geologic units of Dominica

GEOLOGY	WMAP	*0-10	*10-20	*20-35	*35-50	>50
Conglomerate and raised limestone	-1.62	-7.99	-8.33	-0.33	-5.88	-2.07
Mafic breccias and thin lavas of Foundland Center	1.18	-0.20	0.06	1.23	1.59	0.62
Miocene	-0.43	-1.67	-1.10	0.10	0.10	-4.48
Pleistocene apron of block and ash	-0.22	-3.02	-2.09	0.22	1.26	1.63

Pleistocene Ignimbrites	-0.35	-2.22	-1.29	0.44	1.36	1.21
Pleistocene Pelean Domes	1.17	-8.26	-1.73	0.98	1.84	1.64
Pliocene	-0.05	-2.22	-1.29	0.44	1.36	1.21
Proto Morne aux Diables	-0.58	-2.30	-1.13	-0.50	0.71	-6.05
River gravel and alluvium	-2.02	-9.19	-7.73	-0.21	-6.58	-3.45

5.2. Soils

For Saint Vincent, to make it easier to analyze, it was reclassified according to its texture obtaining a final map of 13 classes. Analyzing their distribution it is possible to see that close to La Soufriere volcano there are soils with coarser textures (sandy and gravelly) and far away from the volcano, there are the finer textures (loam and clay). In the middle close to all the eruptive centres there is one large unit without further classification (skeletal soils). For Dominica it was used the map without modifications.

From the analysis made of the contrast factor values it was also concluded that there was no consistency on the behavior of the landslide types per landslide inventory, also, that DeGraff and Pleiades inventories presented a similar conducts.

After that, it was also analyzed how many landslides per soil unit and slope class were. Noticing that there is indeed a relation among soils and slope. For Saint Vincent most of the landslide happen on Skeletal and Loamsoils with slopes between 30-45. For Dominica most of the landslides happen on Allophanoid Latosolics soils with slopes 20-35.

Table 18. Matrix showing amount of landslides combining Soil units and slope classes for Saint Vincent

Soil Texture	> 45	0 - 10	20 - 30	30 - 45	10-20	Grand Total
Alluvial-Colluvial	3		1	3	1	8
Cindery Gravelly Sandy Loam	88	1	11	88	3	191
Clay Loam	5	2	14	20	8	49
Gravelly Loam	14		4	28	1	47
Gravelly Sandy Loam	15		7	35	2	59
Loam	50	2	56	150	14	272
Loamy Sand	9		4	4		17
Sandy Clay Loam	2	1	2	6	1	12
Sandy Loam	2	1	2	4		10
Skeletal	244		38	177	13	472
Grand Total	432	7	139	516	43	1138

Table 19. Matrix showing amount of landslides combining Soil units and slope classes for Dominica

Soil Type	>50	0 - 10	20 - 35	35 - 50	10 - 20	Grand Total
Allophanoid Latosolics	6	13	215	112	38	384
Allophanoid podzolics		1	22	11	7	41
Hydrogenic Group		1				1
Kandoid latosolics		7	130	39	41	217
Kandoid latosols			1	7	1	9
Phytogenic Group			2	4		6
Protosols	1		25	21	1	48
Skeletal	22		108	118	5	253
Smectoid Clay Soils			12	3	4	19
Unclassified		1				1
Young Soils		3	64	34	8	109
Grand Total	29	26	579	349	105	1088

The following are the WOE values for the different classes and classes combined with sloe angle.

Table 20. WOE values for the Soil classes of Saint Vincent

Soil Texture	WMAP	*0-10	*10-20	*20-30	*30-45	>45
Alluvial-Colluvial	-0.32	-7.68	-1.09	-0.91	0.16	1.23
Cindery Gravelly Sandy Loam	0.81	-2.26	-1.51	-0.57	0.89	1.89
Clay Loam	-0.82	-2.22	-1.51	-0.79	0.09	0.63
Gravelly Loam	0.68	-7.19	-0.95	-0.07	0.88	1.20

Gravelly Loamy Sand	-7.01	-6.56	-5.42	-4.34	-4.30	-3.16
Gravelly Sandy Loam	0.01	-8.63	-1.67	-0.78	0.46	1.13
Loam	-0.11	-2.86	-1.54	-0.33	0.42	0.82
Loamy Sand	-1.07	-10.23	-9.29	-0.79	0.09	0.63
NA	-5.17	-4.26	-2.40	-2.35	-2.98	-3.44
San+A38d	-8.30	-7.75	-6.80	-5.64	-5.04	-4.04
Sandy Clay Loam	-0.87	-2.15	-2.16	-1.16	0.32	1.67
Sandy Loam	-1.56	-3.04	-9.51	-1.27	-0.07	1.11

Table 21. WOE values for the soil classes of Dominica

Soil type	**WMAP**	**0-10**	**10-20**	**20-35**	**35-50**	**>50**
Allophanoid Latosolics	-0.12	-1.93	-1.51	0.42	1.38	0.85
Allophanoid podzolics	-0.31	-3.15	-0.86	0.48	1.27	-5.31
Beach Sand	-7.07	-6.90	-4.67	-2.88	-	-
Beach Sand + Shingle	-4.51	-4.20	-3.21	-0.25	0.26	-
Hydrogenic Group	-2.26	-2.00	-7.38	-6.43	-4.47	-0.59
Kandoid latosolics	-0.10	-2.25	-0.79	0.55	1.48	-5.69
Kandoid latosols	0.13	-6.40	-0.83	-1.29	1.66	-4.97
Other Clay Latosolics	-8.37	-7.78	-7.13	-6.56	-3.99	0.17
Phytogenic Group	0.07	-5.76	-6.87	-0.53	1.43	-3.63
Pond	-4.80	-4.81	3.30	-	-	-
Protosols	0.78	-8.54	-1.69	1.05	1.87	1.66
Shingle	-5.56	-4.85	-3.16	-4.13	-3.23	-0.28
Skeletal	0.87	-8.89	-1.42	0.61	1.41	1.76
Smectoid Clay Soils	-1.07	-9.63	-1.65	-0.36	0.47	-4.40
Soufriere	-6.65	-6.43	-4.82	-3.37	-2.39	0.74
Unclassified	-1.53	-1.11	-6.80	-6.55	-4.30	-0.16
Young Soils	-0.35	-2.32	-1.94	0.16	1.07	-6.27

5.3. Geomorphology

Regarding the geomorphology, any of the islands had it, and due to the good quality of Saint Vincent DEM, it was generated in order to be included in the analysis.

After doing the analysis of the combination of Geomorphology and Sloe classes, it was discovered that there is also a relationship among slope classes and geomorphological units, finding that most of the llandsides happen on the unit Grand_Bonhomme_dissected_pyroclastic_slopes with slopes 30-45 and >45.

Table 22. Matrix showing amount of landslides combining Geomorphologic units and slope classes for Saint Vincent

Geomorphology	**> 45**	**0 - 10**	**20 - 30**	**30 - 45**	**10-20**	**Grand Total**
Alluvial_active_debrisflows_channels	3			3		6
Alluvial_fans_floodplain _and_slope_deposits			2			2
FAult_scarp			1	2		3
GRand_Bonhomme_Caldera_slope	8		1	14		23
Grand_Bonhomme_dissected_pyroclastic_slopes	86		17	106	8	217
Grand_Bonhomme_Lava_Flow_topslope	5		2	5		12
GRand_Bonhomme_Lavaflow_slopes	22		5	13	3	43
GRand_Bonhomme_Old_Caldera_rim	6		2	10	1	19
GRand_Bonhomme_Old_dissected_caldera	21		10	49	4	84
Old_dissected_pyroclastic_slopes	10		18	52	1	82
Old_Lava_flow_hillss_with_Pyroclastic_coiver	32	1	33	62	12	140
Old_Lava_Flow_slopes	26		1	12	1	40
Old_Pyroclastic_flow_Fan	1	1				2
Old_Red_scoria_hills		2		1		3
Pre_Soufriere_caldera	1					1
PRe_Soufriere_Caldera_rim	3			1		4
Pre_Soufriere_Lavaflow_slopes	32		2	23	1	58
Pre_Soufriere_Lavaflows_near_VC	4		3	4		11
Pre_Soufriere_Lavalaflow_hilltops	2		1	10	1	14

Pre-Soufriere_dissected_pyroclastic_slopes	18		8	24	2	52
Slope_deposits	2	2	8	11	3	26
Soufriere_volcano_dissected_recent_sideslope	67		7	29	2	105
Soufriere_volcano_dissected_semi_recent_slopes	26		6	19	3	54
Soufriere_volcano_older_lava_flow_slopes	7			10		17
Soufriere_volcano_older_lavaflow_hills	7	1		7		15
Soufriere_volcano_older_pyroclastic_slopes	10		3	15		28
Soufriere_volcano_pyroclastic_flow_fan	3		2	7	1	13
Soufriere_volcano_secondary_crater_bottom	2		1	1		4
Soufriere_volcano_semi_recent_lavaflows	13		5	23		41
Soufriere_volcano_ssteep_valley_incision	14		1	3		18
Soufrieree_volcano_quarterly_collapse_scarp	1					1
Grand Total	432	7	139	516	43	1138

Table 23. WOE values for the geomorphological classes of Saint Vincent.

GEOMORPHOLOGY	WMAP	0-10	10-20	20-30	30-45	>45
Soufriere_volcano_recent dome	-7.42	-5.71	-6.42	-5.87	-5.72	-4.64
Soufriere_volcano_Recent_craterrim	-8.14	-5.66	-5.11	-6.00	-6.79	-7.44
Soufriere_volcano_Recent_Crater	-7.15	-6.64	-4.93	-5.21	-4.82	-4.14
Soufriere_volcano_Second_calderarim	-7.78	-4.14	-4.90	-6.06	-6.82	-6.74
Soufrieree_volcano_quarterly_collapse_scarp	-1.27	-4.84	-5.24	-6.52	-7.31	-0.07
Soufriere_volcano_older_pyroclastic_slopes	-0.29	-6.66	-7.66	-0.73	-0.23	0.05
Soufriere_volcano_older_lava_flow_slopes	0.90	-4.84	-5.88	-6.76	1.23	1.09
Alluvial_fans_floodplain _and_slope_deposits	-3.19	-10.29	-9.35	-0.71	-7.58	-6.06
Soufriere_volcano_pyroclastic_flow_fan	-1.20	-10.15	-2.24	-0.67	0.86	1.47
Alluvial_active_debrisflows_channels	-0.48	-8.49	-7.71	-7.11	1.19	2.03
Pre_Soufriere_caldera	-2.63	-6.92	-6.49	-8.38	-8.65	-0.72
PRe_Soufriere_Caldera_rim	-0.44	-4.76	-4.50	-6.64	-0.90	0.07
Pre_Soufriere_Lavaflows_near_VC	-0.62	-6.61	-6.69	-0.37	-0.80	-0.34
Slope_deposits	-1.17	-2.10	-2.19	-0.96	-0.27	-0.19
Soufriere_volcano_dissected_recent_sideslope	0.78	-7.87	-0.91	-0.54	0.35	1.88
Soufriere_volcano_dissected_semi_recent_slopes	-0.34	-7.97	-0.65	-1.12	-0.63	0.74
Soufriere_volcano_secondary_crater_bottom	-0.08	-7.05	-6.42	-0.42	0.22	2.05
GRand_Bonhomme_Old_dissected_caldera	0.34	-8.89	-1.12	-0.33	0.88	1.11
GRand_Bonhomme_Old_Caldera_rim	0.60	-5.51	0.01	-0.13	0.73	1.02
GRand_Bonhomme_Lavaflow_slopes	0.41	-6.50	0.22	-0.05	0.07	0.94
Grand_Bonhomme_Lava_Flow_topslope	-0.25	-7.30	-8.16	-0.79	-0.08	2.00
Grand_Bonhomme_dissected_pyroclastic_slopes	0.28	-9.14	-1.09	-0.86	0.40	1.20
Pre-Soufriere_dissected_pyroclastic_slopes	-0.44	-8.74	-1.67	-0.85	-0.29	0.44
Soufriere_Debirsflow_terrace	-7.47	-6.19	-6.37	-5.80	-5.56	-4.41
Pre_Soufriere_Lavaflow_slopes	1.07	-6.50	-0.37	-0.42	1.05	1.49
GRand_Bonhomme_Caldera_slope	0.52	-6.55	-7.54	-1.09	0.89	1.17
Old_dissected_pyroclastic_slopes	-0.21	-9.36	-3.16	-0.44	0.48	0.82
Old_Red_scoria_hills	-1.28	-0.26	-8.16	-7.86	-0.60	-4.96
Old_Lava_Flow_slopes	0.59	-6.19	-0.07	-0.99	0.29	1.06
Old_Lava_flow_hillss_with_Pyroclastic_coiver	-0.16	-3.01	-1.26	-0.27	0.29	1.14
Old_Pyroclastic_flow_Fan	-0.24	0.24	-7.15	-5.90	-4.69	3.98
Marine_reworked_sediments_along_faultscarp	-6.71	-6.40	-4.70	-2.78	-2.02	-0.69
Soufriere_volcano_semi_recent_lavaflows	0.96	-6.36	-7.53	0.33	1.08	1.84
Soufriere_volcano_older_lavaflow_hills	0.67	0.75	-6.86	-7.41	0.58	2.28
Pre_Soufriere_Lavalaflow_hilltops	0.79	-5.02	0.69	-0.24	1.11	0.56
FAult_scarp	-0.42	-5.99	-6.71	-0.28	0.10	-5.40
Soufriere_volcano_ssteep_valley_incision	1.44	-6.40	-6.53	0.16	0.79	2.87

5.4. Land-cover

For both islands, before using the maps, they were modified in order to include all roads and building footprint, as well as the airport, quarries and cuts and fills

After analyzing the contrast factor values it was found that again there was no consistency between landslide inventories regarding landslide type. Also, comparing the behavior between landslide inventories, it was found that DeGraff and Pleiades were similar, as can be sen on the following figure..

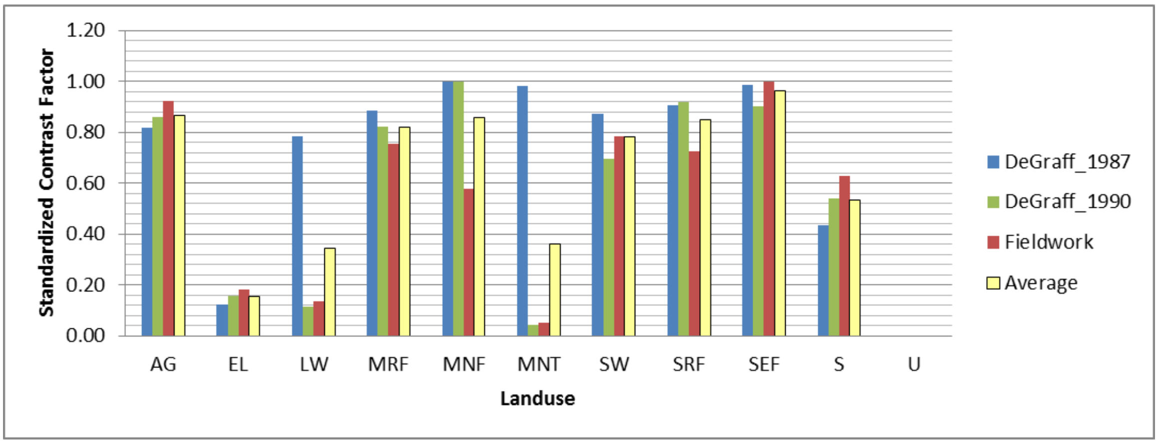


Figure 24. Bar graph showing the contrast factor of each Landuse unit for each landslide inventory in Dominica.

After analyzing the bar graph it was possible to oserv that some units were more important than others so in order todig in more on this relationship, a matrix showing number of landslide presente on each landuse class combines with slope classes. From this it was possible to observe that for Saint Vincent, The landcover classes more important are Elfin Evergreen and Ebergreen Foresthaving most of the landslides on slopes >45, the Evergreen forest and Pasture, cultivated land and herbaceous agriculture with landslides os slopes 30 to 45.

Table 24. Matrix showing amount of landslides combining Landcover units and slope classes for Saint Vincent

Landcover	> 45	0 - 10	20 - 30	30 - 45	10-20	Grand Total
	1					1
Bare ground (e.g. sand, rock)	3		1	3		7
Blue Mahoe plantation	1			1		2
Buildings	2		2			5
Drought Deciduous, coastal Evergreen and mixed forest or shrubland	75	1	25	90	9	200
Elfin, Evergreen and Sierra Palm tall cloud forest (above ~550m)	106		14	66	7	193
Evergreen forest	109	1	22	114	7	253
Montane non-forested vegetation (e.g. high-altitude pastures)	1					1
Pasture, cultivated land and herbaceous agriculture	58	3	46	131	12	250
Roads and other built-up surfaces (e.g. concrete, asphalt)	2			1	1	4
Sea				1		1
Seasonal Evergreen forest	4		2	5	2	13
Semi-deciduous forest	66	1	21	94	5	187
Woody agriculture (e.g. cacao, coconut, banana)	4	1	6	10		21
Grand Total	432	7	139	516	43	1138

For Dominica it was found a relation among Agriculture and Mature rain forest with slopes among 20 and 35 degrees.

Table 25. Matrix showing amount of landslides combining Landcover units and slope classes for Dominica

Landuse	0 - 10	20 - 35	35 - 50	10-20	Grand Total
AGRICULTURE	9	128	63	36	239
LITTORAL WOODLAND		2			2
MATURE RAIN FOREST	8	199	91	27	331
MONTANE RAIN FOREST	3	47	48	8	111
MONTANE THICKET		4	10		14
Quarry		1			1
Road		3		1	4

SCRUB WOODLAND	1	35	21	8	68
SECONDARY RAIN FOREST	3	78	36	14	135
SEMI-EVERGREEN FOREST	2	82	80	11	183
Grand Total	26	579	349	105	1088

The following are the WOE values of the landcover and landuse map and their combination with slope classes.

Table 26. *WOE values for the lancover classes of Saint Vincent.*

LANDCOVER	WMAP	0-10	10-20	20-30	30-45	>45
Evergreen forest	-0.15	-2.75	-1.61	-1.10	-0.09	0.82
Seasonal Evergreen forest	-0.01	-6.28	0.50	-0.15	-0.16	0.19
Semi-deciduous forest	-0.29	-3.23	-2.27	-1.09	0.12	1.08
Pasture, cultivated land and herbaceous agriculture	0.25	-2.95	-1.56	0.00	1.20	2.02
Bare ground (e.g. sand, rock)	-0.32	-8.29	-7.63	-0.25	0.97	1.49
Roads and other built-up surfaces (e.g. concrete, asphalt)	-1.63	-9.06	-1.87	-8.06	-0.48	1.92
Buildings	-1.65	-9.41	-9.05	-0.57	-7.07	2.67
Drought Deciduous, coastal Evergreen and mixed forest or shrubland	0.89	-2.55	-0.74	0.10	1.23	2.08
Water	-6.19	-5.21	-4.30	-3.84	-3.33	-4.72
Elfin, Evergreen and Sierra Palm tall cloud forest (above ~550m)	-0.09	-9.07	-0.82	-1.15	-0.36	0.77
Woody agriculture (e.g. cacao, coconut, banana)	-0.55	-1.92	-9.07	-0.40	-0.04	0.89
Montane non-forested vegetation (e.g. high-altitude pastures)	-0.81	-3.63	-4.06	-6.18	-7.15	0.84
Blue Mahoe plantation	0.32	-5.27	-5.67	-5.81	0.64	2.04
Mangrove	-4.36	-4.18	-2.19	-0.57	0.87	-
Sea	-0.66	-4.88	-5.01	-5.16	1.16	-5.47

5.5. DEM Derivatives

For Saint Vincent there is a Lidar DEM with cell-size resolution of 5m, , however due to clouds, it had two holes in the middle, that were filled with the SRTM DEM where possible. For Dominica, the DEM was produced from contour lines every 10 meters. Because of this this DEM present very rounded topography, and the percentage of steep slopes is underestimated. Besides it is not known how the contour lines were generated.(***Figure 25***)

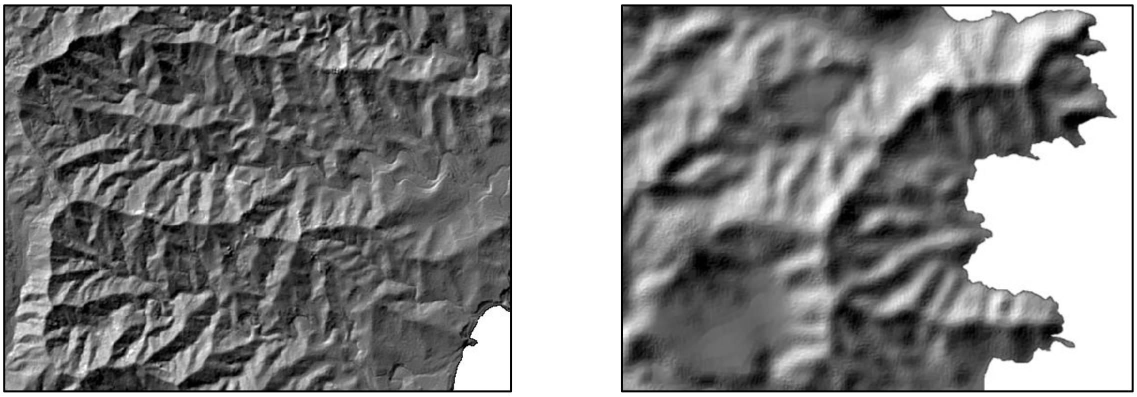


Figure 25. *Dem subsets at the same scale, for Saint Vincent (left) and Dominica (right). Notice the differences in detail existing between them.*

From both DEM, it was obtained an elevation map, slope angle map, slope aspect map and flow accumulation map. As mentioned in the methodology they were classified obtaining the following maps:

- *Elevation map*:

After analyzing the contrast factor values for both islands it was possible to observe that again, DeGraff and Pleiades inventories behave similar for Saint Vincent, as well as both DeGraff inventories behave similar in dominica. Looking at the averaged contrast factor values (yellow bar) it is possible to interpret a relationship among the importance of the classes regarding landslides, having more landslides on intermediate elevations 135 to 300 for Saint Vincent, and 500 to 825 to Dominica.

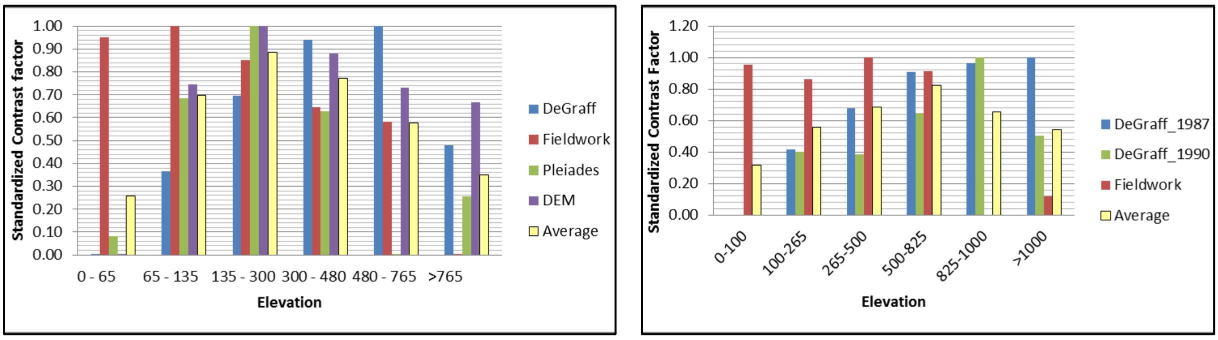


Figure 26. *Bar graph showing the contrast factor of each elevation class for Saint Vincent (left) and Dominica (right)*

The final WOE values are the following:

Table 27WOE Values of Elevation for Saint Vincent (left) and Dominica (Right)

Elevation	WMAP
0 - 65	-1.42
65 - 135	-0.26
135 - 300	0.39
300 - 480	0.28
480 - 765	-0.04
>765	-0.68

Elevation	WMAP
0 - 65	-1.42
65 - 135	-0.26
135 - 300	0.39
300 - 480	0.28
480 - 765	-0.04
>765	-0.68

- *Slope Angle map*:
  For Saint Vincent 6 classes were used: 0-10, 10-20, 20-30, 30-45, 45-60 and >45; where the class 30 to 45 had the highest amount of landslides. For Dominica 5 classes were used: 0-10, 10-20, 20-35, 35-50, and >50; where the class 25 to 35 had the highest amount of landslides.

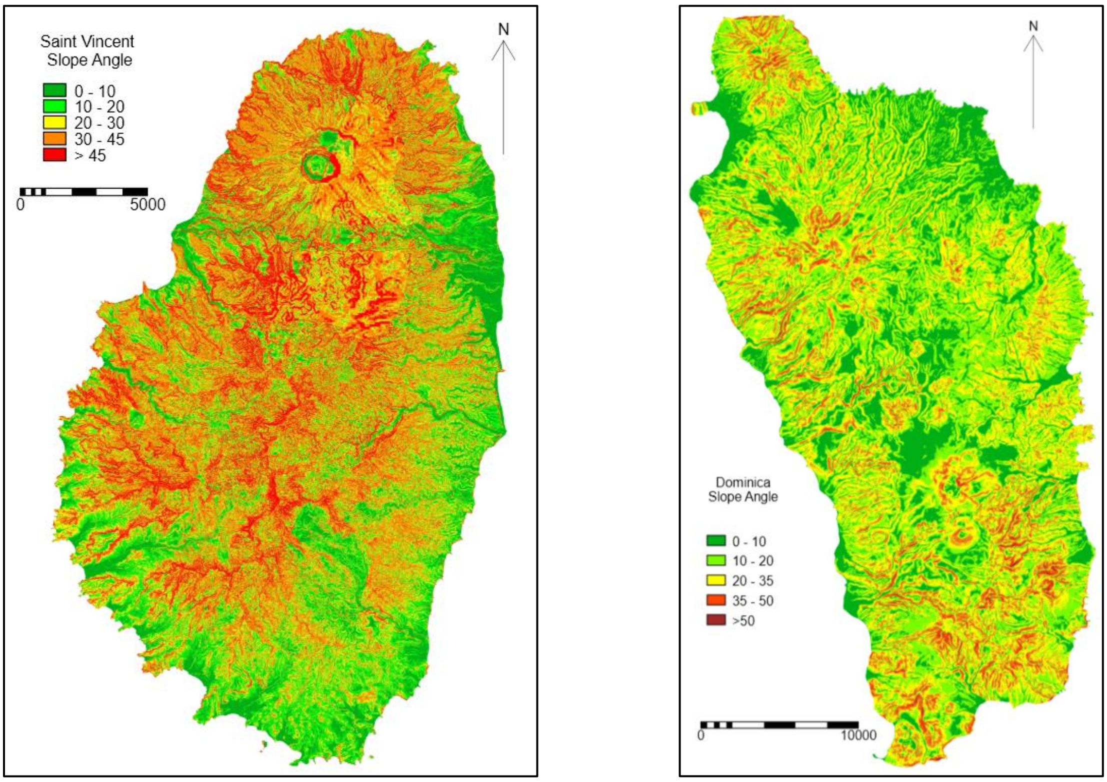


Figure 27*. Slope angle map for Saint Vincent (left) and Dominica (Right)*

After analyzing the contrast factor values, it was really evident the strong relationship among Slope Angle and the occurrence of landslides, since al landslide inventories displayed the same behavior for booth islands, presenting more landslides while the slope angle increased.

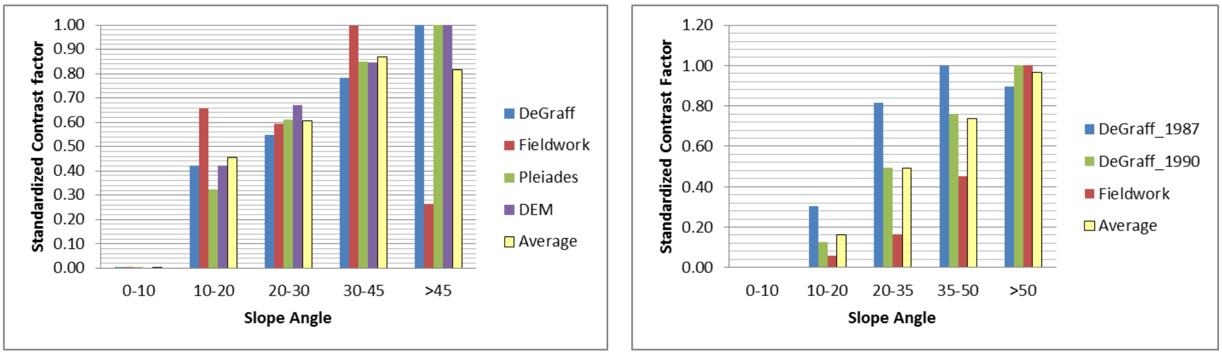


Figure 28. Bar graph showing the contrast factor of each slope angle class for Saint Vincent (left) and Dominica (right)

The following are the WOE values calculated for the slope angle classes for both islands.

Table 28WOE values of Slope angle units for Saint Vincent (left) and Dominica (Right)

Slope	WMAP
0 - 10	-3.31
10 - 20	-1.79
20 - 30	-0.84
30 - 45	0.35
> 45	1.28

Slope	WMAP
0 - 10	-2.56
10 - 20	-1.63
20 - 35	0.60
35 - 50	1.52
>50	1.22

- *Slope Aspect map*: for both islands, this map was classified on 8 classes, each class corresponding to an interval of 40 degrees: N (337.5-22.5), NE(22.5-67.5), E(67.5-112.5) SE(112.5-157.5), S157.5-202.5), SW(202.5-247.5), W(247.5-292.5) and NW(292.5-337.5).

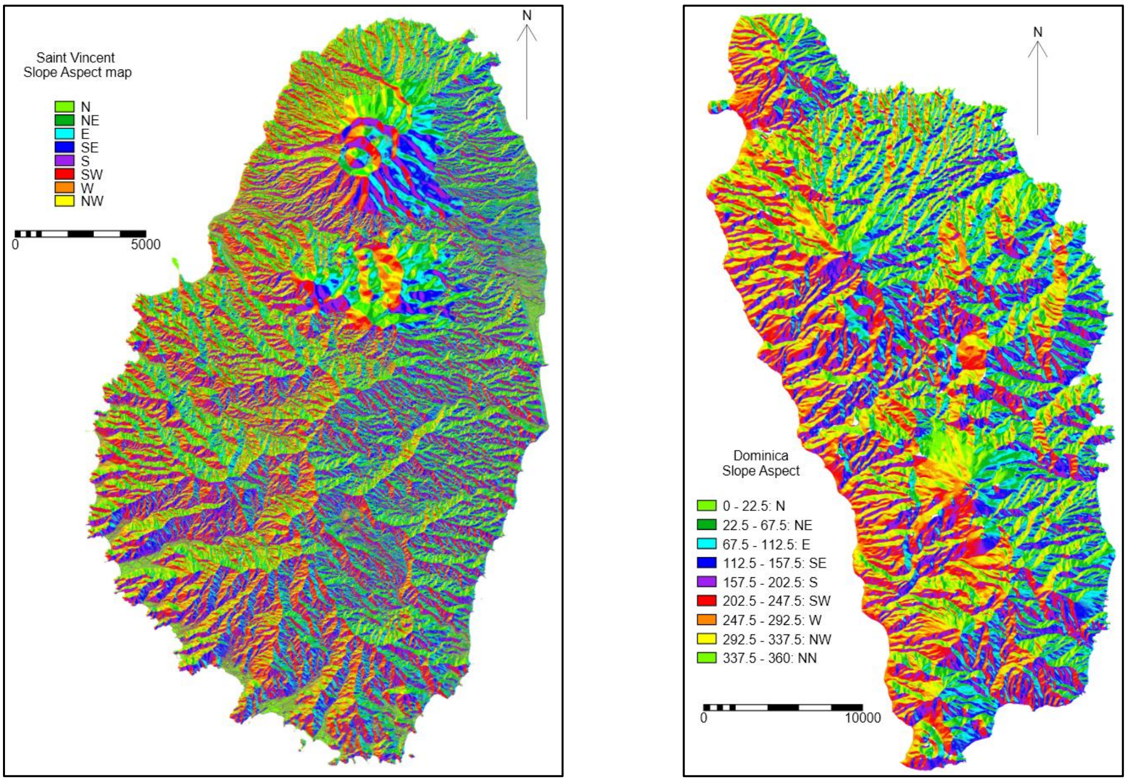


***Figure 29**. Slope aspect map for Saint Vincent (left) and Dominica (right)*

As can be seen from the analysis of the contrast factor values, it doesn't seem to be a consistent relation among landslide inventories, indicating that this factor map may be not so relevant.

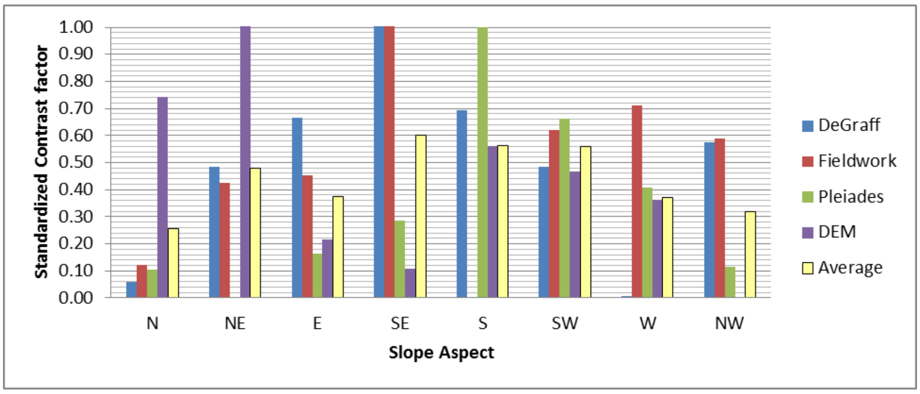


Figure 30. Bar graph showing the contrast factor of each Aspect class for Saint Vincent (left)

The following are the WOE values assigned to each Aspect class. It called the attention that for Dominica after running the OWE, a new class was generated called NA, investigating this class resulted being the flat areas presents on the top of the hills doe to the fact that the DEM came from Contour lines every 10 meters.

Table 29. WOE values of Aspect classes for Saint Vincent (left) and Dominica (right)

Aspect	WMAP
N	-0.39
NE	-0.28
E	-0.13
SE	0.08
S	0.52
SW	0.18
W	-0.17
NW	-0.18
NN	-0.33

Aspect	WMAP
N	-0.15
NE	0.05
E	0.10
SE	0.10
S	0.06
SW	0.11
W	0.04
NW	-0.16
NN	-0.42
NA- Flat	-1.27

- *Flow Accumulation map*. This factor map is important because it shows how far from the water divide a pixel is located, which could be a good indication for landslide initiation points. For both islands 4 classes were used. For Saint Vincent they had the ranges 0-12, 12-29, 29-45, and >45; where the class 0-12 had the highest amount of landslides. For Dominica the ranges were 0-10, 10-20, 20-42, and >42 with the highest concentration of landslides on the class 0-10. On this parameter it is possible to say that both islands behave in the same way.

After analyzing the contrast factor values it was possible to observe that there was a relationship among Flow Accumulation and Landslides, For Saint Vincent it was the expected result, having more landslide for low flow accumulation values due to the closeness to the ridges, however for Dominica, it was not like that. This could be because of the poor Dem quality.

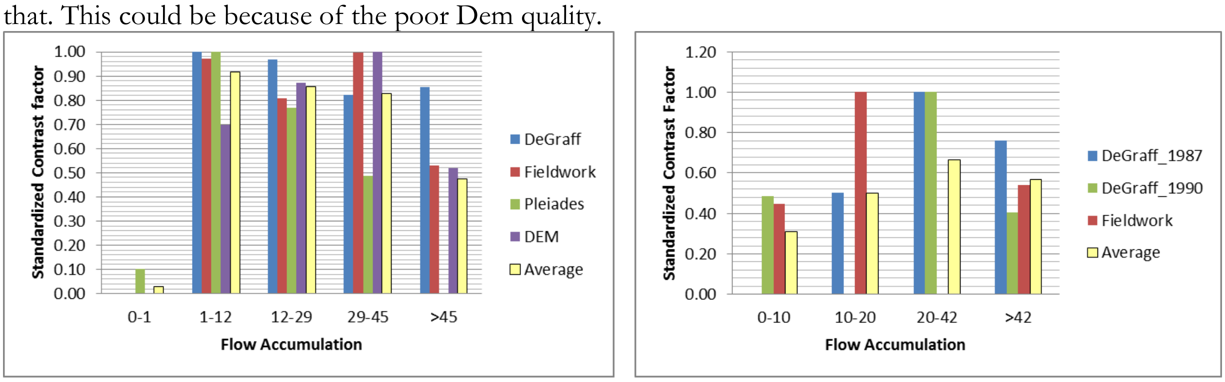


Figure 31. *Bar graph showing the contrast factor of each Flow accumulation class for Saint Vincent (left) and Dominica (right)*

The following are the WOE values for flow accumulation classes for both islands.

Table 30. WOE values of Flow Accumulation classes for Saint Vincent(left) and Dominica (right)

Flow accumulation	WMAP
0 - 1	-0.88
1 - 12	0.32
12 - 29	0.17
29 - 45	-0.09
>45	-0.28

Flow accumulation	WMAP
0 - 1	-0.07
1 - 12	0.02
12 - 29	0.23
29 - 45	0.10
>45	-0.07

5.6. Distance from Streams.

For Saint Vincent, the information regarding streams and rivers was incomplete or did not match with the DEM and/or the Pleiades satellite image. Because of this it was necessary to generate a new stream network from the DEM. For Dominica it was used the shapefile provided by the government.

For both islands, it was used the distance from streams, based on Fieldwork and Image interpretation a distances smaller than 150 meters were considered as important to landslides, while far away from this was not important.

5.7. Distance from Roads

As it happened with the streams, using only the roads did not had any relationship with landslides, so distance from roads was used instead. For this it was consideres as prone areas those that are closer than 30 meters, while those that are far away are considered not important.

For Saint Vincent there was also available a layer regarding roadcuts, in order to be used it was modified run two times a filter of majority where neighborhood undefined pixels to pixels with value took that value. Then three classes were produced: cut above, cut below and not applicable.

From the analysis of the WOE for roadcuts call the attention that most of the values are negative including the woe values assigned to both classes withouth combination with slope, indicating that this factor map mmigh not be so important. It is also possible to observe that for slopes lower than 20 degrees roadcuts are not important, but for slopes >45 degrees are significant.

Table 31WOE values of Roadcut classes and cliff classes for Saint Vincent

ROADCUT	WMAP	*0-10	*10-20	*20-30	*30-45	*>45
Roadcut_above	-1.77	-7.39	-7.74	-0.62	-7.12	2.03
Roadcut_below	-3.08	-6.65	-7.04	-6.91	-6.65	-5.70
NA	0.01	-3.30	-1.77	-0.83	0.36	1.28

CLIFF	WMAP	0-10	10-20	20-30	30-45	>45
Cliff_Below	1.69	-5.75	-6.02	0.32	-0.51	1.66
Cliff_Above	1.45	-5.67	-6.17	0.35	0.84	0.99
NA	-0.02	-3.30	-1.77	-0.84	0.36	1.26

5.8. Distance from Ridges

This layer was generated for Dominica in order to be used instead of the Flow Accumulation, which resulted being not useful due to the poor quality of the DEM. This layer was classified on 2 classes 0-200 meters, and >200 meters. Where the class 0-200 where important for landslides generation.

5.9. Distance from the coast

From fieldwork and Image interpretation it was taken a threshold value of 400 meters to divide those areas prone to landslides (0-400 meters) and those not related to the coast (>400 meters).

For Saint Vincent it was available a layer with the cliff areas for which it was calculated the weight of evidence

From the analysis of the WOE, it was possible to observe that being on cliff areas have a positive weight, being an important factor, also when combining this factor with slopes it is clear its relation with slope having the most positive weights on slopes >45 followed by slopes ranging from 30-45 degrees.

6. GENERATION OF SUSCEPTIBILITY MAPS

6.1. Landslide initiation susceptibility assessment using SMCE

In order to use SMCE, the factor maps need to be ordered, and standardized inside of a criteria tree. In order to decide the final criteria tree to be used to produce the final maps, several scenarios were tried as a sensitivity analysis to find out the best combination and ordering of the factor maps, and to compare how different methods of standardization can affect the results. in order to do this to main stages will be made: 1rst the selection of the best factor maps combination (preliminary scenario selection) using Benefit-Interval as standardization method. 2nd Using that combination test what happens when changing the standardization method to Benfit-Goal.

6.1.1. Running SMCE with all factor maps standardized as Benefit-Interval.

Under this standardization method it was made several scenarios to find out the best combination of factor maps (preliminary scenario slection). Once this combination was found, this multicriteria tree was used to test the standardization method Benefit-Goal.

After the analysis made before it was possible to obtain a general order of importance of the factors (from more important to less important): Slope Angle, Elevation, Flow Accumulation, Slope Aspect, Geology, Soils, and Land Cover.

However it was not known the best way to organize them inside of the criteria tree: should they be grouped or not. In order to try this, several scenarios were made from which two of them got the best success rates, but different spatial patterns. One of those scenarios, the general order obtained from the analysis was not used, and on the other scenario that order was taken into account and the factors were grouped.

The first scenario consisted on running SMCE with all factor maps standardized as Benefit-Interval. On this standardization all values were scaled from 0 to 1. On this scenario all factor maps were organized according to its maximum weights of evidence value.

Dominica	Min	Max
D_Landuse_Slope	-9.45	8.02
D_Geology_Slope	-9.51	6.39
D_RidgedistCl_Slope	-9.8	5.85
D_Soiltype_Slope	-9.45	5.72
D_StreamdistCl_Slope	-9.15	5.35
D_Coastdist_Slope	-10.03	5.12
D_RoadistCl_Slope	-8.86	4.64
D_Slope_class	-2.55	1.51
D_Elevation_class	-1.58	1.031
D_Flowacc_class	-0.07	0.22
D_Aspect_class	-1.27	0.11

Saint Vincent	Min	Max
SVG_Geom_Slope	-8.61	8.01
SVG_LC2014_Slope	-9.11	6.62
SVG_Geology_Slope	-9.05	5.5
SVG_Soil_Slope	-9.08	5.01
SVG_RoadistCl_Slope	-9.46	3.49
SVG_StreamdistCl_Slope	-9.48	3.39
SVG_CliffsActive_DG_P	-0.02	1.68
SVG_SlopeCl	-3.31	1.28
SVG_AspectClActive_DG_P	-0.38	0.51
SVG_ElevationClActive_DG_P	-1.42	0.38
SVG_FlowAccCl	-0.88	0.32
SVG_Roadcuts	-3.07	0.01

***Figure 32**. Order assigned to the factor maps on the first trial according to the maximum weight value present on each factor map.*

Of course the result of this scenario was the best according to the success rate (***Figure 35***. TI-SR in dark red); however, the order of importance of the factors was not logical if aspects as quality and accuracy of the different maps were considered. Besides, it was not logical visually since almost the whole mountainous area of the islands resulted having a high susceptibility (red colors).

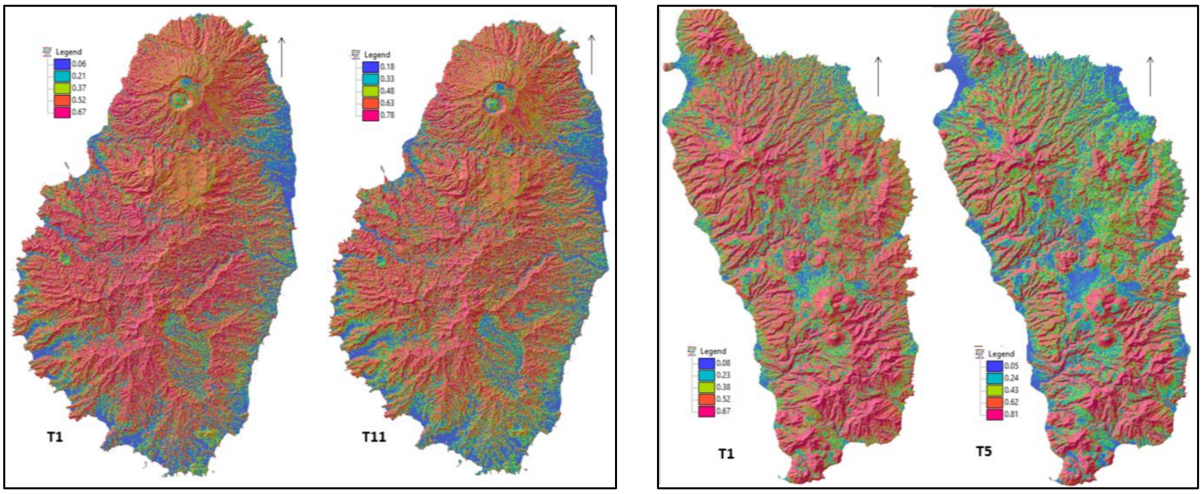


Figure 33. *Landslide susceptibility maps obtained on the first and last trials (T1 and T11) for Saint Vincent (left) and (T1 and T5) for Dominica (right).*

Then a second trial was made reorganizing the factors in a logical order, the success rate was a little bit worse, but at least the order of importance of the factors was logical.

Then a third trial was made grouping the factor maps on topography factors, land-cover factors, geologic factors and drainage factors. Next, other trials were made as a sensitivity analysis reordering and removing some factors. From this analysis, it was clear that for both islands the factors distance from roads and distance from streams, didn't played a role on the modelling, Due to this the selected scenario didn't contained any of those parameters for the respective islands.(***Figure 29***).

As part of the sensitivity analysis, and in order to understand how important the DEM derivatives were it was run a success rate for each one: (slope angle, slope aspect, elevation and flow accumulation).

From this analysis it become clear that for both islands the slope played an important role in explaining and predicting landslides. On the other hand, the other three derivatives have a tendency that is close to a line of 45 degrees indicating that those paremeters are not good indicators of landslide prone areas. However from those three parameters it is still possible to see that for Saint Vincent the Flow Accumulation has a better relation while for Dominica it is the elevation. Due to this, parameters as aspect and flow accumulation for Dominica and aspect and elevation for Saint Vincent were not taken into account on the final selected scenario of this stage. (***Figure 34***)

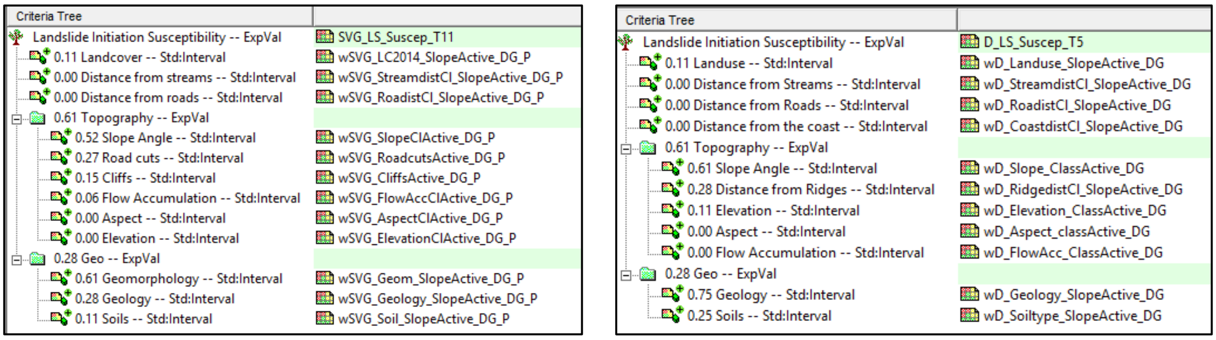


Figure 34. *Preliminar Criteria tree selected for Saint Vincent (left) and Dominica (right)*

From the analysis of the success rates, it calls the attention that for Saint Vincent, the success rate of using all factors organized by their maximum weight (T1) was very similar that the success rate of the preliminary scenario selected (T11) where the factors were grouped, and some factors were not considered.(***Figure 35***).

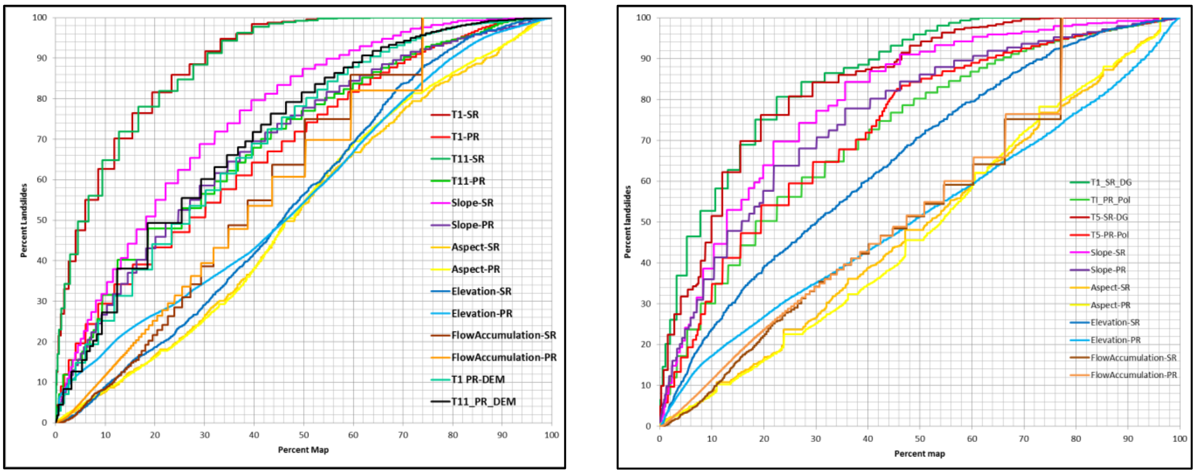


Figure 35. *Success and Prediction rate for the initial and final models with standardization method Benefit-Interval, as well as for DEM derivatives for Saint Vincent (left) and Dominica (right).*

On this graphs, For Saint Vincent, the scenario T1 is represented as red lines, the scenario T11 is represented by green lines. For Dominica the scenario T1 is represented by green lines while the scenario T5 is represented by red lines. The other lines represent the success rates made to the DEM derivatives as part of the sensitivity analysis.

In order to validate the results, it was used the polygon based landslide inventory for both islands running the success rate with it, obtaining the prediction rate. As seen in the ***Figure 35***, while the success rate has a ratio of 70/12, the prediction rate have a ratio of 70/32. For Dominica, the success rate has a ratio of 70/16, and a prediction rate of 70/38.

From those results it is possible to say that the model explains really well the landslide inventory, however for predicting is not so good, being better the model obtained for Saint Vincent than the one obtained for Dominica.

This differences can be explained on the fact that for modelling it was used a point based inventory, while for validation it was used the polygon based landslide inventory that included not only the initiation point of the landslides but also the body and deposit of them.

6.1.2. Running SMCE with all factor maps standardized as Benefit-Goal.

From the scenarios made before, it was selected the best one (T11 for Saint Vincent, and T5 for Dominica), and the standardization method was changed to Benefit-Goal. On this method all negative values will be standardized as 0 and only positive values between 0 and 1

After running the SMCE with those parameters, the maps obtained had too much area on low susceptibility, presenting patches of this class on mountainous areas where at least a moderate class should be expected, (***Figure 36***).

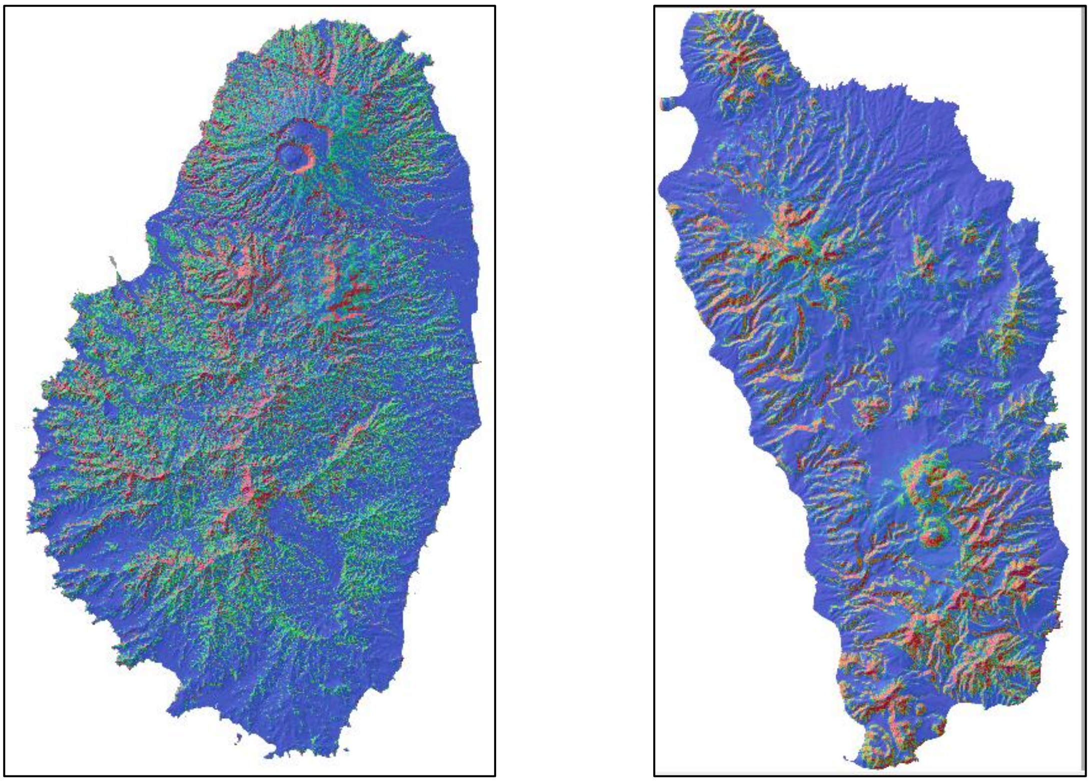


***Figure 36**. Maps generated with new standardization method. Saint Vincent on the left and Dominica on the Right.*

After doing the success and prediction rate, it was clear that the model was not better since the success rate became worst and the prediction rate keeps being relatively the same. (*Figure 37*).

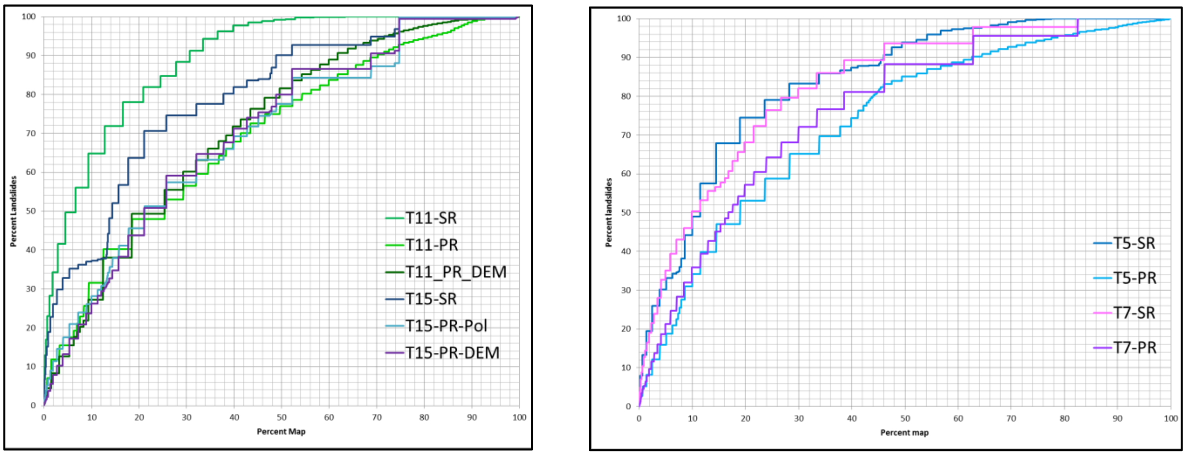


Figure 37. Success and Prediction rate for the initial and final models with standardization method Benefit-Goal, as well as for DEM derivatives for Saint Vincent (left) and Dominica (right).

Finally, from this analysis, the preliminary scenarios selected became on the final scenario that was used to produce the final landslide initiation susceptibility map for both islands.

6.1.3. Final Landslide Susceptibility maps

Since the difference between success rate and prediction rate is not so huge, and also from the visual analysis most of the landslide polygons are included on the red areas, this landslide initiation susceptibility were used as the final landslide susceptibility maps.

After having the final maps, the histogram of each map was used in order to classify them in three classes.

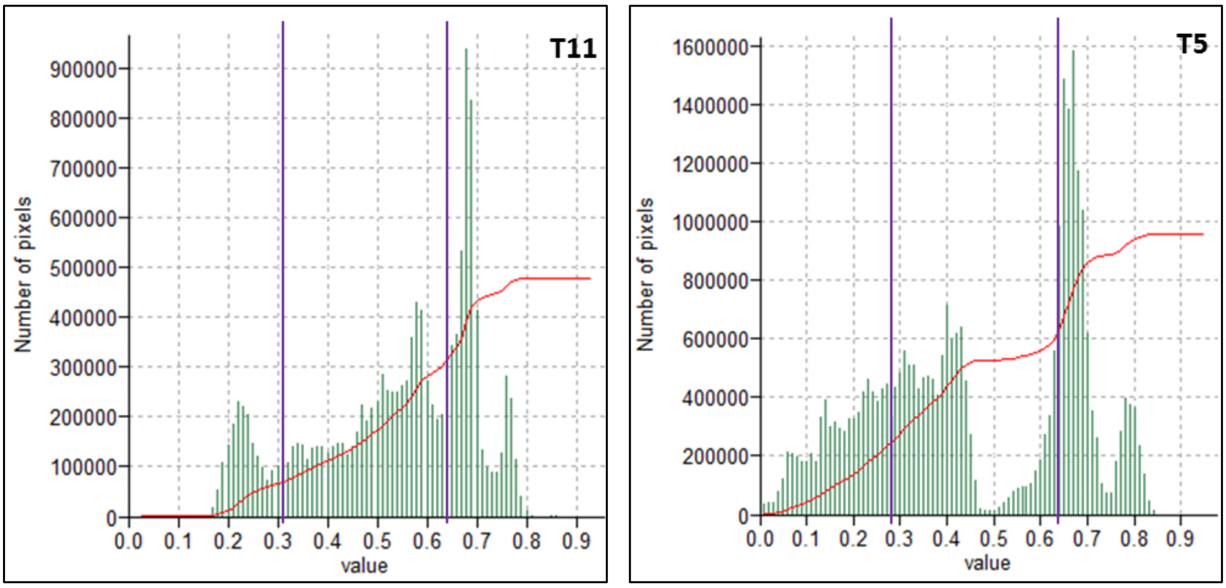


Figure 38. *Histograms used to classify the final landslide susceptibility maps of Saint Vincent (left) and Dominica (right), the limits of the classes are shown as purple vertical lines..*

For Saint Vincent the three landslide susceptibility classes are low 0-0.31, Moderate 0.31-0.63 and high >0.63 for Dominica are Low 0-0.29, Moderate 0.29-0.64 and High >0.64.

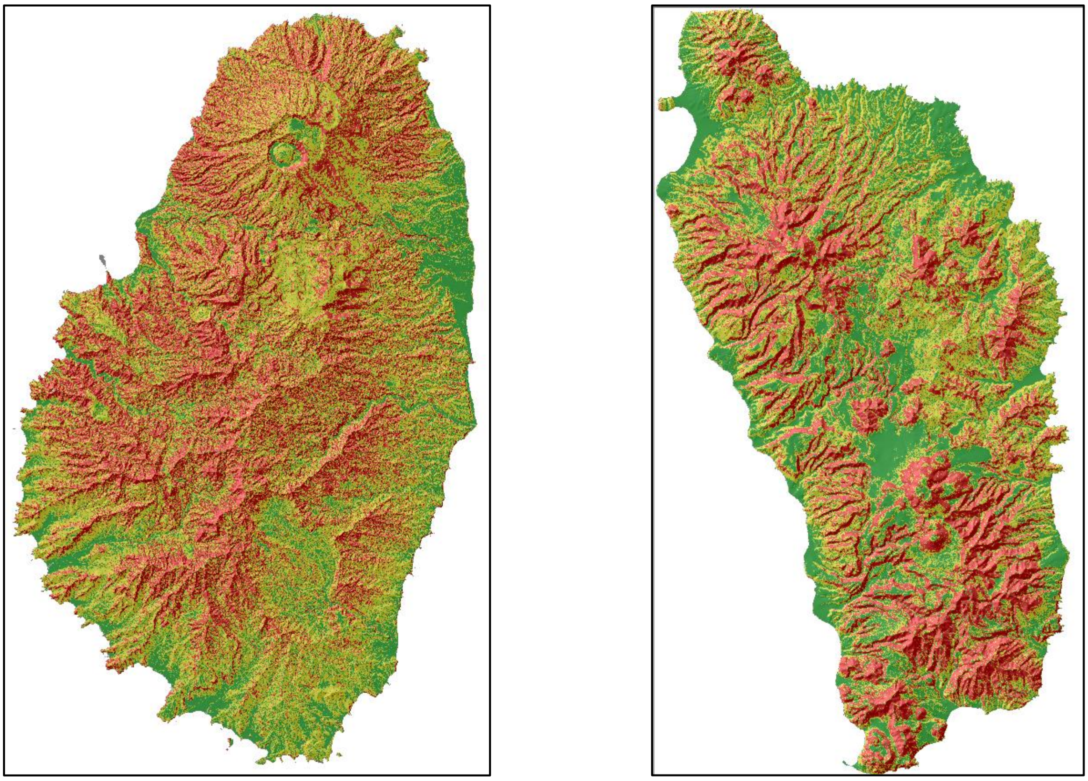


Figure 39. *Final landslide susceptibility maps for Saint Vincent (left) and Dominica (right).*

Analyzing how many landslides existed per class it was obtained that for Dominica the low susceptibility class is characterized by a density os 0.01 landslides/km^2. Moderate susceptibility class has 0.53landslides7km^2. High susceptibility class has 3.30 landslides/km^2.

For Saint Vincent the low class has a density od 0 landslides/km^2. Moderate class has 1.13 landslides/km^2 and high susceptibility class has a density of 7.50 landslides/km^2.

7. DISCUSSION AND CONCLUSIONS

Several landslide inventories were obtained for both islands. They were point based landslide inventories and polygon based landslide inventories. From those inventories most of them were multitemporal landslide inventories. The landslide inventories made from the image interpretation of the Pleiades images of 2014, (final point based landslide inventory of saint Vincent) can be considered as an event landslide inventory because most of the landslides mapped there correspond to those landslides triggered by the Christmas Eve event of December 2013.

Even though most of the landslide inventories had an attribute table identifying the landslide type, it was not possible to reconstruct landslide type based inventories. Since the distinction between Debris Flow and Debris Slide is really difficult to make.

From the fieldwork and literature review it was possible to obtain the dates of some landslides, however as shown in tables 8 and 9, for Dominica there are almost one landslide per triggering event, and for Saint Vincent 4 landslide correspond to the Christmas eve Triggering event. Because of this there was no enough data to make a statistical analysis and be able to correlate the landslide occurrence with rainfall triggering events. and so be able to produce a landslide hazard map.

In order to be assessed the differences on the quality of landslide inventories an analysis of the contrast factor values of each one respect to the factor maps was done.

This analysis was done for each landslide inventory (DeGraff 1988; Pleiades, 2014; DEM; and Fieldwork), and per landslide type. For Saint Vincent, it was not possible to obtain a logical and consistent relation of the values obtained for the same landslide type and factor map unit through the different landslide inventories. As example rockslides had a CW of 2.21 for the geologic class Lava flows, domes, and associated deposits (LFD) on DeGraff landslide inventory, while for the same unit it had -5.17 on the Pleiades landslide inventory.

Because of this lack of consistency on the different landslide inventories it was decided that even though there was a classification of landslides per type, the final model would be made for landslides in general, and not per landslide type.

Comparing the general CW for each landslide inventory, it was clear that each landslide inventory had its own behavior, however, comparing their CW with the averaged CW of all point based landslide inventories it was possible to select the inventories that had a similar behavior in order to be used in the modelling.

For Saint Vincent DeGraff-1988 and Pleiades-2014 were similar, due to this both point based landslide inventories were integrated in one and used to model. For Dominica, DeGraff 1987 and DeGraff 1990 point based landslide inventories were integrated in one, to be used in the modeling.

From the different analysis made: Contrast factor value, weight of eviden and success rates it was possible to observe that the slope angle is the most important factor for both islands.

Because of this, a combination of slope with each factor map was used to produce the final models for both islands.

The assessment of different spatial representation was made by using the point landslide inventory to model and the polygon based landslide inventory to validate through a prediction curve.

From running success rates curves with point landslide inventories and polygon landslide inventories it is evident that with a point landslide inventory the produced map have a better success rate but a bad prediction rate, when the prediction rate is made with a polygon based landslide inventory.

After changing the standardization method it was clear that the benefit-goal can underestimate the real weight of some classes, giving as a result a huge area with los susceptibility.

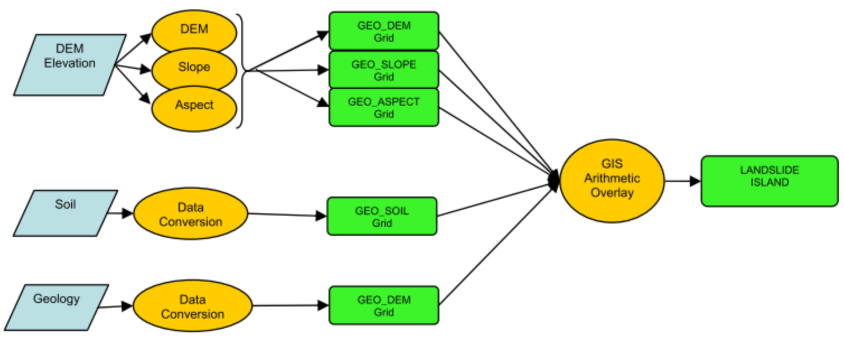
A national-scale landslide susceptibility assessment was done for Dominica and Saint Vincent, focusing on the generation of multi-temporal landslide inventory maps.

Comparing the results from this study with the existing landslide hazard maps (***Figure 1***) it is evident that the result obtained on this study is really different. In the case of Saint Vincent is much better. In the case of Dominica it is similar but it have also been improved.

These differences can be due to the amount of parameters used as well as the methods employed. For Saint Vincent, the existing map was made using geology (5 classes) and the topography factor was a slope map with 6 classes. For each factor map each class was weighted based on the landslide occurrences. On this study it is being used geology, landcover, geomorphology, soils, and topography (slope angle, and flow accumulation).

For Dominica, the existing model was made using topography (elevation, slope angle and slope aspect), geology and soils. For each factor map each class was weighted based on the landslide occurrences. To combine the maps it was used Arcgis using the methodology presented in Figure 40. Instead for this study it was also included the landcover map and the distance from ridges, and the method used was SMCE in ILWIS.

Figure 1: Model Data Processing: Equation Factor Grids as Model Input, Dominica



The map equation utilized in the development of susceptibility maps for Dominica is defined mathematically:

$$SM = E \bullet HS \bullet A \bullet SI \bullet GI$$

where, E is elevation classified, HS is the slope factor, S is a soil susceptibility index and G is a geology susceptibility index

Figure 40Model used by (USAID, 2006) to produce the landslide hazard map.

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ANNEXES


Dominica
Landslide Susceptibility
Scale 1:50,000
0 0.5 1 2 3 4 5 Kilometers
1 cm = 0,5 Km.
Connor Bay
Marceau Bay
Toucari Bay
Douglas Bay
Autrou bay
Batibou Bay
Hampstead Bay
Woodford Hill Bay
Rough Bay
Londonderry Bay
Pagua Bay
St.David Bay
Grand Marigot Bay
Petit Saufriere Bay
Rosalie Bay
Bout Sable Bay
Plaisance Bay
Pointe Mulatre Bay
Petite Savanne Bay
Grand Bay
Soufriere Bay
Woodbridge Bay
Pringles Bay
Roseau
Portsmouth
Layou River
Location map
Caribbean Sea
VENEZUELA
GUYANA
Susceptibility class
Low
Moderate
High
Landslide types
Debrisflow
Debrisslide / Debris avalanche
Earthflow
Flashflood and debrisflow channel
Coastal cliff
Rockslide
Rockfall
Quarry
Period of mapping
Mapped by J. DeGraff in 1987
Mapped by J. DeGraff in 1990
Mapped by ITC in 2014
Caribbean Handbook on Risk Information Management
GFDRR
ACP-EU Natural Disaster Risk Reduction Program
An initiative of the African, Caribbean and Pacific Group, funded by the European Union and managed by GFDRR
World Bank LAC
opportunities for all
ITC
UNIVERSITY OF TWENTE.

Saint Vincent
Landslide Susceptibility
Scale 1:50,000
0 0.5 1 2 3 4 5 Kilometers
1 cm = 0,5 Km.
Susceptibility class
Low
Moderate
High
Poor quality of input data
Landslide types
Debrisflow
Debrisslide / Debris avalanche
Earthflow
Flashflood and debrisflow channel
Coastal cliff
Rockslide
Rockfall
Quarry
Period of mapping
Mapped by J. DeGraff in 1988
Mapped by ITC in 2014
Location map
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GFDRR
World Bank LAC
opportunities for all
ITC
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Fancy
Owia
Owia Bay
Point Village
Sion Hill
London
Overland Village
Orange Hill
Waterloo
Georgetown
Chateaubelair
Chateaubelair Bay
Fitz-Hughes
Richmond
Lashum
Petit Wallibou
Byera
Mangrove
Colonaire Vale
Friendly
Keartons
Barrouallie
Princes Bay
Layou
Layou Bay
Questelles
Campden Park
Lowmans
Kingstown
Kingstown Bay
Cane Garden
Calliaqua
Calliaqua Bay
Biabou
Bridgetown
Spring
Peruvian Vale
Mt Pleasant
Ra-wa-cou