The World Bank

CHARIM
Caribbean Handbook on Risk Information Management

National Scale Landslide Susceptibility Assessment for Dominica

DOMINICA

May 2016

C.J. Van Westen
Faculty of Geo-information Science and Earth Observation (ITC), University of Twente.
E-mail: c.j.vanwesten@utwente.nl

WORLD BANK GROUP

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

Table of Contents

Summary 5
Acknowledgements 6
1. Introduction 7
1.1. About CHARIM 7
1.2. Definitions and requirements 8
1.3. Previous work on landslide susceptibility assessment 9
2. Method used for the national-scale landslide susceptibility assessment 10
2.1. Presentation of the method used 10
2.2. Considerations for selecting this method 13
3. Evaluating landslide triggering characteristics 15
3.1 Collection of existing data 15
3.2 Results 16
3.2.1 Disaster impact 16
3.2.2 Analysing main triggering events 17
3.3 Rainfall analysis 23
3.3.1 Analysing the distribution of rainfall over the island 24
3.3.2 Evaluation of rainfall thresholds 26
3.3.3 Rainfall frequency analysis 27
4. Landslide inventory mapping 29
4.1 Available landslide inventories 29
4.2 Landslide inventory mapping in 2014 33
4.3 Landslide inventory mapping in 2015 39
4.4 Some examples of landslide characteristics in Dominica 41
4.4.1 The Good Hope Landslide. 41
4.4.2 Layou Valley landslides: domino effects of landslides 41
4.4.3 San Saveur slide in 2010 42
4.4.4 Large landslides related to volcanic activity. 43
4.4.5 Landslides along the road network 43
4.4.6 Landslide during tropical storm Erika in the south-eastern part of Dominica 44
5. Landslide conditioning factors 46
5.1 Digital Elevation data 46

5.2 Geology and soils 47
5.3 Land-cover 51
6. Landslide susceptibility assessment 53
6.1. Evaluation of landslide factors using bi-variate statistical analysis.. 53
6.2 Results of the statistical analysis for Dominica 55
6.3 Summary.. 62
6.4 Landslide initiation assessment using SMCE 63
6.5 Generation of the susceptibility maps for Dominica.. 64
6.6 Validation of the final susceptibility maps 65
6.7 Combining and classifying the susceptibility maps 67
6.8 Evaluating the quality of the susceptibility map 69
7 Landslide susceptibility assessment along the road network.. 74
7.6 Segmentation of the road network into homogeneous sections. 74
7.7 Generation of landslide inventories for specific events.. 75
7.8 Landslide susceptibility assessment along the road network 77
8 Characterizing the susceptibility classes.. 79
8.1 Density and frequency information 79
8.2 Buildings located in the susceptibility classes.. 80
9 Conclusions and recommendations 82
9.1 Conclusions.. 82
9.2 Recommendations.. 85
10 References.. 88

Author:
Dr. Cees J. van Westen
Associate Professor
University Twente, Faculty of Geo-Information Science and Earth Observation (ITC)
PO Box 217, 7500 AA Enschede, The Netherlands
T: +31534874263
E: c.j.vanwesten@utwente.nl
I: http://www.itc.nl/about_itc/resumes/westen.aspx

This report should be cited as:
Van Westen, C.J. (2016) National Scale Landslide Susceptibility Assessment for Dominica. CHARIM Caribbean Handbook on Risk Information Management, World Bank GFDRR, ACP-EU Natural Disaster Risk Reduction Program.

Summary

The aim of this study was to generate a national-scale landslide susceptibility map for Dominica. As the available data turned out to be insufficient to generate reliable results, we decided to generate several new data layers, and significantly improved some of the existing data. We generated a new database of disaster events for Dominica, making use of many different sources. This is the most complete inventory to our knowledge. It is quite clear from this database that the landslide reporting became more frequent in recent years, and less information on landslides is available when going back in time, whereas the data on tropical storms and hurricanes seems to be much more constant over time. The underreporting of landslides is a big problem in trying to evaluate landslide frequency/magnitude relations. We also compiled all available landslide occurrence data from different sources. We had to digitize some of the older inventories which were only available in paper format. Eventually we compiled landslide inventories for 1987, 1990, 2007 and we generated a completely new landslide inventory using multi-temporal visual image interpretation, and generated an extensive landslide database for Dominica. The resulting landslide database contains 980 landslides from 1987, 183 from 1990, 161 from 2007 and 986 new landslides were mapped representing the situation in 2014. We also compiled landslide inventories along the road network for five recent events from the maintenance records of the Ministry of Public Works. These contained 27 landslides for September 2009, 20 for October 2010, 84 for September 2011, 74 for November 2011 and 44 for April 2013. After completing the first version of the report a large number of landslides were triggered by tropical storm Erika in August 2015. We decided to include these data in this second version of the report, and also update the landslide inventory and susceptibility map. UNOSAT mapped a total of 1554 new landslides as polygons using semi-automatic image classification and BRGM mapped 89 landslides as points in the field.

We analyzed the triggering conditions for landslides as far as was possible given the available data, and generated rainfall magnitude-frequency relations. However, there were not enough data (both in terms of landslide dates and date-related inventories) to be able to calculate magnitude-frequency relations for landslides, in terms of the number or density of landslide per different frequencies. We applied a method for landslide initiation susceptibility assessment that is the best possible, given the availability of data. A bi-variate statistical analysis provided indications on the importance of the possible contributing factors, but the actual combination of the factor maps was done using a subjective expert-based iterative weighing approach using Spatial Multi-Criteria Evaluation (SMCE). The method is transparent, as the stakeholders (e.g. the engineers and planners from the four countries) and other consultants can consult the criteria trees and evaluate the standardization and weights, and make adjustments. The method analyses only landslide initiation susceptibility; landslide runout susceptibility should be included in local and site-investigation studies.

The first version of the landslide susceptibility map was generated in June 2015. Shortly after that, in August 2015, tropical storm Erika triggered hundreds of landslides in Dominica. We decided to include the new event in the analysis, as this was a major event with many landslide, and to adjust the landslide susceptibility map so that the new landslides were included in the high and moderate susceptibility classes. The method for landslide susceptibility assessment was further expanded by including the historical landslides in the susceptibility map and by manual editing of the final map. The whole map was visually checked, and the modelled zones of high, moderate and low susceptibility were adapted when necessary, so that they reflect the best situation according to the mapping geomorphologist. This was a rather time consuming activity, but it allowed to analyse the different parts of the map separately, and therefore obtain results that also are valid for a local scale, and not only for a national scale. The manual editing of the susceptibility map was also done to simplify the susceptibility units.

In the final landslide susceptibility map, 3% occurs in low susceptibility, 8 % in moderate, and 89 % in high susceptibility. Of the landslides that were triggered during tropical storm Erika 5% occurred in low susceptibility areas, 13% in moderate and 83% in high susceptibility classes. When considering the landslide density, the values for low, moderate and high 0.039, 0.262 and 5.658 % respectively based on area density and 0.174, 0.997 and 9.849 nr/km^2 respectively for number density. It was very difficult to determine the frequency of the landslide densities due to a lack of sufficient event-based inventories. We have separated four types of events: frequent, moderate, large and major events. We selected landslide inventories with increasing densities to represent these four events.

For the road network we also generated a landslide susceptibility map by subdividing the primary road network into homogeneous segments which were characterized by information from a road database provided by the Ministry of Public work. We also used SMCE to generate a susceptibility map which we characterized using the five available landslide inventories along the road. We calculated the maximum and average landslide density, as the number of landslides per kilometre of road. For the road network we also made an estimation of the

average landslide density (as number per kilometer of road) for frequencies. Also exposure analysis was carried out for buildings. We mapped all buildings in Dominica using a combination of satellite image classification and visual interpretation.
One should be careful when using the national-scale landslide susceptibility and hazard map for evaluating the landslide hazard of individual buildings and critical infrastructure. The scale of this map is not appropriate to utilize it for local or detailed scale analysis. Other, more detailed landslide hazard methods should be used for these scales, which also require more detailed information on soil characteristics, such as soil depth, hydrological and geotechnical properties.

Acknowledgements

We would like to thank the following persons who carried out MSc research in Dominica in the framework of this project: Diana Patricia Lozano Zafra, who worked with us on the national scale landslide susceptibility assessment and Jovani Yifru for his work on the landslide susceptible assessment along the road network. We also thank Xsa Cabria for her study on the effects of weathering in rocks along coastal road cuts in Dominica. Susmita Dhakal helped in the susceptibility assessment. Marcella Soriano did a lot of the rainfall analysis, and Victor Jetten did the rainfall frequency analysis. Lixia Chen helped us in mapping the buildings and roads. Koert Sijmons generated the cartographic products in the form of a landslide inventory map and landslide susceptibility map. Wim Feringa developed the web-based platform where all results can be found: www.charim.net. We thank Dinand Alkema for his patience and work as project coordinator.

We would like to thank the following persons for their great support while being in Dominica for fieldwork and during several of the workshops in Dominica, Saint Vincent and the Netherlands:

- Kelvin Rolle (Chief Planner), Annie Edwards (Physical planner, Physical planning division), Lyn Baron (GIS technician, physical planning division), Miguel StVille (Development control officer, physical planning division), Naomi Dorival (Development control officer, physical planning division).
- Kendell Johnson (Chief Engineer), Emile B. Lancelot (Senior Engineer, Ministry of Public Works), Jodie Dublin (Civil Engineer, Ministry of Public Works), Nicole S. Tyson (Engineer, Ministry of public Works), Malcolm Belle (Road surveyor, Ministry of Public Works), Terbby Edwards (Civil Engineer, Ministry of Public Works),
- Don Corriette (Office of Disaster Management), Mandela Christian (Office of Disaster Management)
- Nick LaRocque (GIS specialist, Survey department), Kendell Barrie (GIS specialist, Survey department) and Vernie Marcellin – Honore (HydroMet department).

We would like to thank Jerome DeGraff, who was supporting us and giving advice though e-mail with landslide guides, to make image interpretation as well as different reports and articles.

1. Introduction

1.1. About CHARIM

In 2014 the World Bank initiated the Caribbean Risk Information Program with a grant from the ACP-EU Natural Disaster Risk Reduction Program. A consortium led by the Faculty ITC of the University of Twente is responsible for conducting capacity-building workshops, generating training materials, and creating hazard maps to expand the capabilities within participating infrastructure and spatial planning ministries to use hazard and risk information for decision-making.
The main objective of this project is to build capacity of government clients in the Caribbean region, and specifically in the countries of Belize, Dominica, St. Lucia, St. Vincent and the Grenadines and Grenada, to generate landslide and flood hazards and risks information 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. The results of the CHARIM project are shared through a web-based platform: www.charim.net

One of the sub-objectives of the project was to "***develop a theoretical framework for landslide and flood hazards and risks assessments, based on the review of existing quantitative and qualitative assessment methods and their appropriate use".*** Another sub-objective was to ***"develop nine national hazard mapping studies in the five target countries. One in Belize related to floods and two on each island for landslides and flood".***

This report addresses specifically the methods and results used for the national-scale landslide susceptibility assessment for the country of Dominica.
It will do so by first introducing the method of analysis, and the reasons for selecting this method. In the next chapter the available data for landslide susceptibility assessment will be presented, focusing on the existing landslide inventories and factor maps.
The third chapter presents the methods and results used for generating the compiled landslide inventory. The fourth chapter presents the method used for statistical analysis and the presentation of the results. The fifth chapter presents the method of Spatial Multi-Criteria Evaluation and the results for the country of Dominica. The Sixth chapter will present the validation and generation of the final susceptibility map. The report will end by discussing the critical points in relation to the available data and suggestions for additional data collection.

1.2. Definitions and requirements

The terminology used in this report follows that of the Guidelines for landslide susceptibility, hazard and risk assessment and zoning, produced by the comprehensive landslide research project "SAFELAND, Living with landslide risk in Europe: Assessment, effects of global change, and risk management strategies", funded by the European Commission. The guidelines were also worked out as a publication by Corominas et al. (2014), based on a large number of literature sources, among which Fell et al (2008), TC32, UN-ISDR (2004):
For this reports the following three definitions are of importance:

Landslide inventory*: The collection of landslide features in a certain area for a certain period, preferably in digital form with spatial information related to the location (as points or polygons) combined with attribute information. These attributes should ideally contain information on the type of landslide, date of occurrence or relative age, size and/or volume, current activity, and causes. Landslide inventories are either continuous in time, or provide so-called event-based landslide inventories, which are inventories of landslides that happened as a result of a particular triggering event (rainfall, earthquake).*

Landslide susceptibility map*: A landslide susceptibility map contains a subdivision of the terrain in zones that have a different spatial likelihood that landslides may occur. The likelihood may be indicated either qualitatively (as high, moderate low, and not susceptible) or quantitatively (e.g. as the density in number per square kilometres, or area affected per square kilometre). Landslide susceptibility maps should indicate the zones where landslides have occurred in the past and where they may occur in future and possibly also the run-out zones.*

Landslide hazard map*: 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. Landslide hazard maps should indicate both the zones where landslides may occur as well as the run-out zones. 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. A complete quantitative landslide hazard assessment includes:*

- *Spatial probability: the probability that a given area is hit by a landslide.*
- *Temporal probability: the probability that a given triggering event will cause landslides*
- *Volume/intensity probability: probability that the slide has a given volume/intensity*
- *Run-out probability: probability that the slide will reach a certain distance downslope*

Depending on the scale of the hazard assessment, and the available input data, hazard may be expressed in different ways. At large scales it could be expressed as failure probability, using a factor of safety approach, and given certain triggering events with a given return period. At medium to small scales it may be expressed as the expected landslide density within particular units for a given return period.

Based on these definitions and the situation in the country of Dominica, it is currently only possible to generate landslide susceptibility maps at the national scale, and it is not possible to generate a national landslide hazard map, as we are not able to represent spatial, temporal, size and run-out probability for landslides for the entire island at a scale of around 50.000, giving the limitations in the available data. These limitations are mostly related to lack of sufficient information between the relation of the frequency and magnitude of triggering events (extreme rainfall) and the landslide caused by them. At a national scale we were only able to generate a qualitative map that shows the subdivision of the terrain in zones that have a different likelihood that landslides of a type may occur, without actual information on the frequency of landslides for different return periods, the size probability and the run-out probability. At best we were able to generate national scale qualitative landslide hazard maps that have semi-quantitative descriptions of the legend classes, indicating the expected landslide densities for different return periods.

1.3. Previous work on landslide susceptibility assessment

In the country of Dominica previous attempts to generate landslide susceptibility maps have been carried out. 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, data published in articles was used, and integrated with a Geology map of all the Caribbean islands to obtain a national 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).

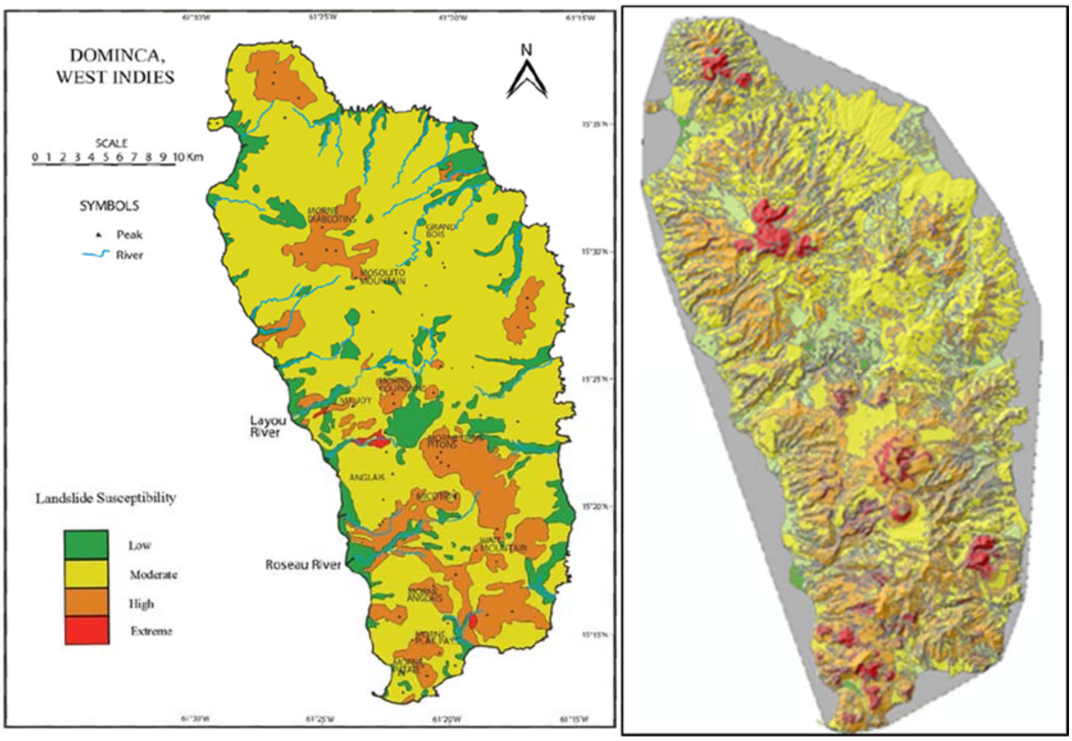


Figure 1-1. Previous landslide susceptibility maps for Dominica: Left: study carried out by DeGraff (1987, 1990) Right: study carried out by CIPA for USAID in 2006, as part of a multi-hazard mapping project.

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 by DeGraff in 1987 and 1990 with the interpretation of aerial photographs and fieldwork. The aerial photographs were from February 2 of 1992 at a scale of 1:10,000. The fieldwork was carried out 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, using an expert-based weighting approach to generate the landslide susceptibility map, which they named as hazard map.

Finally, in 2007 Mr. Zachary Dean Andereck did a Master thesis analysing a case study of the villages of Grand Fond, Petite Soufriere and Mourne Jaune, where various landscape indicators were utilized in multiple logistic regressions to calculate landslide probabilities. Infrastructural components were examined in relationship to a landslide probability map developed for the research area.

2. Method used for the national-scale landslide susceptibility assessment

2.1. Presentation of the method used

Figure 2-1 presents the method which was used for the national scale landslide susceptibility assessment for the Commonwealth of Dominica. The method focuses on the assessment where landslides are likely to initiate, and not on the possible run-out areas. Run-out susceptibility assessment should be taken into account when doing local and site-investigation studies.
The method consists of a number of steps which are described in detail in the following sections. Here a summary of the steps is give:

Step 1: Generating landslide inventories. The first, and very important step is to generate a comprehensive landslide inventory. Several landslide inventories were available for Commonwealth of Dominica. However, these are far from complete, and an attempt was made to update these using several sources of information: interpretation of high resolution satellite images, collection of historical information on the dates of occurrence of past landslide events, collection of available data from the national emergency management organisation and from road maintenance records. The resulting landslide inventory map contains many more landslides than were initially available. Landslides were also classified based on their type, and a differentiation was made between initiation and runout areas.

Step 2: Analysis of triggering events. An analysis of triggering events is carried out in order to be able to correlate landslide inventories of particular triggering events to the frequency of rainfall related to these events. If such a relation could be established we could also characterize the landslide susceptibility classes with indicative landslide densities for different frequencies, and would then be able to convert the susceptibility map into a hazard map. From the available data on landslide occurrences a series of triggering events were identified. Rainfall data was used to estimate return periods of daily rainfall, with the aim to correlate these with triggering events for which landslide information was available.

Step 3: Generation of factor maps that contribute to landslide occurrence. A Digital Elevation Model was generated using available data, which was used for generating derivative maps, such as elevation classes, slope steepness, slope direction and flow accumulation. Exiting geological maps, and soil maps were used. Drainage lines, roads, coastlines and ridges were used to generate distance maps to evaluate the effect of landslide occurrence close to these features. Land cover maps were generated by the BGS using object oriented image classification based on Pleiades images.

Step 4: Bivariate statistical analysis. The weights of evidence modelling (WOE) was used as an exploratory tool to evaluate the importance of the factor classes. A GIS-based script was used to carry out the WOE modelling for each factor map in combination with the landslide inventory map. Different analysis was done for shallow soil-related landslides and for rock related landslides and rockfall as they were expected to have different importance of causal factors. Based on the calculated weights of evidence a selection was made of the most relevant causal factors. When the results of the statistical analysis provided inconclusive results we went back to the creation of the factor maps. Several new combinations of factor maps were made which were again tested using the weights of evidence method. For instance a factor map lithology can be combined with a map of slope classes, so that the resulting map gives a better relation with landslides, and the combined classes have higher weight values. The process of generating factor maps and evaluating their importance is done in an iterative process, and the factors used may be different for each individual situation.

Step 5 - 7: Spatial Multi-Criteria Evaluation. We decided not to use the results of the weights of evidence directly as the basis for the landslide susceptibility assessment, due to the inaccuracies encountered with the input data, and with the landslide inventories, and due to inconclusive results from the statistical analysis. The importance of the various factor maps should be explainable in terms of their contribution to landslide processes, and therefore we decided to include expert opinion in the process through the SMCE process which consists of several steps.

.

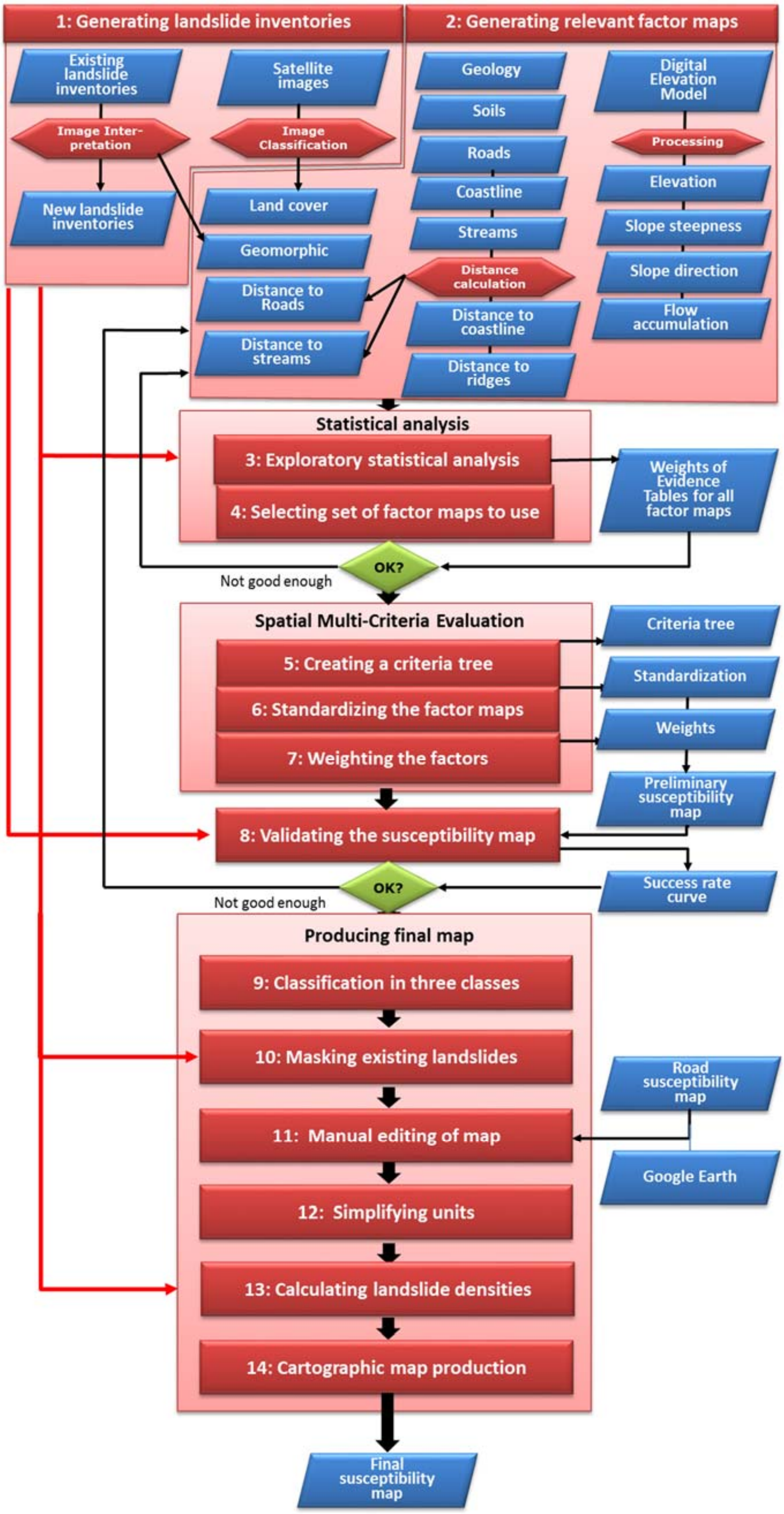


Figure 2-1: *Flowchart of the method used for the generation of the national scale landslide susceptibility maps. See text for explanation. See also : http://www.charim.net/use/83*

First we generated a *criteria tree* in which we grouped the various causal factors in groups. Then we *standardized* the individual causal factors, based on the calculated weights of evidence. However, we used the calculated weights as a guidance and in several occasions we decided to adjust these as they seemed to be more logical based on our observations in the field and our knowledge on landslide occurrences. The standardization resulted in values for each factor map ranging from 0 to 1
After standardization we weighted the individual factor maps and the various groups by comparing them with each other and by assigning a certain rank to them. This resulted in weights which were also represented in a range of 0 to 1. The last stage of the Spatial Multi-Criteria Evaluation was the generation of a composite index map, which integrated the standardization and weighing for all indicators in the criteria tree, resulting a susceptibility map with values ranging from 0 to 1.

Step 8: Validation of the susceptibility map. In order to validate the susceptibility map we combined the composite index map resulting from the Spatial Multi-Criteria Evaluation with the original landslide inventory map. We then calculated the success rate, which indicates the relation between the percentage of the susceptibility map ordered from the highest to the lowest values, and the percentage of landslides occurring in the locations of these values. We applied different methods for analysing the success rate. For instance we only took the initiation areas of all landslides, or separated the landslides in groups with different types and analysed the success rate for them. When we had landslide inventories from different triggering events we also tested the quality of the map for these different inventories. We also carefully analysed the spatial distribution of the susceptibility values visually in the map by overlaying it with a hill shading image of the country and with the landslide inventory in order to evaluate whether the highly susceptible zones were in accordance with our experience in the field, and with the overall geomorphological situation. When we considered that this relation was not good enough or when the success rate was not good enough (e.g. by applying certain rules such as that 70 percent of the landslides should be located within 30 percent of the map) we decided to go back to the selection of relevant factor maps and repeated the statistical analysis and the spatial multi-criteria evaluation for other combinations of factors. So the landslide susceptibility assessment was an iterative procedure, which was done until we were satisfied with the results. We also discussed the results with a landslide expert (Jerome DeGraff) that was involved in earlier landslide inventory and susceptibility assessments on the island, and also with a group of professionals from the country that visited ITC in the Netherlands during a period of one month in spring of 2015. Based on their suggestions a number of modifications were made.

Step 9: Classification of the landslide susceptibility map. We used the susceptibility value map, and the success rate to subdivide the map in three classes of susceptibility (high, moderate and low). The high susceptibility class has the highest landslide density and the areas should be a small as possible and limited to those zones where landslides have occurred in the past and are most likely to occur in future. The low landslide susceptibility class is used for those areas where landslides are not expected to occur at all, or in very seldom cases. Moderate landslide susceptibility forms the middle class, which should be kept as small as possible, as this is the class which is neither dangerous nor safe, and further studies are needed before planning decisions can be taken.

Step 10: Masking existing landslides. The final map should also contain the areas where landslides have occurred in the past. They should be included in the high susceptible zone, as it is possible that landslides may happen again in these conditions, unless remedial measures have been adopted after the landslide occurrence. Therefore the existing landslide inventories were used and the locations were masked as “high susceptibility”” in the map. Zones immediately surrounding these were indicated a “Moderate susceptibility”.

Step 11: Manual editing. The landslide susceptibility map with the added historical landslides still is in a shape that is too generalized. This is due to the poor quality of the input data, and due to the nature of the analysis method using a combination of statistical analysis and spatial multi-criteria evaluation, which use generalized weights for maps applied to the entire area, whereas there may be exceptions that need to be taken into account locally. Therefore it is important that the final susceptibility map is checked carefully and edited. This is done by exporting the map to an external photo-editing software (CorelPhotoPaint) where it is possible to edit the three classes using the Paint tool. The best is to do this on a dual screen, by comparing the map with a Google Earth image and with a hill shading image overlain with the landslide susceptibility map, plus topographic information, like rivers, roads, buildings etc. This way each part of the area can be visually checked, and the modelled zones of high, moderate and low susceptibility can be adapted, so that they reflect the best situation according to the mapping geomorphologist. If there is a landslide susceptibility map available that is made for the road network, it is also relevant to use this map in editing the final susceptibility map. This is a rather time consuming activity, but it allows to analyse the different parts of the map separately, and therefore obtain results that also are valid for a local scale, and not only for a national scale.

Step 12: Simplifying units. The manual editing of the susceptibility map is also done to simplify the susceptibility units. After running the statistical analysis and spatial multi-criteria analysis, the resulting landslide susceptibility raster map shows many small areas with different degrees of susceptibility. Sometimes the susceptibility differs from pixel to pixel, due to variations in the input maps (e.g. slope classes may differ very locally). In order to be able to use the resulting map as a basis for planning, the area should be subdivided into zones with different likelihood of landslide occurrence. Therefore during the manual editing phases, areas are simplified, and classified into one of the three classes, removing the large local variation. Also after completing the manual editing process, still many locations with isolated pixels remain. These were subsequently removed in GIS using a majority filter. The resulting landslide susceptibility map can also be converted into a polygon map.

Step 13: Calculating densities. One the final landslide susceptibility map has been obtained, it is now possible to calculate the number of landslides in the three susceptibility classes. This is now not done anymore to validate the map, as the historical landslides were included in the map in step 10, but now the aim is to characterize the susceptibility classes in terms of landslide density (both in area and in numbers). If different event-based inventories are available, it is also possible to calculate landslide densities for each of them, and if also frequency information is available it is also possible to give an indication of the spatio-temporal probabilities (the density of landslides per class for different return periods of the triggering event). It is also possible to calculate the number of exposed buildings and other infrastructure if available. Especially the manual editing in step 11 allows a much more realistic estimation of the exposure.

Step 14: Cartographic map production. The final stage of the landslide susceptibility assessment consisted of the cartographic map production. Also a separate map with the landslide inventory itself was produced. The base map was generated using a hill shading map generated from the Digital Elevation Model, together with the drainage network, the road network, the buildings, airports, administrative units, names and other relevant topographic information in order to make the map better readable. These maps are available as PDF's on the CHARIM webpage. Also the digital versions of the landslide inventories and the landslide susceptibility maps were made available through the GeoNode.

2.2. Considerations for selecting this method

The method described above for the national scale landslide susceptibility assessment was selected based on the following considerations:

The mapping scale. The maps are made at a scale of 1:50.000. This allows to represent the entire country into one single map sheet. The map cannot be used for local scale or site investigation scale analysis, however, when the editing of the map is step 11 is done carefully, the map can also be reasonable at the local level. The application of more detailed methods based on physically-based modelling was not possible due to the lack of sufficiently detailed soil information, and Digital Elevation data. For more detailed studies more information should be available on soil depth and on the geotechnical and hydrological soil characteristics so that more detailed types of analysis can be carried out. We decided also to exclude landslide run-out analysis at a national scale as the available data was insufficient for that and the run-out zones are not that significant when looking at a national scale.

The objective of the assessment.
Such national scale maps are intended to be used by the governments to:

- Serve as living and dynamic baseline map for the planning, design, management and implementation of a long-term landslide reduction strategy. This map should be updated regularly as new/improved data becomes available

- Include them as a factor in national scale land use planning, by outlining the zones that are most susceptible to landslides;
- Identify the areas where more detailed investigations are required for the planning of critical infrastructure;
- Form the basis for identification of the strategies to increase the resilience of the national road network by prioritizing the development of contingency plans and required complementary studies during planning and design of new infrastructure;
- Use for the prioritization of creation of contingency plans for exposed communities;
- Contribute to inform required expansions of the hydro-met monitoring system as well as monitoring of landslides;
- Inform watershed management, environmental assessments and studies on environmental degradation; and
- Be used to inform the planning of agricultural or mining activities that could increase slope instability.

The objectives mentioned above are such that the national scale landslide susceptibility should be used a baseline information for national level planning, and for risk communication. The map should also be able to outline areas that should be avoided in future developments, and the high susceptible zones are considered to be a basis for restrictive zoning as a basis for building control, together with other hazard maps. The susceptibility map can also be used together with susceptibility and or hazard maps for other hazardous processes (flash flooding, coastal flooding, tsunamis, volcanic hazards, seismic hazards and wildfire hazard) as a basis for multi-hazard assessments. The maps can also be used for analysing the exposure of the existing buildings, people and road infrastructure.

The complexity of the area. The geology of the island is composed of volcanic rocks with strongly varying composition, such as ignimbrites, lava flows, lahar deposits, and volcanic ashes. They are very heterogeneous and have not been mapped in great detail. There is often a vague difference between the term rocks and soils in engineering terms, as many of the volcanic deposits have a relative low degree of cementation and consolidation. Also due to the intense tropical weathering unconsolidated materials may be very thick. These deposits may sustain near vertical road cuts which are stable, however, when weathering is taken into account such road cuts may cause problems in the future.

The available data. After a first inventory of the existing data we discovered that there were major deficiencies with respect to the available data, both in terms of the available landslide inventories and with the available factor maps for carrying out the analysis. The large heterogeneity of volcanic deposits is unfortunately not portrayed in the available maps for the island. The geological maps are rather general and do not focus on the specific volcanic deposits. The soil map is more detailed and show a large differentiation, but they are focusing on pedologic soil characteristics for agriculture purposes.

The resources available. As the assessment was originally planned as a desk study, only limited time was available for image interpretation and fieldwork. Nevertheless, after evaluating the problems with the existing data we decided to spend more time in carrying out a detailed image interpretation for landslide characterization, and also to involve a number of Master of Science students in the basic data collection. Also a collaboration was established with the British Geological Survey that supported in the creating of land cover maps and landslide inventory maps for some of the islands. Due to the many landslides that were triggered by Tropical Storm Erika in August 2015, we decided to generate a new version of the landslide susceptibility map that incorporates the new data and we also carried out an extensive check of the final map.

3. Evaluating landslide triggering characteristics

One of the key factors for the generation of landslide susceptibility and hazard maps is information on when landslides occurred in the past, and triggered by which events. Intense rainfall is considered to be the most important trigger of landslides. Even though there might be earthquakes occurring on the island, their expected intensity is generally not considered to be high enough to cause substantial landslide problems. Also human interventions may increase the susceptibility to landslides, e.g. through deforestation, clear cutting, improper drainage practices, or slope cutting, but still a rainfall would be required to actual trigger the landslides.

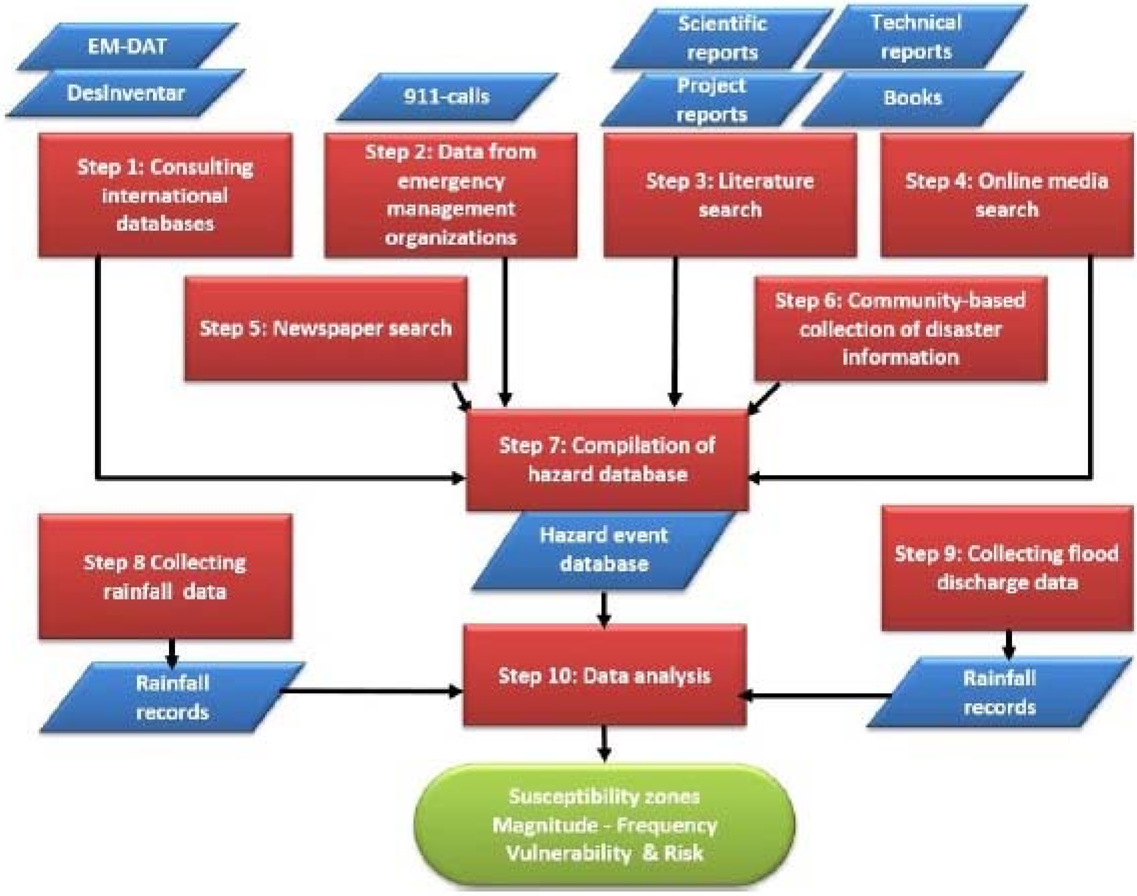


Figure 3-1: Overview of method for collecting information of past events.

3.1 Collection of existing data

In order to collect information on dates of historical disaster events a study was carried out using various sources to reconstruct the major disaster events in the history of the island (see Figure 3-1). Disaster data was downloaded from the CRED-EMDAT database (Guha-Sapir et al., 2015). The information in this database is rather limited (See Table 3-1). No specific landslide information

We visited the Office of Disaster Management (http://odm.gov.dm/) but they only had a very simple record about historical disasters in the country (http://odm.gov.dm/index.php/resources/major-events-affecting-dominica-1975-2010) which was also not updated after 2010. We asked our local counterparts if there had been searches using local newspaper records for the past decades, but unfortunately there weren't any. We also consulted the online media for the island, and especially the information on DominicaNewOnline (http://dominicanewsonline.com/news/?s=landslide) was very useful. However, information was only available for a limited period of time. We also collected information from various other sources on the internet. Some of the best sources for older information were Lockhart (1879) and O'Keefe and Conway (1977) for the older disaster occurrences. They based their own data on extensive analysis of newspaper searches for the various countries.

Table 3-1: Disaster information from the EMDAT database: http://www.emdat.be/country_profile/index.html

Date	Disaster Type	Deaths	Affected	Economic loss (Million US$)
03/09/1930	Storm	2000	?	?
25/09/1963	Storm (Hurricane Edith)	?	?	2.6
29/08/1979	Storm (Hurricane David)	40	72100	44.650
09/10/1984	Storm (Hurricane Klaus)	2	10000	2
17/09/1989	Storm (Hurricane Hugo)	0	710	20
03/09/1995	Storm (Hurricane Marilyn)	2	5001	20
14/09/1995	Storm (Hurricane Luis)	0	?	175
17/11/1999	Storm (Hurricane Lenny)	0	715	?
06/10/2001	Storm (not mentioned in other sources	3	175	?
21/11/2004	Earthquake	0	100	?
21/08/2007	Storm (Hurricane Dean)	2	7530	20
25/09/2011	Storm (Layou flooding)	0	240	?
26/08/2015	Storm (Tropical Storm Erika)	30	28594	482.8

Also Benson et al., (2001) give an overview and we also consulted http://www.hurricanecity.com/city/dominica.htm. Road maintenance and clearance reports were obtained from the Ministry of Public Works and Ports for five rainfall events: September 3/2009 (tropical storm Erica), October 31/2010 (Hurricane Tomas), September 28/2011 (tropical storm Ophelia), November 28/2011, and April 17-25/2013. The reports don't have any spatial references for the landslide locations, they only have the road sections starting and end point where landslide clearance had been done and the amount of money spent for clearance. To locate those areas and prepare them as geo-spatial dataset, the available high resolution images and thematic maps of the island were used. After generating the first version of the national landslide susceptibility map for Dominica in June 2015, the tropical storm Erika hit the island on 27 August 2015, which triggered many landslides. We also received later the landslide data for this event from different sources (Commonwealth of Dominica, 2015, Garnier et al., 2015).

3.2 Results

The preliminary results of the data collection on disaster events are presented in this section and all data are aggregated into a single table (Table 3-5). The data covers a long period starting in the 18th century. For many of the historical events it was possible to reconstruct the date of occurrence. This is important in order to correlate these dates of occurrence with rainfall data for the same period.

3.2.1 Disaster impact

Between 1925 and 2015 thirty-five Dominicans lost their lives due to landslides based on data from DeGraff et al. (1989b) and our own compilation. However, for some of the major events it is not clear whether the reported casualties are landslide related. In 1979, Hurricane David passed over the southern part of Dominica and was followed several days later by close passage of Hurricane Frederic. A total of 42 people were killed, although some other sources mention 53. It is not clear whether there are landslide victims among them. Landslide damage to roads was estimated to be $23,000 (CEPAL, 1979). Because landslides are triggered by storms other than hurricanes, slide clearance and road repair has a long-term cumulative economic impact. Between June 1983 and July 1987, over $4621000 was spent on Dominica on clearing landslides debris and associated repairs (Table 3-2). This represents an average annual expenditure of $121,000 (DeGraff et al., 1989). We couldn't find more recent information related to road damage in economic terms, however, the online news media had frequent reports about economic damage for parts of the road network and about huge loans for the Dominican government to improve the road network.

Table 3-2: Annual costs of landslide damage to roads in Dominica (Source: DeGraff et al., 1989)

Fiscal year	Landslide costs (in thousands of dollars)
1983-1984	92.8
1984-1985	269.0
1985-1986	71.7
1986-1987	63.0

Landslide events that caused most attention are the 1927 Trafalgar landslide (04/10/1924), which killed 7 persons, the Boetica landslide (11/11/1967), which killed 5, the 1979 Bagatelle landslide (22/09/1977) killing 11 people, and the Layou valley landslides that occurred between 1987 and 1998. Dramatic failures occurred on November 18 and 25 1997, and a natural dam was formed which breached on November 21. It caused the temporary evacuation of 600 residents, loss of an access road to banana producing areas, closure of Layou Valley Hotel, loss of Swing Bridge, loss of income through fisheries and tourism related sales and severe disruption of traffic (Benson et al., 2001; DeGraff et al., 2010) . A landslide lake was formed after subsequent landslides in the same year (1979). This lake survived until May 2011 when the dam was broken and the dam break flood caused a lot of damage in the Layou River downstream. Recent landslide events that caused casualties were the San Sauveur landslide (24-5-2010) which killed 3 people, and the Pont Cassé road accident where a culvert was washed out in April 2012, and two people were killed in a car which fell in the hole. A landslide occurring on July 25 2012 in Picard hit a power line and caused power outage in a large part of Dominica (Sugar Loaf to Caupuchin down to Ti-Baie, to North End Marigot, entire Portsmouth from Fond Cole to Ti-Baie on the west coast, entire South Feeder from Morne Prosper to Petite Savanne, and part of Belfast Feeder from National Bank in Canefield to Wet Area and DCP). This also shows the vulnerability of the infrastructure as one single landslide can have a lot of effect.

Benson et al. (2001) studied the impact of natural disasters on the economy of Dominica for the period between 1975 and 1999. Hurricane David, a Category 4 hurricane, directly impacted the country on August 29, 1979, and was particularly devastating, resulting in considerable world media attention and international disaster relief. It caused 42 casualties, 3000 people needed medical attention, and made 75000 persons homeless, 12 % destroyed (2000 units) 50% severely damaged (8000 units) and 22% moderately damaged. The total estimated damage was over EC$ 53.8 million. Hurricane Frederick, which closely followed, and Hurricane Allen in 1980 exacerbated the effects of David. Hurricane Hugo, another Category 4 storm, dealt a glancing blow to Dominica whilst devastating St Kitts and Montserrat to the north. Hurricane Hugo impacted the country on September 17, 1989, although it was not directly hit, it still had a serious impact with total damage estimated at EC$ 20 million. Three storms in 1995 had a severe cumulative impact. Tropical storm Iris on August 27, Hurricane Marilyn on September 5 and Hurricane Luis on September 18. They caused 1 casualty, and caused a projected economic growth rate of 4.5% to be converted into a decline of 2%. Hurricane Lenny, also a Category 4 storm, which occurred on November 18-19, 1999, was unprecedented in moving from west to east across the northern Caribbean. It caused largely coastal damage to Dominica and neighbouring Guadeloupe and Martinique. Recent data from the damage and needs assessment report (Commonwealth of Dominica, 2015) after the tropical storm Erika, indicated a total damage and loss of EC$1.3 billion (US$483 million), equivalent to approximately 90% of Dominica's Gross Domestic Product (GDP). The majority of damages were sustained in the transport sector (60 percent), followed by the housing sector (11 percent) and agriculture sector (10 percent). Out of a total population of 72,340 persons, 11 persons were confirmed dead, 22 missing, 574 homeless and 713 evacuated with approximately 7,229 impacted by the event in disaster declared areas. Later on death toll was established at 30.

3.2.2 Analysing main triggering events

For analysing the frequency of tropical storms and hurricanes, which are important in order to establish a relation with landslide occurrence, as they are the main landslide triggering events in Dominica, we analysed different sources. Benson et al. (2001) cite information about the frequency of tropical storms and hurricanes in Dominica (See Table 3-3). Another source (http://www.hurricanecity.com/city/dominica.htm) reports 31 tropical storms and 22 Hurricanes in the period 1872-2014. From the table it can be concluded that major Hurricanes such as David, occur on average once every 125 years in Dominica. This was also the most devastating event in historic times, apart from tropical storm Erika. However, we do not know about the number of landslide that were triggered by hurricane David. There is a bad quality map available (See later on when we discuss the available landslide inventories), but it is not possible to see individual landslides on this map.

Hurricanes with lesser intensity (<4) and tropical storms are much more frequent in Dominica, and their average interval ranges from 2.9 to 23.8 years. Again, it will be quite difficult to establish a relation between the frequency of these triggering events and the number of landslides caused by them, as we will see later on.

*Table 3-3 OAS (1996) and Wagenseil and Watsons (1996) summary of the general statistics of tropical storms in Dominica, based on Hurstat database from 1886 to 1996. * Category 4 Hurricane interval is difficult to establish based on limited data. Given that there were 2 events (1834 and 1979) we estimated the values.*

Category of storm	Tropical Storm	Category 1	Category 2	Category 3	Category 4
Intervals found	35	17	7	4	2
Average interval (years)	2.9	5.8	13.6	23.8	125*
Maximum interval (years)	12	20	34	70	145*
Minimum interval (years)	1	1	2	2	70*

Landslides might also be triggered by earthquakes. Earthquakes in Dominica derive from two different sources. The Eastern Caribbean is a zone of subduction in which the Atlantic Plate pushes under the Caribbean Plate, causing tectonic earthquakes, which may be quite large (a 7.4 Magnitude earthquake occurred in nearby Martinique in 2007). The second source of earthquakes originates from the seismic events relating to Dominica's origin as a volcanic island, a consequence of plate-tectonic forces (SRU, 2000). The earthquake of 8 February 1843 was reported to have an intensity of VIII to IX, and causing fault displacement of 20 feet vertically and several feet horizontally in the Melville Hall area. This records indicate that "*Mountains were visibly crumbling away*" (O'Keefe and Conway, 1977), which might be a poetic way of indicating that there were many earthquake induced landslides. Earthquakes have not caused serious disruption in recent times. There is little publicly available information on earthquakes in Dominica. In 2004 a 6.3 earthquake occurred 50 km NNW of Roseau (15.699°N, 61.654°W). At least twenty houses were damaged and power outages occurred in northern Dominica, and a church tower collapsed in Portsmouth (See photo). There were no clear reports on co-seismic landslides. However, in a study in the east part (Grand Fond, Petite Soufriere and Mourne Jaune) Andereck (2007) reported that local villages indicated that on this day a large number of landslides occurred, after a number of days with intense rainfall. Another evidence is a report by the Physical Planning department that after the earthquake in 2007 a large crack appeared in the slopes near the village of Penville. The northern coast of Dominica appears to follow an active fault, and several large rockslides are visible along this line. According to Teeuw et al. (2009) there is a possibility for a large earthquake-induced rockslide that might even trigger a potentially dangerous tsunami. Overall, there is a significant chance of earthquakes that may trigger landslides.

Another possible triggering factor for landslides are volcanic eruptions. Volcanic related debris flows (lahars) are common processes during and after volcanic eruptions. Only one volcanic event in Dominica's recorded history has occurred: a phreatic eruption causing ash cover in 1880 in the Valley of Desolation. Also a small event occurred in 1997. However, there are several clear signs of continuing volcanic activity in Dominica, such as fumarolic activity, hot springs and even a boiling lake. There were also periods with so-called seismic swarms, consisting of increasing volcanic related earthquakes with low magnitude in different recent periods Several volcanic alerts associated with periods of increased seismic activity (seismic swarms) have also occurred (SRU, 2000). The most recent one is recorded in the south western part of Dominica from October 1998 to 2000, with a maximum of 183 earthquakes per day on October 23, 1998. Volcanologist consider the south western part of the island also the most probable location for the next phreatic or magmatic eruption. However, the probability for a magmatic eruption is quite low (e.g. any time within the next 800 years). Therefore the relation with landslides as triggering factor is not so relevant. Also it is not really possible to include the volcanic hazard maps in the spatial planning, as the high hazard area cover many of the current settlements. There is a large level of uncertainty as to the probability for new eruptions: when and where, as illustrated by table 3.4.

Figure 3-2: Collapsed church tower in Portsmouth caused by the 2004 earthquake.

In conclusion, it appears that only tropical storms/ hurricanes and heavy rainfall events outside of the hurricane season are the relevant triggering events for landslides in Dominica. If it would be possible to establish a relation between the magnitude of the event (e.g. hurricane category or associated rainfall amount), its frequency and the number of landslides generated (or the density pf landslides within the various susceptibility zones) we could make an estimation of the landslide hazard (probability of occurrence). This be attempted later on in this chapter.

Table 3-5 provides the compiled historical disaster data for Dominica, derived from many sources. The table also indicates for the various events whether there were indications of landslide occurrence, and if so whether the location of the landslides are known. Unfortunately this is not the case for most of the events. We believe that this catalogue is the most comprehensive that was made for Dominica until now.

It is quite clear from this table that the landslide reporting becomes more frequent in recent years, and less and less information on landslides is available when going back in time, whereas the data on tropical storms and hurricanes seems to be much more constant over time. The underreporting of landslides is a big problem in trying to evaluate landslide frequency/magnitude relations. Also because no proper landslide inventories are available for different magnitudes of rainfall events. In the next section we will analyse the relation between landslides and rainfall.

Table 3-4: Overview of past volcanic activity of the eruptive canters on the island. Source: http://odm.gov.dm/index.php/resources/volcanoes-of-dominica. The right 3 columns are from a report by the University of the West Indies (http://pdf.usaid.gov/pdf_docs/pnadj327.pdf) Note the large disagreement between the two sources, although source 1 claims it is based on source 2.

Volcano	**Last Known Eruption**	**Age of most recent eruption**	**Nr of eruptions in last**	
			50,000	**10,000**
Foundland	Probably > 50,000 years ago	?	?	?
Morne Diablotins	Probably < 40,000 years ago	<40000	2-?	0-?
Morne aux Diables	Probably < 40,000 years ago	?	?	?
Grand Soufriere Hills	Approximately 11,000 years ago	11000	1-?	0-?
Morne Anglais	Probably < 10,000 years ago	6700	5-10	1
Morne Trois Pitons/Micotrin Complex	Approximately 1,100 years ago	1160	10-20	1
Morene Plat Pays Complex	Approximately 500 years ago	685	20-40	2
Valley of Desolation/Watt Mountain Complex	Phreatic eruption 1880, 199	1020	3-6	2

Table 3-5: Historical disaster events in Dominica collected from different sources (NI = No Information). C = casualties. Red records have landslides reported.

Year	**Day**	**Events**	**Reported incidents**	**Landslide Location known?**	**C**
1764	NI	Hurricane / Tropical storm?	NI	Unknown	
1766	October	Hurricane / Tropical storm?	NI	Unknown	
1769	26/07/1769	Hurricane / Tropical storm?	NI	Unknown	
1772	30/08/1772	Hurricane / Tropical storm?	NI	Unknown	
1776	06/09/1776	Hurricane / Tropical storm?	NI	Unknown	
1780	09/10/1780	Hurricane / Tropical storm?	NI	Unknown	
1787	03/08/1787	Hurricane / Tropical storm?	Also on August 23 and 29	Unknown	
1792	01/08/1792	Hurricane / Tropical storm?	NI	Unknown	

1806	09/09/1806	Hurricane / Tropical storm?	Landslides and Flooding. hurricane struck the island In the 1806 hurricane 131 people died mainly as a result of the Roseau river shifting its course and flooding the capital	Unknown	131
1813	23/07/1813	Hurricane / Tropical storm?	Flooding. Tidal wave	Unknown	
1813	25/08/1813	Hurricane / Tropical storm?	Flooding of Roseau to a depth of 10 ft.	Unknown	
1815	NI	Hurricane / Tropical storm?	NI	Unknown	
1816	15/08/1816	Earthquake	5 Richter scale		
1817	21/10/1817	Hurricane / Tropical storm?	NI	Unknown	
1818	NI	Hurricane / Tropical storm?	NI	Unknown	
1819	NI	Hurricane / Tropical storm?	NI	Unknown	
1820	26/09/1820	Hurricane / Tropical storm?	NI	Unknown	
1826	NI	Hurricane / Tropical storm?	NI	Unknown	
1834	10/09/1834	Hurricane / Tropical storm?	NI	Unknown	
1834	20/09/1834	Hurricane	Landslides and Flooding. Very severe event, like Hurricane David	Unknown	200
1838	??/06/1838	Earthquake	5 on Richter scale		
1839	21/09/1839	Earthquake	5 on Richter scale		
1843	08/02/1843	Earthquake	IX Richter scale ?? Probably mean IX on Mercalli scale, although hey also report VIII intensity. Several walls and chimneys fell down, many wall cracked. In the North at Londonderry and Melville Hall many sugar mills were destroyed. Melville hall, river sinks with several inches and was diverted 20 feet south. Mountains were visible crumbling away.		1
1844	10/01/1844	Earthquake	5 on Richter scale. Experienced in all windward islands		
1845	17/12/1845	Earthquake	5 on Richter scale		
1847	16/08/1847	Earthquake	5 on Richter scale		
1849	19/04/1849	Earthquake	VIII on Richter (?) probably Mercalli scale. Severe shock, especially in Grand Bay. Geneva estate and Bericoa estate the mill house and chimney were damaged.		
1851	NI	Hurricane / Tropical storm?	NI	Unknown	
1872	NI	Tropical storm	NI	Unknown	
1876	NI	Hurricane / Tropical storm?	NI	Unknown	
1878	NI	Tropical storm	NI		
1879	10/09/1879	Earthquake	5 on Richter (?) scale		
1880	NI	Volcanic	Phreatic eruption of Valley of Desolation/Watt Mountain Complex		
1883	04/09/1883	Hurricane	125mph winds from the ESE just south	Unknown	
1889	NI	Tropical storm	NI	Unknown	
1891	18/08/1891	Hurricane	125mph from the S.E	Unknown	
1893	15/08/1893	Hurricane	80mph from the S.E	Unknown	
1893	17/02/1893	Earthquake swarm	From 17/02 to 18/03 a serious of shocks in the northern part of Dominica. No damage reported		
1894	20/09/1894	Hurricane	115mph from the ESE	Unknown	
1896	30/08/1896	Hurricane	80mph from the S.E	Unknown	
1899	07/08/1899	Hurricane	145mph winds just north while moving WNW	Unknown	
1901	NI	Tropical storm	NI	Unknown	
1903	07/03/1903	Earthquake	5 on Richter (?) scale		
1903	07/03/1903	Earthquake	5 on Richter (?) scale		
1905	30/03/1905	Earthquake	5 on Richter (?) scale		
1906	16/02/1905	Earthquake	6 on Richter (?) scale		
1907	22/08/1905	Earthquake	5 on Richter (?) scale		
1908	NI	Tropical storm	NI	Unknown	
1912	08/02/1912	Earthquake	5 on Richter (?) scale		
1914	03/10/1914	Earthquake	5 on Richter (?) scale		
1916	28/08/1916	Hurricane	Landslides and Flooding. A strengthening tropical storm becomes a hurricane 85mph from the east. The hurricane advanced over the island with but little warning; a number of lives were lost and much property was destroyed on the northern and eastern sides It was evidently of small diameter and great intensity while passing over Dominica. 200 buildings destroyed. 8 ships lost	Unknown	50
1917	NI	Tropical storm	NI	Unknown	
1920	NI	NI	Landslides and Flooding	Unknown	
1921	12/05/1921	Earthquake	5 on Richter (?) scale		
1921	NI	Hurricane	NI	Unknown	
1924	04/10/1924	Rainfall event	Trafalgar, landslide killed 7 persons	Location more or less known	7

1926	24-7-1926	Hurricane	Landslides and Flooding. Road blocked, serious damage to electric and telephone system	Unknown	
1927	NI	Tropical storm	NI	Unknown	
1928	12-9-1928	Hurricane	125mph winds just north from the ESE. Sea front damaged. Extensive damage to buildings and cultivation. Damage estimated 66,000 Pounds. Dissatisfaction over Hurricane Relief Fund distribution.	Unknown	
1930	1-9-1930	Hurricane	Landslides and Flooding. 90mph winds hit the area from the east. Whole year crop lost. 60% of estates uprooted. 1000 houses destroyed, 850 damaged. All services out of action. All fruit trees were gone. Very high waves causing large damage in coastal area. E.g. Mahaut estate. Plantations went bankrupt.	Unknown	200
1933	04/02/1935	Earthquake	4 on Richter (?) scale		
1934	NI	Tropical storm	NI	Unknown	
1945	NI	Tropical storm	NI	Unknown	
1946	21/05/1946	Earthquake	6 on Richter (?) scale		
1948	NI	Tropical Storms	Landslides and Flooding	Unknown	
1949	??/09/-49	Tropical Storms	NI	Unknown	20
1951	NI	Tropical storm	NI	Unknown	
1953	19/03/1953	Earthquake	6 on Richter (?) scale.		
1955	??/09/1955	Hurricane Janet	Ni	Unknown	
1956	11/08/1956	Hurricane	95mph from the ESE		
1958	NI	Tropical storm	NI	Unknown	
1960	NI	NI	Landslide Bellevue Chopin	Location known	
1963	28-9-1963	Hurricane Edith	Landslides and Flooding. area gets 80mph gusts Destroyed 50% of all fruit bearing trees,	Unknown	
1964	22/08/1964	Hurricane Cleo	passes just north from the ESE with 130mph winds		
1964	?	Fire	No information		
1966	??/06/1966	Tropical Storms	Landslides and Flooding. 10,000 Pound aid	Unknown	
1966	27/09/1966	Hurricane Inez	hits from the east with 125mph winds just north		
1967	11/11/1967	Rainfall event	Landslide Boetica killing 5 persons	Location known	5
1970	20-8-1970	Hurricane Dorothy	Landslides and Flooding. Mostly wind damage. North and East hit mostly. South and central area had river flooding. EC 1.5 million loss in production of bananas.	Unknown	
1970	?	Drought	Drought is reported each year from 1970 to 1975		
1977	22/09/1977	NI	Landslide (Bagatelle Disaster) killed 11 persons. Disrupts the village of Bagatelle and temporarily cuts road access to Petite Savanne.	Location known	11
1979	29-8-1979	Hurricane David (Category 5)	caused 42 - 56 casualties, 3000 people needed medical attention, and made 75000 persons homeless, 12 % destroyed (2000 units) 50% severely damaged (8000 units) and 22% moderately damaged. The total estimated damage was over EC$ 53.8 million. 150 mph wind speed lasting 6 hours.	Bad map only	42
1979	01/09/1979	Hurricane Frederick	Damage mixed with the one from Hurricane David that happened shortly before	Unknown	
1980	04/08/1980	Hurricane Allen (Cat1)	NI	Unknown	
1981	NI	Tropical storm	NI	Unknown	
1983	NI	NI	Landslide Bellevue Chopin	Location known	
1984	NI	NI	Landslides	Unknown	
1984	6-11-1984	Hurricane Klaus	Landslide at Bellevue Chopin killed 1 person temporarily blocked road access to the south and south-eastern communities from Bellevue Chopin to Petite Savanne, including Grand Bay.	Location known	1
1986	12-11-1986	Several days of heavy rainfall	Landslide Good Hope happened on 12 November, And killed 1 person. Landslide Castle Bruce cuts road access to part of Good Hope village, and to San Sauveur and Petite Soufriere; disrupts way of life of these communities.	Location known	1
1987		Hurricane Emily			
1988	??/09/1988	Hurricane Gilbert	Landslides Matthieu and Layou River	Location known	
1989	17/09/1989	Hurricane Hugo	Total damage more than EC$ 20 million, 1 person killed by a landslide	Unknown	1
1990	??	Landslide	Morne Micotrin Slide: Occurs in the form of a long, wide swath, from high up on the southern side of the mountain. Temporarily cuts access to Freshwater Lake, Boeri Lake Trail and Chimen L'etang. The rubble from that slide temporarily interrupts the flow of the tributary of Roseau River coming from Freshwater Lake, and creates a small, short-lived landslide dam and lake. Ti-Tou Gorge becomes very shallow (temporarily) due to sediments being washed from the small lake at the foot of the slide following the dam-break		
1994	10/09/1994	Hurricane Debbie	2,800 acres of banana were affected by the storm. 143 acres of plantains, 355 acres of root crops and 355 acres equivalent of tree crops were also damaged	Unknown	
1995	27-8-1995	Hurricane Iris	Combined effects as they occurred very close to each other. Flooding, Large landslides Mathieu River. They caused 1 casualty, and caused a projected economic growth rate of 4.5% to be converted into a decline of 2%.	Unknown	1
1995	4-9-1995	Hurricane Marilyn			
1995	18-9-1995	Hurricane Luis (Cat 1)			

1995	??	Landslide	Trafalgar Falls Rockslide: Physically and visually impacts the "Father Falls" at Trafalgar; buries the hot springs and pools. Pointe Michel / "Solomon" Slide: Mass of landslide material / rubble temporarily blocks off road access to the southern communities of Pointe Michel, Soufriere, Gallion and Scotts Head. Carholm Slide: Severs the Layou Valley to Carholm Road, and begins to affect the lower Matthieu River Valley. Its impacts on Layou River receive media attention only a year and a half later.	Location known	
1997	18-11-1997 25-11-1997 28-11-1997	NI	Debris Flow Mathieu River. Two (2) major landslides within one week in November result in major flooding on each occasion, loss of agricultural lands and buildings, a dramatic transformation of the Layou River channel downstream, raising of the river bed. Resulted in the formation of Mattheiu Dam, Matthieu Lake, and two temporary dams and lakes on the Layou River. The way of life of the village of Layou is also impacted and temporarily disrupted.	Location known	
1997	NI	Volcanic	Phreatic eruption of Valley of Desolation/Watt Mountain Complex		
1999	18/11/1999	Hurricane Lenny	Landslides in the north, and severe damage to coastal infrastructure on the leeward side of the island	Location of landslides unknown	
2001	06/10/2001	Tropical storm?	Mentioned in EM-DAT but not in other sources	Unknown	
2003	NI	NI	Carholm landslide	known	
2003	9-12-2003	NI	Landslide Bellevue Chopin	known	
2004	21/11/2004	NI	Series of Landslides reported by Andereck in east part Grand Fond, Petite Soufrie and Mourne Jaune	inventory map	
2004	21-11-2004	Earthquake	Earthquake 6.3 at 14 km depth. 50 km NNW of Roseau. http://earthquake.usgs.gov/earthquakes/eqinthenews/2004/usrcaz/ At least twenty houses damaged and power outages occurred in northern Dominica	Partial inventory	
2007	NI	NI	Landslide Campbell	known	
2007	NI	NI	Landslide Bellevue Chopin	known	
2007	29/11/2007	Earthquake	7.4 Magnitude earthquake that occurred 36 km from Sainte-Marie Martinique. North part of Dominica was declared disaster area. Not clear what the damage was	Unknown	
2007	21/08/2007	Hurricane Dean (Cat 2)	Flash Flooding. Soufriere Sulphur Springs Debris Flow: Major debris flow from the Soufriere Sulphur Springs' Upper Fumarole Area on the night of Hurricane Dean severely impacts the Glo Gayak stream at Soufriere; results in heavy flooding and sedimentation around the area of the Soufriere School and playing field, etc. Playing field destroyed, and the village's and schools sporting activities affected.	Unknown	2
2008	??/10/2008	Hurricane Omar	NI	Unknown	
2009	??/07/2009	NI	Flooding	Unknown	
2009	04/09/2009	Hurricane Erica	27 landslides reported along the road network	Known	
2009	19/12/2009	Landslide	Landslide along road to Scotts head, approximately 150ft south of Melvina's Bar on the outskirts of Pointe Michel,	known	
2010	10/03/2010	Landslide	Landslide occurred on the Laudat road which toppled a car and almost killed two people. It also caused a blockage and later another slide happened close to the Laudat Trafalgar	Known	
2010	24/05/2010	Heavy rains Overnight	Saint Sauveur Slide, which killed 3 residents. Also landslides were reported in other locations.	known	3
2010	15/08/2010	Landslides	Landslide on the trail to boiling lake. Trail closed	Unknown	
2010	05/10/2010	Landslide	A landslide – caused by heavy rains – occurred early this morning at Blenhim in northern Dominica (just before the village of Anse De Mai).		
2010	31/10/2010	Hurricane Tomas	20 landslides reported along the road network.	inventory	
2010	09/11/2010	Landslide	The Antrim Valley land slippage, has caused a blockage of the river and a larger blockage might threaten the downslope houses. The main road keeps sinking	Exact location not known	
2011	07/05/2011	Landslide	Landslide in Deux Branches area, along the road from Pont Casse to Melville hall airport, required the closure of the road		
2011	16/05/2011	Landslide	Cliff collapse in Atkinson, caused 1 casualty	Not exactly	1
2011	28/06/2011	Landslide dam break	Heavy rainfall caused breach of the Matthieu Dam that was formed as a result of the Carholm landslide in 1997 and caused a massive flooding in Layou River washing out the Gleau Chaud Bridge	known	
2011	28-7-2011	NI	Miracle Lake Flooding	known	
2011	29-7-2011	NI	Landslide Soufriere	known	
2011	03/08/2011	Ni	Several landslides along road at Dubuc	Known	
2011	28/09/2011	Hurricane Ophelia	Severe flooding in Layou, bus flooded, village flooded. 84 landslides along the road. 84 landslides along the road network	inventory	
2011	29/10/2011	Rain	Road in Fond Cani area blocked by landslides	Known	
2011	28/11/2011	Heavy rain	Many landslides were reported, e.g. in Dubuc, Fad and Fond St Jean community, Castle Brice and Carib Territory, two major slides in the Penville area with blockages. Morne Jaune to Laplain, Reviere Cyrique and Grand Fond which were blocked. 74 landslides along road network	Inventory	
2011	30/11/2011	Storm	Three families had to evacuate their homes in Petite Soufriere yesterday because of landslides and more than seven landslides were reported in Castle Bruce. Airport was flooded. Rainfall for several days.	Inventory along roads	

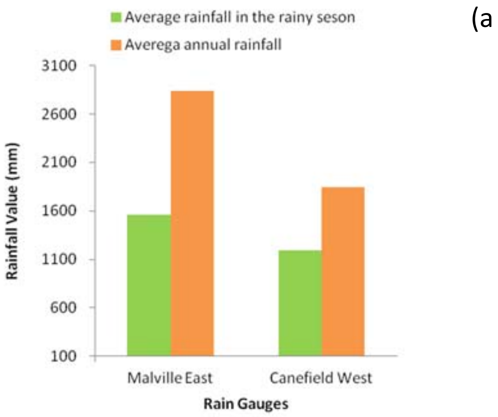
2011	06/12/2011	Heavy rain	Flooding and landslides in Good Hope and Petite Soufriere. People evacuated. Castle Bruce: 7 to 10 seven major landslides. landslides had been reported in Grand Fond	Not exactly known	
2011	03/08/2011	Heavy rain	Landslide at Dubuc	known	
2012	25/07/2012	Heavy rain	Landslide at Picard hit a powerline and caused power outage in certain areas		
2012	29-8-2012	Tropical Storm Isaac	Landslides and flash flooding. Prime Minister ordered people to stay home on 22 August	Inventory along roads	
2012	19/10/2012	Heavy rain	Landslide along road at Dubuc	known	
2013	23/04/2013	Heavy rain	30 Landslides were reported between April 17-20 across the country, including southern community of Petite Savanne, Dubuc, and road to good Hope, Petite Soufriere, Melville Hall to Pont Casse, and Pont Casse to East coast and on Emerlad pool to Castle Bruce area. Also flash floods were reported. Two people were killed when the culvert was washed out near Pont Casse. 44 landslides reported along the road network	Inventory along roads	2
2013	20/08/2013	Heavy rain	Landslide blocking the main road between Soufriere and Pointe Michel	known	
2013	5-9-2013	NI	Landslide Morne Prosper main road	known	
2013	24-12-2013	Christmas Eve trough	Landslides and flooding. Flooding in places like Beau Bois, Castle Comfort, and some parts of Newtown Two slides happened on the hiking trail: • Along section 13 (Penville to Capuchin). • segment one of the Waitukubuli National Trail at the summit of Morne Crabier	Inventory along roads, image interpreted inventory	
2014	07/01/2014	Landslide	Landslide on road near Mero	Not known	
2014	16/01/2014	Landslide	Two slides happened	Not known	
2014	01/08/2014	Tropical storm Bertha	50mph winds	-	
2015	27/08/2015	Tropical storm Erika	Total damage and loss of EC$1.3 billion (US$483 million), equivalent to approximately 90% of Dominica's Gross Domestic Product (GDP). The majority of damages were sustained in the transport sector (60 percent), followed by the housing sector (11 percent) and agriculture sector (10 percent). Out of a total population of 72,340 persons, 11 persons were confirmed dead, 22 missing, 574 homeless and 713 evacuated with approximately 7,229 impacted by the event in disaster declared areas.	Yes, UNOSAT mapped them from satellite images, and BRGM in field	11

3.3 Rainfall analysis

The study area is characterized by a humid tropical climate. The rainy season is normally from May to November, when the rainfall intensity is concentrated over a short period which triggers most of the landslides, flooding, and erosion in the study area. The rainfall data available from 2 rain gauges are based on daily measurements. The historical rainfall record for the past 32 years, that is, for the period 1982 to 2013 shows that the mean annual rainfall ranges from 1,757 mm in the Canefield station on the western side to 2,622 mm in the Melville Hall station on the eastern side (Table 3-6). The annual rainfall ranged from 1,263.2 mm in 2000 to 2,451 mm in 2011 for the Canefield rain gauge, with an average value of 1,757 mm (Figure 3-3). In the Melville rain gauge, the annual rainfall ranged from 1,950.60 mm in 1994 to 3,937 mm in 2011 (Table 3-6). The average annual rainfall is lowest in the western rain gauge (Canefield) as compared to the eastern side (Melville Hall). But it is interesting to observe that in Figure 3-3 that the highest rainfall in Canefield is recorded in the period July-September, instead in Melville the largest contribution to the annual rainfall is in the months of September-November. The most important characteristic of rainfall in the study area is that it is concentrated in a few days with a maximum daily rainfall exceeding 100 mm. The maximum rainfall recorded in a single day varies from 44.2 mm in 2000 to 211 mm in 1985 at the Canefield rain gauge, and for Melville from 77.7 mm in 1983 to 422.3 mm in 2004.

Table 3-6 Available precipitation data in Dominica

Rain Gauge	Elevation (m)	Mean Annual precipitation (mm)	Max annual (mm)	Minimum annual (mm)	Maximum daily (mm)	Minimum daily (mm)	Data available
Melville (East)	4	2,622	3,937 (2011)	1,951 (1994)	422.3 (2004)	77.7 (1983)	1982-2013
Canefield (West)	22	1,757	2,451 (2011)	1,263 (2000)	211 (1985)	44.2 (2000)	1982-2013



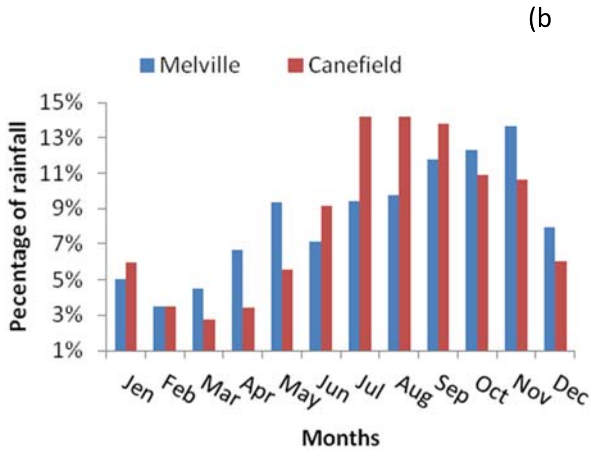


Figure 3-3: Distribution of rainfall, annually and monthly (A: average total annual rainfall and average rainfall in the rainy season b) percentage of rainfall per month in relation to annual rainfall from 1982 to 2013 for the two rain gauges considered: Melville on the East side and Canefield on the West side.

The climate of Dominica is more variable than would seem at first glance. Its location in the trade wind belt would lead to classification as a humid tropical climate (Walsh, 1985). However, the high central peaks modify conditions leading to a highly seasonal climate on the western (leeward) coast and weakly seasonal on the eastern (windward) coast (Rouse and others, 1986). The seasonal climate is characterized by rainfall occurring mainly in summer and autumn. This is due to the close proximity of the Intertropical Convergence Zone (Walsh, 1985). With the Azores subtropical anticyclone being closer during the winter leads to a dry period. The high mountainous interior of Dominica creates orographic uplift and associated instability which enhances summer and autumn rainfall and generates significant winter rainfall (Walsh, 1985).

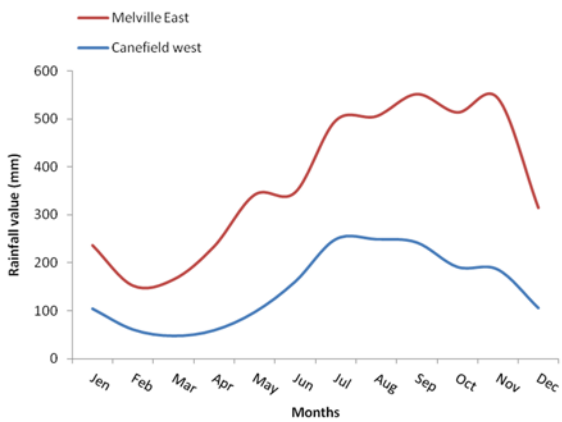


Figure 3-4: Mean Monthly rainfall for 32 years from 1982 to 2013 for two rain gauges.

3.3.1 Analysing the distribution of rainfall over the island

The next step was to analyse the rainfall variation over the island. The availability of a series of rain gauges from a US research project called DOMEX made it possible to evaluate the trend of rainfall with altitude. The DOMEX project installed 10 stations with data from 2008 to 2013. The result plotted rain data with elevation is note that the rain increases with increasing altitude (Figure 3-5).

Nr	Station	East-West	Elevation [masl]
1	Rosalie (RO)	east	10
2	LaPlaine (LP)	east	70
3	Grand Fond (GF)	west	262
4	Freshwater Lake (FW)	west	800
5	Boeri Lake (BL)	West	877
6	Laudat (LT)	east	592
7	Pont Casse (PC)	west	650
8	Springfield (SP)	east	400
9	Canefield (CA)	west	4
10	Botanical Garden (BG)	West	30

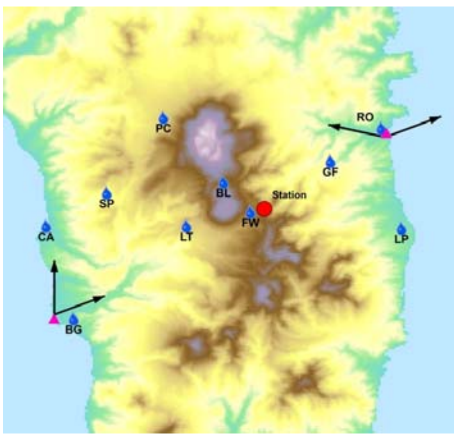


Figure 3-5: Location of 10 rain gauges installed for the DOMEX project at different altitudes and sides of the island in Dominica (Source: http://www.domex2011.com/rain-gauge-network)

When comparing the rainfall for the stations Rosalie (RO) and Melville Hall (ML) one the east sides, and Botanical Gardens (BG) and Grand Fond (GF) on the western side (Figure 3-5) it is visible that on the eastern slopes the rainfall amount is slightly higher. There is some seasonality to the rainfall distribution but the amounts typically range from 500 cm to over 900 cm annually. This rainfall coupled with the island's steep topography contributes to the increased chance of landslide and floods. When considering the landslide distribution, more unstable areas are located on the southern and south eastern slopes and on the highlands in the centre of the country. The result show that the rainfall is generally higher on the eastern side, as hurricanes universally come from this direction.

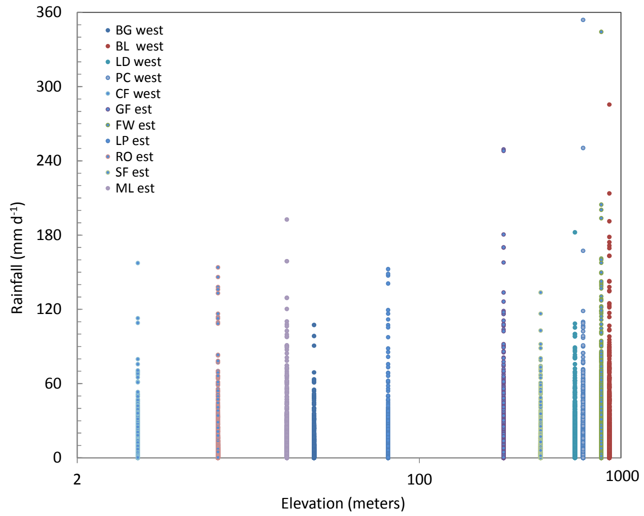


Figure 3-6: Relation between rainfall and elevation on Dominica for different rain gauges.

From Figure 3-7 it is interesting to note that there is good correlation between the elevation and rainfall. Only the 98th percentiles presents a lower correlation, perhaps this is due to a more chaotic pattern of rainfall during extreme precipitation. It is noted also a more pluviometrical gradient as the percentile distribution increases.

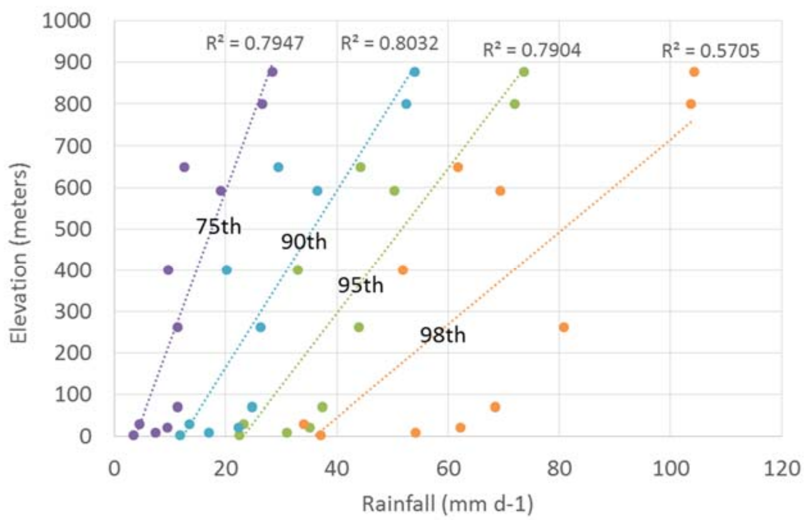


Figure 3-7: Percentiles distribution (from 75th to 98th) of rainfall-elevation relationship with related interpolation line

3.3.2 Evaluation of rainfall thresholds

Rainfall thresholds can be defined on physical (process-based, conceptual) or empirical (historical, statistical) bases (Corominas, 2000; Crosta and Frattini, 2001; Aleotti, 2004; Wieczorek and Glade, 2005). The determination of rainfall thresholds for landslide initiation is considered as a basic task in landslide hazard assessment, and various methods have been proposed to establish rainfall thresholds (Dahal et al., 2008; Guzzetti et al. 2007; Zezere et al. 2005; Giannecchini et al. 2012; Frattini et al. 2009; Crosta 1998; Corominas and Moya 1999; D'Odorico and Fagherazzi 2003; Glade 2000; Godt et al. 2006; Marques et al. 2008; Saito et al. 2010). In general, they can be classified into five threshold groups: (1) empirical; (2) physical-based; (3) intensity duration; (4) normalized intensity-duration; and (5) antecedent rainfall. For rainfall threshold estimation, the four most common variables used in the literature are as follows: daily rainfall (Dahal and Hasegawa, 2008), antecedent rainfall (Glade, 2000), cumulative rainfall (Polemio and Sdao, 1999), and normalized critical rainfall (Aleotti, 2004). The selection of the right parameters in constructing rainfall thresholds is mainly dependent on the landslide type (Martelloni et al., 2011) and on the environmental conditions. One of the largest difficulties when using antecedent rainfall for landslide prediction is to determine the number of days to be used (Guzzetti et al. 2007). A detailed literature review revealed a complex relationship on the correlation between the numbers of days for the antecedent rainfall with the triggering of a landslide. Different authors such as Glade (2000), Aleotti (2004) considered antecedent days ranging from 1 to maximum 15 days. Zezere et al. (2005), Polemio and Sdao (1999) considered until 180-day cumulative daily rainfall data. In summary, antecedent rainfall between 3 and 120 days could be significant for explaining the landslide occurrence (Dahal et al. 2009). The large variability on the number of antecedent rainfall days may be influenced by factors such as (i) diverse lithological, morphological, vegetation, and soil conditions, (ii) different climatic regimes and meteorological circumstances leading to slope instability, (iii) and heterogeneity and incompleteness in the rainfall and landslide data used to determine the thresholds (Guzzetti et al., 2007).

In the case of Dominica we only have daily rainfall available for the period from 1977 to 2013, for two stations: Melville Hall Airport at 22 meters above sea level on the east side, and Canefield airport on the west side at 4 meters above sea level. Based on the known landslide triggering days derived from Table 3-5 we selected rainfall data from one of the two rain gauges depending on the nearest location (west or east side of the island). Figure 3-8 shows, in log-mm scale, the rain that occurred on the day that triggered the landslide (called Rainfall Event, Re) in mm on the y-axis, and the normalized antecedent rainfall (NAR) over 5 days on the x-axis. We have normalized it for the average annual precipitation over 32 years. We were able to use 28 empirical rainfall days for known landslide initiation in Dominica, in a 38-year period (plotted in the figure as orange points). The blue dots represent rain days without reported landslide events. The manually defined threshold in blue represented in the graph is the minimum quantity necessary to trigger a landslide (Guzzetti et al., 2007), and the blurred blue area that bounded the blue threshold is the uncertainty range which was determined visually. The equation for the threshold follows an S-shaped curve with the following equation:

$$\mathrm{Re} = \exp\left(\frac{3.20986 + 0.00853618}{NAR}\right) \quad (1)$$

Where RE is the rainfall of the event, NAR is the 5-days antecedent rainfall, normalized for the mean annual rainfall over 32 years for the two rain gauges considered.

As can be seen in the figure 3-8 we have plotted both the events where landslides have occurred, and the events that do not have reported landslides. Therefore, while analysing the result, we have in the area above the thresholds, more false alarms that true alarms. This makes the application of such thresholds rather problematic, for landslide hazard assessment in Dominica given the current availability of data. The poor separation of landslide days from non-landslide days is probably due to several reasons. It could be that the rain (blue dots) which falls above the line took place only around the rain gauge considered and the rest of island didn't receive the same amount rain to trigger landslides. Another reason could be that landslides weren't recorded. And also the orographic effects that play an important role as we saw before are not taken into account.

Using data from volcanic terrain in Puerto Rico, Larsen and Simon (1993) proposed a threshold relationship between rainfall intensity and duration: $I = 91.46D^{-0.86}$, where D and I are the duration (h) and the intensity (mm h^{-1}). According to this formula, a rainfall intensity greater than 91.46 mm h^{-1} over one hour will trigger landslides. If the duration is 13 h, the critical rainfall intensity is 11 mm h^{-1} with a total amount of 143 mm. Smith et al. (2009) conclude that with no orographic enhancement, the 13 h of accumulated precipitation would have been in the range of 100–200 mm—close to the landslide threshold. In reality, the actual precipitation on the high terrain exceeded 500 mm—several times the landslide threshold. It is obvious that the orographic effect is important for producing landslides. However, when we are carefully examining the existing landslide inventories, it is also not very evident that the number of landslide increases with increasing elevation on the windward slopes. Orographic enhancement of precipitation must be accounted for in forecasts of landslides.

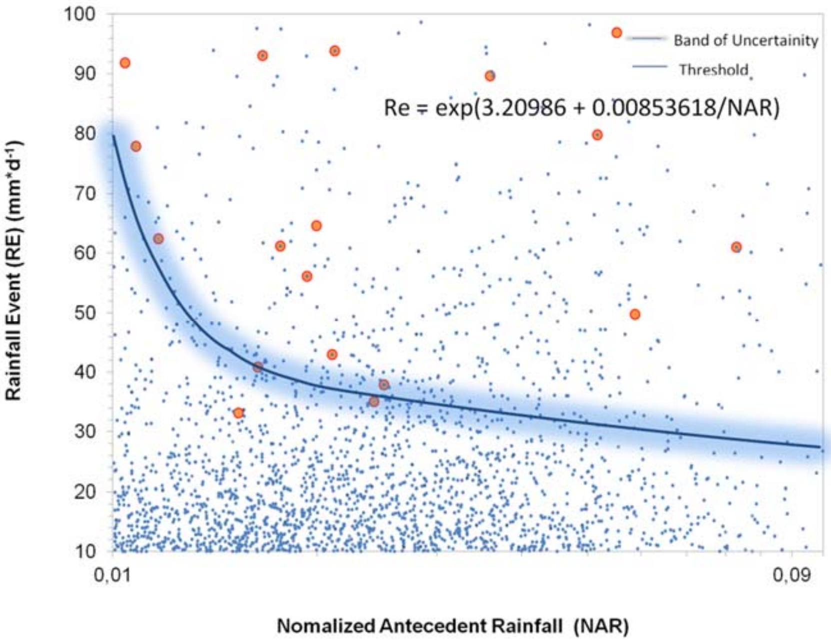


Figure 3-8: Landslide rainfall threshold for Dominica. RE is the threshold rainfall, and NAR is the 5-day antecedent rainfall; the orange points are the reported landslide events; blue points are the rainfall days without landslides, the blue line is the estimated rainfall threshold; the blurred blue area is the band of uncertainty which was visually identified.

3.3.3 Rainfall frequency analysis

To analyse the distribution of extreme events of rainfall and calculate their return periods, both Generalized Extreme Value (GEV) and Gumbel distribution models were used. The data from the stations were analysed separately and return period of extreme events were calculated for each. Annual daily maximum values of each recoding period was calculated for all the stations that were considered. Then each records were fitted to GEV and Gumbel models using RStudio. RStudio has an extreme value analysis package called "extRemes" (Gilleland, 2015). Two functions contained in this package were used for the analysis namely: Fit an Extreme Value Distribution to Data (fevd) and Likelihood-ratio Test (lr.test). The FEVD function can be used to fit the data into GEV distribution model or Gumbel distribution model. As an output, it gives different set of plots such as: QQ and QQ2 plots of the empirical quantiles against model quantiles, histograms of the data against the model density, return level period plots of the return level period against the return period rainfall with 95 percent confidence intervals, etc. The lrLR.test function tests the likelihood ratio of two model fits and indicates which model has a greater fit.

For the frequency analysis we used data from the two rainfall stations that have long records of daily rainfall, located at the two airports: Melville Hall Airport at the eastern side of the island and Canefield Airport at the western side. Melville Hall has generally higher rainfall, although in some years the maximum rainfall recorded is nearly identical, on the same day (or in the same period of 2-3 days). Figure 3-09 shows that there is some similarity apart from a few very high values at Melville Hall. Because these dominate the Gumbel distribution, a procedure was used to arrive at average values of daily maxima for return periods of 5, 10, 20 and 50 years. Figure 3-10 shows the two stations in one frequency magnitude analysis.

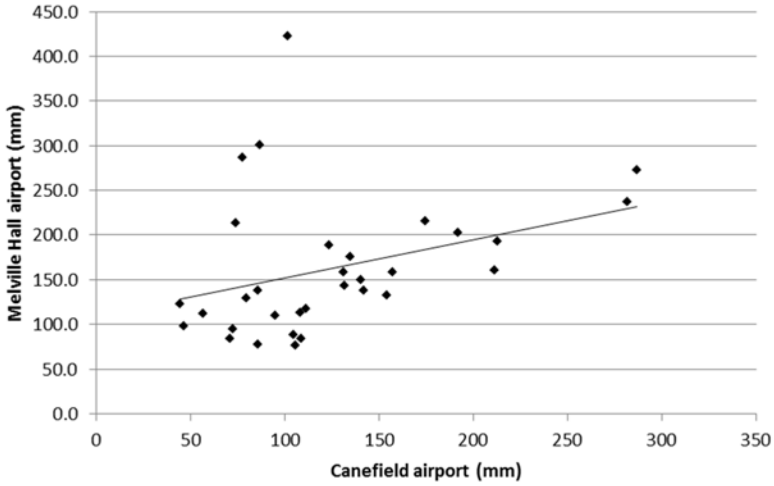


Figure 3-9. Comparison of the annual maxima of the two stations (common subset 1982-2013). There is a general agreement but the windward station (Mellville Hall) has much higher values on a few occasions than the Leeward side station of Canefield.

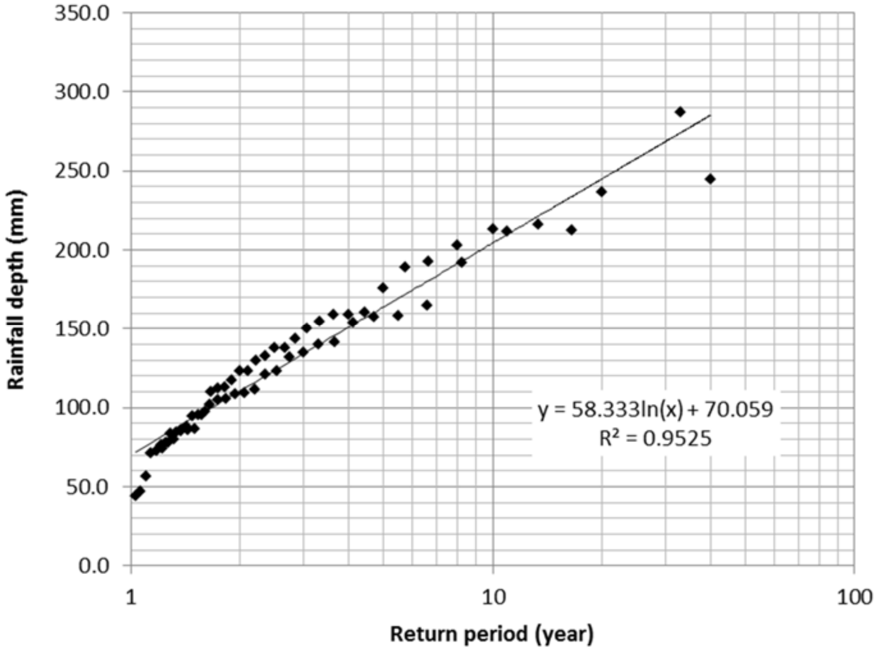


Figure 3-10. Gumbel analysis of the two stations on Dominica (Melville Hall and Canefield). The average return periods are derived from the log linear fit.

Later on we would like to use this relation of daily rainfall frequency together with the frequency of tropical storms and hurricanes, as a guideline for subdividing triggering events according to the density of landslides they produce. This will be done in an attempt to characterize the classes of the landslide susceptibility map with expected landslide densities for different frequencies.

4. Landslide inventory mapping

Landslide inventories are the basis for assessing landslide susceptibility, hazard and risk (Soeters and Van Westen, 1996; Aleotti and Chowdury, 1999; Ardizzone et al., 2002; Dai and Lee, 2008; Galli et al., 2008; Van Westen et al., 2008). They are essential for susceptibility models that predict landslide on the basis of past conditions. If these are not sufficiently available more emphasis should be given on expert assessment and evaluation. Therefore we need to know where landslides happened in the past. The conditions under which landslides happened in the past are analyzed and the relevant combinations are used to predict future ones. We need to understand the causal relations between landslides and the causal factors. These conditions differ for different landslide types, and therefore landslides should be classified into different types. Temporal information is essential to estimate the frequency of landslides. Therefore we need to know when they happened. Landslide inventories are also used to validate landslide susceptibility, hazard and risk maps.

Landslides are generally isolated, rather small but frequent occurring events. In a tropical environment such as Dominica they are visible for some time but quickly become difficult to recognize. Fresh landslide scarps become overgrown by vegetation within a few years after they happen. Signs of landslides become also difficult to interpret from images, when the image is taken more than a few months after the landslide occurrence. On the other hand major triggering events such as tropical storms might cause many landslides at the same time, and then it is important to rapidly map the landslides triggered by that event so that we can link the temporal probability of the triggering rainfall to the spatial probability of landslide occurrence.

4.1. Available landslide inventories

In many of the eastern Caribbean countries there is no single agency that has the responsibility for maintaining a landslide database. This is one of the major problems in Dominica as well. No agency feels responsible to collect landslide locations and dates, and keep a database up-to-date. The Office for Disaster Management doesn't seem to maintain a database of emergencies. This is the case both for mapping landslides in the rural areas, as well as for collection landslide data along the road network. The Ministry of Public Works and Ports also doesn't convert the road maintenance reports into an updatable landslide database. Therefore the valuable data on landslide locations and occurrence dates is quickly lost. However, there seems to be a growing awareness of the importance of collecting such information, and some of the recent events have been described in reports. That is why all landslide inventories have been generated by consultants, organizations and individuals from outside the islands. For Dominica there are only a limited number of landslide inventories available (See Table 4-1).

The first map on which landslides related to a triggering event are indicated is from a study related to the impact of Hurricane David in 1979. This very devastating hurricane could be seen as the worst case scenario for Dominica, given the reported casualties and damage. However, the map doesn't indicate actual landslide location, but merely the stretches of road that have to be repaired because of landslides. A full overview of the landslides caused by this category 4 event (which is considered to have a return period around 125 years) is not known. Walsh (1982) reported that small rotational failures triggered by Hurricanes David and Frederic were only noted on cultivated slopes. Unfortunately we were not able to obtain a corresponding landslide map to corroborate this.

Other websites (e.g. http://www.cakafete.com/dm/davidphotos.html) do not show photos with a visible landslides, and it appears that this event was characterized more by the excessive wind speed than by the excessive rainfall. Hartford and Mehigan (1984) also documented landslides on Dominica. They performed lab tests on the residual soils and found that the high plasticity of the soil and angle of internal of friction were conducive to failures when saturated. They also found that failures tended to occur on slopes greater than 31 degrees (Hartford and Mehigan, 1984). Walsh (1985), examining landslides following Hurricanes David and Frederic in 1979, documented that a majority of the landslides involved failures at depths of approximately two meters, while Prior and Ho (1972) found that greater occurrences of landslides on nearby St. Lucia occur on slopes greater than 35 degrees.

Rouse et al. (1986) conducted a detailed analysis of volcanic soil properties in Dominica which guides a model for explaining how vegetation might be influencing slope stability. Residual strength values for kanoid and allophoid clay soils were determined from laboratory testing. The samples were largely drawn from latosolic soils. The residual strengths were above those expected based on experience with temperate clays and more akin to those found for granular soils. Rouse et al. (1986) concluded that the high porosities and high water holding capacities of these soils meant that exceptionally high rainfalls are required to induce translational slope failures.

Table 4-1: Landslide inventories for Dominica.

Year	Author	Characteristics	Number of landslides reported	Possible triggering event
1987	DeGraff	For OAS. Interpretation of 1:20000 aerial photos from 1984 and fieldwork in 1986-Jan 1987. Landslides mapped on 1:25000 topomaps with classification. Digital map available.	980	1979 David (major event) 1980 Allen 1984 Klaus
1990	DeGraff	Field verified only in 1990. Mapped on 1:25000 scale topographic map. Digitized by us.	183	1987 Emily 1988 Gilbert 1989 Hugo
2006	CIPA USAID	Photos of 1:10,000 from 02/02/1992. One week field checking along roads. No inventory map available to us.	685 points reported, but doubtful	No major event between DeGraff 1990 and photos of 1992 Fieldwork might have included landslide from: 1994 Debbie 1995 Iris, Marilyn, Luis 1999 Lenny
2007	Andereck	Landslide inventory in villages of Grand Fond, Petite Soufriere and Mourne Jaune	246 (but the study area is only 22.48 km^2)	21/11/2004 2007 Dean
2009	Public works	Road clearance reports	27 along the roads	04/09/2009 Erica
2010	Public works	Road clearance reports	20 along the roads	31/10/2010 Tomas
2011	Public works	Road clearance reports	84 along the roads	28/09/2011 Ophelia
2011	Public works	Road clearance reports	74 along the roads	28/11/2011 Rain event
2013	Public works	Road clearance reports	444 along the roads	21/04/2013 Rain event
2015	UNOSAT	Landslides from TS Erika mapped from satellite images	1554 polygons mapped	27/08/2015 Erika
2015	BRGM	Landslides from TS Erika mapped in the field	89 points mapped	27/08/2015 Erika

The baseline study for landslides in Dominica is the work carried out by Jerome DeGraff from the US Forest Service for the OAS in 1987. He carried out detailed image interpretation of landslides using detailed stereoscopic image interpretation of 1:20,000 scale black and white aerial photographs, which were taken in 1984, so five years after the occurrence of Hurricane David, which was very destructive in Dominica. The aerial photos covered the entire island with the exception of a mile-wide strip from north to south in the east-central part of the island. Unfortunately, the rain gauge data for this event is missing. We only received rainfall data from the Canefield station since 1982 and the data around August 28 1979 for the Melville Hall station is missing. DeGraff differentiated mapped landslides with a minimum size of 2000 m^2 and also differentiated between main landslide types (fall, slide, flow). He also carried out extensive field checking in 1986. DeGraff clearly mentions in the report (DeGraff, 1987) that in this environment it is difficult to identify landslides that are older than a few years, and that the landslides caused by Hurricane David (5 years before the photos were taken and 7 years before field checking in January 1987) were difficult to recognize due to revegetation with undergrowth and young trees. He indicated that rockslides and rockfall are very frequent along the cliff coasts, and that most of these slope are considered landslide prone. Also inland cliffs in ignimbrite present frequent rockfall

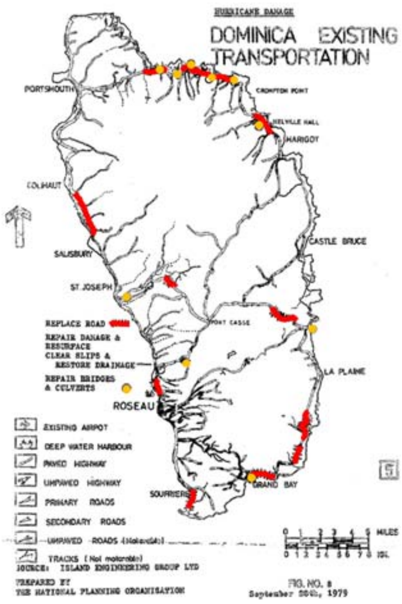


Figure 4-1: Map of damage to road infrastructure by

problems. Debris slides are also common, but the main landslide type is debris flows. DeGraff also carried out similar work in St. Lucia and St. Vincent. Table 4-2 summarizes the results.

Island	**Number of landslides**	**Landslide Size in hectares**		**Landslide density (per km^2)**	**Terrain disturbed (in percentage)**
		Average	Largest		
St. Vincent	475	0.5	4.0	1.4	1
St. Lucia	430	3.0	5.0	0.7	2
Dominica	980	4.0	12.5	1.2	2

Table 4-2 Number, size and area disturbed by past landslides on three islands mapped by DeGraff in the 1980's (from DeGraff et al., 1989).

DeGraff revisited the area several years later in 1990 to check the quality of the earlier landslide zonation, and he mapped the landslide that occurred in the years 1987-1990 (DeGraff, 1990). In this period two hurricanes produced significant rainfall amount (1987 Emily, 1988 Gilbert, and 1989 Hugo) and also a number of tropical storms and other rainfall events occurred. He only used field verification to map the new landslides, as no new images were available after 1984. He mapped 183 new landslides, with clear and unvegetated scarps, of which 31 along the roads. Most of these occurred along the road from Springfield estate to Point Cassé, which was reconstructed in 1988-89. The failures there occurred after hurricane Hugo. Only 5 of the new landslides were rockslides and the rest debris slides and debris flows, with shallow depth. He concluded that 77 of the 151 new landslides that occurred in soil were more frequently occurring in managed vegetation areas (cultivated crops) than in secondary rainforest and natural vegetation. He wasn't able to find a good statistical relation between vegetation and landslides however.

In 2006, under a USAID programme, a multi-hazard assessment was carried out for Dominica (USAID 2006). This included a landslide susceptibility assessment, which also incorporated a limited data collection for new landslides. The report indicates that a detailed landslide inventory was beyond the scope of the work. An aerial photo analysis was carried out using 1:10,000 scale black and white aerial photos from 02/02/1992. A short field verification was done during one week in April 2006. Field verification was concentrated on the following areas: Belle Vue, Pichelin, Carib territory, Fond Cole, Point Michel, Belles, D'Leau Gommier, Wall house, Grand Fond, Carholm. However, the verification was concentrated mostly along the roads. The study reports that 685 points were collected using GPS. It is not clear whether these are all new landslides, and how many of these were already reported by DeGraff (1987, 1990). Unfortunately the landslide inventory map from this study is not available. In the statistical analysis in their report they indicate 947 landslides. If they really combined their landslides with those of DeGraff, who had 980 landslides in the 1987 study and an additional 183 landslides in the 1990 study, this is not possible.

A landslide inventory map for a small part of the eastern side of Dominica, focusing on the villages of Grand Fond, Petite Soufriere and Mourne Jaune, was carried out in 2007 by Mr. Zachary Dean Andereck, who did a Master thesis for the University of Miami (USA) (Andereck, 2007). He used a Quickbird high resolution satellite image from January 2005 for image interpretation. Field mapping took place in June-July 2006. He reported that the local people indicated that most of the landslides occurred on 21/11/2004, as a result of several days of intense precipitation followed closely by a magnitude 6.3 earthquake. He identified landslides at 1:15000 scale. He reported 246 landslides in this relatively small area (225 km^2).

Road maintenance and clearance reports were obtained from the Ministry of Public Works and Ports for five rainfall events: September 3/2009 (tropical storm Erica), October 31/2010 (Hurricane Tomas), September 28/2011 (tropical storm Ophelia), November 28/2011, and April 17-25/2013. An example of the latter is given in Table 4-3. Unfortunately no information was available for earlier events, as this type of data is not kept in a database. The reports don't have any spatial references for the landslide locations, they only have the road sections starting and end point where landslide clearance had been done and the amount of money spent for clearance. To locate those areas and prepare them as geo-spatial dataset, the available high resolution images and thematic maps of the island were used.

Figure 4-4 provides a summary of the available landslide inventories for Dominica. If we compare the available inventories with the list of triggering events shown in Table 3.5 and Table 4.1 we can conclude that it will be difficult to link one of the inventories to a major triggering event, such as hurricane. Detailed landslide inventories for the latest hurricanes (e.g. David, 1979, Dean in 2007, Lenny in 1999, David in 1979) are not available. Therefore we might not be able to apply the proposed method for the conversion of susceptibility maps into hazard maps due to the lack of sufficient event-based landslide inventories.

Location	**Cost of clearing**	**No. of slides**
Castle Bruce to Petite Soufriere	59196	5
Bois Diable to Castle Bruce, including Emerald Pool	63463.25	3
Castle Bruce village and environs	22493.75	6
Castle Bruce to Hatton garden road	7000	3
Grand Fond to Rosalie	3550	1
Bois Diable to Delices	4390	1
Dubuc to Petit Savanne	16016	2
Petit Savanne and enviros	113222	7
Portsmouth to Hatton garden	1960	1
Portsmouth to Capuchin road including Cabrits	9435	2
Blenheim - Thibaud - Veille Case - Penville	11240	4
E.o. Leblanc highway - Morne - Espagnol to Tibay	14300	5
E.o. Leblanc highway - St.Joseph (Otrobando to I.T.S.S)	1800	2
Layou to St.Joseph (undercliff)	3600	1
Jimmit to Warner	1330	1
Clarke hall, Morne Habbat, Warner Saltoun	6600	2
Fortune road	500	1
Brooks hill road	14030	4
Cochrane road	2070	1
At Loubiere	1196	1

Table 4-3: Example of a road clearance report for the event of April 17 -25 2013, 75 landslides

Possible Landslide triggering event	No. of Landslides Reported	Daily Rainfall amount (mm)		Estimated Return Period (years)	
		Melville	Canefield	Melville	Canefield
Klaus (6-11-1984)	980				
Hugo (17/09/1989)	183				
Iris, Marilyn, Luis (4-18/09/1995)	685 (?)				
Rain & earthquake (21/11/2004)	>>246 (only in 22.5 km^2)				
Erica (04/09/2009)	>27 (roads only)	192.6	212.7	5	7
Tomas (31/10/2010)	>20 (roads only)		121.2		<2
Ophelia (28/09/2011)	84 (roads only)		157.4		3
Rain (28/11/2011)	74 (roads only)	158.9		3	
Rain (21/04/2013)	44 (roads only)	129.4		2	

Table 4-4: Available landslide inventories, with associated number of landslides and rainfall amount, and rainfall return periods.

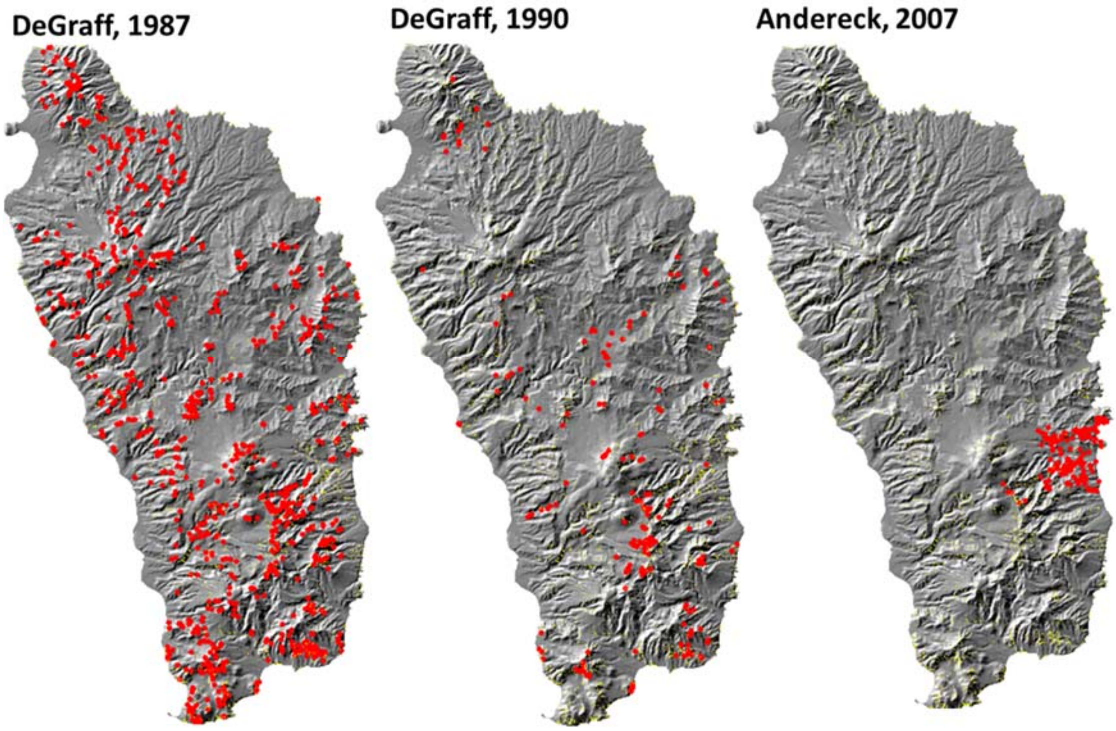


Figure 4-2: Landslide inventories that are available for Dominica. Above: Landslide inventory made by DeGraff in 1987, and DeGraff in 1990, and Andereck, 2007. Road related inventories will be shown in Chapter 7.

4.2. Landslide inventory mapping in 2014

The available landslide inventories presented in the previous section are relatively old. Complete landslide inventories from DeGraff were made in 1987 and 1990, and Andereck (2007) mapped landslides only in a small part on the eastern side of the island. Therefore it was decided to carry out a detailed landslide inventory that complements the earlier ones, and that portrays the current situation, incorporating also the older landslide inventories into a single new and comprehensive analysis.

The generation of landslide inventories and a landslide database that covers a certain period of time is a tedious procedure. The methods that are considered useful for the generation of landslide inventory maps can be classified into the following main groups (Van Westen et al., 2008):

- **Image interpretation** from aerial photographs, high resolution satellite images, or hill shading images derived from detailed Digital Elevation Models. Also image interpretation using multi-temporal images from Google Earth has become a useful tool for landslide inventory mapping.
- **(Semi) automatic classification** of landslides from satellite images or Digital Elevation Models.
  - Based on spectral information by detecting fresh landslide areas from multi-spectral satellite images;
  - Based on altitude information by detecting landslides from multi-temporal high resolution (LiDAR) DEMs, or through radar interferometry
- **Field investigation**, by mapping landslide signs, scarp area, accumulation areas, and verification of landslides mapped through image interpretation and/or classification;
- **Community reporting**, by interviewing local people on locations, dates and impacts of past landslide event;
- **Archive studies**, by studying newspaper archives, old reports, road maintenance reports etc., as explained in chapter 2.

The method used for generating the landslide inventory in Dominica is illustrated in Figure 4-3. We started by collecting all available landslide inventories. But, as these were in most cases not sufficiently, reliable or available, we also decided to collect landslide inventories ourselves. This was done using image interpretation and field work. Image interpretation played a major role in generating updated landslide inventories.

Image interpretation can be defined as the study of the imaged objects of the earth surface, the extraction of those features relevant to the object of study, the analysis of the selected features with the objective to come to a deduction of their significance for the specific field of study (Soeters and Van Westen, 1996). Stereoscopic image interpretation is important tools to recognize and map landslides. The interpretation of images is an empirical and subjective process. It is a systematic scanning of a stereo model assisted by logical and scientific evidences. Stereo image interpretation (API) is an art as much of a science, and it requires well trained, experienced investigators.

We obtained through the EU FP7 Copernicus project INCREO (http://www.increo-fp7.eu/) the possibility to order very high resolution satellite images (Pleiades images, with 0.5 m spatial resolution for panchromatic and 2 m multi-spectral) for Dominica (See Table 4-5). We received the images that were obtained in the first months of 2014.

Table 4-5: Available satellite images for Dominica

Satellite	Date	Type	Columns, Rows
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

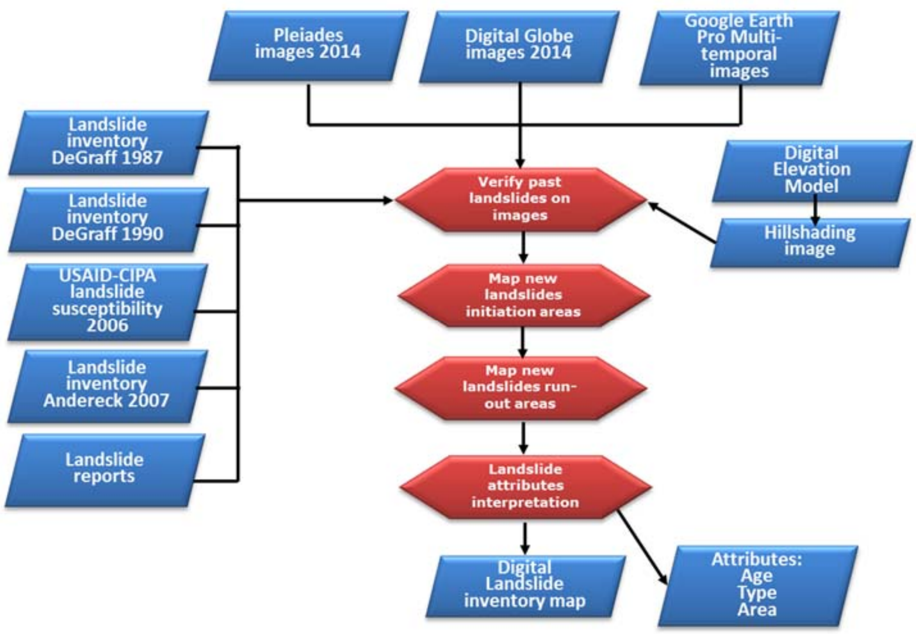


Figure 4-3: Method used for the generation of a landslide inventory map for Dominica

The high resolution images from 2014 covered different parts of the island, and also had sometimes serious cloud coverage which didn't allow us to map the entire island.

Therefore we decided to carry out an extensive interpretation of landslides using different sets of satellite images, and also using historical imagery from Google Earth Pro. Figure 4-4 gives an example of the use of multi-temporal satellite images for analysing the changes in landslide distribution and activity over time. This figure shows the Matthieu landslide, which was described by DeGraff and Rogers (2003), DeGraff et al (2010) and

Arlington (2014). It is possible to see the situation in 2005, 8 years after the damming in 1997, and the situation after the breaking of the landslide dam in 2011.

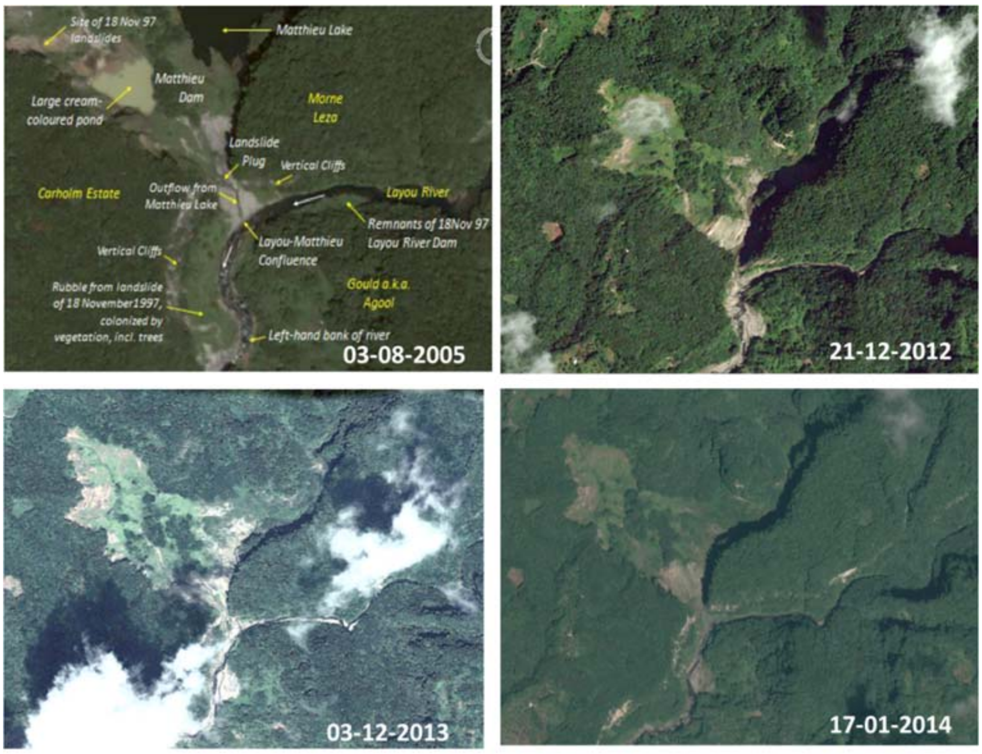


Figure 4-4: Example of multi-temporal images for the Matthieu landslide. The upper left image is from Arlington (2014), the upper right and lower left are from Google Earth, and the lower right is a Pleiades image.

We incorporated in our inventory also the landslides from the previous inventories and checked these in the images. Many of these were no longer visible on the images from later years, although when using older images from around 2005, many of them could still be detected, even though many were revegetated. During the process we also were in contact with Jerome DeGraff, who carried out the landslide inventories in 1987 and 1990, and we compared his results with ours. He also provided us with examples of landslides interpreted from images, such as the one shown in Figure 4-5.

In Figure 4-5 you can see four examples of landslides interpreted from Google Earth images, based on a commentary from DeGraff:

- Example A is from a coastal area in the SE part of Dominica. The photo shows the interpretation with gold dashed lines outlining debris slides and red outlining rock slides. The blue arrow on the lower photo points to a rock slide where you can see the rock exposed in the upper head scarp area.
- Example B shows landslides that 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. This debris flow was probably initiated during Hurricane Hugo (1989). The debris flow passes under the road (and penstock) between Laudat and what was then called “Freshwater Lake” and now is noted as “Letang”. A closer view of this debris flow shows that cleared fields also have a similar contract in vegetation colour to the landslide scars (squared areas below the road in the lower left quadrant of photo). The dashed gold line outlines where the debris flow initiated. There is an overlapping pattern that could be interpreted as retrogression of the initiation area upslope and/or some lateral enlargement of the initiation area. The dashed red line encloses the deposit made from the debris transported sown the debris flow path to the river valley. Where sufficient area exists on relatively low gradient, fan shaped deposits will be found. According to DeGraff in the Eastern Caribbean these depositional areas are relatively rare. So most debris flow evidence will be limited to the scar where it initiated and the path where the flow passed to the nearest drainage area.

- Example C shows clearly recognizable fresh landslides, which will appear as a brown to reddish-brown against the background of the vegetation (especially within forested vegetation). The Event in the upper left is a debris flow starting with the arcuate scar where movement was initiated extending downslope to the natural channel. There are faint lines showing fluvial erosion of the bare soil exposed by the debris flows passage. There may be a small amount of deposit at the very bottom next to the channel. But most of the mobilized material was likely transported downstream. The indicated landslide is a debris slide. The gold-coloured dashed line shows the top of the head scarp. The solid red line is the upslope edge of the slide mass extending to the channel. The arcuate bare area (compare to the first image) is diagnostic for a debris slide. It would also occur in a rock slide. This example is interpreted as a debris slide due to the lack of resistant escarpments suggesting resistant rock with only a thin soil. The presence of the debris flow shows that a significant thickness of weathered soil overlies the bedrock in this area.
- Example D is an image of the Boiling Lake area. There is a faint set of parallel lines on the slope above (and north) of the lake. Closer inspection (within blue circle) shows a number of debris flow scars (partly re-vegetated). It is worth noting because several coalesce into a single runout path toward the lower slope. This is not an uncommon occurrence with debris flows on steep slopes.

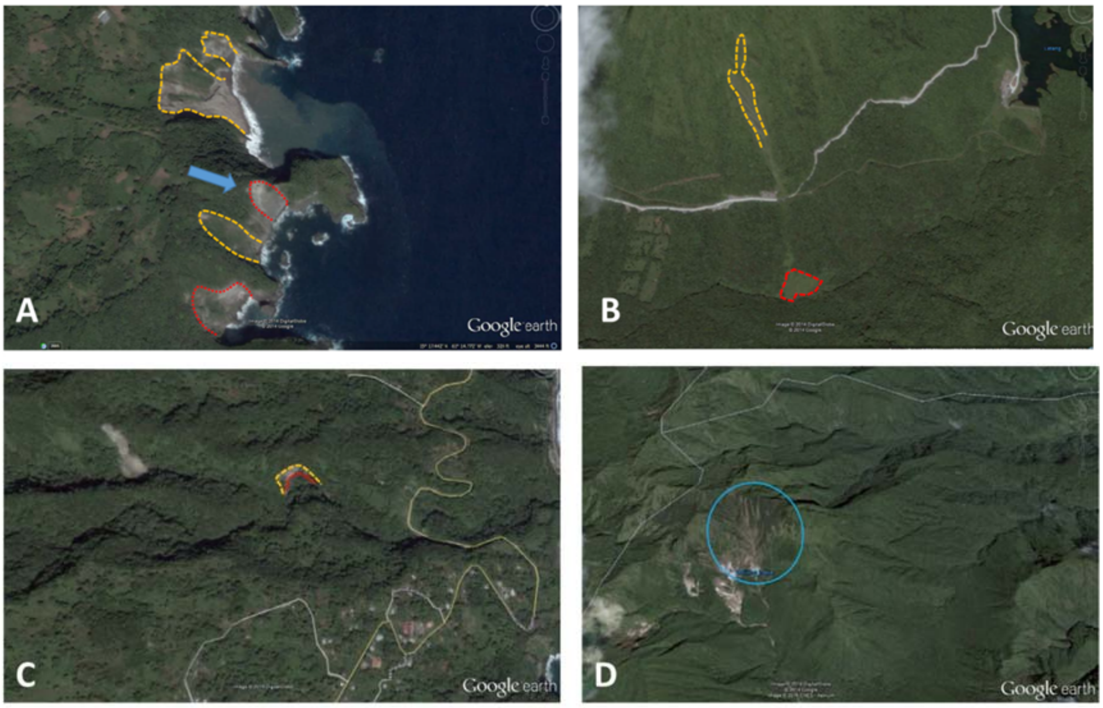


Figure 4-5: Example of interpreted landslides for different areas in Dominica. The explanation is given above.

We interpreted the landslides as polygons, separating between scarp and body, assigning a unique identifier to each landslide and describe each landslide with a number of attributes. We made a complete classification for all landslides. Also the mapping of coastal landslides was carried out.

The landslide inventories were checked in the field during a fieldwork period of 3 weeks in September-October 2014. During the fieldwork several of the features that were identified through image interpretation as potential landslides, were actual bare field or other features. As the stereo-image interpretation focused not only on the absence of vegetation in potential landslide areas, but more on the morphological characteristics of old landslides, many more landslides were interpreted than the ones caused by the 2013 Christmas eve event. However, for these older ones, it was difficult to establish the age. During the fieldwork also specific emphasis was given to the collection of landslide inventories along the road network.

The resulting landslide inventory map is shown in figure 4.6 and 4.7. Table 4-4 and table 4-5 give a summary of this landslide inventory that includes the previously mapped landslides. It was not possible to indicate the dates of landslides in the inventory, due to a lack of data. Therefore the date information was collected in the form of tables (See Table 3.5). The table also contains a summary of the landslides mapped in 2015 (See next section).

	1987	1990	2007	2014	2015 (UNOSAT)	2015 (BRGM)
number	980	183	161	896	1554	99
Area (hec)	584	9	3	52	183	-
Study area (km^2)	752	752	38.8	752	752	752
Density	0.00777	0.00012	0.00077	0.00069	0.00243	
percent	0.777	0.012	0.077	0.069	0.243	
nr/km2	1.30	0.24	4.15	1.19	2.07	0.13

Table 4-4: Summary of landslide inventories, with number, area, area density and number density. The figures presented by DeGraff in table 4.2 seem to be a bit too large compared to our GIS data analysis.

Type	1987 DeGraff	1990 DeGraff	2007 Andereck *	2014 VanWesten	2015 UNOSAT	2015 BRGM	Total
Debris flow	483	28	21	120	-	4	656
Debris slide	318	142	125	464	-	50	1099
Debris Avalanche	0	5	2	65	-	20	92
Rockfall / Rockslide	8	5	11	183	-	11	218
Coastal Cliffs	0	0	0	47	-	-	47
Unknown	81	3	2	17	1554	4	1661
	890	183	161	896	1554	89	3773

*Table 4-5: Summary of landslide information for the available landslide inventories for Dominica. The numbers indicate new landslides mapped in the various years. * Andereck (2007) only mapped landslides in a small part on the eastern slope of the island.*

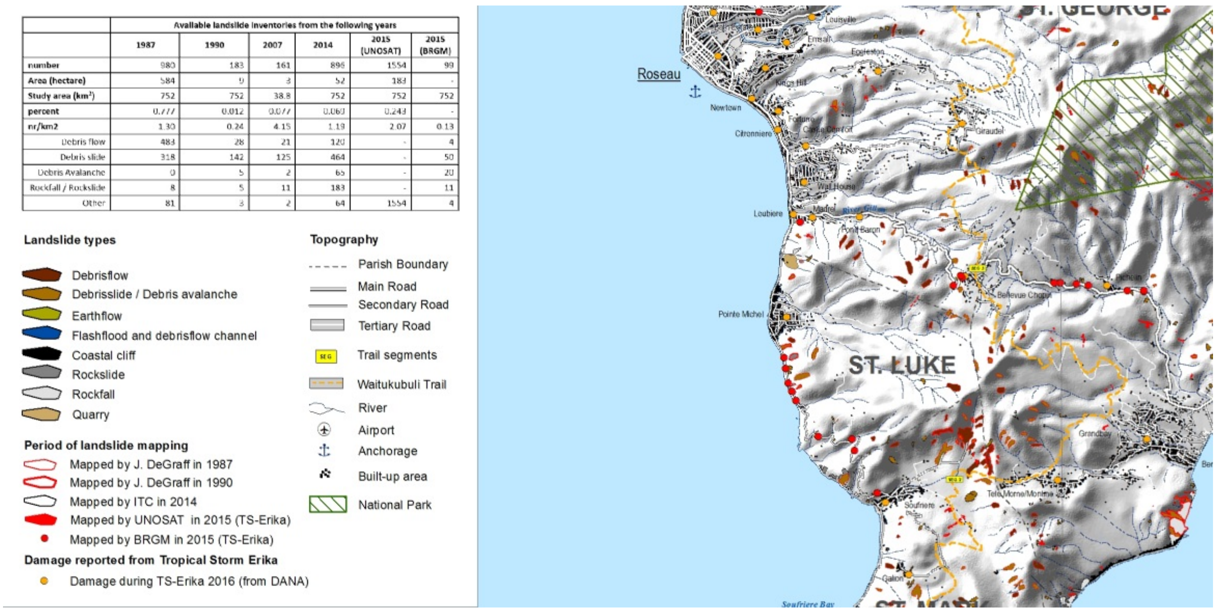


Figure 4-6: Legend of the final landslide inventory map for Dominica. The full map can be downloaded as pdf from the following website: hhttp://www.charim.net/dominica/maps

Figure 4-7: Final landslide inventory map for Dominica. The full map can be downloaded as pdf from the following website: http://www.charim.net/dominica/maps

4.3. Landslide inventory mapping in 2015

The first version of the landslide inventory map for Dominica was completed in June 2015. However, on 27 august 2015 Dominica was very severely hit by tropical Storm Erika, which produced extreme rainfall amounts. Around 200 mm was recorded between 7 a.m. and noon in Canefield airport, and the D`leau Gommier station, located in the mountains near the center of the island recorded 434 mm between 1 a.m. and 5 p.m., of which 359 between 4 a.m. to 9 a.m. (Commonwealth of Dominica, 2015). The event was very devastating. Table 4-6 gives a summary of the damage.

Sectors	Damage EC$	Loss EC$	Total EC$	Damage US$	Loss US$	Total US$
Productive						
Agriculture, Fisheries and Forestry	114.22	13.11	127.33	42.46	4.87	47.33
Tourism	52.40	31.48	83.88	19.48	11.70	31.18
Industry & Commerce	24.56	1.50	26.06	9.13	0.56	9.69
Infrastructure						
Water and Sanitation	46.11	6.39	52.50	17.14	2.38	19.52
Air and Sea Ports	40.08	0.21	40.29	14.90	0.08	14.98
Roads and bridges	643.59	129.87	773.46	239.25	48.28	287.53
Electricity	5.89	0.88	6.77	2.19	0.33	2.52
Telecomm	26.90	0.00	26.90	10.00	0.00	10.00
Social						
Housing	119.80	25.86	145.66	44.53	9.61	54.15
Education	9.55	1.20	10.75	3.55	0.45	4.00
Health	1.73	3.50	5.23	0.64	1.30	1.94
TOTAL	**1084.82**	**214.01**	**1298.83**	**403.28**	**79.56**	**482.84**

Table 4-6: Summary of damage caused by tropical storm Erika in Dominica in million (Commonwealth of Dominica, 2015).

Two initiatives were taken to map landslides triggered by TS Erika in Dominica. The first one was carried out by UNITAR-UNOSAT (2015). UNITAR-UNOSAT analyzed imagery collected by the WorldView-2 satellite on 03 September 2015 and detected the presence of landslides over multiple areas in this portion of the island. There is very limited information available about the procedure which was followed. UNITAR-UNOSAT (2015) report a total of about 700 landslides that were detected in the analyzed areas. However, the GIS data shows that there are 1548 landslide polygons, and 697 landslide points which have probably been generated automatically from the polygons. The landslide polygons mostly join several landslides together. Unfortunately the landslides have no classification in types, and they were also not checked in the field. Figure 4-8 gives an example of the map focusing on the South-eastern part where the number of landslides was highest. Some parts of the island could not be analyzed due to the heavy cloud cover. It is not clear which parts.

The second landslide inventory was made by BRGM Guadeloupe, at the request of the World Bank. They visited the island from August 31 to September 02 2015, and from 9 to 16 September 2015. The purpose was to establish a diagnosis of the risks, and if necessary, outline security measures for the main instabilities affecting road infrastructures (central and southern parts of the Dominica territory), with specific emphasis on the Petite Savanne sector, and the access roads to Petite Savanne from Bagatelle in the south and Boetica in the north (Garnier et al., 2015). The BRGM team made a landslide inventory along the main roads of the island, and mapped 89 landslides as points. They made a classification of the landslides and also prioritized them with regards to residual risks and the need to implement security measures. Obviously this inventory was not exhaustive, and focused on the most problematic ones that required immediate attention. The inventory is shown in Figure 4-8. Unfortunately the two inventories have been made using entire different procedures (automated mapping from satellite images versus field identification), using different representation methods (one as polygons and the other as points) and different characteristics (one not classified). They are also very different in terms of the areas covered, the number of landslides mapped, and the locations of landslides mapped. Only about 13 out of 89 of the landslide points mapped by BRGM actually are located within polygons mapped by UNITAR-UNOSAT.

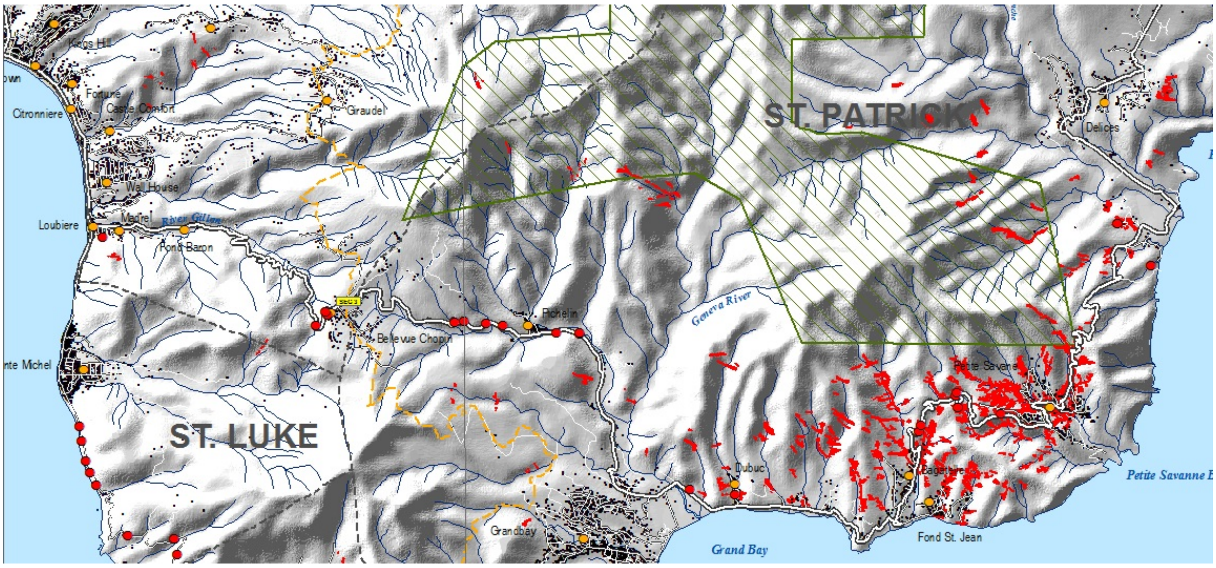


Figure 4-8: Landslides caused by tropical storm Erika in August 2015. The red polygons are the ones mapped by UNITAR-UNOSAT, the red dots by BRGM, and the organ dots are damage points mapped by the damage and loss estimation survey. The full map can be downloaded as pdf from the following website: http://www.charim.net/dominica/maps

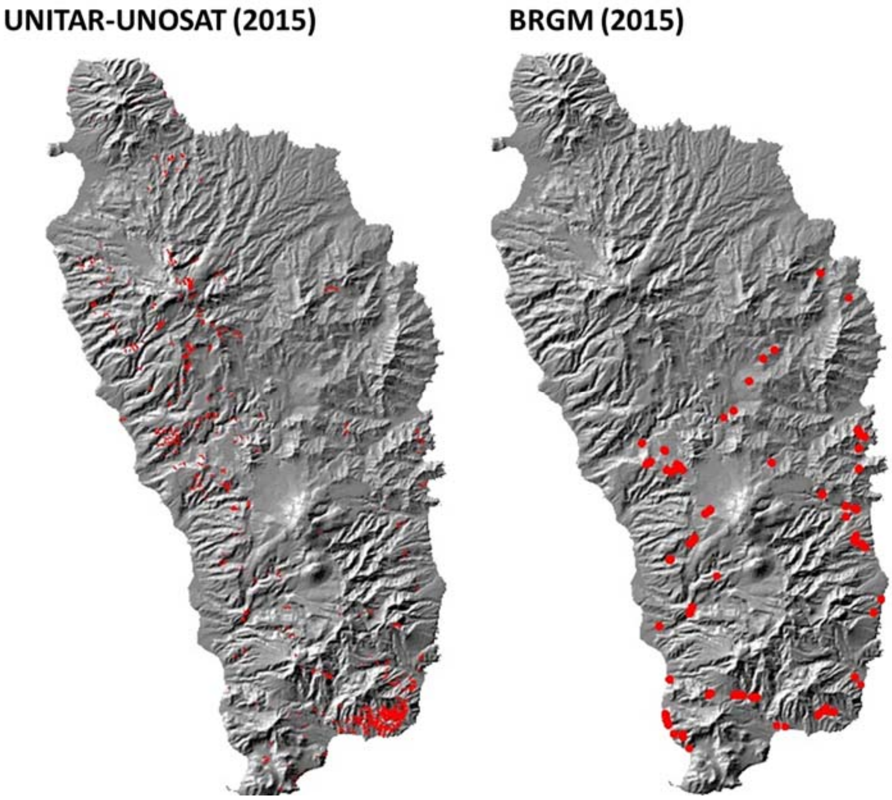


Figure 4-9: Landslides caused by tropical storm Erika in August 2015. Left: polygons mapped by UNITAR-UNOSAT. Right: Points mapped by BRGM

4.4. Some examples of landslide characteristics in Dominica

This section gives some illustrations of landslide examples in Dominica. The largest landslide in Dominica in terms of casualties was the Bagatelle landslide which occurred on September 22, 1977. Rain-saturated soil on a hillslope adjacent to the community mobilized into a rapidly moving mass. It engulfed four homes at the edge of the village killing eleven inhabitants (DeGraff et al., 1989).

4.4.1 The Good Hope Landslide.

DeGraff et al. (1989) describe the Good Hope landslide event as a typical example of rainfall triggered landslide in the volcanic environment of the West Indies. The landslide occurred on November 12, 1986, and involved 17000 m^3 of soil and weathered rock above the Castel Bruce- Petit Soufriere road. The landslide affected a health clinic and a school and a 90 meter stretch of road was blocked. The landslide injured one person and killed another one. The location of this landslide is now not visible anymore, therefore for mapping such historical events it is important to go back to original literature sources.

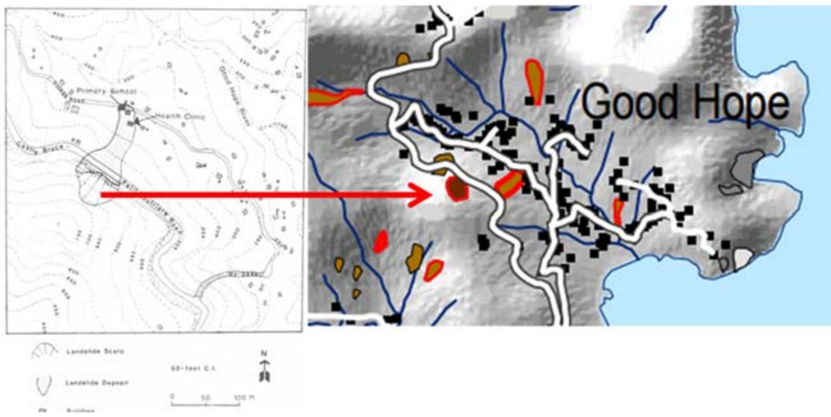


Figure 4-10: the Good Hope landslide as mapped by DeGraff et al (1989) (left) and how it appears in the landslide inventory map.

4.4.2 Layou Valley landslides: domino effects of landslides

The Layou-Carholm Landslides represent a complex series of landslides that achieved climactic proportions in 1997 and 2011 remains a hazard today. The Layou River, with a length of 17 km is one of the largest watersheds in Dominica (70 km^2) and drains about 9% of the land (ACOE, 2004). The Layou Tuff forms vertical walls along the lower Matthieu and Layou Rivers through these reaches. This welded tuff resulted from ignimbrite eruptions in the Late Pleistocene centred on Morne Couronne (Roobol and Smith, 2004). In addition to the Layou Tuff, both, 1.8 Ma and 2.0 to 1.8 Ma year old block and ash deposits from this eruptive centre are the primary bedrock present throughout the drainage basins for these two rivers (Roobol and Smith, 2004).

Landslides were common in the area, with specific reports occurring between 1987 and 1997. There is an eyewitness account of a slide following Hurricane Hugo in 1989 and also following Hurricanes Iris, Luis and Marilyn in 1995. There was a major change to the pattern of small landslides. Dramatic slumping occurred between November 18 and 25, 1997. Two major slides blocked the river and created a natural dam. The dam was breached on November 21 with mudflows reaching the sea accompanied by extensive flooding of the lower river valley. The larger of the Layou flood events on November 28, 1997, measured 1,325,000 m^3. A wall of material estimated at 50 feet high was washed downstream. The riverbed rose dramatically in its lower reaches. This elevation was estimated at 30 feet at the location of the swing bridge. The river had dried up between November 18-20 1997 and then flooded on November 21. Further landslides occurred on November 25, 1997 and October 8 and 11, 1998 with subsequent dam breaks being significant events. Measurements show that the lake depth increased from 22 m in 1998 to nearly 40 m in 2008 (DeGraff et al., 2010). The maximum volume estimate is 3,611,985 m3, assuming failure by overtopping and complete draining of the lake (Breheny, 2007). A major dam break event occurred on 28/06/2011. Heavy rainfall caused breach of the Matthieu Dam that was formed as a result of the Carholm landslide in 1997 and caused a massive flooding in Layou River washing out the Gleau Chaud Bridge and causing destruction to roads. The road along the Layou River to Pont Cassé was closed, due to flood hazard.

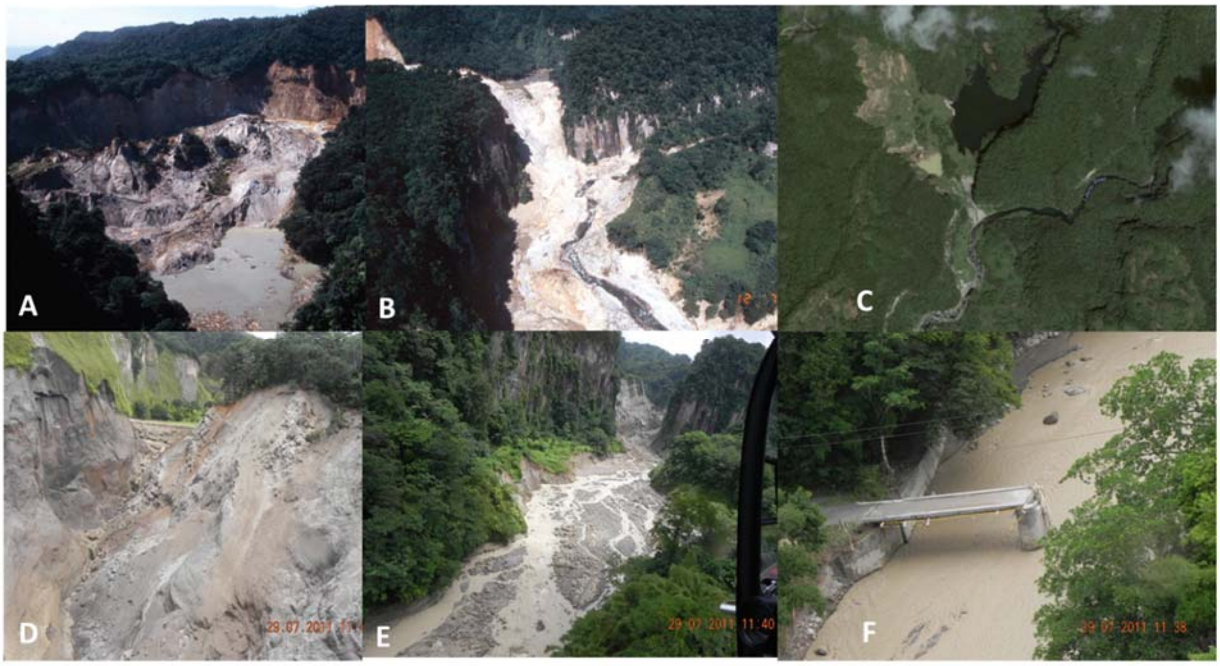


Figure 4-11: Mathieu landslide dam development. A: Carholm landslide blocking the Mathieu River and forming a lake in 1997 (Photo: J. DeGraff), B: View from downstream along the Layou valley towards the confluence of Layou and Mathieu river, with landslide dam location in 1997 (Photo: DeGraff, 1997); C: Google Earth image 3/8/2005 showing dammed lake. D: landslide dam washed out after dam break in May 2010; E: View from downstream towards former landslide dam, note the large area affected by dam break flooding; F: Bridge destroyed by dam break flood.

On Dominica, the geologic and physical conditions conducive to forming landslides and landslide dams are not unique to the Layou and Matthieu Rivers on Dominica. In late August 1989, a debris slide mobilized within the volcanic glacis on a 70-percent, southeast-facing slope of Morne Micotrin (DeGraff, 1990). This storm-generated debris slide developed into a debris flow, which passed down slope to the Roseau River (DeGraff, 1995). Along the way, it damaged the pipeline pad for the Laudat and Trafalgar hydroelectric power plants and the road to Freshwater Lake. The passage of Hurricane Hugo a few weeks later in September 1989 caused additional movement that added to the debris flow deposit and nearly caused a landslide dam (DeGraff et al., 2010).

4.4.3 San Sauveur slide in 2010

A relocation project was initiated and completed for 10 families, who were affected by the notorious 2010 San Sauveur landslide that claimed the lives of three people.

Figure 4-12: San Sauveur landslide which occurred on 24/05/2010 and which killed three people. The government decided to relocate 10 families and with a donation from the Chinese government a resettlement was carried out which was completed in 2015. The area was affected again in August 2015 during tropical storm Erika (right Figure from Garner et al, (2015)

4.4.4 Large landslides related to volcanic activity.

Lindsay et al. (2005) consider the likelihood of gravitational collapses on the flanks of Dominica's volcanoes to be "low but not negligible." However, according to Teeuw et al. (2009) many factors make Dominica particularly prone to large landslides (>1 million tons):

- extensive zones of weakened rock, due to hydrothermal alteration and/or intense tropical weathering;
- over steepened slopes associated with tectonic uplift and erosion of volcanic edifice foot slopes;
- large amounts of rainfall on the volcanic uplands, especially during the hurricane season (June–October), with annual averages of up to approximately 6000 mm; and
- occasional severe seismic activity, e.g., a magnitude 7.3 earthquake on 29 November 2007, with its epicentre between Dominica and Martinique, and another of magnitude 6.2 on 21 November 2004, with its epicentre between Dominica and Guadeloupe

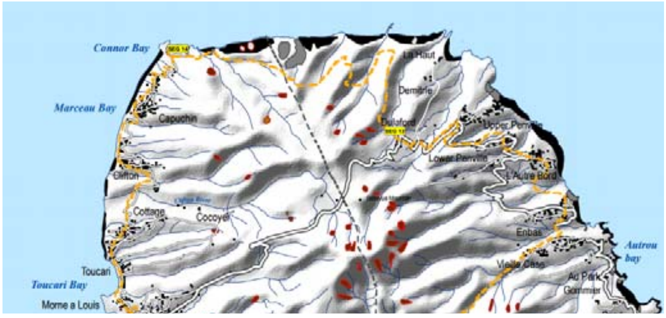


Figure 4-13: Large rockslides along the northern coast of Dominica. The slopes around these, according to Teeuw et al (2009, might have the potential to produce large landslides that could trigger a tsunami.

According to Teeuw et al. (2009) there are geomorphological, bathymetric, and seismic evidences that suggest that Dominica's northern coast is bounded by an active fault structure, with the north flank of Morne aux Diables volcano displaying evidence of both shallow and deep-seated slope instability (See Figure 4-13). A probable landslide block of approximately 1 million tons on the northern flank of the volcano has large tension cracks on its upslope margin and is strongly undercut and might lead to a tsunami generating landslide (McGuire, 1996).

4.4.5 Landslides along the road network

The road network in Dominica is very vulnerable to landslides, due to the steep slopes, weathered volcanic soils and high rainfall amounts. Figure 4-14 shows one of the main problem areas in the Stowe-Dubuc area along the south coast of Dominica. This stretch of road is bounded by the Atlantic Ocean to the south and steep hill sides to the north making it vulnerable to both landslides and sea surges. It connects the neighbouring communities to the city of Roseau making it an important segment to the road network. Communities in the area are well known for fishing hence making the flow of traffic heavy at certain times of the day. This stretch of road experiences frequent landslides and rock falls during periods of heavy rain. Studies are being planned to evaluate possible mitigation works for this area.

Figure 4-14: Landslide and rockfall problems in the Stowe-Dubuc area in the SE of Dominica.

Another notorious problem zone for landslides is the road between Pont Cassé and the Melville Hall airport. This stretch of road has been recently upgraded and new road cuts were made, which are properly designed with terraces, and drainage. Also a number of new bridges were constructed. However there are still two chronic problem areas along this road, where deep seated landslide cause subsidence of the road. Currently there are no structural measures taken to remediate the problems, other than adding new asphalt or concrete to make it possible for vehicles to pass the side scarps. The Ministry of works is monitoring the two movements, hoping they will slow down so that large engineering interventions wouldn't be necessary.

Figure 4-15: Landslide subsidence along two problem areas along the road from Canefield to Melville hall.

4.4.6 Landslide during tropical storm Erika in the south-eastern part of Dominica

The landslides that were triggered by tropical storm Erika on 27 august 2015 are the latest example of the devastating impact of landslides on Dominica. Garnier et al. (2015 give a description of the landslide problem, of which the following is an abstract. Landslides happened all over the island, but the largest concentration took place in the Southeast part of the island. The access road in the south of the island from the Plaine is cut off a few hundred meters to the north of Boetica, after the massive rupture of the embankment structure over several tens of meters wide and a height spanning the river (Figure 4-16). A large number of landslide scars have affected the area above the road (from tens of meters to more than a hundred meters high). The runout zones are between a few meters and several tens of meters wide, with start areas located at different elevations above the road, but mostly starting at the drainage divides. The volumes range from several hundreds to several thousands of m^3, with colluvial blocks, scree, weathered material, vegetation debris and various-sized rocks (up to several m^3). Most of the settlement areas of Petite Savanne have been more or less severely affected by landslides. To the south of the river that divides Petite Savane, the area is built over more than 1 km on a narrow ridge line, which have been the origin of a significant number of slides, often starting near the top of the slope. Others started in the lower or middle parts and have the danger of a possible retrogression in the short term (Garnier et al., 2015).

Figure 4-16: Landslides triggered by tropical storm Erika in the south-eastern part of Dominica. Upper left: road washed out to the north of Boetica; Upper right: access from the south to Petite Savanne – section of the road located after the washed-out bridge; Middle left: section of a satellite image showing the destruction near Petite Savanne; Middle right and lower: landslides in Petite Savanne. Sources: Garnier et al. (2015) and UNITAR-UNOSAT (2015).

5. Landslide conditioning factors

In this chapter an evaluation is made of the available factor maps for landslide susceptibility assessment in Dominica. Data was obtained in many different formats, and several different projections, from many different persons and organizations. Most of the spatial data that we obtained from the organizations on Dominica were actually in Geographic coordinates (Lat, Long) without a projection definition. All the data was transformed to UTM WGS84 projection, and is now available as shape files (for vector data), and GeoTIFF (for raster data), through the CHARIM Geonode (http://charim-geonode.net/).
In the description of the data attention is given to the spatial, thematic and temporal accuracy of the data. A summary of the data types is given in table 5-1.

- *Spatial accuracy* is a major problem for Dominica, as many of the available factor maps do not spatially match, due to differences in source data and coordinate systems;
- *Thematic accuracy* relates to the accuracy of the content of the factor maps. From our analysis it became clear that several of the critical layers for landslide susceptibility assessment are very general;
- T*emporal accuracy* refers to the fact that some of the thematic maps are not up-to-date. This is important for example for the land cover maps, which should be representing the situation under which the landslides occur;
- *Differences in scale*. Another important factor is the large variation in mapping scale of the input data. Some of the data was obviously digitized from very general base maps, where others are much more detailed.

In the following sections some examples are given of the problems involved with the input data.

5.1. Digital Elevation data

The only source for generating a Digital Elevation Model we were able to obtain was a vector file with contour lines, with a contour interval of 10 meters. There was no metadata available, so we do not know who made this, when, and using which method. However, when generating a DEM from it through contour interpolation, we discovered that the resulting DEM was very smoothed, and after carefully evaluating the contour lines, we noticed that these were also smoothed. We assume that the contour lines were generated from an existing DEM, with a wrong method, resulting in over smoothened lines (Figure 5-1 illustrates this).

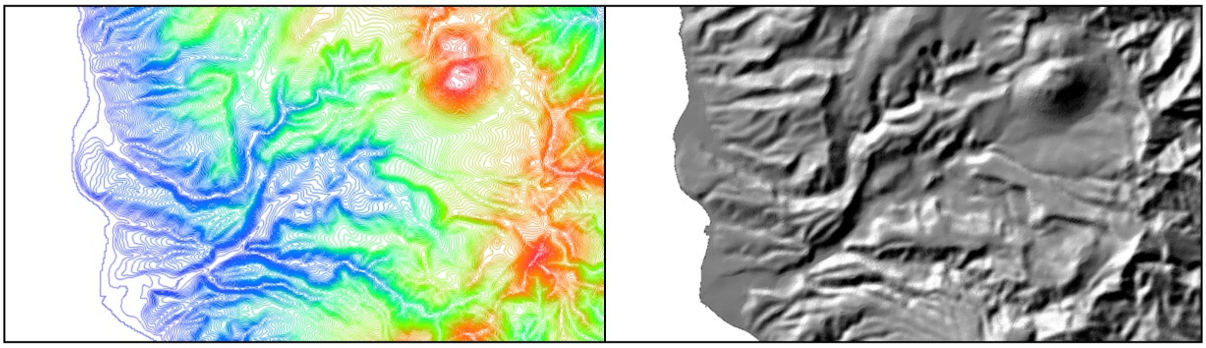


Figure 5-1: The Digital Elevation Model for Dominica is of poor quality. The figure shows a detail of the hill shading image that clearly shows the rounded and generalized topography.

We generated the following derivative maps:

- Elevation classes: this map consisted of 6 altitude classes. This was done because we assumed that there might be a relation between altitude and landslide occurrence, as rainfall amounts strongly increase with increasing altitude.
- Slope steepness classes: an algorithm was used to calculate the slope steepness per pixel in degrees. This map was classified in 5 classes. We assumed that there is a clear relation between slope steepness and landslide occurrence, where the class 20 to 35 degrees might have the highest density of landslides. This will be later analysed in the statistical analysis.
- Slope direction classes: slope direction was calculated using a special algorithm from the DEM. The resulting map was classified into 8 classes, each class corresponding to an interval of 45 degrees.
- Part of the island. We subdivided the island in windward and leeward parts because we assumed that there would be more landslides on the windward side of the island.

- Flow accumulation classes. This map was generated from the DEM using a special algorithm, which counts for each pixel how many other pixels are located upslope. This map was classified into 4 classes. We assumed that there is a relation between the locations where streams are initiated, close to water divided, and landslide occurrence.

Table 5-1: Overview of input maps for landslide susceptibility assessment, with indication of their quality of the data for Dominica in green (good), yellow (sub-optimal), yellow (poor) and red (not available).

Group	Factor	Available	Quality
Topographic factors	Digital Elevation Model	Yes	Poor. Available contour lines have been smoothed quite a bit.
	Altitude zones	Yes	Good, generated from the DEM. Low quality of DEM doesn't affect the altitude zones
	Slope steepness	Yes	Poor. Poor quality of the DEM is cause of poor quality of slope steepness map. Steep slopes are underrepresented.
	Slope aspect	Yes	Moderate. Low quality of DEM affect the slope direction to some extent.
	Upslope contributing areas	Yes	Poor. Low quality of DEM affect the calculation of upslope contribution areas.
	Windward / Leeward side	Yes	Good. Based on digitized boundaries.
Drainage factors	Eroding sections of mains rivers	Yes	Moderate. There are some problems with fitting of the drainage lines to the DEM. Automatic extraction of drainage from the DEM is not an option.
	Distance from stream initiation	Yes	Good
	Distance from ridges	Yes	Due to poor DEM quality automatic extraction of ridges is not very good.
Geologic al factors	Lithological map	Yes	Moderate, Too general to be of much use for landslide work, no differentiation between volcanic materials.
	Fault map	No	Not available
	Geomorphological map	No	Not available
Soil map	Pedologic Soil type map	Yes	Moderate. Detailed map. Extensive legend. Made in 1967 for agricultural purposes. No clear relation with topography and lithology
	Engineering soil type map	No	Not Available. Would be very important for local and site investigation analysis. Should contain information on geotechnical and hydrological parameters of the engineering soils.
	Soil depth map	No	Not available. Would be very important for local and site investigation analysis
Land cover factors	Land cover existing	No	Not existing.
	Land cover (earlier)	Yes	Moderate, Two land cover maps available, one from 2000 made from image classification/, not clear what date. Very general, poor quality
	Road cuts	No	Not available.
	Distance from roads	Yes	Good quality, we improved the road map and made also an improved classification.

5.2. Geology and soils

Practically all rocks in Dominica are of volcanic origin, with the exception of a small unit consisting of limestone on the Leeward side. Dominica is characterized by a series of 8 major volcanoes (SRU, 2000). 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 Dominica.

The geologic map for Dominica contains only 10 units, subdivided according to its origin (volcanic or sedimentary) and to its age. The units are very general, and generally do not differentiate between lithological units that have a different behaviour with respect to landslides (e.g. lavas and pyroclastic deposits which have different characteristics such as texture, cementation, and strength).

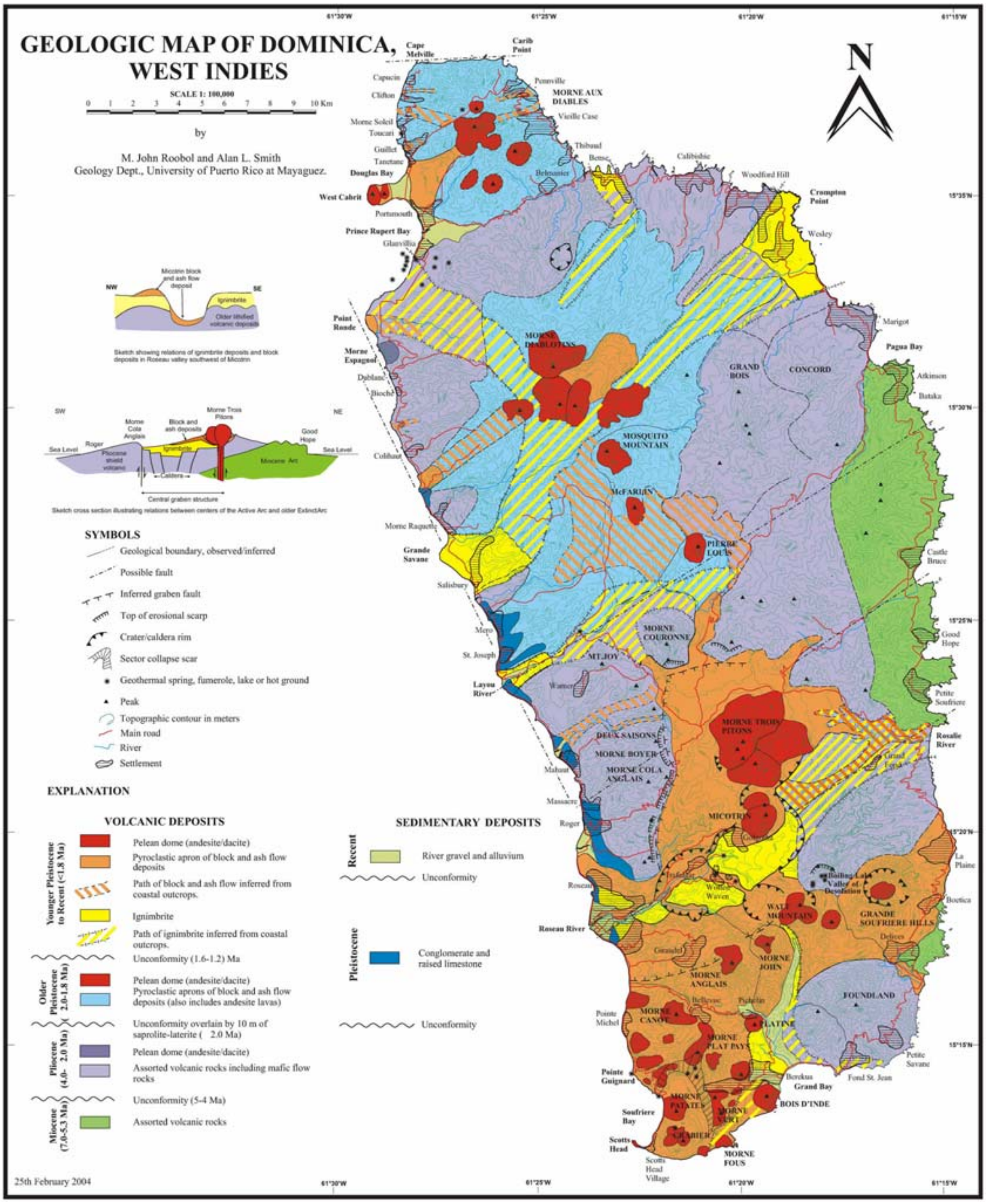


Figure 5-2: Geological map of Dominica (Roobol and Smith, 2004)

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. The volcanic deposits are usually very thick. This can be observed in near vertical road-cuts (See Figure 5-3). Analysing the behaviour of road cuts in volcanic ash soils requires a detailed analysis of soil types which is not possible in this study. Volcanic bedrock in tropical climates is susceptible to deep weathering and mass wasting (Prior and Ho, 1972; Hartford and Mehigan, 1984; Rouse, et al. 1986; DeGraff, 1991). Weathered volcanic soil is weaker than the original bedrock and the high precipitation on the island increases pore-water pressure within discontinuities decreasing soil shear strength. The loss of shear strength generates zones of failure in which the mass destabilizes in the form of a landslide or debris flow (Faugeres, 1966; Walsh, 1982;

DeGraff, 1991). The original geological map that we obtained from the department of physical planning had some serious topological errors. In order to overcome problem associated with missing polygons, it was necessary to re-digitize the geology map again. In order to make the lithological map more realistic we decided to combine it with the slope class map, thus allowing to evaluate the combination of lithological units under different slope classes.

Figure 5-3. Examples of outcrops in volcanic deposits in Dominica. Note the high degree of weathering in the middle photo.

The available soil type map was generated in 1967 (Lang, 1967) through physiographic interpretation of aerial photographs, combined with field work and soil testing. The map consists of 2 map sheets, with a very complicated legend. There are over 100 different legend classes, and soils are named after a locality (most often an estate), with a suffix related to the parent material. 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. The legend classes show a combination of the soil type (indicated as a number), the slope class and the erosion categories.
Four distinct soil types are important in Dominica, these are: smectoid soils, kandoid soils, allophane latosolics and allophane podzolics. Rouse et al. (1986) investigated the properties of these soil types which is summarized below.

- *Smectoid soils* (montmorillonite-rich): these soils occur in the highly seasonal parts of the island (annual rainfall below 2100 mm) where leaching is low, interrupted and incomplete. The montmorillonite content, together with an occasional cemented silica pan makes these soils impermeable when wet. Compared with the other soils of Dominica, smectoid soils have high subsoil dry unit weights and low porosities that ranges from 12.1 to 17.8 kN/m^3 and from 0.36 to 0,61 respectively.
- *Kandoid soils* (mostly latosolics) (Kaolin/halloysite-rich): these soils typify areas receiving rainfall between 2100 mm and 3750 mm annually and a shorter duration of dry season, leaching is moderately intense and uninterrupted. Kandoid soils take a longer time to mature than smectoid and allophane soils, they are only found in older volcanic areas i.e. in the north and east part of the island. They have much lower subsoil dry unit weights (5.9 - 9.5 kN/m^3) than smectoid and as a result their porosities are much higher (0.66 - 0.79).
- *Allophane latosolics* (allophane-rich): in areas with high annual rainfall greater than 3750 mm and no dry season, where leaching is intense and constant, allophane soils predominate. With continued leaching even the silica may be removed to form gibbsite, but because of the youthfulness of the relief and the effectiveness of the slope erosion, allophane latosolic soils tend to persist and indeed cover large parts of the island interior. Generally, these soils have very low subsoil dry unit weights and extremely low topsoil dry unit weights, 5.5 - 10 kN/m^3 and 1.9 - 4.1 kN/m^3 respectively. As a result, their subsoil porosities are very high (0.66 -0.81) and top soil porosities even higher (0.86-0.93).
- *Allophane podzolics* (allophane-rich): in the wettest areas with annual rainfall greater than 7000 mm, where leaching is extremely high, a peculiar variant of allophane is found. The allophane podzolics are characterized by deep litter and organic humic Ah horizons, a bleached highly leached subsoil, and a subsoil pan formed by accumulation of a complex of organic matter and amorphous sesquioxides. Their dry unit weights and porosities are higher than for allophane latosolics.

From the map, it is possible to observe that the main soil is *Allophanoid Latosolics* (Very highly permeable, low bulk density and at least 40% of matrix-clay size) occupying the middle area of the island. According to Lang (1967) *Allophanoid* soils (e.g. BP and BL soils) are normally exceptionally stable even on very steep slopes and mass movements are limited except when the slope is undercut by a stream. Where unstable soils of this type occur as in maturely dissected areas having underlying impervious or less pervious materials at small depth this is indicated in the map. Dominant soils in the northeast 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).

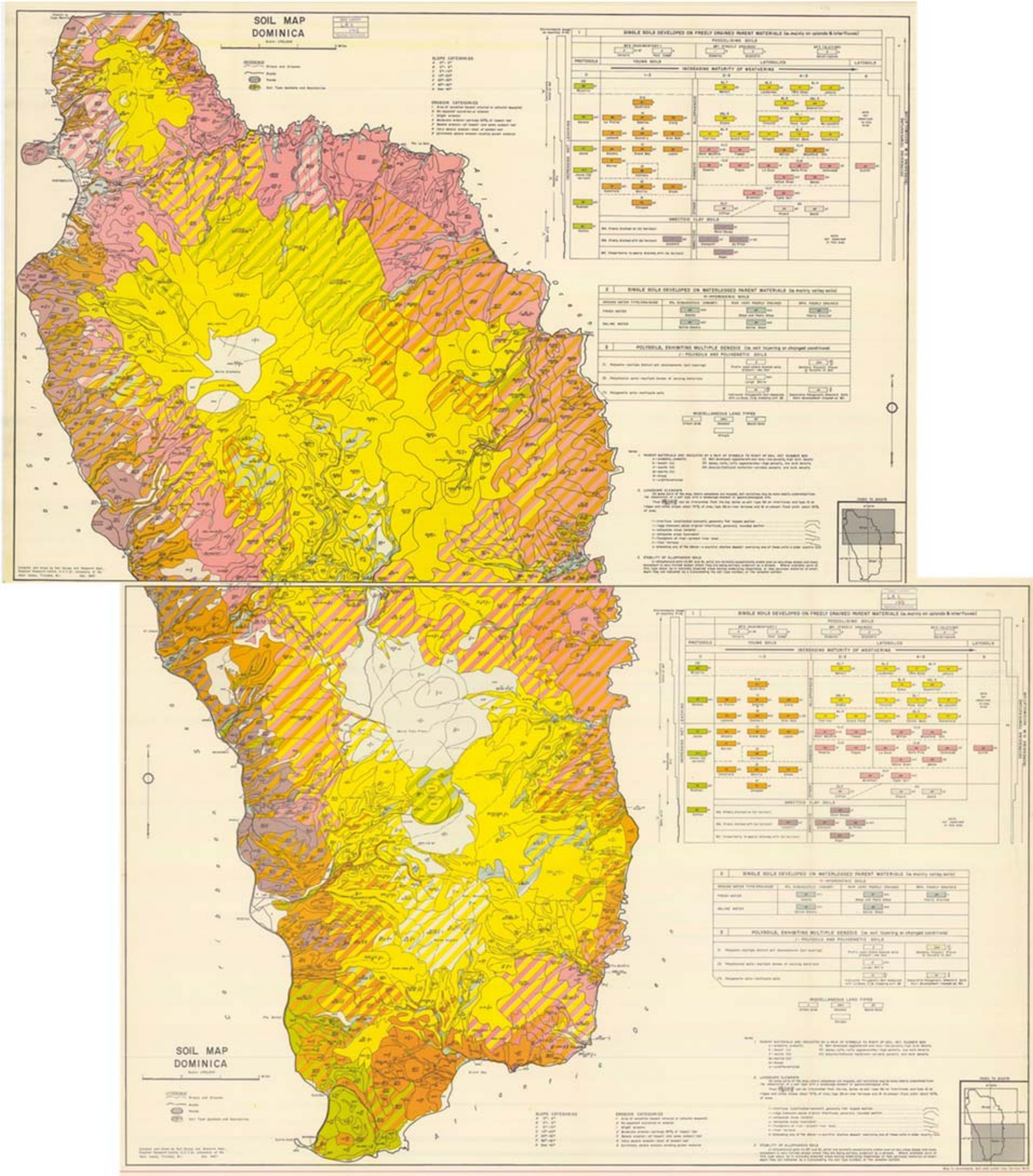


Figure 5-4: Soil map of Dominica (Lang, 1967)

The conversion of this complicated soil map into a GIS layer turned out to be a major challenge. We obtained a digital soil map from the physical planning department, which contained 17 units. The topology of this map was also problematic, and we had to fix this using a number of GIS operations. We did not attempt to re-digitize the original map, as this would be too time consuming, and also the legend would pose a serious problem in the use of this in the landslide susceptibility assessment. We did link it with a slope class map, to make soil classes in relation to the slope classes, which were considered to be better indicators for slope stability than the soil classes alone.

5.3. Land-cover

Initially we only obtained a vector-based land cover map without any metadata, so it is not clear how old this map is, who made it, using which techniques. This map is very general when comparing it with a satellite image. The land-use map consists of 18 units. Later on we obtained another land cover map from developed from satellite imagery as part of a multi-organization project. For Dominica, Landsat and SPOT images acquired between 1996 and 1999. A preliminary unsupervised classification was generated to identify areas of distinct spectral characteristics to guide field inspections and the collection of training data (Arces et al., 1999; Coan et al., 2007).

The available road map was adjusted based on a very high resolution satellite image (Pleiades, with spatial resolution of 2 meters multi spectral and 0.5 meter panchromatic). Screen digitizing was done to map the road and make a road classification. Building information was initially only available for Roseau. In order to obtain building data for the entire country, the very high resolution satellite image was used, and thresholds were made for the individual bands. The resulting building mask was converted to polygons, and subsequently to points. The points were edited subsequently manually through screen digitizing using the very high resolution satellite image, and each building in Dominica was digitized using a point. Drainage lines were generated from the Digital Elevation Model and through editing. Place names in Dominica were obtained from an existing dataset, and through available maps and Google Earth. Airports, and other landmarks were digitized using the very high resolution images. Quarries were also mapped from these images.

Figure 5-5: Detail and legend of the Land cover map of Dominica. The map can be downloaded from: [*http://www.charim.net/dominica/maps*](http://www.charim.net/dominica/maps)

6. Landslide susceptibility assessment

The best approach for landslide initiation susceptibility assessment at a scale of 1:25,000 - 1:50,000 is the use of statistical methods in combination with expert-based weighting approaches. Since we do not have a very reliable landslide data set, we used the available landslides to check the statistical relation with the factor maps, but generate the actual landslide initiation susceptibility map using Spatial Multi-Criteria evaluation. Although we have reconstructed a considerable number of past landslide in the landslide inventory, the factor maps are of poor quality, and therefore the relationships between landslides and these factors are only indicative, and should not be used automatically. Therefore a combination of statistical methods and expert-based methods should be used.

6.1. Evaluation of landslide factors using bi-variate statistical analysis

When enough landslides are available in the landslide inventory, it is advisable to use bi-variate statistical methods as exploratory tool to learn which contributing factors, or combinations of contributing factors are important in the study area. One of the most frequently used methods for bi-variate statistical analysis is the Weights-of-Evidence method, further referred to as WoE. The method is explained in Figure 6-1

	Factor class present (B)	Factor class not present ($\overline{B}$)	
Landslides present (S)	180	20	200 (total landslide area)
Landslides not present ($\overline{S}$)	3420	6380	9800 (total area free of landslides)
	3600 (total area of factor class)	6400 (total area outside3 factor class)	10000 (total study area)

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

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

P{B|S} = 180/200 = 0.9

P{B|$\overline{S}$} = (3600-180)/(10000-200) = 3420/9800 = 0.349

P{$\overline{B}$|S} = (200-180)/(200) = 20/200 = 0.1

P{$\overline{B}$|$\overline{S}$} = (10000-3600-200+180)/(10000-200) = 6380/9800 = 0.6510

Figure 6-1: Illustration of the Weights of Evidence model. Above: Example of a matrix which is calculated for the spatial overlay of a factor class (e.g. a certain slope class, or lithological unit) with landslides. The area for each combination is shown in a hypothetical example. Lower left: equations used for the Weights of Evidence modelling. Lower right: worked out example, based on the values in the matrix above.

The WoE technique was originally developed for quantitative mineral potential mapping to predict the location of possible mineral deposits (Bonham-Carter et al., 1988; Bonham-Carter et al., 1989). However, it has been successfully applied in many landslide susceptibility assessments (van Westen, 1993; Lee et al., 2002; van Westen et al., 2008; Lee and Choi, 2004; Süzen and Doyuran, 2004; Neuhäuser and Terhorst, 2007; Thiery et al., 2007; Blahut et al., 2010;) and is based on the assumption that factors causing landslides in the past will determine the spatial occurrence of future landslide initiation in areas currently free of landslides. A probabilistic Bayesian approach is applied to determine the conditional probability between the presence/absence of each causative factor and the presence/absence of a landslide. For every factor map (e.g. land-cover, lithology, etc.) a weighting table is produced that includes for each class (e.g. grassland, bare rock) the positive weight (W+), which indicates the importance of the "presence" of this class on the occurrence of landslides. The table also has the negative weight (W-) which evaluates the importance of the "absence" of the class on landslide occurrence and the Contrast factor (W+ - W-). The contrast factor is considered a measure of the overall importance of a factor map class on the conditions causing landslide occurrence. The advantages of WoE are its quick and cost effective approach and the capability of combining the subjective choice of the classified factors by the expert with the objective data driven statistical analysis of the GIS. For details on the WoE methodology applied for landslide susceptibility the reader is referred to Lee et al. (2002).

There are several useful tools available that can be used with a conventional GIS system, without the need of external statistical models. These methods basically calculate landslide densities within the contributing factors, or the classes of the contributing factors, and then compare these with the overall density in the map. Also in ArcMap there are extensions for making these calculations, such as ARC-SDM (http://www.ige.unicamp.br/sdm/default_e.htm; Sawatzky et al., 2009)

The calculation of the Weights of Evidence is carried out using a script in the ILWIS software. A script contains a series of commands that allow the automatic execution of a series of calculation steps for different maps. The script used is indicated in the Figure 6-2.

Figure 6-2: Weights of evidence script used in the ILWIS software.

When executing the script an input screen will ask for the input data (See Figure 6-3)

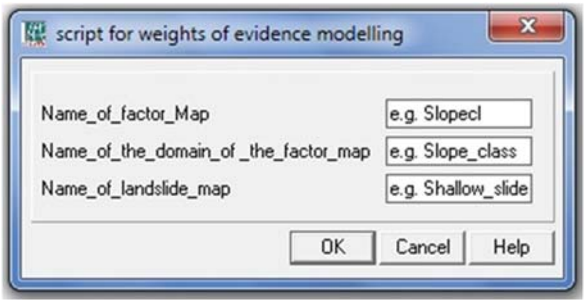


Figure 6-3: Input screen for the Weights-of-Evidence script used in the analysis. The script needs three inputs: name of the factor map (e.g. slopeclass, lithology), name of the domain of the factor map, and name of the landslide map, which should be a binary map (0= no landslide, 1= landslide).

The script was analysed for each of the factor maps in combination with two landslide input maps: one for shallow soil slides, and one for rockslides and rockfalls. After running the script a table is made for each factor map with the Weights of Evidence for all classes of the factor map and also the Contrast Factor, which is the absolute difference between W+ and W-.

The results from the Weights of Evidence modelling were used to evaluate the relative contribution of the various factor maps, and the classes of the factor maps, to landslide occurrence. We also tested out whether specific combinations of factors had a better relation with landslides, e.g. by combining lithology with slope classes.

6.2. Results of the statistical analysis for Dominica

The landslides described in chapter 4 were subdivided into two dataset: one group consisting of rockslides and rockfalls, and the other group consisting of soil-related landslides. This was done because these two main groups were expected to have occurred under different conditions, and the analysis of the various contributing factor was therefore done for these groups separately. Figure 6-4 shows the two landslide input maps, which were converted into binary maps (1= landslide, 0= no landslide).

For Dominica the following factor maps were analysed using the Weights of Evidence method (See Table 6-1).

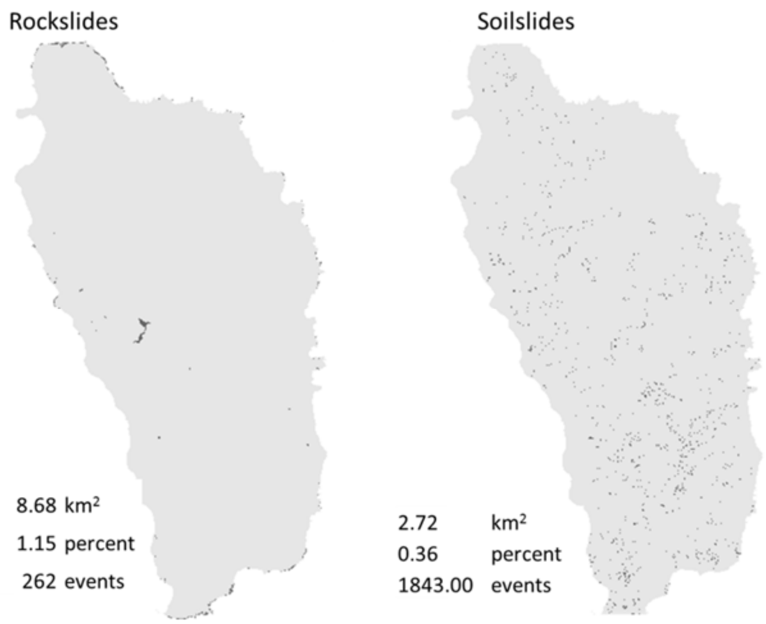


Figure 6-4: Landslide inventory maps for rockslides and soil-related landslides that were used in the analysis.

Table 6-1: Overview of the factor maps used for the statistical analysis for Dominica.

Name of factor map	Explanation	Classes
Coast_dist_class	Distance from coastline	8 classes (0-50, 50_100, 100_150, 150_200, 200_250, 250_350, 350_500, >500 m
Elevation_Class	Elevation classes	6 classes (0 - 100, 100 – 265, 265 – 500 500 – 825, 825 - 1000 , >1000 m.a.s.l.)
River_dist_cl	Distance from rivers	4 classes (0_25, 25_50, 50_100, >100 meter)
Ridge_dist_cl	Distance from ridges	8 classes (0-25 , 25_50, 50_75, 75_100, 100_150, 150_200, 200_300, >300 meter)
Road_dist_cl	Distance from roads	4 classes (0-2, 25-50, 50-100, > 100 meter)
Geology	Lithological units	10 geological units, without clear differentiation between lithological types. Most group several types.
Landuse_map	Land use map	17 classes but still very general
Slope_cl	Slope steepness classes	5 classes (0 - 10 , 10 - 20, 20 - 35 , 35 – 50, >50)
Aspect_cl	Slope direction classes	9 classes (N, NE, E, SE, S, SW, W, NW, Flat)
WindLeeward	Main parts of the island	4 classes (windward, leeward, and northern windward & leeward)
Soil_type	Soil types	17 main classes, but many subdivision. Very complicated legend
Soil_erosion_class	Soil erosion classes, indicated in soil legend	8 simplified classes ranging from very high to very low, and a large class unclassified
Soil_landslide_class	Soil stability classes, indicated in the soil legend	10 classes with different problems related to soils from flooding, waterlogging to stability.
Soil_watertable_cl	Water table classes, indicated in the soil legend	6 classes, ranging from perched water tables to deep water table.
Geology_Slopecl	Combination of geology and slope classes	45 classes combining the 10 geological units with 5 slope classes.
Landuse_Slopecl	Combination of land use and slope classes	78 classes combining 17 land use classes with 5 slope classes.
SoilType_Slopecl	Combination of soil types and slope classes	78 classes combining 8 soil classes with 5 slope classes.
WindLee_Slopecl	Combination of main sides of the island with slope classes	20 classes, combining 4 classes of windward/leeward/north/south with 5 slope classes
Elevation_Side	Combination of elevation and main sides of the island	20 classes, combining 4 classes of windward/leeward/north/south with 6 elevation classes
Elevation_Side_Slopecl	Combination of elevation, exposure and slope steepness	100 classes, combining 4 exposure classes, with 6 elevation classes and 5 steepness classes

Slope steepness.

Both rockslides and soil slides show a relation with slope steepness, with negative weights for the lower slope steepness classes, and increasing weights for the steeper slope classes. Both show a similar behaviour although rockslides occur more on very steep slopes.

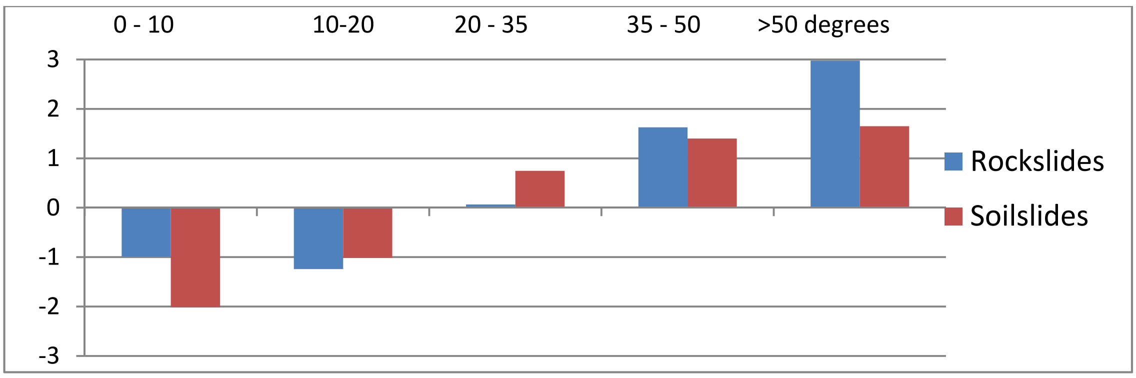


Figure 6-5: Contrast factors for slope steepness classes for rockslides and soilslides.

Slope direction.
When using slope direction directly from the Digital Elevation Model (See Figure 6-6) the relation is less clear than when using the major subdivision in windward and leeward sides of the island (Figure 6-7).

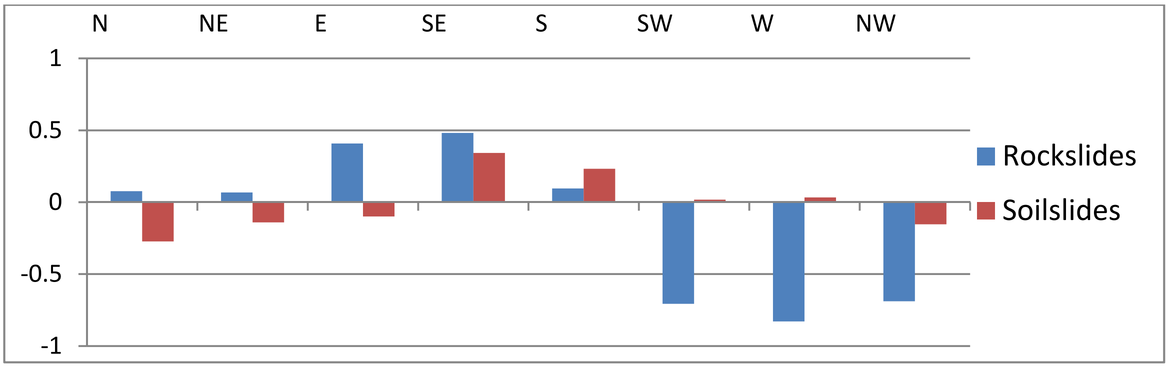


Figure 6-6: Contrast factors for slope direction classes for rockslides and soilslides.

It is interesting to see that rockslides have a quite different relation with respect to slope direction than soil slides (Figure 6-6). Rockslides occur considerable more on the northern side of the island, both on the windward and leeward sides. The contrast factors for the leeward side is slightly negative and the one for the windward side more negative. According to the statistics, but contrary to the overall impression, soil slides occur relatively more on the leeward side than on the windward side, taking into account the landslide density. This is a bit misleading because of the large areas in the northeast where there are hardly any soil slides, whereas the windward side in the south and south western sides have relatively many landslides.

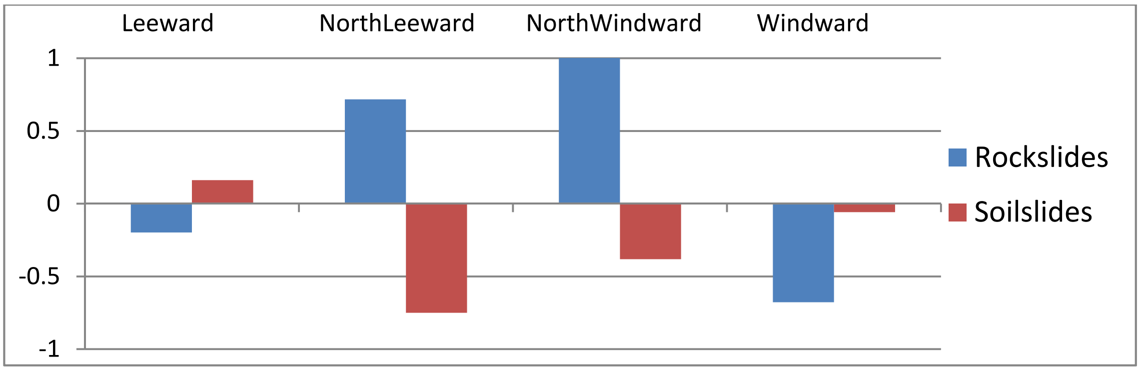


Figure 6-7: Contrast factors for main exposure classes for rockslides and soilslides.

When we combine the main exposure classes with the slope classes and run the statistical analysis for the combination the results show that in both windward and leeward side there is an increase with increasing slope steepness classes. Contrast factors on the windward side are a bit higher for the various slope classes than on the Leeward side.

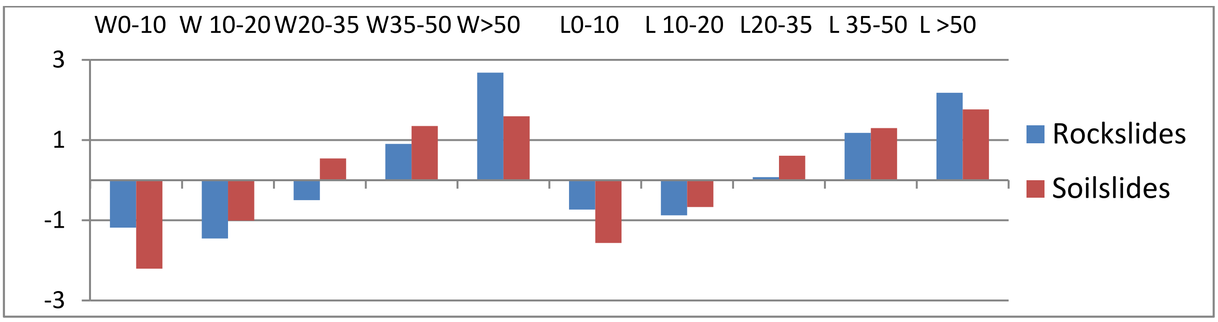


Figure 6-8: Contrast factors for the combination of the main exposure classes and slope steepness classes for rockslides and soilslides.

Elevation

Also elevation plays a different role for rockslides and soilslides. As can be seen in Figure 6-9, rockslides are most prominent at low elevation, whereas soilslides have a relation with increasing elevation.

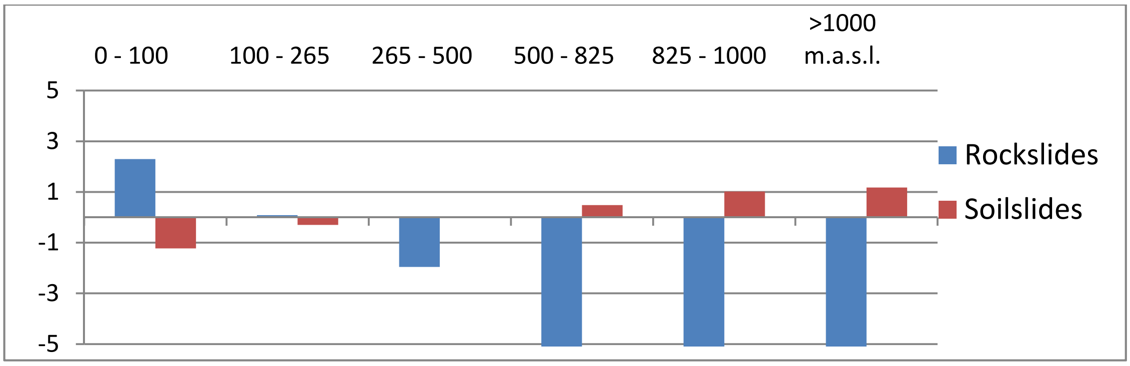


Figure 6-9: Contrast factors for elevation classes for rockslides and soilslides.

Table 6-2: Contrast factors for the combination of elevation classes and Leeward and Windward zones for rockslides and soilslides.

Rockslides

Elevation	Wind-ward	Lee-ward	North Wind-ward	North Lee-ward
0-100	1.35	1.30	3.68	1.53
100-265	-0.90	0.61	1.38	0.16
265-500	-3.55	-1.15	-1.97	-1.70
500-825	-16.10	-16.33	-12.20	-12.31
825-1000	-14.36	-14.19	-	-
>1000	-13.44	-13.72	-	-

Soil Slides

Elevation	Wind-ward	Lee-ward	North Wind-ward	North Lee-ward
0-100	-1.17	-0.89	-2.40	-4.94
100-265	-0.42	0.08	-2.06	-0.74
265-500	-0.15	0.15	-0.14	-0.35
500-825	0.67	0.09	1.70	0.85
825-1000	0.99	1.00	-	-
>1000	1.37	0.97		

Distance from the coast

There is a very clear relation with rockslides and distance from the coast. As most of the rockslides occur along the coastal cliffs there is an obvious relation (See Figure 6-10). Soil slides do not have a clear relation with the distance from the coast.

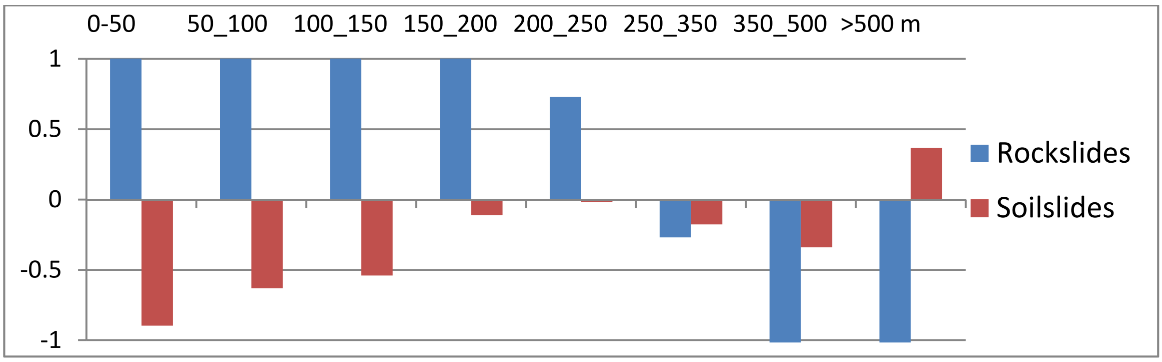


Figure 6-10: Contrast factors for distance to the coast for rockslides and soilslides.

Distance from ridges

Soil slides have a clear relation with distance from major ridges and watershed divides, as can be observed from Figure 6-11. Soil slides are most frequently occurring at a distance of around 75-150 meters from watershed divides, in locations where enough ground water can accumulate to start a gully or stream. The rockslides do not seem to have a relation with the distance to ridges.

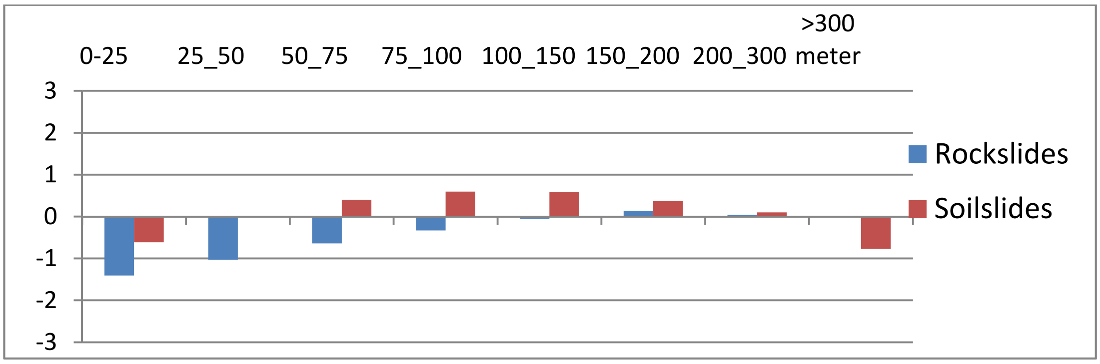


Figure 6-11: Contrast factors for distance to ridges for rockslides and soilslides.

Distance from rivers

Rock slides have a clear relation with the distance to rivers, as they appear more frequently close to streams, within a distance up to 50 meters. This is both due to the undercutting effect of rivers, as well as the abundance of landslide in the starting points of rivers. Soil slides, on the contrary do not show this relation. This is in fact contrary to what we expected. We still would like to keep the distance to rivers also as a factor for soil slide susceptibility assessment.

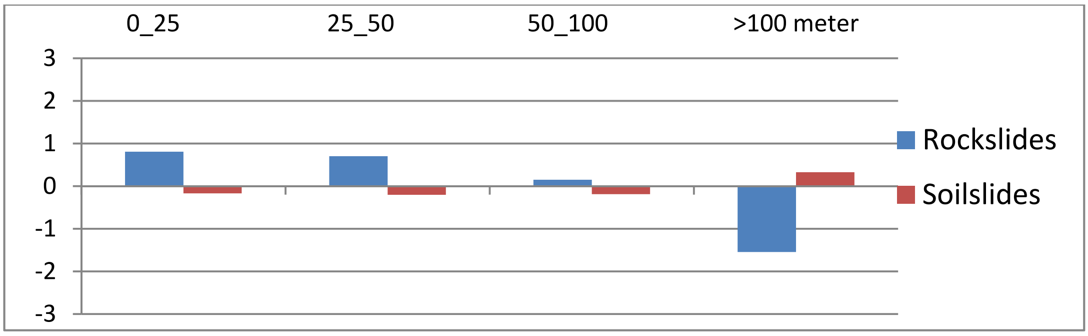


Figure 6-12: Contrast factors for distance to rivers for rockslides and soilslides.

Distance from roads

Although one would assume that landslides are closely related to roads, and roads in Dominica are often affected by landslides, there is no evidence from this from the statistical analysis. Both rockslides and soil slides have negative contrast factors for the distance classes close to roads. This is due to the fact that the landslide database that was used as input didn't have many road related landslides as many of the landslide data that was collected from the ministry of public works doesn't have a geolocation, and therefore couldn't be incorporated in the landslide inventory database. That is why we decided to carry out a separate landslide hazard analysis along the road network.

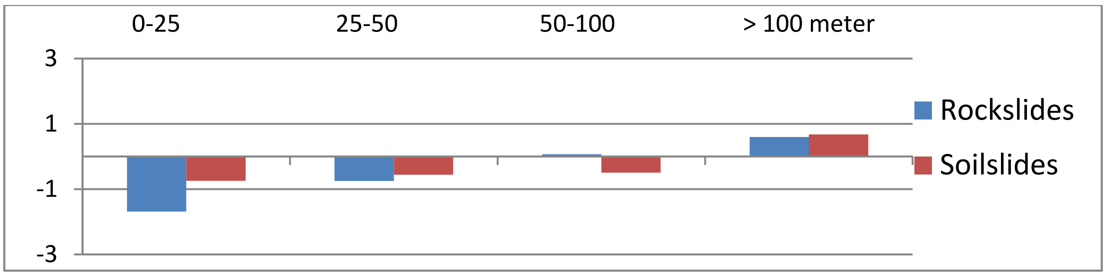


Figure 6-13: Contrast factors for distance to roads for rockslides and soilslides.

Geological units

The relationship between landslides and the geological units is rather complex. Therefore we decided to also combine the geological map with slope classes and show the resulting contrast factors in Tables 6-3 and 6-4. From Table 6-3 it can be seen that the contrast factors change quite a bit when comparing the overall ones (left column) with the ones within the various slope classes. There are four geological units susceptible to rock slides, and especially within the steeper slope classes, with some exceptions (e.g. Mafic Breccias). The positive contrast factor for this geological unit for slopes between 0 and 10 degrees is a good indication of the poor quality of the DEM, and the general low level of quality of this very important data layer. Pleistocene Ignimbrites, Pelean Domes, and Proto Morne aux Diables (Pyroclastic apron of block and ashflow deposits, with andesitic lavas) in the north of the island, have a considerable number of rockslides. The behaviour of the contrast factors for the soil-related landslides is completely different when you compare the overall values per geological unit with the ones that were generated from the combination of geology and slope classes. Whereas overall only two units show positive contrast factors, nearly all geological units do so for steeper slopes. This means that soil related landslides occur basically within all the geological units, but mostly in the steeper slope ranges. Therefore one can conclude that the available geological map, which has relatively little detail as to the type of deposits, is not so very useful for landslide susceptibility assessment for soil related landslides.

Table 6-3: Contrast factors for the combination of Geological units and slope classes for rockslides

		Slope classes				
Geological units	All	0-10	10-20	20-35	35-50	>50
Conglomerate and raised limestone	-0.90	-1.49	-0.63	-0.59	-1.17	-6.40
Mafic breccias and thin lavas of Foundland Center	0.95	0.69	-0.27	0.24	1.26	3.89
Miocene	-0.97	-2.07	-1.22	-0.38	-0.07	-8.82
Pleistocene apron of block and ash	-0.65	-1.91	-1.69	-0.18	0.86	1.30
Pleistocene Ignimbrites	0.75	-0.07	0.61	1.50	1.67	2.17
Pleistocene Pelean Domes	0.86	-0.75	-1.80	-1.80	1.60	3.08
Pliocene	-0.77	-0.65	-1.29	1.57	0.69	1.79
Proto Morne aux Diables	1.93	-0.02	-0.18	1.57	3.36	5.40
River gravel and alluvium	-2.64	-13.76	-5.31	-1.18	-1.72	-7.85

Table 6-4: Contrast factors for the combination of Geological units and slope classes for soilslides

		Slope classes				
Geological units	All	0-10	10-20	20-35	35-50	>50
Conglomerate and raised limestone	-0.02	-2.67	-0.62	0.90	1.56	-7.61
Mafic breccias and thin lavas of Foundland Center	0.90	-0.10	0.32	0.88	1.40	0.73
Miocene	-0.29	-1.27	-0.81	0.34	0.75	0.56
Pleistocene apron of block and ash	-0.02	-1.96	-1.06	0.46	1.27	1.93
Pleistocene Ignimbrites	-0.41	-2.18	-0.74	0.76	0.73	0.86
Pleistocene Pelean Domes	1.17	-1.17	-0.05	1.03	1.75	2.07
Pliocene	-0.18	-1.87	-0.89	0.38	1.13	1.40
Proto Morne aux Diables	-1.02	-2.90	-1.69	-0.55	-0.13	-0.41
River gravel and alluvium	-1.16	-3.46	-0.75	0.08	0.28	0.16

Soil types

The soil map which is available has a very complicated legend. Therefore it was decided to split this map into several sub-maps, which show different aspects of the soil characteristics. The first one is the classification of the soil types. Figure 6-14 shows the contrast factors for the various soil types. We do not expect any useful relation between the soil types and the rock slides, as the soils describe the upper meter or and rockslides are much deeper. Nevertheless there seems to be a clear relation between Kandoid latosols and rockslides, however, this is in our opinion a case of a pure coincidental relation. Some relation is expected with the shallow landslides, which is indeed the case. Allophanoid podzolics, Phytogenic group, skeletal soils and protosols have positive contrast factors for soil related landslides. However, when we calculate the contrast factors for the combination of soil types and slope classes, many more soiltypes show positive contrast factors for the steeper slope ranges, except for obvious ones like beach sand, therefore the relationship between soil types and soil related landslides is not as clear as one would expect. This could be due to the relatively old soil map, which focuses on pedologic soil descriptions and not on engineering soils. But also there may be coding problems as the original soil map (shown in Figure 5-4) is difficult to capture in a GIS layer. We also analysed the relation between landslides and some of the other soil-related characteristics. The soil map also contains information on soil erosion hazard. Figure 6-15 shows the resulting contrast factors for the various soil erosion hazard classes. There is no very clear relation, as one would expect that the highest soil erosion hazard class would also have the highest positive contrast factors for soil-related landslides, which is not the case. Only the moderate classes have positive contrast factors. We also analysed a characteristic in the soil map related to slope stability. Figure 6-16 shows the results, which are partly confusing. There is one class, called unstable, that also has positive contrast factors, though. We also analysed the relation with a legend description of the soil map related to groundwater depth, but we didn't find a clear relation with the soil related landslides. The class "shallow water table" was expected to have positive contrast factors, but it didn't.

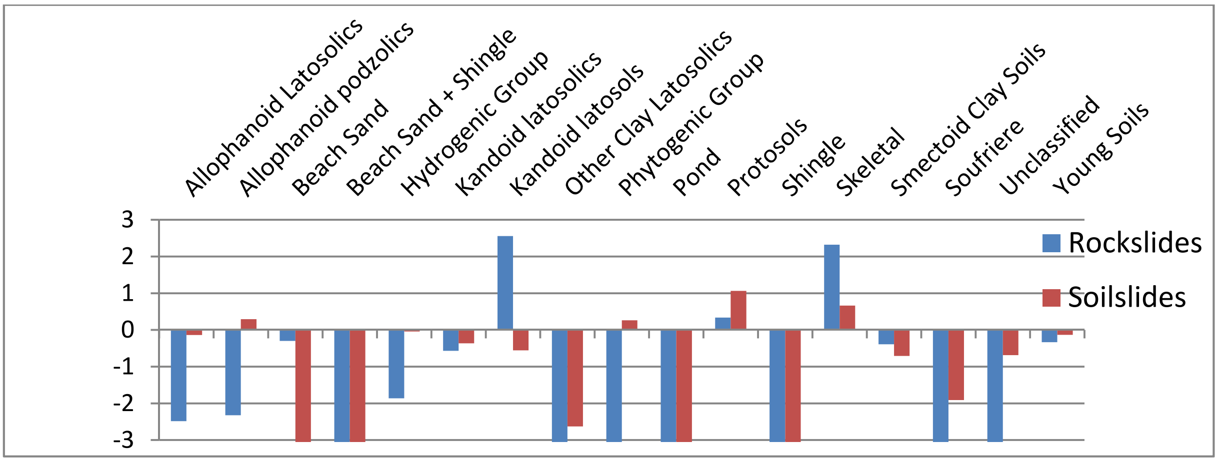


Figure 6-14: Contrast factors for soil types for rockslides and soilslides.

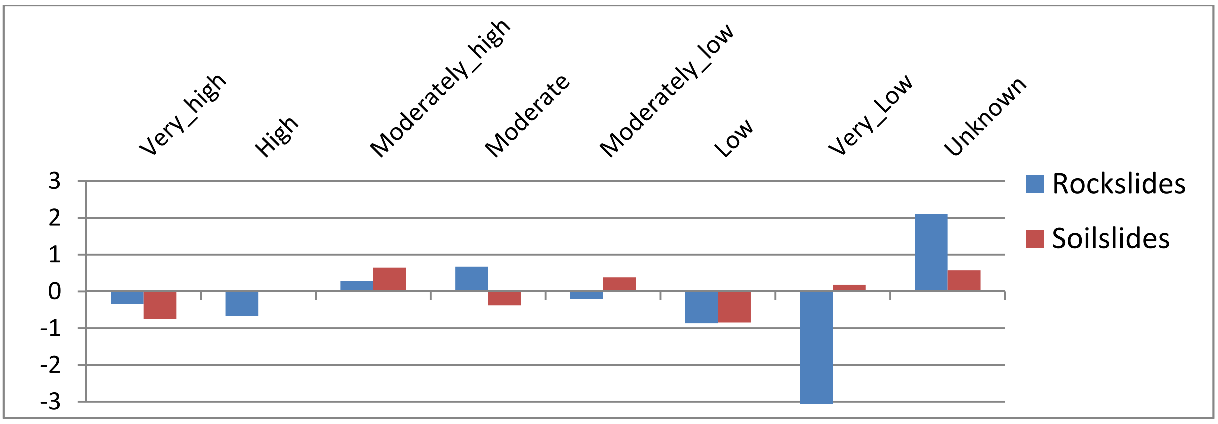


Figure 6-15: Contrast factors for soil erosion hazard classes for rockslides and soilslides.

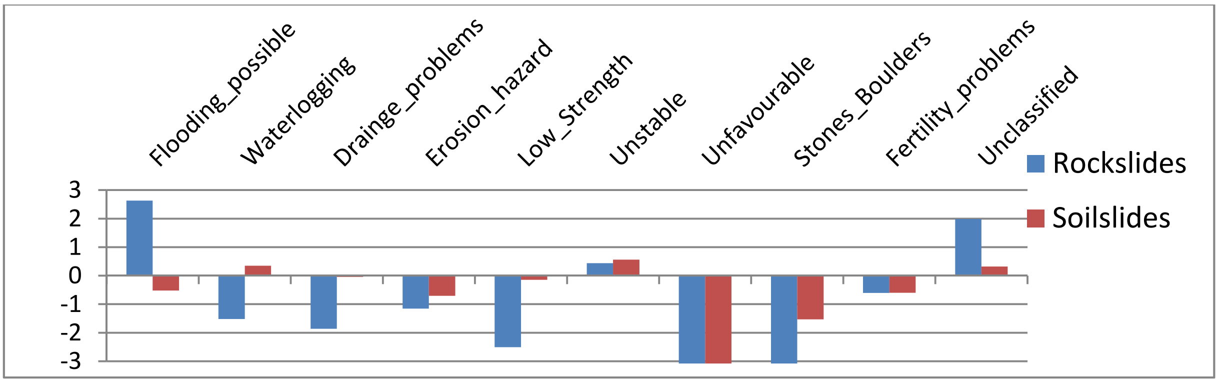


Figure 6-16: Contrast factors for soil-related problems for rockslides and soilslides.

Land use

As was indicated in chapter 5, the available land use map is of unknown date, and has a poor quality. Therefore we didn't expect that there would be a clear relation with the landslides. This is also what comes out of the analysis. There is a clear relation between bare areas and rockslides, but this is perhaps a chicken-and-egg problem as the areas are probably bare because of recent large rockslide activity, as in the case of the Matthieu river landslide. Also the coastal cliff, where a lot of landslide occur, are generally bare. For the soil-related landslides there is a less clear relation. Vegetation types occurring on higher altitude have more landslides, but this is more because of their location than because of the specific land use. The results are summarized in Figure 6-17.

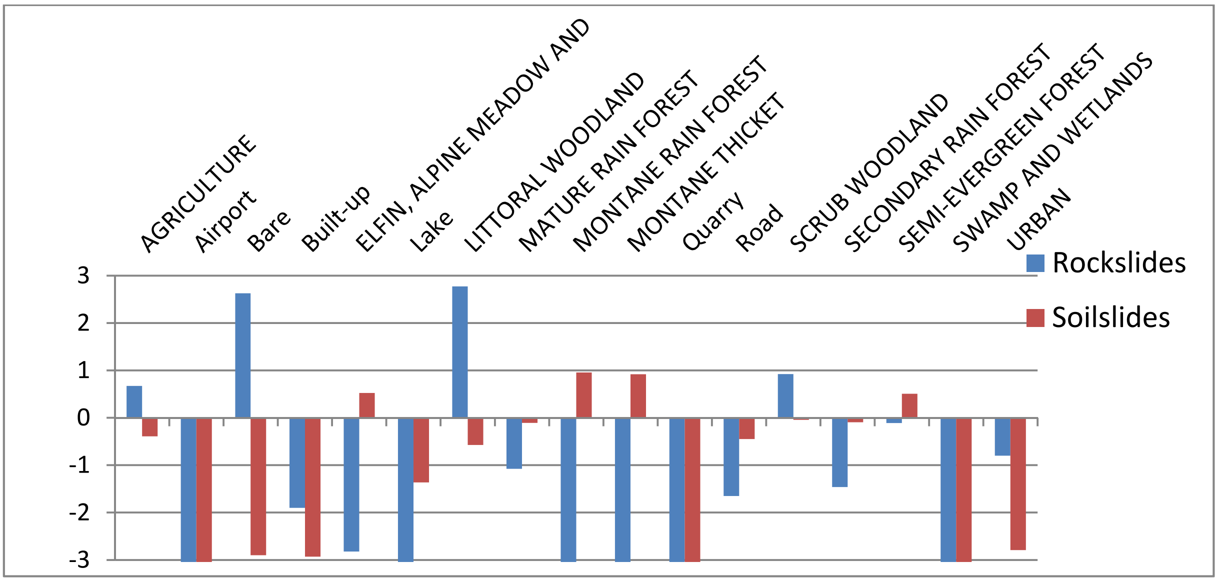


Figure 6-17: Contrast factors for land use classes for rockslides and soilslides.

6.3. Summary

Finally, after evaluation all the factor maps and combinations of factor maps, we have drawn conclusions on the usefulness of the various maps for the susceptibility assessment for rockslides and for soil slides. The results are summarized in Table 6-5.

There is a clear difference between the factor maps that are considered useful for the susceptibility assessment of soil slides and rockslides. Obviously soil-related factors are less useful as factor maps for the analysis of the susceptibility of rockslides, which are much deeper, and where soil type doesn't play an important role as causal factor. The soil related factors are only relatively useful for soil slides as well, as the relations that we obtained through the statistical analysis are often rather confusing. For example the relation with soil erosion hazard classes, soil stability classes, and water table classes do not show what one would have expected, for example that areas with shallow water tables are more prone to landslides. Also the geological map is perhaps more useful as a factor map for the rockslides, which show a clearer relation with the geological units, than the soil slides, as landslides seem to occur in nearly all units. Nevertheless we will use this factor, but only in combination with slope classes, to avoid illogical combinations. We also do the same for other factor maps, such as soil types, and land use types.

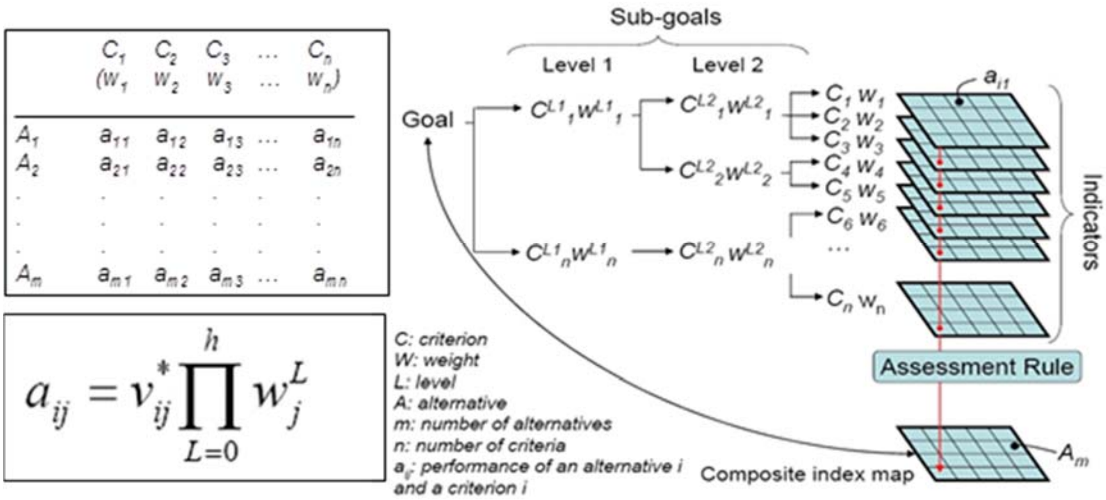
The weights obtained from the Weights-of-evidence modelling are a useful indication for the importance of the various factor classes and factor maps. However, the bottom-line is that an expert should be able to explain why a certain factor class contributes to the occurrence of landslides from a process point of view. This is difficult in many cases, and the weights for a given factor class might be actually due to other factors that are related. As the factor maps have problems with positional, thematic, and temporal accuracy and with lineage as well, we do not want to use the weights from the Weights-of-evidence simply as they are, but will adjust them in an expert based method for combining the factor maps, which will be discussed in the next section.

Table 6-5: Summary of the usefulness of the various factor maps used for the statistical analysis for Dominica.

Name of factor map	Explanation	Rockslides	Soil slides
Coast_dist_class	Distance from coastline	Very useful	Not useful
Elevation_Class	Elevation classes	Useful	Useful
River_dist_cl	Distance from rivers	Somewhat useful	Ambiguous but useful
Ridge_dist_cl	Distance from ridges	Not useful	Very useful
Road_dist_cl	Distance from roads	Not useful	Ambiguous but useful
Geology	Lithological units	Useful	Ambiguous
Landuse_map	Land use map	Somewhat useful	Somewhat useful
Slope_cl	Slope steepness classes	Very useful	Very useful
Aspect_cl	Slope direction classes	Somewhat Useful	Useful
WindLeeward	Main parts of the island	Useful	Somewhat useful
Soil_type	Soil types	Not useful	Ambiguous
Soil_erosion_class	Soil erosion classes, indicated in soil legend	Not useful	Ambiguous
Soil_landslide_class	Soil stability classes, indicated in the soil legend	Not useful	Ambiguous
Soil_watertable_cl	Water table classes, indicated in the soil legend	Not useful	Ambiguous
Geology_Slopecl	Combination of geology and slope classes	More useful than individual geological units	More useful than individual geological units
Landuse_Slopecl	Combination of landuse and slope classes	Not so very useful	More useful than individual landuse types
SoilType_Slopecl	Combination of soil types and slope classes	Not useful	More useful than individual soil types
WindLee_Slopecl	Combination of main parts with slope classes	Useful	Useful
Elevation_Side	Combination of elevation and major exposure units	Useful	Useful
Elevation_Side_Slopecl	Combination of elevation, exposure and slope steepness	Very useful	Very useful

6.4. Landslide initiation assessment using SMCE

For the actual landslide susceptibility assessment we have chosen to use the results of the bi-variate statistical analysis in an expert-based weighting approach, using Spatial Multi-Criteria Evaluation.
Spatial multi criteria evaluation is a technique that assists stakeholders in decision making with respect to a particular goal (in this case a qualitative landslide susceptibility assessment). It is a spatial tool for transparent decision making, using spatial criteria (in the form of maps), which are combined and weighted with respect to the overall goal, based on expert opinion. In this analysis we decided to use the SMCE module of the ILWIS software as it is one of the best tools for SMCE. The theoretical background for the multi-criteria evaluation is based on the Analytical Hierarchical Process (AHP) developed by Saaty (1980).
The input is a set of maps that are the spatial representation of the criteria, which are grouped, standardised and weighted in a 'criteria tree.' The output is one or more 'composite index map(s),' which indicates the realisation of the model implemented. See Figure 6-18
From a decision-making perspective, multi-criteria evaluation can be expressed in a matrix as shown in the Figure 6-18. The matrix A contains the criteria in one axis (C_1 to C_n), and a list of possible alternatives, from which a decision has to be taken on the other axis (A_1 to A_m). Each cell in the matrix (a_{ij}) indicates the performance of a particular alternative in terms of a particular criterion. The value of each cell in the matrix is composed of the multiplication of the standardised value (between 0 and 1) of the criterion for the particular alternative, multiplied by the weight (W_1 to W_n) related to the criterion. Once the matrix has been filled, the final value can be obtained by adding up all cell values of the different criteria for the particular alternative (e.g. a_{11} to a_{1n} for alternative A_1).



$$a_{ij} = v^*_{ij} \prod_{L=0}^{h} w^L_j$$

Figure 6-18: Schematic procedure for spatial multi-criteria evaluation based on the analytical hierarchical process

For implementing this matrix according to the AHP, three principles steps need to be considered. The first one decomposes the problem (and the weights) into a hierarchical structure. The second one considers the weighting process, employing the pairwise comparisons of the criteria, and the synthesis is related to the multiplications among the hierarchical levels. Additionally, in the spatial implementation of this procedure, every criterion (C_j) becomes a raster layer, and every pixel (or set of pixels) of the final composite index map eventually becomes an alternative A_j. The goal (risk index) has been decomposed into criteria levels C^{L1} and C^{L2}.

The intermediate levels are often indicated as sub-goals or objectives (e.g. in level 1, the sub-goals are a 'topographic index' and a 'soil index'). Each criterion of each level will also have an assigned weight. Therefore, the values for the layers of the intermediate levels are obtained through the summation of the performance for the alternative at lower levels. As the criteria consist of raster maps, their spatial performance (a_{ij}) and the alternative (A_i) will be identified for particular raster cells

The composite risk index map is obtained by an assessment rule (sometimes also called decision rule), which is calculated by adding up the performance of all cell values of the different criteria (aij) for the particular alternative. However, the performance of every element in the matrix (aij) is obtained in a different way (See equation in Figure 6-18).

In this equation, v_{ij} refers to the standardised value of criterion (C_j) for alternative (A_i), and weight w^L_j refers to the weight of criterion (C_j) for level L (0–h levels). During the analysis, it could be desirable (and sometimes necessary for a better definition of the weights wLj) to produce the intermediate criteria maps.

The general steps in the process are:

- **Definition of the problem**. Structuring of the problem into a criteria tree, with several branches or groups, and a number of factors and/or constraints.
- **Standardization of the factors**. All factors may be in different format (nominal, ordinal, interval etc.) and should be normalized to a range of 0-1. SMCE has some very handy tools for that especially for value data, making use of different transformation graphs.
- **Weighting of the factors within one group**. SMCE has some very handy tools for that derived from Analytical Hierarchical Processing (AHP), such as pair wise comparison and rank ordering. The weights that are derived from the statistical analysis are used as the basis for the weighting. However, users can deviate from that based on their expert opinion.
- **Weighting of the groups**, in order to come to an overall weight value.
- **Classification of the results**.

6.5. Generation of the susceptibility maps for Dominica

Based on the results from the statistical analysis, which were presented in the previous section, two criteria trees were constructed: one for rock slides and one for soil slides. The selection of the criteria, and the grouping, the standardization of the criteria and the weighing of the individual factors was done iteratively. Each time the

resulting susceptibility maps were compared with the existing landslide inventory pattern to evaluate whether the areas representing high susceptible zones were in agreement with the expert opinion derived from the image interpretation of the island. A second method to check the quality of the resulting landslide susceptibility maps was made using the application of success rate curves, which will be explained later.
The resulting criteria trees for the generation of susceptibility maps for rockslides and soil slides are shown in Figure 6-19.

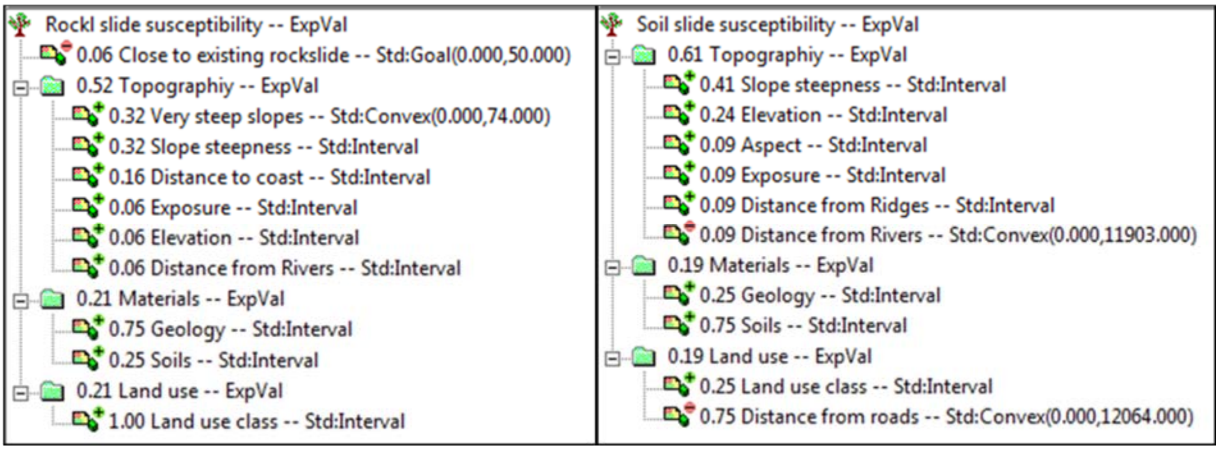


Figure 6-19: Criteria trees used for the susceptibility assessment of rockslides (left) and soil slides (right)

For the criteria selection the results from the bi-variate statistical analysis were leading, however not decisive. For several of the criteria we decided to substitute the weights derived from the statistical analysis with expert-derived weights. This was done for the following reasons:
Many of the factor maps used are rather poor in quality, and have problems in relation to:

- Positional accuracy: due to digitizing problems and projection problems the boundary lines of some of the maps are not always logical. It was not possible to re-digitize all these factor maps, as we didn't have the original maps and this would also take too much time.
- Thematic accuracy: the actual thematic content of the maps is often problematic. Either the units used are too general (e.g. for the geological map, and the land use map) or are not matching internally with the units from other maps, therefore giving a number of rather illogical combinations. These were removed when assigning weights. However, this may not actually improve the final result, as the maps themselves were not improved.
- Temporal accuracy: the maps may not present the situation under which the landslides actually occurred. This is the main problem for the landuse map, for which we have no metadata, and therefore do not know from which year this map is. The land use situation may have changed considerably since the time the map was made.

Since we are not using the weights of the statistical analysis directly as they were, we didn't separate the available landslide data set into a test data set and a training data set, which is customary in statistical landslide susceptibility assessment. We used all the landslides in the exploratory statistical analysis, in order to be able to get a complete picture of the importance of the various factors classes.
We then used the statistically derived weights as a guidance for assigning the expert-based weights in the SMCE. And after generating the final susceptibility maps we calculated the success rates with all landslides of the same type. The resulting susceptibility maps for the two landslide types are shown in Figure 6-20.

6.6 Validation of the final susceptibility maps

In the iterative process of using the Spatial Multi-Criteria Evaluation for the generation of the landslide susceptibility maps, two methods were used to evaluate the quality of the resulting maps":

- Visual inspection of the resulting susceptibility classes in relation with the landslide inventory pattern. We overlaid the landslide inventories for rockslides and soil slides on the respective susceptibility maps and evaluated the patterns. Are most of the landslide on or near to highly susceptible area? If not, what are the factors that occur in these landslides, and could these factors be weighted more without making too much other, currently landslide free areas, also highly susceptible? What are the reasons that some landslides are not in the susceptible zones? This is clearly an iterative procedure, and many runs were carried out using different configurations of the criteria trees in SMCE to adjust the result until an optimal result was obtained.

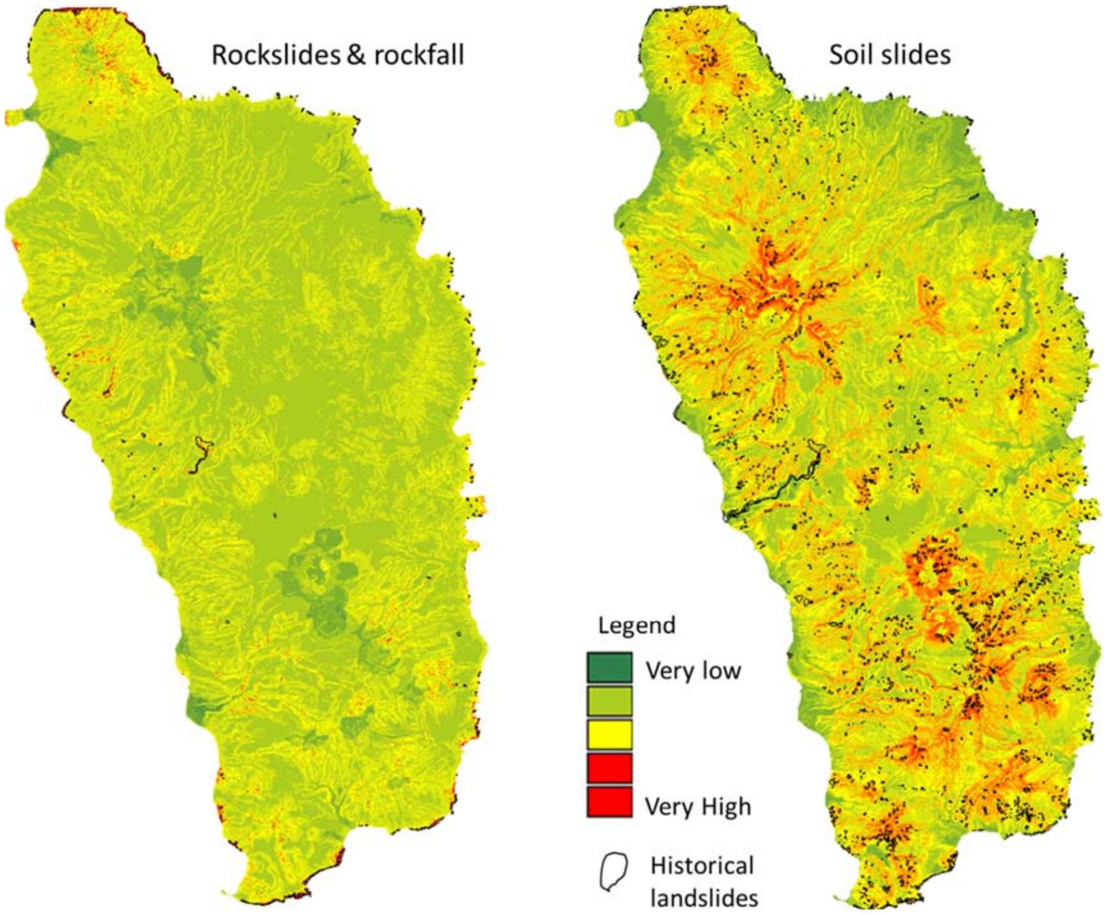


Figure 6-20: Unclassified susceptibility maps for rockslides (left) and soil slides (right) resulting from the SMCE analysis.

- The generation of so-called *success rate curves*. A success rate curve is made by overlaying the susceptibility map (before classification) with the landslide inventory map. The percentage of the susceptibility map with values ranging from the highest to the lowest is 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.

The resulting success rate curves are shown in Figure 6-21. We have shown two success rate curves for each landslide type. One where we didn't include the proximity to existing landslides as a factor, and one where this factor is also included. Of course it makes sense to assume that areas close to existing landslides are also more prone to future landslides. However, this method will also bias the result as the success rates improve dramatically when this factor is taken into account.

As can be seen from the Figure 6-21 the success rates improve substantially when we take the factor "proximity to existing landslides" into account. This means that more landslides have high susceptibility values. On the other hand the predictive power for new landslides might decrease as a result of that.

From the figures it is clear that the susceptibility map for rockslides is better than the one for soil slides. Rock slides have a more narrowly defined set of conditions under which they occur, and soil slides may occur to a wide variety of conditions, that are not always well depicted in the factor maps.

Overall, the success rate is one of the methods to evaluate the quality of the resulting susceptibility map, but not the only one. Previous work has shown that with different combinations of factors, susceptibility maps could be generated with similar success rate curves but very different spatial patterns. Therefore the combination of the two methods is the best in generating the best maps given the limitations in the input data.

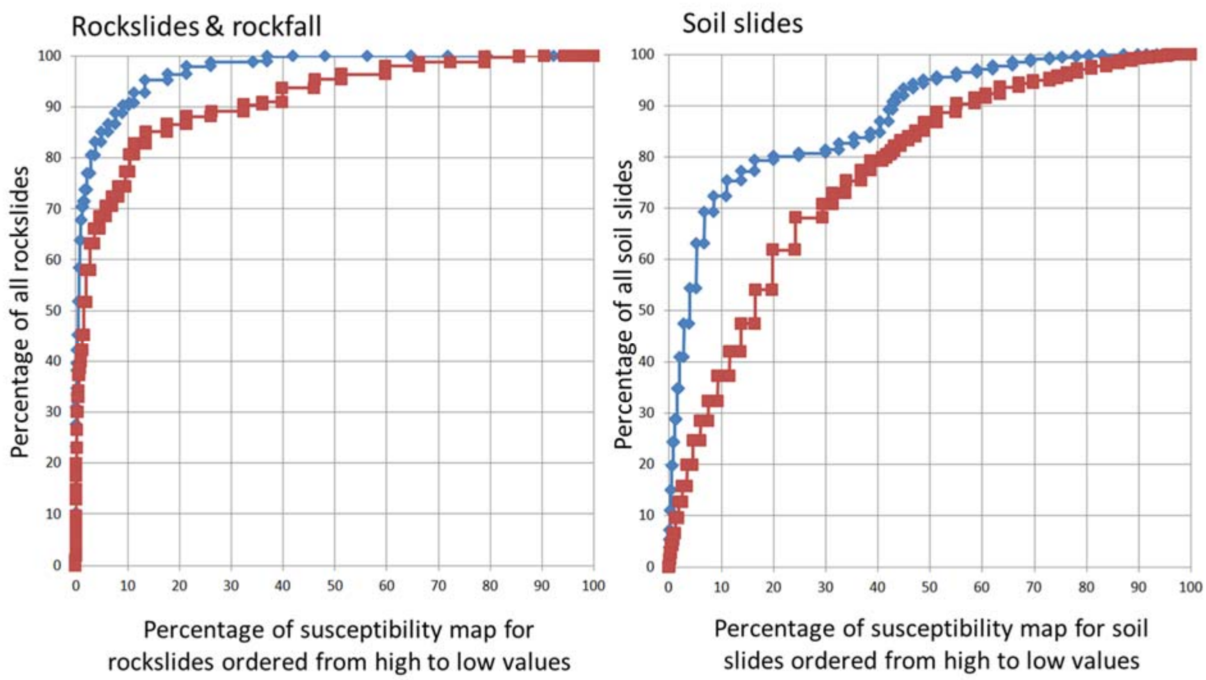


Figure 6-21: Success rate curves for the susceptibility maps for rockslides (left) and soil slides (right). For both the curves are shown without taking into account the factor "proximity to existing landslides" (red lines) and the ones that do take into account this proximity as a factor (blue curves).

6.7 Combining and classifying the susceptibility maps

The success rates can also be used to classify the susceptibility maps into a limited number of classes. It is generally best to use only a few classes as this gives the best information for decision makers, and more classes might lead to confusion. After consultation with planners and engineers from Dominica and the other target countries in the CHARIM project, we have decided to classify the susceptibility maps into the following three classes:

- **Low landslide susceptibility class**: this class generally is landslide free, although under very special circumstances it may be possible that a landslide might occur in this zone, but the density and frequency will be extremely low.
- **Moderate susceptibility**: the intermediate zone is actually the most problematic for use in spatial planning and planning/maintenance of infrastructure. This zone has some probability that landslides might occur, although not very frequent and not with a high density. In the process of susceptibility assessment the analysist should make sure to make the size of the moderate class as low as possible, as it is the intermediate, or "left-over" class, which is not as meaningful as the other two classes.
- **High susceptibility**: this class has the highest density and frequency of landslides. Density is derived from previous inventory and frequency by combining it with the frequency of triggering factors.

The criteria that were used for subdividing the landslide susceptibility maps are given in Table 6.6. It is clear that the results for rockslides are better than those for soilslides. However, even these are rather good, with 80% of the landslides in the high susceptibility class, which covers 20% of the island, resulting in a landslide density of 4.6 %.

It is not useful to have individual landslide susceptibility maps for different landslide types or causal mechanisms, as this would confuse users. We separated the landslide types because they are caused by different combinations of causal factors. Once the susceptibility class maps are made we can combine them again. We combined them into one single map, using a following combination table (See Table 6-7).

We are combining two layers with qualitative classification schemes which don't follow the same classification criteria. This might create problems when using many classes, but when using the three classes as indicated above, it is valid to combine high susceptibility of one type with moderate for the other, where the highest susceptibility will overrule the other.

Table 6-6: Criteria for subdividing the unclassified susceptibility maps into three classes: high, moderate and low landslide density

		Rockslides	Soilslides
High susceptibility	Cut-off value	0.44	0.56
	Percentage of the map	10 %	20 %
	Percentage landslides	90 %	80 %
	Landslide density	2.84 %	4.6 %
Moderate susceptibility	Cut-off value	0.38	0.46
	Percentage of the map	15 %	25 %
	Percentage landslides	7 %	14 %
	Landslide density	0.1 %	0.58 %
Low susceptibility	Cut-off value	0	0
	Percentage of the map	75 %	55 %
	Percentage landslides	3 %	6 %
	Landslide density	0.01 %	0.17 %

The resulting landslide susceptibility maps for rockslides and soil slides are shown in Figure 6-22.

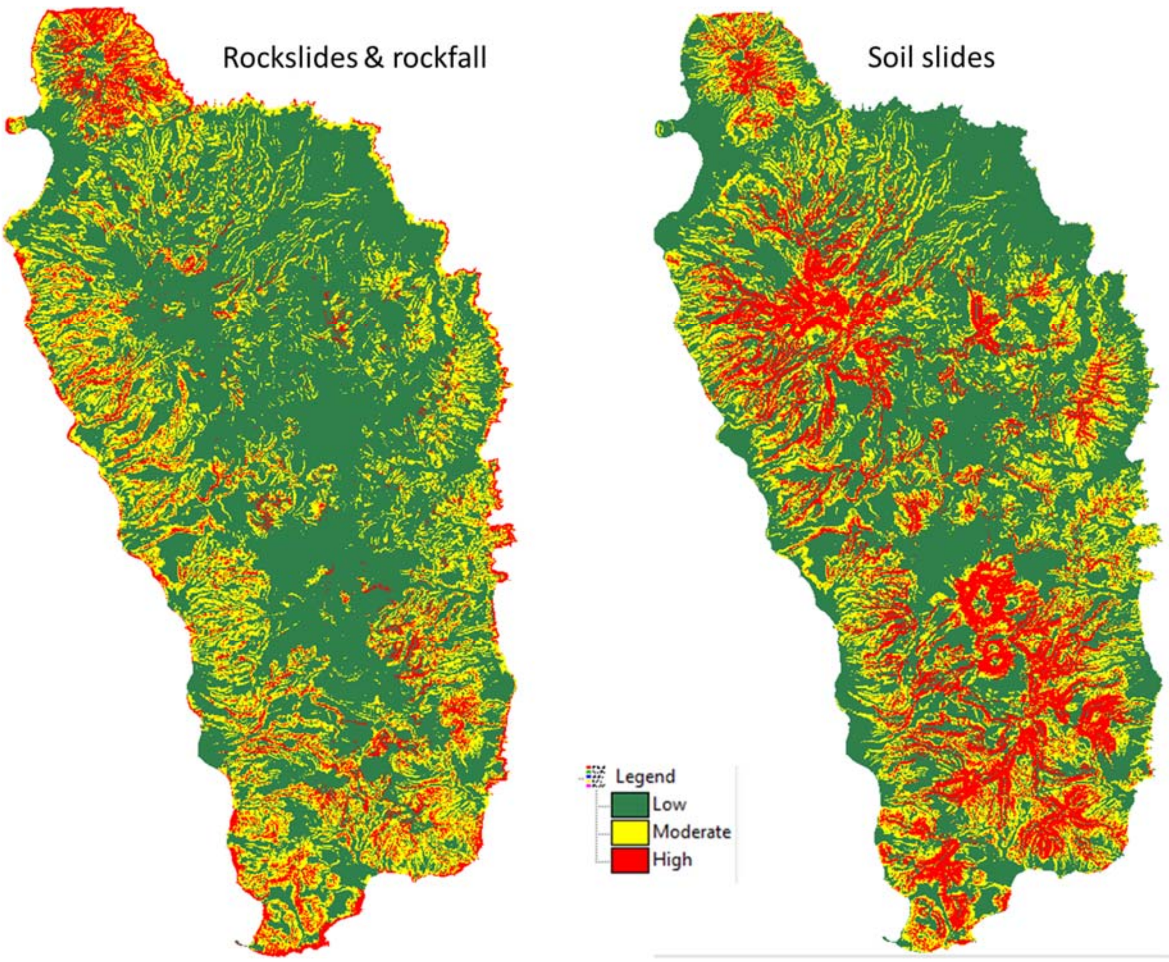


Figure 6-22: Classified landslide susceptibility maps for rockslides (left) and soil slides (right)

Table 6-7: Combination table for generating the final susceptibility map.

		Soil slide susceptibility map		
Rockslide susceptibility map		Low	Moderate	High
	Low	Low	Moderate	High
	Moderate	Moderate	Moderate	High
	High	High	High	High

The combined landslide susceptibility map is shown in Figure 6-23 and Figure 6-24 (southern part). The resulting data for the combined susceptibility map is shown in Table 6-8

Table 6-8: Summary information for the combined susceptibility map.

	Low susceptibility	Moderate susceptibility	High susceptibility
Area in square kilometres	380.4	195.9	174.2
Percentage of total area	50.7	26.1	23.2

6.8 Evaluating the quality of the susceptibility map

The original landslide susceptibility map was generated in June 2015. On 27 August 2015 many landslides were triggered by tropical storm Erika. As can be seen in Figure 4-8 and Figure 4-9, the landslides had an extremely high density in the southwest part of the country. We checked how many of the landslide occurred in the three landslide susceptibility classes. The results are shown in Table 6-9.

Table 6-9. Summary information of different landslide inventories within the low, moderate and high susceptibility classes

		Landslide susceptibility			**Triggering event**
Source	**Characteristics**	**Low**	**Moderate**	**High**	**Event**
Susceptibility map	Area in square kilometres	380.4	195.9	174.2	
	Percentage of total area	50.7	26.1	23.2	
All landslides	Landslide area (m^2)	539240	1095157	9810412	
	Number of landslides	166	248	1711	
	Landslide density (percentage)	0.142	0.559	5.631	
	Landslide density (nr/km^2)	0.436	1.266	9.822	
DeGraff 1987	Landslide area (m^2)	57398	363423	5420517	David Klaus (6-11-1984)
	Number of landslides	14	52	824	
	Landslide density (percentage)	0.015	0.186	3.111	
	Landslide density (nr/km^2)	0.037	0.265	4.730	
DeGraff 1990	Landslide area	153656	83230	694881	Hugo (17/09/1989)
	Number of landslides	28	30	125	
	Landslide density (percentage)	0.040	0.042	0.399	
	Landslide density (nr/km^2)	0.074	0.153	0.718	
Andereck 2007	Landslide area	57916	35256	228303	Rain & earthquake (21/11/2004) Only for an area of 22 km^2
	Number of landslides	37	18	106	
	Landslide density (percentage)	0.015	0.018	0.131	
	Landslide density (nr/km^2)	0.097	0.092	0.608	
This study 2014	Landslide area	762338	622051	3766213	Accumulation of many events
	Number of landslides	90	143	663	
	Landslide density (percentage)	0.200	0.318	2.162	
	Landslide density (nr/km^2)	0.237	0.730	3.806	
Tropical storm Erika, August 2015	Landslide area	636406	515136	675608	Tropical storm Erika (27/08/2015)
	Number of landslides	392	439	641	
	Landslide density (percentage)	0.167	0.263	0.388	
	Landslide density (nr/km^2)	1.030	2.241	3.680	

If we compare the results of the landslide inventories before 2015 there is a relatively good relation between the susceptibility classes and the landslide densities, with increasing landslide density for the moderate and high susceptibility classes. However, there are still too many landslides within the low and moderate classes. This is particularly so for the landslides of the tropical storm Erika, where they are almost equally distributed over the three classes. See also Figure 6-23.

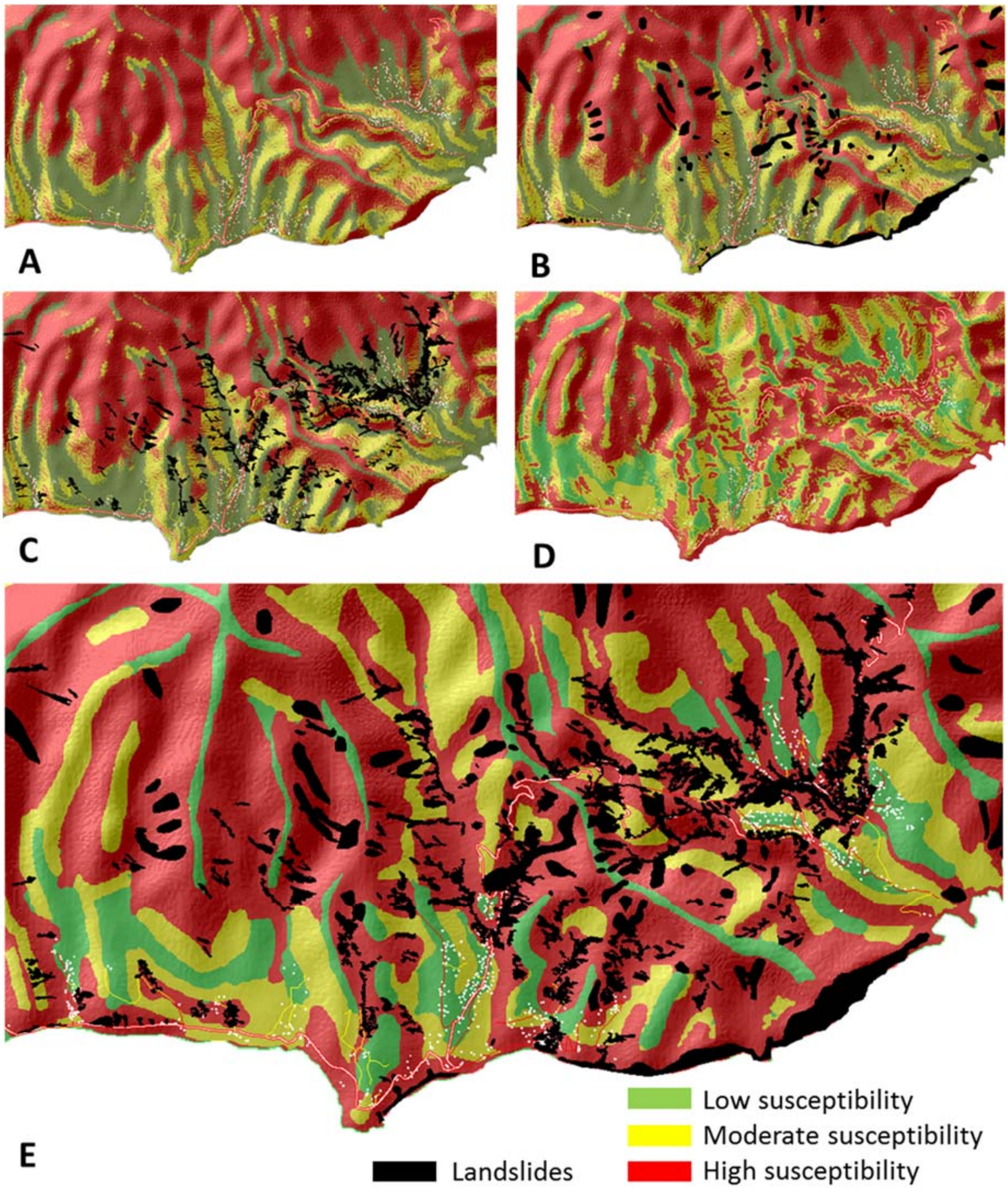


Figure 6-23: Different versions of the landslide susceptibility maps. A: combined soil slide and rockslide susceptibility map; B: overlay of all pre-2015 landslides; C: overlay of the Erika triggered landslides; D: incorporation of landslide inventories in the susceptibility map; E: final landslide susceptibility map generated after extensive editing.

There are several reasons for that:

- First of all related to the landslide locations. We have carefully checked the locations of the landslides during the image interpretation phase, but we are able to check whether the landslides mapped by others are located in the right location. Even a shift of 10 meters might result in a change in landslide susceptibility when making the map overlay between landslides and susceptibility map.
- Secondly, the landslides are mostly mapped as either single polygons, or points. When they are mapped as single polygons (e.g. as is the case in the inventory for TS Erika in 2015), most of the polygon will consist of the runout and accumulation areas of the landslides, which may not correspond well with the landslide initiation susceptibility classes represented on the map. This is clearly illustrated in Figure 6-23 C.
- Thirdly, the factor maps with which the analysis has been carried out, are mostly of poor quality. As was mentioned in chapter 5, the slope steepness data is very general, and therefore may not represent the actual situation well. This is also illustrated in Figure 6-23 A, where the effect of slope classes, results in a mottled patterns of high and moderate pixels mixed together in certain location. The effect of using such problematic data in combination with landslide locations that are also uncertain is that the resulting weights calculated in the bivariate statistical analysis, often have a lot of noise, and are difficult to interpret.
- Finally, the method used in this chapter thus far generalizes the situation as it brings it back to a combination of a number of factor maps, without paying much attention to the local conditions. For instance when landslides are in general more frequent along the coast, and one would use a certain distance buffer as factor map, this may also have influence on the susceptibility of places that are near the coast but are not susceptible due to other reasons.

In order to improve the final map we carried out steps 10 to 13 as described in section 2.2. First we masked with GIS all historical landslides in the susceptibility map as class “high”, as it is possible that landslides may happen again in these conditions, unless remedial measures have been adopted after the landslide occurrence (See Figure 6-23 D). The next step was to carefully check and edit the susceptibility map. This was done by exporting the map to an external photo-editing software (CorelPhotoPaint) where it is possible to edit the three classes using the Paint tool. We did this using a dual screen, by comparing the map with a Google Earth image and with a hill shading image overlain with the landslide susceptibility map, plus topographic information, like rivers, roads, buildings etc. This way each part of the area was visually checked, and the modelled zones of high, moderate and low susceptibility were adapted when necessary, so that they reflect the best situation according to the mapping geomorphologist. This was a rather time consuming activity, but it allowed to analyse the different parts of the map separately, and therefore obtain results that also are valid for a local scale, and not only for a national scale. The manual editing of the susceptibility map was also done to simplify the susceptibility units (See Figure 6-23 E). After running the statistical analysis and spatial multi-criteria analysis, the resulting landslide susceptibility raster map shows many small areas with different degrees of susceptibility. Sometimes the susceptibility differs from pixel to pixel, due to variations in the input maps (e.g. slope classes may differ very locally). In order to be able to use the resulting map as a basis for planning, the area should be subdivided into zones with different likelihood of landslide occurrence. Therefore during the manual editing phases, areas are simplified, and classified into one of the three classes, removing the large local variation. Also after completing the manual editing process, still many locations with isolated pixels remain. These were subsequently removed in GIS using a majority filter. The resulting landslide susceptibility map can also be converted into a polygon map. Once the final landslide susceptibility map was obtained, we recalculated the number of landslides in the three susceptibility classes. The results is shown in Table 6-10.

When you compare the landslide density values from Table 6-9 and Table 6-10 it is clear that the final landslide susceptibility map, made after the above described procedure, is a much better susceptibility map than the one which was resulting from the bivariate statistical and multi-criteria evaluation. The size of the low and high susceptibility classes have increased and the size of the moderate class decreased. When looking at all pre-2015 landslides 3% occurs in low susceptibility, 8 % in moderate, and 89 % in high susceptibility. Of the landslides that were triggered during tropical storm Erika 5% occurred in low susceptibility areas, 13% in moderate and 83% in high susceptibility classes. This is a realistic outcome, although it is of course logical that most landslides occur in the high susceptibility class as we applied a mask of the landslides. Afterwards during the editing phases a number of areas were changed again from high to moderate or even low depending on the local situations. When considering the landslide density, the values for low, moderate and high 0.039, 0.262 and 5.658 % respectively based on area density and 0.174, 0.997 and 9.849 nr/km^2 respectively for number density.

Table 6-10. Summary information of different landslide inventories within the low, moderate and high susceptibility classes of the final landslide susceptibility map for Dominica

		Landslide susceptibility			Triggering event
Source	**Characteristics**	**Low**	**Moderate**	**High**	**Event**
Susceptibility map	Area in square kilometres	391.7	168.6	191.8	
	Percentage of total area	52.08	22.42	25.5	
All landslides	Landslide area (m^2)	153033	441010	10851565	
	Number of landslides	68	168	1889	
	Landslide density (percentage)	0.039	0.262	5.658	
	Landslide density (nr/km^2)	0.174	0.997	9.849	
DeGraff 1987	Landslide area (m^2)	69995	148007	5623336	Klaus (6-11-1984)
	Number of landslides	17	35	838	
	Landslide density (percentage)	0.018	0.088	2.932	
	Landslide density (nr/km^2)	0.043	0.208	4.369	
DeGraff 1990	Landslide area	7507	88819	835441	Hugo (17/09/1989)
	Number of landslides	7	21	155	
	Landslide density (percentage)	0.002	0.053	0.436	
	Landslide density (nr/km^2)	0.018	0.125	0.808	
Andereck 2007	Landslide area	11367	32666	277442	Rain & earthquake (21/11/2004) Only for an area of 22 km^2
	Number of landslides	9	17	135	
	Landslide density (percentage)	0.003	0.019	0.145	
	Landslide density (nr/km^2)	0.023	0.101	0.704	
This study 2014	Landslide area	64164	177698	4909539	Accumulation of many events
	Number of landslides	33	86	777	
	Landslide density (percentage)	0.016	0.105	2.560	
	Landslide density (nr/km^2)	0.084	0.510	4.051	
Tropical storm Erika, August 2015	Landslide area	34605	141395	1651152	Tropical storm Erika (27/08/2015)
	Number of landslides	69	188	1215	
	Landslide density (percentage)	0.009	0.084	0.861	
	Landslide density (nr/km^2)	0.176	1.115	6.335	

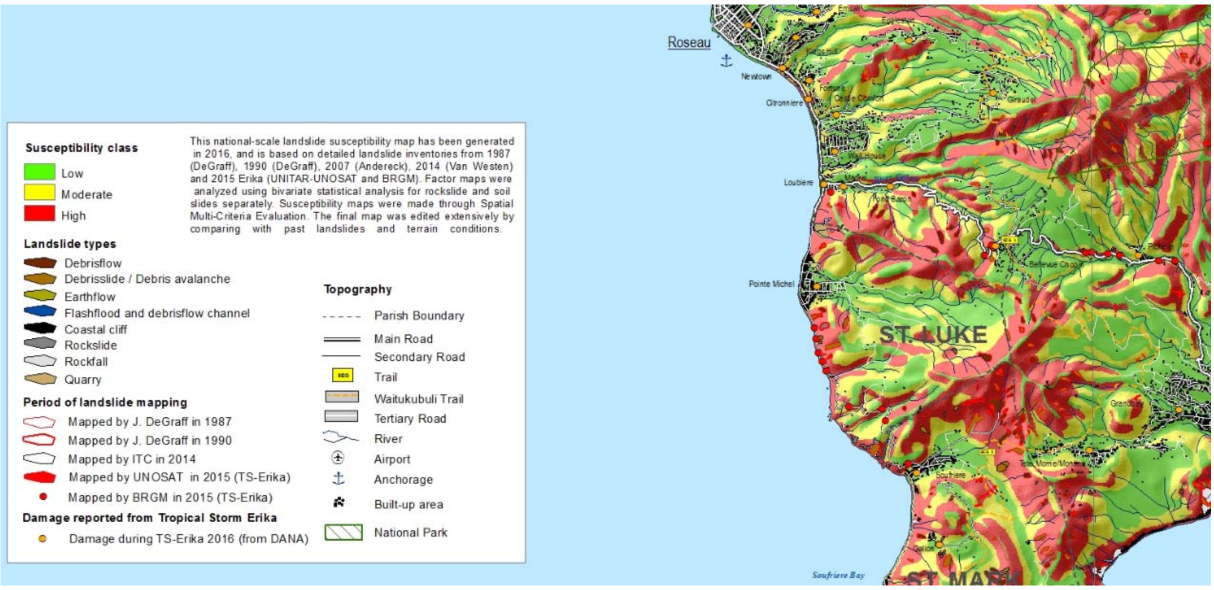


Figure 6-24: Legend of the final landslide susceptibility map for Dominica, and enlarged example of the Southwestern part.

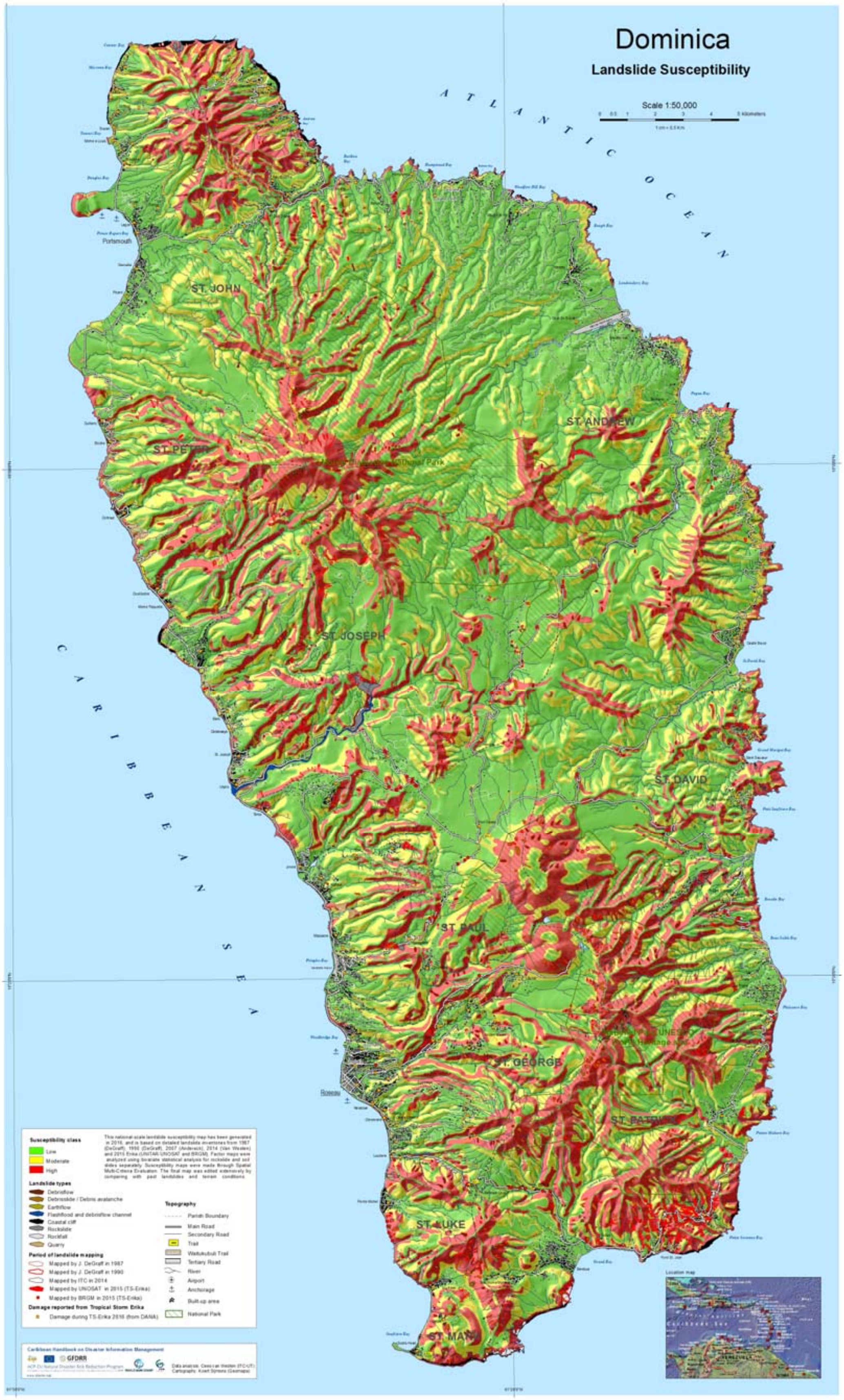


Figure 6-25: Final landslide susceptibility map for Dominica. The full map can be downloaded as pdf from the following website: http://www.charim.net/dominica/maps

7 Landslide susceptibility assessment along the road network

The national-scale landslide susceptibility map, which was presented in the previous chapter, is a generalization, and may not represent the situation always correctly for local situations. This is particularly so for the road network. The nation-wide analysis doesn't take into account the specific conditions along the road network, as information is often lacking on the location of cut slopes, conditions of drainage along the road, and the presence of slope stabilization measures along the road network. Also there is limited information available on the landslides that occurred along the roads, as the road department doesn't keep a database of these events, and the road clearance reports are lost after a few years. Therefore it is also important to focus specifically on the road network and derive a susceptibility map using a slightly different approach than the one for the nation-wide study. As mentioned earlier, the landslide information along the national road network is not available as a geo-coded dataset. Therefore these could not be taken into account when generating the landslide susceptibility assessment at the national scale. Since landslides are a major problem along the road network in Dominica, it was decided to make a separate analysis for landslide susceptibility along the road network. The method used is presented in Figure 7-1.

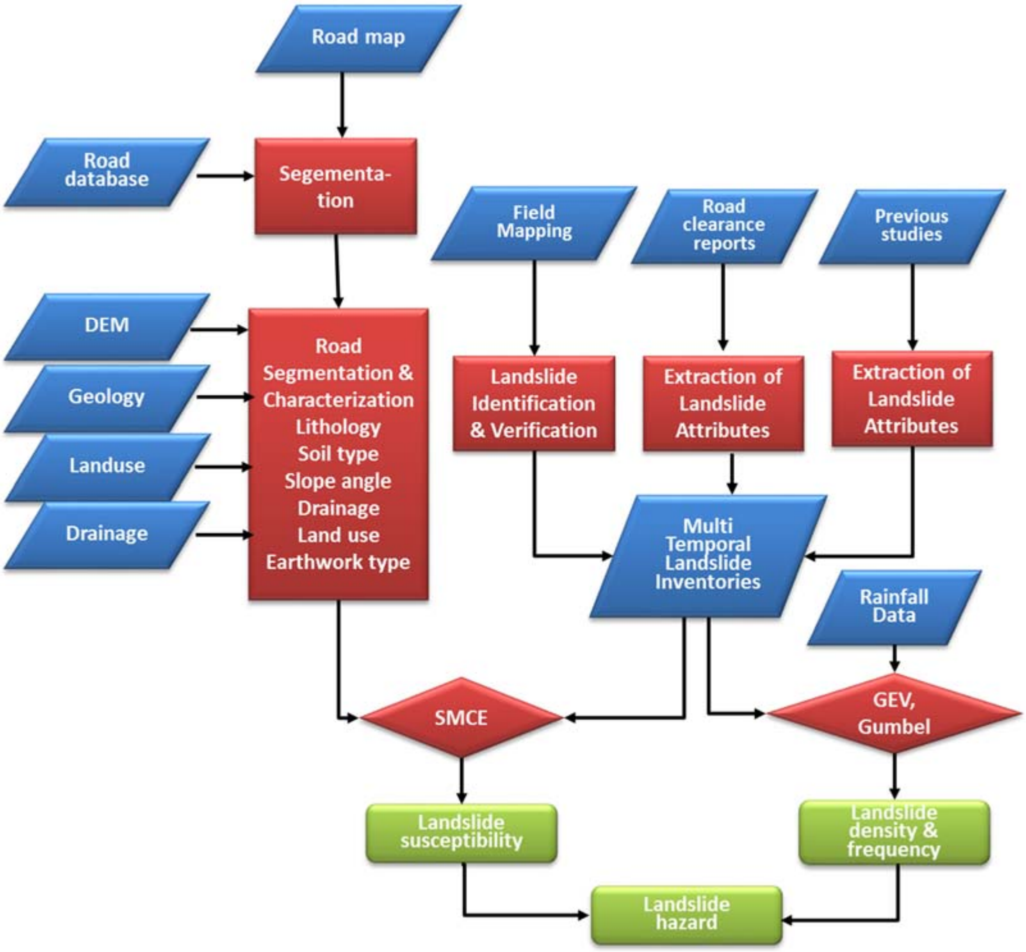


Figure 7-1: Method used for assessing the landslide susceptibility (and hazard) along the national road network in Dominica. Landslide hazard is obtained by combining the susceptibility classification with the results of the density-frequency analysis.

7.1 Segmentation of the road network into homogeneous sections.

Road segmentation and characterization refers to subdividing the road network into smaller segments that possess the same spatial characteristics. This was done using available road maps, which had to be digitized again, as they had a significant positional error when compared to ortho-rectified satellite data. Therefore a new road layer was digitized with a subdivision of the roads into the following categories:

- Primary road
- Secondary road
- Tertiary road

- Road under construction

Also the sections of the island-wide hiking trail were digitized into a separate file. Figure 7-1 shows the roads and trails for Dominica. For this study only the primary road network was considered.

From the Ministry of Works we obtained a database of the primary road network that was generated in 2009 for another project. The road database has been updated after major changes in the road network. This database contains information on the following items: drainage type and drainage width both on the left and right side of the road, indication whether the roadside is a cut slope, valley or flat, and land use of the area around the road section. These data are available on average with a 1 km interval. In the database the road sections are indicated only by their starting and end points.

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

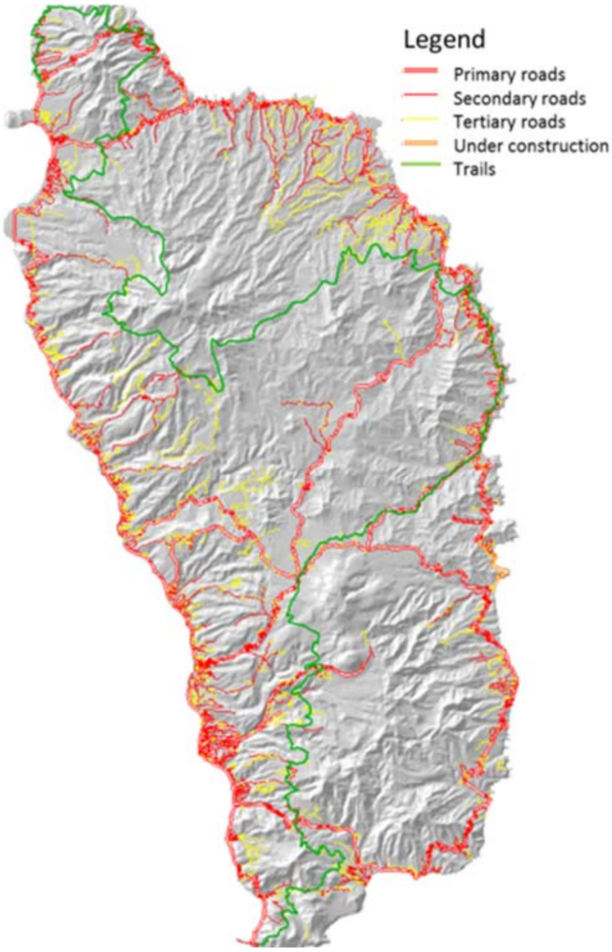


Figure 7-2: Roads and trails in Dominica.

The road segmentation shape file has the following attributes:

- adjacent ground terrain left and right (whether it is a cut slope, valley or flat),
- drainage type left and right,
- Adjacent ground land use.

The road data from the database were available per one kilometre segments, and further segmentation of the roads was not possible. The lithology, soil type and slope angle of the one kilometre road segments were extracted from the available geology map, soil map and digital elevation model (DEM) respectively. For this purpose buffer maps along the road network were prepared taking a 50 m buffer distances on both sides. For each road segment the upslope side buffer was identified based on the information obtained from the road database and image interpretation. Then, for each road segment the upslope side was selected and the other side was deleted from the buffer map. The buffer map was then crossed with the factor maps. Finally, the geology, soil type and slope angle were assigned for road segments, taking the predominant value (weighted by area) of each of the segment from the crossed tables. These attributes were used by other authors for similar studies and they are proved to be significant factors for road related landslides (e.g., Das et al, 2010; Jaiswal et al, 2011; Jaiswal and Van Westen, 2013).

7.2 Generation of landslide inventories for specific events

As mentioned in section 4.1 road maintenance and clearance reports were obtained from the Ministry of Public Works and Ports for five rainfall events: September 3/2009 (tropical storm Erica), October 31/2010 (Hurricane Tomas), September 28/2011 (tropical storm Ophelia), November 28/2011, and April 17-25/2013. An example of the latter was given in Table 4-3. Unfortunately no information was available for earlier events, as this type of data is not kept in a database. We did not receive road clearance reports for the August 2015 tropical storm Erika event as well. The reports don't have any spatial references for the landslide locations, they only have the road sections starting and end point where landslide clearance had been done and the amount of money spent for clearance. To locate those areas and prepare them as geo-spatial dataset, the available high resolution images and thematic maps of the island were used. Landslide density is expressed as the number of landslides per one kilometre section of the road. First the information on the number of slides per road section from the landslide inventories were joined to the road database. Then, the length of all road sections was calculated by excluding the sub-sections where the terrain is flat on both sides. The flat sub-sections were identified based on the high resolution images and the information obtained from the road database. Finally, the number of landslides per kilometre (landslide density) was calculated for each road section by dividing the number of slides by the length of the road section. This was done for all the five storm events separately. Figure 7-3 shows the landslide along the road for which we were able to get the position.

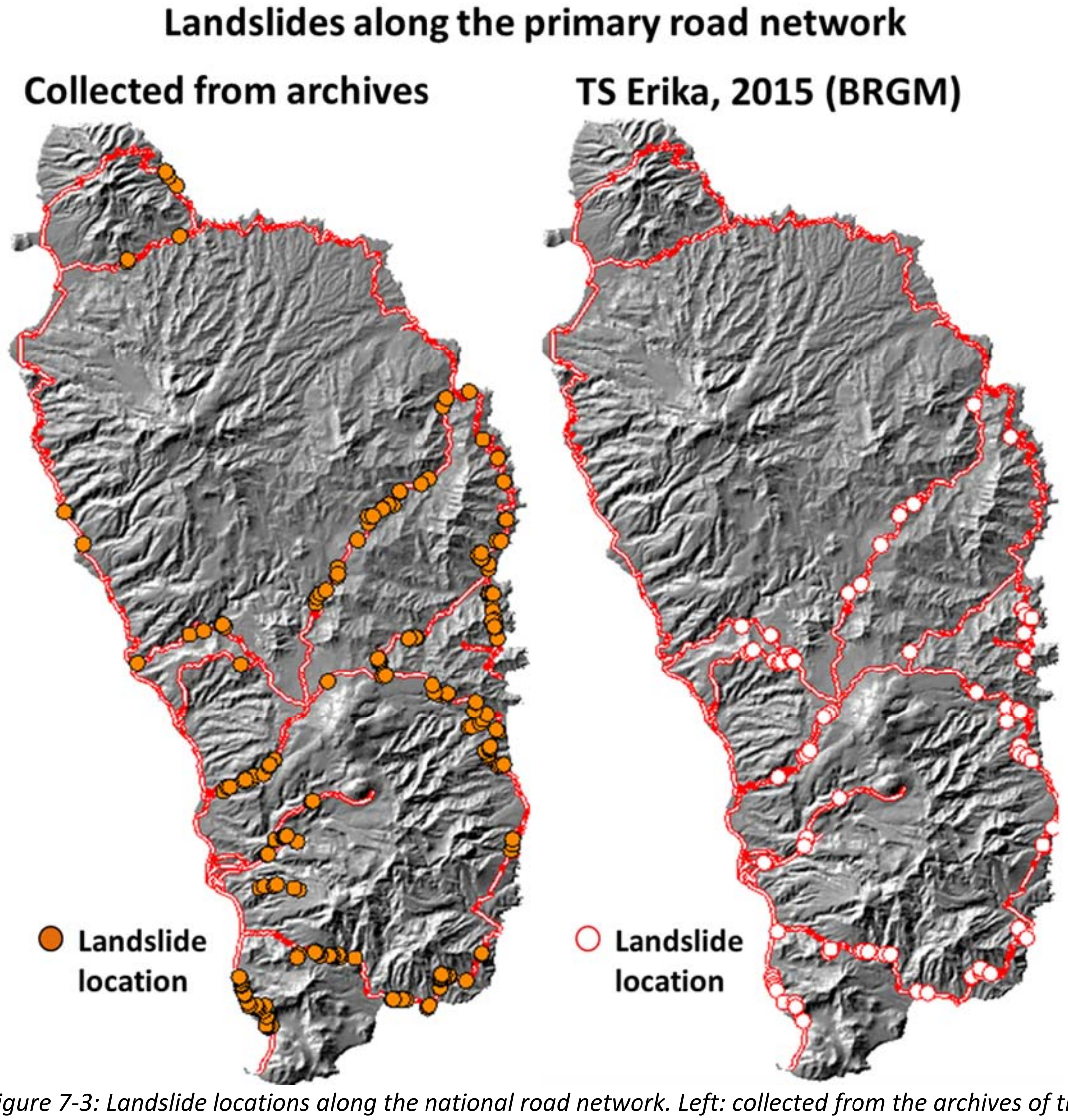


Figure 7-3: Landslide locations along the national road network. Left: collected from the archives of the road department and from field work in 2014. Right: landslides along the road caused by tropical storm Erika in 2015.

7.3 Landslide susceptibility assessment along the road network

The landslide susceptibility assessment along the road network was also carried out using Spatial Multi-Criteria Evaluation (SMCE). The criteria tree for Dominica was prepared using slope, drainage, material and land use attributes as spatial factors. Under the slope factor, slope type of adjacent ground left and right and slope angle were included. The slope angle was given 80% weight of slope factor. The slope type of the adjacent ground indicates whether the road segment is a cut-slope, valley or flat section, and it takes the remaining 20% weight of the slope factor. It was standardized using pair wise comparison. In some stretches of the road the slope is vertical, but landslides do not occur, because of the specific conditions of soil type or geology. Unfortunately, this method doesn't allow to make this separation as slope angle is receiving a high weight separately of the weight for soils or geology. The slope factor (considered independently) works in an ambiguous way in the case of road cuts. The steepest slopes do not correspond unequivocally to the more susceptible slopes and for that reason the weights to inclination ranges should not be considered in the same way as in the other soil types or natural slopes. More emphasis should be given to this in future projects on landslides susceptibility along roads. In the drainage spatial factor, the presence of a side ditch left and right were included. The side ditch has 4 types namely: concrete lined rectangular, concrete lined V drain, kerb and no drainage. And it was standardized pair wise, giving the highest importance for no drainage and the lowest for concrete lined rectangular and V drain. The material spatial factor (geology and soil) is treated in similar way as presented earlier. The last spatial factor, land use type beside the road segment, has four types: residential, commercial, forest, agricultural and empty lot. This factor is standardized by rank ordering, giving the 1st rank for empty lot and the last for residential and commercial. Also one attribute was used as a constraint to exclude the flat sections from the analysis. In the weighing of the spatial factors, which was done by a direct method, the highest weight was given for slope (0.6). Material was given the next higher weight of 0.3. Drainage and land use took equal weight of 0.05. Figure 7-4 shows the SMCE criteria tree of Dominica. The results obtained from the SMCE show that the road segments have landslide susceptibility scores ranging from 0 to 0.75 for Dominica, representing road segments from the lowest to the highest susceptibility. To check the validity of the analysis result of Dominica, a success rate calculation was made. The success rate was done using 214 landslide points along the major roads, 71 of these landslides were mapped during field work and the remaining were obtained from the landslide inventory dataset of the whole country presented earlier. Figure 7-5 shows the success rate graph of the susceptibility analysis for Dominica. As the graph shows, about 60% of the landslides are located in 30% of the road segments with high susceptibility scores. Considering the relatively low quality and quantity of the data available for the analysis, we believe this is the best possible so far, although we hope in future such results could be improved when a consistent landslide database would be maintained on the island.

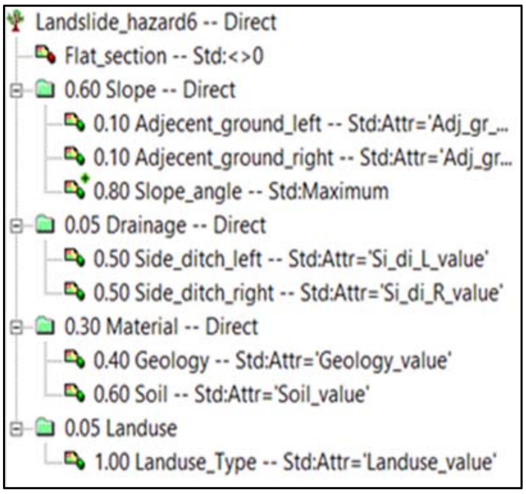


Figure 7-4: Criteria tree for analysing landslide susceptibility along the road network in Dominica.

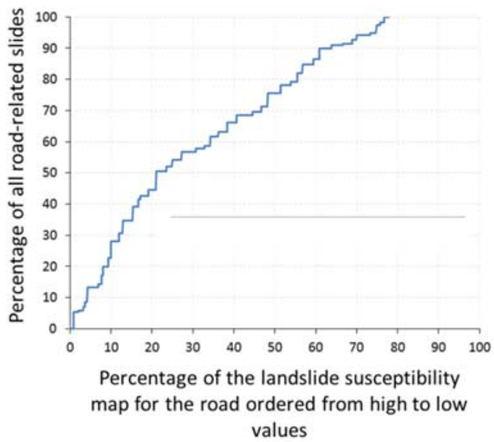


Figure 7-5: Success rate for the road-related landslide map.

Based on the success rate result, the susceptibility map was classified into three classes of susceptibility level i.e. high, moderate and low. The boundaries of these classes were determined by considering the percentage of the landslides. It was found that 60% of the landslides are located within the high susceptible class, 30% within the moderate class and the remaining 10% within the low susceptibility classes of the road segments. With this classification, 40% of the major road segments fall in the low, 30% in the moderate and the remaining 30% in high susceptibility zones. The landslide susceptibility map along the major roads is shown in Figure 7-6. In the map, the known previous landslide locations are indicated with black dots.

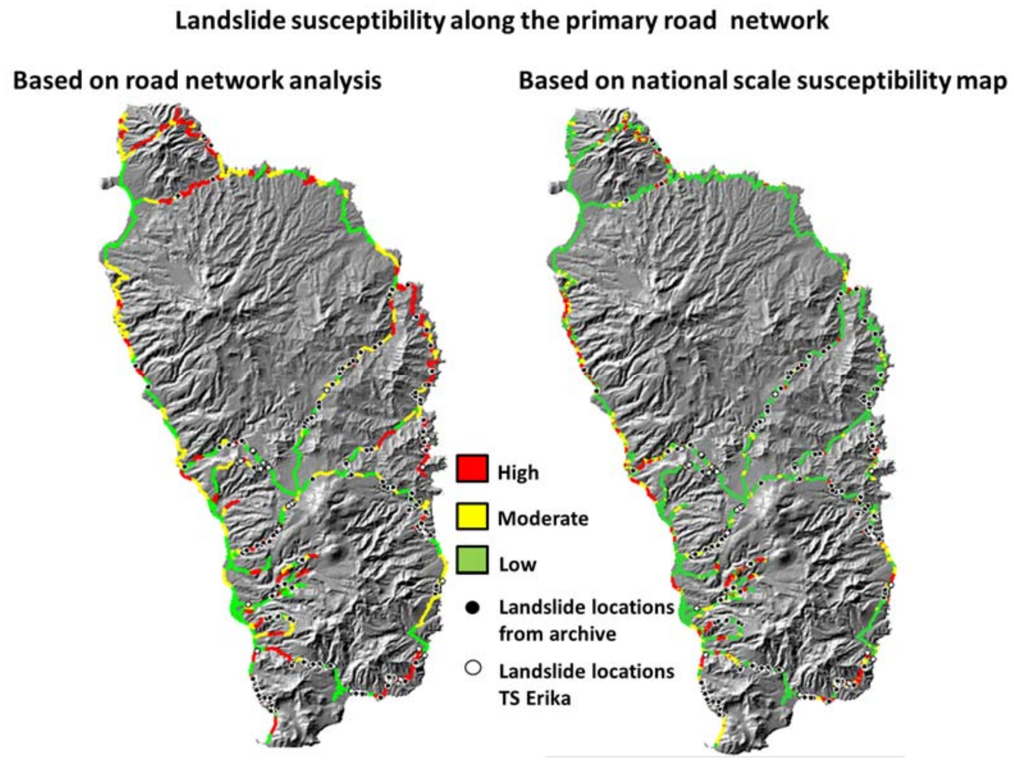


Figure 7-7. Left: Landslide susceptibility map along the major roads of Dominica as generated from the road analysis. Right: landslide susceptibility of the road network taken from the national scale landslide map.

Table 7-1 provides the summary information for the landslide susceptibility classes for the primary road network. The results show an almost equal percentage of the primary road network in high, moderate and low susceptibility classes. We also combined in GIS the road susceptibility map with the national landslide susceptibility map presented in chapter 6. From table 7-1 you can see that there is much more area in the low susceptibility class and that almost all landslides are in the moderate and high classes. This shows that the national scale landslide susceptibility map is better for the road network. Although the method presented here has the potential of being useful on the long run, it is not so reliable still, mainly because of the problems involved in subdividing the road into meaningful segments, characterization of the road and most of all, collection of locations of landslides rather than using the number of landslides along broad stretches of the road, as was the case now. Road maintenance records should be converted into location maps by using GPS in the field during the clearing inspection of roads. Another improvement that should be made is in the criteria evaluation, where road cuts in different types of soil should be evaluated separately and slope shouldn't be an independent factor of soils in the analysis. However, this requires more detailed information on soils, and road cuts, based on detailed field data collection along the road network.

Table 7-1. Summary information of different landslide susceptibility classes along the road network

From road analysis	Landslide susceptibility class		
	Low	Moderate	High
Road length (km)	106.3	106.8	103.4
Percentage	33.6	33.8	32.7
From national scale susceptibility map			
Road length (km)	187.3	59.3	69.9
Percentage	59.2	18.7	22.1
Known landslides	8	54	241

8 Characterizing the susceptibility classes

This chapter aims to show how the landslide susceptibility classes could be characterized in terms of the expected landslide density (in area and number) for different frequencies, and also how many buildings are located in the various susceptibility classes.

8.1 Density and frequency information

Conversion of landslide susceptibility maps into landslide hazard maps requires estimates of spatial, temporal and magnitude probabilities of landslides (Guzzetti et al., 1999; Glade et al., 2005; Fell et al., 2008; Van Asch et al., 2007; Corominas and Moya, 2008; van Westen et al., 2008). The difference between susceptibility and hazard is the inclusion of probability (temporal, spatial and size probability). Temporal probability can be established using different methods. A relation between triggering events (rainfall events) and landslide occurrences is needed in order to be able to assess the temporal probability. Temporal probability assessment of landslides is either done using rainfall threshold estimation, and through the use of multi-temporal data sets. Rainfall threshold estimation is mostly carried out using antecedent rainfall analysis, for which the availability of a sufficient number of landslide occurrence dates is essential. If distribution maps are available of landslides that have been generated during the same triggering event, a useful approach is to derive susceptibility maps using statistical or heuristic methods, and link the resulting classes to the temporal probability of the triggering events. For the Caribbean countries the event-based landslide inventories play a crucial role in characterizing the landslide susceptibility classes with density and frequency information. The number and quality of these maps will determine whether this can be based on a quantitative analysis or also on an expert-based estimation of landslide densities in relation with return periods. For the classified landslide initiation susceptibility map, the historical landslides are used to characterize the classes.

In the previous two chapters landslides susceptibility maps were presented for the entire island and for the road network. These maps show the relative likelihood that a certain area or road segment may be affected by landslides. However, for a hazard assessment it is also important to indicate how severe and frequent an area might be affected. In table 6-6 landslide densities were given for the various susceptibility classes, separately for rockslides and soil slides. However, these are for all inventories and are not separated into single inventories caused by a single triggering event. In this section we will try to indicate what the expected landslide densities are for various return periods.

We therefore combined the landslide inventories for the different periods, which were described in section 4.1 with the final landslide susceptibility map. The results was shown in Table 6-10. What can be concluded from this table is that the overall landslide density varies from 5.658 % (9.8 landslides/km2) for the high susceptibility class, via 0.262% (0.997 nr/km2) for the moderate class and 0.039% (0.174 nr/km2) for the low susceptibility class. However, for individual events these values are much lower, as less landslides are expected to be triggered by a single triggering event.

It is quite difficult to determine the frequency of the landslide densities due to a lack of sufficient event-based inventories. As you can see out of the five inventories perhaps the ones from 1987, 1990 and 2015 could be linked to a single triggering event, although this is also questionable for the 1987 event. The 2007 inventory is only for a small part of the island, and our inventory from 2014 is not linked to a single triggering event as well. Therefore as a summary we need to make an estimation as indicated in Table 8-1. These values are estimations based on the data from Table 6-10, and from the description of the inventories a shown in Table 4.1. The spatial probability represents the chance that a landslide may occur in a single location. It is similar to the area density presented in Table 6-10 but now shown as probability, instead of percentage values. We have rounded the values of Table 6-10. Also the number density is shown as the number of landslides per km2. The return periods indicated in Table 8-1 are pure estimations, and not based on actual calculations. Although we have calculated return periods for daily rainfall in section 3.3.3 (Figure 3-10), these are not useful either because we do not have the information on rainfall amounts for the specific triggering events, or because these rainfall amounts vary extensively with elevation and exposure (See Figure 3-7), and the return periods are calculated for the two stations located near sea level only.

We have separated four types of events: frequent, moderate, large and major events. We selected landslide inventories with increasing densities to represent these four events.

Table 8-1. Estimated landslide probabilities for the low, moderate and high susceptibility classes. Landslide probability (in area) increases for low to high susceptibility classes, and from frequent to major triggering events. Landslide frequency (in time) decreases from frequent to major events

Event	Frequency	Landslide inventory taken as example	Landslide probability for susceptibility classes			
				Low	Moderate	High
Frequent	1 – 10 years	Trigger: 1989 Hugo 1990 DeGraff inventory	Spatial probability	0.00002	0.00053	0.00436
			Landslide density (nr/km^2)	0.018	0.125	0.808
Moderate	10 – 25 years	Trigger: 2015 Erika 2015 UNOSAT inventory	Spatial probability	0.00009	0.00084	0.00861
			Landslide density (nr/km^2)	0.043	0.208	4.369
Large	25-50 years	Trigger: 1979 David & 1984 Klaus 1987 DeGraff inventory	Spatial probability	0.00018	0.00088	0.02932
			Landslide density (nr/km^2)	0.176	1.115	6.335
Major	50-100 years	We take the data from all landslides	Spatial probability	0.00039	0.00262	0.05658
			Landslide density (nr/km^2)	0.174	0.997	9.849

8.2 Buildings located in the susceptibility classes

The final susceptibility classes can also be characterized by calculating the number of buildings located in the various classes. Building data was not available for Dominica. We only had a building footprint map for the Roseau area. In order to be able to calculate building exposure, we applied a method for the generation of a building footprint map for the entire country. We used the satellite data as indicated in Table 4.5, and we used a thresholding method for the three spectral bands, separating areas with high reflection. We combined the three masked areas into one single map, which was still overestimating the number of buildings and contained also other high reflection areas, like bare surfaces, road, quarries etc. Next we converted this raster map into a polygon map, and the polygon map was again converted into a point map. This resulted in a large number of points, many of which didn't represent buildings but other features. Therefore we analysed the point visually on top of a colour composite image of the satellite image. The resulting building map was developed as a point map, and was carefully checked. Figure 8-1 shows an example for a part of the country.

Figure 8-1. Example of the building extraction as points for the whole island of Dominica. Left: example for the centre of Roseau for which also building footprints were available show a good correlation. Right: example from Pointe Michel.

The results of the building exposure analysis is shown in Table 8-2. The results show that in the entire country 1508 buildings (4.5 % of the total) are exposed to a high landslide susceptibility, 3832 (11.5 %) exposed to moderate and the remaining 27954 buildings exposed to low landslide susceptibility. When we evaluate these values per Parish, St Patrick (332), St George (280), and St David (213) have the highest number of exposed buildings in the high hazard class. Percentage-wise the following parishes are most exposed: St Peter (16), St Patrick (7.9) and St David (7.7).

Table 8-2. Buildings exposed to low, moderate and high susceptibility classes for the whole country and for individual Parishes.

Parish	Characteristic	Landslide susceptibility classes		
		Low	Moderate	High
All	Nr of buildings exposed	**27954**	**3832**	**1508**
	Percentage of all buildings	**84.0**	**11.5**	**4.5**
St. David	Nr of buildings exposed	2134	418	213
	Percentage of all buildings	**77.2**	**15.1**	**7.7**
St. Paul	Nr of buildings exposed	3479	416	144
	Percentage of all buildings	**86.1**	**10.3**	**3.6**
St. George	Nr of buildings exposed	6556	1239	280
	Percentage of all buildings	**81.2**	**15.3**	**3.5**
St. Luke	Nr of buildings exposed	442	228	29
	Percentage of all buildings	**63.2**	**32.6**	**4.1**
St. Mark	Nr of buildings exposed	572	260	34
	Percentage of all buildings	**66.1**	**30.0**	**3.9**
St. Patrick	Nr of buildings exposed	3514	334	332
	Percentage of all buildings	**84.1**	**8.0**	**7.9**
St. Joseph	Nr of buildings exposed	2640	372	185
	Percentage of all buildings	**82.6**	**11.6**	**5.8**
St. Peter	Nr of buildings exposed	622	146	146
	Percentage of all buildings	**68.1**	**16.0**	**16.0**
St. Andrew	Nr of buildings exposed	4882	343	137
	Percentage of all buildings	**91.0**	**6.4**	**2.6**
St. John	Nr of buildings exposed	3113	76	6
	Percentage of all buildings	**97.4**	**2.4**	**0.2**

One should be careful when using the national-scale landslide susceptibility and hazard map for evaluating the landslide hazard of individual buildings and critical infrastructure. The scale of this map is not appropriate to utilize it for local or detailed scale analysis. Other, more detailed landslide hazard methods should be used for these scales, which also require more detailed information on soil characteristics, such as soil depth, hydrological and geotechnical properties.
It is also possible to overlay the final susceptibility map with the roads, and agricultural fields and calculated the number, length or area per administrative unit, exposed to high, moderate and low susceptibility. However, given the extent of this report, we decided not to present that here.

9 Conclusions and recommendations

9.1 Conclusions

The original aim of this study was to generate a national-scale landslide susceptibility map for Dominica. The available data turned out to be insufficient to generate reliable results. We therefore generated several new data layers, and adjusted quite some of the existing data:

- We generated a new database of disaster events for Dominica using all available data, making use of many different sources, which was presented in Table 3-5. This is the most complete inventory up to our knowledge.
- We also compiled all available landslide data from different sources, which was not an easy task. We had to digitize some of the older inventories (e.g. DeGraff 1990, Andereck, 2007) which were only available in paper format.
- We compiled landslide inventories for five recent events from the maintenance records of the Ministry of Public Works.
- We generated a completely new landslide inventory using multi-temporal visual image interpretation, and generated an extensive landslide database for Dominica.
- We updated the land use map as much as possible.
- We generated a national building map in the form of building points.

We analyzed the triggering conditions for landslides as far as was possible given the available data, and generated rainfall magnitude-frequency relations. Rainfall magnitude-frequency relations for different landslide densities might not be required for a landslide susceptibility assessment, but they are important to convert susceptibility into hazards. However, there were not enough data (both in terms of landslide dates and date-related inventories) to be able to calculate magnitude-frequency relations for landslides, in terms of the number or density of landslide per different frequencies. In the end the estimation of these relations as shown in Table 8-1 are highly questionable. We did it anyway in order to show the order of magnitude that could be expected, however, the frequencies are just a guess.

We applied a method for landslide initiation susceptibility assessment that is the best possible, given the availability of data. The bi-variate statistical analysis provided indications on the importance of the possible contributing factors, but the actual combination of the factor maps was done using a subjective expert-based iterative weighing approach using Spatial Multi-Criteria Evaluation. Table 9-1 gives a summary of the indicators and weights used for analyzing the rock slide and soilslide susceptibility, which were the most contributing factors, and what was their relative importance.

Table 8-1: Summary of contributing factors and relative importance used in the analysis

Rock slide susceptibility		**Soil slide susceptibility**	
Indicator	**Weight**	**Indicator**	**Weight**
Close to existing rockslide	0.06	Slope steepness	0.41
Very steep slopes	0.32	Elevation classes	0.24
Slope steepness	0.32	Aspect classes	0.09
Distance to coast	0.16	Exposure classes	0.09
Exposure	0.06	Distance from ridges	0.09
Elevation classes	0.06	Distance from rivers	0.09
Distance from rivers	0.06	Geology	0.25
Geology	0.75	Soils	0.75
Soils	0.25	Land use	0.25
Land use	1.00	Distance from roads	0.75

The method is transparent, as the stakeholders (e.g. the engineers and planners from the four countries) and other consultants can consult the criteria trees and evaluate the standardization and weights, and make adjustments. It is important to state here that this method doesn't propose to come to a fixed number of contributing factors or to fixed weights that should be used. In each country or situation the experts that do the analysis should decide what the main contributing factors are, what their relative importance is, and assign the weights.
We also generated different landslide susceptibility maps for different landslide types, as they were related to varying combinations of causal factors (See Figure 9-1). The two susceptibility maps made for rockslides/rockfall and for soil-related landslides were combined into one single map, which is easier to use by the end users.

The first version of the landslide susceptibility map was generated in June 2015. Shortly after that, in August 2015, tropical storm Erika triggered hundreds of landslides in Dominica. We decided to include the new event in the analysis, as this was a major event with many landslide, and to adjust the landslide susceptibility map so that the new landslides were included in the high and moderate susceptibility classes.

The method for landslide susceptibility assessment was further expanded by including the historical landslides in the susceptibility map and by manual editing of the final map. The whole map was visually checked, and the modelled zones of high, moderate and low susceptibility were adapted when necessary, so that they reflect the best situation according to the mapping geomorphologist. This was a rather time consuming activity, but it allowed to analyse the different parts of the map separately, and therefore obtain results that also are valid for a local scale, and not only for a national scale. The manual editing of the susceptibility map was also done to simplify the susceptibility units.

When you compare the landslide density values from Table 6-9 and Table 6-10 it is clear that the final landslide susceptibility map, made after the above described procedure, is a much better susceptibility map than the one which was resulting from the bivariate statistical and multi-criteria evaluation. The size of the low and high susceptibility classes have increased and the size of the moderate class decreased. When looking at all pre-2015 landslides 3% occurs in low susceptibility, 8 % in moderate, and 89 % in high susceptibility. Of the landslides that were triggered during tropical storm Erika 5% occurred in low susceptibility areas, 13% in moderate and 83% in high susceptibility classes. This is a realistic outcome, although it is of course logical that most landslides occur in the high susceptibility class as we applied a mask of the landslides. Afterwards during the editing phases a number of areas were changed again from high to moderate or even low depending on the local situations. When considering the landslide density, the values for low, moderate and high were 0.039, 0.262 and 5.658 % respectively based on area density and 0.174, 0.997 and 9.849 nr/km^2 respectively for number density.
We initially were also planning to generate both initiation and accumulation (run-out) susceptibility. However, given the small scale of the analysis and the large area covered (and the related large computation time using an empirical run-out model like FLOW-R) we decided not to do that. In more local scale assessments such runout analysis should be incorporated though.
Finally we characterized the landslide susceptibility classes in terms of the expected landslide density (in area and number) for different frequencies, and also how many buildings are located in the various susceptibility classes. We therefore combined the landslide inventories for the different periods, which were described in section 4.1 with the final landslide susceptibility map. The results was shown in Table 6-10. What can be concluded from this table is that the overall landslide density varies from 5.658 % (9.8 landslides/km2) for the high susceptibility class, via 0.262% (0.997 nr/km2) for the moderate class and 0.039% (0.174 nr/km2) for the low susceptibility class. However, for individual events these values are much lower, as less landslides are expected to be triggered by a single triggering event.
It is quite difficult to determine the frequency of the landslide densities due to a lack of sufficient event-based inventories. As you can see out of the five inventories perhaps the ones from 1987, 1990 and 2015 could be linked to a single triggering event, although this is also questionable for the 1987 event. The 2007 inventory is only for a small part of the island, and our inventory from 2014 is not linked to a single triggering event as well. Therefore as a summary we need to make an estimation as indicated in Table 8-1. These values are estimations based on the data from Table 6-10, and from the description of the inventories a shown in Table 4.1.
The national scale landslide susceptibility and hazard assessment should not be used to evaluate local scale or site-investigation problems. The analysis was done using raster maps with a spatial resolution of 5 meters, containing 9543 lines and 5347 columns. Most of the input data was obtained from 1:25000 or even 1:50000 scale maps. Also given the relatively poor quality of the factor maps (especially the Digital Elevation Model, the geological map and the land use map) the local variations are not properly depicted in the final map.

For these scales the optimal approach is the use of physically-based landslide susceptibility assessment methods. These methods are based on modelling the processes of landslides using physically-based slope stability models. An overview of physically based models and their application for landslide susceptibility assessment is given in Brunsden (1999), Casadei et al. (2003), Van Asch et al. (2007) and Simoni et al., (2008). Most of the physically-based GIS models that are applied at a local scale (SINMAP, TRIGRS, SHALSTAB, STARWARS, PROBSTAB) make use of the infinite slope model and are therefore only applicable to modelling shallow translational landslides. At site investigation scale it is possible to apply 2-D Limit equilibrium methods with groundwater flow and stress analysis (E.g., SLOPE/W, SLIDE, GALENA, GSLOPE), 3-D slope stability analysis (e.g. CLARA-W, TSLOPE3, SVSLOPE) or numerical modelling (e.g. continuum modeling (e.g. finite element, finite difference) , like FLAC3D, VISAGE, or discontinuum modeling (e.g. distinct element, discrete element), e.g. UDEC).

The final national landslide susceptibility and hazard map is called that because it is basically a landslide susceptibility map, which divides the country in three zones with a different likelihood of landslide occurrence. However, based on the available data we also tried to express information on the magnitude of landslides (in terms of the expected landslide density) and the related frequency, which are both related to the hazard component. The final legend of the susceptibility map is given in Table 9-1.

Table 9-1. Characterization of the landslide susceptibility classes.

Susceptibility	Explanation	Characteristics	Estimated landslide probabilities for different return periods			
			Frequent	Moderate	Large	Major
Low	This class generally is landslide free, although under special circumstances it may be possible that a landslide might occur in this zone, but the density and frequency will be low.	Area: 391.7 km^2 Landslide area: 18 hectares Number of landslides: 137 Spatial probability: 0.0005 Landslide density: 0.35 landslides /km^2	0.00002	0.00009	0.00018	0.00039
Moderate	This class has some probability that landslides might occur, although not very frequent and not with a high density.	Area: 168.6 km^2 Landslide area: 58 hectares Number of landslides: 356 Spatial probability: 0.0035 Landslide density: 2.11 landslides /km^2	0.00053	0.00084	0.00088	0.00262
High	This class has the highest density and frequency of landslides.	Area: 191.8 km^2 Landslide area: 1250 hectares Number of landslides: 3104 Spatial probability: 0.0652 Landslide density: 16.2 landslides /km^2	0.00436	0.00861	0.02932	0.05658

9.2 Recommendations

This study tried to generate the best possible landslide susceptibility and hazard map at a national scale given the limitations of data availability and time. Nevertheless, in order to be able to make a reliable landslide hazard map that also represents future changes the following recommendations are given:

1. **Establishment of a national landslide database**.

Currently there is no single organizations responsible for generating and maintaining landslide data in Dominica. The Ministry of Public Works generates road clearance reports that could be easily converted into a landslide database. However, the current situation is that these data get lost after some years. The Office of Disaster Management receives information about emergencies, which also include landslide events. However, when we asked them for a database they were not able to provide one. Also the spatial planning division requires landslide data for generating land use plans, and for building permit issuing. The current practice is that landslide data is collected by external parties within international projects.

Figure 9-1: Screenshot of a web-based hazard reporting system developed for another country

There is a need to develop a national landslide database, which requires that one organization is made responsible for generating and maintaining such a database, and where several other organizations should contribute. This will require additional funding from a donor agency to set it up. The landslide inventory should be stored in a web-mapping application, with a Google Earth or other background, where various national and international organizations can consult the existing landslide information, and where new landslide events can be added by government organizations, local people, news media, NGO's etc. A close collaboration with the online newsmedia in Dominica (http://dominicanewsonline.com/) is highly recommended, as they have reported many landslide events, with additional photo or video footage, which could be easily linked to a geolocation, and stored in such a database so that the information is not lost. It is very important to get better data on the location, type, damage and especially the date of landslide events, so that in future a correlation between rainfall characteristics and landslide incidences, and the establishment of rainfall thresholds, and frequency/magnitude relationships can be properly carried out. These reported events would be stored in a separate database, which is used by the national responsible organization for landslide inventory mapping, as the basis for checking. These are added to the actual database only after they have been checking by an expert. This will also allow the continuation of the landslide database in future. It is essential that there is a close collaboration between the various national organizations that have to deal with landslides. However, one organization should be the nodal agency responsible for setting-up the national landslide database.

2. **Generating a national LiDAR survey.**

Currently, the Digital Elevation Data for Dominica is of poor quality. The available contour data have no metadata, and it is not clear how these were generated. But their quality is very poor, and the resulting Digital Elevation Model doesn't depict the actual steep topography and surface conditions that are so essential for landslide susceptibility assessment. Dominica also doesn't have a national building footprint map which is also essential for generating exposure and risk maps. And the current landuse map is also old and too generalized, leading to poor correlations with landslide occurrence. The generation of a national LiDAR-based survey would enable improvement of many of the above mentioned deficiencies. Topographic data would greatly improve when it is based on LiDAR data, allowing generation of a so-called bare-surface model of the terrain, even under dense vegetation, provided that the density of LiDAR points during the survey is high enough. A detailed bare-surface model would allow for interpretation of geomorphological evidence of old landslides, and other relevant geological and geomorphological features much better (Razak et al., 2013), as we did for Saint Vincent and Grenada, which already have such a LiDAR–derived Digital Elevation Model (DEM). DEM derivatives such as slope steepness, slope direction, local drain direction, flow accumulation, slope convexity and slope length would be much more accurate than they are now. LiDAR-derived DEMs are also essential for other applications, such as for flood hazard assessment, where very local topographic differences are important, and also for many other application related to hazard and risk assessment, forestry, agriculture, and tourism. LiDAR data would also allow to generate building footprint maps in an automatic way, and would also allow to record building heights, which are very useful for exposure and risk assessment, but also for a large number of other planning and management activities related to housing, schooling, shelter planning, health, social aspects etc. And LiDAR survey would also allow to generate an improved landuse map, in combination with the optical images that are normally collected simultaneously with a LiDAR survey. Vegetation characteristics (height of vegetation, density etc.) can be derived from LiDAR data.

3. Generating an updated landuse map

As indicated above the current land use map for Dominica is of poor quality, and is outdated. Whereas new land use maps were generated for the other three island countries within the CHARIM project (Satin Lucia, Saint Vincent and Grenada), this was not done for Dominica. Such a land use map should be made through a combination of LiDAR-based analysis and high resolution image classification. LiDAR data can be used for generated vegetation height maps, tree density maps, and even maps of individual trees with height, canopy width, Breast Height Diameter (BHD), and Biomass. Local experts should be involved to ascertain that the land use classes used are relevant and realistic. Extensive field checking should be carried out as well, as the experience from the other three island has shown that automatic classification with limited field checks lead to many local erroneous results.

4. Updated engineering geological map

The available soil map was made a long time ago without the new technology that is now available. The available map is also focusing on pedologic soils, which makes it less useful for landslide applications, where we are more interested in engineering soils and their characteristics. The existing geological map focuses on the description of the age and origin of the rocks rather than on their engineering characteristics. Therefore there is a need to generate an engineering geological map for Dominica that would describe engineering soil and rock types. Engineering soils need to be described with respect to their origin (e.g. weathering soil, colluvial soil, alluvial etc.), grainsize composition, depth, geotechnical characteristics (soil strength, atterberg limits etc.) and hydrological characteristics (infiltration capacity, hydraulic conductivity, pore space etc.). Engineering rock types should focus on their lithology, depth of weathering zones, and geotechnical characteristics (rock strength, discontinuities etc.) (Chacon et al., 2006). The updated engineering geological map should be generated on the basis of a detailed terrain mapping, which should be done using the LiDAR-based hillshading image as a basis, by an experienced geomorphologist. Based on the terrain classification, individual material units are outlined, which are subsequently described in term of material types, vertical sequences and depths of soil layers. Based on the classification of the material types a stratified sampling scheme should be designed to sample the various types of materials and test them in the field for infiltration capacity, and in the laboratory for saturated hydrological conductivity, density, porosity, swelling clay potential, cohesion and angle of internal friction.

5. Improvement of the HydroMet system for Dominica

We were only able to obtain daily rainfall data for two stations (Melville hall, and Canefield) and some project-related rainfall data from the DOMEX project. In order to be able to make better predictions for landslides as well as floods, and droughts it is essential that the HydroMet system is improved. Continuous recording stations should be installed in more locations, and the data should be made available through the web. Given the small size of Dominica it may be desirable that the CIMH would take the lead in this. Rainfall stations should be located at different elevations, and exposures (windward, leeward) sides. Closer connections should be established with the meteorological organisations in Martinique and Guadeloupe, and the weather radar data from these countries should also be used regularly for Dominica.

6. Carrying out a landslide run-out assessment.

The method focuses on the assessment where landslides are likely to initiate, and not on the possible run-out areas. Run-out susceptibility assessment should be taken into account when doing local and site-investigation studies.

For run-out assessment at the local scale an empirical run-out model Flow-R, developed by the University of Lausanne, could be used. Flow-R (Horton et al., 2013) is a modelling software that uses a GIS empirical distribution model to probabilistically estimate the flow path and run-out extent of gravitational mass movements at regional scales. Flow-R first requires the identification of source areas before the actual run-out can be modelled. Two parameters are required to model the run-outs for each return period in the Flow-R model: (1) the minimum travel angle and (2) the maximum velocity. These two parameters can be estimated based on

literature review or back calibrated based detailed run-out models. The software calculates probably flowpaths from source points based on energy line calculations. The method doesn't require source volumes, or rheological parameters. It also doesn't consider entrainment. It can calculate the flowpaths from many different source zones at the same time. This makes the model suitable for use at a regional to medium scale. The results are indicative, but previous work has shown that the calculated distances correlate well with more detailed run-out models. The model can also be applied for different types of movement, e.g. debrisflows, flowslides, and rockfall, by varying the reach angles.
For run-out assessment at the site-investigation scale it is advised to use physically-based run-out models, such as Flow-2D or RAMMS. An overview of available models is given by Quan Luna (2012).

7. Further training and discussion

The current version of the landslide susceptibility and hazard map should be discussed extensively with the experts in the various government departments, but especially with the Spatial Planning Division and the Ministry of Public Works. The use of this map in land use planning, building permit issuing and land subdivision process should be further discussed. Also recommendations with respect to landslide hazard assessment at the local and detailed level should be discussed with the local organizations. Further training on the use of the maps and the method for generating them would also be important, especially when one government organization would be give the responsibility for generating and maintaining a national landslide database, this organization should also be trained in using that data for updating the national and local scale landslide hazard maps. Further training is also required in the use of spatial data and the sharing of spatial data through the GeoNode.
We recommend that the landside susceptibility and hazard map is updated once more detailed input data become available (e.g. the LiDAR data) or after a major triggering event.

8. Implications of the susceptibility classes for planning

The landslide susceptibility map should be used by planners and other professionals as the source of information on where landslide problems can be expected in future. Although the map is a national scale map, in the preparation also local situations were taken into account during the map editing stage. However, the map is still a national scale map and cannot be used for local or site specific planning.

We recommend the following use of the susceptibility classes:

- **Low susceptibility**: For planners there is no limitation with respect to expected landslide problems in the development of these areas. No special care should be taken by engineers with respect to planning and maintaining infrastructure in these areas with respect to landslides. Of course it is important to also check the other hazard maps for these areas. Of course it is important to also check the flood hazard maps for these areas, as areas that are flat and near a river or coast might be still flood prone.
- **Moderate susceptibility**: It is advised to carry out a more detailed landslide study for residential development and for critical infrastructure. There is no need to avoid these areas altogether, but care should be taken that landslides might occur. This class is actually the most problematic for use in spatial planning and planning/maintenance of infrastructure, as it is an intermediate class.
- **High susceptibility**: There are severe restrictions with respect to expected landslide problems in these areas. The best is to avoid these areas in the development of future residential areas or critical infrastructure whenever possible. Development plans should always incorporate a more detailed study of landslide hazard in these areas. Engineers should consider the high landslide hazard when designing or maintaining infrastructure. Further evaluations would have to be carried out before allowing new constructions – be that an expert inspection of the site, detailed slope stability evaluations – that may depend on the importance of the asset (e.g. a private building would be dealt with differently than a hospital)

One could argue that it is not possible to make the underlying implications for planning, given the high level of uncertainty, related to the poor quality of data, and that making restrictions based on this map can generate an immediate conflict with the inhabitants of the areas that are located in areas of "high sensitivity". However, the alternative is not to use any guidance map and wait until more detailed maps are available with the utopy that these will be without uncertainty. It is better to act now, even based on maps that are uncertain, than to increase the risk in potentially dangerous area, leading to losses of life and investments.

10 References:

Aleotti P (2004) A warning system for rainfall-induced shallow failures. Eng Geol 73: 247–265.

Aleotti, P. and Chowdury, R. 1999. Landslide hazard assessment: summary review and new perspectives. Bull. Eng. Geol. Env. (1999): 21-44, pp 21- 44

Andereck, Z. D. (2007). Mapping Vulnerability of Infrastructure to Destruction by Slope Failures on the Island of Dominica , WI : A CASE STUDY OF GRAND FOND , PETITE SOUFRIERE , AND MOURNE JAUNE. Faculty of Miami University.

Anderson, M. G., Holcombe, E., Blanke, J.R., Ghesquir, F., Holm-Nielsen, N., & Fisseha, T. (2011). Reducing landslide Risk in communities: evidence from the Eastern Caribbean. Applied Geography, 31(2), 590-599.

Ardizzone, F., Cardinali, M., Carrara, A., Guzzetti, F. and Reichenbach, P.: Impact of mapping errors on the reliability of landslide hazard maps, NHESS, 2(1/2), 3–14, 2002.

ACOE (ARMY CORPS OF ENGINEERS), 2004, Water Resources Assessment of Dominica, Antigua, Barbuda, St. Kitts andNevis: Mobile District and Topographic Engineering Center Report, U.S. Army Corps of Engineers, Mobile, AL, 94 p.

Areces-Mallea, A., Weakley, A.S., Li, X., Sayre, R.G., Parrish, J.D., Tipton, C.V., and Boucher, T., 1999. A guide to Caribbean vegetation types: classification systems and descriptions. Arlington, Va., The Nature Conservancy.

Arlington, J. (2014) THE LAYOU, CARHOLM and MATTHIEU STORIES 1997-2014. A Compilation of Dominican Newspaper Items and Local Journal Articles on the Layou-Carholm-Matthieu Disasters of 1997 and 2011, and on the Precursors and Aftermaths of those Disasters. Report.

Benavot, A. and Riddle P., 1988. The Expansion of Primary Education, 1870-1940: Trends and Issues. Sociology of Education, Vol. 61, No. 3 pp. 191-210.

Benson, C., Clay, E., Michael, F.V., and Roberston, A.W., 2001, Dominica: Natural Disasters and Economic Development in a Small Island State, Disaster Risk Management Working Paper Series No. 2

Blahut, J., van Westen, C.J., Sterlacchini, S., 2010. Analysis of landslide inventories for accurate prediction of debris-flow source areas. Geomorphology, 119(1–2), 36-51.

Bonham-Carter, G.F., Agterberg, F.P., Wright, D.F., 1988. Integration of geological datasets for gold exploration in Nova Scotia. Photogrammetric Engineering and Remote Sensing, 54(11), 1585-1592.

Bonham-Carter, G.F., Agterberg, F.P., Wright, D.F., 1989. Weights of evidence modelling: a new approach to mapping mineral potential. In: D.F. Agterberg, G.F. Bonham-Carter (Eds.), Statistical Applications in Earth Sciences. Geological Survey of Canada, Ottowa.

Breheny, P., 2007, Hydrogeologic/Hydrological Investigation of Landslide Dam and Impounded Lake in the Matthieu River Valley, Commonwealth of Dominica, West Indies: Unpublished M.S. Dissertation, University of Leeds, United Kingdom.

Brunsden, D. (1999). Some geomorphological considerations for the future development of landslide models: Geomorphology. 30(1-2), p. 13-24.

Casadei, M., Dietrich, W.E., and Miller, N.L. (2003). Testing a model for predicting the timing and location of shallow landslide initiation on soil mantled landscapes: Earth Surface Processes and Landforms. 28(9), p. 925-950.

CEPAL 1979. Report on effeccs of Hurricane Davidon the island of Dominica. UN Economic and Social Council Rept. 1099

Chacon J, Irigaray C, Fernandez T, El Hamdouni R (2006) Engineering geology maps: landslides and geographical information systems. Bull Eng Geol Environ 65:341–411.

Coan, M., Wood, E., and Reillo, P. (2007). Forest Formation and Land Cover Map Series: Dominica. http://lca.usgs.gov/lca/carland/data/dominica/dominica_lulc_final.tif.htm

Commonwealth of Dominica (2015). Rapid Damage and Impact Assessment Tropical Storm Erika – August 27, 2015. 86 p.

Corominas J, Moya J (1999) Reconstructing recent landslide activity in relation to rainfall in the Llobregat River basin, Eastern Pyrenees, Spain. Geomorphology 30(1–2):79–93. doi:10.1016/s0169- 555x(99)00046-x

Corominas J (2000) Landslides and climate. Keynote lecture- In: Proceedings 8th International Symposium on Landslides, (Bromhead E, Dixon N, Ibsen ML, eds). Cardiff: A.A. Balkema, 4: 1–33

Corominas, J. C.J. van Westen, P. Frattini, L. Cascini, J.-P. Malet, S. Fotopoulou, F. Catani, M. Van Den Eeckhaut, O. Mavrouli, F. Agliardi, K. Pitilakis, M. G. Winter, M. Pastor, S. Ferlisi, V. Tofani, J. Hervas, and J. T. Smith (2014) Recommendations for the quantitative analysis of landslide risk. Bulletin of Engineering Geology and the Environment, V 73, N 2, pp 209–263.

Crosta G (1998) Regionalization of rainfall thresholds: an aid to landslide hazard evaluation. Environ Geol 35(2):131–145. doi:10.1007/s002540050300

Crosta GB, Frattini P (2001) Rainfall thresholds for triggering soil slips and debris flow. In: Proceedings 2nd EGS Plinius Conference on Mediterranean Storms (Mugnai A, Guzzetti F, Roth G, eds). Siena: 463– 487

Crozier, M.J. (2005). Multiple occurrence regional landslide events in New Zealand: hazard management issues. Landslides,2: 247-256

Dahal RK, Hasegawa S (2008) Representative rainfall thresholds for landslides in the Nepal Himalaya. Geomorphology 100(3–4):429–443. doi:10.1016/j.geomorph.2008.01.014

Dai, F.C., Lee, C.F. and Ngai, Y.Y. (2008). Landslide risk assessment and management: an overview . Engineering Geology, 64 (1), 65-87

Das, I., Sahoo, S., van Westen, C.J., Stein, A. and Hack, H.R.G.K. (2010) Landslide susceptibility assessment using logistic regression and its comparison with a rock mass classification system along a road section in the northern Himalayas. In: Geomorphology, 114 (2010)4 pp. 627-637

DeGraff, J.V., 1987a. Landslide hazard on Dominica, West Indies-Final Report. Washington, D.C., Organization of American States.
DeGraff, J.V. 1987b. Geological Reconnaissance of the 1986 landslide activity at Good Hope, D'Leau Gommier, and Belvue Slopes, Commonwealth of Dominica, West Indies, Report submitted to: Commonwealth of Dominica and the OAS
DeGraff, J.V., Bryce, R., Jibson, R.W., Mora, S., and Rogers, C.T., 1989, Landslides: Their extent and significance in the Caribbean, Proceedings of the 28th International Geological Congress: Symposium on Landslides
DeGraff, J.V. 1990a. Post-1987 Landslides on Dominica, West Indies: An Assessment of LandslideHazard Map Reliability and Initial Evaluation of Vegetation Effect on Slope Stability, Submitted to The Commonwealth of Dominica and the OAS
DeGraff, J.V. 1990b, Potential Landslide-Dam Hazard Below Freshwater Lake, Commonwealth of Dominica, West Indies, Report submitted to Commonwealth of Dominica and the OAS
DeGraff, J. V., 1991: Determining the significance of landslide activity: Examples from the Eastern Caribbean. Caribb. Geogr., 3, 31–42.
DeGraff, J. V., 1995, Natural Hazards Vulnerability of the Dominica Hydroelectric Expansion Project: Caribbean Disaster Mitigation Project Final Report, Organization of American States, Washington, DC, 26 p.
DeGraff, J. V., 1997, Technical Assessment of the Landslide-Dam Emergency, Commonwealth of Dominica, W.I.: U.S. Agency for International Development Report, Office of the U.S. Foreign Disaster Assistance, Washington, DC, 24 p.
DeGraff, J.V., James, A. and Breheney, P., 2010. The Formation and Persistence of the Matthieu Landslide-Dam Lake, Dominica, W.I.. Environmental & Engineering Geoscience, Vol. XVI, No. 2, May 2010, pp. 73–89
DeGraff, J.V., Romesburg, H.C., Ahmad, R, and McCalpin, J. 2012. Producing landslide-susceptibility maps for regional planning in data-scarce regions. Nat Hazards (2012) 64:729–749
DeGraff, J. V. and Rogers, C. T., 2003, An unusual landslide dam event in Dominica, West Indies: Landslide News, No. 14/15, pp. 8–11.
Disaster Risk Management in Latin America and the Caribbean Region: GFDRR Country Notes(2009). The combination of rainfall, geology and topography in Dominica is particularly favorable to the development of landslides of various types.
D'Odorico P, Fagherazzi S (2003) A probabilistic model of rainfall-triggered shallow landslides in hollows: a long-term analysis. Water Resour Res 39(9). doi:10.1029/2002wr001595
DOMEX project. : http://www.domex2011.com/rain-gauge-network
DominicaNewOnline (http://dominicanewsonline.com/news/?s=landslide)
Fairbridge, R.W., 1975c. Windward Islands. In R.W. Fairbridge (ed.), The Encyclopedia of World Regional Geology, Part 1: Western Hemisphere, p. 667. Stroudburg, Dowden, Hutchinson and Ross.
Faugeres, M.L., 1966. Observations dur le modele des versants dans la region des Pitons du Carbet (Martinique). Assoc. Geographes Francaise Bull. 342-343: 52-63
Fell,R., Corominas, J., Bonnard, C., Cascini, L., Leroi, E., Savage, W.Z., and on behalf of the JTC-1 Joint Technical Committee on Landslides and Engineered Slopes (2008): Guidelines for landslide susceptibility, hazard and risk zoning for land use planning. Engineering Geology, Vol. 102, Issues 3-4, 1 Dec., pp 85-98. DOI:10.1016/j.enggeo.2008.03.022
Frattini P, Crosta G, Sosio R (2009) Approaches for defining thresholds and return periods for rainfalltriggered shallow landslides. Hydrol Process 23(10):1444–1460. doi:10.1002/hyp.7269
Galli, M., Ardizzone, F., Cardinali, M., Guzzetti, F. and Reichenbach, P.: Comparing landslide inventory maps, Geomorphology, 94(3-4), 268–289, 2008.
Garnier C. and Legendre Y. – coll. Devenoges Q. (2015) – Technical assistance mission to the Government of Dominica - Expertise on land movements following the passage of tropical storm Erika, 26 - 28/08/2015. Final report. BRGM/RC-65203-FR, 67 p., 52 ill., 4 app.
Giannecchini R, Galanti Y, Avanzi GD (2012) Critical rainfall thresholds for triggering shallow landslides in the Serchio River Valley (Tuscany, Italy). Nat Hazards Earth Syst Sci 12(3):829–842. doi:10.5194/ nhess-12-829-2012
Gilleland, E. (2015). Package " extRemes " (p. 115).
Glade T (2000) Applying probability determination to refine landslide-triggering rainfall thresholds using an empirical ''antecedent daily rainfall model''. Pure Appl Geophys 157(6):1059–1079. doi:10.1007/ s000240050017
Glade T., Anderson M. & Crozier M.J. (Eds) (2005): Landslide hazard and risk.- Wiley. 803 p
Godt JW, Baum RL, Chleborad AF (2006) Rainfall characteristics for shallow landsliding in Seattle, Washington, USA. Earth Surf Proc Land 31(1):97–110. doi:10.1002/esp.1237
Guha-Sapir, D., Below,R., Hoyois, P. - EM-DAT: International Disaster Database – www.emdat.be – Université Catholique de Louvain – Brussels – Belgium.
Guzzetti, F., Carrara, A., Cardinali, M. and Reichenbach, P., (1999). Landslide hazard evaluation: a review of current techniques and their application in a multi-scale study, Central Italy. Geomorphology, 31(1-4): 181-216.
Guzzetti F, Peruccacci S, Rossi M, Stark CP (2007) Rainfall thresholds for the initiation of landslides in central and southern Europe. Meteorol Atmos Phys 98(3):239–267. doi:10.1007/s00703-007-0262-7
Hartford, D., and Mehigan, P.J., 1984, Rain -induced slope failures in the Commonwealth of Dominica, West Indies: 5th International Symposium on Landslides, vol.3, p.87-89
Horton, P., Jaboyedoff, M., Rudaz, B., Zimmermann, M., 2013. Flow-R, a model for susceptibility mapping of debris flows and other gravitational hazards at a regional scale. Natural Hazards and Earth System Sciences 13, 869-885.
Hurricane City (http://www.hurricanecity.com/city/dominica.htm)
INCREO (http://www.increo-fp7.eu/)
Iverson, R. M., 2000: Landslide triggered by rain infiltration. Water Resour. Res., 36, 1897–1910.

Jaiswal, P., van Westen, C.J. and Jetten, V.G. (2011) Quantitative assessment of landslide hazard along transportation lines using historical records. In: Landslides : journal of the International Consortium on Landslides, 8 (2011)3 pp. 279-291.
Jaiswal, P. and van Westen, C.J. (2013) Use of quantitative landslide hazard and risk information for local disaster risk reduction along a transportation corridor : a case study from Nilgiri district, India. In: Natural hazards : journal of the international society for the prevention and mitigation of natural hazards, 65 (2013)1 pp. 887-913
James, A., 1998, The 1997 Layou Carholm Disaster: Its Environmental and Socio-Economic Impacts: Forestry and Wildlife Division Internal Report, Ministry of Agriculture & the Environment, Roseau, Dominica, 26 p.
James, A., 2000, Observations Made from Monitoring of the Matthieu-Carholm-Layou Landslide Area in 1999: Forestry and Wildlife Division Internal Report, Ministry of Agriculture & the Environment, Roseau, Dominica, 5 p.
James, A., 2002, Observations Made from Monitoring of the Matthieu-Carholm-Layou Landslide Area 2001: Forestry and Wildlife Division Internal Report, Ministry of Agriculture & the Environment, Roseau, Dominica, 9 p.
James, A., 2003, Summary Report on the Monitoring of the Matthieu-Layou Disaster Area in 2002: Forestry and Wildlife Division Internal Report, Ministry of Agriculture & the Environment, Roseau, Dominica, 9 p.
James, A., & De Graff, J. V. (2012). The draining of Matthieu landslide-dam lake, Dominica, West Indies. Landslides, 9(4), 529–537. doi:10.1007/s10346-012-0333-9
Jones, P.D.; Harris, I. (2008). Climatic Research Unit (CRU) time-series datasets of variations in climate with variations in other phenomena. NCAS British Atmospheric Data Centre, date of citation. http://catalogue.ceda.ac.uk/uuid/3f8944800cc48e1cbc29a5ee12d8542d
Lang, D.M. 1967. Soil map of Dominica. 2 sheets
Larsen, M. C., and A. Simon, 1993: A rainfall intensity-duration threshold for landslides in a humid-tropical environment, Puerto Rico. Geogr. Ann., A75, 13–23.
Lee, S., Choi, J., 2004. Landslide susceptibility mapping using GIS and the weight-of-evidence model. International Journal of Geographical Information Science, 18(8), 789-814.
Lee, S., Choi, J., Min, K., 2002. Landslide susceptibility analysis and verification using the Bayesian probability model. Environmental Geology, 43(1-2), 120-131.
Lindsay, J. M., A. L. Smith, M. J. Roobol, and M. V. Stasuik (2005), Dominica, in Volcanic Hazard Atlas of the Lesser Antilles, edited by J. M. Lindsay et al., pp. 1–48, Seismic Res. Unit, Univ. of the West Indies, St. Augustine, Trinidad and Tobago.
Lockhart, A. L. 1879. Leeward Islands Almanack. Roseau: Official Gazette Office
Marques R, Zeˆzere J, Trigo R, Gaspar J, Trigo I (2008) Rainfall patterns and critical values associated with landslides in Povoaçao County (Sa˜o Miguel Island, Azores): relationships with the North Atlantic Oscillation. Hydrol Process 22(4):478–494. doi:10.1002/hyp.6879
Martelloni G, Segoni S, Fanti R, Catani F (2011) Rainfall thresholds for the forecasting of landslide occurrence at regional scale. Landslides:1–11. doi:10.1007/s10346-011-0308-2
Martin-Kaye PHA (1960) Preliminary notes on the geological map of Dominica. Unpublished progress reports of the Government Geologist 1-12. Geological Survey, Windward Islands.
McGuire, W. J. (1996), Volcano instability: A review of contemporary themes, in Volcano Instability on the Earth and Other Planets, edited by W. J. McGuire, A. P. Jones, and J. Neuberg, Geol. Soc. Spec. Publ., 110, 1–23
Mehigan, P.J. & D.N.D.Hartford l-985. Aspects of slope stability in relation to road design in the Commonwealth of Dominica. Proc. llth Internat. Conf. Soil Mech. Found. Eng. L:2339-2343
Natural Hazard and Disasters : Landslides (1999).Retrieved July 27, 2014 from http://www.mona.uwi.edu/uds/Landslides.html
Neuhäuser, B., Terhorst, B., 2007. Landslide susceptibility assessment using “weights-of-evidence” applied to a study area at the Jurassic escarpment (SW-Germany). Geomorphology, 86(1–2), 12-24.
Office of Disaster Management (http://odm.gov.dm/)
O’Keefe, P. and Conway, C. (1977). Natural Hazards in the Windward Islands. University of Bradford, Disaster Research Unit, Occasional Paper Nr, 14. http://www.ilankelman.org/miscellany/BDRU14.pdf
OAS (1996) History of Storms on Dominica: HURSTAT. Caribbean disaster Mitigation Project. http://www.oas.org/cdmp/document/dominica_waves/2_History/History.htm
Polemio M, Sdao F (1999) The role of rainfall in the landslide hazard: the case of the Avigliano urban area (Southern Apennines, Italy). Eng Geol 53(3–4):297–309. doi:10.1016/s0013-7952(98)00083-0
Prior, D.B. and C. Ho, 1972. Coastal and mountain slope instability on the islands of St. Lucia and Barbados. Eng. Geol. 6:1-18.
Quan Luna, B. (2012) Dynamic numerical run - out modelling for quantitative landslide risk assessment. Enschede, University of Twente Faculty of Geo-Information and Earth Observation (ITC), 2012. ITC Dissertation 206, ISBN: 978-90-6164-330-2. http://www.itc.nl/library/papers_2012/phd/quan.pdf
Razak, K.A., Santangelo, M., van Westen, C.J., Straatsma, M.W. and de Jong, S.M. (2013) Generating an optimal DTM from airborne laser scanning data for landslide mapping in a tropical forest environment. In: Geomorphology, 190 (2013) pp. 112-125.
Roobol, M. J. and Smith, A. L., 2004, Geologic Map of Dominica, West Indies: Geology Department, University of Puerto Rico at Mayaguez. Electronic document, available at http://www.caribbeanvolcanoes.com/dominica/content/dominicamap.pdf
Rouse, C., 1990. The mechanics of small tropical flowslides in Dominica, West Indies. Eng. Geol., 29:227-239.
Rouse, W.C., A.J. Reading, and R.P.D. Walsh, 1986. Volcanic soil properties in Dominica, tr]est Indies : Eng. Geol . 23: 1- 28 .

Saaty. T.L. 1980. The Analytic Hierarchy Process, Planning, Piority Setting, Resource Allocation. McGraw-Hill, New york, 1980.
Saito H, Nakayama D, Matsuyama H (2010) Relationship between the initiation of a shallow landslide and rainfall intensity–duration thresholds in Japan. Geomorphology 118(1–2):167–175. doi:10.1016/ j.geomorph.2009.12.016
Sawatzky, D.L., Raines, G.L., Bonham-Carter, G.F., Looney, C.G., 2009. Spatial Data Modeller (SDM): ArcMAP 9.3 geoprocessing tools for spatial data modelling using weights of evidence, logistic regression, fuzzy logic and neural networks.
Sigurdsson H, Carey SN (1991) Caribbean Volcanoes: A Field Guide to Martinique, Dominica and St. Vincent. Geological Association of Canada, Toronto 1991 field trip guidebooks, pp 1-101.
Simoni, S., Zanotti, F., Bertoldi, G., and Rigon, R., (2008). Modelling the probability of occurrence of shallow landslides and channelized debris flows using GEOtop-FS: Hydrological Processes. 22(4), p. 532-545.
Smith, RB, Schafer, P, Kirshbaum, D, Regina, E (2009) Orographic Enhancement of Precipitation inside Hurricane Dean. J. Hydrometeorol., 10, 820-831
Smith, RB, Schafer, P, Kirshbaum, D, Regina, E (2009) Orographic Precipitation in the Tropics: Experiments in Dominica. J Atmos Sci 66, 1698-1716
Soeters, R., Van Westen, C.J., 1996. Slope instability recognition, analysis and zonation. In: Turner, A.K., Schuster, R.L., (Eds.), Landslides, Investigation and Mitigation
SRU 2000, Seismic Research Unit, University of the West Indies. Volcano Hazard Report for Southern Dominica: Interpretation of 1998-2000 Earthquakes and Hazard Mapping Results. 49 pages. http://www.mona.uwi.edu/cardin/virtual_library/docs/1146/1146.pdf
Süzen, M.L., Doyuran, V., 2004. Data driven bivariate landslide susceptibility assessment using geographical information systems: a method and application to Asarsuyu catchment, Turkey. Engineering Geology, 71(3–4), 303-321.
Technical Committee 32 (Engineering Practice of Risk Assessment and Management) of the International Society of Soil Mechanics and Geotechnical Engineering (ISSMGE): Risk assessment – Glossary of terms. http://www.engmath.dal.ca/tc32/2004Glossary_Draft1.pdf
Teeuw, R., Rust, D., Solana, C. and Dewdney, C. 2009. Large Coastal Landslides and Tsunami Hazard in the Caribbean. EOS Magazine, Eos, Vol. 90, No. 10, 81-82
Thiery, Y., Malet, J.P., Sterlacchini, S., Puissant, A., Maquaire, O., 2007. Landslide susceptibility assessment by bivariate methods at large scales: Application to a complex mountainous environment. Geomorphology, 92(1–2), 38-59.
UN-ISDR, 2004. Terminology of disaster risk reduction. United Nationas, International Strategy for Disaster Reduction, Geneva, Switzerland http://www.unisdr.org/eng/library/lib-terminology-eng%20home.htm
UNITAR-UNOSAT (2015). Landslide Affected Areas in Southeastern Dominica. Product ID: 2281 – English, Published: 1 Oct, 2015, GLIDE: TC-2015-000119-DMA. http://www.unitar.org/unosat/node/44/2281?utm_source=unosat-unitar&utm_medium=rss&utm_campaign=maps
USAID, 2006. Development of Landslide Hazard Map and Multi-Hazard Assessment for Dominica, West Indies. United States Agency for International Development (USAID), Caribbean Open Trade Support (COTS) Program. 51 pages.
Van Asch, T.W.J., Malet, J.P., Van Beek, L.P.H. and Amitrato, D. (2007) Techniques, issues and advances in numerical modelling of landslide hazard. Bull. Soc. géol. Fr., 2007, 178 (2), 65-88
Van Westen, C. J.: 1993, Application of Geographic Information Systems to Landslide Hazard Zonation, Ph-D Dissertation Technical University Delft. ITC-Publication Number 15, ITC, Enschede, The Netherlands, 245 pp.
Van Westen, C.J., Soeters, R. and Sijmons, K. (2000) Digital geomorphological landslide hazard mapping of the Alpago area, Italy. In: International journal of applied earth observation and geoinformation : JAG, 2 (2000)1, pp. 51-60.
Van Westen, C.J., Castellanos Abella, E.A. and Sekhar, L.K. (2008) Spatial data for landslide susceptibility, hazards and vulnerability assessment : an overview. In: Engineering geology, 102 (2008)3-4, pp. 112-131
Wagenseil, Ross and Charles C. Watson. 1996. Wave Hazard Assessment for Selected Sites on the West Coast of Dominica, West Indies. Washington, D.C.: Caribbean Disaster Mitigation Project, Organisation of American States, Unit of Sustainable Development and Environment .
Walsh, R.P.D., 1982. A provisional survey of the effects of Hurricanes David and Frederic in 1979 on the terrestrial environment of Dominica, West Indies. Swansea Geog. 19:28 35.
Walsh, R.P.D., 1985. The influence of climate, lithology, and time drainage density and relief development in the volcanic terrain of the Windward Islands. In I. Douglas and T. Spencer (eds.), Environmental change and tropical geomorphology, p. 93-122. London: Allen and Unwin.
Wieczorek GF, Glade T (2005) ,Climatic factors influencing occurrence of debris flows. In: Debris flow Hazards and Related Phenomena (Jakob M, Hungr O, eds). Springer Berlin Heidelberg, 325–362
Zezere JL, Trigo RM, Trigo IF (2005) Shallow and deep landslides induced by rainfall in the Lisbon region (Portugal): assessment of relationships with the North Atlantic Oscillation. Nat Hazards Earth Syst Sci 5(3):331–344