CHARIM

Caribbean Handbook on Risk Information Management

National scale landslide susceptibility assessment for Grenada

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Summary

The aim of this study was to generate a national-scale landslide susceptibility map for Grenada. 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 hydro-meteorological disaster events for Grenada, for the period 1822 to 2014, making use of many different sources. This is the most complete inventory up to our knowledge. It is quite clear from this database that the disaster reporting became more frequent in recent years, although limited information on landslides is available for Grenada, even more 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 evaluation landslide frequency/magnitude relations, which are required to convert susceptibility maps into hazard maps. We also compiled all available landslide data from different sources. Unfortunately there was only one point-based inventory available, which contained 142 landslides points along the road network. We generated a completely new landslide inventory using multi-temporal visual image interpretation, and generated an extensive landslide database for Grenada. The resulting landslide database contains 818 landslides, 163 were considered to have occurred before 2005, 643 were triggered by hurricane Ivan in 2004 and Hurricane Emily in 2005, and only 3 events are mapped for the period 2005-2014. It is clear from these inventories that landslides are related to major rainfall events in Grenada.

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 for different frequencies. We applied a method for landslide 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. 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 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. The manual editing of the susceptibility map was also done to simplify the susceptibility units. The method is transparent, as the stakeholders (e.g. the engineers and planners) and other consultants can consult the criteria trees and evaluate the standardization and weights, and make adjustments. In the final landslide susceptibility map 56.8% of the area has a low susceptibility, 28.6 moderate and 14.6 high susceptibility, in which also all historical landslides are included. The total area of the historical landslides (including debris flow runout zones) is 416.4 hectares, which is 1.3 % of the total area of the country, and which covers 9% of the high susceptibility class. However, for individual events these values are expected to be lower, as less landslides are expected to be triggered by a single triggering event. Also some landslides are expected to occur in the moderate classes, although with a much lower density, and hardly none in the low susceptibility zones. The exception however might be the river channels that are close to higher area, and which may be affected by a combination of flash floods and debris flows. However, not enough historical information was available to indicate which ones are susceptible to that. Generally it was very difficult to determine the frequency of the landslide densities due to a lack of sufficient event-based inventories.

Future work should also focus on landslide susceptibility along the road network by subdividing the primary road network into homogeneous segments which could be characterized by information from various GIS layers. But primarily by data from field studies along the road network.

A basic landslide exposure analysis was carried out for buildings. We analyzed all buildings in Grenada using a gIS overlay with the edited building footprints. The results show that in the entire country 1301 buildings (2.1 % of the total) are located in high landslide susceptibility zones, 13351 (21.7 %) in moderate susceptibility zones and the vast majority of 46966 buildings (76.2%) in low landslide susceptibility zones. When we evaluate these values per Parish, St John parish has the largest percentage of buildings located in high susceptibility zones (238 buildings, which is 5.3 %), followed by St Mark (93 buildings, 4.4 %), and St. George (624 buildings, 2.5 %). One should be careful when using the national-scale landslide susceptibility 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.

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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 infrastruct60ure 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 Grenada, 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 Grenada previous attempts to generate landslide susceptibility maps have been carried out.
In 1994 there appears to have been a project to define vulnerable areas to coastal erosion and inundation by DIWI Consult International. No map could be found for this study (DIWI, 1994).
In 2006 a project was carried out on landslide hazard assessment for Grenada by CDB/CDERA (2006). The Caribbean Development Bank (CDB) through the Disaster Mitigation Facility for the Caribbean (DMFC), and the Caribbean Disaster Emergency Response Management Agency (CDERA) through the Caribbean Hazard Mitigation Capacity Building Program (CHAMP), collaborated on a multi-phased project to support the development of national hazard mitigation plans in Saint Lucia, Grenada and Belize. The development of landslide hazard maps for Saint Lucia and Grenada was one component of a series of hazard mapping consultancies intended to inform vulnerability assessments in each of the three pilot states. The landslide mapping project was initiated by combined project inception meetings and field reconnaissance in Saint Lucia and Grenada. For Grenada, the major study area covers the entire island but does not include the adjacent island of Carriacou. The consultants used five factors to evaluate the landslide susceptibility using a weighted approach: Slope steepness, Slope Aspect, Elevation, Geology, and Soils. Unfortunately none of the agencies had a digital version of the resulting map. Only NaDMA had a paper map on their wall. In a later stage of the project we received also a digital version. The resulting map is shown in Figure 1-1.

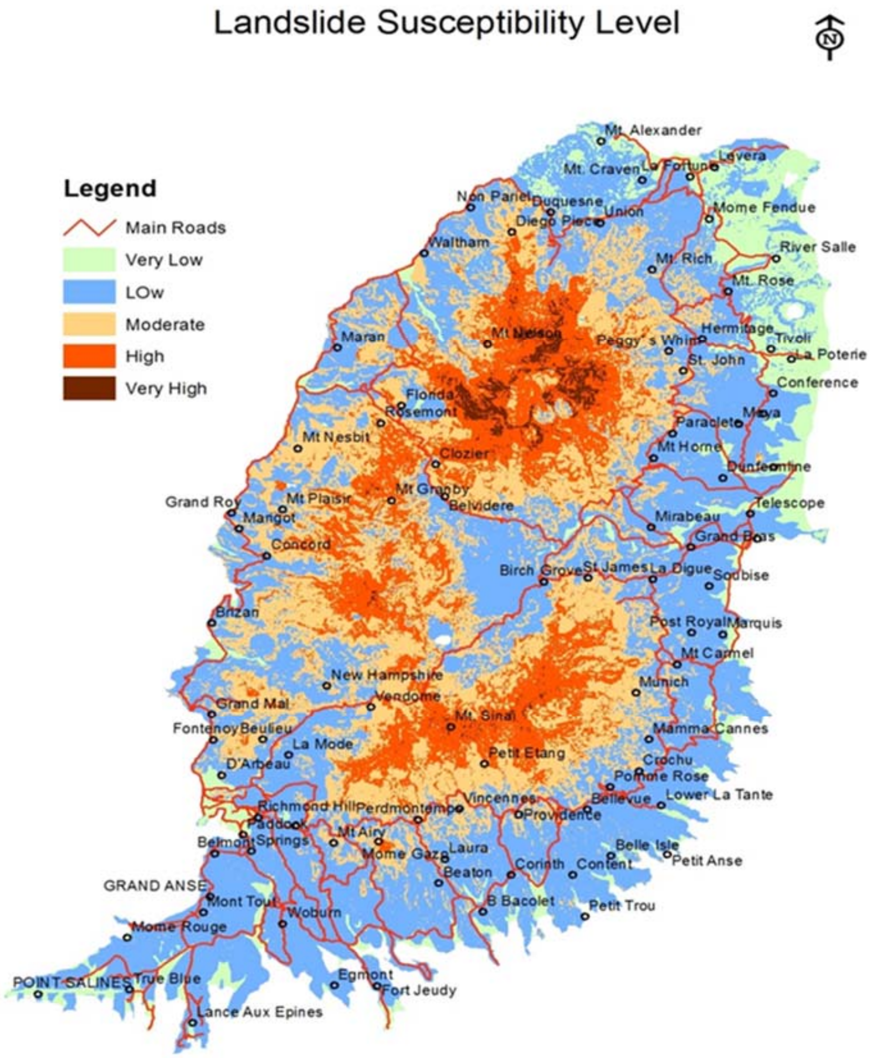

Figure 1-1: Landslide susceptibility map generated in 2006 by the CDB/CDREA project.

An island-wide flood hazard assessment study was carried in 2006 by consultants (Vincent Cooper and Jacob Opadeyi) for the Caribbean Development Bank. The map (1:25.000 scale) was based on a ranking method. Figure 1-2 show one of the two map sheets generated.

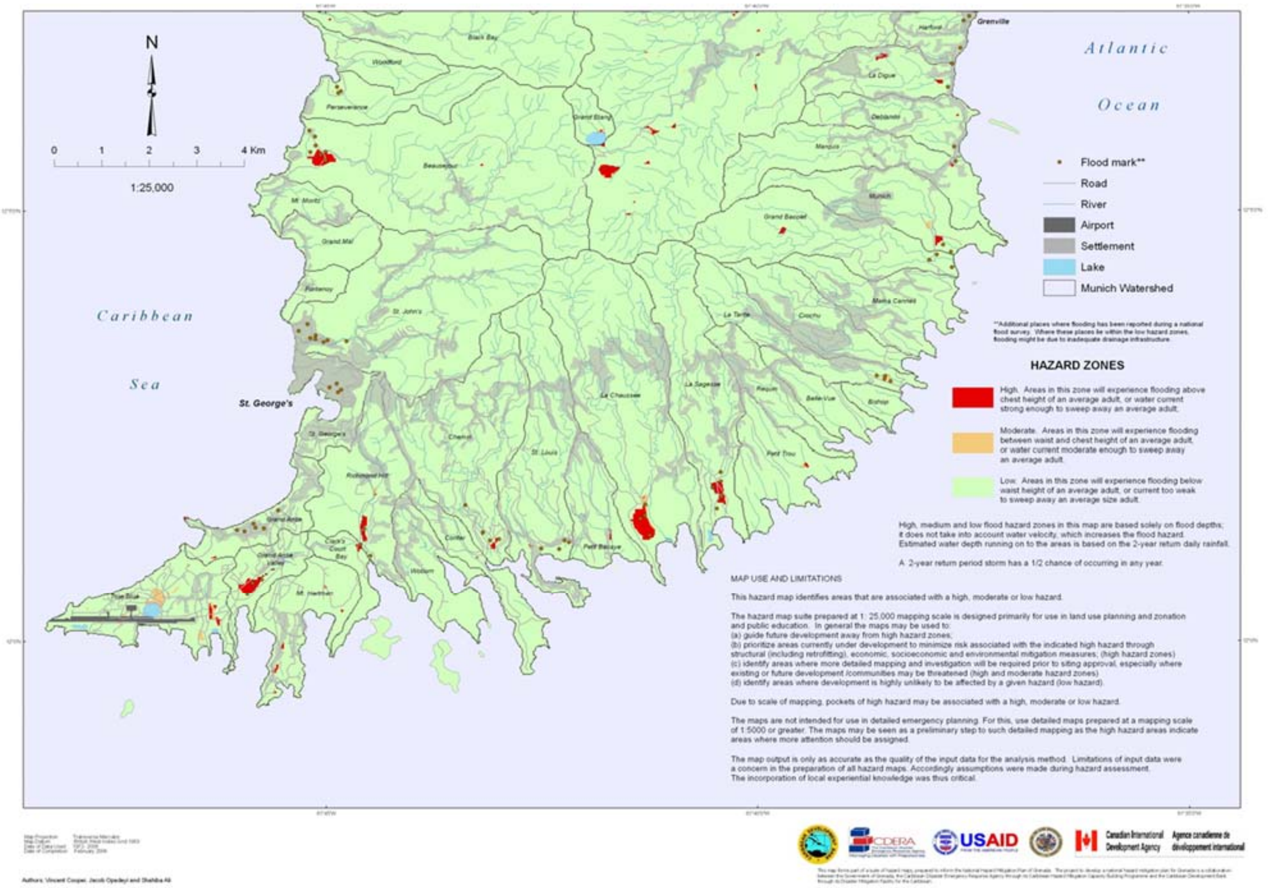

Figure 1-2: Resulting flood hazard map generated in 2006 by the CDB/CDREA project.

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. Almost no landslide inventories were available for Grenada. Therefore an attempt was made to generate one 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 British Geological Survey 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.

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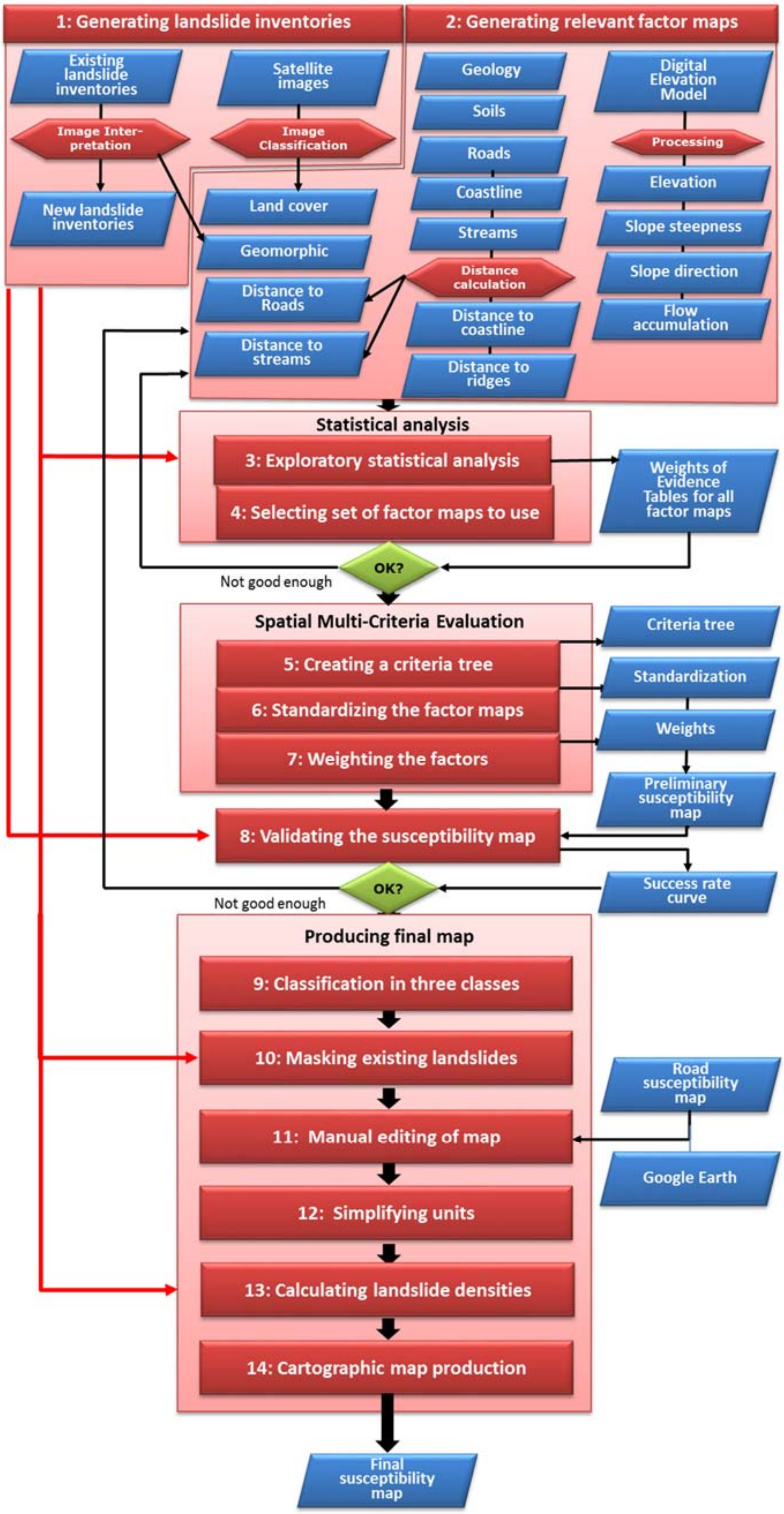


Figure 2-1: Flowchart of the method used for the generation of the national scale landslide susceptibility maps. See text for explanation. See also: http://www.charim.net/methodology/43

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 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 (http://www.charim.net/grenada/maps). Also the digital versions of the landslide inventories and the landslide susceptibility maps were made available through the GeoNode (http://charim-geonode.net/maps/162).

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 as 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 susceptibility 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.

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 by which triggering events. Intense rainfall events are considered the most important triggering events. 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 trigger landslides, e.g. through deforestation, clear cutting, improper drainage practices, or slope cutting, but still a rainfall trigger would be required to actual cause the landslides.

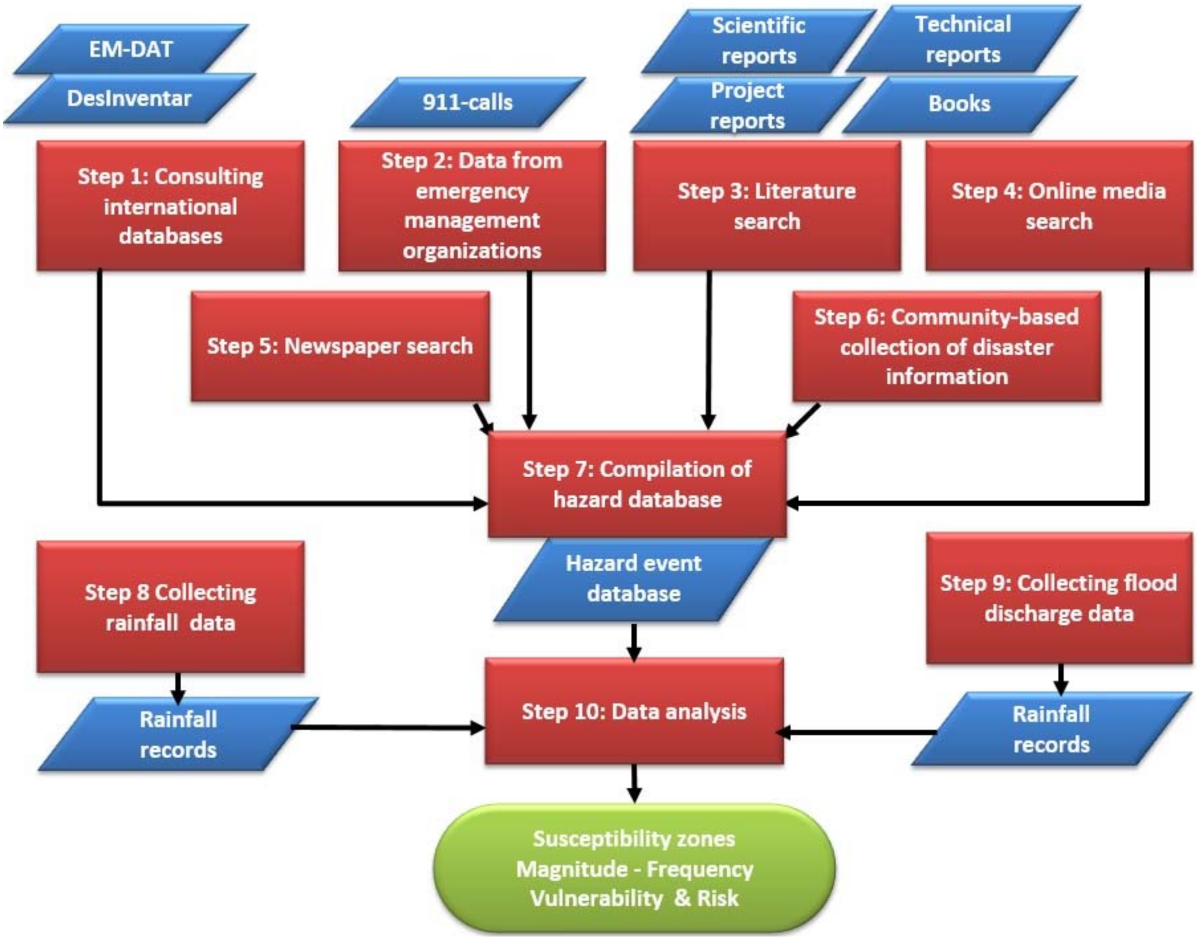


Figure 3-1: Overview of method for collecting information of past events.

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 was found related to landslides.

As stated in the Grenada country profile for disaster risk reduction (DipEcho, 2014) "There is no systematic documenting and archiving of information on the occurrence and impact of these hazards, no mechanisms to systematically compile, store, update and manage the data and information relating to these hazards in a central location. The information that is available is stored in an ad hoc manner by a number of different local, regional and international entities".

We visited the National Disaster Management Agency (NaDMa) (http://www.gov.gd/departments/nadma.html) but they only had a very simple recording of historical disasters in the country which was also not updated. 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 NowGrenada (http://nowgrenada.com/?s=landslide&x=0&y=0) was very useful, as was WikiGrenada (http://www.barnaclegrenada.com/) (http://www.caribbeannewsnow.com/) and others. However, information was only available for a limited period of time. We also collected information from various other sources on the internet, such as Charles (2014). 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. Also Benson et al., (2001) give an overview and we also consulted http://www.hurricanecity.com/city/grenada.htm. Unfortunately we were not able to obtain any road maintenance and clearance reports from the Ministry of Public Works.

3.2. Results

The various sources provided a lot of information in historical events, such as tropical storms, hurricanes, earthquakes and drought. Table 3-1 shows the very meagre results from the EM-DAT records.

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$)
17-07-2005	Storm	1	1650	
09-09-2004	Storm	39	60000	889
15-11-1999	Storm	0	210	5.5
26-07-1990	Storm	0	1000	
04-08-1980	Storm			5.3
00-11-1975	Storm			4.7
30-09-1963	Storm Flora	6	?	

Table 3-2 provides the full list of events. It is remarkable that there are so many earthquakes reported for Grenada in the 19th and 20th century but none in the last 60 years. This may be related to the activity of the Kick 'm Jenny submerged volcano north of Grenada. However, there are no clear indications if that assumption is correct.

Volcanic activity

Kick 'em Jenny (also: Kick-'em-Jenny or Mt. Kick-'Em-Jenny) is an active submarine volcano or Seamount on the Caribbean Sea floor, located 8 km north of Grenada. Kick-'em-Jenny rises 1,300 m above the sea floor on the steep inner western slope of the Lesser Antilles ridge. The South American tectonic plate is subducting the Caribbean tectonic plate to the East of this ridge and under the Lesser Antilles island arc.

The first record of the volcano was in 1939, although it must have erupted many times before that date. On 23–24 July 1939 an eruption broke the sea surface, sending a cloud of steam and debris 275 m into the air and generating a series of tsunamis around two metres high when they reached the coastlines of northern Grenada and the southern Grenadines. A small tsunami also reached the West coast of nearby Barbados, where a sea-wave suddenly washed over a coastal road. The volcano has erupted on at least twelve occasions between 1939 and 2001 (the last being on December 4, 2001), although none of the eruptions have been as large as the 1939 one, and most were only detected by seismographs.

Mount Saint Catherine is a stratovolcano and the highest mountain on Grenada. It is located in St. Mark's, Victoria. It is the youngest of five volcanoes which comprise the island. The volcano has a horseshoe-shaped crater open to the east, with several lava domes within it. Mount Saint Catherine has no known eruptive history during Holocene times (Robertson, 2005).

Hurricanes

Grenada has been hit heavily by hurricanes and tropical storms 25 times in 143 years. On average it is brushed or hit by a tropical storm or hurricane once every 6 years. The most significant hurricanes to affect Grenada were Janet in 1955, Lenny in 1999 and Ivan in 2004. The major event recently was Hurricane Ivan in 2004, and the last major event was in 2007 (Tropical storm Felix).

Most information is available for Hurricane Ivan as this was the last major event hitting Grenada relatively short time ago. Hurricane Ivan struck Grenada on September 7, 2004. Classified as a Category 3 hurricane with sustained winds of 120 mph (195 km/h) and gusts of up to 133 mph (215 km/h), at Point Salines International Airport. The airport recorded 5.26 inches (134 mm) of precipitation during the hurricane's passage. The southern end of Grenada was hit by the northern portion of the eye and spent the majority of the storm exposed to the eye wall section of the hurricane. During the course of the storm, the area of St. George's experienced approximately 20 minutes of respite associated with eye passage before re-entering the eye wall. The southern portion of Grenada was exposed to severe winds in excess of 135 mph. The island was exposed to hurricane force winds for approximately 6 hours. The storm moved through Grenada fairly rapidly and did not produce a large volume of rainfall. The relative lack of rain coupled with the hurricanes arrival during daylight hours served to mitigate the potential loss of life (37 confirmed dead), and limit damages to road and drainage infrastructure. The majority of the severe damage was experienced in the southern portion of the island below a line drawn roughly from Grenville to north of St. George's. Visible damages included the partial or total loss of building structures, broken and uprooted trees, broken utility poles and damaged vehicles (World Bank, 2004)

A damage assessment jointly conducted by the Organization of Eastern Caribbean States (OECS) and the United Nations Economic Commission of Latin America and the Caribbean (ECLAC) estimated damage over US$800 million or twice Grenada's Gross Domestic Product (GDP). Specific losses were as follows:

- Housing, 89 percent of the country's housing stock was damaged, almost 30 percent of which required complete replacement, with only 15 percent of private homes insured, representing a significant problem of underinsurance;
- Public Buildings, in excess of 80 percent of building structures on the island sustained some form of damage; Education, all but two of the primary and secondary schools were affected;
- Health, 11 health facilities, including the second largest hospital, were seriously damaged; Environment, 91 percent of the forest lands and watershed were stripped of vegetation;
- Tourism, close to 70 percent of hotel infrastructure was rendered inoperable.

Other areas severely affected include the Power Sector, where nearly the entire electricity distribution system was destroyed, and the Agricultural Sector, which suffered a near complete loss of the year's crop. Nearly 85 percent of the nutmeg crop (Grenada is the second biggest nutmeg producer in the world) was affected and 60 percent was completely destroyed. The hurricane also destroyed virtually the entire banana crop and roughly 60 percent of the cocoa trees. Damages were compounded with the passage of Hurricane Emily in July 2005, a Category 1 hurricane. Losses related to Emily, while not nearly as severe, had a serious impact on the agriculture sector in particular (World Bank, 2005).

As Ivan was a relatively dry hurricane, damage from flooding and landslides was not extensive. Streams did flood and where debris piled up to block water flow, in areas such as bridges and culverts, flooding was more pronounced. Roadways were blocked by debris and fallen trees, but generally remained intact with little evidence of landslides or washouts. The storm surge associated with Ivan was apparently not a major factor and sea defences appear to have resisted the wave action forces without damage.

Watershed loss is extensive with trees down or damaged. Agricultural resources were severely affected, however water sources and agricultural lands quickly recovered. Crop damage was nearly 100% for banana and sugar cane. Nutmeg and other spice production infrastructure was seriously affected. Nutmeg plantations in St. Andrews parish were devastated but farms located predominately in the northern portion of the island (e.g. St Patrick Parish) had less losses (World Bank, 2005).

Ivan damaged a large part of the Grenada's watershed, affecting roughly 90 percent of forest vegetation. Initial fears of water supply shortages—stemming from the watershed's inability to absorb rainwater—have abated, but the poor condition of the watershed resulted in flash floods and landslides during hurricane Emily. The Government has elected to focus on conservation and natural re-growth, as opposed to planned human interventions.

Emily passed directly over Grenada. Point Salines International Airport, just to the south of the path of the centre, reported a peak gust of 58 kt and 3.28 inches of rain. The north-eastern tip of the island of Grenada, as well as the smaller islands of Carriacou and Petite Martinique to the northeast, bore the brunt of the hurricane, but no wind measurements from these areas are available. During this event at least one person has been reported killed in a landslide. Some structural damage has also been reported in Grenada, where 50,000 people remained without permanent homes 10 months after Hurricane Ivan

The Caribbean Disaster Emergency Response Agency reported that in Grenada, damage was concentrated in the northern parishes of St. Patrick's and St. Andrew's, where many homes lost their roofs, and on the outlying islands of Petite Martinique and Carriacou, where a portion of the roof of the island's only hospital was damaged, forcing the evacuation of patients to another portion of the building. There were also scattered reports of flooding, and media reports mention the destruction of crops (Franklin and Brown, 2006).

Summary

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 3-2). 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.

Unfortunately we do not have much information on the casualties or economic damage related to landslides in Grenada. Compared to the other 3 islands within the CHARIM project, we expect this to be much lower, as landslides are much less frequent on Grenada, than on Saint Vincent, Saint Lucia and Dominica. This is also due to the lower rainfall amounts and to the southern location of Grenada, where most of the tropical storms and Hurricanes takes a more northern route, and the island is less frequently affected than the others.

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 Grenada. If it would be possible to establish a relation between the magnitude of the event (e.g. hurricane category or associated rainfall amount), it 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).

Finally, Table 3-2 provides the compiled historical disaster data for Grenada, 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 Grenada until now.

Table 3-2: Historical disaster events collected from different sources (NI = No Information). C = casualties. Red records (may) have landslides reported.

Year	Day	Events	Reported incidents	C
1822	01/12/1822	Earthquake	Magnitude 8 (Richter)?? probably Mercalli scale with great damage to buildings	
1822	29/12/1822	Earthquake	Magnitude 7, Rock fall reported!	
1831	04/12/1831	Earthquake	7 Richter (?) scale. St. George church bells rang	
1834	25/11/1834	Earthquake	6 Richter (?) scale in North of the island. Cracks in buildings	
1844	19/01/1844	Earthquake	7 Richter (?) scale. St George front wall of church guardroom partly collapsed	
1846	06/09/1846	Earthquake	6 Richter (?) scale	
1856	13/08/1856	Hurricane	H1	
1877	22/09/1877	Hurricane	H1	
1878	02/09/1878	Hurricane	H2, brushed the island	
1885	13/11/1885	Earthquake	5 Richter (?) scale	
1886	02/02/1886	Earthquake	5 Richter (?) scale	
1886	16/08/1886	Hurricane	Hurricane H2 brushed the island	
1887	06/05/1887	Earthquake	5 Richter (?) scale	
1887	20/07/1887	Tropical storm	Tropical storm	
1888	09/01/1888	Earthquake	8 Richter (?) but probably Mercalli scale. In St George many stone buildings were severely damaged. Serious damage to churches	
1889	06/09/1889	Heavy rainstorms	Severe flooding along the West coast as a result of heavy rainstorms. The Gouyave and St. Mark's River overflowed their banks and cause considerable damages, sweeping through the town of Gouyave and Victoria and tearing up the roads	
1890	06/10/1990	Earthquake	5 Richter (?) scale	
1891	12/10/1891	Tropical Storm		
1892	17/02/1892	Earthquake	5 Richter (?) scale. It is indicated from 17/02/1892 to 18/03/1892, similarly as for 1893 in Dominica (same dates but different year). Probably a mistake	
1892	07/10/1892	Tropical Storm		
1894	?	Drought		
1894	28/09/1984	Tropical Storm	Damage to farms and causeway. Flooding Persistent rainfall for 24 hours led to rivers overflowing their banks in the parish of St. Andrew's. Roads, bridges and crops were damaged	
1895	15/10/1895	Tropical storm	Flooding	
1896	26/11/1896	Earthquake		
1896	15/11/1896	Heavy rain	Heavy rains resulted in damage to the river bank at Gouyave from overflowing streams.	
1896	30/11/1896	Tropical storm	Flooding. The river embankment at Gouyave was seriously damaged by flood	
1897	08/11/1897	Tropical Storm	Flooding. The fourth consecutive year in which destructive floods occurred in Grenada. On November 8th there were heavy rains in St. John's, flooding the Gouyave River and once more damaging the recently erected boulder bank and again on December 6th further damaging the boulder bank and destroying the stone bridge at the mouth of the Gouyave River	
1898	?	Earthquake		
1899	08/11/1899	Heavy rain	Heavy rain in St. John's caused the Gouyave River to overflow damaging boulder –bank.	
1901	?	Drought		
1901	05/07/1901	Heavy rain	Heavy rains resulted in damages to roads; and Dunfermline bridge	

1901	20/08/1901	Tropical storm		
1904	?	Severe drought		
1905	?	Severe drought		
1905	24/12/1905	Earthquake	5 Richter (?) scale. Possible rock fall occurrences	
1905	07/09/1905	Tropical storm	Tropical storm brushed the island	
1906	?	Earthquake	5 Richter (?) scale	
1911	24/09/1911	Rainstorm	Severe storm resulting in heavy rains damaging the roads and cultivations in Gouyave and Concord	
1915	?	Tropical storm	20-25 acres of cocoa damaged, 3 bridges and roads damaged. Reported as "most serious rain event in living memory"	
1918	24/02/1918	Earthquake	5 Richter (?) scale	
1918	01/08/1918	Tropical storm		
1918	23/08/1918	Hurricane	H1	
1921	?	Tropical storm	Heavy winds. Damage to cocoa. Houses destroyed. Electricity and roads damaged. Landslides and flooding	
1924	21/05/1924	Earthquake	Magnitude 5. Severe and prolonged earthquake.	
1928	03/08/1923	Tropical storm		
1933	12/08/1933	Tropical storm		
1933	17/08/1933	Tropical storm		
1933	17/09/1933	Tropical storm		
1938	10/08/1938	Tropical storm		
1938	??/10/1938	Heavy rain	Unprecedented violent rain-storm resulted in the loss of 5 lives, widespread damage to cultivation, roads, bridges and telephone lines over the southern portion of the island. The main bridge over the St. John' river which led to the town of St. George's was completed destroyed.	5
1939	23/24/07/1939	Volcanic eruption and tsunami	An eruption of Kick 'em Jenny broke the sea surface, sending a cloud of steam and debris 275 m (902 ft) into the air and generating a series of tsunamis around two metres high when they reached the coastlines of northern Grenada	
1944	24/07/1944	Tropical storm	Brushed the island	
1946	04/10/1946	Rainstorms	Severe rainstorms in Grenada: 15 persons were killed in Victoria and 13 houses washed away	15
1954	07/10/1954	Hurricane **Hazel**	Several trees uprooted, houses blown down. Electricity and road damaged.	
1954	04/12/1954	Earthquake	6 Richter (?) scale	
1955	22/09/1955	Hurricane **Janet**	Hurricane **Janet**. 15 inches of rain in 9 hours. Very heavy wind and rain for 9 hours. 95% of nutmeg trees and coconut trees were uprooted. 120 persons killed. 6,000 dwellings totally destroyed. 20 out of 50 schools seriously damaged. Agricultural losses were immense, This was the most serious hurricane in a long time in Grenada. Landslides and flooding	120
1961	`20/07/1961	Tropical storm **Anna**		
1963	24/09/1963	Hurricane **Edith**	Hurricane Edith. Minor repercussions. Most damage in St. Lucia.	
1963	01/10/1963	Hurricane **Flora**	Hurricane **Flora**, airport, bridges and roads damaged. Estimated damage 20,000 Pound. Over a period of 4 months there was a reduction in the average monthly output of 25% (13,000 stems instead of 20,000 stems)	6
1970		Drought	Lack of rainfall for 5 months	
1971		Drought	Lack of rainfall for 5 months	
1972		Drought	Lack of rainfall for 6 months	
1973		Drought	Lack of rainfall for 8 months	
1974		Drought	Lack of rainfall for 5 months	
1975		Drought	Lack of rainfall for 5 months	
1975	30/09/1975	Tropical storm	Tropical Storm, causing 6 casualties	6
1975	??/11/1975	Heavy rain	Flooding caused US$4.7 million in losses	
1978	11/08/1978	Tropical storm **Cora**		
1979			Hurricane **David**	
1980	04/08/1980	Storm	Hurricane **Allen**. 5.3 million US $ losses	
1985	11/09/1985	Tropical depression	Unknown effects	
1986	08/09/1986	Tropical storm **Danielle**	Brushed the island	
1988	10/10/1988	Tropical storm **Joan**	Unknown effects	
1990	25/07/1990	Tropical Storm **Arthur**	1000 people affected,	
1991	?	Rock fall	in 1991 in the village of Cotton Bailey parish of St. John when a large boulder fell on a passenger bus, resulting in the loss of nine lives	9
1994	?	Drought	Lack of sufficient rainfall for 6-7 months. Tourism belt affected by lack of pipe borne water.	
1995		Tropical storm **Marilyn**		
1999	15/11/1999	Hurricane **Lenny**	210 people affected, 5.5 million US$ damage, 27% of GDP	
2000	?	Tropical storm Joyce		
2002	??/09/2002	Tropical storm Lili		
2003	12/12/2003	Heavy rain	The St. John's River overflowed its banks causing damage to damage to private houses, vehicles, schools, commercial buildings, and the newly built National Stadium. Estimated cost of damage was EC$1.2M	
2004	14/08/2004	Tropical Storm Earl	Tropical Storm Earl damaged at least 34 roofs and knocked down twelve trees and six electrical poles.	

2004	07/09/2004	Hurricane **Ivan**	Hurricane **Ivan**. 39 Casualties, 81,553 people affected out of the total population of 102,632 and losses over 889 million US $. 27,735 out of the total of 31,122 houses were damaged. The major disaster that has hit Grenada in the last century.	39
2005	04/07/2005	Tropical despression	Unknown effects	
2005	13/07/2005	Hurricane **Emily**	Hurricane **Emily**. 1 casualty in St. Patrick North. 1,660 persons in shelters in Grenada and Carriacou. 16 houses were destroyed and well over 200 more were damaged, and two of the main hospitals were flooded.[3] The estimated damage from Emily in Grenada was USD $110 million.	1
2007	31/08/2007	Tropical storm **Felix**	Hurricane Felis. Unknown effects	
2009	29/07/2009	Landslide	obstruction to the flow of traffic in Parade, St Paul's close to Andall's Supermarket due to a landslide	
2009-2010			Severe drought. In 2009 a 24 year lowest annual rain fall total recorded. 17% decline in banana production.	
2011	12/04/2011	Flooding and landslide	Numerous reports of flooded houses, landslides, road blockages, sunken boats and destroyed houses. In Gouyave, one house was destroyed by the violent river, which overflowed its bank. Road access from Waltham St. Mark to Victoria has been blocked. Also, the Balthazar bridge has been flooded as well. In Clozier, St. John, access to Gouyave has been cut off due to a land slide. 11 boats have sunk sink in Victoria, St. Mark. Five major landslips in Gouyave, with about three houses lost along the river and other properties flooded. However, there are no reports of loss of lives. Rains have affected other parts of the island, including South West and North West St. Andrew, resulting in rising water levels in some rivers and landslides in the Grand Etang area. Estimated cost of damage ECD 11.2M	
2011	29/11/2011	Landslide and Flooding	Flooding occurred in several places. The town of Grenville was worst hit. There have also been reports of several landslides within the vicinity. In view of the flooding, all schools within the Parish were closed.	
2012	20/04/2012	Landslide	A landslide that took place in the parish of St. Mark. The Balthazar Bridge which was flooded making it un-motor able.	
2012	??/01/2012	Earthquake	3.5 Magnitude on Richter scale	
2012	??/02/2012	Earthquake	4 Magnitude on Richter scale	
2013		Earthquake	4.8 Magnitude on Richter scale	
2014		Earthquake	4 Magnitude on Richter scale	
2014	21/09/2014	Landslide	A landslide has deposited large rocks at the exit of the Sendall tunnel Sunday night, making it impassable to vehicular traffic. There were also reports of flooding in the south of the island	
2014	23/10/2014	Flood	Sendall tunnel closed due to flooding. Several flooding has also been reported in areas such as Balthazar Bridge and parts of the town of Grenville, affecting Ben Jones and George Patterson streets	
2015	05/11/2015	Landslide	Heavy rain caused landslide in Hope, St. Andrews, where a retaining wall collapsed on a car, killing one person	1

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 evaluation landslide frequency/magnitude relations. Especially so if also 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.

1.4. Rainfall frequency 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.

There are 58 rainfall stations in Grenada, but only few rainfall stations that have been operational for a long period of time. However, many stations have records with many discontinuities. On Grenada several stations are established since 2003 which record 30 minute or 1 hour rainfall. Unfortunately most of them have very scattered records, between 1 and 5 years of measurement. The longest records are from Maurice Bishop International Airport (MBIA) having daily rainfall form 1986-2014. The rainfall station of Maurice Bishop International Airport (MBIA) was called Point Salines International Airport (PSIA) before. This rainfall data is used to analyse the frequency of daily rainfall.

The daily rainfall records for Maurice Bishop International Airport started in 1986 and data is available till 2014. During this period, the average annual rainfall was 1.109,6 mm. The highest annual rainfall occurred in 2010 with 1.513,3 mm and the lowest annual rainfall occurred in 1992 with only 338, 6 mm.

Table 3.2-3 Maximum Daily Rainfall and Annual Rainfall (mm) during 1986-2014

Year	Maximum daily rainfall (mm)	Annual Rainfall (mm)	Year	Maximum daily rainfall (mm)	Annual Rainfall (mm)
1986	57	1130.6	**2001**	71.6	1060.4
1987	86.2	1094.5	**2002**	71.6	1208.2
1988	80.9	1402.4	**2003**	112.2	1312.2
1989	65.4	917.1	**2004**	256	1220.8
1990	177.5	693.9	**2005**	79.6	1090.7
1991	103.5	1328.4	**2006**	71.7	1021.5
1992	52.9	338.6	**2007**	86.6	1299.2
1993	63.8	744.9	**2008**	72.5	1341.4
1994	93	790.6	**2009**	53.2	1228.8
1995	72.1	1358.9	**2010**	80.7	1513.3
1996	60.1	1154.3	**2011**	172.9	927.1
1997	48.3	1050.5	**2012**	62	1063.3
1998	81.9	1249.2	**2013**	74.3	1079.4
1999	39.6	1016.9	**2014**	55	1231.7
2000	66.2	1310.2			

Source: Primary Data from Maurice Bishop International Airport (MBIA), Grenada

Rainfall characteristics in Grenada are:

- Rain is distributed into a rainy season from June to December – which receives about 77 percent of the annual rainfall – and a dry season from January to May.
- Grenada experiences wide variations in annual precipitation at different locations, with, for example, the Grand Etang Forest receiving an average annual rainfall of about 3,880 mm.
- Rainfall intensities are often greater than 50 mm/hr, and intensities up to 132 mm/hr have been reported.
- Average annual rainfall recorded at the Point Salines International Airport (PSIA) for the period 1986-2003 was 1,125.6 mm.

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.

The highest recorded daily rainfall prior to hurricane Ivan is 177.5 mm in 1989 which has a return period of 1:30 years. Figure 3-2 shows a frequency magnitude analysis based on a Gumbel distribution. The rainfall for 5, 10, 20 and 50 years return period is given in figure 3-3.

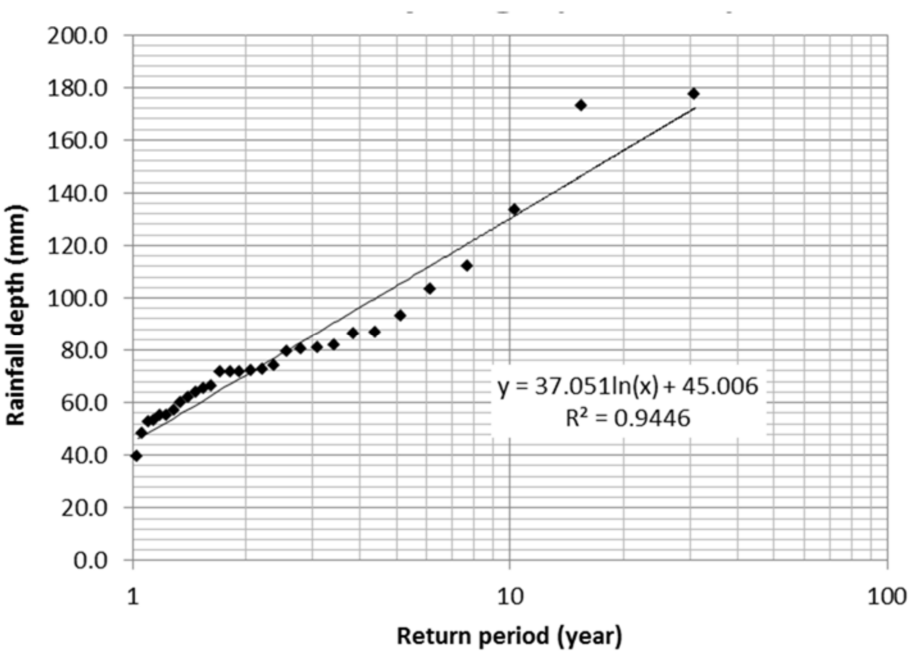


Figure 3-2. Frequency magnitude of annual maximum daily rainfall at Maurice Bishop international airport (1986-2014).

During Hurricane Ivan the rainfall measured at the Point Salines International Airport (PSIA) now called Maurice Bishop International Airport (MBIA) indicated a total amount of 256.0 mm between the hours of 11:00 AM and 5:00 PM. This translates to an average rainfall rate of 42.7 mm/hour during that six-hour period.
The comparison of rainfall received during the hurricane, with seasonal rates, indicates that relatively little rainfall fell during this event. This was very beneficial, as had there been heavy rains, combined with the deforestation that occurred, significant landslides and further loss of life would almost certainly have occurred.

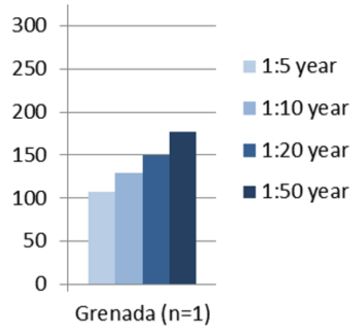


Figure 3-3. Maximum daily rainfall (mm) at Maurice Bishop international airport for return periods of 5, 10, 20 and 50 years.

As we have seen in other countries (e.g. Dominica) there is a clear relation between elevation and exposure and rainfall amount, as rainfall amounts increase with increasing elevation, and also tend to be higher on the windward side than on the leeward side. Therefore the return periods that have been determined for the rainfall stations at Maurice Bishop International Airport, may not be representative for those in other elevations and other exposures on the island. Unfortunately there is not enough data to generate magnitude-frequency relations for different parts of the island. In future, this should get more attention, as this has important implications for flood and landslide hazard assessment. Different watersheds in the area might have different magnitude-frequency relations. Also the spatial pattern of rainfall amount during extreme events is important to know as the correlation of causal factors with landslides triggered during these events, could lead to entirely different conclusions when rainfall distribution can be taken into account. For example during Hurricane Ivan the eye of the hurricane passed over the south Western part of the island, and the north western part was relatively less affected, whereas in hurricane Emily the northern part of the island received much more rainfall as compared to the southern part.

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).

Unfortunately we do not have sufficient landslide dates (See table 3-2) that fall within the period for which rainfall data is available (1986-2014) to be able to evaluate possible rainfall thresholds for landslides in Grenada. Also a correlation between landslide numbers and landslide densities and triggering rainfall characteristics (amount of daily rainfall, and related return period) is not possible, as we basically have only one event that might be represented as a landslide inventory. Even for this event it is not clear whether it captures landslides during Hurricane Ivan (2004) or Hurricane Emily (2005) and therefore the relation with rainfall and return period is also a bit problematic. If we assume a rainfall amount of 256 mm for this event, the landslide triggering event would represent a return period of more than 100 years.

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 events. In a tropical environment such as Grenada 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 Grenada as well. No agency feels responsible to collect landslide locations and dates, and keep a database up-to-date. The National Disaster Management Agency (NaDMA) 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 Communications, Works, Physical Development, Public Utilities, ICT & Community Development 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. That is why all landslide inventories have been generated by consultants, organizations and individuals from outside the islands.

For Grenada we have found only one landslide inventory map generated in 2006 by CDB/CDERA (2006). The Caribbean Development Bank (CDB) with the Disaster Mitigation Facility for the Caribbean (DMFC), and the Caribbean Disaster Emergency Response Management Agency (CDERA) through the Caribbean Hazard Mitigation Capacity Building Program (CHAMP), have collaborated on a multi-phased project to support the development of national hazard mitigation plans in Grenada in 2006. No image interpretation was carried out for this study. Field reconnaissance along the roads was carried out for five days in early September 2005. This was within one year after the occurrence of Hurricane Ivan in 2004, and two months after the passing of Hurricane Emily, which passed Grenada on 14 July 2005. According to the report the surveyors collected two hundred and forty five (245) GPS points along the road network of Grenada. However, in the GIS point file we only had 142 points that were actually landslides. The landslide types were indicated with codes, which were not always very clear. We checked the points using visual image interpretation of satellite images and Google Earth. For a number of them it was quite difficult to associate them with landslides. The inventory is shown in Figure 4-1. The field reconnaissance spanned over five days in early September 2005 and was conducted by an engineering geologist, environmental planner and geographer, in addition to local government representatives with good knowledge of the island who helped locate recent and historical landslide events. Once landslides were located, the field reconnaissance team took a Geographical Positioning System (GPS) reading and then evaluated the physiographic, geologic and human influences that may have played a role in causing the landslide.

In 2014 the British Geological Survey carried out a landslide inventory mapping based on image interpretation of very high resolution satellite images from 2010 to 2014. Because they did not evaluate images from the years directly after hurricane Emily, they were not able to not map any landslides, except one landslide, located close to Grand Etang Lake.

No one seems to have mapped landslides caused by Hurricane Ivan and Emily based on image interpretation. We have tried to collect satellite images pre- and post-Ivan/Emily from the government agencies, but these only cover a part of the island. We also obtained some landslide locations from the engineers of the ministry of works.

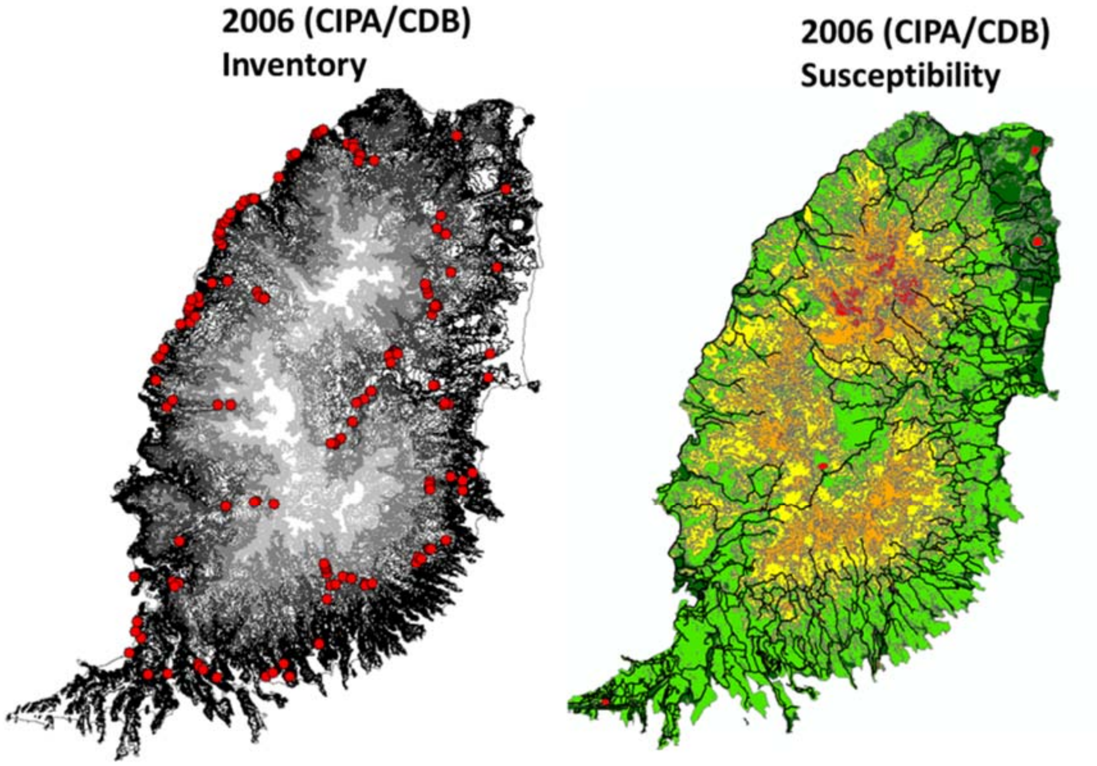


Figure 4-1: Landslide inventory maps for Grenada Left: the map generated by CDB/CDERA in 2006. Right: landslide susceptibility map made by CDB/CDERA in 2006.

4.2. New landslide inventory mapping

The available landslide inventory presented in the previous section is quite limited. Landslides are shown as points, and all are concentrated along the road network. Therefore we decided to generate a landslide inventory for the entire island.

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 hillshading 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 Grenada is illustrated in Figure 4-2. 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 Grenada (See Table 4-1). We received the images that were obtained in the 2013. The most important images however, were found in the data that was obtained from the organizations in Grenada. The comparison of the Ikonos image from 2004 with the Digital Globe image from 2005 allowed to map the landslides associated with hurricane Emily.

Table 4-1: Available satellite images for Grenada

Satellite	Date	Type	Columns, Rows
Ikonos	2004	1 meter, Only of the West coast and Grenville area	8269, 5797
Digital Globe	25/07/2005 17/08/2005 26/12/2005 05/12/2005	Post Hurricane Emily, in different parts covering most of the island, but with a lot of clouds 3 bands , 1 m resolution	23628, 35495 19440, 35495
Digital Globe	2010	1 meter, only of SE part	16384, 15700
Pleiades	2013 08 06 About 5 % clouds	0.5 meter panchromatic 2 meter multispectral. Entire island except SE corner	45354, 65909
Pleiades	2013 11 17	0.5 meter panchromatic 2 meter multispectral. SE corner of the island	49947, 48707
Google Earth data	From different years: 03/11/2003 02/03/2004 30/10/2014		

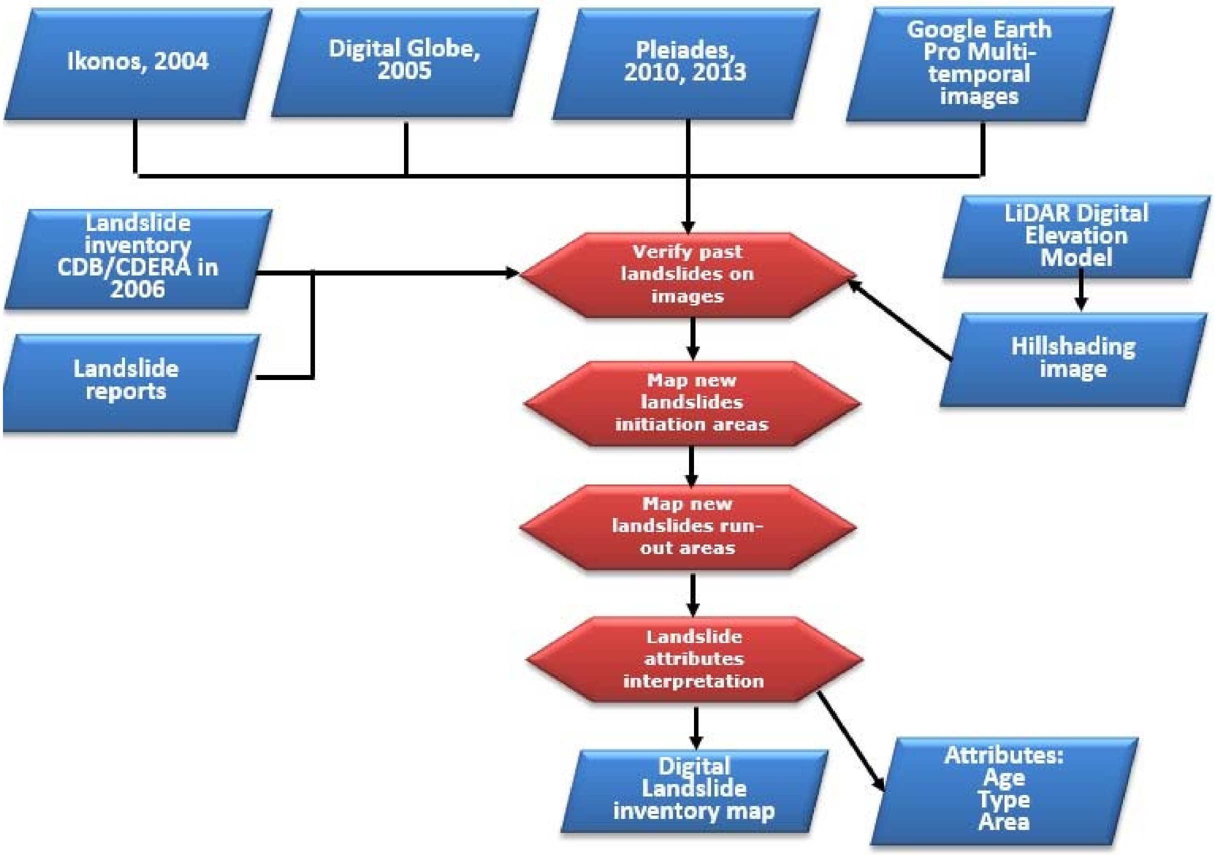


Figure 4-2: Method used for the generation of a landslide inventory map for Grenada

The most useful images were the Digital Globe images from 2005. These images were taken after hurricane Emily, which produced much more landslides and debris flows than Hurricane Ivan in the year before that.

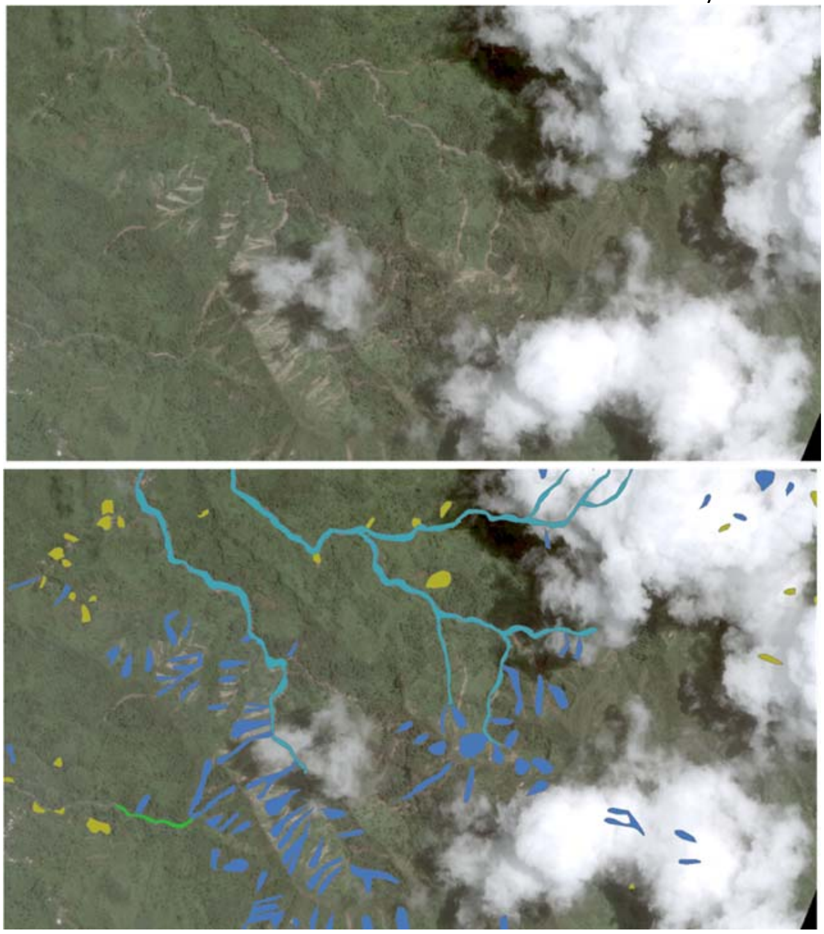


Figure 4-3: Example of high resolution satellite image taken in August 2005, one month after Hurricane Emily. The area shows many shallow landslides which join together into debris flow and flash flood channels, which connect to Victoria.

Also the shaded relief map that we produced from the detailed Digital Elevation Model (with pixel size of 5 meters) derived from LiDAR data, turned out to be very useful for mapping older landslide features, that were covered by vegetation but where the bare surface model still showed clear signs of landslide activity. Unfortunately, as will be discussed later, the quality of the DEM was not equally everywhere good due to missing data.

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, many of them could still be detected, even though many were revegetated.

We interpreted the landslides as polygons, separating between scarp and body, assigning a unique identifier to each landslide and we described 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 1 week 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 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. However, the landslides caused by Hurricane Emily couldn't be identified in the field anymore, as the vegetation regrowth was very high. Also because during Hurricane Ivan in 2004 a lot of vegetation was removed, and therefore regrowth patterns of the 2004 Hurricane Ivan related wind damage and the 2005 Hurricane Emily related landslide damage could not be differentiated.

The resulting landslide inventory map is shown in figure 4-5, and 4-6. Table 4-2 gives a summary of this landslide inventory that includes the previously mapped landslides.

	Pre-Ivan	Post-Emily (points)	Post-Emily (polygons)	Recent landslides
Number of landslides	163	142	510	3
Landslide area (hectares)	90.93	60.56	263.11	4.14
Study area (km^2)	312.55	312.55	312.55	312.55
Density of landslides	0.0029	0.0019	0.0084	0.0001
Percent of landslide area	0.29	0.19	0.84	0.01
Nr of landslides/km^2	0.522	0.454	1.632	0.010
Landslide types				
Creep	0	7	0	0
Subsidence	0	2	0	0
Rockslide	1	1	0	1
Rock fall	0	13	1	0
Coastal cliff	28	0	0	0
Rotational Slide	5	60	15	0
Debris slide	77	36	250	2
Debris avalanche	52	20	235	0
Debris flow	0	3	9	0
Total number of landslides	**163**	**142**	**510**	**3**

Table 4-2: Summary of landslide inventories, with number, area, area density and number density. Pre-Ivan: landslide mapped through image interpretation that are clearly older than 2004. Post-Emily points: landslide mapped originally as point along the road network by CDB/CDERA (2006) which were later converted into polygons based on image interpretation; Post-Emily (polygons): all landslides mapped from post-Emily satellite images; Recent landslides: landslides that occurred after 2005.

4.3. Some examples of landslide characteristics in Grenada

This section gives some illustrations of landslide examples in Grenada.

Landslide along coastal road to Gouyave

One of the most problematic landslide areas in Grenada is located along the road from St. George to Gouyave, at the location called Nesbit Hill-Maboya. The entire hillslope is part of a large deep-seated landslide which is slowly moving towards the coast. The rocks in this area consist of alternating shales and sandstone. The shale layers form the sliding surface of the landslide. The landslide started before the onset of Hurricane Ivan. It is not clear how long ago the actual landslide movement started. However, at a certain point the problems were becoming so severe for the road that the road was closed, and a deviation route was designed that goes around Nesbitt hill to reach Gouyave. In recent years the rate of subsidence of the road seems to have decreased again, and the old road is being used occasionally. Mitigation strategies for this slide have not been implemented. It is estimated that the cost of repairs to this location is approximately EC$1.2 million. No indirect costs have been assigned to this project, as the length of the diversion roadway is sufficiently short that it does not present a significant difference from the main route.

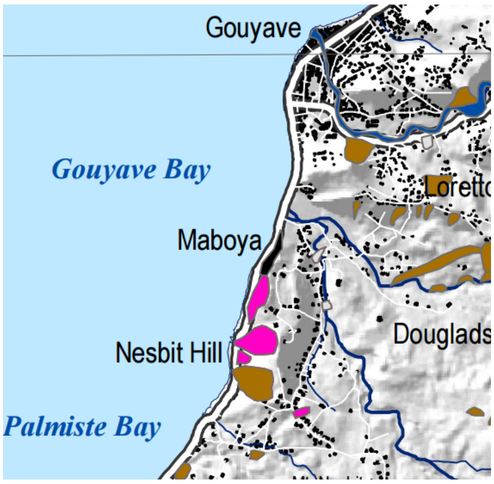


Figure 4-4: Section of the landslide inventory map showing the problem area for landslides around Maboya

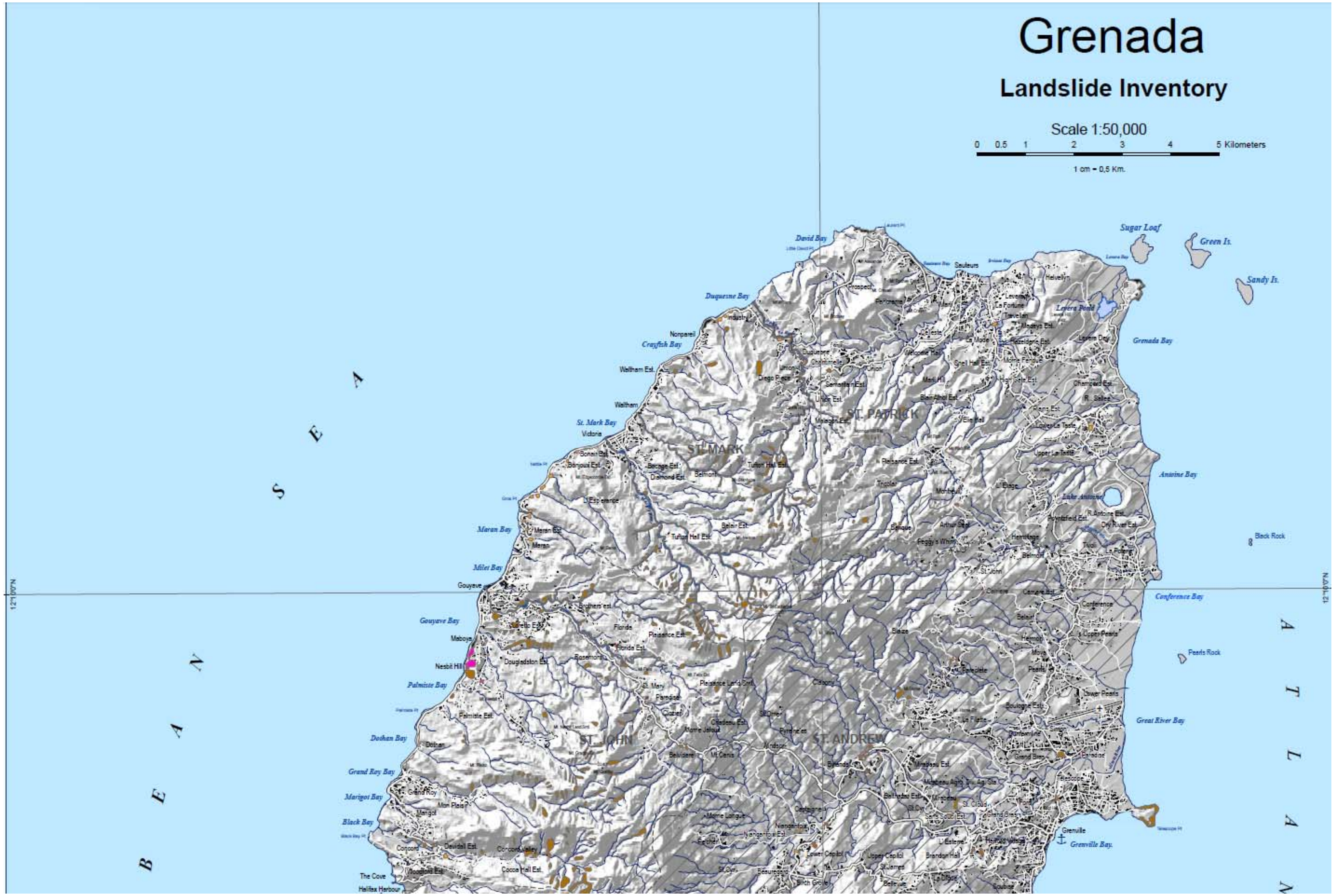
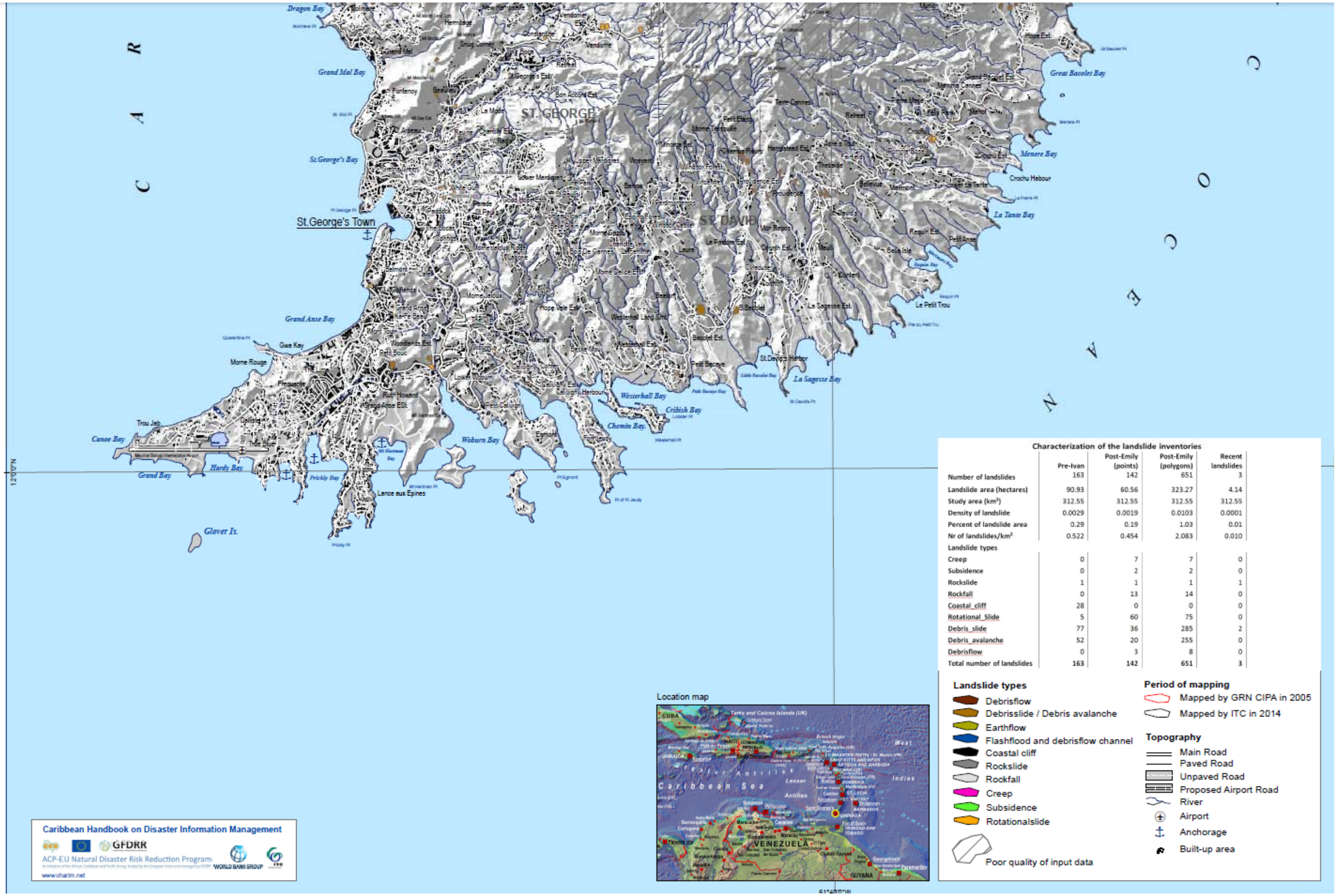


Figure 4-5: Northern part of the final landslide inventory map for Grenada. The full map can be downloaded as pdf from the following website: http://www.charim.net/grenada/maps



Characterization of the landslide inventories

	Pre-Ivan	Post-Emily (points)	Post-Emily (polygons)	Recent landslides
Number of landslides	163	142	651	3
Landslide area (hectares)	90.93	60.56	323.27	4.14
Study area (km²)	312.55	312.55	312.55	312.55
Density of landslide	0.0029	0.0019	0.0103	0.0001
Percent of landslide area	0.29	0.19	1.03	0.01
Nr of landslides/km²	0.522	0.454	2.083	0.010
Landslide types				
Creep	0	7	7	0
Subsidence	0	2	2	0
Rockslide	1	1	1	1
Rockfall	0	13	14	0
Coastal_cliff	28	0	0	0
Rotational_Slide	5	60	75	0
Debris_slide	77	36	285	2
Debris_avalanche	52	20	255	0
Debrisflow	0	3	8	0
Total number of landslides	163	142	651	3

Figure 4-6: Southern part of the final landslide inventory map for Grenada. The full map can be downloaded as pdf from the following website: http://www.charim.net/grenada/maps

Rock fall event

The most damaging event occurred in 1991 in the village of Cotton Bailey, parish of St. John when a large boulder fell on a passenger bus, resulting in the loss of nine lives. The Caribbean Development Bank funded a slope stabilization project for Cotton Bailey and also for Melville Street in St George's where rock anchors were installed and ring nets to avoid future rock fall events.

Figure 4-7: Rock fall problems around the coastal road from St. George's to the North. Left: Rock fall in Maran St. John's in April 2011; Right: location of rock fall tragedy claiming 9 lives of persons in a bus that was hit by a rock in the village of Cotton Bailey in 1991.

Landslides during Hurricane Ivan

As was mentioned before, the amount of rainfall during Hurricane Ivan in 2004 was not extremely large, and the damage was predominantly by wind. Nevertheless some landslides were observed at St. Paul's, where clean-up efforts took approximately three days (Figure 4-8). Other sites of slippage included River Road and Brizan. In addition, the effects of the storm worsened the effects of a major landslide that had occurred previously on the Western Main Road on the approach to Gouyave (Figure 4-4).
Erosion of road edges was noted particularly at Grand Etang and Westerhaul (Figure 4-8). This type of road failure is characterised by removal of a section of the road, through the action of a slope failure. Remedial works included a retaining wall. Estimated costs to repair these two locations were EC$ 500,000.

Figure 4-8: Landslides affecting the road network caused by Hurricane Ivan in 2004. Left: Landslide at St. Paul's; Right: Landslide at Grand Etang and Westerhaul.

Hurricane Ivan stripped large parts of the island of its forests. The less protected slopes were more susceptible to landslides in the following years. One year after Ivan, hurricane Emily hit the northern part of the island and many landslides were triggered along the slope of Mount Saint Catherine, which amalgamated into debris flow channels, which turned into flash floods when approaching the coast, flooding Gouyave and Victoria (See Figure 4-3). Also smaller rainfall events, like the ones from April and November 2011 caused significant landslide problems along the road network. See Figure 4-9.

Figure 4-9: Small landslides affected the road network that occurred in Morne Delice in January 2011.

Figure 4-10: Clean-up works for the landslide/rockfall that blocked the entrance to the Sendall tunnel in September 2014

A recent landslide event occurred on 21 September 2014. A steady downpour of rain due to a tropical wave which passed over Grenada on 21 September 2014 left a trail of damage to public and private properties. Water flooded roads, buildings and open spaces and created landslides in some vulnerable areas. The most significant landslide was just underneath the Presbyterian Church onto the area next to Sendall Tunnel. Large boulders and earth tumbled down on Sunday evening, blocking the Bruce Street exit of the tunnel near the hospital steps. The Royal Grenada Police Force (RGPF) reported no fatality nor injuries as a result of the landslide. The area was already assigned to benefit from an EC$2 million rock stabilisation project, and it was just a matter of time for the World Bank to release the funding to commence the work. The church's foundation may be affected significantly. The church itself was destroyed by Hurricane Ivan in 2004. One of the challenges since the post-Ivan inspection, was the need to build a massive retaining wall to protect the land from sliding. Another, more recent problem involving the failure of a retaining wall, occurred in November 2015, when a landslide toppled a wall which crashed a car underneath and killed one person in Hope, St. Andrews parish (See Figure 4-11).

Figure 4-11: Landslide pushing a retaining wall over which killed one person in a vehicle at Hope, St Andrew, November 5, 2015

Landslides and waste disposal site problems

The overall management of solid waste is controlled by the Grenada Solid Waste Management Authority (GSWMA), a fully autonomous statutory body within the local Government structure. GSWMA has retained control of all disposal services with all of the collected waste being received either at the existing Perseverance site in Grenada or the new Dumfries site in Carriacou. As shown in figure 4-12, this landfill site is already operational for 50 years and attempts have been made to extend the site in the nearby areas. The image from 1970 is not very clear but the large bare and sparsely vegetated area to the East appears to be a large landslide rather than a landfill, given that it extends high up on the slope and a faint scarp is visible. Nevertheless due to the fact that the full capacity of the landfill site was reached and extension was made in the upslope areas visible on the images of 2003 and 2011. A landslide caused by heavy rains in late 2001 interfered with the operation of the new Perseverance landfill site. In the interim, the old landfill has been put back into service. Repairs to the damaged cell have been delayed by the need to assess the causes of the landslide and mitigation measures required to prevent a recurrence. The older Perseverance landfill is, at best, a controlled landfill as opposed to a modern sanitary landfill. Its continued use for more than two years after the damage to the new site suggests that the problems with the new site are of major proportions. Also later another landslide seems to have taken place.

Figure 4-12: Four images from Google Earth showing the development of the Perseverance landfill site in Grenada. Upper left: in 1970 the eastern area seems to be a large landslide, although the image is not very clear. Upper Right: in 2003 another attempt is made to open a new part of the landfill higher on the slope, after a landslide occurred in 2001. Lower Left: in 2011 the upper landfill site is operating again. Lower right: another landslide in the upper area lead to the abandonment of this part of the landfill and return to the old site, which is now at full capacity.

Flash Flooding is generally a bigger problem in Grenada than landslides. There are a number of problematic areas, and the most severe problems are in Gouyave, Victoria, St. John's and Grenville.

With Chinese funding the St. Mark's Flood Mitigation Project was carried out, with the objective to enhance the protection of Victoria town from flooding, situated at the mouth of a river. The project involved watercourse dredging, slope protection and reconstruction, flood mitigation structure and construction and waterfront and road sub grade repairs. Steps to better access the river were laid and clearly marked swimming basins/areas were put in place to further cater to the needs of the community. It was completed in July 2014.

Recently the World Bank has initiated the Regional Disaster Risk Reduction Project. This multi-sectoral project is jointly funded by the World Bank and the Climate Investment Fund to the tune of $70.7 million. The aim of the Project is to reduce vulnerability and risk through a number of initiatives, including institutional strengthening and improved public building infrastructure.

The major components of the project include:

- Rehabilitation and construction of the Lance and Hubble Bridges
- Rehabilitation of two schools
- Flood mitigation
- Landslide and Rock fall Mitigation, e.g. near Sendall tunnel.

Figure 4-13: Flood problems in Grenada. Upper left: Frequent flooding of urban area of Grenville; Lower left: tragic accident of cars taken by the flood of St. John 's River in 2011; Right: flood situation in 2011 in Gouyave, where a part of a house was destroyed. The situation as it is now is show right below.

5. Landslide conditioning factors

In this chapter an evaluation is made of the available factor maps for landslide susceptibility assessment in Grenada. 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 Grenada were in different projections. 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/people/profile/grenada/?content=layers).

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 several of the islands, as many of the available factor maps do not spatially match, due to differences in coordinate systems, and the fact that the conversion factors for some of the coordinate systems are not well defined. Therefore it was difficult to overlay the data with the satellite images that we obtained, but also several of the factor maps from the same country provided by different organizations had severe problems in spatial matching.
- 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. For instance lithological maps are generally very general, and lack the detail that would be required to match the landslides with specific volcanic deposits. The same is true for the available soil maps, which are generally almost useless as a factor map for the slope stability assessment. Also Digital Elevation Models are quite different in quality.
- Finally also the temporal accuracy is a point, specifically for the land cover maps, which are generally rather old, and should be updated. Fortunately we can make use of the updated and more detailed land cover maps that are provided by the British Geological Survey.
- Differences in scale. Another aspect related to spatial accuracy 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.

Table 5-1: Overview of input maps for landslide susceptibility assessment in Grenada, with indication of the quality of the data in green (good), yellow (less good), and orange (not available).

Group	Factor	Availability and quality of the data in Grenada.
Topographic factors	Digital Elevation Model	Good, except for North-eastern sector, which has less quality DEM
	Altitude zones	
	Slope steepness	
	Slope aspect	
	Upslope contributing areas	
Drainage factors	Eroding sections of mains rivers	Good
	Distance from stream initiation	Good
Geological factor	Lithological map	Too general to be of much use for landslide work
	Fault map	Not available, but generated during the project
	Geomorphological map	Not available, but generated during the project
Soil map	Soil type map	Detailed map. Extensive legend. No clear relation with topography and lithology. Improved by combining with slope.
	Soil depth map	Very general, as attribute of soil map
Land cover factor	Land cover existing	Generally good, but has problems in some parts (due to clouds)
	Land cover (earlier)	Two maps, not clear what date. Very general, poor quality
	Road cuts	Moderate

Digital Elevation data

Since topographic information and its various derivatives play an important role in landslide susceptibility analysis, the use of high-resolution digital elevation models (DEMs) is crucial (Corominas et al., 2013). For Grenada a LIDAR derived DEM was available. We do not have metadata for this dataset, so we don't know which consultant made the survey, with which instrument and with which point density. The point map had 11 million points for the island of Grenada, however, no data was available for the centre of the island. The points were already filtered out for the terrain elevation, so all vegetation and building points were removed. The point density was not so high (See Figure 5-1). Nevertheless the quality of the resulting DEM was quite good, and displaying the image as a hill shading map in 3-D was very helpful in outlining the landslides. The DEM had one large problem though: the centre and NE of the island was not covered by LiDAR data. We had another raster dataset (also for this we had no metadata) that we used to fill up the hole in the LiDAR data. However, at the boundaries of the missing LiDAR data there are a number of artefacts (errors in the DEM) that gave problems especially in the flood modelling (See Figure 5-2).

Nr points	Percentage
0	51.243
1	17.111
2	13.177
3	8.095
4	5.296
5	2.573
6	1.410
7	0.530
8	0.333
9	0.099
10	0.070
11	0.022
12	0.016
13	0.016
14	0.004
15	0.001
16	0.003
18	0.001

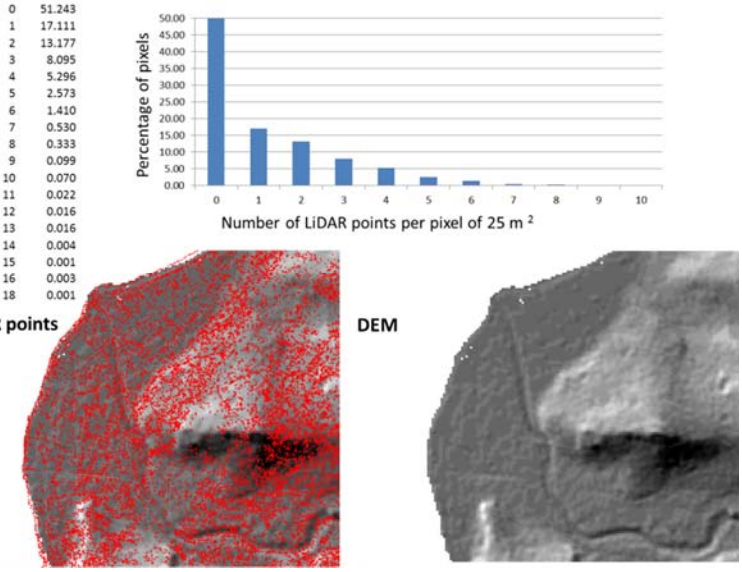


Figure 5-1: The Digital Elevation Model for Grenada was generated from LiDAR points. The table and graph show the number of points per pixel of 25 m^2 (5 by 5 meter pixel). The map on the lower left shows the LiDAR points for a sample area around Gouyave, and the image on the lower right the resulting DEM.

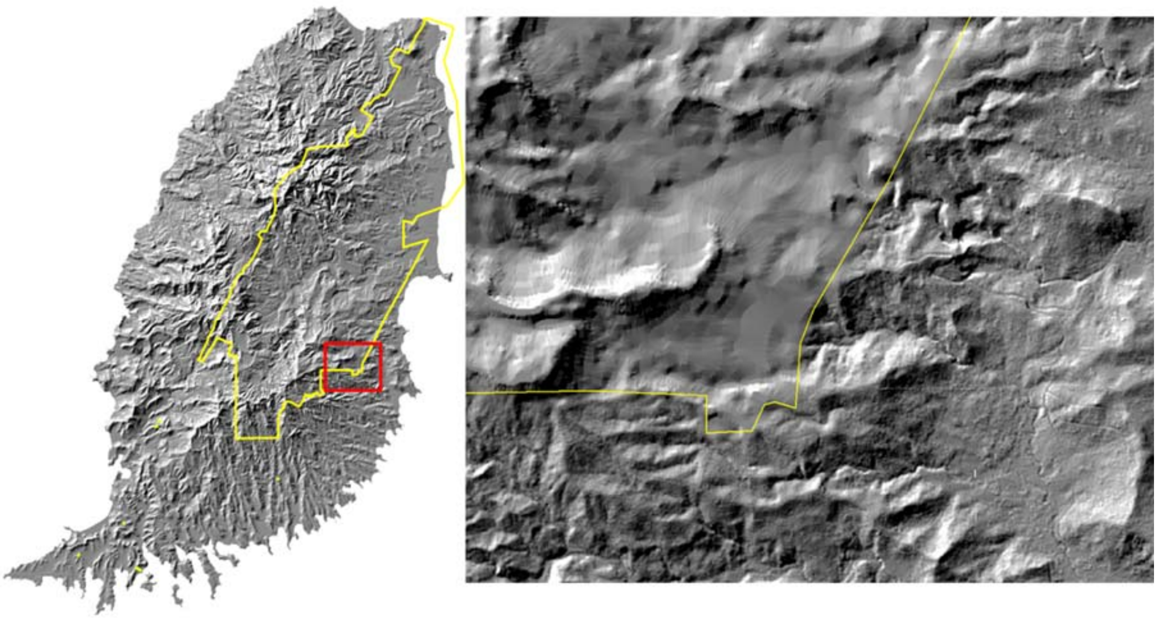


Figure 5-2: The area in the centre of Grenada didn't have LiDAR coverage so we had to fill it with another DEM of lesser quality, as can be seen from the detailed hill shading map on the right. The area in the upper left corner is the lower quality DEM.

The areas within the yellow line in Figure 5-2 have a poor data quality. So the landslide susceptibility of this particular zone is less reliable. Users should take this into account when using the map. The outline of the area with lower quality has been included in the final landslide susceptibility map.
The DEM was used as the basis for a number of derivative maps for the landslide susceptibility analysis:

- 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.

Geology
A detailed geological investigation in Grenada was carried out by Arculus (1973, 1976). Practically all rocks in Grenada are of volcanic origin. A series of volcanic centres ranging from Pliocene to Recent in age are present overlying a folded Lower to Middle Tertiary volcano-sedimentary formation (Tufton Hall Formation which is found in the NW and N of the island). Eruptions of basalt and picrate magma have occurred repeatedly during the evolution of these centres. There have been no erupted volcanics in historical time reported on the island of Grenada. Arculus quotes earlier work that dismisses the eruptions of sulphurous vapours within the harbour of St. George's, in 1867 and 1902, as being overdramatised phenomena associated with tidal waves generated by eruptions elsewhere in the Lesser Antilles. The only indications of volcanic activity are the presence of numerous hot springs, especially in the vicinity of Mount Saint Catherine (Arculus, 1973). The closest active volcano is the submarine volcano Kick-em-Jenny, located north of Grenada.
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 Grenada. The geology map was developed in 1981 as part of a reconnaissance study of the geothermal resources conducted by Geothermica Italiana. The geology base maps (1:25,000) were digitized by the Ministry of Agriculture in 1994.The geologic map for Grenada contains only 19 units, subdivided according to its location and to its age. Despite this, 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). The legend also contains units that have nothing to do with geology, but are to land cover, like lake, mangrove, town, airport. We were not able to remove them as we have no information on the underlying geology.
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; they may sustain vertical road-cuts, however, after weathering processes take place such road-cuts may cause problems (See Figure 5-4). 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). 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.

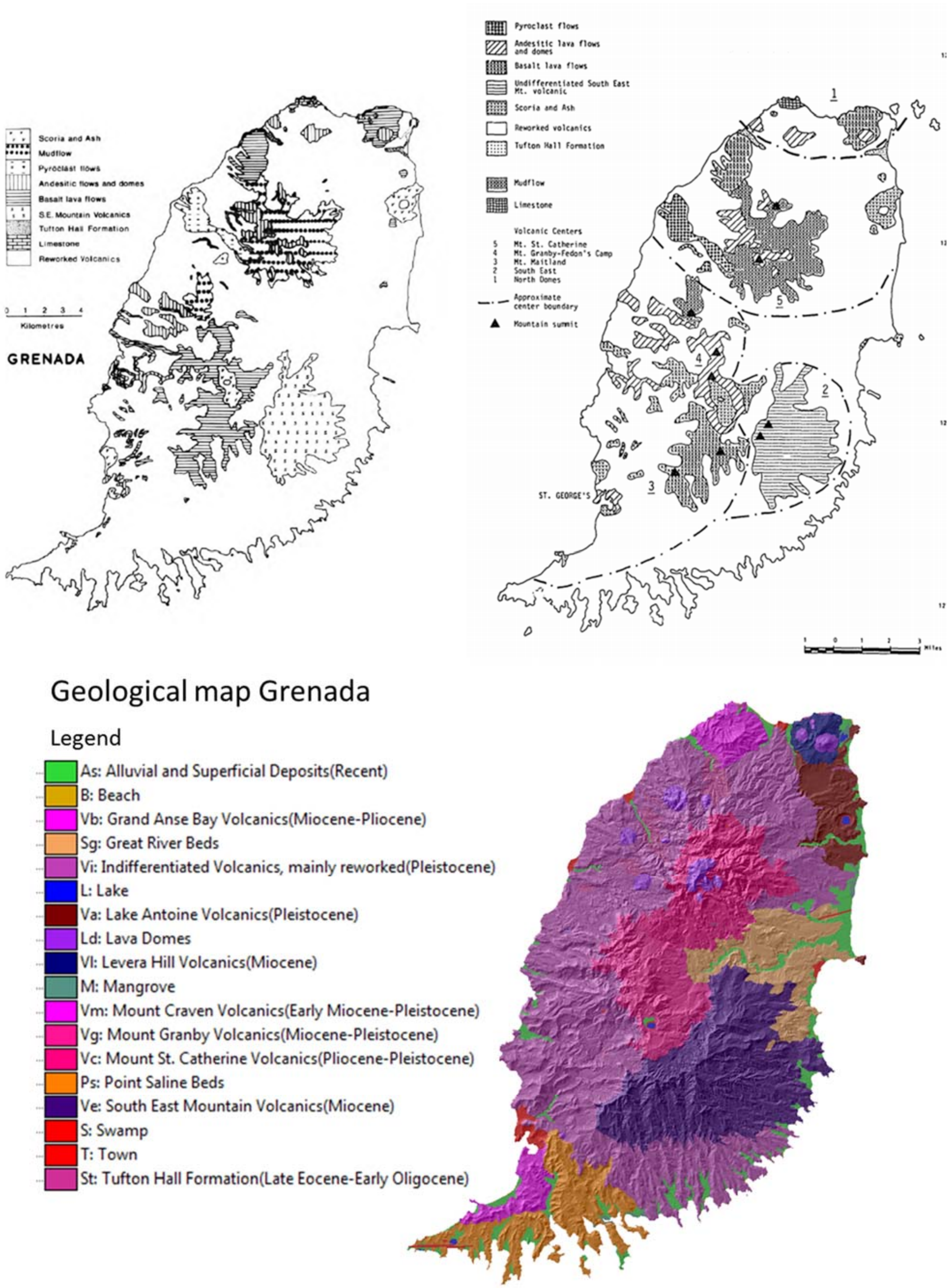


Figure 5-3: Geological maps of Grenada. Upper Left: Map from Arculus (1973); Upper right: map from Weaver (1989). Below Geological map available for this research from Geotermica Italiana (1981)

Figure 5-4 Examples of outcrops in volcanic deposits in Grenada. Note the high degree of weathering in the middle photo.

Geomorphology

The island has an asymmetric profile, with the Leeward side being steeper and shorter, and with deeper valleys than the Windward side, which is also found on other islands (e.g. Saint Vincent). This in combination with the bathymetry which is much steeper on the western side than on the eastern side suggest a long term tectonic tilting to the West. Grenada is composed of a mixture of monogenitic and polygenetic volcanic centres, some of which have erupted during historic periods. Many of the monogenetic volcanic centres look still very “fresh”, especially the craters which are abundant in the northeast of the island, but also in the centre and centre-west part. They seem to be aligned in a SE-SW trend across the island. Grenada is exceptional in terms of the large number of monogenetic basaltic explosion craters (Robertson, 2005). The most recent of these recent volcanic centres is believed to be less than 1000 years old (scoria cone near Radis valley). Lake Antoine is the best preserved of the craters, which is surrounded by a 60 m high tuff ring, resembling the morphology of so-called maars (explosion craters like in the German Eiffel). Some of the craters in the NE of the island are located on pyroclastic flow deposits, and could also have been secondary explosion craters, caused by phreatic explosions of water within still hot pyroclastic materials. However, in that case they should be related to eruptions of Mount Saint Catherine, for which recent eruptions are not assumed to be in Holocene periods (Aculus, 1973 reports ages of 20,000 to 50,000 years). Other clear craters are the Punchbowl crater, 3 km NW of Lake Antoine, and Grand Etang, which is composed of two explosion craters with an estimated age of 12,000 years (Arculus, 1976). Also St-George’s has a number of explosion craters. Weaver (1989) noted that at least five different volcanic centres of activity can be identified across the island; each dominated by either basalt or andesite eruptions at different stages of the island’s geological history. These volcanic centres of activity, namely North Domes, South East, Mt. Maitland, Mt. Granby-Fedon’s Camp and Mt. St. Catherine, are associated with basalt and andesitic lava flows and are also associated with volcanoclastics, tuff or scoria deposits. Earle (1923) also observed the predominance of relict massive un-decomposed lava scattered on slopes at locations such as Black Bay and Woodford.

The island is characterized by extensive secondary or reworked volcanic materials, e.g. the large eroded surface in the south side of the island, where it is no longer clear from which eruptive centre this material has been derived. The southern coastline appears to represent the recent drowning of a ridge-valley topography. The ridges are flat topped and inland slope gently upward. The inlets are shallow and swampy. It appears that this topography is caused by an uplift of the land, which is locally as similar features are not seen on other sides of the island. According to Arculus (1973) this is caused by a combination of local tectonic, sedimentary and structural conditions, together with sea-level rise during the Holocene.

Geomorphological interpretation

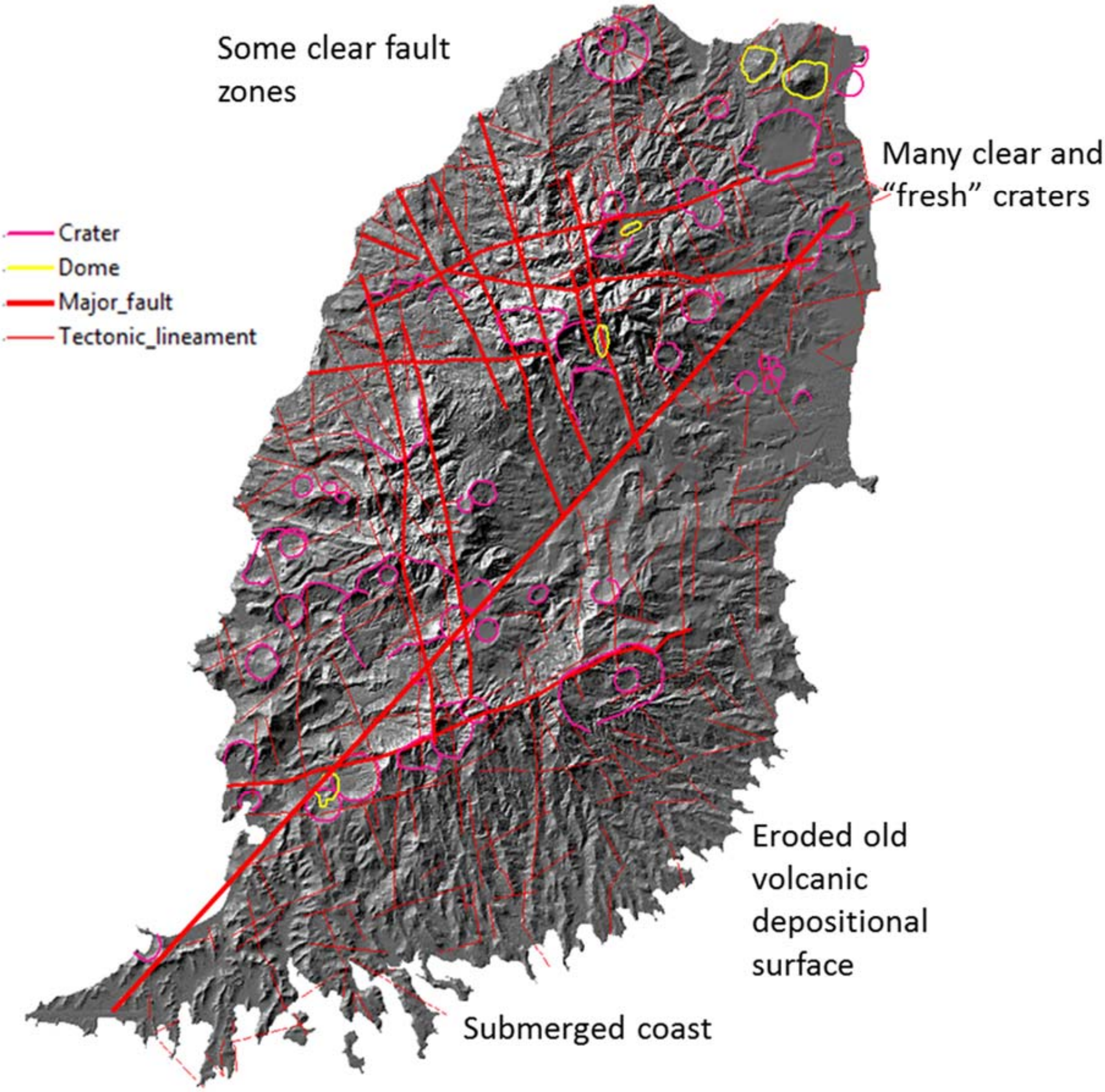


Figure 5-5. Geomorphological interpretation of Grenada (Van Westen) outlining the visible craters, domes, major faults and lineaments.

Soils

The best description on soils in Grenada we could find was given by USAID (1991), which was based on Vernon, et al. (1959) who reported on the results of an island-wide soil survey and mapping exercise conducted by his team in 1956-57. CDB/CDERA (2006) indicate that soils map was developed in 1959 by the Soil Research Unit of the University of the West Indies, St. Augustine, Trinidad. The soil map was made through physiographic interpretation of aerial photographs, combined with field work and soil testing, and not according to pedology which emphasizes how the soils originated. The map has a very complicated legend. There are 42 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 was 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 soiltype (indicated as a number, the slope class and the erosion categories.

Table 5-2: Classification of Grenada's soil series according to the U.S. Dept. of Agriculture's Soil Taxonomy. Source: Smith, 1983.

Soil group	Subgroup	Grainsize
Belmont (in wetter areas)	Typic Tropudolls	fine
Belmont (in drier areas)	Vertic Eutropepts	Fine montmorillonitic
Bonair	Not classified	Not classified
Capitol (in wetter areas)	Oxic Humiiropopts	very fine, kaolinitic
Capitol (in drier areas)	Typit Ustropepts	fine, mixed
Concord	Typic Chromuderts	fine, montmorillonitic, non·acid
Hartman	Typic Chromusterts	fine, montmorillonitic, non-acid
Hope	Cumulic Tropaquolls	very fine, mixed
La Tante	Not classified	Not classified
Palmiste	Vertic Tropudalfs	very fine, mixed
Parnassus	Vertic Tropudalfs	very fine, mixed
Pearls	Not classified	Not classified
Perseverance	Udorthentic Chromusterts	fine, montmorillonitic, non acid
Plains	Fluventic Tropudolls	fine loamy, mixed
Simon	Not classified	Not classified
Woburn	Paralithic Vertic Ustropepts	clayey, montmorillonitic
Woodlands	Vertic Ustropepts	fine, montmorillonitic

According to Ternan, et al. (1989), the soils of Grenada are dominated by clay loams (84.5 percent), followed by clays (11.6 percent) and sandy loams (2.9 percent). The three major types of clay loam, which between them make up 77.8 percent of the soils, are Woburn, Capitol and Belmont. The description here on the highland soils is derived from USAID (1991) which is again is based on Vernon et al., 1959)

Woburn Clay Loams are lithosolic "brown earth~ soils (latosols) which are well drained, shallow, highly erodible, dark brown to grey in colour, and usually occur on steep slopes. Some occur over ash and agglomerates usually in relatively dry coastal areas, and they are characterized by very poor water retention.

The soils of most of the hill slopes in the high rainfall areas are Capitol Clay Loam and Belmont CIay Loam (and their stony and boulder phases). The former is a brick-red, well-weathered "red earth" (latosol) which usually occurs over highly weathered basic igneous rocks. The latter is a 'brown earth", usually occurring over basic ash and agglomerate. Both soils are moderately to well drained, with good water retention. Belmont Clay Loam is only moderate erodible, but Capital Clay Loam much more. The rocky, shallow phases of Capitol Clay Loam and Belmont Clay Loam are found mainly in the mountainous areas with very steep slopes and high rainfall. The best use of these soils is for forest, since they are subject to massive erosion when cleared of their natural vegetation; agriculture should be kept to an absolute minimum (Vernon, et al. 1959). Landslides may occur often in these areas, causing the loss of the entire shallow soil above the parent material. Concord Clay Loam (and its stony and boulder phases) is found partly on ash and agglomerate and partly on colluvial material, usually on moderate to steep slopes. This is a heavy soil with only moderate internal drainage and appears to be almost an intermediate soil between Belmont Clay Loam and Perseverance Clay. Its natural fertility is fairly high and its water retention and resistance to erosion are good, but poor drainage is often a problem. In the drier areas, at relatively low elevations and mainly around the periphery of Grenada, clays are common. These include a group of moderately to poorly drained heavy soils, usually found over ash and agglomerate. Parnassus Clay and Perseverance Clay (and its stony and boulder phase) have the poorest drainage and are usually found on gentle to moderate slopes. These are very heavy, tough “shoal” soils with little effective depth, moderate to low natural fertility, but high water retention and resistance to erosion.

Both hurricane damage and clearcutting may cause a decline in soil nutrients in areas where the trees have been felled. However, hurricane damage to forests is often patchy, of variable intensity and is a relatively infrequent event. Diversity is increased as secondary vegetation grows up, and nutrients are returned to the soil relatively rapidly by the rotting of the downed vegetation. By contrast, when trees are clear cut, there is a permanent loss of nutrients if the felled vegetation is removed as in logging, and an even greater loss if the slash is burned. On steep slopes denuded of their cover, accelerated erosion further exacerbates the loss of nutrients by transporting soil downslope. Alterations in the pathways and rates of water flow due to a disturbance can also cause changes in the timing of peak flow and greater flood discharges downstream.

When topsoil is lost, the formation of replacement soils is an extremely slow process. It may take an estimated 200 to 700 years to form just 2.5 cm of top soil weighing about 360 tons/hectare (USAID, 1991).

The available soil map showed several problems, related to topological errors, and also related to the correlation with other factors. As slope steepness is used as one of the characteristics of the soil units, a mismatch with slope units derived from the DEM was evident. The conversion of this complicated soil map into a GIS layer turned out to be a major challenge. The topology of this map was also problematic, and we had to fix this using a number of GIS operations. The complicated legend would pose a serious problem in the use of this in the landslide susceptibility assessment. We combined the soil map 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.

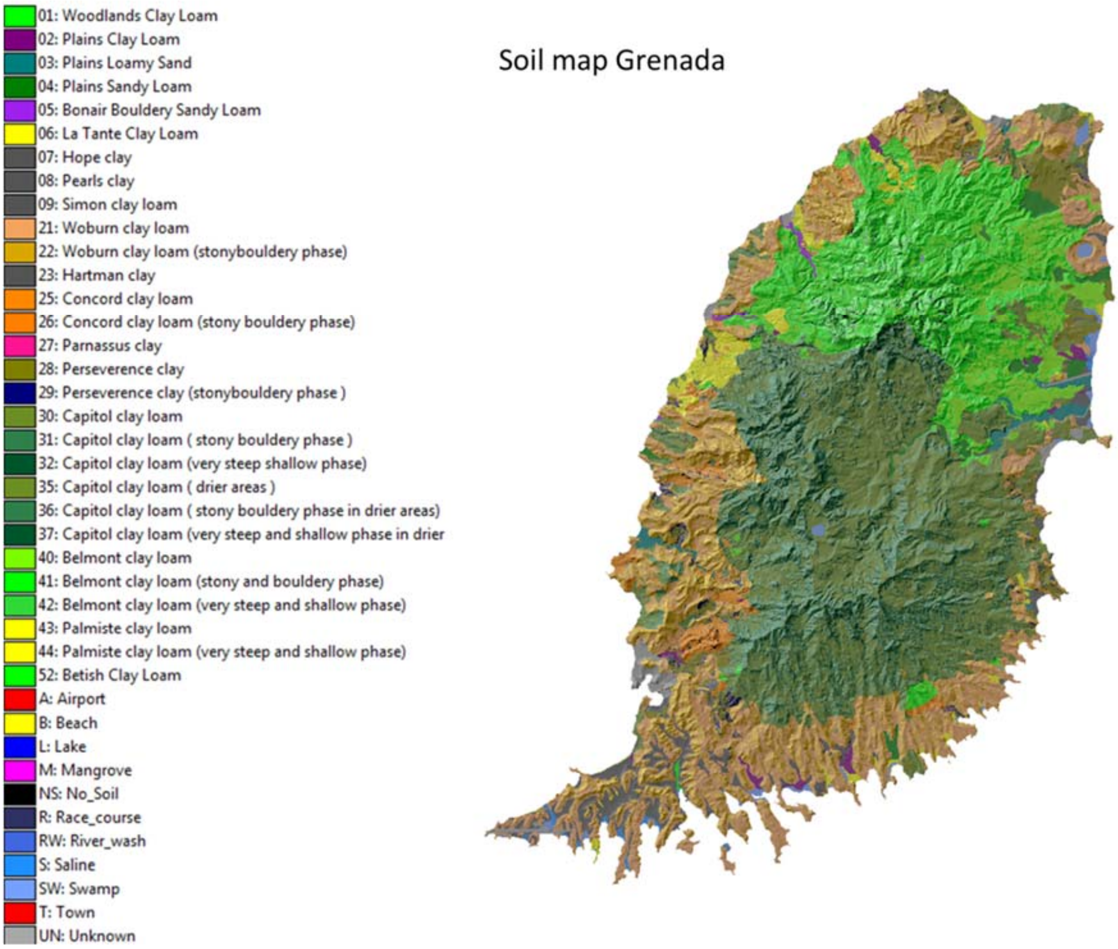


*Figure 5-6: Soil map of Grenada (*CDB/CDERA, 2006)

Land-cover

We have three land cover maps for Grenada, two of which without any metadata. However, we found out that one is from 2000 and one from 2009. We understood from the people that gave them to us that these were made using image classification of Landsat images by The Nature Conservancy. The maps from 2000 and 2009 show large differences as can be seen from Table 5-3. Between 2000 and 2009 Hurricane Ivan in 2004 caused major changes in the vegetation pattern within Grenada. This is reflected by the large number of changes of landcover to "Abandoned and underutilized cropland" in 2009. The largest change was 49 km^2 of mixed cultivation in 2000 that was not used anymore in 2009. We also obtained a recent land use map from an international project. The European Space Agency (ESA) and the World Bank (WB) have been collaborating under the umbrella of the "Earth Observation for Development" initiative - branded Eoworld - since 2008. The form of this collaboration has been to develop, produce and deliver examples of EO-based information products that respond specifically to the geo-information requirements of on-going World Bank projects. ESA provided the financial and technical capacity to procure high resolution satellite images which were processed by the British Geological Survey. They used Object-Based Image Classification with Definiens and ENVI software and produced a detailed land cover map for Grenada. Both the detail of this map as well as the legend are so different from the previous land cover maps from 2000 and 2009 that it is difficult to compare them. The large class “Abandoned and underutilized cropland” in 2009 has completely disappeared in 2014. Also the urban areas that were mapped very general in 2009, are much smaller in the detailed land cover map from 2014. Although the new land cover map was a major improvement, it still had a number of problems. One of them is related to cloud cover, where other satellite image data (e.g. Landsat) had to be used to fill these missing parts, leading to large differences in detail (See Figure 5-7).

Table 5-3: Land cover changes between 2000 and 2009 in km^2. Only major changes (larger than 0.5 km2) are shown here.

		Land cover 2009										
		Abandoned underutilized	Cocoa	Evergreen Rainforest	Food crops & Vegetables	Food crops, Veg& Fruit Trees	Mixed Cultivation	Mix Primary & Rain Forest	Moist Deciduous Rainforest	Residential	Scrub	Scrub & Cactus
Land cover 2000	Abandoned Cultivation	3.3								0.3		
	Banana, Cocoa & Spices	0.2	0.4				0.3					
	Cocoa	0.7	3.0				2.1					
	Cocoa, Banana & Spices	0.1	1.6									
	Coconut	0.2							0.1			
	Food crops & Vegetables	0.2		0.1	4.0				0.1			
	Food crops, Veg & Fruit Trees	0.1				7.1	0.1			0.6		
	Mixed Cultivation	49.0	0.1	0.4	0.1	0.3	49.0		1.1	2.3		
	Mix Primary & Rain Forest	0.5			2.5		0.1	32.3				
	Moist Deciduous Rainforest	0.1					0.1		40.1			
	Nutmeg	8.1		0.2	1.8		16.3	0.4				
	Nutmeg & Banana	0.6										
	Nutmeg & Cocoa						0.4					
	Open Scrub & Cactus									0.1		
	Orchard											
	Pasture									0.2		0.1
	Residential									13.3	0.1	0.2
	Scrub & Cactus									0.5	0.1	11.8

Also the characterization of different vegetation types was problematic so that the new land cover map is less accurate when separating natural forest from plantation areas. Also bare areas, built-up areas, and roads often show large differences with the actual situation (e.g. bare rocks along the coast mapped as buildings, waste disposal site mapped as buildings etc.). Therefore the available building footprint map and road map were used to mask out the areas of buildings and roads. Also airports, seaports, quarries, and waste disposal sites were manually digitized by us, and were masked into the land cover map. Figure 5-8 shows some of the changes that we made to the land cover map of 2014.

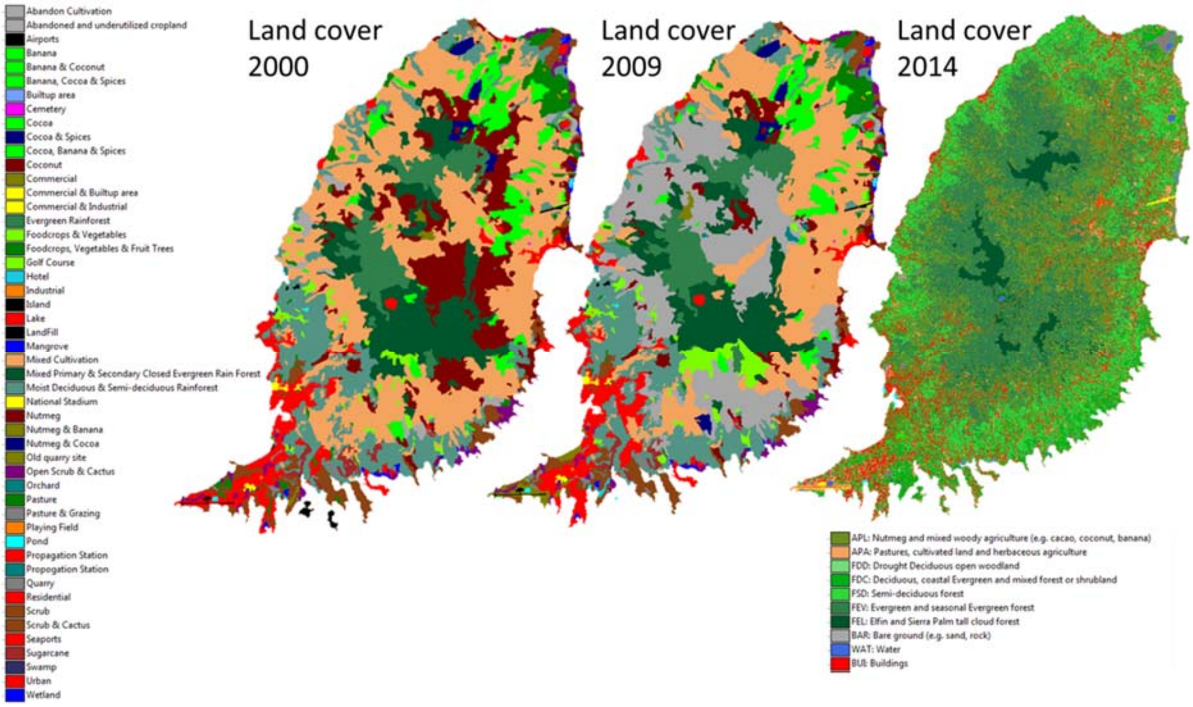


Figure 5-7: Land cover map of Grenada, with detail on the right.

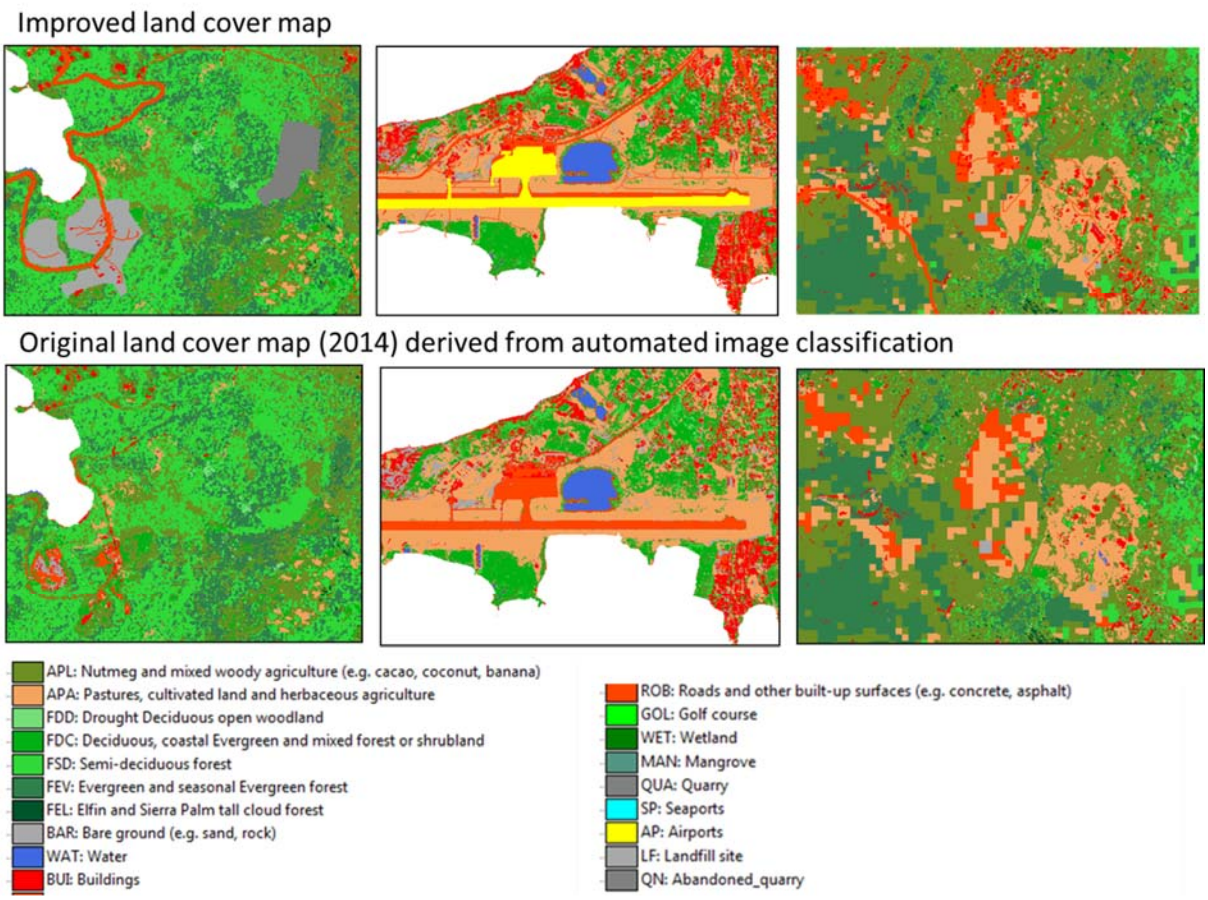


Figure 5-8: Land cover map of Grenada, with detail on the right.

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)

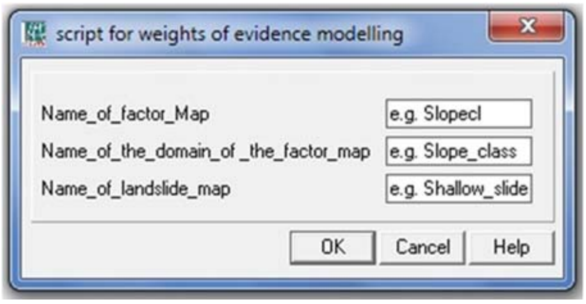


Figure 6-3: Input screen for the Weights-of-Evidence script used in the analysis. The script needs three inputs: name of the factor map (e.g. slope class, lithology), name of the domain of the factor map, and name of the landslide map, which should be a binary map (0= no landslide, 1= landslide).

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 rock falls. 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 Grenada

The landslides described in chapter 4 were subdivided into two dataset: one group consisting of rockslides and rock falls, 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 Grenada the following factor maps were analysed using the Weights of Evidence method (See Table 6-1).

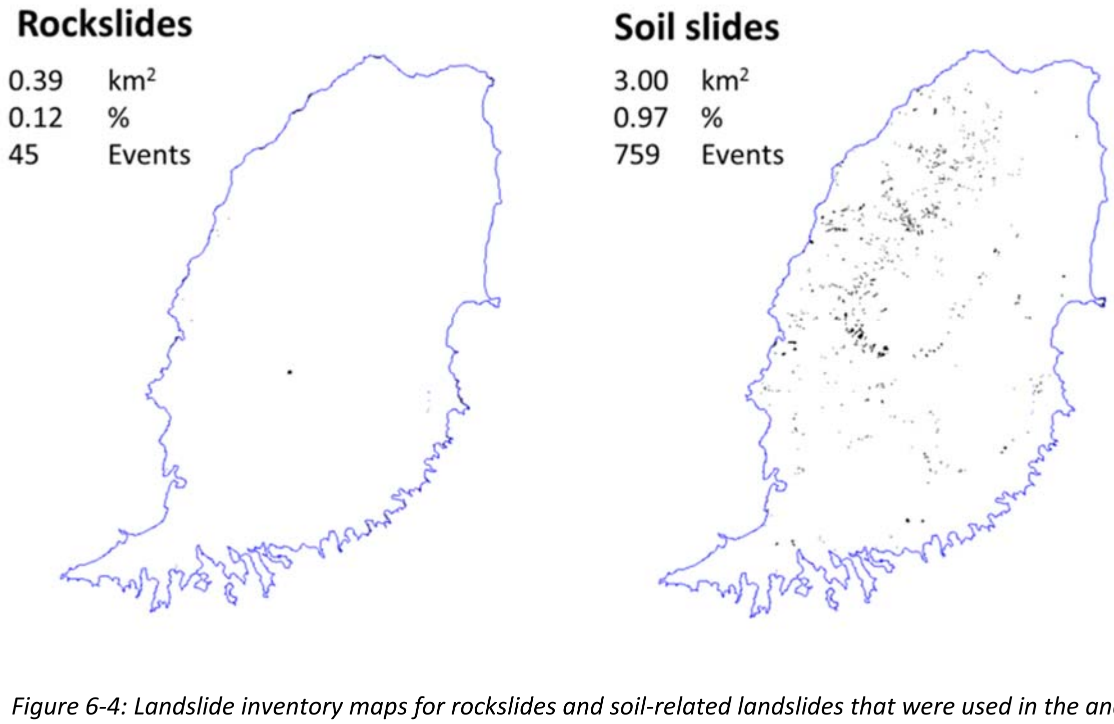


Figure 6-4: Landslide inventory maps for rockslides and soil-related landslides that were used in the analysis.

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

Name of factor map	Explanation	Classes
Coast_dist_class	Distance from coastline	5 classes (0-50, 50_100, 100_150, 150_200, >200 m
Elevation_Class	Elevation classes	8 classes (in classes of 100 meters)
River_dist_cl	Distance from rivers	4 classes (0_25, 25_50, 50_100, >100 meter)
Ridge_dist_cl	Distance from ridges	6 classes (0-100 , 100-200, 200-300, 300-400 and >400, meter)
Road_dist_cl	Distance from roads	3 classes (0-50,50-100, > 100 meter)
Geology	Lithological units	17 geological units, without clear differentiation between lithological types. Most group several types.
Landuse_map	Landuse map	23 classes
Slope_cl	Slope steepness classes	4 classes (0 - 20 , 20 - 40, 40 - 60 , >60)
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, northern & southern parts)
Soil_type	Soil types	45 classes, but many subdivision. Very complicated legend
Soil_parent_materials	Soil erosion classes, indicated in soil legend	5 simplified classes
Soil_depth	Watertable classes, indicated in the soil legend	4 classes, (0-30, 30-100, 100-150, > 150 cm)
Geology_Slopecl	Combination of geology and slope classes	69 classes combining the 17 geological units with 4 slope classes.
Landuse_Slopecl	Combination of landuse and slope classes	68 classes combining 23 landuse classes with 4 slope classes.

Slope steepness.
Both rockslides and soil slides show a relation with slope steepness (Figure 6-5), 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.

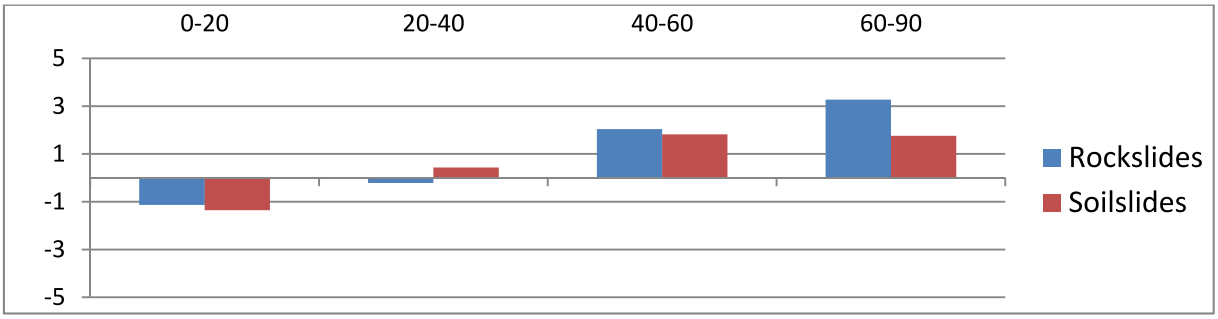


Figure 6-5: Contrast factors for slope steepness classes for rockslides and soil slides.

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).

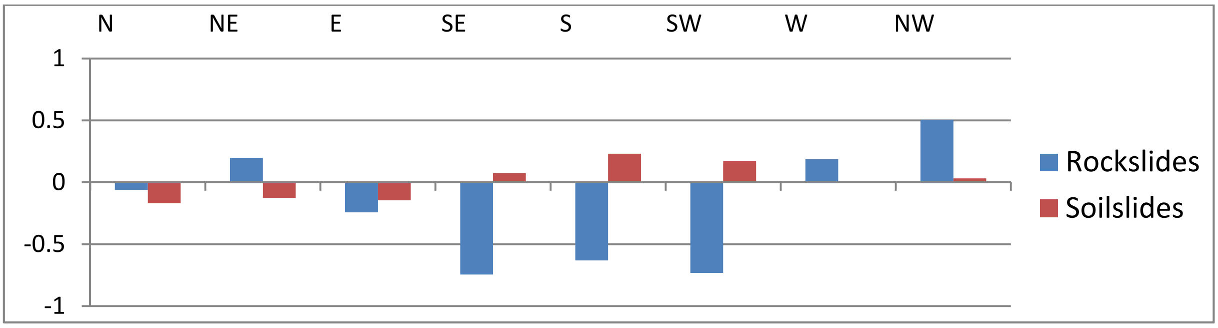


Figure 6-6: Contrast factors for slope direction classes for rockslides and soil slides.

It is interesting to see that rockslides have a quite different relation with respect to slope direction than soil slides. Soil slides occur considerable more on the Leeward side of the island. Rockslides occur on the Leeward side a bit more than in the north and south slopes. The windward side has less landslides.

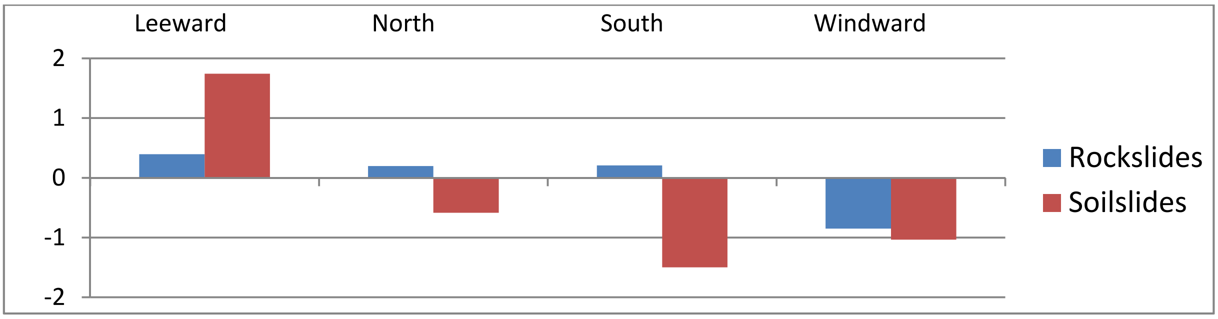


Figure 6-7: Contrast factors for main exposure classes for rockslides and soil slides.

When we combine the main exposure classes with the slope classes and run the statistical analysis for the combination the results (Figure 6-8) show a much more differentiated picture. In the Leeward side there is a clear increase with increasing slope classes for both types. The south shows only an increase for rockslides with increasing slope steepness. Contrast factors for soil slides are very low in the south.

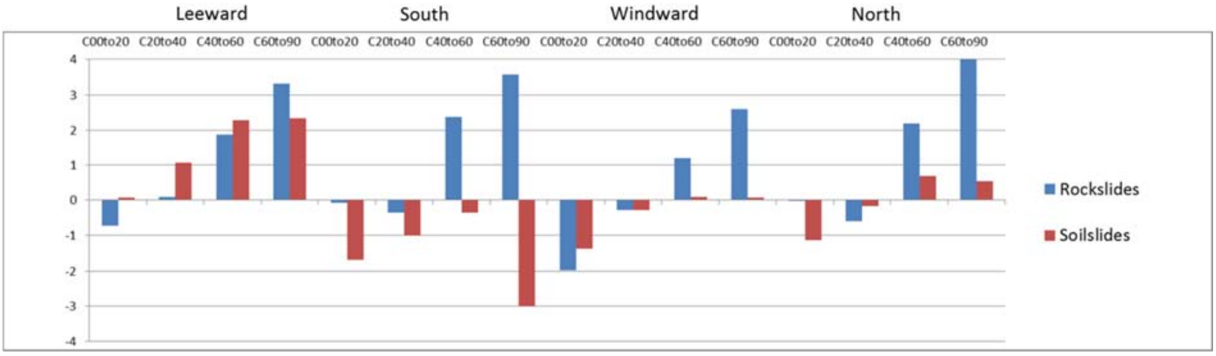


Figure 6-8: Contrast factors for the combination of the main exposure classes and slope steepness classes for rockslides and soil slides.

Elevation

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

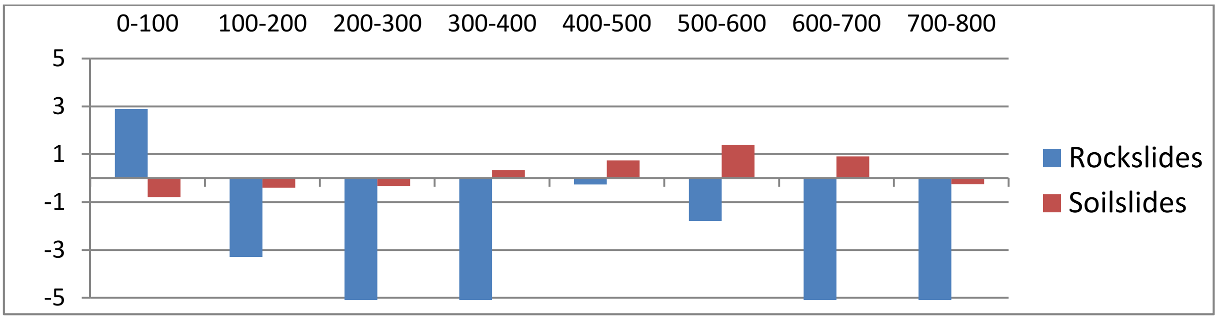


Figure 6-9: Contrast factors for elevation classes for rockslides and soil slides.

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 such a clear relation with the distance from the coast.

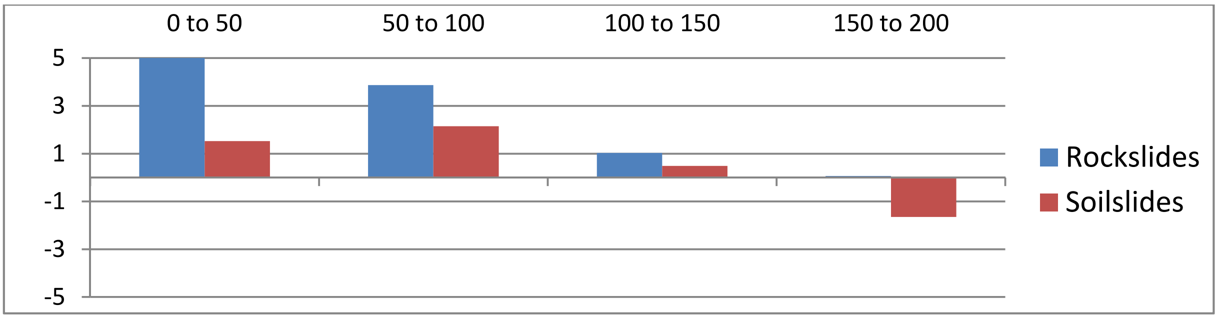


Figure 6-10: Contrast factors for distance to the coast for rockslides and soil slides.

Distance from ridges

We made two types of analysis. One is the relation with the distance to all watershed divides and one with the distance to the major ones only. As can be seen from the result (Figure 6-11) soil slides have a clear relation with distance from major ridges and watershed divides. Soil slides are most frequently occurring at a distance less than 200 meters from watershed divides, in locations where enough ground water can accumulate to start a gulley or stream. The rockslides do not seem to have a relation with the distance to ridges.

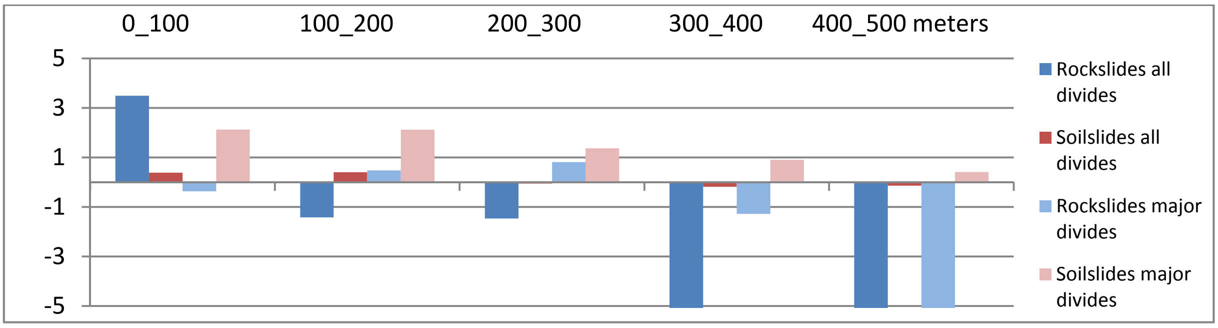


Figure 6-11: Contrast factors for distance to ridges for rockslides and soilslides.

Distance from rivers

We calculated the distance from rivers and made a buffer of 50 meters. Then we combined it with the slope gradient map, and generated three classes: close to rivers and gentle slopes, close to rivers and steep, and far from rivers. The results are shown in Figure 6-12. Rock slides have no relation with the distance to rivers. Soil slides, on the contrary do show a positive relation for steep areas close to rivers, due to undercutting effects.

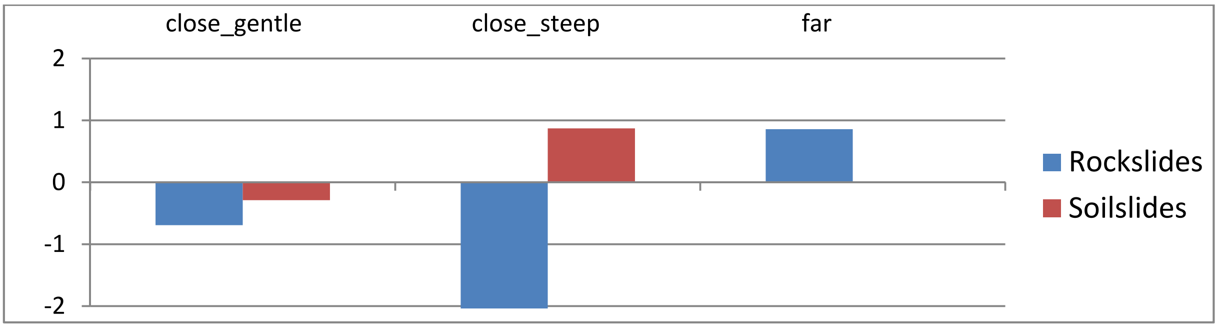


Figure 6-12: Contrast factors for distance to rivers for rockslides and soilslides.

Distance from roads

For analysing the relations between landslides and the distance to roads we generate distance classes from the main roads in combination with slope steepness classes. The results (Figure 6-13) show that both rockslides and soil slides have a relationship with the distance to roads. Especially rockslides have a high contrast factor for those area steeper than 30 degrees that are close to the main roads.

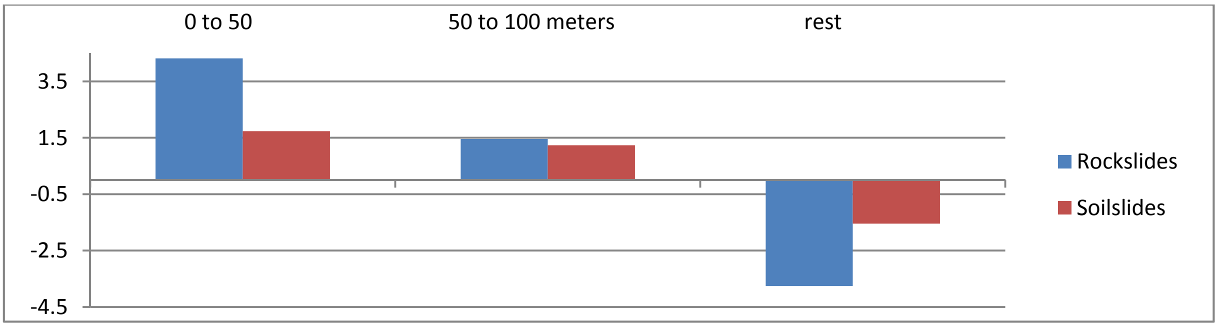


Figure 6-13: Contrast factors for distance to roads for rockslides and soilslides.

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 6-2 and 6-3. From Table 6-2 it can be seen that the contrast factors change quite a bit when comparing the contrast factors for the same geological unit within the various slope classes. There are quite some illogical results, due to problems in the detail of the geological map. For instance the positive scores for alluvial and beach. The following geological units have a positive relationship with rockslides: Tufton Hall formation, Southeast Mountain Volcanics, Mount Granby Volcanics and Undifferentiated Volcanics.

For soil slides there are positive relations for the following units: Undifferentiated Volcanics, Mount Granby Volcanics, Mount St. Catherine Volcanics, Lake Antoine Volcanics, Lava Domes and Tufton Hall Formation.

However, none of the contrast factors is very high, which indicates that the relations are not very strong and that landslides occur basically on all of those formations with positive values in an equal manner. There is a general tendency that the contrast factors within the same geological unit increase with increasing slope steepness, although this relation is also not very outspoken.

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 that show different aspects of the soil characteristics. The first one is the classification of the soil parent materials. The relation is shown in Figure 6-14. The relationship is confusing, especially when considering the positive relationship between "no_soil" and soil slides, which clearly indicates that there is a problem with the soil map boundaries and legend classes. Table 6-4 shows the relation for the soil types.

Table 6-2: Contrast factors for the combination of Geological units and slope classes for rockslides

	0 to 20	20 to 40	40 to 60	60 to 90
Alluvial and Superficial Deposits(Recent)	-2	1	3	3
Beach	3	6	7	0
Grand Anse Bay Volcanics(Miocene-Pliocene)	-12	-11	-9	-5
Great River Beds	-3	0	2	2
Undifferentiated Volcanics, mainly reworked(Pleistocene)	0	0	2	4
Lake	-10	-3	0	0
Lake Antoine Volcanics(Pleistocene)	0	1	0	-4
Lava Domes	-11	-12	-11	-8
Levera Hill Volcanics (Miocene)	-12	-10	-6	-4
Mangrove	-1	2	-2	0
Mount Craven Volcanics (Early Miocene-Pleistocene)	-3	-2	1	-6
Mount Granby Volcanics (Miocene-Pleistocene)	0	0	1	1
Mount St. Catherine Volcanics (Pliocene-Pleistocene)	-13	-13	-12	-9
Point Saline Beds	-13	-13	-9	-5
South East Mountain Volcanics (Miocene)	0	0	2	4
Swamp	-9	-5	-4	0
Tufton Hall Formation(Late Eocene-Early Oligocene)	-2	0	3	6

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

	0 to 20	20 to 40	40 to 60	60 to 90
Alluvial and Superficial Deposits(Recent)	-2	0	2	3
Beach	-11	-8	-6	0
Grand Anse Bay Volcanics(Miocene-Pliocene)	0	0	0	-7
Great River Beds	-1	0	1	1
Undifferentiated Volcanics, mainly reworked(Pleistocene)	-1	1	2	2
Lake	-12	-6	0	0
Lake Antoine Volcanics (Pleistocene)	-1	1	2	2
Lava Domes	-1	0	2	2
Levera Hill Volcanics(Miocene)	-2	-1	-8	-6
Mangrove	-13	-7	-4	0
Mount Craven Volcanics(Early Miocene-Pleistocene)	-1	-1	0	-8
Mount Granby Volcanics(Miocene-Pleistocene)	0	1	2	2
Mount St. Catherine Volcanics(Pliocene-Pleistocene)	0	0	1	1
Point Saline Beds	-3	-1	-1	-8
South East Mountain Volcanics(Miocene)	-1	-1	0	0
Swamp	-11	-7	-6	0
Tufton Hall Formation(Late Eocene-Early Oligocene)	0	1	2	2

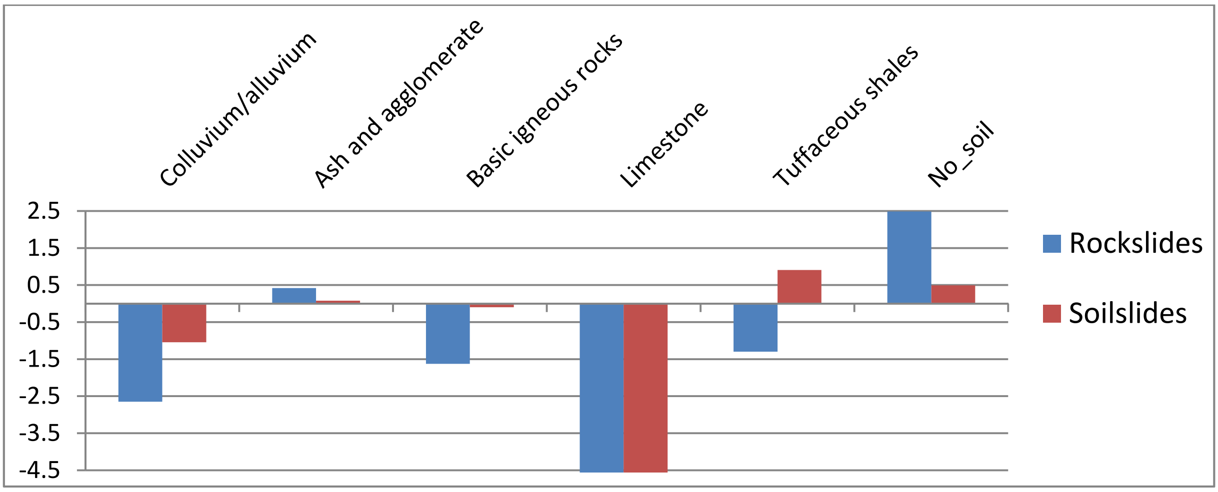


Figure 6-14: Contrast factors for parent materials of soils for rockslides and soil slides.

Table 6-4: Contrast factors (ordered from high to low for soil slides) for soil types. The units with highly negative values have been omitted.

Soil type	**Contrast factors for**	
	Rockslides	**Soil slides**
Belmont clay loam (very steep and shallow phase)	-6.17636	1.69405
Palmiste clay loam (very steep and shallow phase)	-1.93848	1.674853
Capitol clay loam (very steep shallow phase)	-0.07461	1.124584
Bonair Bouldery Sandy Loam	-10.1282	0.762901
Palmiste clay loam	-1.04735	0.354914
Woburn clay loam (stonybouldery phase)	1.562902	0.29621
Concord clay loam (stony bouldery phase)	-3.86982	0.287852
Belmont clay loam (stony and bouldery phase)	-2.81772	0.250955
Capitol clay loam (stony bouldery phase)	-1.46678	0.084423
Capitol clay loam (very steep and shallow phase in drier	-0.34838	-0.263028
Concord clay loam	-12.0068	-0.423944
Plains Loamy Sand	-11.5933	-0.52672
Capitol clay loam (stony bouldery phase in drier areas)	-1.28973	-0.60676
Capitol clay loam (drier areas)	-2.69318	-0.63566
Capitol clay loam	-1.6656	-0.765097
Belmont clay loam	-4.02948	-0.877698
Hartman clay	-12.6401	-0.914869
Plains Clay Loam	-11.1951	-1.006909
Woburn clay loam	0.610062	-1.055886
Plains Sandy Loam	-2.61212	-1.517265
Perseverence clay (stonybouldery phase)	1.164591	-1.770179

For the first three soils in the table (Belmont clay loam very steep and shallow phase), Palmiste clay loam very steep and shallow phase and Capitol clay loam very steep shallow phase) there is a positive relation for soil slides but a negative one for rockslides. These are the soil types occurring on steeper slopes along the slopes of the higher parts of the higher, where Hurricane Emily triggered most of the shallow landslides. Figure 6-15 shows the relation between soil depth classes (soil depth is an attribute of the soil units) with landslide occurrence. The relationship is not very clear and actually a bit confusing, and it is questionable whether soil depth can be used as an attribute to soil units, as in fact soil depth will vary from place to place. Besides the soil depth here doesn't refer to engineering soils (loose materials) but only to the upper soil horizons.

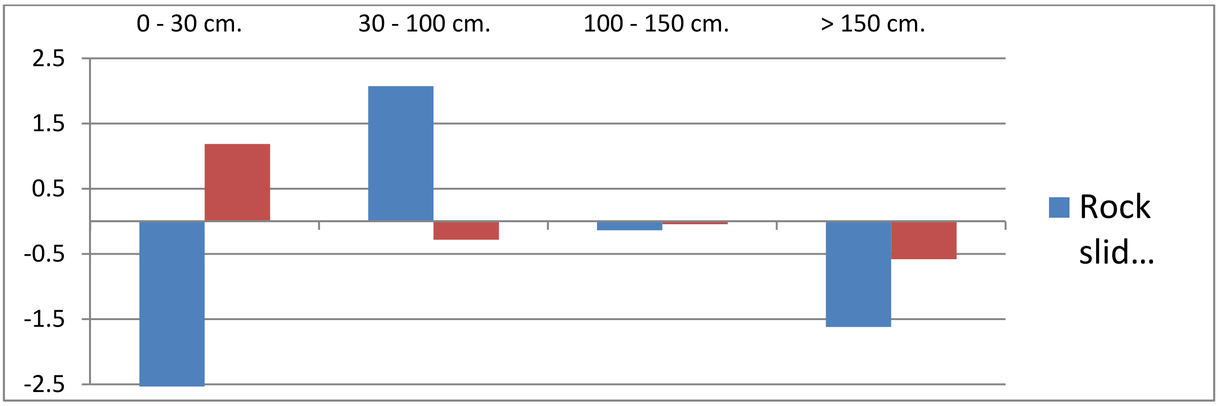


Figure 6-15: Contrast factors for soil depth classes for rockslides and soil slides.

Land cover/ land use

The result for the relation between land cover and landslide types are summarized in Figure 6-16. The data has been ordered from high to low for rockslides. As can be assumed bare areas have the highest relation with rockslides, however this is a "chicken-and-egg" problem: are the landslides there because the land cover was bare, or is the area bare due to the landslides? Fortunately both rockslides and soil slides have a negative relationship with buildings. Rock slides have a positive relationship with roads in this case as well (meaning that a number of roads are located in rockslide areas, like Mabouya). The positive relation of soil slides with landfill site is due to a single, but fairly large landslide that affected the landfill site at Perseverance, which is not very large in size.

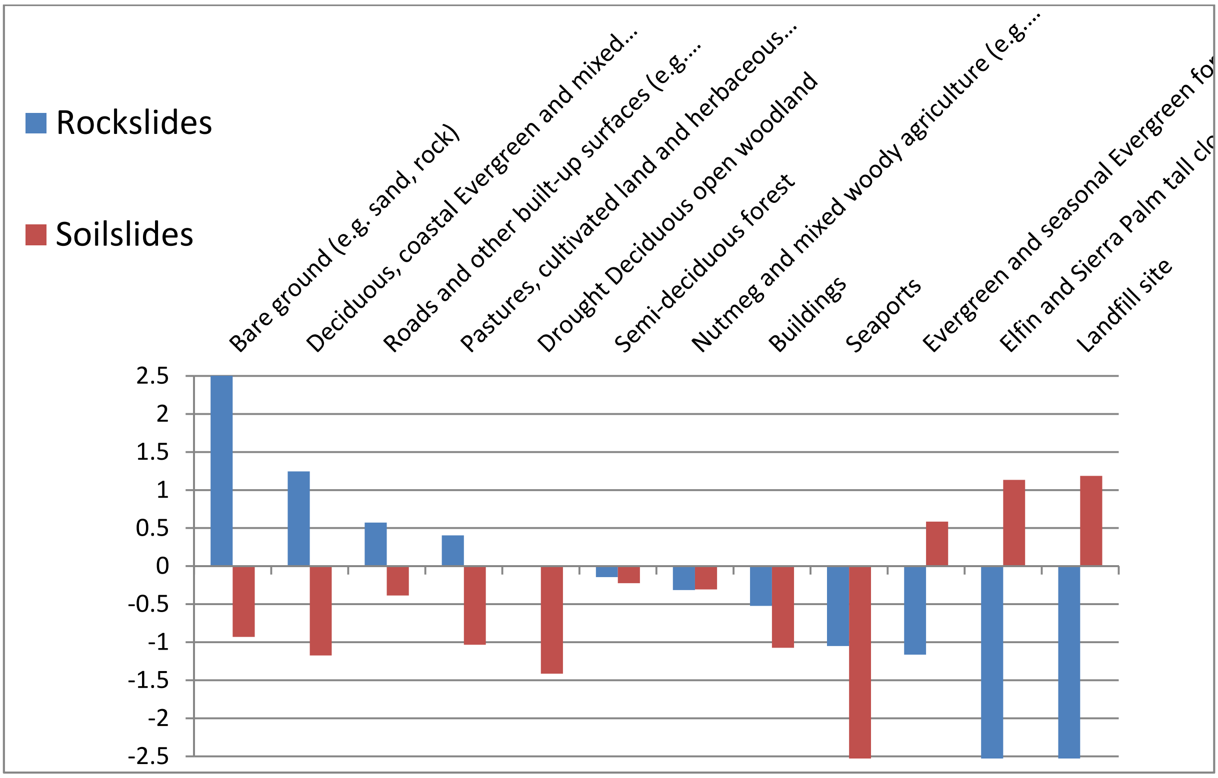


Figure 6-16: Contrast factors for land use classes for rockslides and soil slides.

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 factor are less useful as factor maps for the analysis of the susceptibility of rockslides, which are much more 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. 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 Grenada.

Name of factor map	**Explanation**	**Rockslides**	**Soil slides**
Coast_dist_class	Distance from coastline	Most useful	Less useful
Elevation_Class	Elevation classes	Useful	Useful
River_dist_cl	Distance from rivers	Not useful	Useful
Ridge_dist_cl	Distance from ridges	Less useful	Most useful
Road_dist_cl	Distance from roads	Useful	More or less useful
Geology	Lithological units	Useful	More or less useful
Landuse_map	Landuse map	Useful	More or less useful
Slope_cl	Slope steepness classes	Very useful	Very useful
Aspect_cl	Slope direction classes	More or less useful	More or less useful
WindLeeward	Main parts of the island	Useful	Useful
Soil_type	Soil types	Not so useful	Useful
Soil_parent_materials	Soil erosion classes, indicated in soil legend	Not so useful	Useful
Soil_depth	Watertable classes, indicated in the soil legend	Not useful	Not so useful
Geology_Slopecl	Combination of geology and slope classes	Useful	Useful
Landuse_Slopecl	Combination of landuse and slope classes	Useful	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 6-17
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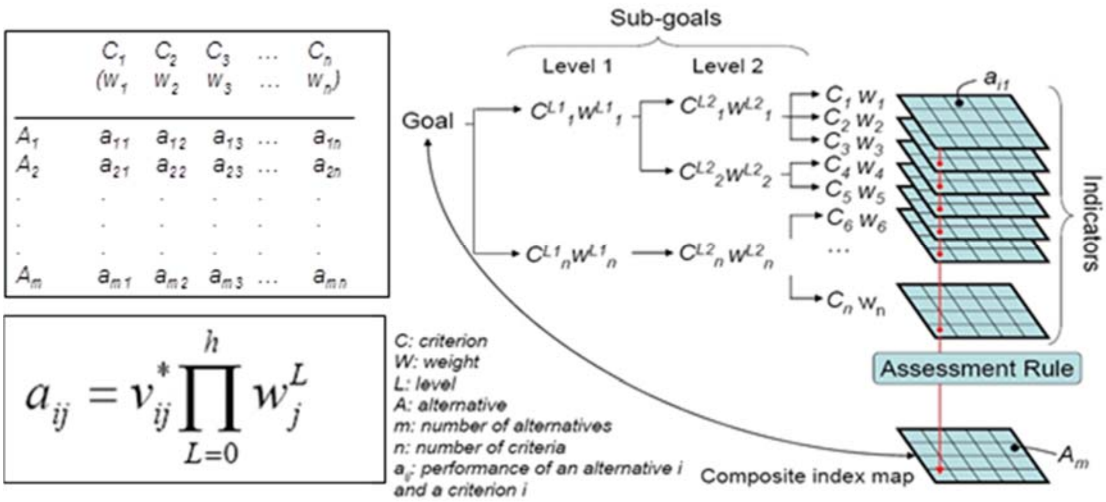

Figure 6-17: Schematic procedure for spatial multi-criteria evaluation based on the analytical hierarchical process

From a decision-making perspective, multi-criteria evaluation can be expressed in a matrix as shown in the Figure 6-17. 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).
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 6-17).
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 Grenada

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 6-18.

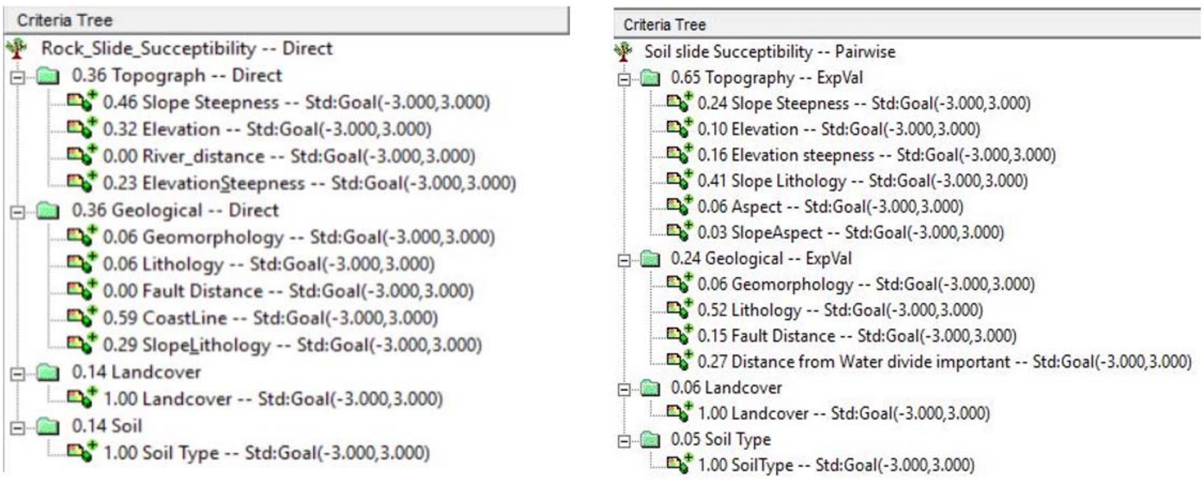

Figure 6-18: Criteria trees used for the susceptibility assessment of rockslides (left) and soil slides (right)

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.
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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.
- 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 6-19. We have shown two success rate curves for each landslide type.

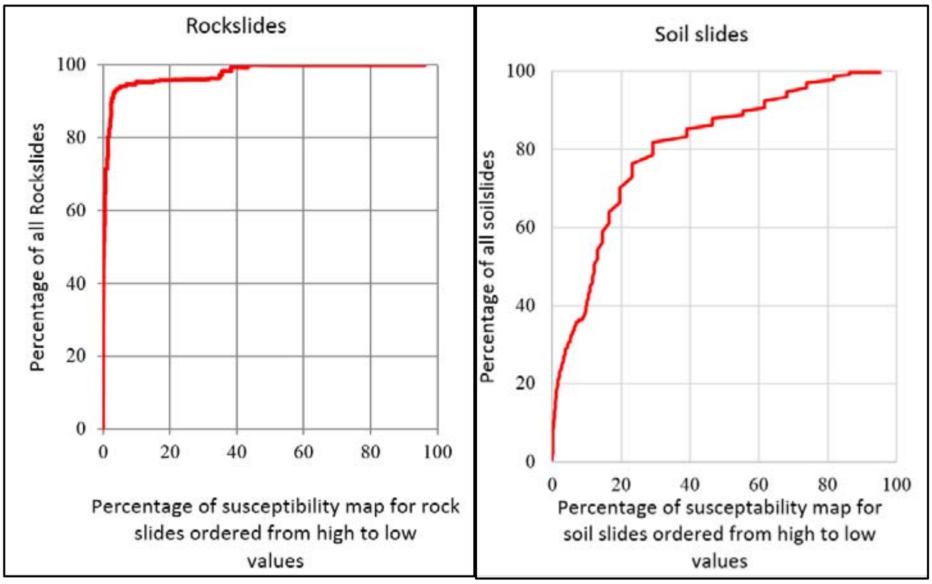

Figure 6-19: Success rate curves for the susceptibility maps for rockslides (left) and soil slides (right). For both the curves are shown without taking into account the factor "proximity to existing landslides" (red lines) and the ones that do take into account this proximity as a factor (blue curves).

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.

6.7. Combining 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 Grenada 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 soil slides. However, even these are rather good, with 70% of the landslides in the high susceptibility class, which covers 23% of the island, resulting in a landslide density of 2.73 %.

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

		Rockslides	Soil slides
High susceptibility	Cut-off value	0.58	0.46
	Percentage of the map	3%	23%
	Percentage landslides	90%	70%
	Landslide density	2.85%	2.73%
Moderate susceptibility	Cut-off value	-	0.43
	Percentage of the map	-	24%
	Percentage landslides	-	15%
	Landslide density	-	0.66%
Low susceptibility	Cut-off value	0	0
	Percentage of the map	97%	53%
	Percentage landslides	10%	15%
	Landslide density	0.01%	0.24%

From the rockslide susceptibility map it is clear that almost all the rockslides are concentrated along the coast, and there a very few inland areas with rock slide susceptibility. As a result, the rockslide susceptibility map is classified into 'High' and 'Low' only, where the high susceptibility area contains 90% of all landslides and the low susceptibility zone contain the rest 10%. For soil slides, the susceptibility are categorized into high, moderate and low which corresponds to 70%, 15% and 15% landslide happenings respectively. The resulting landslide susceptibility maps for rockslides and soil slides are shown in Figure 6-20.

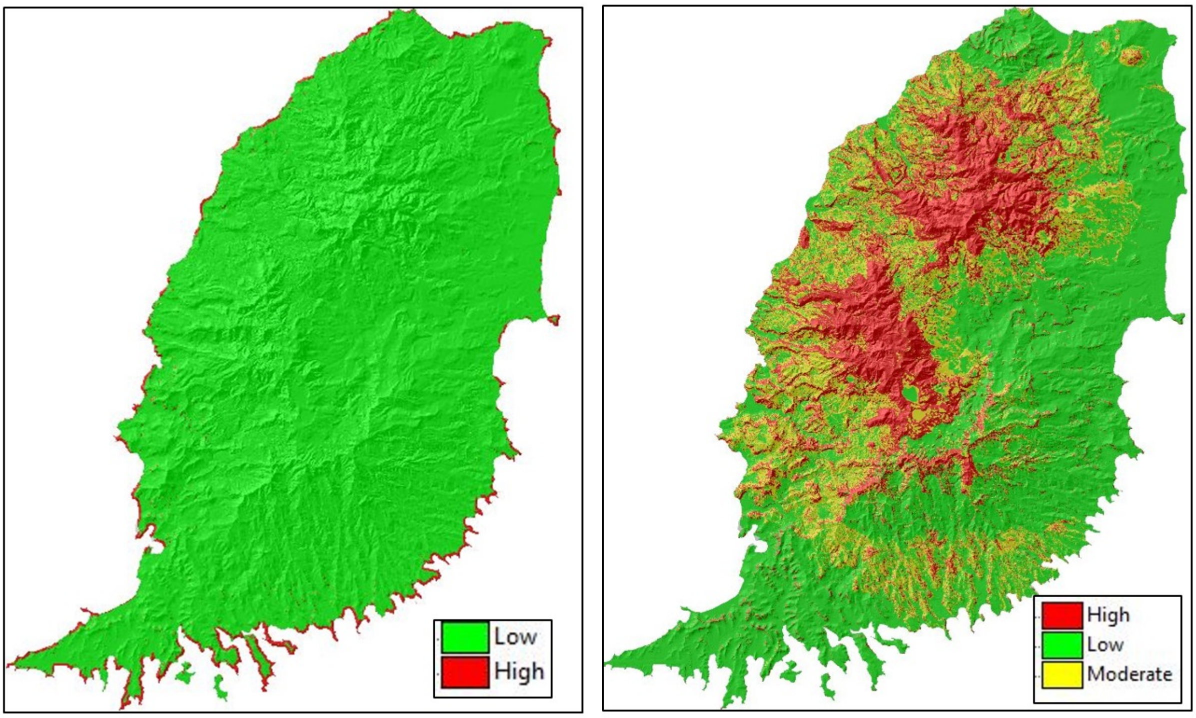

Figure 6-20: Classified landslide susceptibility maps for rockslides (left) and soil slides (right)

For decision makers it is not useful to have two individual landslide susceptibility maps. Therefore we have combined them into one single map, using the following combination table (Table 6-7)

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

After generating the susceptibility map, we still found a number of inconsistencies between the pattern of the mapped landslide and the landslide susceptibility classes. 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, 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.
- Thirdly, the factor maps with which the analysis has been carried out, may be the cause. As was mentioned in chapter 5, the digital elevation model was derived from LiDAR data, and the slope data is very detailed. Therefore local variations in slope steepness may be seen in the map as a mottled pattern of high and moderate pixels mixed together in certain locations. We tried to avoid the mottled pattern in the final landslides map (See Figure 6-21).
- 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 2.1. 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 6-21). 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 6-21). 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.

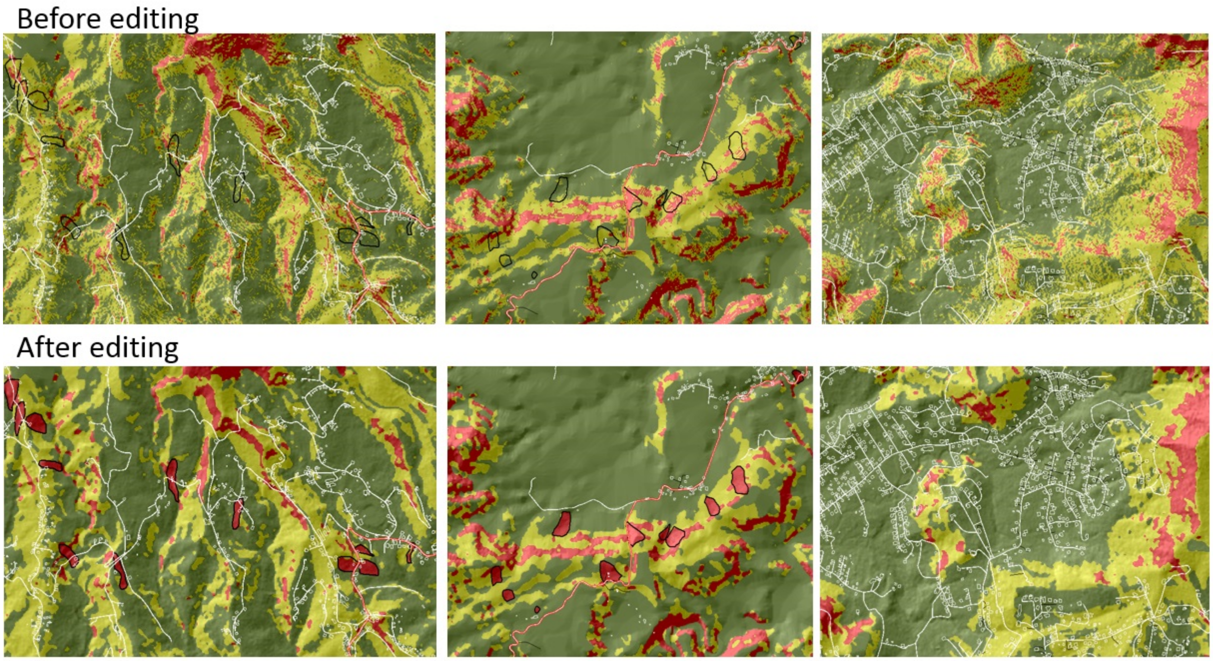

Figure 6-21: The effect of editing the final susceptibility map. Above row is before editing and below row is after editing. The colours show the susceptibility classes (red= high, yellow= moderate, and green=low). The black lines indicate historical landslide locations. The white lines building footprints and roads.

The final landslide susceptibility map is shown in Figure 6-22 (northern part) and Figure 6-23 (southern part). The resulting data for the final susceptibility map is shown in Table 6-8

Table 6-8: Summary information for the final landslide susceptibility map of Grenada.

	Low susceptibility	Moderate susceptibility	High susceptibility
Area in square kilometres	177.4	89.4	45.8
Percentage of total area	56.8	28.6	14.6

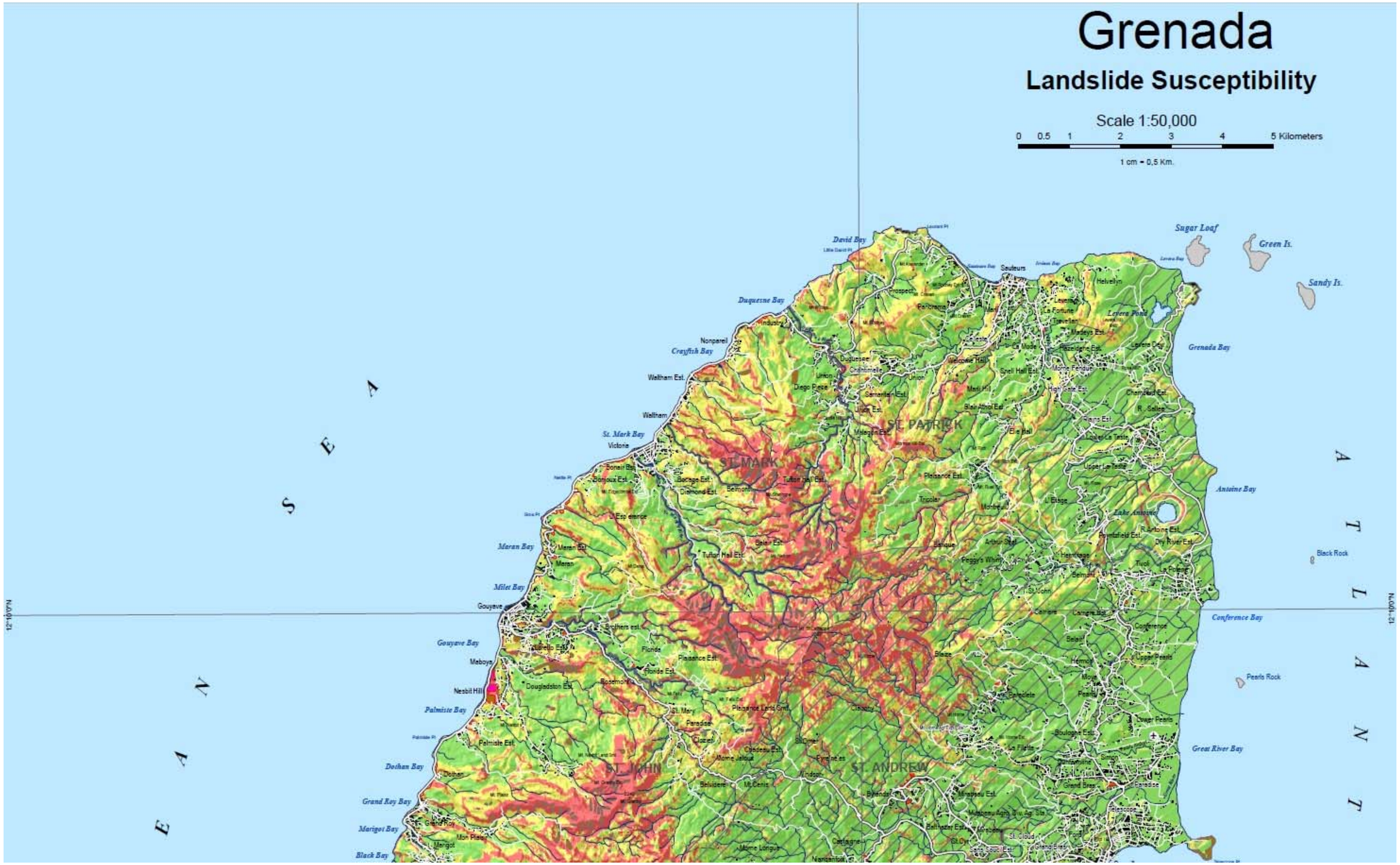

Figure 6-22: Final landslide susceptibility map for Grenada (North part). The full map can be downloaded as pdf from the following website: http://www.charim.net/Grenada/maps

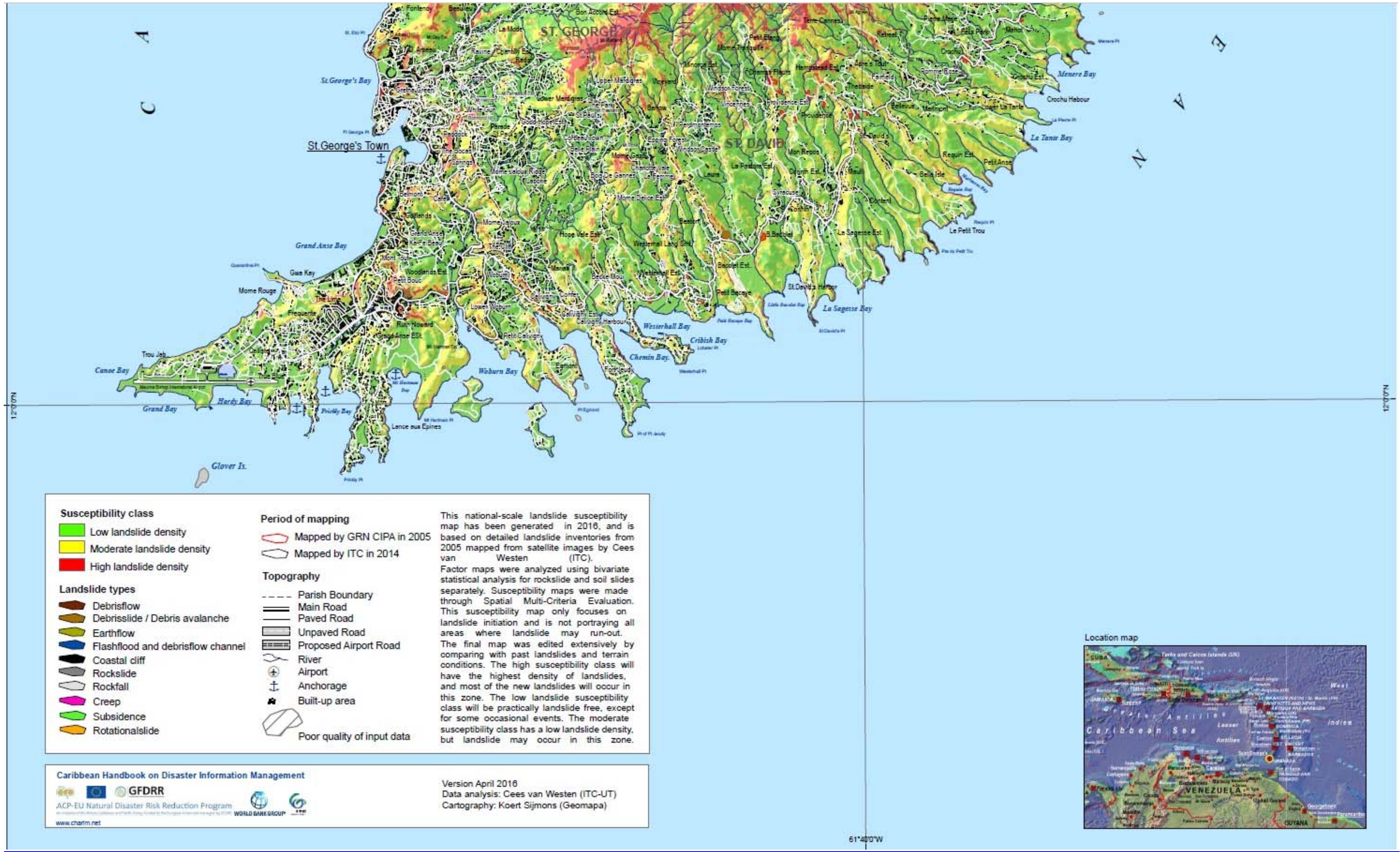

Figure 6-23: Final landslide susceptibility map for Grenada (South part). The full map can be downloaded as pdf from the following website: http://www.charim.net/Grenada/maps

7. 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.

7.1. 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 chapter the landslides susceptibility map was presented for the entire island. This map shows the relative likelihood that a certain area 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 7-1 landslide densities are given for the various susceptibility classes. Unfortunately for the study area very limited information is available in terms of event-based landslide inventories for different return periods. We only have the inventory that was generated through image interpretation from pre- and post-hurricane Ivan and Emily data, and the point-based inventory from CBR/CDEM (2005). In section 1.4 we concluded that, based on the scarce rainfall data available, the return period of the rainfall during hurricane Emily in the Maurice Bishop International Airport rain gauge was in the order of 100 years. However, the major rainfall amount during that event occurred in the North, and we do not have a raingauge to validate the return period for the rainfall that occurred in the Mount saint Catherine region, where most of the landslides occurred. We can therefore only assume that the hurricane Emily event was a rare event with a return period of rainfall lower than once in 100 years. The resulting landslide densities are shown in Table 7-1.

Table 7-1. Summary information of different landslide inventories within the low, moderate and high susceptibility classes

		Landslide susceptibility		
Source	**Characteristics**	**Low**	**Moderate**	**High**
The study area	Area in square kilometres	177.4	89.4	45.8
	Percentage of total area	56.8	28.6	14.6
CBD/CDERA 2005	Landslide area (m^2)	5600	4150	596875
	Number of landslides	74	44	142
	Landslide density (percentage)	0.003	0.005	1.305
	Landslide density (nr/km^2)	0.4	0.5	3.1
Pre-Emily (mapped by ITC)	Landslide area	1725	31725	850625
	Number of landslides	28	41	162
	Landslide density (percentage)	0.001	0.035	1.859
	Landslide density (nr/km^2)	0.2	0.5	3.5
Post-Emily (mapped by ITC)	Landslide area	9850	10875	2607775
	Number of landslides	136	105	505
	Landslide density (percentage)	0.0006	0.012	5.7
	Landslide density (nr/km^2)	0.8	1.2	11

7.2. Exposure analysis

The final susceptibility map can be used for calculation the exposure of buildings, roads and other infrastructure. Building data was available for Grenada. However, the data was not editable in a GIS due to many digitizing and topological errors, with overlapping boundaries and double digitized boundaries of building footprints. The buildings also didn't have any attribute data. Since, no attribute information was attached with building footprints the only possible option was make use of latest available satellite imagery and Google Earth. High resolution imagery of the satellite Pléiades was available for the whole island. The resolution of multi-spectral image is 2 meters whereas, panchromatic is 0.5 meters. Both images were fused to get highest possible resolution with colour. This provided a good quality data that could be used together with building footprints to characterize buildings. Building footprints were overlaid on Pléiades satellite imagery in the ArcGIS for visual interpretation. Two attributes; 'Use type' and 'occupancy' were added in the buildings table to add relevant information. Similarly, the building footprint map was exported to KML (Keyhole Markup Language) format to view with Google Earth. Luckily, for many parts of the country, high resolution images were existed on the Google Earth. Obviously, it was not possible to easily distinguish residential buildings from other buildings even on very high resolution imagery. So, the strategy was to identify and isolate large buildings, which could potentially be hotel, industry, school, church, office, business centre, or supermarket etc. After identifying these visible and known structures, the remaining buildings will potentially be residential establishments. In Grenada, over 85 % residential houses are separate houses, therefore; one cannot expect large population living in the big buildings or apartments. Through, the visual inspection all large buildings and other obvious buildings like schools, forts, churches etc. were identified and characterized manually. The remaining buildings were considered as residential houses and attributed them 'residential'.

The building footprints were subsequently overlain with the landslide susceptibility map and with the Parish map. The results of the building exposure analysis is shown in Table 7-2. The results show that in the entire country 1301 buildings (2.1 % of the total) are located in high landslide susceptibility zones, 13351 (21.7 %) in moderate susceptibility zones and the vast majority of 46966 buildings (76.2%) in low landslide susceptibility zones.

When we evaluate these values per Parish, St John parish has the largest percentage of buildings located in high susceptibility zones (238 buildings, which is 5.3 %), followed by St Mark (93 buildings, 4.4 %), and St. George (624 buildings, 2.5 %).

Table 7-2. Buildings exposed to low, moderate and high susceptibility classes for the whole country and for individual Parishes.

	Landslide susceptibility			
Parish	**Low**	**Moderate**	**High**	
St Andrew	13493	1526	123	15142
St David	5489	2385	150	8024
St George	17683	6855	624	25162
St Mark	1447	595	93	2135
St John	3129	1117	238	4484
St Patrick	5725	873	73	6671
Total	46966	13351	1301	61618

Table 7-3: Percentage of buildings located in low, moderate and high landslide susceptibility zones per parish.

	Landslide susceptibility			
Parish	**Low**	**Moderate**	**High**	
St Andrew	89.1	10.1	0.8	
St David	68.4	29.7	1.9	
St George	70.3	27.2	2.5	
St Mark	67.8	27.9	4.4	
St John	69.8	24.9	5.3	
St Patrick	85.8	13.1	1.1	

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.

8. Conclusions and recommendations

8.1. Conclusions

The original aim of this study was to generate a national-scale landslide susceptibility and hazard map using the available data for Grenada. However, 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 Grenada using all available data, making use of many different sources, which was presented in Table 3-2. This is the most complete inventory up to our knowledge.
- We also compiled all available landslide data from different sources, and generated a completely new landslide inventory using multi-temporal visual image interpretation, and generated an extensive landslide database for Grenada.
- We generated a geomorphological map.
- We improved the land use map as much as possible.
- We improved the national building footprint map and added information on occupancy types, and number of people, based on census data.

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 8-2 and 8-4 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 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. 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 different combinations of causal factors. The two susceptibility maps made for rockslides/rockfall and for soil-related landslides were combined into one single map, which is more easy to use by the end users.

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.

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 8-1.

Table 8-1. Characterization of the landslide susceptibility classes.

Susceptibility	Explanation	Characteristics
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: 177.4 km^2 Landslide area: 1.72 hectares Number of landslides: 238 Spatial probability: 0.0001 Landslide density: 1.3 landslides /km^2
Moderate	This class has some probability that landslides might occur, although not very frequent and not with a high density.	Area: 89.4 km^2 Landslide area: 4.8 hectares Number of landslides: 190 Spatial probability: 0.0005 Landslide density: 2.1 landslides /km^2
High	This class has the highest density and frequency of landslides.	Area: 45.8 km^2 Landslide area: 405 hectares Number of landslides: 809 Spatial probability: 0.09 Landslide density: 17.7 landslides /km^2

8.2. Recommendations

This study tried to generate the best possible landslide susceptibility and hazard map at a national scale gievne 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 Grenada. The Ministry of Communications, Works, Physical Development, Public Utilities, ICT & Community Development, and the Ministry of Agriculture, Lands, Forestry, Fisheries & Environment, should collaborate with the NADMA to store the landslide information into a landslide database. However, the current situation is that these data get lost after some years. NADMA receives information about emergencies, which also include landslide events. However, when we asked them for a database they were not able to give this. Also the physical 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. 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 Grenada is highly recommended, as they are 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.

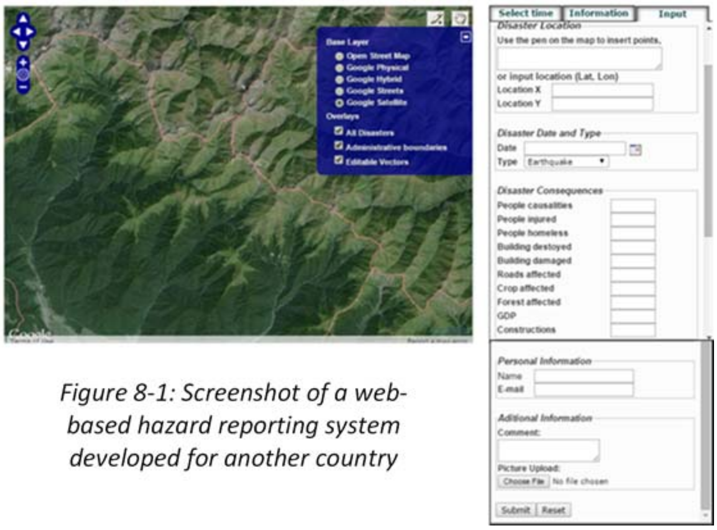

Figure 8-1: Screenshot of a web-based hazard reporting system developed for another country

2. Generating landslide susceptibility map along the road network.

Landslide information along the national road network is not available as a geo-coded dataset, except for the 124 landslide points mapped in 2005 by CDB/CDERA (2006). This is too small to be able to use these in a landslide susceptibility assessment along the road network. Therefore we didn't perform this analysis for Grenada. The method used is presented in Figure 8-2. Such approaches 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).

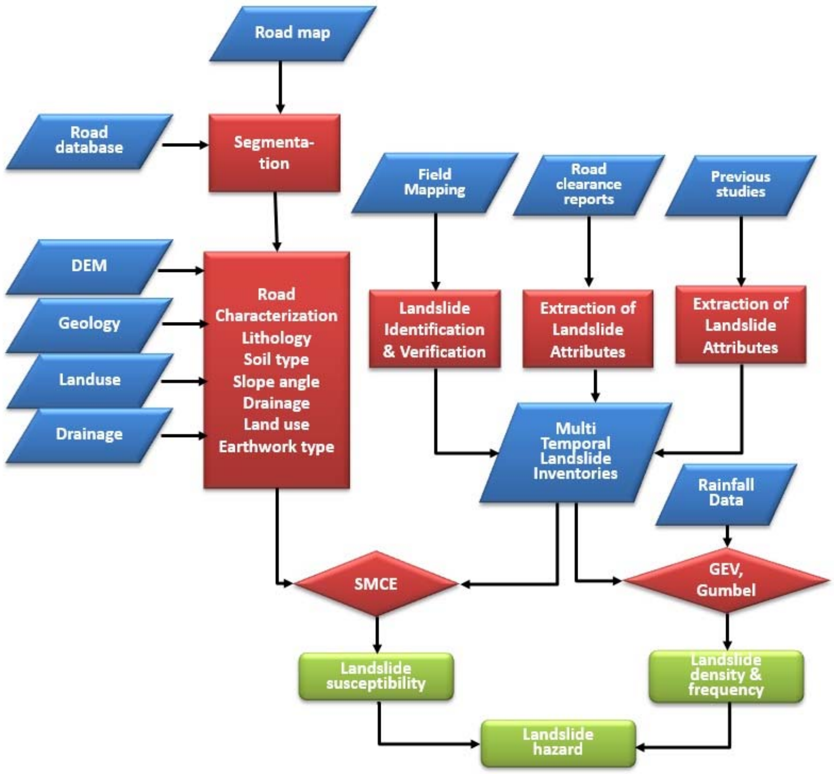

Figure 8-2: Method used for assessing the landslide susceptibility along the national road network in Grenada.

Road segmentation and characterization refers to subdividing the road network into smaller segments that possess the same spatial characteristics. This can be done using available road map, with a subdivision of the roads into the following categories:

- Primary road
- Secondary road
- Tertiary road
- Road under construction

For such a study only the primary road network should be considered. Normally in such type of project a road database from the Ministry of Works should be used. Such a road database should be updated after major changes in the road network. Such a database should contain 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 cutslope, valley or flat, indication of landslide mitigation measures along the road, indication of historical landslide locations along the road, and land use of the area around the road section. These data should be made available for road homogenous road section that have a length preferably of less than 1 km. In the database the road sections should be indicated by their starting and end points, and should be linked to a GIS layer which has the same codes. The lithology, soil type and slope angle of the road segments can be extracted from the available geological map, soil map and digital elevation model (DEM) respectively. For this purpose buffer maps along the road network can be prepared taking a 50 m buffer distances on both sides. For each road segment the upslope side buffer should be identified based on the information obtained from the road database and image interpretation.

Road maintenance and clearance reports should be prepared by the Road Department after each rainfall event that leads to landslides and flooding. Unfortunately no information was available in Grenada for such events, except one in 2005. The results should be stored in the road database, and should also be located with GPS, so a link should be made with a point file of these incidents.

The landslide susceptibility assessment along the road network can also be carried out using Spatial Multi-Criteria Evaluation (SMCE). The basic units are the road segments that are generated from the road database. The criteria tree for Grenada could contain factors such as slope conditions along the road, drainage, material and land use attributes as spatial factors. Under the slope factor, slope type of adjacent ground left and right and slope angle can be included. The slope type of the adjacent ground indicates whether the road segment is a cut-slope, valley or flat section. In the drainage spatial factor, side ditch type left and right can be included. To check the validity of the analysis results also success rate calculations could be made using available landslide inventories along the road. In future such results could be improved when a consistent landslide database would be maintained on the island. Based on the success rate results, the susceptibility map can be classified into three classes of susceptibility level i.e. high, moderate and low.

3. Improve the LiDAR derived DEM for Grenada

Although Grenada has a Digital Elevation Model derived from LiDAR data the data quality of the LiDAR-derived DEM varies considerably. The DEM had one large problem though: the centre of the island was not covered by LiDAR data. We had another raster dataset (also for this we had no metadata) that we used to fill up the hole in the LiDAR data. However, at the boundaries of the missing LiDAR data there are a number of artefacts (errors in the DEM) that gave problems especially in the flood modelling (See Figure 5-2). The areas within the yellow line in Figure 5-2 have a poor data quality. So the landslide susceptibility of this particular zone is less reliable. Users should take this into account when using the map.

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). 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 land use 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.

4. Updated engineering geological map for Grenada

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 Grenada 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. Updating the landslide susceptibility map

It is advisable to update the landslide susceptibility map regularly, as land cover and other relevant contributing factors related to landslide occurrences might change. We advise to update the landslide susceptibility map at least once every five years. We also advise to update the map after every major extreme rainfall event that has triggered a substantial (>15) number of landslides. The updating could be done by organizations in the country, although it is advisable to ask consultants or University of the West Indies to do this work. The landslide susceptibility map should have small high and moderate classes, and as high as possible low susceptibility classes. This means that it is important to incorporate new landslide in the high susceptible class and re-analyze the factors using the method indicated in this report. In the classification of the final susceptibility zones, it is then important to check with success rate curves and adjust the modelling until the highest success rate possible is obtained, which is then used to determine the thresholds between the high, moderate and low classes. It is also important to manually edit the final susceptibility map, as indicated earlier on in this report.

6. Including runout assessment in the susceptibility assessment

This report only discussed the generation of an initiation susceptibility map at a national scale, which was classified into three classes. At this scale it is not yet possible to also analyse runout susceptibility for the entire country, as this would be extremely time consuming with the existing methods. In local scale studies it would be relevant to extract the high susceptible initiation areas, and use these in a regional scale run-out model. One of these models is the Flow-R model, which was developed by the University of Lausanne, and is freely available from the following website: http://www.flow-r.org/ 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 over larger areas. It was successfully applied to different case studies in various countries. 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. It is possible to use different travel angles and maximum stopping velocity for different return periods, assuming that larger triggering events will result in larger landslides with longer travel angles.

The software calculates probably flow paths from source points based on energy line calculations. The energy calculation is illustrated by the below example. Initially the potential energy is converted into kinetic energy, and the most likely flow paths are determined, until the runout reaches a certain distance where the line between the starting points and the end point is characterised by the reach angle, related to the H/L ratio, and the process stops. The method doesn't require source volumes, or rheological parameters. It also doesn't consider entrainment. It can calculate the flow paths 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.

7. Improvement of the HydroMet system for Grenada

We were only able to obtain daily rainfall data for a one station (Maurice bishop International Airport) in Grenada that covers a substantial number of years of data. We have cleaned the data and made them available to the organizations in Grenada. There are also some other rain gauges that have shorter records and some project-related rainfall data (e.g. JICA Early Warning 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 Grenada it may be desirable that the CIMH would take the lead in this. Weather radar will be extremely important as this will allow to measure the spatial distribution of rainfall over the islands, and therefore have better inputs into the flood modelling, and a better correlation of causal factors with landslides. There has been an attempt to manage water related data in Grenada, through the CARIWIN project which launched a web-based platform in 2009 (https://www.mcgill.ca/cariwin/2009/grenadanwis the Cariwin website can be accessed through: 216.110.113.11. Username: demo, Password: demo). The aim was that the National Water Information System would become the official repository for all hydrologic, climate, land, watershed, infrastructure and water related data in Grenada. Currently only the starting page can be accessed but not the actual application. However, this initiative should be brought back to life, perhaps guided directly by the Caribbean Institute for Meteorology and Hydrology.

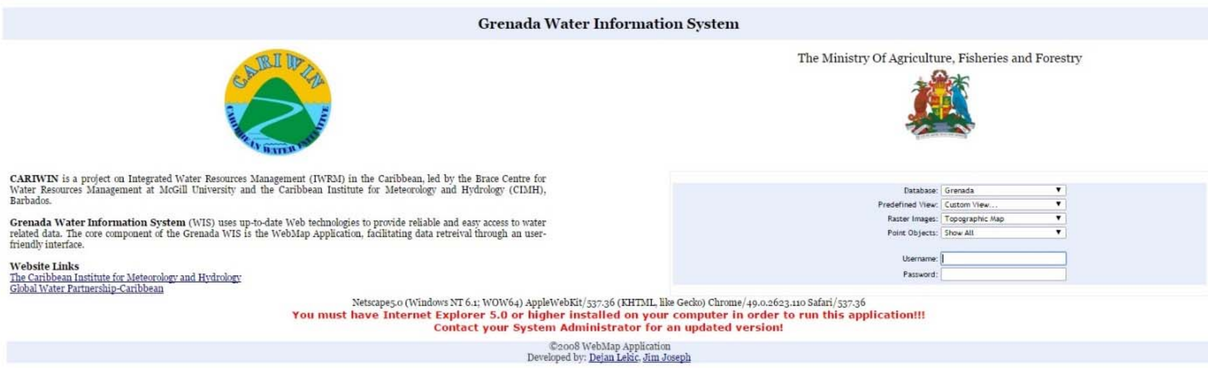

Figure 8-3: Starting page of the Grenada Water Information System under the CARIWIN project

8. 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 Physical Planning Unit and the Roads Unit of the Ministry of Communications, Works, Physical Development, Public Utilities, ICT & Community Development. 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: http://www.charim-geonode.net/people/profile/grenada/?content=layers

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. We have generated the datasets and calculation script for updating the landslide susceptibility maps for each of the countries, and will make these available to interested parties, and possibly also through the GeoNode. The analysis was carried out using the Open software ILWIS, which is also made available.

9. 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.

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