The World Bank

CHARIM
Caribbean Handbook on Risk Information Management

National Scale Landslide Susceptibility Assessment for Saint Lucia

St LUCIA

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Summary

The aim of this study was to generate a national-scale landslide susceptibility map for Saint Lucia. As the available data turned out to be insufficient to generate reliable results, we decided to generate several new data layers, and significantly improved some of the existing data. We generated a new database of disaster events for Saint Lucia, making use of many different sources. This is the most complete inventory to our knowledge. It is quite clear from this database that the landslide reporting became more frequent in recent years, and less information on landslides is available when going back in time, whereas the data on tropical storms and hurricanes seems to be much more constant over time. The underreporting of landslides is a big problem in trying to evaluate landslide frequency/magnitude relations. We also compiled all available landslide occurrence data from different sources. For received great support from the British Geological Survey, as a team from BGS generated new landslide inventory maps for 2010 to 2014 using high resolution satellite images in the framework of the European Space Agency (ESA) "eoworld 2" initiative. Eventually we compiled landslide inventories for 1985, 1995, 2009, 2010, 2011, 2012, 2013, and 2014. The resulting landslide database contains 430 landslides in 1985 (Hurricane Allen), 713 in 1995 (Tropical Storm Debby), 27 in 2009, 1025-1132 in 2010 (Hurricane Tomas), 489 in 2011, 198 in 2012 and 459 in 2013 (Christmas Eve storm). We also compiled landslide inventories along the road network for several events from existing studies (Mott MacDonald, 2013) and maintenance records of the Ministry of Infrastructure, Port Services and Transport. 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 landslides for different frequencies. We analyzed the quality of the input data and conclude that the existing Digital Elevation Data is quite problematic and that there are several areas which lack both topographic as well as geological data. We applied a method for landslide initiation susceptibility assessment that is the best possible, given the availability of data. A bi-variate statistical analysis provided indications on the importance of the possible contributing factors, but the actual combination of the factor maps was done using a subjective expert-based iterative weighing approach using Spatial Multi-Criteria Evaluation (SMCE). The method is transparent, as the stakeholders (e.g. the engineers and planners from the four countries) and other consultants can consult the criteria trees and evaluate the standardization and weights, and make adjustments. The method analyses only landslide initiation susceptibility; landslide runout susceptibility should be included in local and site-investigation studies. The method for landslide susceptibility assessment was further expanded by including the historical landslides in the susceptibility map and by manual editing of the final map. The whole map was visually checked, and the modelled zones of high, moderate and low susceptibility were adapted when necessary, so that they reflect the best situation according to the mapping geomorphologist. This was a rather time consuming activity, but it allowed to analyse the different parts of the map separately, and therefore obtain results that also are a basis for the analysis at a local scale. The manual editing of the susceptibility map was also done to simplify the susceptibility units. In the final landslide susceptibility map, 50% of the area was classified as low susceptibility, 24 % as moderate, and 26 % as high susceptibility. When considering the landslide density, the values for low range from 0.0003 to 0.001, for moderate from 0.0014 to 0.006 and for high from 0.006 to 0.04. In terms of numbers per square kilometre, these values are 0.1 to 0.4 for low, 0.2 to 1.3 for moderate and 1 to 9.6 for high susceptibility. The ranges reflect the expected densities for frequent to rare events. It was very difficult to determine the frequency of the landslide densities due to a lack of sufficient event-based inventories. We have separated four types of events: frequent, moderate, large and major events. We selected landslide inventories with increasing densities to represent these four events. For the road network we also generated a landslide susceptibility map by subdividing the primary road network into homogeneous segments which were characterized by information from a road database provided by Mott MacDonald (2013). We also used SMCE to generate a susceptibility map which we characterized using the available landslide inventories along the road. We calculated the maximum and average landslide density, as the number of landslides per kilometre of road. For the road network we also made an estimation of the average landslide density (as number per kilometer of road) for frequencies. Also exposure analysis was carried out for buildings.

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.

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British Geological Survey NATURAL ENVIRONMENT RESEARCH COUNCIL esa eoworld 2

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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 infrastructure and spatial planning ministries to use hazard and risk information for decision-making.
The main objective of this project is to build capacity of government clients in the Caribbean region, and specifically in the countries of Belize, Dominica, St. Lucia, St. Vincent and the Grenadines and Grenada, to generate landslide and flood hazards and risks information and apply this in disaster risk reduction use cases focusing on planning and infrastructure (i.e. health, education, transport and government buildings) through the development of a handbook and, hazard maps, use cases, and data management strategy. The results of the CHARIM project are shared through a web-based platform: www.charim.net

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

This report addresses specifically the methods and results used for the national-scale landslide susceptibility assessment for the country of Saint Lucia.
It will do so by first introducing the method of analysis, and the reasons for selecting this method in chapter two. In the next chapter (three) we will evaluate the historical data on landslides, floods and other hazards for Saint Lucia, and analyse rainfall data in terms of frequency and relation with landslides.
The fourth chapter presents the various landslide inventories that were compiled and discusses the landslide problems in Saint Lucia. The fifth chapter focuses on the evaluating of the main landslide conditioning factor maps, such as the Digital Elevation Model, geological map, soil map and land cover map. We also identify the quality of the input data.
Chapter six deals with the landslide susceptibility assessment for Saint Lucia. It starts with an explanation of the method used, and presents the results of the bi-variate statistical analysis, which are subsequently used in an expert based method. The final map was visually checked and improved. Chapter seven presents the method for landslide susceptibility assessment along the road network. Chapter eight aims to characterize the landslide susceptibility classes in terms of frequency and density of landslides, and shows the results of a building exposure analysis. The report ends 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 Saint Lucia, it is currently only possible to generate a landslide susceptibility map 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 Saint Lucia previous attempts to generate landslide susceptibility maps have been carried out. In Saint Lucia, in 1985, (DeGraff, 1985) a national landslide hazard assessment was done through the analysis of three factors: geology, geomorphology and topography. The geomorphology was represented by a 1:25,000 landslide inventory map obtained through the interpretation of aerial photographs. For the geology, data published in articles was used, and integrated with a Geology map of all the Caribbean islands to obtain a national geology map. The topography was represented by 3 slope classes. No rainfall information was used, as well as any land cover/use. In 1995 a landslide susceptibility map was generated by Rogers (1995, 1997), based on landslide inventory data from DeGraff, plus additional landslide mapping: airphoto-interpretation of black and white 1:10,000 scale photos of coastal regions from 1991, and field mapping after tropical storm Debby in September 1994.

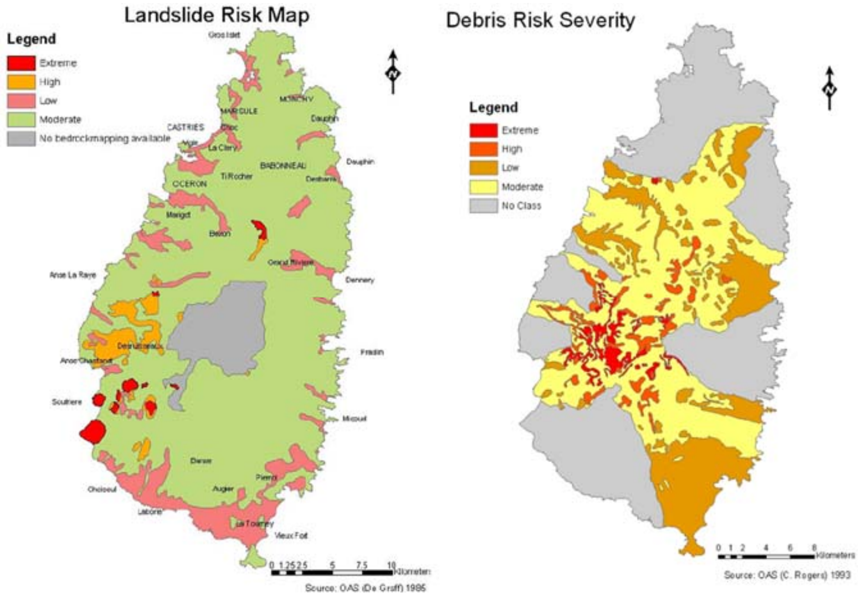

Figure 1-1. Previous landslide susceptibility maps for Saint Lucia: Left: study by DeGraff (1985) for OAS. Right: study carried out by Rogers (1995).

Rogers produced a debris flow susceptibility map using the above mentioned inventories, based on grids of 200 by 200 m. She used four critical factors for debris flow susceptibility assessment: slope gradient, slope curvature, rainfall (mean annual precipitation) and soil type, which were integrated using a weighting approach. The resulting debris flow susceptibility map does not reflect current conditions anymore. After Hurricane Thomas a number of initiatives were taken to address landslide hazards along the road network (Mott Macdonald, 2013). Also extensive work has been done on community-based landslide management in Saint Lucia (Anderson, 1983; Anderson et al., 2011; Holcombe and Anderson, 2010; Holcombe et al., 2011; Anderson and Holcombe, 2013).

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 Saint Lucia. 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.

Step 1: Generating landslide inventories. The first, and very important step is to generate a comprehensive landslide inventory. Several landslide inventories were available for Saint Lucia. However, these are far from complete, and an attempt was made to update these using several sources of information: interpretation of high resolution satellite images, collection of historical information on the dates of occurrence of past landslide events, collection of available data from the national emergency management organisation and from road maintenance records. We were fortunate to be able to use the landslide inventories generated by the British Geological Survey for this project. The resulting landslide inventory map contains many more landslides than were initially available.

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 of relatively poor quality was used for generating derivative maps, such as elevation classes, slope steepness, slope direction and flow accumulation. Exiting geological maps, and soil maps were used. Drainage lines, roads, coastlines and ridges were used to generate distance maps to evaluate the effect of landslide occurrence close to these features. Land cover maps were generated by the BGS using object oriented image classification based on Pleiades images.

Step 4: Bivariate statistical analysis. The weights of evidence modelling (WOE) method 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. 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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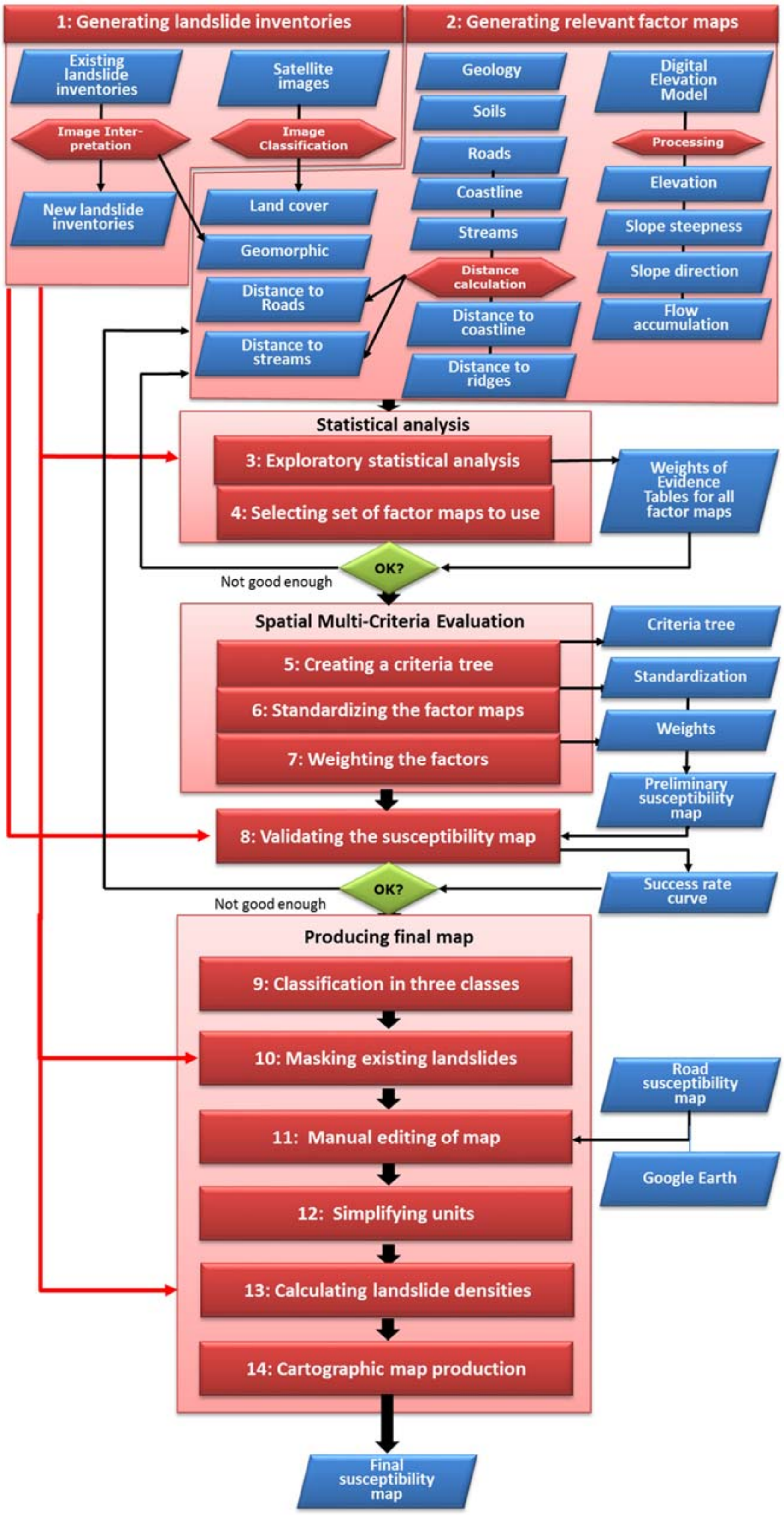

Figure 2-1: Flowchart of the method used for the generation of the national scale landslide susceptibility maps. See text for explanation. See also: http://www.charim.net/use/83

First we generated a *criteria tree* in which we grouped the various causal factors in groups. Then we *standardized* the individual causal factors, based on the calculated weights of evidence. However, we used the calculated weights as a guidance and in several occasions we decided to adjust these as they seemed to be more logical based on our observations in the field and our knowledge on landslide occurrences. The standardization resulted in values for each factor map ranging from 0 to 1

After standardization we weighted the individual factor maps and the various groups by comparing them with each other and by assigning a certain rank to them. This resulted in weights which were also represented in a range of 0 to 1. The last stage of the Spatial Multi-Criteria Evaluation was the generation of a composite index map, which integrated the standardization and weighing for all indicators in the criteria tree, resulting a susceptibility map with values ranging from 0 to 1.

Step 8: Validation of the susceptibility map. In order to validate the susceptibility map we combined the composite index map resulting from the Spatial Multi-Criteria Evaluation with the original landslide inventory maps. 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. 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 we decided to go back to the selection of relevant factor maps and repeated the statistical analysis and the spatial multi-criteria evaluation for other combinations of factors. So the landslide susceptibility assessment was an iterative procedure, which was done until we were satisfied with the results. We also discussed the results with a landslide expert (Jerome DeGraff) that was involved in earlier landslide inventory and susceptibility assessments on the island, and also with a group of professionals from the country that visited ITC in the Netherlands during a period of one month in spring of 2015. Based on their suggestions a number of modifications were made.

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

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

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

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

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

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

2.2. Considerations for selecting this method

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

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

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

- Serve as living and dynamic baseline map for the planning, design, management and implementation of a long-term landslide reduction strategy. This map should be updated regularly as new/improved data become available;
- Include them as a factor in national scale land use planning, by outlining the zones that are most susceptible to landslides;
- Identify the areas where more detailed investigations are required for the planning of critical infrastructure;
- Form the basis for identification of the strategies to increase the resilience of the national road network by prioritizing the development of contingency plans and required complementary studies during planning and design of new infrastructure;

- Use for the prioritization of creation of contingency plans for exposed communities;
- Contribute to inform required expansions of the hydro-met monitoring system as well as monitoring of landslides;
- Inform watershed management, environmental assessments and studies on environmental degradation; and
- Be used to inform the planning of agricultural or mining activities that could increase slope instability.

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

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

The available data. After a first inventory of the existing data we discovered that there were major deficiencies with respect to the available data, both in terms of the available landslide inventories and with the available factor maps for carrying out the analysis. The large heterogeneity of volcanic deposits is unfortunately not portrayed in the available maps for the island. The geological map is rather general and does not focus on the specific volcanic sequences and depth. 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 triggered by which events. Intense rainfall is considered to be the most important trigger of landslides. Even though there might be earthquakes occurring on the island, their expected intensity is generally not considered to be high enough to cause substantial landslide problems. Also human interventions may increase the susceptibility to landslides, e.g. through deforestation, clear cutting, improper drainage practices, or slope cutting, but still a rainfall would be required to actual trigger the landslides.

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, and doesn't contain specific landslide information

We visited the National Emergency Management Organizations (http://www.nemo.gov.lc/home/default.aspx) but they had limited data about historical disasters in the country. 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 Saint Lucia News Online (http://www.stlucianewsonline.com/) was very useful. However, information was only available for a limited period of time. We also collected information from various other sources on the internet. Some of the best sources for older information were Lockhart (1879) and O'Keefe and Conway (1977) for the older disaster occurrences. They based their own data on extensive analysis of newspaper searches for the various countries.

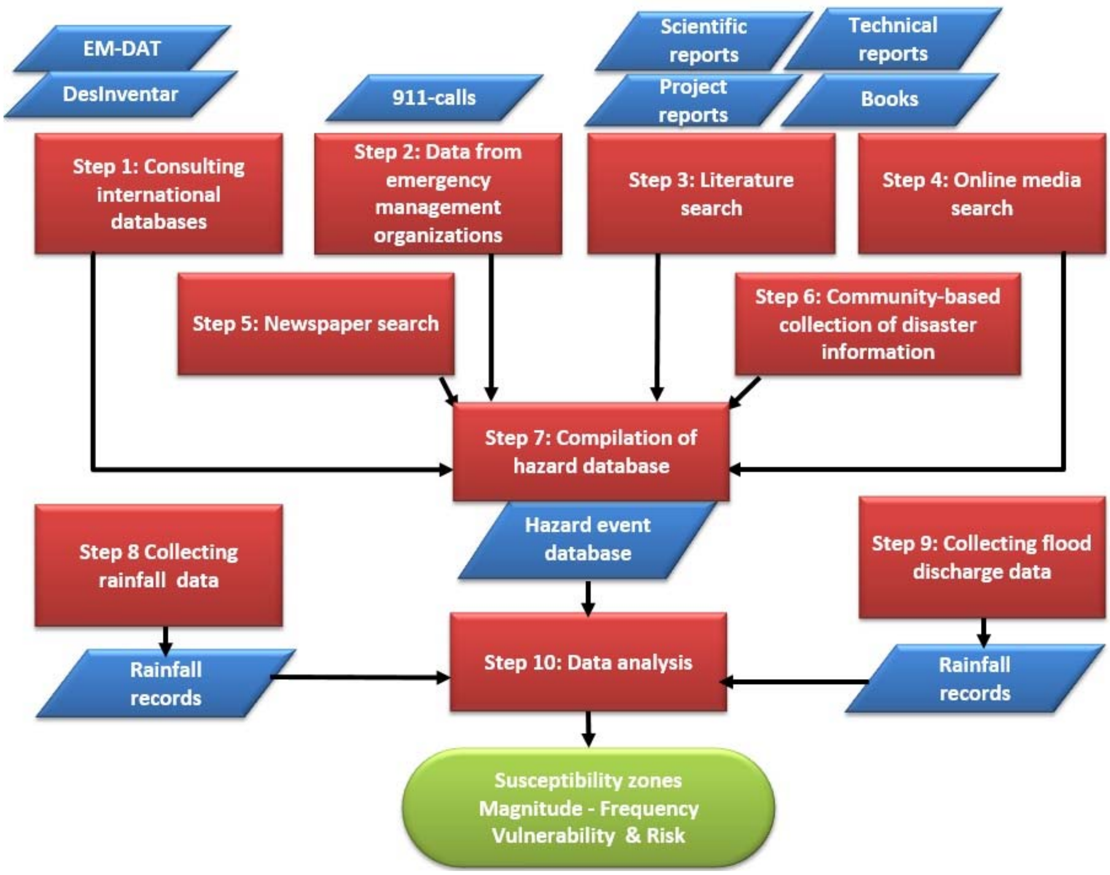

Figure 3-1: Overview of method for collecting information of past events.

We also consulted http://www.hurricanecity.com/city/saintlucia.htm. Road maintenance and clearance reports were obtained from the Ministry of Infrastructure, Port Services and Transport for several rainfall events. The reports don't have any spatial references for the landslide locations, they only have the road sections starting and end point where landslide clearance had been done and the amount of money spent for clearance. To locate those areas and prepare them as geo-spatial dataset, the available high resolution images and thematic maps of the island were used.
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.
Owing to the country's mountainous topography, volcanic geological formation and heavy rainfall St. Lucia is affected by frequent flooding and landslides. Landslide occur in Saint Lucia on an annual basis, however, there are years when the number of landslides is very large as a result of tropical storms or hurricanes. One of such events was reported in 1938 when, within one-hour interval, two landslides developed in the Ravine Excricisses and nearby Ravine Poisson areas, claiming 62 lives and causing 32 injuries (DeGraff et al., 1989). Tropical storm Debby (September 1994) was also devastating in terms of landslides. Numerous debris flows were triggered, resulting in severe losses to the infrastructure and 58% of the banana crop was destroyed (Rogers, 1997).
In 1999 a large slow moving landslide at Black Mallet / Maynard Hill in the southeast of Castries moved approximately 80,000 m^3 of soil, which destroyed several concrete structures and ruptured public utilities. Another landslide problem at Tapion located to the west of the City of Castries happened on September 26, 2004 when approximately 1,800 m^3 of colluvial material moved downslope, resulting in the destabilization of two concrete structures and ruptured public utilities serving the community.
Hurricane Tomas was the worst recent event that struck the country, and happened on October 31 2010. The country experienced a drought period longer than usual before the event, which caused severe damage due to flood and landslides throughout the country. Statistically, windspeed that occurred in this event was a 1 in 15 year event. However, when considering the rainfall the return period was in the order of 1 in 180 years. The disaster killed seven persons and injured 36. The total cost of the damage was estimated to be 336.2 million US dollar which accounts for 43.4% of St. Lucia's GDP. The road infrastructure has suffered badly as result of landslides, river bed erosion and river sedimentation. According to an estimation by the Ministry of Works of Saint Lucia, the transportation subsector has incurred a total damage of 100 million Eastern Caribbean Dollar, around 37.2 million US dollar (ECLAC, 2011).
Road sections around the Canneries, Soufriere and Dennery regions were mostly affected by this event. The extent of the landslides and their effect was still visible in 2014 during fieldwork. For instance, four embankment failures occurred in the Dennery region that destroyed almost half of the road in each failure spot. The failures occurred with 500 meter intervals on average and now the road is being reconstructed (Figure 3-2). In addition, the rock falls occurred in Soufriere region during this event were quite considerable. The falling rocks were on average 1 to 1.5 m^3 in size. Even though, there was no property damage, the road was closed for some time until it was cleared of the rocks. Also landslides occurred in Canneries. This road section was also closed for some time.

Figure 3.2: Landslides along the major roads of Saint Lucia, resulting from Hurricane Tomas that were still visible in 2014

The Christmas Eve trough in 2013, occurred on December 24 2013. This disaster event caused the death of 6 persons and displaced 550. A total of 99.88 Million US dollar damage was reported from different sectors of the country due to the disaster, of which 72% was sustained by transportation infrastructure sector (GSL & WB, 2014). Figure 3-3 shows some of the damage areas resulting from the Christmas Eve event in Saint Lucia, which was more related to flash flooding than to landslides. A landslide inventory map along the major roads of Saint

Lucia was prepared by Mott MacDonald (2013). The inventory mainly contain landslides occurred during hurricane Allen (August, 1980) and hurricane Tomas (October, 2010).

Figure 3-3: Some of the damaged areas during the 2013 Christmas Eve event. Above: landslides along the road to Dennery. Lower Left: culvert failure leading to road collapse and two casualties along Micoud Highway in the Southeast. Lower right: Bailey bridge due to bridge washout at Sapphire (Southwest).

Table 3-1: Landslide damage caused by the 2013 Christmas Eve event (data from Renata Philogene-McKie, MIPST)

Location	Infrastructure Damaged	Description of Damage	Quanitity (m^3)	Cost (EC $)
Morne Fortune	Drains	Land Slippage	50.00	$3,000.00
Barre D'Isle	Road	Land Slippage	297.33	$17,840.00
La Bayee	Road	Land Slippage	116.88	$7,012.50
Canaries	Road	Land Slippage	215.00	$12,900.00
Anse Gallet	Road	Land Slippage	33.33	$2,000.00
Anse Gallet/ Anse La Verde	Road	Land Slippage	41.67	$2,500.00
Anse La Verde	Bridge	Debris on road	25.00	$1,500.00
Anse La Verde	Road & Drain	Land Slippage	116.67	$7,000.00
Anse La Verde	Road	Rock slide and Backfilling to wall washed away	75.00	$4,500.00
Roseau/ Masscre	Road & Drains	Land Slippage	41.67	$2,500.00
Masscre/ Anse La Raye	Road	Land Slippage	33.33	$2,000.00
Anse La Raye/ Anse Gallet	Drains	Land Slippage	41.67	$2,500.00
Anse La Raye	Drains	Land Slippage	83.33	$5,000.00
Anse La Verde/ Canaries	Drains	Rock/Land slides	50.00	$3,000.00
Anse La Verde / Plas Kassav	Drains	Land Slippage	66.67	$4,000.00
Mon Repos Main Road	Road	Land Slippage	166.67	$10,000.00
Soufriere to Bouton	Road	Land Slippage	1,016.67	$61,000.00
Soufriere to Myers Bridge	Road	Land Slippage	550.00	$33,000.00
Belvedere/ Morne Roseau	Road	Land Slippage	950.00	$57,000.00

Landslides can also be triggered by earthquakes. Earthquakes in Saint Lucia derive from two different sources. The Eastern Caribbean is a zone of subduction in which the Atlantic Plate pushes under the Caribbean Plate, causing tectonic earthquakes, which may be quite large (a 7.4 Magnitude earthquake occurred in nearby Martinique in 2007). The second source of earthquakes originates from the seismic events relating to Saint Lucia's origin as a volcanic island, a consequence of plate-tectonic forces (SRU, 2000). Earthquakes have not caused serious disruption in recent times. There is little publicly available information on earthquakes in Saint Lucia (1998, 2004), some of which have reports on a few landslides. However, in a study in the east part of Dominica Andereck (2007) reported that local villages indicated that on a after an earthquake in 2007 a large number of

landslides occurred, after a number of days with intense rainfall. According to Teeuw et al. (2009) there is a possibility for a large earthquake-induced rockslides in the region that might even trigger a potentially dangerous tsunami. Overall, there is a significant chance of earthquakes that may trigger landslides.
Another possible triggering factor for landslides are volcanic eruptions. Volcanic related debris flows (lahars) are common processes during and after volcanic eruptions. There are several clear signs of continuing volcanic activity in Saint Lucia, such as fumarolic activity, and hot springs. However, the probability for a magmatic eruption is quite low (e.g. any time within the next 800 years). Therefore the relation with landslides as triggering factor is not so relevant on the short term. Also it is not really possible to include the volcanic hazard maps in the spatial planning, as the high hazard area cover many of the current settlements. There is a large level of uncertainty as to the probability for new eruptions: when and where.
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 Saint Lucia. If it would be possible to establish a relation between the magnitude of the event (e.g. hurricane category or associated rainfall amount), its frequency and the number of landslides generated (or the density pf landslides within the various susceptibility zones) we could make an estimation of the landslide hazard (probability of occurrence). This be attempted later on in this chapter.

Table 3-2 provides the compiled historical disaster data for Saint Lucia, 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. It is quite clear from this table that the landslide reporting becomes more frequent in recent years, and less and less information on landslides is available when going back in time, whereas the data on tropical storms and hurricanes seems to be much more constant over time. The underreporting of landslides is a big problem in trying to evaluate landslide frequency/magnitude relations. Also because no proper landslide inventories are available for different magnitudes of rainfall events. In the next section we will analyse the relation between landslides and rainfall.

Table 3-2: Historical disaster events in Saint Lucia collected from different sources. See also http://www.charim.net/stlucia/historical

Year	Day	Events	Notes	Information available
1872	09-20/09/1872	Hurricane	NI	
1875	08-18/09/1875	Hurricane	NI	
1876	01/11/1876	Hurricane	NI	
1879	09-16/10/1879	Tropical Storm	NI	
1880	15-20-08/1880	Hurricane	NI	
1886	15-27/08/1886	Hurricane	NI	
1887	08/08/1887	Tropical Storm	NI	
1887	11-22/09/1887	Hurricane	NI	
1888	01-08/11/1888	Tropical Storm	NI	
1891	18-25/08/1891	Hurricane	NI	
1894	11-20/10/1894	Tropical Storm	Landslides and Flooding	
1895	22-30/08/1895	Hurricane	NI	
1896	11/09/1896	Tropical Storm	Landslides and Flooding	
1898	05-20/09/1898	Hurricane	NI	
1901	04-13/07/1901	Hurricane	NI	
1903	06-16/08/1903	Hurricane	NI	
1916	10-22/07/1916	Hurricane	NI	
1916	12-20/08/1916	Hurricane	NI	
1916	06-15/10/1916	Tropical Storm	NI	
1917	20-30/09/1917	Hurricane	NI	
1918	09-14/09/1918	Tropical Storm	NI	
1921	10-9-1921	Tropical Storm	Landslides and Flooding	
1924	16-18/08/1924	Hurricane	NI	
1928	19-9-1928	Tropical Storm	Landslides and Flooding	
1931	10-21/08/1931	Tropical Storm	NI	
1938	21-11-1938	Tropical Storm	Landslides and Flooding	
1938	22-11-1938	Tropical Storm	Landslides Ravine Excricisses and nearby Ravine Poisson areas, claiming 99 lives	
1939	7-1-1939	Tropical Storm	Landslides Ravine Poisson and Flooding	
1940	7-8-1940	Tropical Storm	Landslides and Flooding	
1941	23-30/09/1941	Hurricane	NI	
1942	21-31/08/1942	Hurricane	NI	

1942	15-22/09/1942	Tropical Storm	NI	
1943	11-18/10/1943	Hurricane	NI	
1948	1-9-1948	Tropical Storm	NI	
1949	3-9-1949	Tropical Storm	NI	
1951	5-9-1951	Hurricane Dog	NI	
1954	12-12-1954	Tropical Storm	Landslides Ravine Poisson and Flooding	
1958	4-7-1958	Tropical Storm	Landslides and Flooding	
1958	6-9-1958	Hurricane Ella	NI	
1960	10-7-1960	Hurricane Abbey	Landslides in Fond St Jacques, 6 persons killed and EC 4$ million damage	
1963	24-9-1963	Hurricane Edith	NI	
1965	27-9-1965	Hurricane Betsy	NI	
1965	25-10-1965	Tropical Storm	Landslides and Flooding	
1966	jun-66	Tropical Storm	Landslides and Flooding	
1966	27-30/09/1966	Tropical Storm Judith	NI	
1967	8-9-1967	Hurricane Beulah	NI	
1967	26-9-1967	Tropical Storm Edith	NI	
1969	25-27/07/1969	Tropical Depression	NI	
1970	17-23/08/1970	Tropical Storm Dorothy	NI	
1970	2-10-1970	Tropical Depression	Landslides and Flooding	
1971	18-25/08/1971	Tropical Storm Chole	NI	
1976	03-12/10/1976	Tropical Depression	NI	
1979	19-24/06/1979	Tropical Storm Ana	NI	
1980	3-8-1980	Hurricane Allen	Widespread landslides particular Barre de l'isle	
1981	nov-81	Storm	Landslides	
1983	23-7-1983	Storm	NI	
1984	24-26/07/1984	Tropical Depression	NI	1985 map De GRaff
1988	11-9-1988	Tropical Storm Gilbert	Landslides reported	
1990	6-11-1990	NI	Landslides More du Don	
1992	29-11-1992	NI	Landslides	
1993	14-17/08/1993	Tropical Storm Cindy	NI	
1994	09-10/10/1994	Tropical Storm Debby	More than 400 Landslides shallow debris flow in the upper areas, debris and rock slides along roads. 3 persons killed, EC $ 250 million damage.	Mapped by Cassandra Rogers
1995	7-9-1995	Hurricane Iris	Landslides Millet Primary school,	
1998	sep-98	Earthquake and incessant rain	Landslides Boguis	
1999	7-10-1999	Seismic Event	Soil creep and slow gravitational movement and Flooding. Black Mallet/ Maynard Hill near Castries: slow moving landslides. 80,000 m^3	
2001	14-22/08/2001	Tropical Storm Chantal	NI	
2001	04-09/10/2001	Tropical Storm Jerry and Hurricane Iris	NI	
2003	07-17/07/2003	Hurricane Claudette	NI	
2004	03-14/08/2004	Tropical Storm Bonnie	NI	
2004	26-9-2004	Seismic Event ?	Landslides Tapion , 1800 m3 destroying 2 buildings rupturing pipes. Hospital out of function for some time.	
2005	1-7-2005	Heavy rainfall prior to the failure	Landslide Windjammer Landing Beach Resort	
2007	13-23/08/2007	Hurricane Dean	NI	
2010	30-31/10/2010	Hurricane Tomas	Many landsides Colombette, Fond St Jacques, along the Barre De L'ile, Millet and on the hills east and south of Castries	BGS landslide inventory Rock and Abrahams landslide inventory
2013	24-12-2013	Christmas Eve trough	Several landslides along the roads	BGS landslide inventory

3.2 Rainfall analysis

Rainfall records from 18 stations were obtained for Saint Lucia. All the stations have records on daily and hourly basis. Since the daily rainfall data contain longer period records than the hourly, the hourly records were not taken into consideration. The daily rainfall records are available for a period ranging from 26 to 51 years on different stations. For the purpose of this study, the stations with the longest record period (51 years) were considered. Nine stations have 51 years record (1955 - 2005), these stations are: Barre De L'Isle, Barthe, George V. Park, Mahaut, Mamiku, Patience, Soucis, Troumasse and Union Agricultural station. Nevertheless, all of these stations have missing data in the middle, five of them even 25 % and more missing data. For instance, Mahaut station has 9512 missing data i.e. more than 50 % of the expected 18628 records for 51 years. We decided to consider only stations with fewer missing data for the analysis: Barre De L'Isle, Barthe and Union. Out of these stations, Barthe and Barre De L'Isle were chosen for the final analysis, considering their spatial representation. Barthe is located in the south west of the island and it is in proximity to the Soufriere region, with road sections affected by frequent landslide occurrences. Barre De L'Isle is located in the middle of the island, which is also in proximity to the other landslide susceptible road section i.e. Barre De L'Isle section of the east coast road. Figure 3-4 shows the geographical location of the stations on the island.

Many of the stations have been upgraded to full automatic stations from 2003 onward with measurements at 1 minute resolution. However of these stations, 2005-2008 were frequently missing and there are spurious values (intensities impossible with respect to the maximum a tipping bucket can record which usually lies around 270 mm/h).

Due to the many data gaps in the records of the stations only two stations Barre De L’Isle and Barthe were considered in Saint Lucia for the analysis. The analysis was made taking the annual daily maxima for each record period, which resulted to 51 records for each station. Figure 3-5 shows the annual daily maximum rainfall of each recording period in the two stations together with the known landslide occurrence events. The records show that the rainfall in both Barre De L'Isle and Barthe stations are almost similar, with maximum annual daily maxima of 464.8 mm and 482.6mm and average annual daily maxima of 121.7 mm and 124.7 mm respectively.

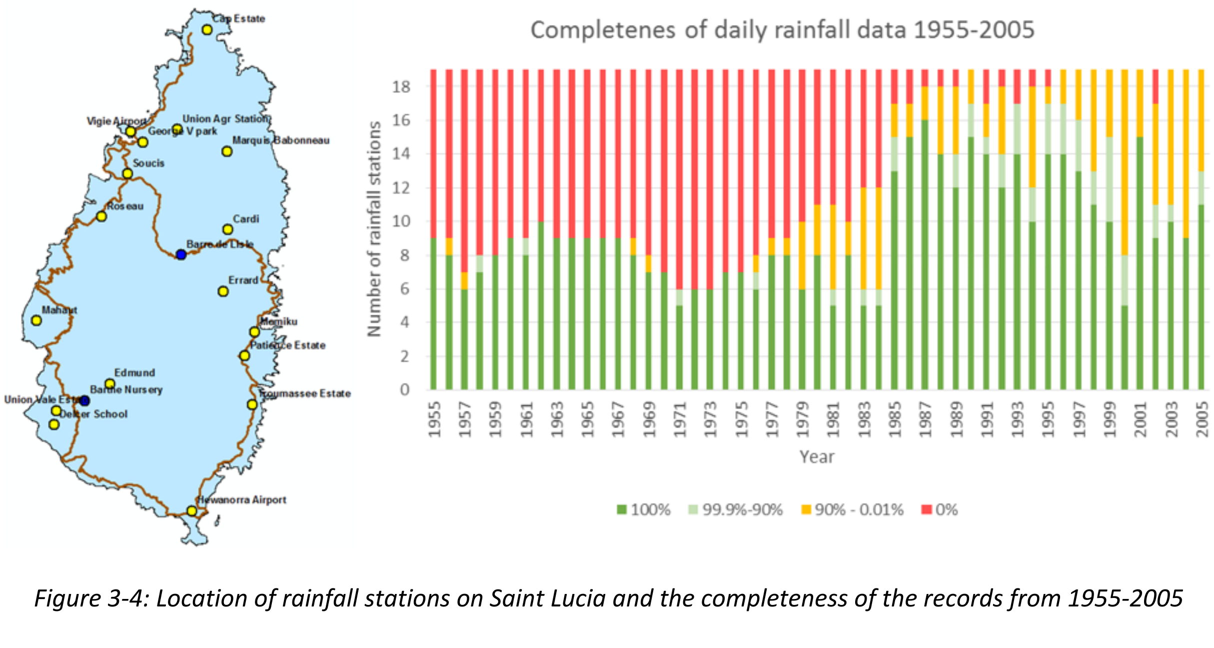

Figure 3-4: Location of rainfall stations on Saint Lucia and the completeness of the records from 1955-2005

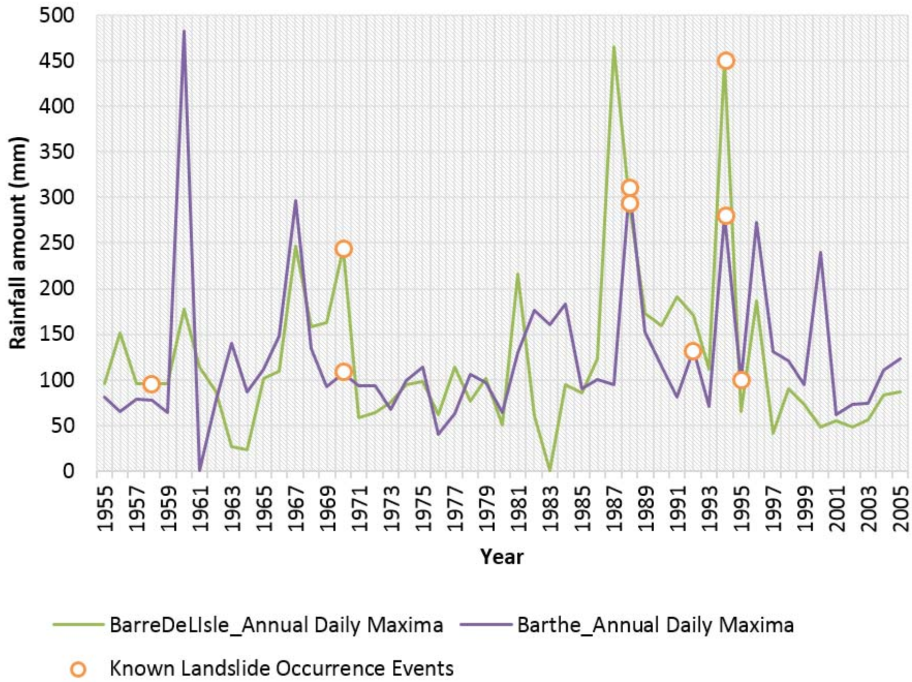

Figure 3-5. Annual daily maxima rainfall amount for two rainfall stations of Saint Lucia

3.1.1 Analysing the distribution of rainfall over the island

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

For the nearby island of Dominica, we analysed the rainfall variation over the island. The availability of a series of rain gauges from a US research project called DOMEX made it possible to evaluate the trend of rainfall with altitude. The DOMEX project installed 10 stations with data from 2008 to 2013 (Figure 3-6). The result plotted rain data with elevation is note that the rain increases with increasing altitude (Figure 3-7). When comparing the rainfall for the stations Rosalie (RO) and Melville Hall (ML) one the east sides, and Botanical Gardens (BG) and Grand Fond (GF) on the western side (Figure 3-6) it is visible that on the eastern slopes the rainfall amount is slightly higher. There is some seasonality to the rainfall distribution but the amounts typically range from 500 cm to over 900 cm annually. This rainfall coupled with the island’s steep topography contributes to the increased chance of landslide and floods. When considering the landslide distribution, more unstable areas are located on the southern and south eastern slopes and on the highlands in the centre of the country. The result show that the rainfall is generally higher on the eastern side, as hurricanes universally come from this direction

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

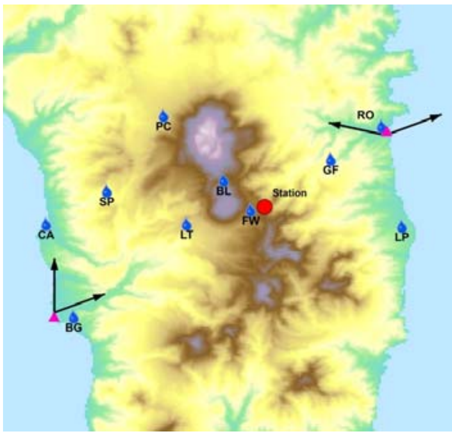

Figure 3-6: Location of 10 rain gauges installed for the DOMEX project at different altitudes and sides of the island in Dominica (Source: http://www.domex2011.com/rain-gauge-network)

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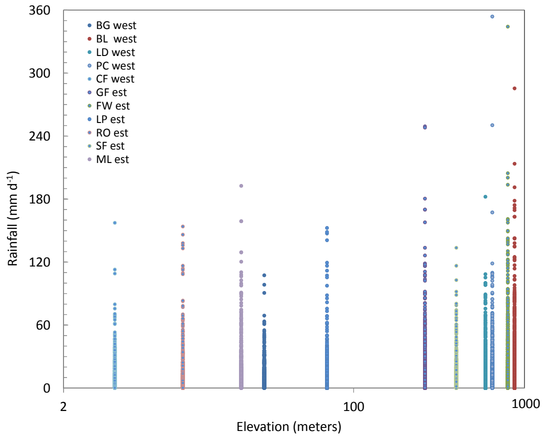


Figure 3-7: Relation between rainfall and elevation on Dominica for different rain gauges.

From Figure 3-8 it is interesting to note that there is good correlation between the elevation and rainfall. Only the 98th percentiles presents a lower correlation, perhaps this is due to a more chaotic pattern of rainfall during extreme precipitation. It is noted also a more pluviometrical gradient as the percentile distribution increases.

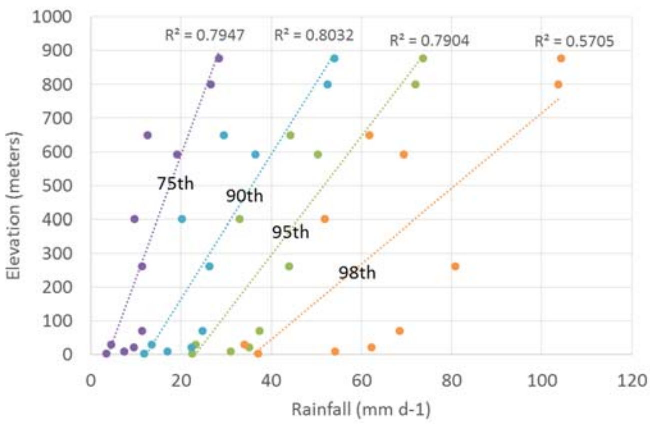


Figure 3-8: Percentiles distribution (from 75th to 98th) of rainfall-elevation relationship with related interpolation line

3.1.2 Evaluation of rainfall thresholds

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

For rainfall threshold we did not have enough data to carry out the work in Saint Lucia, but we used data from the nearby island of Dominica. In the case of Dominica we only have daily rainfall available for the period from 1977 to 2013, for two stations: Melville Hall Airport at 22 meters above sea level on the east side, and Canefield airport on the west side at 4 meters above sea level. Based on the known landslide triggering days derived from Table 3-5 we selected rainfall data from one of the two rain gauges depending on the nearest location (west or east side of the island). Figure 3-9 shows, in log-mm scale, the rain that occurred on the day that triggered the landslide (called Rainfall Event, Re) in mm on the y-axis, and the normalized antecedent rainfall (NAR) over 5 days on the x-axis. We have normalized it for the average annual precipitation over 32 years. We were able to use 28 empirical rainfall days for known landslide initiation in Dominica, in a 38-year period (plotted in the figure as orange points). The blue dots represent rain days without reported landslide events. The manually defined threshold in blue represented in the graph is the minimum quantity necessary to trigger a landslide (Guzzetti et al., 2007), and the blurred blue area that bounded the blue threshold is the uncertainty range which was determined visually. The equation for the threshold follows an S-shaped curve with the following equation:

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

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

As can be seen in the figure 3-9 we have plotted both the events where landslides have occurred, and the events that do not have reported landslides. Therefore, while analysing the result, we have in the area above the thresholds, more false alarms that true alarms. This makes the application of such thresholds rather problematic, for landslide hazard assessment in Dominica given the current availability of data. The poor separation of landslide days from non-landslide days is probably due to several reasons. It could be that the rain (blue dots) which falls above the line took place only around the rain gauge considered and the rest of island didn't receive the same amount rain to trigger landslides. Another reason could be that landslides weren't recorded. And also the orographic effects that play an important role as we saw before are not taken into account.

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

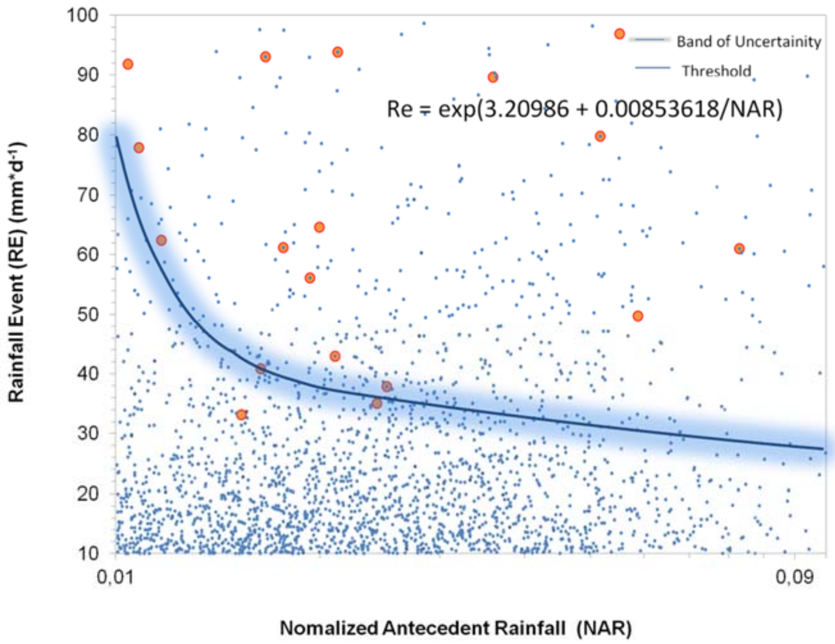


Figure 3-9: Landslide rainfall threshold for Dominica. RE is the threshold rainfall, and NAR is the 5-day antecedent rainfall; the orange points are the reported landslide events; blue points are the rainfall days without landslides, the blue line is the estimated rainfall threshold; the blurred blue area is the band of uncertainty which was visually identified.

3.1.3 Rainfall frequency analysis

An important part of the rainfall analysis was to look at the extremes, but this cannot be done by regarding each station as a separate entity, independent of the others. A major rainfall event should influence many or all stations on the same date to some extent and it is assumed that a large daily rainfall cannot occur in one station only. However, not all stations always record an event on the same day, sometimes a value is the sum of several days, see Figure 3-11. This is an example of Tropical Storm Debby (9/9/1994). It shows that for some records, the instrument has not been read for a number of days, and the rainfall is therefore an accumulated reading (stations Cap and Hewanorra). It was therefore assumed that the maximum recorded daily rainfall in a 10 day period is from the same storm event.

The daily records were extended by the automatic stations that functioned after 2006, which have recorded rainfall in 1 minute time steps. Again these records were checked and corrected for spurious data, and translated to annual daily maxima.

Initially Gumbel distributions were fitted to each station. A Gumbel distribution is a special case of Generalized Extreme Value distributions, suitable for right hand skewed datasets (such as rainfall that cannot be less than 0, but can have extreme maxima). The Gumbel distribution assumes a double logarithmic relation between the maximum rainfall R and the return period T. The return period is the inverse of the probability P. As an example, Figure 3-12 shows the Gumbel analysis of George V Park in Castries. The station is close to Bois d'Orange River and Choc river, that are both known to flood occasionally. It can be seen that a Gumbel analysis linearizes a part of the data, but the 6 highest values are not on the same line. When searching for the dates corresponding to these days, it appears that the 4 largest at least are known class 5 hurricanes (NOAA Hurricane Database, http://www.nhc.noaa.gov/).

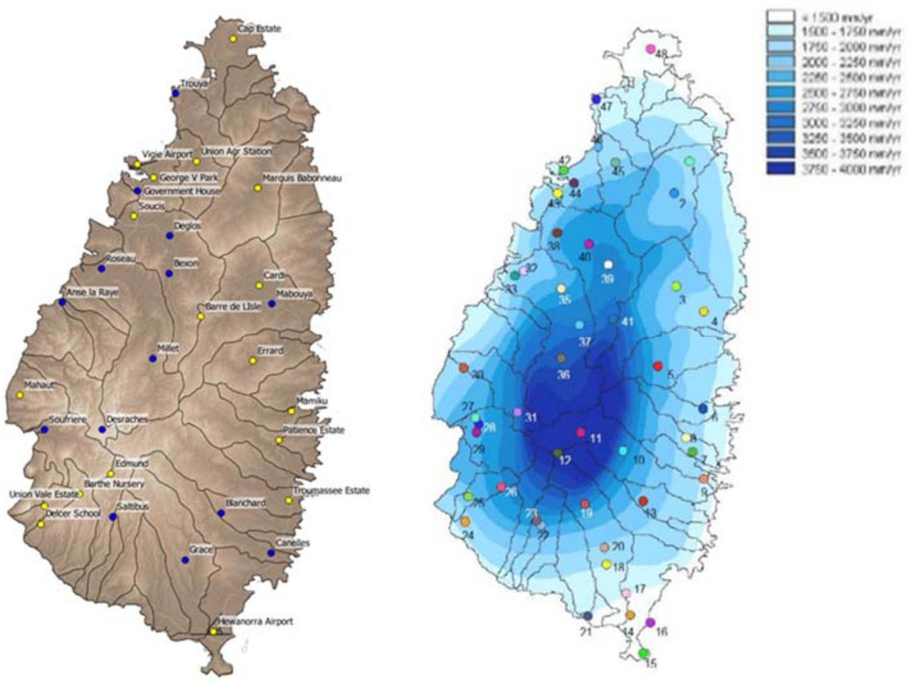


Figure 3-10: Rainfall stations on St Lucia. Left: stations represented as yellow dots are used in the frequency magnitude analysis (1955-2005). Right: average annual rainfall, ranging from 1500 mm/year (white) to 4000 mm/y (dark blue), by Marmagne and Fabrègue (2013)

Day	Month	Year	Soucis	Barre De Lisle	Barthe	Cap	Delcer	Errard	Hewanorra	Troumasse	Union	Union Vale	Vigie
8	Sep	1994	19	14.8	14.6	0	9.3	7.2	1.5	2.8	6.2	9.1	11
9	Sep	1994	230	450	280	0	244.9	323.6	0	184.1	275.6	259	238
10	Sep	1994	20.8	0	30	0	17.2	17.7	212	78.2	30.1	20	10.3
11	Sep	1994	0	0.1	1.2	0	2.2	0	1.6	0	0	1.1	0
12	Sep	1994	3.7	2.3	0.5	200	0	2.9	0	2.7	0	0.1	0.3
13	Sep	1994	3.6	1.7	2.6	0	0.1	0	0	0.8	1.1	0.3	2.1

Figure 3-11: Example of station recordings for Tropical Storm Debby on 9 Sep 94. Arrows show likely delayed readings.

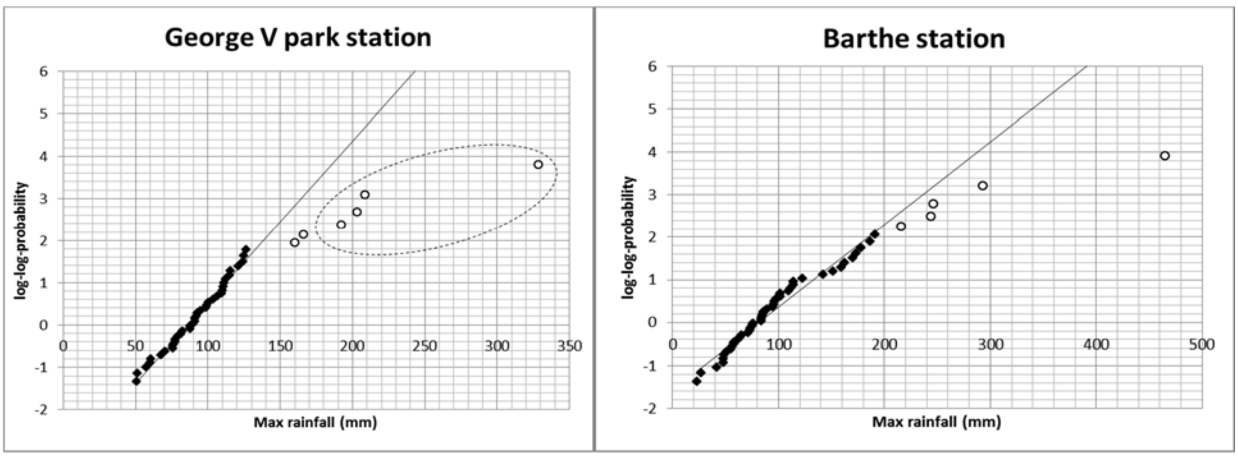


Figure 3-12: Example Gumbel analysis of maximum daily values of Barthe station and George V park station (1955-2005). The four encircled highest values for George V park correspond from low to high to category 5 hurricanes: Aug-Sep 1960 –Donna; Aug-Sep 1980 –Allen; Sep 1988 –Gilbert and Sep 1967 –Buela. For Barthe the highest values correspond with: Oct 1970 – Tropical depression 19, hurricanes Buela and Gilbert and May 1987 tropical depression 1.

Two conclusions are drawn from this:

- The Gumbel analysis does not succeed in fitting the entire dataset of each station, the data is too skewed.
- The hurricane data is not enough for a separate statistical analysis, as there are "only" 4-6 years per station with hurricanes and tropical storms.

It was decided to abandon Gumbel and use a Generalized Extreme Value (GEV) distribution fit. The equation has more parameters that allow for a better linearization of the data (see e.g. Coles, 2001). Each station was fitted with a GEV distribution. The parameters of the distribution are given in Figure 3-13. The stations are grouped with respect to their location on the island: the near coastal stations in the east (E), the near coastal stations in the west (W) and the stations further from the coast towards the centre of the island (C). This grouping was done to explore if there are differences relative to the position of the station. According to Klein Tank et al. (2009), mu and sigma are location parameters that are surprisingly stationary and can be averaged for different stations, while k is a shape parameter that has a more local nature. Figure 3-14 shows the curves using the averages of the fit parameters k, mu and sigma: it can be seen that the east and west of the island show very little difference in return periods structure, while the centre of the island has much higher daily maxima for the same return period values.

It was decided to simply use the average of the fitting parameters of all stations. Because there are 12 coastal zone stations and 5 inland stations in the dataset, this gives a weighted average, i.a. the coastal zone stations dominate. This was considered acceptable as most inhabitation is in the coastal zone.

Station	k	sigma	mu	n	max P	nr days active	loc.
Edmund	0.2	57.3	113.1	21	*450.0*	6325	C
CARDI	0.5	19.9	74.5	21	*403.0*	4841	C
Barthe	0.4	31.5	86.0	52	*482.6*	17991	C
Barre de Lille	0.2	49.3	65.2	54	*464.8*	16862	C
Errard	0.3	52.0	103.2	19	*429.2*	6453	C
Vigie	0.4	25.7	81.9	21	*270.1*	7670	E
UnionVale	0.2	37.3	83.5	30	*268.5*	8629	E
Union	0.2	32.4	87.1	54	*293.4*	18237	E
Soucis	0.3	23.7	69.5	36	*249.2*	11019	E
GeorgeV Park	0.2	28.2	81.9	44	*328.9*	14421	E
Delcer	0.1	53.3	84.7	21	*244.9*	7150	E
Cap	0.2	38.2	82.3	44	*304.8*	15258	E
Troumasse	0.1	47.8	84.2	45	*336.3*	12739	W
Patience	0.1	30.0	82.6	52	*343.8*	17286	W
Marquis de Bab.	0.1	39.6	86.6	47	*345.2*	14454	W
Mahaut	0.1	43.5	93.2	28	*280.9*	9116	W
Hewanorra	0.1	39.4	86.8	21	*245.3*	7670	W

Generalized Extreme Value Distribution

Parameters

k - continuous shape parameter
σ - continuous scale parameter ($\sigma > 0$)
μ - continuous location parameter

Domain

$$1 + k\frac{(x-\mu)}{\sigma} > 0 \quad \text{for} \quad k \neq 0$$
$$-\infty < x < +\infty \quad \text{for} \quad k = 0$$

Probability Density Function

$$f(x) = \begin{cases} \frac{1}{\sigma}\exp\left(-(1+kz)^{-1/k}\right)(1+kz)^{-1-1/k} & k \neq 0 \\ \frac{1}{\sigma}\exp(-z-\exp(-z)) & k = 0 \end{cases}$$

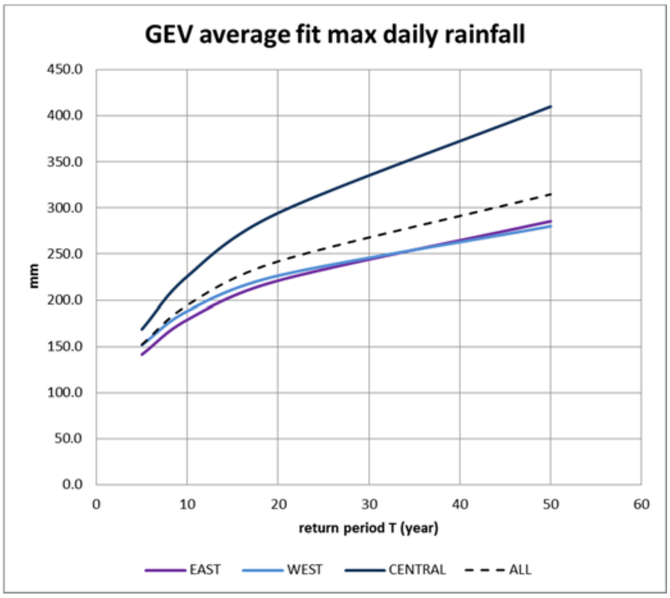
Cumulative Distribution Function

$$F(x) = \begin{cases} \exp\left(-(1+kz)^{-1/k}\right) & k \neq 0 \\ \exp(-\exp(-z)) & k = 0 \end{cases}$$

where $z \equiv \frac{x-\mu}{\sigma}$

Figure 3-13. Left: GEV distribution fit parameters for 19 stations. The indication E, W and C corresponds to stations near the east coast, near the west coast and closer to the center of the island. Right: GEV equations.

Looking at the GEV analysis of the other islands in CHARIM (Grenada, St Vincent and the Grenadines, and Dominica), a north south gradient can be clearly seen in the design storm depth based on the GEV analysis of daily maxima. A possible explanation lies in the nature of hurricanes and severe tropical storms, they cross the Atlantic at the equator and veer north due to Coriolis forces. They influence local weather systems as well, which possibly leads to a North-South gradient in amount of rainfall in the Caribbean. However it should be noted that apart from Saint Lucia, the other islands have only 1 or 2 stations with long records, normally near the airport or the capital. A north-south trend should be seen as a possible indication at best.



T	EAST	WEST	CENTRAL	ALL
5	141.5	151.8	168.8	152.3
10	179.1	188.5	225.8	194.6
20	221.1	226.5	294.5	242.0
50	285.6	280.2	410.1	314.8

Figure 3-14. Left: GEV analysis of stations in Saint Lucia. The coastal zone stations for the east and west side of the island are not significantly different. Right: the corresponding return period T and average daily maximum values used in the hazard analysis.

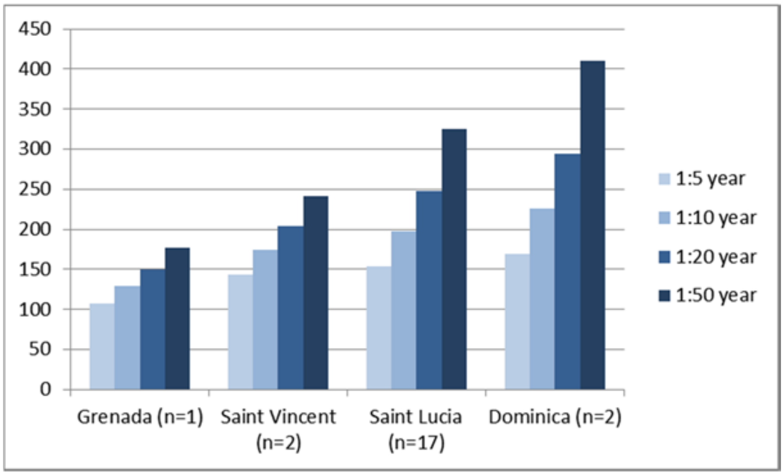


Figure 3-15. Return periods and daily maxima from GEV analyses of rainfall stations at the 4 islands in CHARIM.

4. Landslide inventory mapping

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

Landslides are generally isolated, rather small but frequent occurring events. In a tropical environment such as Saint Lucia 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 Saint Lucia as well. No agency feels responsible to collect landslide locations and dates, and keep a database up-to-date. The National Emergency Management Organization (NEMO) 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 Infrastructure, Port Services and Transport does collect road maintenance reports, and also keeps these records for a number of years. However they are not converted into an updatable landslide database. Therefore the valuable data on landslide locations and occurrence dates is quickly lost. However, there seems to be a growing awareness of the importance of collecting such information, and some of the recent events have been described in reports. That is why all landslide inventories have been generated by consultants, organizations and individuals from outside the islands. For Saint Lucia there are relatively more landslide reports available than for the other CHARIM countries (See Table 4-1).

The baseline study for landslides in Dominica is the work carried out by Jerome DeGraff from the US Forest Service for the OAS in 1985. He carried out detailed image interpretation of landslides using stereoscopic image interpretation of 1:20,000 scale black and white aerial photographs, which were taken in 1984, so five years after the occurrence of Hurricane Allen, which was very destructive in Saint Lucia. The aerial photos covered the entire island with the exception of a mile-wide strip from north to south in the east-central part of the island. DeGraff differentiated mapped landslides with a minimum size of 2000 m^2 and also differentiated between main landslide types (fall, slide, flow). He also carried out extensive field checking in 1985. DeGraff mentions in the report (DeGraff, 1985) that in this environment it is difficult to identify landslides that are older than a few years. He indicated that rockslides and rockfall are frequent along the cliff coasts, and that most of these slope are considered landslide prone. Also inland cliffs in ignimbrite present frequent rockfall problems. Debris slides are also common, but the main landslide type is debris flows. DeGraff also carried out similar work in Dominica and St. Vincent. Table 4-2 summarizes the results. Figure 4-1 shows an example of one of the landslide inventory maps. Unfortunately these were only available as scanned maps. The landslides were digitized and included in the inventory of 1995 by Rogers. The inventory is expected to represent the situation caused by hurricane Allen in 1980.

In 1995 a landslide susceptibility map was generated by Rogers (1995, 1997), based on landslide inventory data from DeGraff, plus additional landslide mapping: airphoto-interpretation of black and white 1:10,000 scale photos of coastal regions from 1991, and field mapping after tropical storm Debby in September 1994. Rogers produced a debris flow susceptibility map using the above mentioned inventories, based on grids of 200 by 200 m. She used four critical factors for debris flow susceptibility assessment: slope gradient, slope curvature, rainfall (mean annual precipitation) and soil type, and used a weighting approach. The resulting debris flow susceptibility map does not reflect current conditions anymore (See Figure 1-1). The landslide inventory map is available as a point map. However, the map seems to have a significant positional error, as in many locations landslide points do not seem to be located in sites where landslides could have occurred.

Table 4. 1: Available landslide work in Saint Lucia

Year	Author	Landslide inventory?	Characteristics
1985	DeGraff	Only as scanned paper maps	For OAS. The report presents maps of landslides detected through interpretation of 1:15000 scale black and white aerial photography taken in 1977 and 1981 combined with field study in selected areas. The landslides points are included in the one from 1995
1995	C. Rogers	Yes, as points	Post Tropical Storm Debby landslide hazard assessment study. The map incorporates the landslides mapped by DeGraff (1985), and new ones were added by Image interpretation for the period 1985 – 1991, and fieldwork after Tropical Storm Debby (1994). Landslide inventory available. Landslides were mapped as points
1998	Hunting Technical Services and Mott MacDonald	No	Watershed and Environmental Management Plan Phase II Final Report. Funded by the World Bank following Tropical Storm Debby. Based on daily rainfall a study was done between rainfall intensity and landslide occurrences. There was poor correlation between the estimated intensity and landslide density, attributed to a bias landslide inventory and limitations in the use of maximum daily rainfall as an estimate of landslide intensity.
2006	MoSSaiC. Anderson et al. Anderson and Holcombe (2013)	No	MoSSaiC: Management of Slope Stability in Communities, was a government led, World Bank funded project that used a community-based and scientific approach for delivering landslide hazard reduction measures in five vulnerable communities. Results were documented in academic journal articles and in a book published in 2013.
2006	CDB/CDERA	No	Landslide Hazard Maps for St. Lucia and Grenada. CDB/CDERA. Landslide susceptibility assessment using the following factors: • Slope – the steepness of the hill slope, expressed as a percentage • Slope Aspect – the orientation of the hill slope to the prevailing winds • Elevation – used as a surrogate for the influence of rainfall intensity • Geology – the underlying bedrock units from geologic surveys • Soils – soil mapping units from soil surveys The maps are not included in the copy of the report available online and have not been found with local departments.
2010	Abraham and Rock	Yes, as polygons	They mapped the landslides from hurricane Tomas from a high resolution RapidEye image, and produced a digital polygon-based inventory map
2012	P. Quinn and Alex Strouth for BGC	Yes, as points	They collected landslide information along the national road network. He also generated a landslide susceptibility map on a national scale based on the inventory used in the CDB/CDERA study
2014	Mott MacDonald	Yes, as points	An extensive study was carried out regarding landslides along the primary road network of Saint Lucia. This consist of a feasibility study, which characterizes the road network according to the landslide frequency during various triggering events, and a site investigation study where a detailed analysis is done for a number of test sites. This study is by far the most extensive one available for the 4 islands.
2014	British Geological Survey	Yes, as polygons maps	Landslide inventory mapping was carried out for Saint Lucia, based on very high resolution satellite data as part of a World Bank – ESA collaborative project. For Saint Lucia images were obtained for each year from 2010 – 2014. Around 1025 landslides caused by hurricane Tomas are mapped, and the reduction in activity over the years is shown, as well as the reactivation by the 2013 Christmas Eve trough. Unfortunately the landslides were mostly not classified in different types.

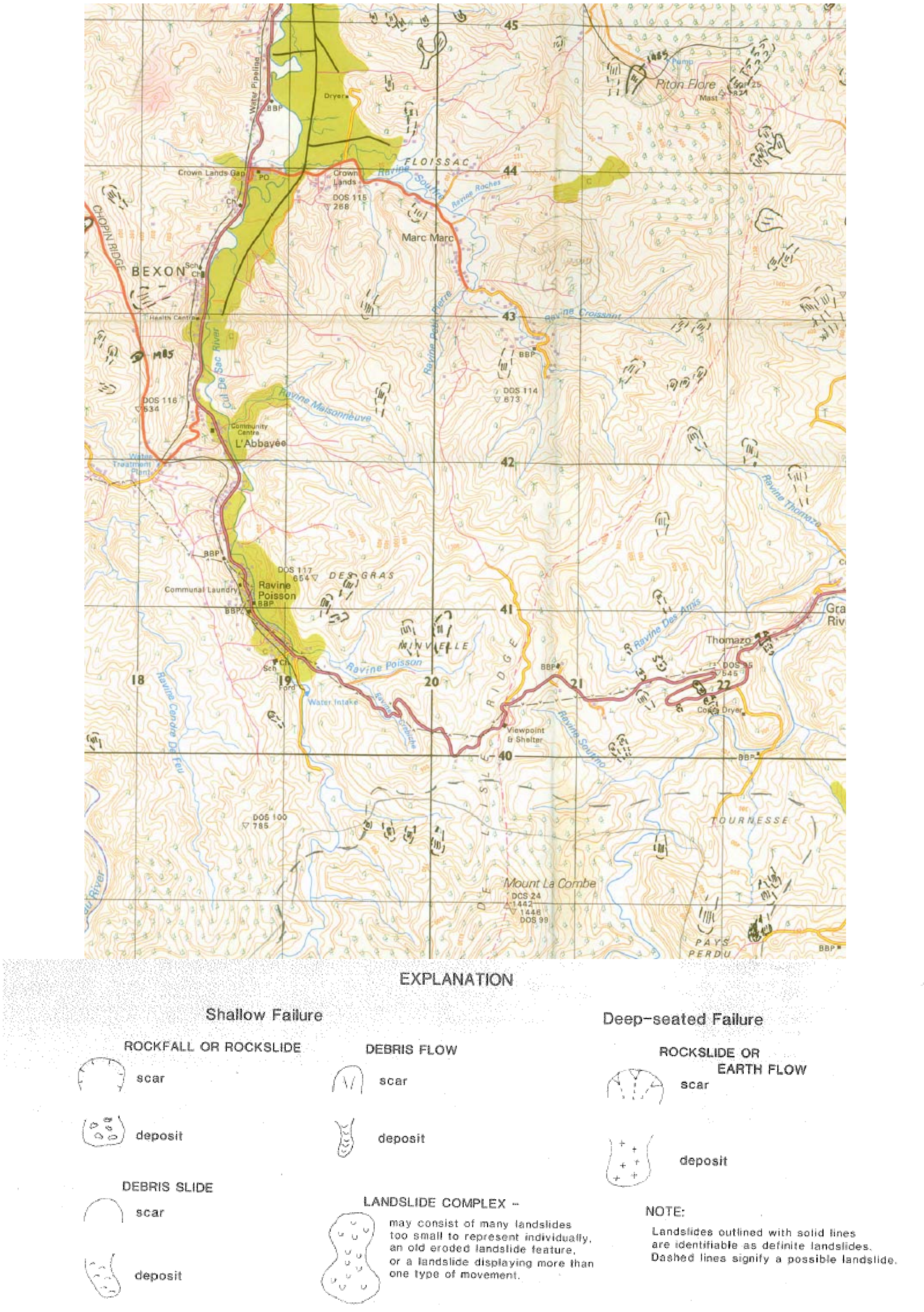


Figure 4-1: Example of the landslide inventory map prepared by DeGraff (1985) for an area along the road from Bexon to Dennery. Unfortunately no digital landslide inventory map was available in GIS format.

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

Island	Number of landslides	Landslide Size in hectares		Landslide density (per km²)	Terrain disturbed (in percentage)
		Average	Largest		
St. Vincent	475	0.5	4.0	1.4	1
St. Lucia	430	3.0	5.0	0.7	2
Dominica	980	4.0	12.5	1.2	2

After Hurricane Tomas, Rebecca Rock from the Forestry Department and Andrina Abraham, Cartographer and GIS Specialist working at the Ministry of Finance, Economic Affairs, Planning & Social Security, carried out an inventory mapping of the landslides triggered by the hurricane, using a RapidEye image taken shortly after the event. Although not being landslide experts, they did a very good job in mapping landslides (Figure 4-2). Unfortunately there were severe problems with the geo-referencing of the satellite image, and we were not able to remove all the locational errors caused by this. Therefore the inventory of Abraham and Rock doesn't match well with the later inventories.

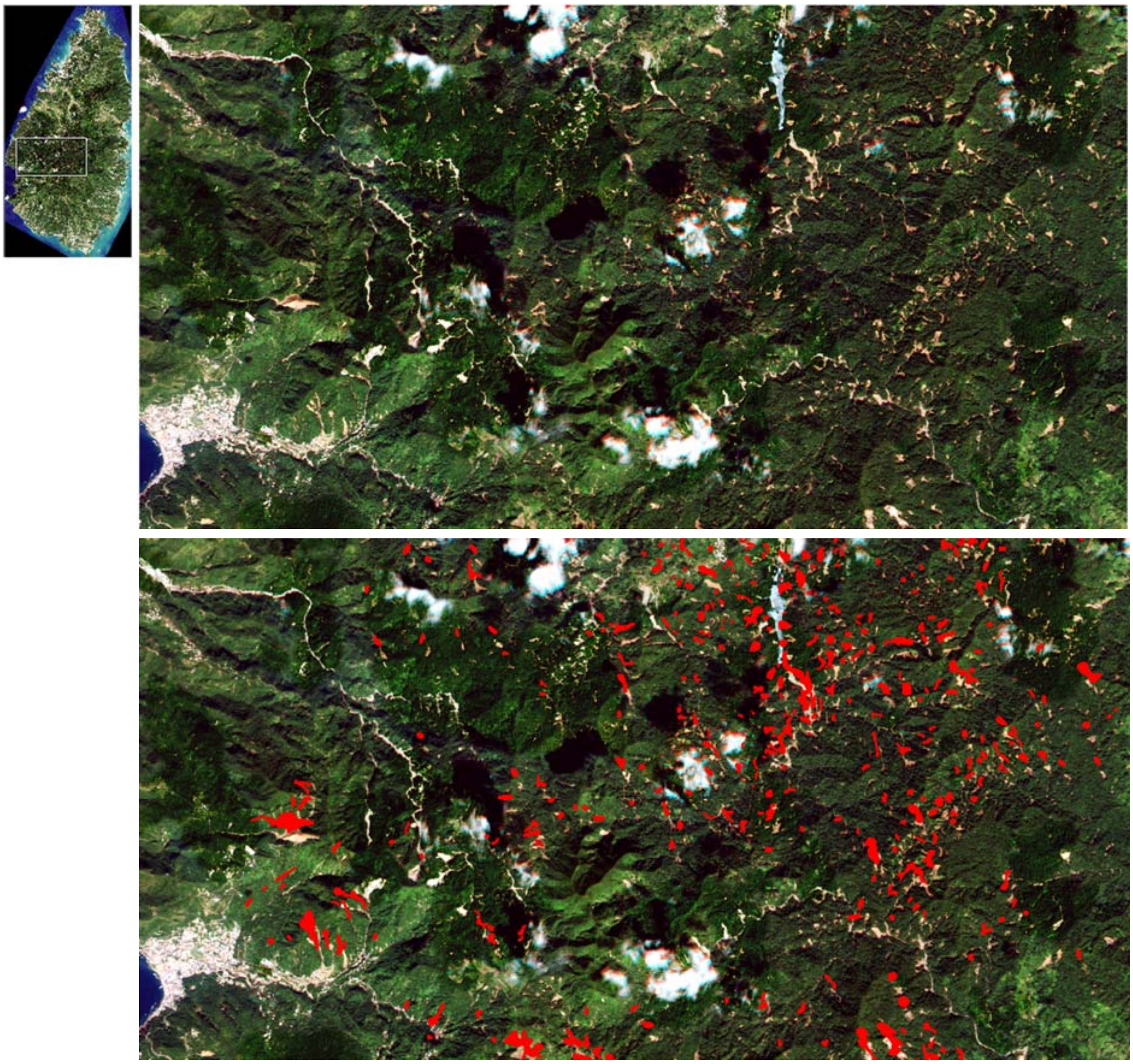


Figure 4-2: RapidEye image from 2011 showing the large number of landslides triggered by the 2010 Hurricane Tomas, and which was used by Abrahams and Rock to map the landslides. Note the distortion in landslide location due to problems in georeferencing the satellite image.

Also extensive work has been done on community-based landslide management in Saint Lucia (Anderson, 1983; Anderson et al., 2011; Holcombe and Anderson, 2010; Holcombe et al., 2011; Anderson and Holcombe, 2013). The Management of Slope Stability in Communities (MoSSaiC) project aimed to increase local capacity-building in the broad area of slope stability whilst simultaneously seeking to minimise resource expenditure, and achieve the vision by identifying key environmental project foci that can be undertaken by existing government-based staff and local communities. The goal was to establish team structures that are key to delivering the vision - a management team that develops and communicates the vision; field teams that develop project strategies and implement specific project plans. The project had three objectives: to control water on cultivated slopes in order to reduce soil erosion and landslide risk; to establish a trial site at which low-cost, appropriate drains could be installed; and to develop an integrated drainage plan involving perhaps as many as 15 farmers. The MoSSAIC project was active for a number of years in Saint Lucia and worked closely with communities on the steep slopes surrounding Castries. Yet, when we visited Saint Lucia in 2013-2015, the government officials didn't seem to know about this project. More information on the MoSSaiC project can be found on: http://mossaic.org/

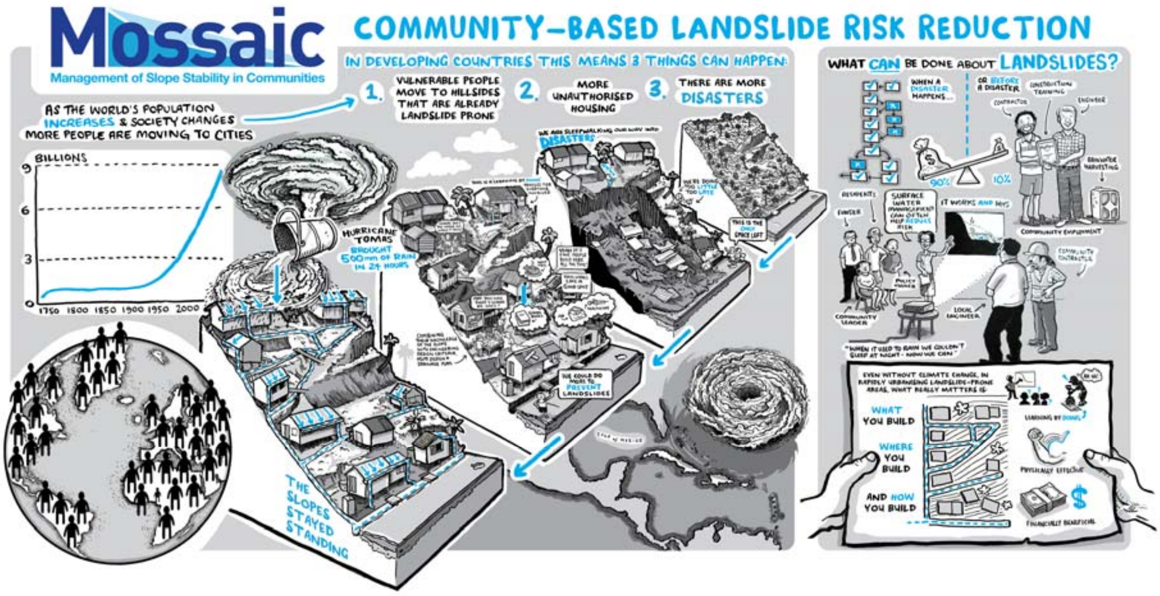


Figure 4-3: Explanation about the MoSSaic project in an information pamphlet. Source: http://mossaic.org/

After Hurricane Thomas a number of initiatives were taken to address landslide hazards along the road network (Mott Macdonald, 2013). "*Landslide hazard assessment has been completed at a network scale and site specific scale in a number of stages to allow a comprehensive understanding of the landslide hazard to be developed.*
A landslide susceptibility map has been created using the existing database within the geographical information system (GIS) to assist with targeting more detailed assessments for the road network (See Figure 4-4).
At the network scale a density analysis of the landslides that occurred in response to different storm events has been attempted to try and evaluate the hazard that is caused by different storm events. The assessment reviewed landsliding following Hurricane Allen and Hurricane Tomas and presents the results as the density of landsliding along different sections of road following the different events. The results show many more landslides occurred along the primary road network during Hurricane Tomas compared to Hurricane Allen which may be a result of the higher rainfall during Hurricane Tomas. At the site scale a geomorphological assessment has been completed by interpretation of 2009 air photographs to identify historical and recent landslides along the network. This air photograph interpretation was then ground truthed by visiting the sites to confirm the desk based assessment was correct and to improve the accuracy of the mapping. Areas along the primary road network have also been zoned to identify slopes adjacent to the road where similar ground conditions, environments and morphology may lead to similar landslide events and ground movements. The zones can assist in highlighting landslide hazards in areas of slopes that may be identified as low landslide risk using the risk matrix approach described below. The zones will assist with network management" (From Mott MacDonald, 2013).

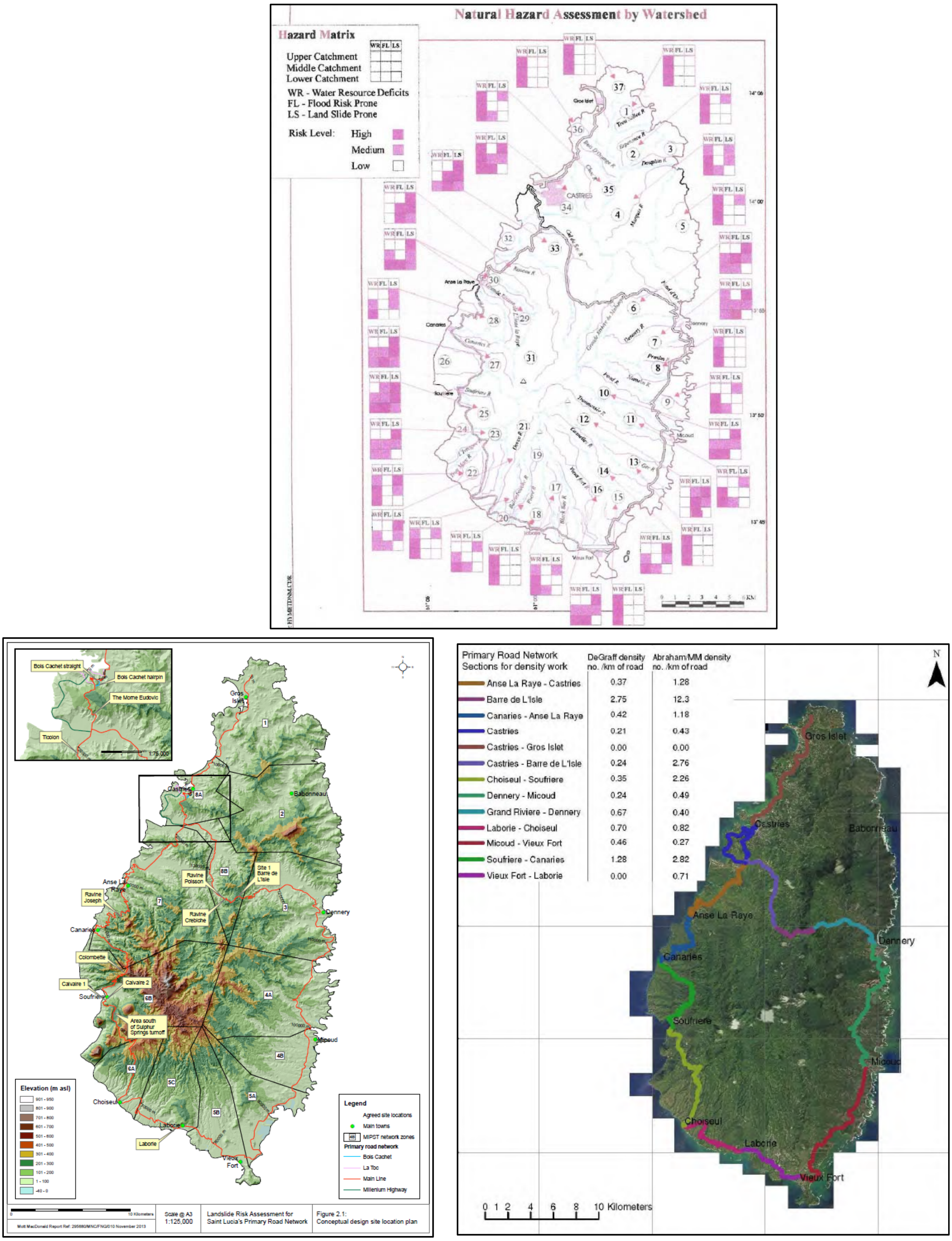


Figure 4-4: Above: Resulting map from the study by Hunting Technical Services and Mott MacDonald in 1998. We did not find the original study but this figure was used in Mot Macdonald (2013). The map shows the relative risk for flooding and landslides in the upper, middle and lower catchment areas. Below: Results of landslide risk assessment work carried out by Mott Macdonald (2013). Left: sites studied in detail, Right: national landslide susceptibility along the road network.

4.2. Landslide inventory mapping carried out by BGS in 2014

Some of the available landslide inventories presented in the previous section are relatively old, and other have positional problems. Therefore it was decided to carry out a detailed landslide inventory that complements the earlier ones, and that portrays the current situation, incorporating also the older landslide inventories into a single new and comprehensive analysis.

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

- **Image interpretation** from aerial photographs, high resolution satellite images, or hill shading images derived from detailed Digital Elevation Models. Also image interpretation using multi-temporal images from Google Earth has become a useful tool for landslide inventory mapping.
- **(Semi) automatic classification** of landslides from satellite images or Digital Elevation Models.
  - Based on spectral information by detecting fresh landslide areas from multi-spectral satellite images;
  - Based on altitude information by detecting landslides from multi-temporal high resolution (LiDAR) DEMs, or through radar interferometry
- **Field investigation**, by mapping landslide signs, scarp area, accumulation areas, and verification of landslides mapped through image interpretation and/or classification;
- **Community reporting**, by interviewing local people on locations, dates and impacts of past landslide event;
- **Archive studies**, by studying newspaper archives, old reports, road maintenance reports etc., as explained in chapter 3.

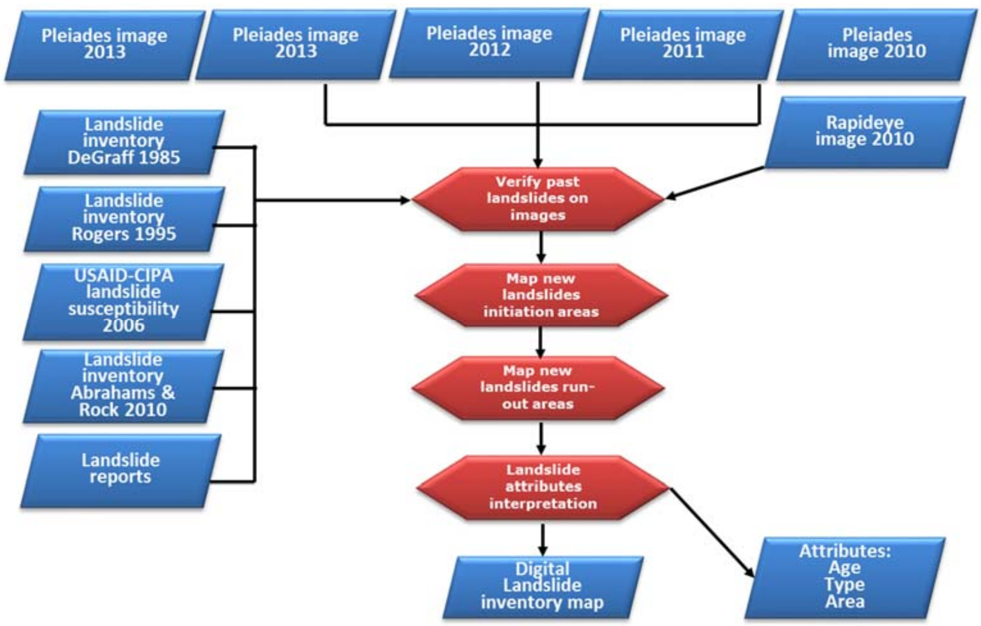


Figure 4-5: Schematic representation of the procedure followed from landslide inventory mapping in Saint Lucia by BGS (Jordan et al., 2015)).

Landslide inventory mapping was carried out by the British Geological Survey. Their team (Colm Jordan, Stephen Grebby, Tom Dijkstra, Claire Dashwood and Francesca Cigna) carried out landslide inventory mapping and land use mapping for Saint Lucia. The following section comes from their report (Colm et al., 2015). This document specifies the EO information products / services delivered to the CHARIM project in the framework of the European Space Agency (ESA) “eoworld 2” initiative. The following pages (34- 48) are taken directly from the report of BGS, and since it was intended to contribute to the CHARIM project (Jordan et al., 2015),

4.2.1 Method

Through the EoWorld 2 project the BGS obtained also a number of images. RapidEye images from 2010, 2011, 2012 2013 and 2014 and one Pleiades image from 2014 were available for interpretation and landslide inventory establishment for St Lucia (Figure 4-6). The satellite images are affected by variable cloud cover, particularly the 2010 and 2014 RapidEye for St Lucia. The SE quadrant of the 2013 RapidEye image for St Lucia was of particularly poor quality and this affected determination of small landslide events.

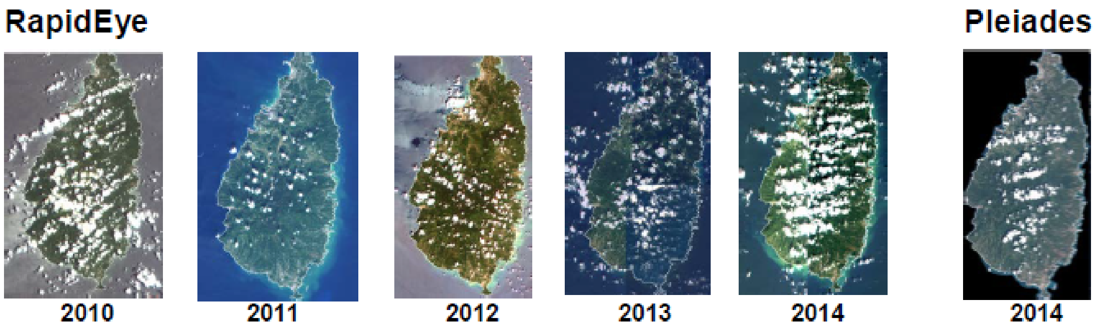


Figure 4-6: Available satellite images for Saint Lucia

The establishment of landslide inventories for St Lucia and Grenada is based on the interpretation of satellite images covering the period 2010-2014. For most of this period RapidEye images are available. Images from the Pleiades satellite are only available for 2014. Landslide activity can result in the disturbance of vegetative cover and exposure of soils at the surface. This spectral signature is combined with an assessment of other information such as position in the landscape, slope morphology, vegetation cover, etc. to interpret the satellite images and create outlines of landslide events. The distribution of landslides for each image (year) was captured manually by skilled operators and the results stored in one event database. The attributes stored for each event are shown in Table 4-3. The interpretation of potential landslide sites was analysed throughout the complete image sequence. This enhanced confidence in the mapping process, particularly if polygons are visible in several images. This approach also helped to reduce the negative effects of cloud cover and occasional poor image quality (e.g. the SE quadrant of the 2013 RapidEye satellite image of St Lucia). It is theoretically possible to capture a landslide spectral signature automatically, but our experience has shown that this leads to an over-representation of cultivated fields necessitating supervised re-classification of every polygon. It was therefore decided not to pursue this approach.

The RapidEye images are available at a resolution of 5 m while the Pleiades image was pansharpened to a resolution of 0.5m. Determination of landslide events at 5 m resolution is not very reliable and results therefore in rather low confidence mapping. However, when polygons persist into the 2014 Pleiades images, much more detailed interpretation can be achieved leading to greater confidence in the mapped product.

The project imposed scale limitations pre-determined that the landslide inventory should be established at a scale of 1:20,000 with key areas (no more than 50%) at 1:10,000 for St Lucia. This scale limitation affects the mappable minimum size of landslides. Based on the experience of mapping landslide polygons in St Lucia using the Pleiades high resolution images as guidance the following limitations apply. At a scale of 1:20,000 the minimum mappable size is approximately 30 by 30m or 900m^2. At 1:10,000 this enhances to mappable polygons of about 15m side lengths (225m^2). At a scale of 1:5,000 it is possible to map elements with effective minimum dimensions of about 10m (100m^2), depending on the terrain. Closely grouped small events were sometimes visible and these have been mapped as landslide clusters. The database therefore contains some polygons that contain several events (too small to map individually).

Considering the difficulties encountered in mapping landslide polygons at 1:20,000 scale this project adopted a pragmatic (though time-consuming) approach where the landscape was interpreted at 1:5,000 scale (or an even more detailed scale where features were uncertain). Outlines were then up-scaled (i.e. generalized) to be representative of polygons at 1:10,000-scale (this is a standard BGS approach). As a consequence of this practice it was possible delineate landslide events in the size range smaller than 1000 m^2 (approximately 100 events) and this has resulted in a more 'complete' landslide inventory.

Table 4-3: Attributes stored for each landslide event in the multi-temporal cumulative inventory

Description	Name	Type	length	information
Landslide ID	LID	Number	7	
Location district	DISTR	Text	30	District name
Location Locale	LOCAL	Text	30	locality name
Mass movement type	TYPE	Code	2	.. (not entered), FL (flow), SR (rotational slide), SP (planar slide), SU (undifferentiated slide), FA (fall), TO (topple), SP (spread), UN (undefined)
Morphology	MORPH	Code	1	L, S, T, A (Landslide undifferentiated, Scarp, Transport zone, Accumulation zone)
Confidence	CONF	Code	1	H, M, L
2010	2010	Code	1	N, I, A (Not present - no slide visible, Inactive - the slide can be recognized but no activity suggested by disturbed vegetation or bare surfaces, Active - slide shows clear signs of recent activity in the form of disturbed vegetation, etc.)
2011	2011	Code	1	N, I, A (Not present - no slide visible, Inactive - the slide can be recognized but no activity suggested by disturbed vegetation or bare surfaces, Active - slide shows clear signs of recent activity in the form of disturbed vegetation, etc.)
2012	2012	Code	1	N, I, A (Not present - no slide visible, Inactive - the slide can be recognized but no activity suggested by disturbed vegetation or bare surfaces, Active - slide shows clear signs of recent activity in the form of disturbed vegetation, etc.)
2013	2013	Code	1	N, I, A (Not present - no slide visible, Inactive - the slide can be recognized but no activity suggested by disturbed vegetation or bare surfaces, Active - slide shows clear signs of recent activity in the form of disturbed vegetation, etc.)
2014	2014	Code	1	N, I, A (Not present - no slide visible, Inactive - the slide can be recognized but no activity suggested by disturbed vegetation or bare surfaces, Active - slide show
Field check	FIELD	Text	50	Free text

The clarity and detail offered by the high resolution (0.5m) Pleiades has been used to carry out detailed investigations of a limited number of individual sites and events. In combination with other data (landuse, topography, etc.) it is possible to generate highly detailed geomorphological maps that not only show the spatial extent of an event, but also can be attributed with information on the likely nature of deformation and, in combination with other images, a timeline of event progression. This level of detailed interpretation falls outside the scope of work for this project but is discussed in case studies in this report to highlight the significant additional value of these new, high resolution products.

The opportunities to capture landslide event outlines is strongly linked with the time period between trigger and image capture. The use of a multi-temporal image stack therefore provides the best opportunity to achieve 'completeness' of the database. The database can then be used to evaluate how quickly a landscape recovers and what the consequences are of subsequent trigger events. For Saint Lucia, the time series captured two major landslide trigger events; the 2010 Hurricane Tomas event and the 2013 December Trough. This has led to important insights into changes in the annual inventories as the landscape firstly recovers and then gets disturbed at a later date.

Two previous inventories were available for comparison with the present dataset. In 1995 some 713 events were identified, whilst an inventory created following 2010 Hurricane Tomas captured 1132 landslide events. The current multi-temporal inventory covered the years of 2010-2014 and contained 1233 landslide polygons that have been classed as active (fresh signs of landsliding) or inactive (no evidence of active movement, but still recognisable landslide features) at least once during this period. Generally, each polygon represents a single event. However, where clusters of very small events (dimensions smaller than about 5m) are encountered, a single polygon can represent more than one landslide. There are considerable benefits offered by a sequential analysis covering several years, including a reduction in the effects of cloud cover, a better insight into persistence of features and a more comprehensive capture of events. Any year looked at in isolation is likely to result in fewer events being recorded.

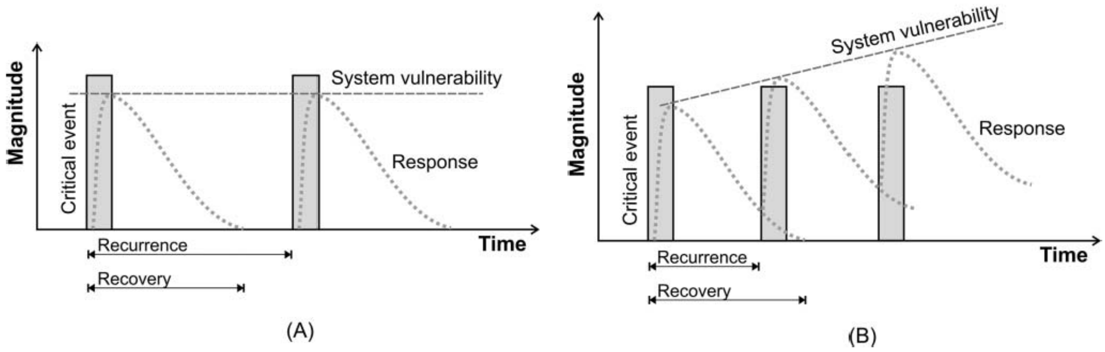


Figure 4-7. Landscape recovery versus trigger event recurrence. When recurrence exceeds recovery, relatively stable system vulnerability can be assumed (A), but when recovery exceeds recurrence, system vulnerability is likely to increase significantly. (From Dijkstra et al., 2014)

The 1995 landslide event database is largely based on field observations. This resulted in the capture of many events along roads and relatively few events in the forested areas where access is very limited. This database was checked against the multi-temporal inventory and relatively little overlap was encountered. Even taking into consideration the large time gap between the 1995 and 2010-14 inventories it is an indication that field capture and satellite image interpretation of events result in different populations and should be regarded as complementary activities.

The 2010 inventory captured the events generated by Hurricane Tomas and is based on satellite image interpretation. It appears that the use of 'bare earth' automated classification provided an important contribution to the establishment of the landslide inventory. As a consequence, the difference between this inventory and our multi-temporal inventory is considerably larger than the numerical difference between the two.

4.2.2 Field verification

During a 6-day field visit to St Lucia more than 650km were covered and as many landslides as feasible were visited. Many rural roads were still blocked as a consequence of landslides generated during Hurricane Tomas and the 2013 December Trough hampering access to landslides in the interior of the Island. The field verification emphasised the importance of satellite image interpretation. Many of the mapped landslides are some distance away from roads. Gaining access to these sites in the field is very laborious and the road network does not reach very far inland. In addition, many of the smaller rural roads in the interior were dramatically affected by landslide events triggered by Hurricane Tomas and the December 2013 Trough. It was therefore often impossible to reach landslide sites beyond those that cut off the roads.

In conclusion the following observations are drawn regarding the use of satellite images for landslide inventory establishment for St Lucia:

- Landslide signatures in St Lucia are recognisable by skilled operators
- Observations are limited by clouds, not by road access, enabling much more comprehensive coverage
- The current database is constrained by scale (1:20,000 and 1:10,000) and identification of events at more detailed scales is possible, particularly with recent Pleiades images at the resolution of 0.5m
- Minimum landslide dimensions in the database are approximately 200 m^2 and many smaller events are known to have occurred
- Very small (<5 m) and obscured (in the shade, on steep slopes, below overhanging vegetation) landslides are difficult to capture
- Small events can still have a significant impact on lives and livelihoods and recording these through different means will complement the database
- Automatic classification is, at present, not conducive to establishing a reliable record
- Temporal proximity of trigger event and satellite image acquisition affects the number of events that can be captured
- Multi-temporal inventory establishment enhances the number of events captured and can be used to establish derived products such as landscape resilience and hazard assessments

- Landslides triggered by Hurricane Tomas (2010) were rapidly covered by vegetation indicating a rapid rate of recovery of the landscape, but many events were re-activated during the 2013 December Trough indicating a still heightened sensitivity of the landscape to disturbance
- Extending the multi-temporal record with ongoing acquisitions will create further insights into landscape response and this will be vital in establishing relevant hazard and risk assessments
- Field verification remains an essential tool to ascertain validity of image interpretations

4.2.3 Results

RapidEye and Pleiades images were available for interpretation and landslide inventory establishment. The RapidEye images are available at resolution of 5m while the Pleiades imagery was pan-sharpened to a resolution of just 0.5m. Visibility of a feature is also dependent upon terrain slope. On very steep slopes the plan dimensions of an event may be much larger than the minimum dimensions discussed above, but the intersection with a near-perpendicular view may become so small that detection is not feasible. Dimensions of the polygons are taken from a 'flat' map and are not adjusted for slope. These simplifications affect the cumulative frequency-area distribution.

Landslide activity can result in the disturbance of vegetative cover and exposure of soils at the surface. Many of the landslides in the inventory were triggered by Hurricane Tomas (30/31 October 2010; Pmax ~ 400-600mm). This hurricane was of an intensity comparable to a 1:180 year event, but as it was preceded by drought conditions it is estimated that the combined likelihood 'drought/rain' exceeds 1:1000 years (ECLAC, 2011). As a consequence, the resultant disturbance of the landscape was much more severe than could be expected on the basis of the severity of the hurricane alone. 'Landslide' is a generic descriptor for slope movements including rotational slide, planar slide, debris flow, mud flow, debris avalanche. Generally these take place in deeply weathered materials, where for dry soil conditions a rapid infiltration can lead to a sudden loss of strength, the initiation of slope deformation and a rapid transition from sliding to flow.

To map a particular landform as a landslide requires a landslide scar and/or landslide deposits to be visible on the satellite image. Mapping of landslide events is in the first instance on the basis of simple spectral/colour signatures. In the case of the relatively low resolution RapidEye images this is not very reliable and results therefore in rather low confidence mapping. The better resolution offered by the Pleiades image enables much more detailed interpretation leading to much higher confidence in the final mapped product. As this exercise involved the establishment of a multi-temporal landslide inventory, the detailed Pleiades image could therefore be used to enhance the overall confidence of the final product. As the differences between exposed soils and vegetated surface are quite distinct the use of automatic classification of 'bare earth' sites was tested in a part of Saint Lucia to aid the landslide identification process, using the 2011 RapidEye image as a pilot study. However, it was found that this approach leads to a large over-estimation of the areas affected by landsliding. Many cultivated fields are included in this automatic classification. The additional effort involved in fine-tuning the classification outweighed the benefits for image interpretation and therefore it was not pursued for other images.

General practice of mapping landslides is to investigate at a more detailed scale and then upscale to the desired level of detail. This enhances the confidence that the features are mapped correctly. The practical approach to this project therefore involved mapping the whole Island at a scale of 1:10,000 or at an even more detailed scale where features were uncertain. Outlines were established on the basis of representation at 1:10,000-scale. As a consequence of this practice it was possible outline landslide events in the size range smaller than 1000 m^2 (approximately 100 events) and this has resulted in a more 'complete' landslide inventory. However, with its high resolution of 0.5m the Pleiades images offer interpretation of the landscape at much greater detail and there are therefore opportunities to enhance the capture of landslide polygons, both in detail of feature outlines and in number of small events (covering less than about 100 m^2). The Pleiades images also offer detailed investigations of individual sites and events. In combination with other data (land use, topography, etc.) it is possible to generate highly detailed geomorphological maps that not only show the spatial extent of an event, but can be attributed with information on the likely nature of deformation and, in combination with other images, a timeline of event progression.

RapidEye images from 2010, 2011, 2012 2013 and 2014 and one Pleiades image from 2014 were available for interpretation and landslide inventory establishment for St Lucia. Table 4-4 and Figures 4-8 & 4-9 provide summaries of the landslide inventories generated for the period 2010 to 2014.

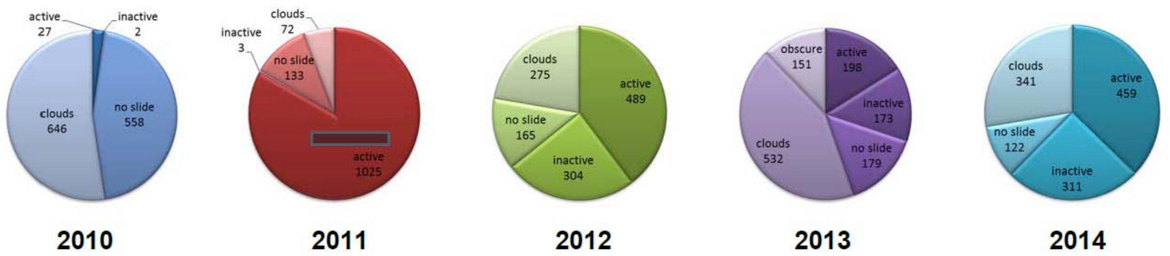


Figure 4-8: Pie diagrams of the number of polygons classified as active, inactive, not a landslide and those where identification was not possible due to cloud cover or, in 2013, due to poor image quality in the SE section of the Island.

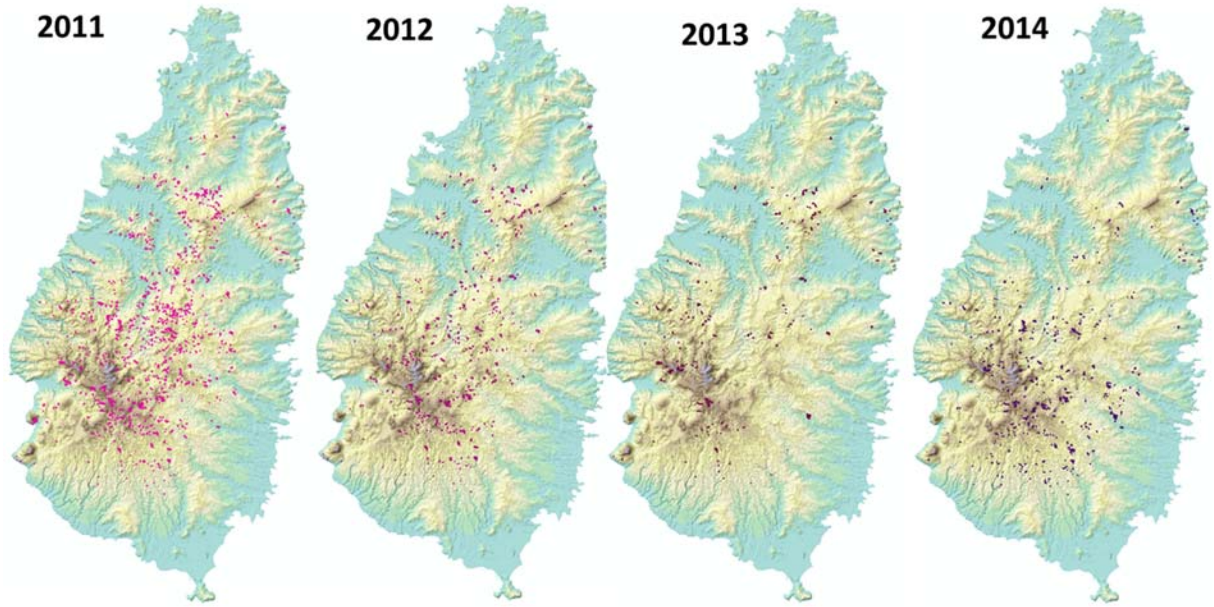


Figure 4-9: Landslide inventory maps of St Lucia showing the distribution of active landslides (NB identification is affected by cloud cover and a poor quality SE quadrant for 2013; see Table 3).

4.2.4 Conclusions

The landslide inventories for St Lucia contain polygons that represent the maximum extent of events mapped during the period 2010-2014. Each polygon is attributed with landslide type, morphology, confidence level of the mapped outline and a statement of activity for each of the five years in the sequence 2010-2014. The inventory thus provides a clear indication of landscape response to trigger events. Interpretation of satellite images requires well-trained operators with a good understanding of mass movement processes and local conditions.

Information on trigger event response, spatial distribution, magnitude-frequency, type of movement, etc. can be very valuable for the development of derived products such as landslide susceptibility maps and landslide risk assessments. It is therefore envisaged that this product will provide context to future studies of landslide hazard (such as e.g. CDB and CDERA 2006, ECLAC 2011) and landslide risk reduction (e.g. MoSSaiC - Holcombe and Anderson, 2010; Anderson and Holcombe, 2013).

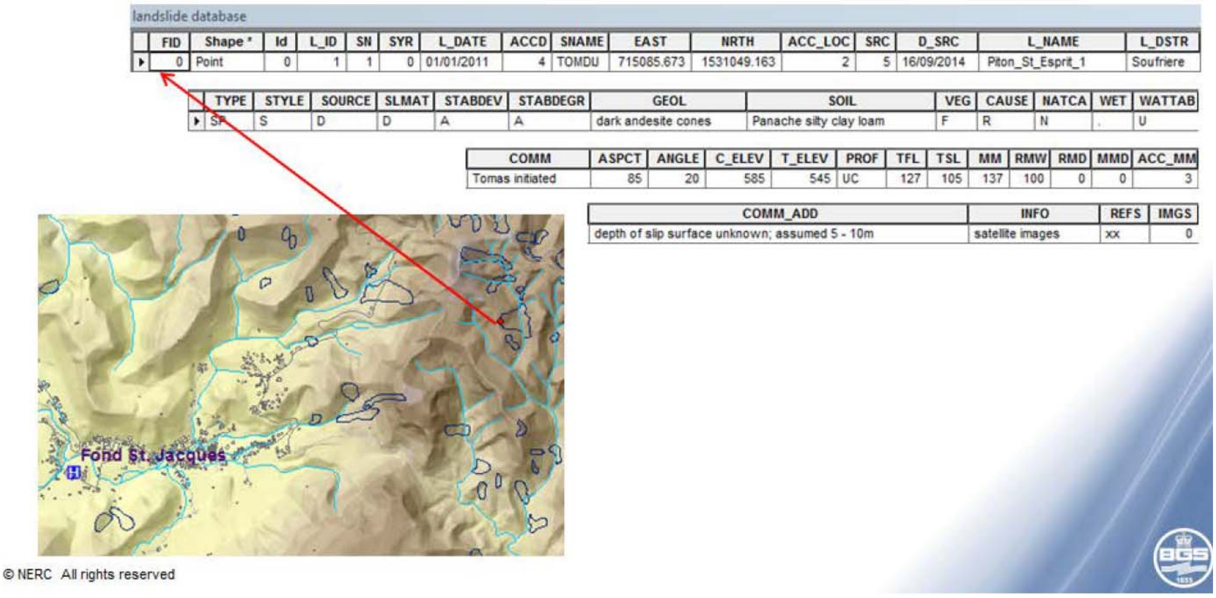
The morphology of the landscape constrains the dimensions of landslides that are encountered with many events occurring on short, steep slopes. A substantial number of landslides have dimensions smaller than 1000 m^2 (the effective minimum size for an event that can be mapped on a 1:20,000 scale) and therefore the inventories were established on a scale of 1:10,000.

Table 4.4: Summary of landslides identified for each year of the multi-temporal image stack from 2010-2014 in St Lucia.

Year, image, date	Landslides	Notes
2010 RapidEye 18/8/2010	27 active, 2 inactive	The image captures the state of the Island before Hurricane Tomas. Some 40% of the land surface was affected by cloud cover (and associated shadow and could-fringe effects). The small number of landslides that were captured where the land surface is visible is likely the result of much vegetation regrowth masking previous events. Many inactive sites, susceptible to re-activation, are therefore not included. Absence of older images (closer in time to major disturbing events such as hurricanes and troughs) limits opportunities of extend the size of this initial dataset.
2011 RapidEye 03/1/2011	1025 active, 3 inactive	This image captures all events generated by Hurricane Tomas (October 30-31, 2010). Thick cloud covers approximately 2% of the Island. For a further 5% the view is obscured by cloud fringe effects. Approximately 10% of the land surface is affected by cloud shadows, but this did not obstruct interpretation significantly.
2012 RapidEye 29/9/2012	489 active, 304 inactive	Only 14 new events were identified (these polygons were not recognised as active in the 2011 inventory). An additional 30 events are identified as active, but initiation of slope instability is uncertain; twenty events were identified in areas where cloud cover was encountered in the images of 2010 and 2011; ten events did not exist in the 2010 inventory and were obscured by clouds in the 2011 inventory. Some 16% of the land surface is not visible due to clouds with a further 2% obscured as a consequence of cloud shadow effects.
2013 RapidEye 14/2/2013	198(238)* active, 173 inactive	*SE quadrant of the Island is not included in first value; the second value represents a larger total where persistence of landslide activity is plausible (i.e. all these polygons are active in the inventories of 2011, 2012 and 2014). Approximately 35% of the land surface is not visible due to cloud cover, with a further 17% obscured as a consequence of shadows and poor image quality.
2014 Pleiades 25/2/2014	459 active, 311 inactive	Some 129 landslides were new events not included in the 2011 inventory. Approximately 5% of the land surface is not visible due to cloud cover, with a further 25% slightly affected by a thin clouds and shadows that only slightly affect image interpretation.
All images	1233	Total number of polygons in the multi-temporal inventory (including 2 polygons mapped as inactive throughout the period 2010-2014). 50% of the landslides were mapped as active in one year only. 27% were observed in two years, 16% in three years and 6% in four years. Less than 0.5% was observed in all five years of the period 2010-14.

The latest satellite images provide substantial improvements in resolution that enable very detailed interpretations of the landscape to take place. There is therefore scope to map events smaller than the minimum size captured by the current inventory. It is also good practice to populate each polygon with additional information that can be stored in a relational database for further analysis (i.e. through connecting landslide polygons to landslide point data; see Gibson et al. (2013); Figure 4-10, and listed in http://nora.nerc.ac.uk/18890/). This will require substantial further work, but will result in an invaluable tool for future landslide hazard and risk assessments.

The current multi-temporal sequence can be extended backwards by incorporating older satellite images thus providing incremental quality enhancements of the database. Regular updates of the inventory (at least annually, but inventory establishment immediately following a trigger event should be a priority) will also provide important value. As the database updates continue, this can be of great value to evaluate the vulnerability of the landscape and estimate the potential consequences of a trigger event (see e.g. Foster et al. 2012; Gibson et al. 2013; Pennington et al. 2014).


landslide database

FID	Shape *	Id	L_ID	SN	SYR	L_DATE	ACCD	SNAME	EAST	NRTH	ACC_LOC	SRC	D_SRC	L_NAME	L_DSTR
0	Point	0	1	1	0	01/01/2011	4	TOMDU	715085.673	1531049.163	2	5	16/09/2014	Piton_St_Esprit_1	Soufriere

TYPE	STYLE	SOURCE	SLMAT	STABDEV	STABDEGR	GEOL	SOIL	VEG	CAUSE	NATCA	WET	WATTAB
SP	S	D	D	A	A	dark andesite cones	Panache silty clay loam	F	R	N	.	U

COMM	ASPCT	ANGLE	C_ELEV	T_ELEV	PROF	TFL	TSL	MM	RMW	RMD	MMD	ACC_MM
Tomas initiated	85	20	585	545	UC	127	105	137	100	0	0	3

COMM_ADD	INFO	REFS	IMGS
depth of slip surface unknown; assumed 5 - 10m	satellite images	xx	0

Figure 4-10: An example of additional point data that can be linked to each landslide polygon to build up a landslide database that can be used for further analysis (see Foster et al. 2012).

The susceptibility of the terrain to generate landslides is not static and therefore trigger magnitudes capable of generating widespread disruption are also variable. For example, in periods shortly following a major disrupting event, much material is still in a critical condition and a relatively small trigger can result in large (re-)mobilisation of hillslope materials. If the landscape has had some time to regenerate a vegetation cover and re-establish a degree of stability fewer events will be active and visible on satellite images. Event capture using satellite images is therefore dependent upon the time difference between a trigger event and the capture of its aftermath by a satellite image. Using a multi-temporal image stack enhances the likelihood that events are being captured and a cumulative inventory will increasingly represent the distribution of unstable terrain.

The landslide inventory database can be interrogated in terms of the annual distribution of active and inactive (but still recognisable) events and this is of great potential value for subsequent analysis, for example in terms of event-response signatures, trigger threshold magnitudes and non-static hazard mapping. There is great value in maintaining and updating a multi-temporal landslide event database at least annually.

The morphology of the landscape constrains the dimensions of landslides that are encountered with many events occurring on short, steep slopes. A substantial number of landslides have dimensions smaller than 1000 m^2 (the effective minimum size for an event that can be mapped on a 1:20,000 scale) and therefore the inventories were established on a scale of 1:10,000.

The cumulative inventory represents the outlines and associated metadata of landslide polygons for the period 2010-2014. Within the constraints of this project only a simple attribution of landslide type and morphology (undifferentiated) was possible, but enhancement of polygon outlines and further distinctions (for example reflecting better spatial constraints of areas of activity as a landslide becomes increasingly less active) are feasible if more time is available for interpretation of the imagery. The additional information could be maintained in a (relational) database with polygons representing the development of the landslide over time and tables identifying the attributes of the landslide at each point in time. Most features are recognised by bare earth and represent the remains of translational or flow type movements. Few polygons contain features of deep-seated rotational movement where it is theoretically possible to max scar, slide body, etc.

4.2.5 Validation

The identification of landslide polygons was quality checked by two operators independently mapping two test areas in Saint Lucia. The results were compared and this led to fine-tuning of interpretation of indicators and establishment of observational guidance (landuse, bare soil signatures, use of elevation models, minimum landslide size, and use of landslide clusters). The final products were again cross-checked by two engineering geologists. Following the establishment of the multi-temporal inventory the results were evaluated against the 2010 landslide inventory. It was observed that there were some differences between the multi-temporal inventory and the 2010 inventory and these were all carefully evaluated. Generally, these differences were the result of an over-emphasis on 'bare-earth' mapping in the 2010 inventory. Additional differences were observed with the more conservative outlines of landslide areas in the multi-temporal inventory as long runouts were not mapped.

The completeness of landslide inventory is a function of the capability of the mode of recording of all the events over a period of time. Clearly, there are several issues therefore that influence completeness. In the case of this project these include, aspects of image resolution, of scale, and of the length of time over which observations are made. Visibility (absence of cloud cover, canopy overhangs, shadow effects, etc.) further influences the completeness of the landslide inventory.

To achieve an insight into the completeness of the landslide inventory of St Lucia, the complete multi-temporal dataset has been analysed. The extent of an individual landslide throughout the multi-temporal dataset is not constant. Deviations from this extent will occur in different years. This can occur through, for example, re-establishment of a vegetation cover leading to increasingly smaller areas remaining 'active'. But it is also possible that slides extent, either downslope as a consequence of continuing displacement of a landslide mass, or upslope and laterally through retrogressive failure involving increasing large amounts of slope. For this exercise, landslide polygons offer an outline representing the maximum extent of an event throughout the time series. It is therefore unrealistic to construct area frequency diagrams for each year.

The analysis of the full dataset (incorporating the dataset mapped at 1:10k) resulted in a cumulative frequency-area distribution shown in Figure 4-11, following an approach outlined by Guzzetti (2005) and Malamud et al. (2004) (see also Hurst et al. 2014). It is interesting that spill-overs or roll-overs (i.e where the largest number of events are found of a particular size) depend on the nature of the survey. For quick reconnaissance surveys this spill-over lies at a characteristic size of about 10^4 to 10^5 m^2 (i.e. landslide dimensions of approximately 100x100 m to 300x300 m). For more detailed geomorphological surveys greater detail can be captured and this results in a trend with a spill-over at about 10^3 m^2 (indicative dimensions of about 30x30 m) which is similar to what was found in our survey.

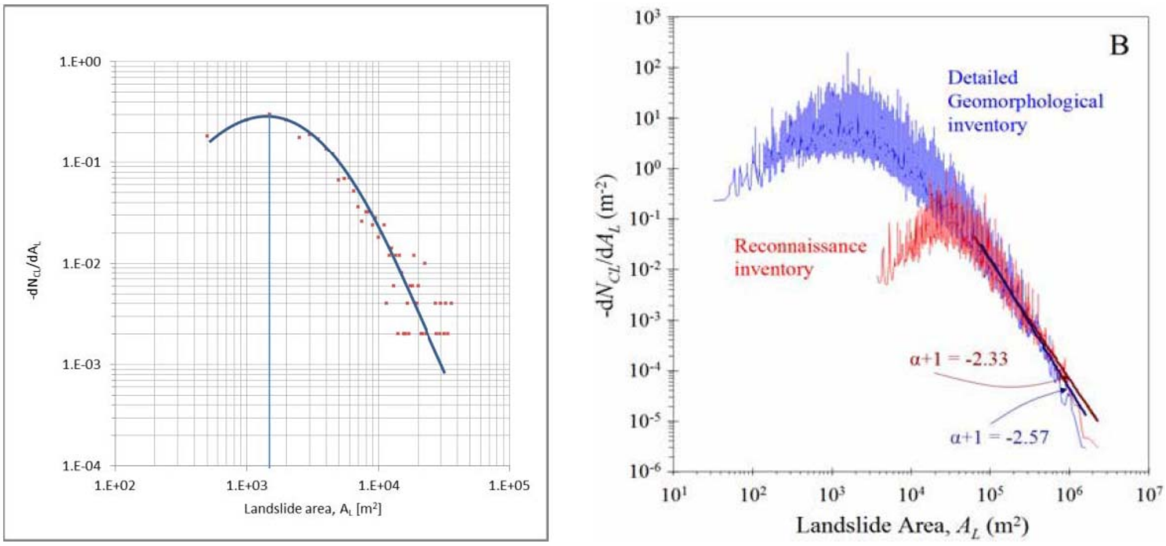


Figure 4-11: Left: Cumulative frequency-area distribution for landslide events in St Luci for the period 2010-2014 and Right: an example of the different cumulative frequency-area distributions for reconnaissance and for detailed geomorphological surveys (Guzzetti 2005).

Minimum dimensions in the database are approximately 200 m^2 and many smaller events are known to have occurred. Very small (<5 m) and obscured (in the shade, on steep slopes, below overhanging vegetation) landslides are difficult to capture but are known to exist in substantial numbers. These small events have a significant impact on lives and livelihoods and recording these through different means will be important to add to the database. It is possible to interrogate the recent Pleiades images (at resolution of 0.5m) at a greater level of detail and it is therefore advantageous to carry out future assessments at scales of 1:5,000 or better. The case study of Chateau Belair highlights the restrictions in using satellite images for interpretation. Subtle changes in topography can be interpreted by skilled operators as signatures of landslides in a complex terrain. At high resolutions (1:10k and better) this can lead to very detailed maps showing geomorphology and engineering geology features relevant to slope instability.

It will remain very difficult to identify very large, relic and inactive landslides. This exercise has shown that very large, and mostly relic, landslides are often difficult to identify and interpret in the context of Caribbean Islands where a substantial vegetation cover masks topographic features. This will require much detailed additional geological and geomorphological investigations that falls beyond the current scope of the project.

4.3. Some examples of landslide characteristics in Saint Lucia

This section gives some illustrations of landslide examples in Saint Lucia, as described in Jordan et al (2015).

At **the Roseau Dam** many landslides were observed from the 2011 image and the road provided good access to the interior. Along the way it was possible to field check many sites mapped as landslides, with those generated in 2010 close to the dam still clearly recognisable (Figure 13). The road was in many places affected by recent landslides, including on the stretch from the Roseau Dam to L'Anse la Raye (Figure 4-12).

Figure 4-12: Landslides near the Roseau Dam. Multiple events in 2010 seriously affected the water quality of the reservoir and a large landslide occurred to the east of the dam (see inset photo from ECLAC 2011). The remains of this landslide are still clearly visible. The direction of the photo is indicated by a red arrow on the satellite image of 2014. Compared with the 2011 image it is evident how much more detail can be observed.

The **Fond St Jacques** area was heavily affected by flowslides triggered by Hurricane Tomas. Many events originated in deforested, cultivated fields in the upper slopes (ECLAC 2011). The Migny road was severely affected and remains out of service. This area was used to evaluate the potential of a 'bare earth' classification for landslide identification (Figure 4-13).

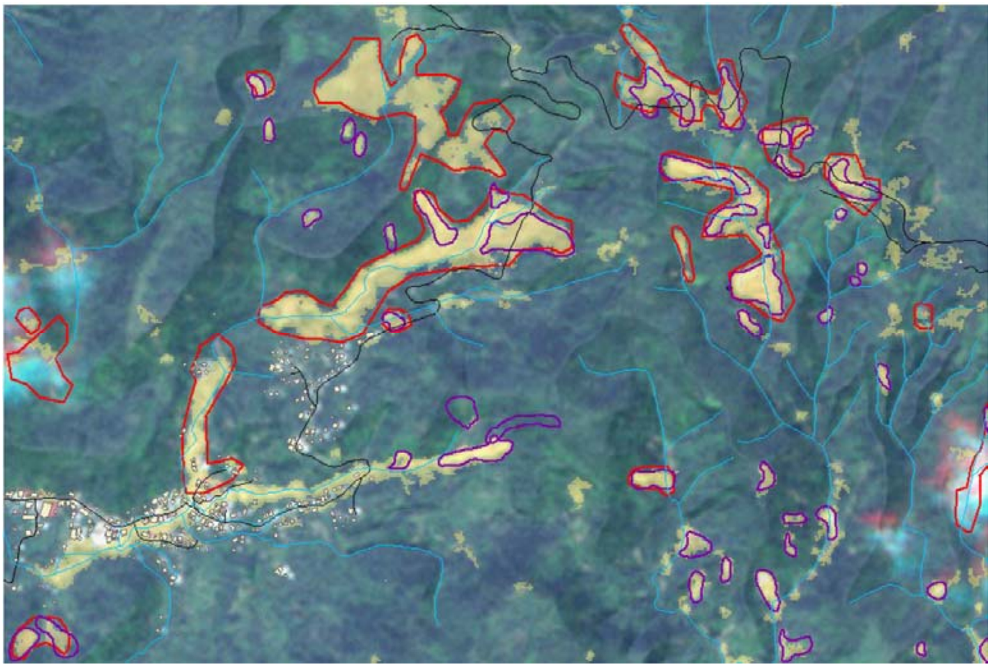


Figure 4-13: The Fond St Jacques/Migny area on the 2011 RapidEye image. The light coloured pixels indicate the result of a 'bare earth' classification (areas larger than 300 m^2). The red polygons represent the 2010 landslide inventory and the purple polygons the multi-temporal inventory where bare earth signatures in valleys and fields have not been included. The two landslide polygons in the centre were generated in 2014.

The **Colombette** landslide was initiated in the upper parts of the flanks of Mount Tabac, north of Soufriere. The deeply weathered pyroclastic bedrock and lightly cemented ash soils rapidly disintegrated to form a debris slide stripping the lower slopes of vegetation, soil and roadway structure (ECLAC 2011). Satellite images clearly show the outlines of the landslide in 2011 through to 2013. However, the 2014 image, albeit providing greater detail, is partly obscured by clouds. If earlier images had not been available, it is unlikely that this landslide would be detected on the basis of the 2014 image alone (Figure 4-14)**.**

Figure 4-14: Colombette Landslide. Top left is the state of the upper part of the landslide in October 2014 and top right shows the landslide in 2011. The lower images represent scenes from RapidEye (2011 and 2013) and Pleiades (2014). Despite the greater resolution of the Pleiades image, the landslide is barely visible.

The **Micoud/Thomazo/Barre de L'Isle** road traverses the steep terrain of the centre of the Island and forms an essential transport link between Vieux Fort and Castries. Along this road many landslides are known to occur and these are subject to substantial stabilisation works.

Figure 4-15: Landslide stabilisation works along the Vieux Fort-Castries road at Thomazo

A debris flow in the **Ti Rocher, Trois Pitons** area was identified on the satellite image of 2011. The translational slide/debris flow has a length of some 300 m. The highest point is at approximately 230m above sea level and its runout drops by more than 110 m. It originated in weathered bedrock comprising andesite, basalt and some agglomerates. Local soils belong to the Bocage Stony clay. On the satellite image of 2012 a substantial part of the lower part of the event was overgrown, making identification very difficult. It shows that, unless captured close to the event occurrence, recognition of landslides is very difficult in an environment where recolonization of affected slopes by vegetation occurs in a very short period of time (Figure 4-16).

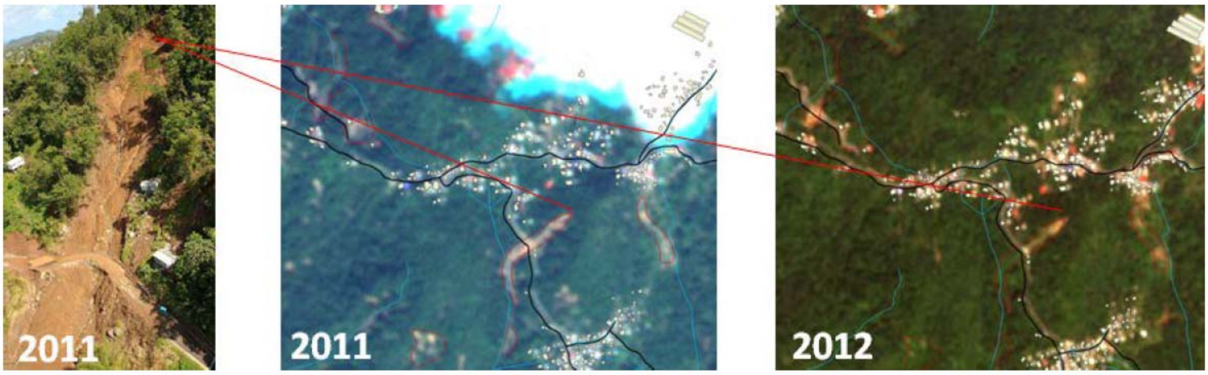


Figure 4-16: The landslide/debris flow event of Ti Rocher. To the left an oblique of the event is shown (source ECLAC 2011). The event is clearly visible on the 2011 RapidEye image, while only a year later all landslide deposits below the road are covered by vegetation.

The **area around Marc** was identified in the ECLAC (2011) report as being particularly affected by landslides. Many of these were small translational or rotational events in deeply weathered bedrock and lightly cemented, mainly granular soils. The landslides occurred on slopes steeper than approximately 25 degrees and rapidly disintegrated to form flows. The events seriously affected communities where the houses were constructed on the hill-slopes. Identification of individual events is difficult in this area because of the patchwork of colours from housing, infrastructure and variations in vegetation on steep slopes and the relatively poor resolution of the 2011 RapidEye image (5 m). In order to map these very small events with some degree of confidence at a 1:10,000 scale the higher resolution of the 2014 Pleiades image is required. However, by the time this image was taken, many of these smaller events were re-vegetated and their signatures difficult to establish. It is not impossible to map these small events using the images available, but it requires interrogation of the data at scales that are much more detailed than stipulated for this exercise.

Figure 4-17: Landsliding near Marc. The oblique photo on the left (source ECLAC 2011) shows the extent of the area affected. The blue outlines in the 2011 image follow the outline of the valley. In the 2014 Pleiades image the landslide complex is barely recognisable.

The Pitons form arguably the most charismatic images representing St Lucia. These steep rock slopes are generating rock falls and several trails were mapped following Hurricane Tomas. Since then the interpretation was downgraded to 'inactive'. However, during the field visit a loud rockfall was heard and the scars of recent events were observed. Local narratives report regular rockfalls from the Petit Piton. It is evident that this area remains one of continued activity and could benefit from careful observation and monitoring.


Figure 4-18: The Petit Piton with fresh trails of rockfalls and the 2011 rockfall trails superimposed on the 2014 Pleiades image. In the SE corner of the image landslide trails were observed in the field (Figure 4-19) but these could not be identified on the satellite images.

Figure 4-19: An example of landslide scars along the main ridge connecting the two Pitons. These events were generated during Hurricane Tomas but could not be picked up in the satellite images because of size, terrain steepness, shadow effects and overhanging vegetation.

The **Chateau Belair** site (approximate location 719400/1527030) has been used to evaluate opportunities that exist for detailed interpretation of satellite images. Comparison of the area of interest at three different scales (1:20k, 1:10k, 1:5k and 1:1k) shows how polygons drawn around landslide signatures range from very course outlines around possible multiple events (this affects the size frequency distribution by over-emphasising larger events) to very detailed metre-scale outlines of surface features. At scales of 1:5k to 1:1k it is possible to create detailed outlines of areas where evidently planar slides disintegrate into flows and where small slides rapidly transfer into debris flows down steep gradients. This is particularly facilitated by the high-resolution of the Pleiades image (see Figure 4-20).

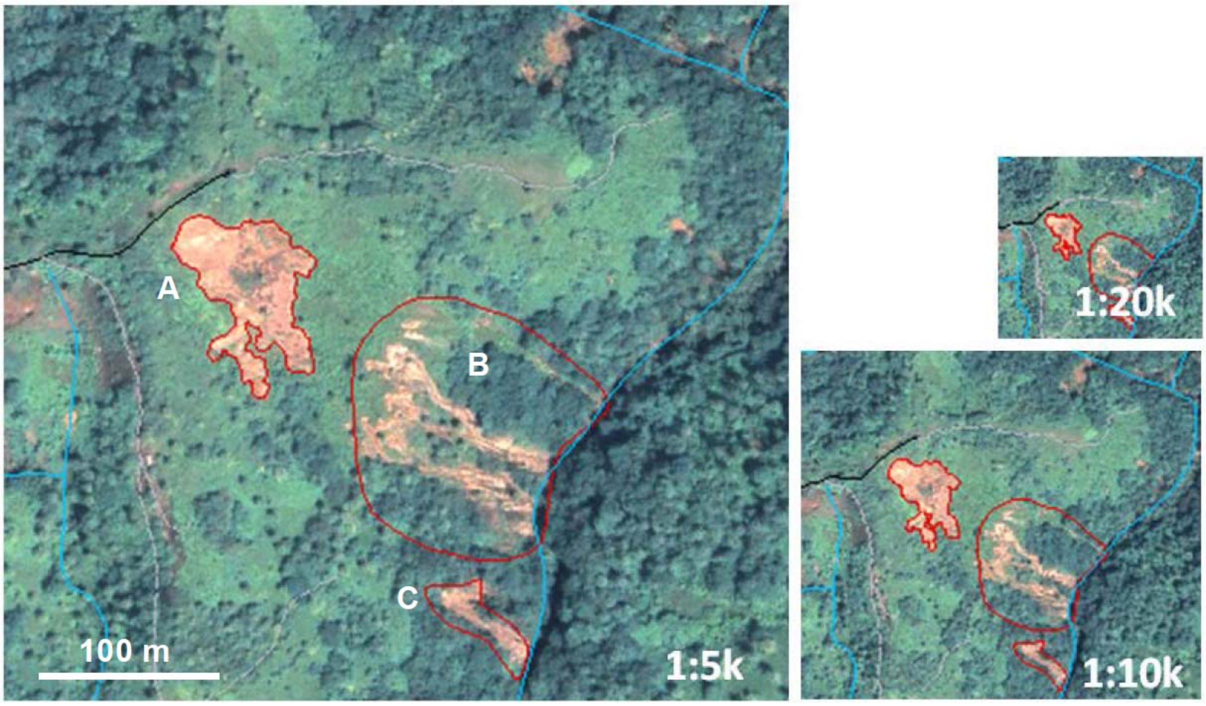


Figure 4-20: An example of mapping at different scales at Chateau Belair using the 2014 Pleiades satellite image as an example (see also Figure xx for an indication of image variability across the multi-temporal image stack). At 1:5,000 scale it is possible to create a detailed outline of freshly exposed soils of a landslide (A), at 1:10k it is possible to roughly outline a small event (C) while at 1:20,000 scale a small cluster of linked events is grouped together (B).

Comparison of the interpretation performed using this image with the stack of RapidEye images of previous years enables determination of the time at which small landslide scars are initiated. The satellite image interpretation initially leads to identification of surface features, but further investigation using a digital elevation model shows that landslide activity at this site is affected by a topography determined by a much larger ancient (and potentially relict) rotational landslide. Combining all information enables the establishment of a detailed geomorphological sketch map that can provide useful information on the changes in activity of deformation at a remote site (Figure 4-21 & Figure 4-22) and considerable detail of morphological features of individual events (Figure 4-23). These interpretations require substantial field verification and the Chateau Belair site was therefore visited in October 2014. Field observations corroborated the satellite based interpretation, and this provided further confidence in the approach taken.

Access to remote sites can be difficult and time consuming. In the case of Chateau Belair, access was particularly problematic as many roads leading into the centre of the Island were compromised by the landslides of Hurricane Tomas in 2010 and the December Trough in 2013. Chateau Belair is situated at the head of a valley with only a small, unpaved road leading up to an adjacent hill where it is possible to obtain an overview of the site. To find suitable locations where a good overview of a site can be achieved on the ground is not an easy task in an environment blessed with exuberant vegetation. There is therefore much merit in the use of satellite images to enable interpretation of features at remote locations.

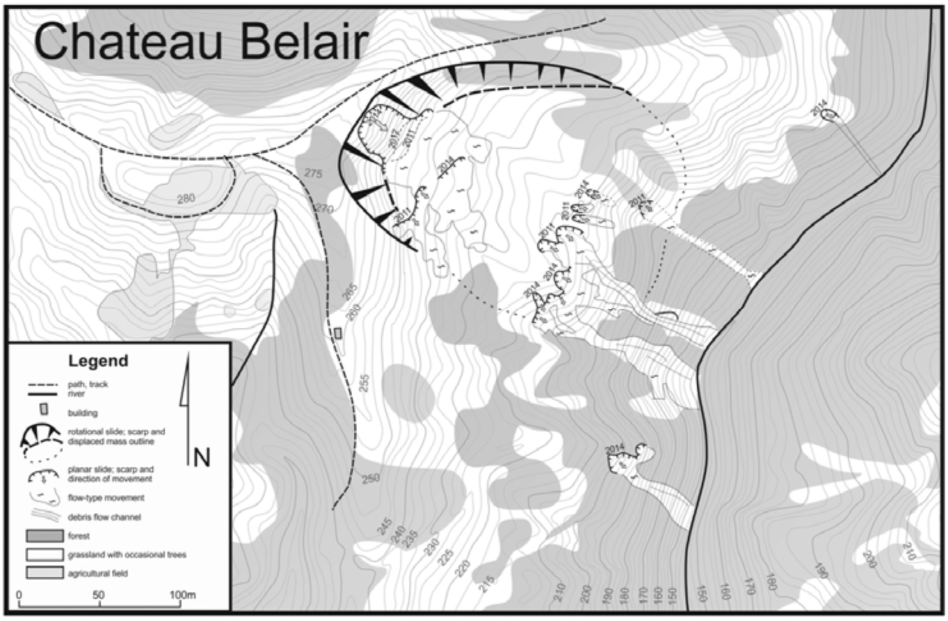


Figure 4-21 .A geomorphological sketch map produced using Pleiades and a surface model. This illustrates the opportunities that are on offer given time to interrogate these information sources at their maximum level of detail.

Figure 4-22: The Chateau Belair landslide as seen from a vantage point during field verification

Figure 4-23: The 2011 image of a landslide enables establishment of just an outline of a landslide feature near the Roseau Dam. However, the 2014 Pleiades image can be used to draw a tentative morphological map of a landslide complex. Field checks are required to ensure these interpretations are realistic.

Up to here the text is taken directly from the BGS report: Jordan et al. (2015)

4.4. Final landslide inventory map for Saint Lucia

We were able to use the landslide maps from 1995 (Rogers), 2010 (Abraham and Rock), 2010 - 2013 (MottMacDonalds), 2013 (DANA) and 2010-2014 (BGS). Table 4-5 summarizes the information. The inventory maps for 1995 and 2013 are point maps, and therefore we cannot calculate the size of landslides nor the total landslide area. The other three maps are polygon maps, not differentiating scarps from accumulation areas. Only two maps (1995 Rogers and 2010-2013 Mott MacDonalds) have a classification of landslide types. The classification of the two maps are very different, so it is difficult to compare them. Unfortunately the 2010-2014 BGS inventory map has a column for type, but nearly all landslides are classified as unknown.
When comparing the maps of Abraham and Rock with the one from BGS, which both map the same event (2010 Hurricane Tomas) it is interesting to note the differences in landslide size and total landslide area. The total landslide area in the BGS map is about 2 times more. The overlap is also relatively low: 202 hectares are mapped as landslide by both, whereas 783 hectares of landslides are mapped differently. This is also illustrated in Figure 4-24 where the landslides from Abraham and Rock and BGS for Hurricane Tomas are compared.

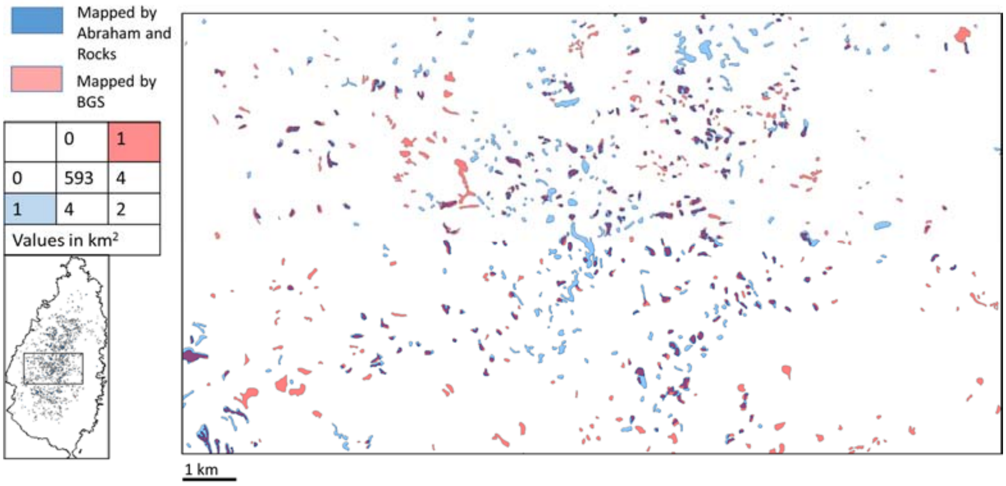


Figure 4-24: Comparing two inventories for the same event (Hurricane Tomas)

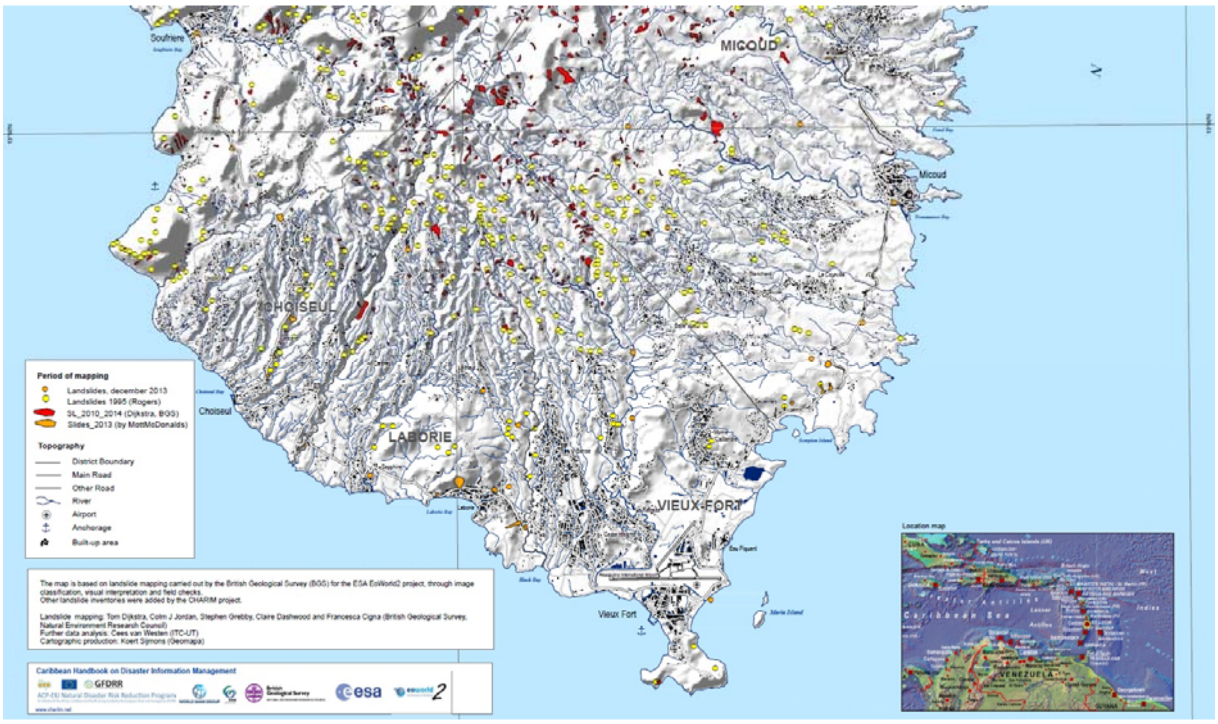


Figure 4-25: Legend of the final landslide inventory map for Saint Lucia. The full map can be downloaded as pdf from the following website: http://www.charim.net/stlucia/maps

We decided to use the BGS inventory instead of the one by Abraham and Rock for the 2010 event. We combined all inventories into a single landslide inventory map (See Figure 4-25 and 4-26). Unfortunately as we do not have enough information on landslide types from the available inventories, we are not able to carry out a landslide susceptibility assessment for different landslide types in the next chapters. We were also not in a position to remap the landslides for Saint Lucia. Therefore we also have to deal with the locational, and thematic errors present in the inventories. Especially the locational errors that are in the 1995 landslide inventory map have been problematic in the subsequent statistical analysis, because the relation with the possible causal factors may not be realistic as the landslide points are not located exactly where the landslide may have taken place in the past.

*Table 4-5: Summary of landslide information for the available landslide inventories for Saint Lucia. * Due to the fact that the inventory doesn't cover the entire island.*

	1995 Rogers	**2010 Abraham and Rock**	**2010-2013 Mott MacDonalds**	**2013 DANA**	**2010-2014 British Geological survey**
Representation	Points	Polygons	Polygons	Points	Polygons
Full coverage?	No, mainly along roads	Yes	No, in a buffer zone around main roads	No, mainly along roads	Yes
number	713	1132	570	45	1233
Total landslide area	-	6.28 km^2	1.77 km^2	-	5.63 km^2
Minimum landslide size	-	352 m^2	17 m^2	-	201 m^2
Average landslide size	-	5550 m^2	146621 m^2	-	72212 m^2
Maximum landslide size	-	93900 m^2	3101 m^2	-	4565 m^2
Study area	603 km^2	603 km^2	603 km^2	603 km^2	603 km^2
Density	-	0.0104	0.0029	-	0.009
percent	-	1.04 %	0.29 % *	-	0.9 %
nr/km^2	1.18 *	1.88	0.95 *	0.075 *	2.044
	Landslide Type				
Debris flow	589	-	87	-	-
Debris slide	12	-	-	-	-
Earthflow	20	-	-	-	-
Rockfall / Rockslide	22	-	190	-	-
Area with creep	-	-	11	--	-
Complex landslide	8	-	-	-	-
Old rotational slide	-	-	18	-	-
Area with small slides	5	-	8	-	-
Uncertain landslide area	-	-	256	-	-
Unknown type	57	1132	/	-	1233
Total	**713**	**1132**	**570**	**45**	**1233**

All these landslide inventories were made available digitally through the Charim GeoNode: http://charim-geonode.net/people/profile/lucia/?content=layers

Figure 4-26: Final landslide inventory map for Saint Lucia. The full map can be downloaded as pdf from the following website: http://www.charim.net/stlucia/maps

5. Landslide conditioning factors

In this chapter an evaluation is made of the available factor maps for landslide susceptibility assessment in Saint Lucia. 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 in Saint Lucia 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/).

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

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

5.1. Digital Elevation data

There were several sources for digital elevation data for Saint Lucia. The first one are contour lines obtained from the Survey Department, which have been derived from the old topographic maps from British Overseas Surveys. The topographic maps at 1:25.000 scale are available in digital format, as scanned maps. The maps are made in 1958, based on aerial photographs from 1951-1955. These maps are in the Transverse Mercator projection, Clarke 1966 Spheroid, and 1927 North American Datum. The contour lines, with interval of 50 feet, are of good quality, but the contours have only been digitized for the coastal areas, and the centre of the island is not covered (See Figure 5-1). The second source of information are contour lines which were generated by an international project, during which the international company FUGRO generated a national topographic map using photogrammetrical methods in 2009 – 2010 (before hurricane Tomas). Due to tropical vegetation and cloud cover the number of photogrammetrical points was often not enough to generate accurate contour lines in forested and cloud covered areas. Therefore the contour lines generated from many forested areas are not very accurate and have sometimes strange results. This is illustrated in Figure 5-2 where the shaded relief image shows the poor quality of the DEM. Here we show for a sample area the grid points that were surveyed, and the break-points that were used for generating the Digital Elevation Model. The resulting Digital Elevation model was generated using Triangular Irregular Networks (TINS) and the resulting DEM therefore shows many of such triangular artefacts that do not represent the real terrain situation in many locations (See Figure 5-2). We also discovered that the original data from the survey of FUGRO was not available anymore in the Survey Department in Saint Lucia. We were able to obtain the original data from FUGRO and shared this again with the departments in Saint Lucia.

The next source of DEM data was the ESA EoWorld2 Project, mentioned earlier in this report. The British Geological Survey generated medium resolution DEMs for Saint Lucia, and Grenada. The DEMs were to be generated from stereo optical satellite imagery with a spatial resolution of 30m or better. The preferred source of imagery from which to produce the DEMs was a European or Canada sensor. With no suitable archived imagery available, a tasking request was submitted to Airbus Defence & Space in early August 2014 in order to have fresh stereo Pleiades imagery acquired for both St. Lucia and Grenada. However, the timing of this request coincides with the hurricane season in the Caribbean. As a result, all attempted acquisitions to date have been affected by considerable cloud and haze cover, thus rendering them inadequate for the generation of DEMs. In the absence of any other alternative stereo imagery, the DEMs for the AOIs were generated based on imagery acquired by the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) sensor. The ASTER sensor has a stereo camera that acquires nadir and backward-looking images for band 3, which can be processed using a photogrammetric approach to extract DEMs.

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

Group	Factor	Available	Quality
Topographic factors	Digital Elevation Model	Yes	Poor. Due to survey method and cloud cover there are areas with very poor DEM data.
	Altitude zones	Yes	Good, generated from the DEM. Low quality of DEM doesn't affect the altitude zones
	Slope steepness	Yes	Poor. Poor quality of the DEM is cause of poor quality of slope steepness map. Steep slopes are underrepresented.
	Slope aspect	Yes	Moderate. Low quality of DEM affect the slope direction to some extent.
	Upslope contributing areas	Yes	Poor. Low quality of DEM affect the calculation of upslope contribution areas.
	Windward / Leeward side	Yes	Good. Based on digitized boundaries.
Drainage factors	Eroding sections of mains rivers	Yes	Moderate. There are some problems with fitting of the drainage lines to the DEM. Automatic extraction of drainage from the DEM is not an option.
	Distance from stream initiation	Yes	Good
	Distance from ridges	Yes	Due to poor DEM quality automatic extraction of ridges is not very good.
Geological factors	Lithological map	Yes	Moderate, Too general to be of much use for landslide work, no differentiation between volcanic materials. Part of the island has no data.
	Fault map	No	Not available
	Geomorphological map	No	Not available
Soil map	Pedologic Soil type map	Yes	Moderate. Detailed map. Extensive legend. Made in 1966 for agricultural purposes. No clear relation with topography and lithology
	Engineering soil type map	No	Not Available. Would be very important for local and site investigation analysis. Should contain information on geotechnical and hydrological parameters of the engineering soils.
	Soil depth map	No	Not available. Would be very important for local and site investigation analysis
Land cover factors	Land cover existing	Yes	Good quality. Generated by the Bristish Geological Survey from satellite images
	Land cover (earlier)	Yes	Moderate, Two land cover maps available, one from 2000 made from image classification/, not clear what date. Very general, poor quality
	Road cuts	No	Not available.
	Distance from roads	Yes	Good quality, we improved the road map and made also an improved classification.

Using an optimised approach, NASA and Japan's Ministry of Economy, Trade and Industry (METI) have already processed an extensive archive of ASTER stereo imagery for the purpose of producing the 30m ASTER Global DEM (ASTER GDEM); released in 2011. With a view to augmenting this ASTER-derived elevation data, different strategies were developed and implemented based on the ancillary data available for the two AOIs. For St. Lucia, ancillary elevation data derived from contour maps was made available by the Physical Planning Office and University of the West Indies. In an attempt to increase the accuracy of the ASTER-derived elevation data, a

vertical calibration approach utilising the contour data was implemented. To achieve this, 32,000 corresponding ASTER- and contour-derived elevation points were extracted and modelled (R^2=0.97) using regression analysis. These data points were then gridded using a Triangular Irregular Network with linear interpolation algorithm to generate a 30m DEM. The resulting shaded relief image in shown in Figure 5-2.
As all sources of DEMs had problems, it was decided to generate a new DEM using interpolation of points from all available sources. These files were each transformed to point files (x,y,z). From the point files a DEM was interpolated using Ordinary kriging, with an exponential semivariogram using the Gstat software (gstat.org). An example of the result is shown in Figure 5-2. Unfortunately this DEM produced blocky artefacts that made it unsuitable for our landslide susceptibility analysis. Therefore we used the DEM from the FUGRO data.
We generated the following derivative maps:

- Elevation classes: this map consisted of 6 altitude classes. This was done because we assumed that there might be a relation between altitude and landslide occurrence, as rainfall amounts strongly increase with increasing altitude.
- Slope steepness classes: an algorithm was used to calculate the slope steepness per pixel in degrees. 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.
- 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.

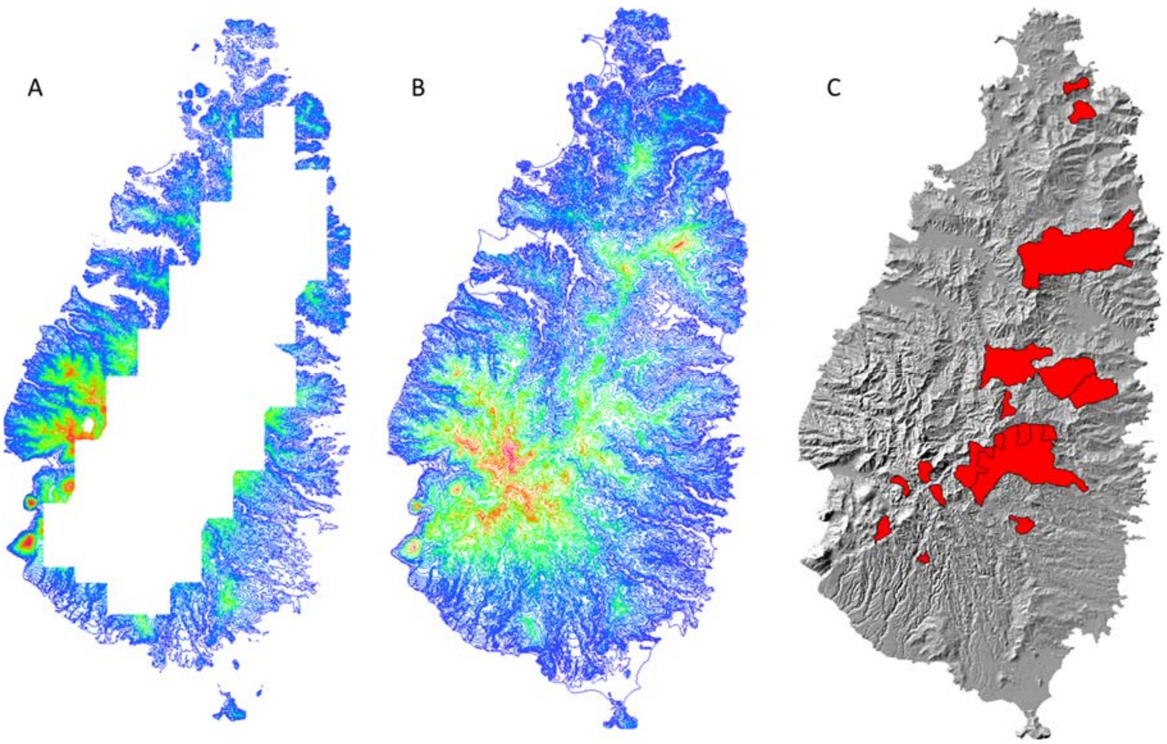


Figure 5-1: The Digital Elevation Model for Saint Lucia is of poor quality. A: detailed contour lines derived from old topographic maps which have a good quality, but are not available for the centre of the country. B: contour lines from the topographic survey project by FUGRO, which cover the entire island, but have low quality in the forested area. C: Examples of a shaded relief map of the central part of the country showing the areas with a poor quality of the Digital Elevation Model. For these area the resulting landslide susceptibility assessment is much less reliable.

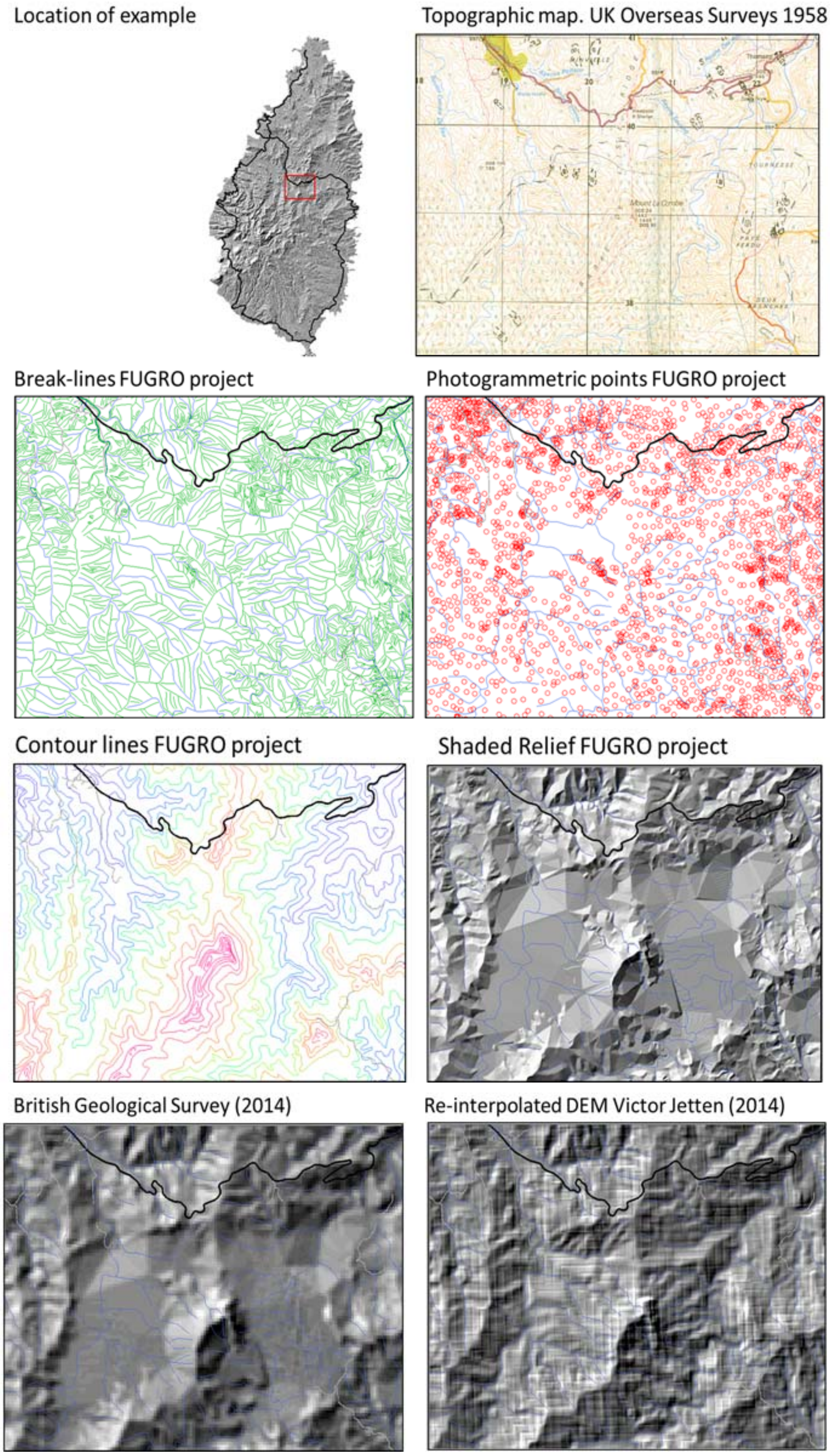


Figure 5-2: Illustrating the problems involved for the various Digital Elevation Models for Saint Lucia for a small area. The grid points and break-lines used in the FUGRO project are not equally dense and missing in some places due to cloud cover in the airphotos used in the photogrammetrical work. The contours from the original topographic map from 1980 are not digitized for the entire area. The BGS DEM is derived from ASTER data which is too general, and the re-interpolated DEM shows artefacts. Overall, the poor quality of the DEM will greatly affect the result of the landslide susceptibility assessment.

5.2. Geology and soils

Saint Lucia is made up almost totally of volcanic origin, presenting andesite, dacite and basalt rock formations resulted from the tertiary or late Quaternary age volcanism. Sedimentary beds occur but are of small extent. Beds of mixed sedimentary and volcanic origin are common; they have good bedding and stratification such as tuffs, agglomerate tuffs and conglomerates (DeGraff, 1985; OAS, 1986). Newman, 1965 (as cited in Lindsay et al., 2002) divide the volcanic centres in Saint Lucia into three categories based on age and geographic distribution. These groups are the Northern, Central and Sothern series, from oldest to youngest.

Lindsay et al., (2002) revised this sub division, owing to the confusion that the original grouping made like: several of the centres within the northern series are actually located in the south and several centres that were grouped as the youngest southern series correlate more to the older northern series. The revised grouping of Lindsay et al., (2002) is:

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

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

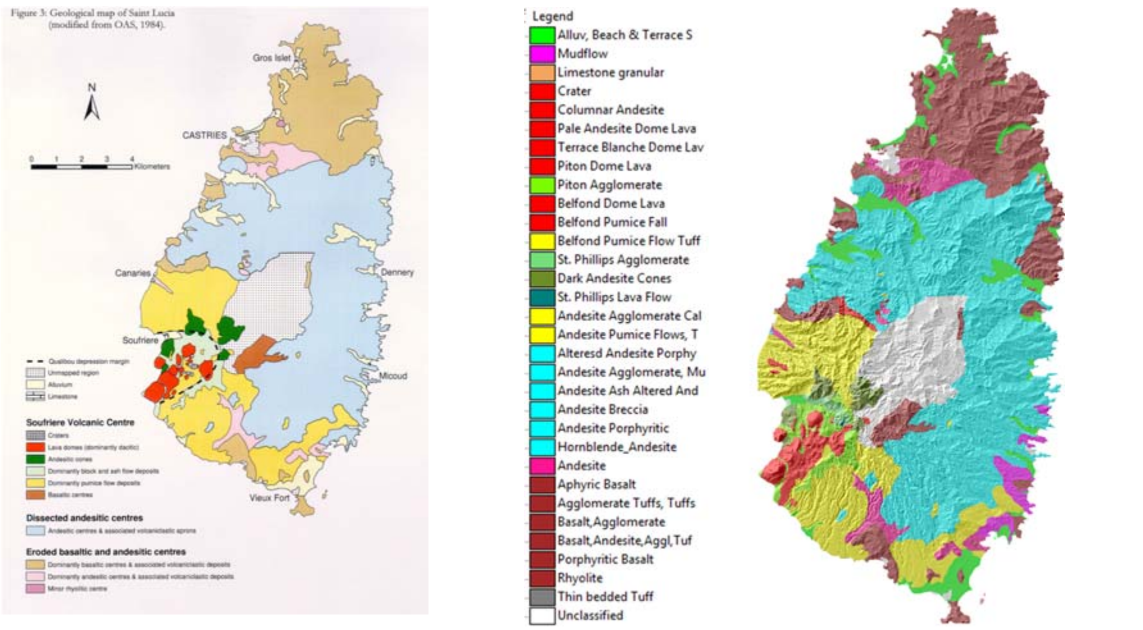


Figure 5-3: Left: Geological map of Saint Lucia (OAS, 1984). Right: digital geological map with more mapping units (source unknown). Note the unmapped centre of the island.

As it could be seen during the fieldwork, the difference between rocks and soils is not clear in engineering terms, due to the relative degree of consolidation of the volcanic deposits, their heterogeneity and the effect of weathering. The volcanic deposits are usually very thick. This can be observed in near vertical road-cuts (See

Figure 5-4). Analysing the behaviour of road cuts in volcanic ash soils requires a detailed analysis of soil types which is not possible in this study. Volcanic bedrock in tropical climates is susceptible to deep weathering and mass wasting (Prior and Ho, 1972; Hartford and Mehigan, 1984; Rouse, et al. 1986; DeGraff, 1991). Weathered volcanic soil is weaker than the original bedrock and the high precipitation on the island increases pore-water pressure within discontinuities decreasing soil shear strength. The loss of shear strength generates zones of failure in which the mass destabilizes in the form of a landslide or debris flow (Faugeres, 1966; Walsh, 1982; DeGraff, 1991). Figure 5-4 shows an example of a cutslope located in the east coast of Dennery village, St. Lucia. It is at the Mandele viewpoint along the main road Castries to Vieux Fort.

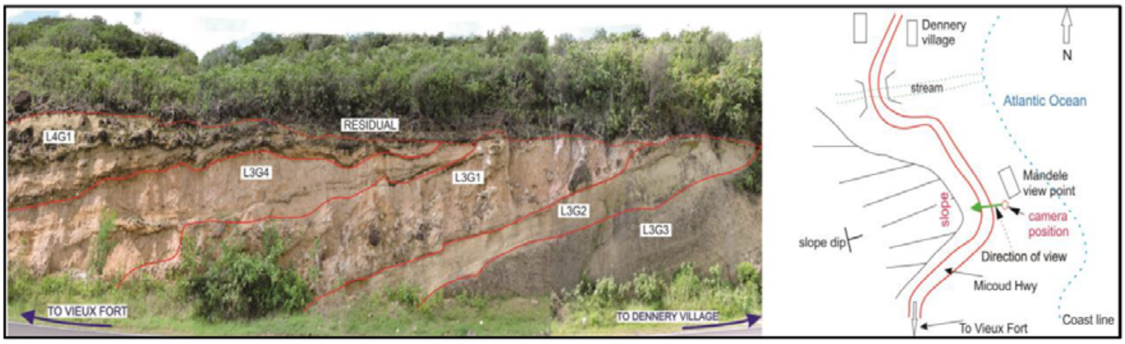


Figure 5-4. Example of an outcrop in volcanic deposits, and the separation into different geotechnical Units (Mulenga, 2015).

The slope length and height are approximately 100m and 5m respectively. The slope was cut in the year 1972 by mechanical excavator. The accessibility was fair though with a lot of vegetation along the scree slope. The slope falls in the Andesite agglomerate formation. The rock mass consists of fine to coarse grained matrix and clasts of pebbles to cobbles, with rock units of agglomerate deposits, tuff, alluvial deposits of agglomerate nature, and well graded ash and lapilli pyroclastics. Four geotechnical units of were mapped on this slope face.

- GEOTECHNICAL UNIT L3G1 – The unit is an agglomerate of approximate length of 20m and mapped height of 3m; highly weathered. The colour is greyish yellowish brownish, with thick bedded, matrix supported, poorly sorted andesitic clasts. The existing slope SDD/SD is 0400/650; the discontinuity orientations SDDdisc and SDdisc are 0120/150, 2920/700, 2560/850, 3580/780 and 0080/750; the spacing (SPA) 0.53; persistence along strike and along dip > 0.2m. Condition of discontinuities: Roughness large scale (Rl) - slightly wavy and curved, and straight; Roughness small scale (Rs) - rough and smooth undulating; Infill material (Im)- no infill –surface staining, and fine non softening and soft sheared material; Karst (Ka)- none. The unit face is eroded, exposing fresh corestones.
- GEOTECHNICAL UNIT L3G2 – The unit is a highly weathered pyroclastic ash deposit of approximate length of 20m and height of 1m. The colour is yellowish greyish darkish, and thin bedded fine matrix and well sorted clasts. The existing slope SDD/SD is 0400/650; the discontinuity orientations SDDdisc and SDdisc are 1440/210, 3540/700, 2320/750, 2980/400 and 1600/650; the spacing (SPA) 0.27; persistence along strike and along dip > 0.07m. Condition of discontinuities: Roughness large scale (Rl) - wavy, curved, slightly curved and straight; Roughness small scale (Rs) – smooth stepped, rough and smooth undulating; Infill material (Im)- fine soft sheared material and no infill-surface staining; Karst (Ka)- none.
- GEOTECHNICAL UNIT L3G3 – The unit is a moderately weathered pyroclastic lapilli deposit of approximate length of 50m and height of 4m. The colour is darkish greyish, and thick bedded well-sorted clasts, and clasts supported. The existing slope SDD/SD is 0280/800; the discontinuity orientations SDDdisc and SDdisc are 1380/320, 1260/200, 3540/700, 0280/750 and 0240/550; the spacing (SPA) 0.34; the persistence along strike and along dip > 0.2m. Condition of discontinuities: Roughness large scale (Rl) - slightly curved, small scale (Rs) – rough and polished undulating, and rough planar; Infill material (Im)- soft sheared material fine and no fill-surface staining; Karst (Ka)- none. The interface between the matrix and clasts is sharp, making discontinuities to be rarely visible.
- GEOTECHNICAL UNIT L3G4 – The unit is a highly weathered tuff deposit of approximate length of 16m and mapped height of 2m. The colour is yellowish brownish and thick bedded weathering horizon, with few andesitic corestones. The existing slope SDD/SD is 0380/670; the discontinuity orientations SDDdisc and SDdisc are 1260/200, 1600/220, 0180/650, 3090/270 and 0400/350; spacing (SPA) 0.29; persistence along strike and along dip > 0.2m. Condition of discontinuities, the roughness large scale (Rl) – wavy,

curved, and slightly curved, and the roughness small scale (Rs) – rough stepped and undulating; Infill material (Im) – fine non softening and soft sheared material; Karst (Ka) – none. The unit shows some layer of iron oxidation (iron oxide), evident of chemical weathering.

The above example illustrates the high variability in terms of engineering soils that can be found. The mineralogy of and weathering characteristics of the volcanic bedrock generally produces fine grained soils often containing high proportions of clay. Due to the widely varying rainfall pattern on the island, the parent materials are subject to different amount of leaching. This together with steep topography of the island and ash layers, contribute to the differentiation of the soil types. In areas with heavy rainfall and little or no dry season, the soils are of latosols or latosolic. The clay of these soils is usually kaolinitic but in special conditions allophane and illite may also exist. In areas with several months of dry season, the soils are of expanding clays of the montmorillonitic type (OAS, 1986). Under the unified soil classification used by engineers and geologists, the soils of Saint Lucia would be fine grained soils such as silty clays, clayey silts, silty clays-inorganic and sandy clays, or inorganic clays of medium plasticity (DeGraff, 1985). In the available soil map of Saint Lucia the classification is made based on parent material and the classes are: agglomerate soils, alluvial soils, clay soils, colluvial soils, miscellaneous soils and volcanic soils. The available soil type map was generated in 1966 (Stark et al., 1966) through physiographic interpretation of aerial photographs, combined with field work and soil testing. The map consists of 3 map sheets, with a very complicated legend. There are over 100 different legend classes, and soils are named after a locality (most often an estate), with a suffix related to the parent material. This classification was made in order to identify agricultural fertility problems. For this the degree of weathering were estimated based on field observation data as pH, texture, structure and X-ray analysis on clay mineral content. Other factors were used as well such as parent materials, climate, plant and animal organisms, age of land and topography. The legend classes show a combination of the soil type (indicated as a number), the slope class and the erosion categories.

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

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

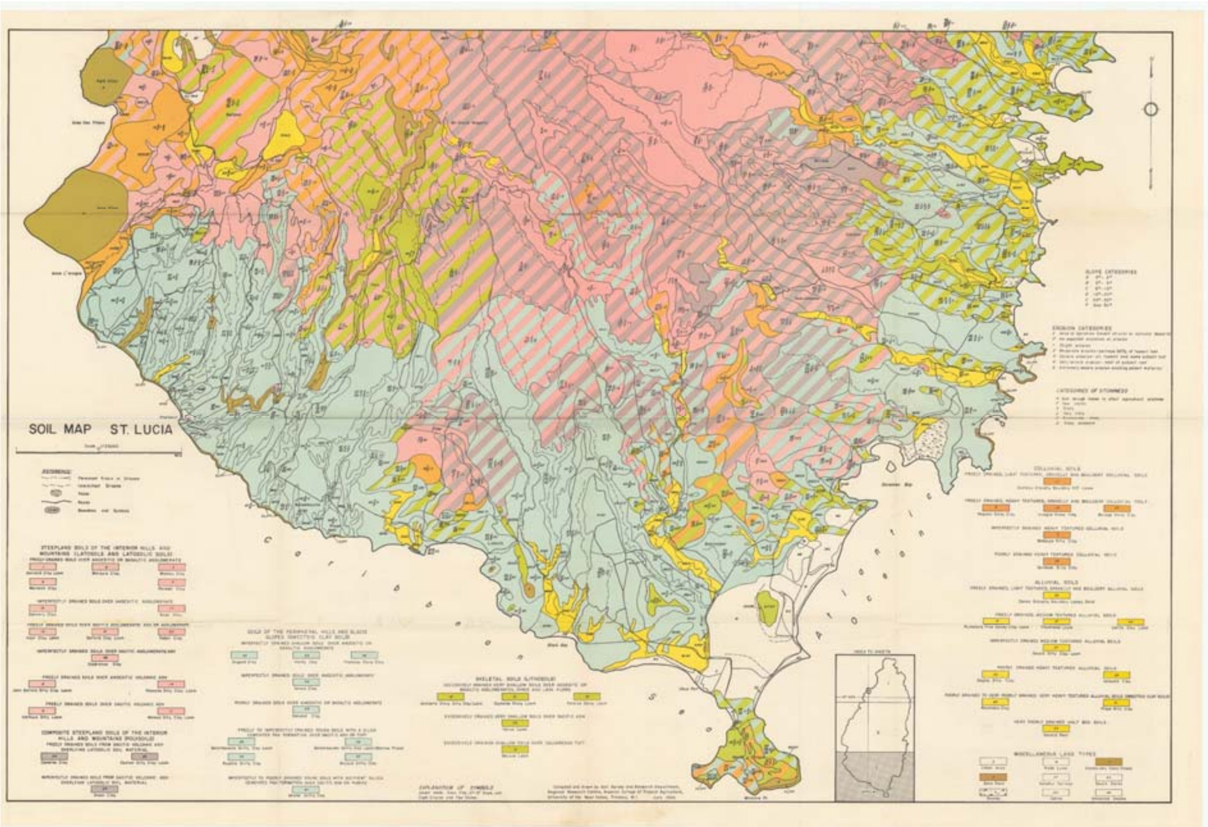


Figure 5-5: Soil map of Saint Lucia. One of three sheets showing the southern part of the country (Stark et al, 1966)

The conversion of this complicated soil map into a GIS layer turned out to be a major challenge. We obtained a digital soil map from the physical planning department, which contained 60 main soil classes. The topology of this map was also problematic, and we had to fix this using a number of GIS operations. We did not attempt to re-digitize the original map, as this would be too time consuming, and also the legend would pose a serious problem in the use of this in the landslide susceptibility assessment. We did link it with a slope class map, to make soil classes in relation to the slope classes, which were considered to be better indicators for slope stability than the soil classes alone. We also reclassified it into 7 main classes.

5.3. Land-cover

We have two land cover maps for Saint Lucia: one from 2000 and one from 2015. The oldest one was made using image classification of Landsat ETM+ and Spot images by USGS, USAID and the Nature Conservancy as part of the USAID CarLand project (CarLand, 2000). We also obtained a recent land use map from the before-mentioned project of European Space Agency (ESA) and the World Bank (WB) "Earth Observation for Development" initiative – Eoworld 2. 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 Saint Vincent. Both the detail of this map as well as the legend are so different from the previous land cover map from 2000 that it is difficult to compare them. 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 5-6). 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.

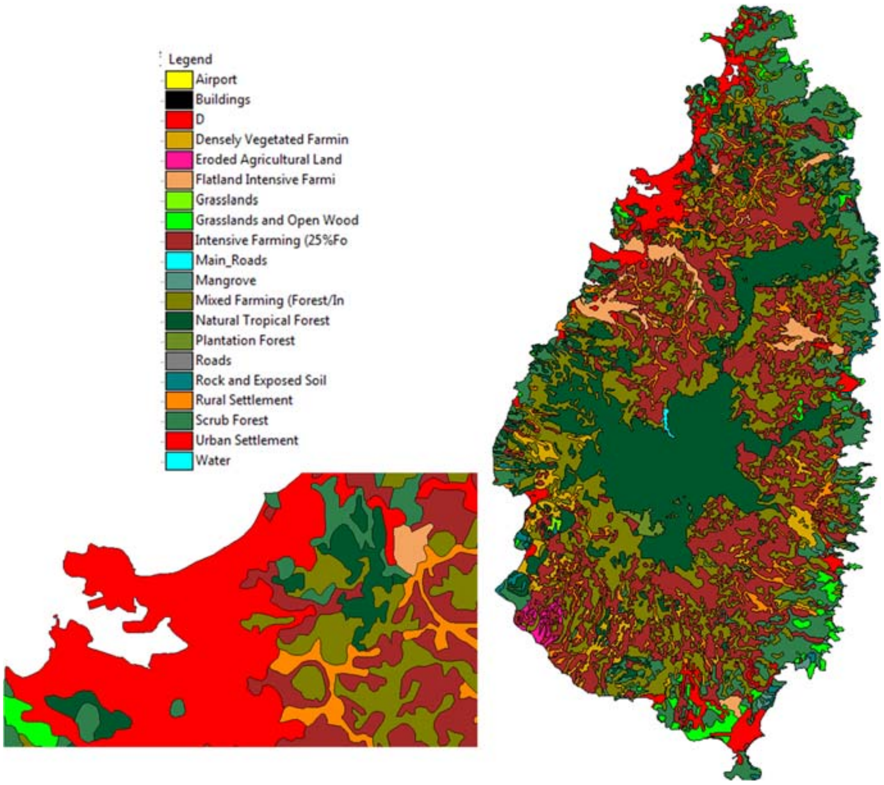


Figure 5-5: Land use/ Land cover map for 2000, generated by the CarLand project (2000)

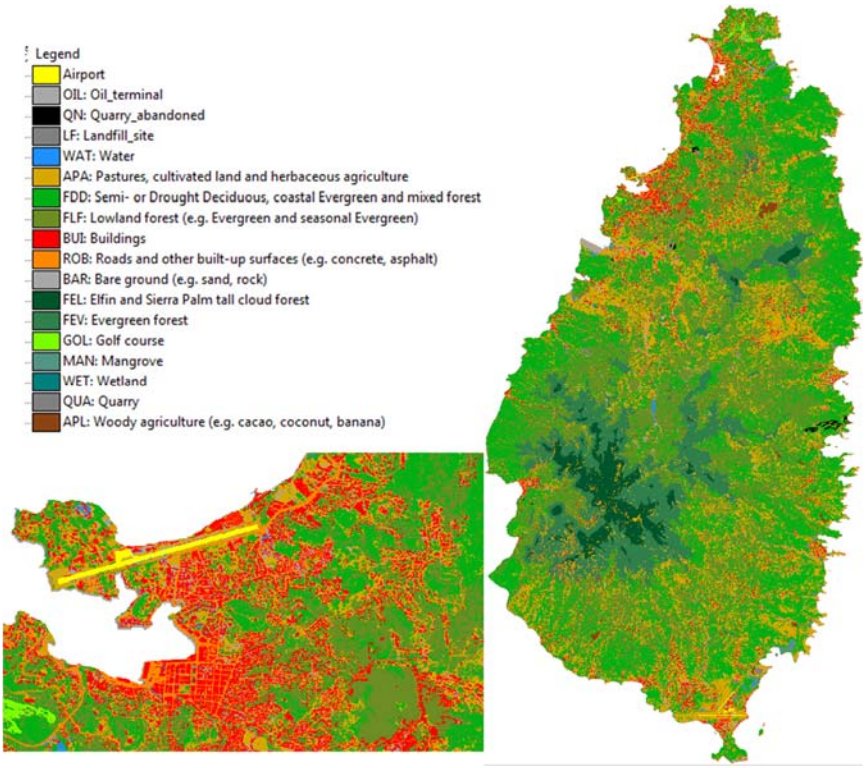


Figure 5-6: Detail and legend of the Land cover map of Saint Lucia. The map can be downloaded from: http://www.charim.net/stlucia/maps

6. Landslide susceptibility assessment

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

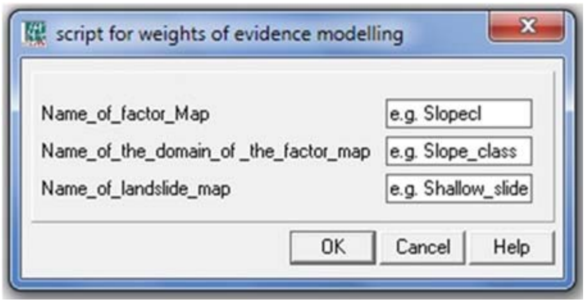


Figure 6-3: Input screen for the Weights-of-Evidence script used in the analysis. The script needs three inputs: name of the factor map (e.g. slope class, lithology), name of the domain of the factor map, and name of the landslide map, which should be a binary map (0= no landslide, 1= landslide).

The script was analysed for each of the factor maps in combination with the landslide input. 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 Saint Lucia

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

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

Name of factor map	Explanation	Classes
Aspect input	Slope direction classes	9 classes (N, NE, E, SE,S,SW, W, NW, North2)
Coastal input	Distance from coastline	3 classes (0-50, 50-100, >100 m)
Elevation2	Elevation classes	5 classes (0 - 100, 100 – 265, 265 – 500, 500 – 825, 825 – 1000 m)
River input	Distance from rivers	4 classes (0-25, 25-50, 50-100, >100 m)
Roads input	Distance from roads	3 classes (0-25, 25-50, >50 m)
Geology	Lithological units	32 geological units defining different lithological units
Landcover_2014	Landcover map	18 classes
Slope_cl	Slope steepness classes	5 classes (0 – 10 , 10 - 20, 20 - 35 , 35 – 50, >50 degrees)
Soil map	Soil types	7 classes defining different soil types
Erosion input	Soil erosion classes	6 classes defining different levels of erosion
Erosion_Soilmap	Combination of erosion and soil types	27 classes, combining 6 erosion classes and 7 soil type classes
Elevation2_ASPECTCL	Combination of elevation and slope direction classes	45 classes, combining 5 elevation classes and 9 direction classes
Elevation2_slopecl	Combination of elevation and slope direction classes	25 classes, combining 5 elevation classes and 5 steepness classes
Elevation2_ASPECTCL_slopecl	Combination of elevation, slope direction classes and slope steepness	225 classes, combining 9 slope direction classes, with 5 elevation classes and 5 steepness classes
Geology_Slopecl	Combination of geology and slope classes	160 classes combining the 32 geological units with 5 slope classes.
Landcover_Slopecl	Combination of land cover and slope classes	278 classes combining 18 landcover classes with 5 slope classes.
Soilmap_Slopecl	Combination of soil types and slope classes	35 classes combining 7 soil classes with 5 slope classes.

Because of the difference in quality of the inventories we used two landslide inventories to analyze the relation with causal factors: 1995 Rogers and 2010-2014 BGS inventories.

Slope steepness

Both data from 1995 and from 2010_2014 show a relation with the occurrence of landslides. Negative contrast factors correspond to the lower slope steepness class while for the steeper slope classes resulted in positive contrast factors due to negative and positive weights, respectively. Briefly, the steeper the slope, the higher the positive value of contrast factor is which indicates the higher probability to find landslides in steep slopes.

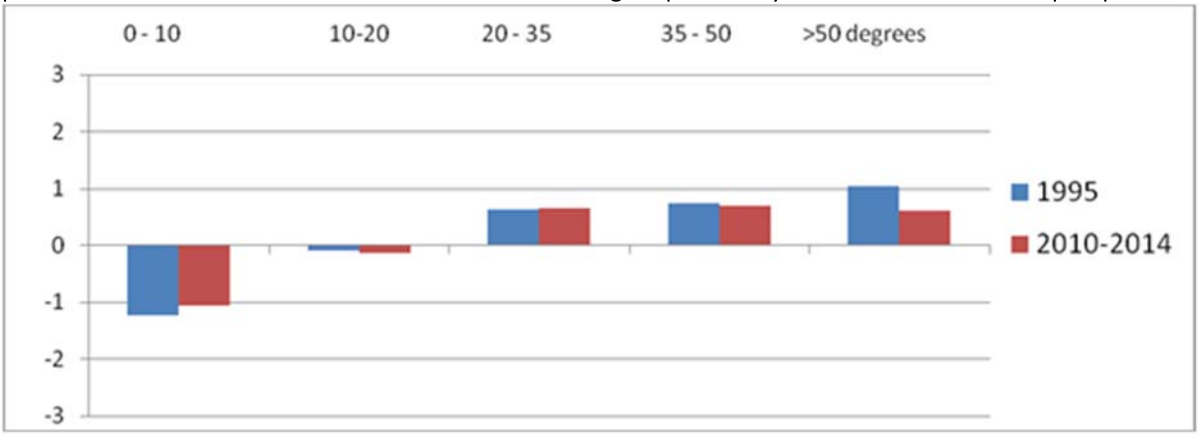


Figure 6-4: Contrast factors for slope steepness classes for landslides in 1995 and landslides in 2010_2014

Slope direction

The relation between landslides and slope direction is different for the two landslide inventories. The 2010-2014 BGS inventory shows a clear relation with slope oriented to the South (from East – West) whereas the 1995 inventory doesn't show that relation as clear. This may be related to the direction in which the Hurricane Tomas affected Saint Lucia, with more intense rainfall on slope oriented to the South.

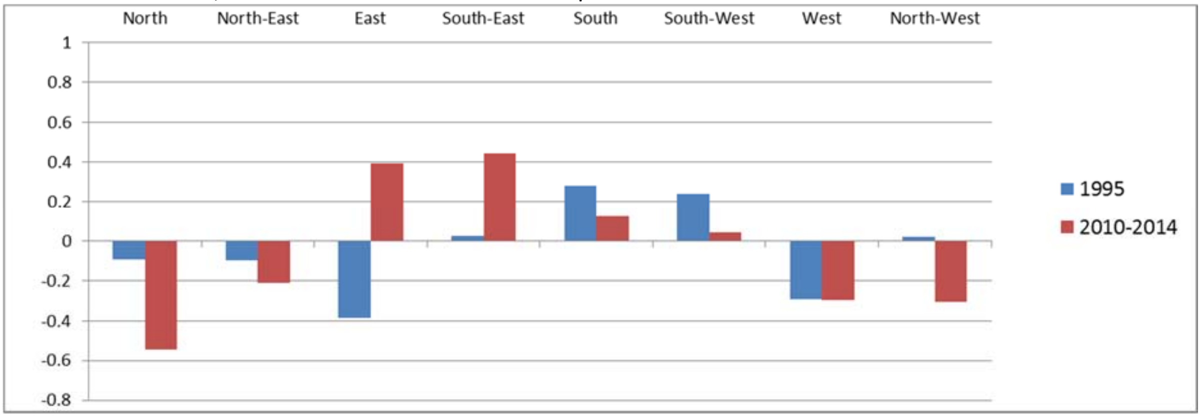


Figure 6-5: Contrast factors for slope direction classes for landslides in 1995 and landslides in 2010_2014

Elevation classes

Also with respect to elevation there is a difference between the two inventories. However, the difference is not very significant. Landslides are most prominent at elevations between 265 – 825 meters. Both the low and high elevation classes have contract factors that become negative. There are less landslide in the coastal areas, and relatively less in the highest parts of the area above 800 m, which actually cover only a small area.

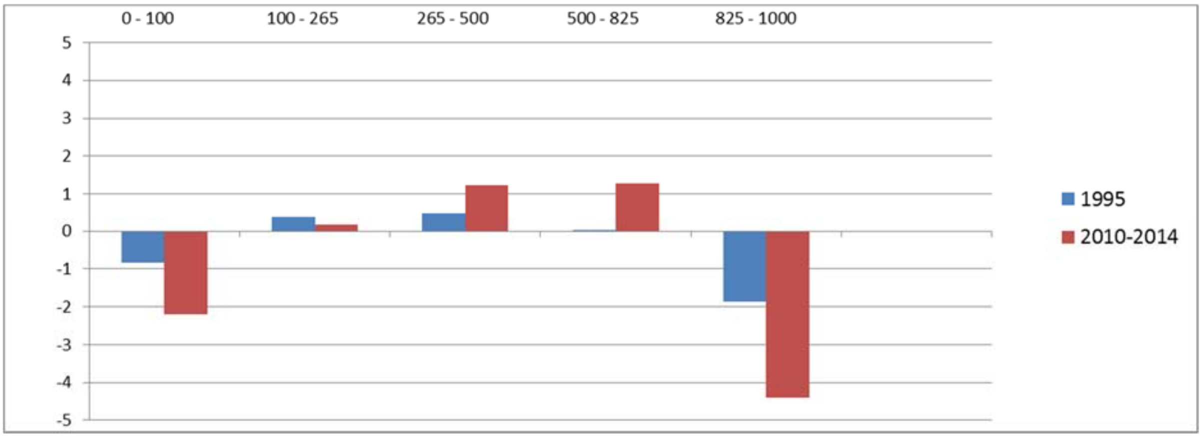


Figure 6-6: Contrast factors for elevation classes for landslides in 1995 and 2010_2014

Distance from coast

The two inventories show a different behavior with respect to distance from the coast. This is particularly so for the 1995 inventory which is not related to this factor at all, and therefore has high negative values for classes close to the coast and high positive values for classes far away from the coast. The contrast factors for the 2010-2014 are close to 0 indicating that there is not much difference.

Figure 6-7: Contrast factors for distance from the coast classes for landslides in 1995 and 2010_2014

Distance from rivers

Both inventories do not show a clear relation with the distance to rivers. The 2010-2014 inventory has values close to 0 indicating no relation at all, whereas the 1995 inventory has less landslides close to rivers. So in any case river undercutting is statistically not a very relevant factor considering all landslides, although in particular cases it may be important, and in some instances it may even lead to possible landslide dams. It has been observed in some of the main triggering events, that discharges were observed that exceeded the calculated ones by far, which could be explained by the temporary existence of landslide dams in the catchments.

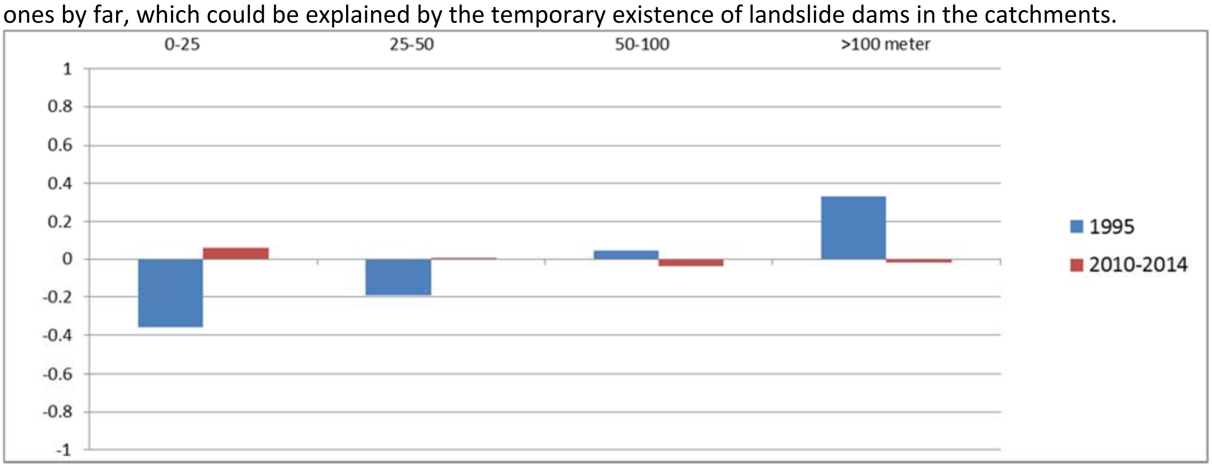


Figure 6-8: Contrast factors for distance from river classes for landslides in 1995 and 2010_2014

Geology

The relationship of landslides with geological units is complicated. As can be observed from Figure 6-9 there are units that show a very clear relationship with landslides. For the 2010-2014 inventory these are: aphyric basalt, columnar andesite, dark andesite cones, St Phillips agglomerate, andesite ash and breccia. The 1995 landslide occur in different geological units. Interesting is that the geological unit mudflow doesn't seem to be favorable to landslides.

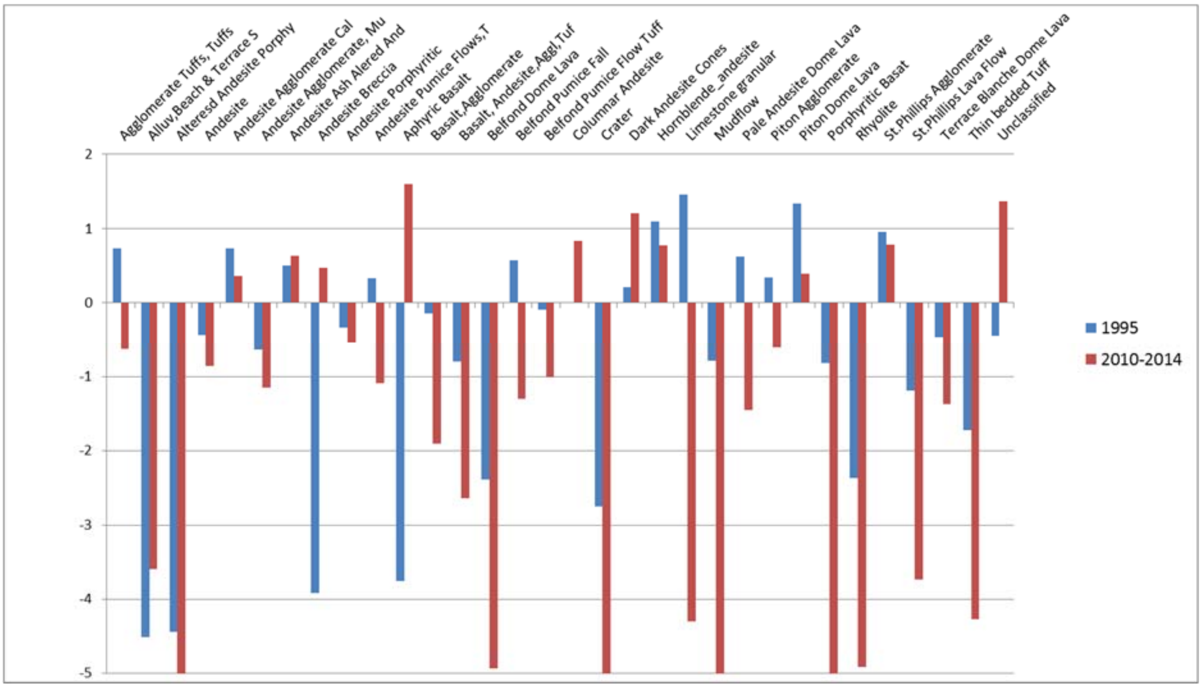


Figure 6-9: Contrast factors for geological units for landslides in 1995 and 2010_2014

Soils

We classified the original soil map into seven main classes. They show a relation with landslides. As expected alluvial soils have less landslides. The low scores for clay soils were different than expected, as were the low scores for skeletal soils for the 2010-2014 BGS inventory. Colluvial soils have a positive relation with landslides.

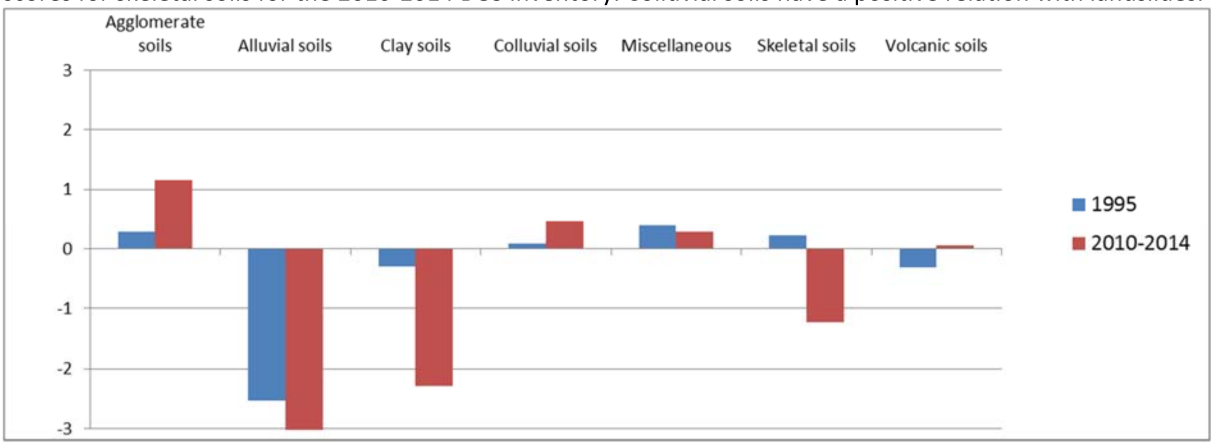


Figure 6-10: Contrast factors for soil units for landslides in 1995 and 2010_2014

Land cover

When using land cover a relevant issue was presented, very positive contrast factor for Wetland land cover resulted in the landslide 1995 data. This was due to the small area of this lands cover unit, and the calculation script which assigns one pixel as landslides in those cases where there are none, to avoid division by 0 problems. However, the undesirably result is that the weight for small units might become positive, as was in this case. We later adjusted these results manually.

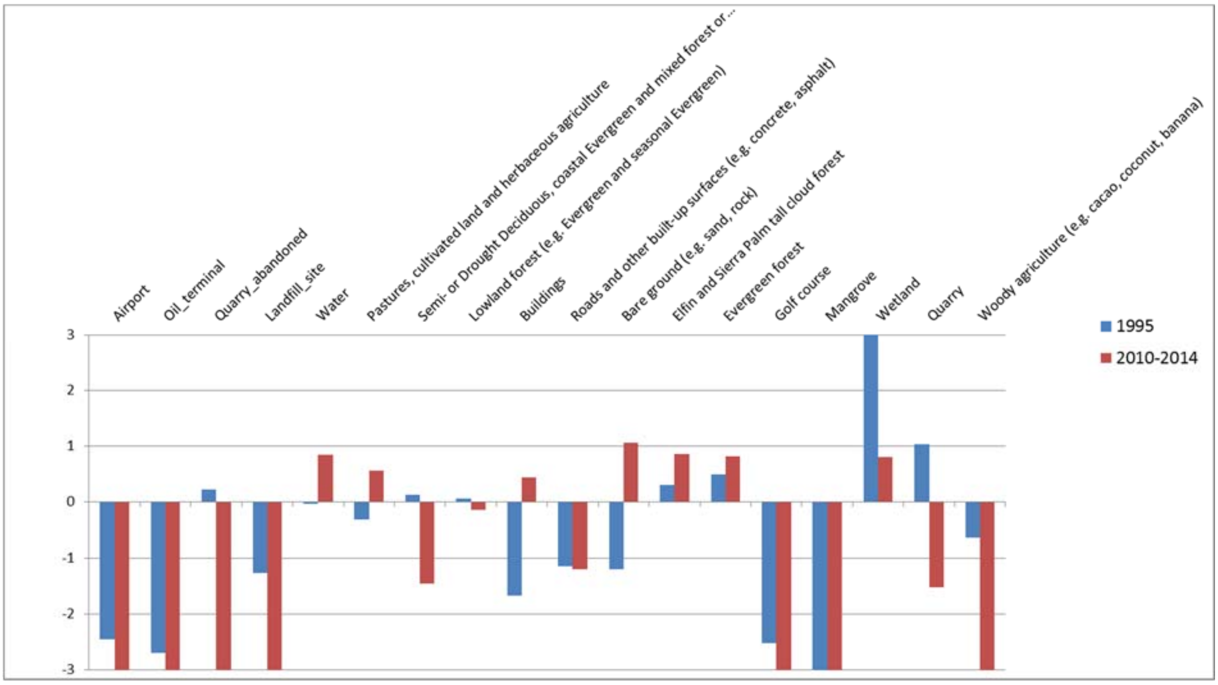


Figure 6-11: Contrast factors for land cover in data from 1995 and data from 2010_2014.

Distance to roads

Finally, in contrast to what we expected, we do not see a clear relation between landslides and distance to roads. That is to say, the relation is clear that landslides are not more frequent in classes close to road than further away. Again, thee relations are based on the entire landslide data set, and one should not conclude that distance to roads is not relevant for landslide susceptibility. That is why it is important to not take the results of the statistical analysis directly as the basis for the susceptibility mapping, but analyze and alter the values based on expert opinion.

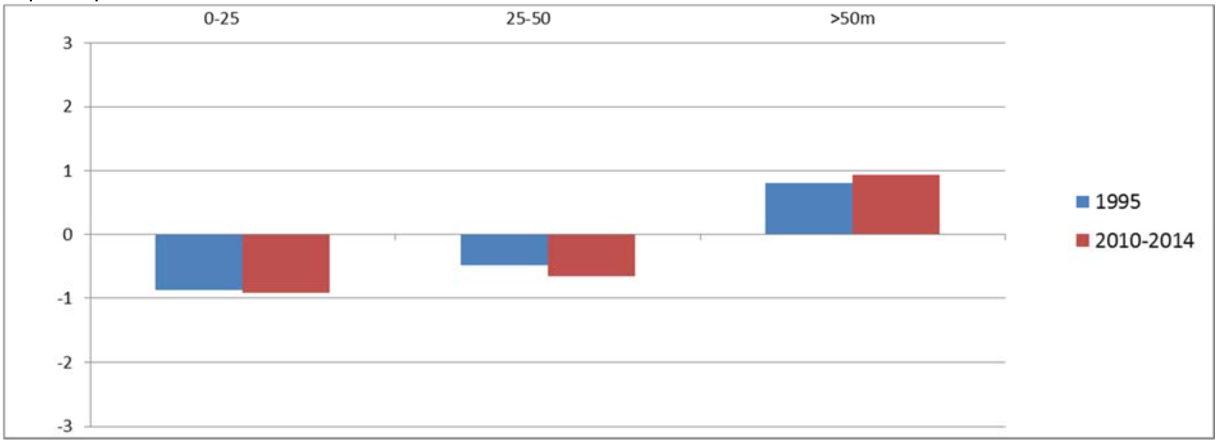


Figure 6-12: Contrast factors for road distance classes for landslides from 1995 and data from 2010_2014.

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 the two inventories. The results are summarized in Table 6-2.

There is a clear difference between the factor maps that are considered useful for the susceptibility assessment for the two inventories. There are less factors that seem to be useful in relation to the landslide inventory of 1995 (which were landslide points mapped by Rogers) than for the 2010_2014 polygon-based inventory generated by the British Geological Survey. As we indicated before the inventory from 1995 has a considerably locational error, which means that the landslide points may not represent the correct locations of landslides. This is why the relation with causative factors becomes rather fuzzy. As we didn't have satellite images or photos that could be used to verify and correct the locational of the landslide points of the 1995 inventory, we were also not able to correct for the positional errors.

As we didn't have enough information to separate the landslides in soil-related and rock-related landslides, we could not evaluate the specific conditions that should be used for both. Obviously soil-related factors are less useful as factor maps for the analysis of the susceptibility of rockslides, which are much deeper, and where soil type doesn't play an important role as causal factor. The 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.
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 6-2: Summary of the usefulness of the various factor maps for landslide susceptibility assessment based on the statistical analysis for Saint Lucia.

Name of factor map	**Explanation**	**1995**	**2010-2014**
Coastal_input	Distance from coastline	Not useful	Not useful
Elevation	Elevation classes	Not useful	Useful
River_input	Distance from rivers	Not useful	Not useful
Roads_input	Distance to roads	Not useful	Not useful
Geology	Lithological units	Somewhat useful	Somewhat useful
Landcover	Landcover map	Not useful	Useful
Slope classes	Slope steepness classes	Useful	Useful
Aspect_input	Slope direction classes	Not useful	Somewhat useful
Soil_map	Soil types	Somewhat useful	Somewhat useful
Erosion_input	Soil erosion hazard classes	Not useful	Somewhat 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 6-13
From a decision-making perspective, multi-criteria evaluation can be expressed in a matrix as shown in the Figure 6-13. 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).

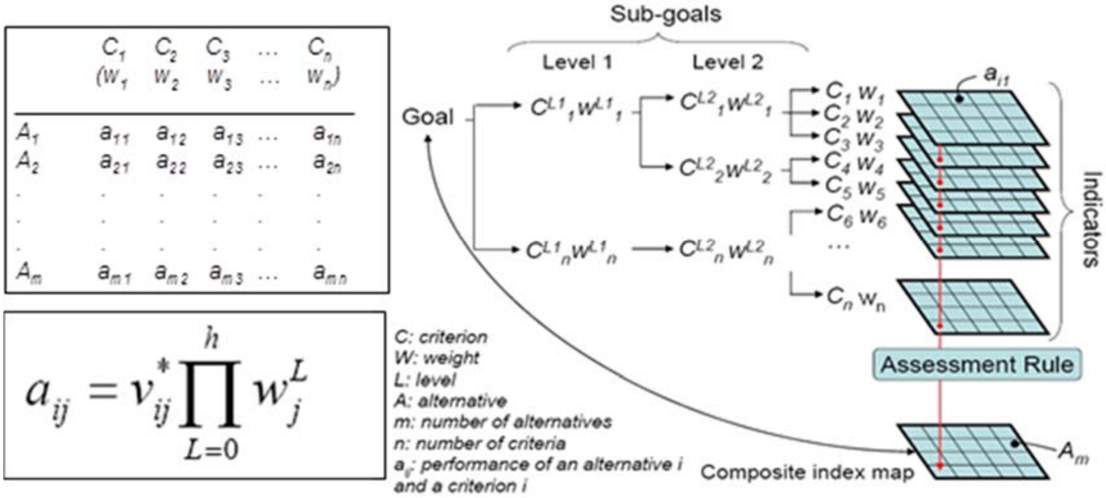


Figure 6-13: Schematic procedure for spatial multi-criteria evaluation based on the analytical hierarchical process

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

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

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

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

The general steps in the process are:

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

Based on the results from the statistical analysis, which were presented in the previous section, a criteria tree was constructed (Figure 6-14). 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.

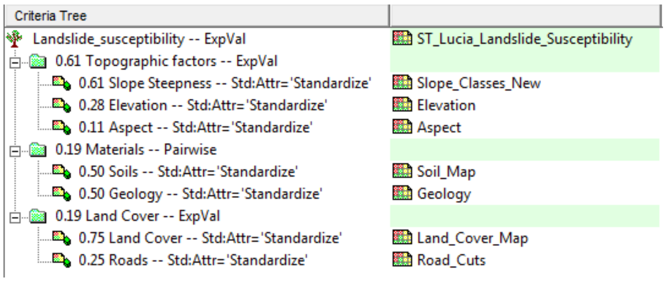


Figure 6-14: Criteria tree for landslide susceptibility assessment for Saint Lucia

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. 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.

6.5. 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 curve is shown in Figure 6-15. From the figure it is clear that the susceptibility map generated for the 2010-2014 inventory is better than for the 1995 inventory, as the latter one has problems with the position of the landslides. The success rate curve for the 2010-2014 map is acceptable, although also not very good (e.g. 70% of the landslides occur in 35% of the susceptibility map with the highest values).
Overall, the success rate is one of the methods to evaluate the quality of the resulting susceptibility map, but not the only one. Previous work has shown that with different combinations of factors, susceptibility maps could be generated with similar success rate curves but very different spatial patterns. Therefore the combination of the two methods is the best in generating the best maps given the limitations in the input data.

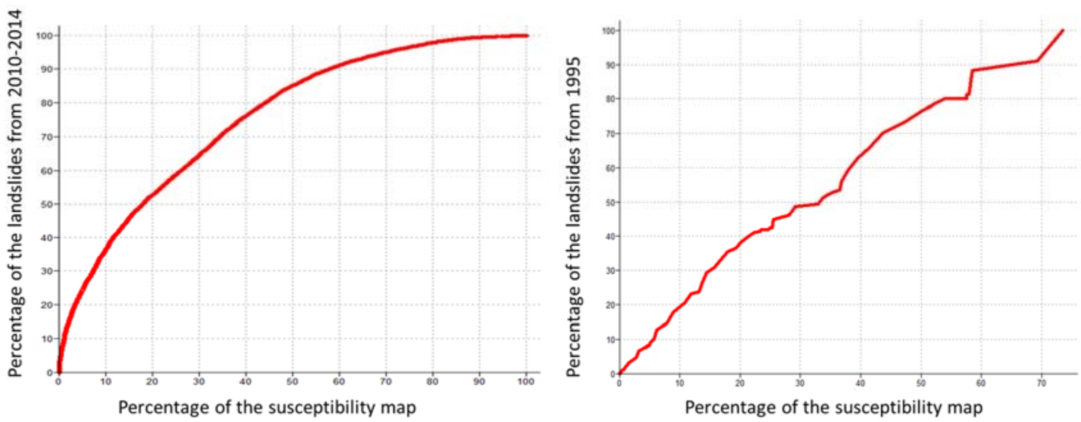


Figure 6-15: Success rate curves for the susceptibility maps for 2010-2014 (left) and 1995 (right).

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 Saint Lucia 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 analyst 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 summary statistical data for the susceptibility map is shown in Table 6-3

Table 6-3. Summary information of the low, moderate and high susceptibility classes

	Landslide susceptibility		
Characteristics	**Low**	**Moderate**	**High**
Area in square kilometres	309.2	143.8	150.1
Percentage of total area	51.3	23.8	24.9

We combined the susceptibility map with the various landslide inventories for the different years, and calculated how many landslides were located in the three susceptibility classes, and also the landslide area. We calculated landslide densities per class, both based on area and number density. The results are shown in Table 6-4. As can be seen from this table the landslide susceptibility map has quite a different success for the various inventories. If we compare the results of the landslide inventories there is a relatively good relation between the susceptibility classes and the landslide densities, with increasing landslide density for the moderate and high susceptibility classes. However, there are still too many landslides within the low and moderate classes. This is particularly so for the landslides of inventories of Rogers (1995), and several others.
There are several reasons for that:

- First of all related to the landslide locations. We are not 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, are mostly of poor quality. As was mentioned in chapter 5, the Digital Elevation Map is of poor quality. Therefore the slope steepness data are very general, and therefore may not represent the actual situation well. 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. Also the geological map misses data in the centre of the island.
- 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.

Table 6-4. Summary information of different landslide inventories within the low, moderate and high susceptibility classes

		Landslide susceptibility		
Source	**Characteristics**	**Low**	**Moderate**	**High**
Susceptibility map	Area in square kilometres	309.2	143.8	150.1
	Percentage of total area	51.3	23.8	24.9
Rogers 1995	Landslide area (m^2)	-	-	-
	Number of landslides	189	172	352
	Landslide density (percentage)	-	-	-
	Landslide density (nr/km^2)	0.611	1.196	2.346
Abraham and Rock 1995	Landslide area (m^2)	1896125	1332125	3053825
	Number of landslides	948	1002	1002
	Landslide density (percentage)	0.6	0.9	2.0
	Landslide density (nr/km^2)	3.07	6.97	6.68
MottMacDonalds 2010-2013	Landslide area (m^2)	895746	330380	539784
	Number of landslides	138	55	74
	Landslide density (percentage)	0.29	0.23	0.36
	Landslide density (nr/km^2)	0.45	0.38	0.49
British Geological Survey 2010	Landslide area (m^2)	36034	25135	84221
	Number of landslides	6	8	13
	Landslide density (percentage)	0.01	0.02	0.06
	Landslide density (nr/km^2)	0.02	0.06	0.09
British Geological Survey 2011 (Hurricane Tomas event)	Landslide area (m^2)	886411	584162	3291387
	Number of landslides	178	126	721
	Landslide density (percentage)	0.29	0.41	2.19
	Landslide density (nr/km^2)	0.58	0.88	4.80
British Geological Survey 2012	Landslide area (m^2)	389379	251827	1770530
	Number of landslides	75	55	359
	Landslide density (percentage)	0.13	0.18	1.18
	Landslide density (nr/km^2)	0.24	0.38	2.39
British Geological Survey 2013	Landslide area (m^2)	235867	92057	850219
	Number of landslides	27	25	146
	Landslide density (percentage)	0.08	0.06	0.57
	Landslide density (nr/km^2)	0.09	0.17	0.97
Christmas Eve 2013 DANA	Landslide area (m^2)	-	-	-
	Number of landslides	26.00	12.00	6.00
	Landslide density (percentage)	-	-	-
	Landslide density (nr/km^2)	0.08	0.08	0.04
British Geological Survey 2014 (Christmas Eve 2013 event)	Landslide area (m^2)	320263	214858	1615159
	Number of landslides	54	62	343
	Landslide density (percentage)	0.10	0.15	1.08
	Landslide density (nr/km^2)	0.17	0.43	2.29

In order to improve the final map we carried out steps 10 to 13 as described in section 2.2. First we masked with GIS all historical landslides in the susceptibility map as class "high", as it is possible that landslides may happen again in these conditions, unless remedial measures have been adopted after the landslide occurrence. 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. 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. The process is illustrated in Figure 6-16.

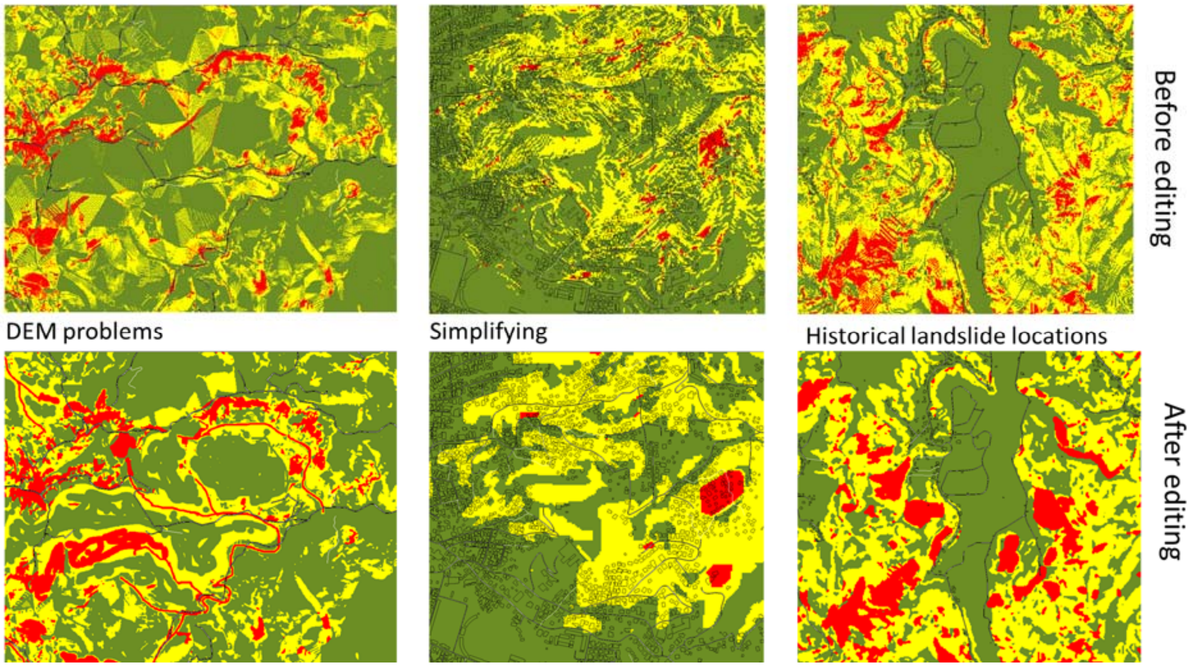


Figure 6-16: Examples of how the landslide susceptibility map was edited manually, by comparing the results with other data (hillshading map, road map, building map, historical landslide map, original topographic map, Google Earth images, etc). The left image shows how problems caused by the poor quality of the DEM were fixed. The middle image shows an example of simplifying the map, by filtering and aggregating units. The right example shows how historical landslides are included in the landslide susceptibility map.

The improved landslide susceptibility map is still quite problematic for a number of areas, where the Digital Elevation Data was so poor that the original topographic is not properly displayed. These areas are indicated in Figure 6-17. The landslide susceptibility map is shown in Figure 6-18.

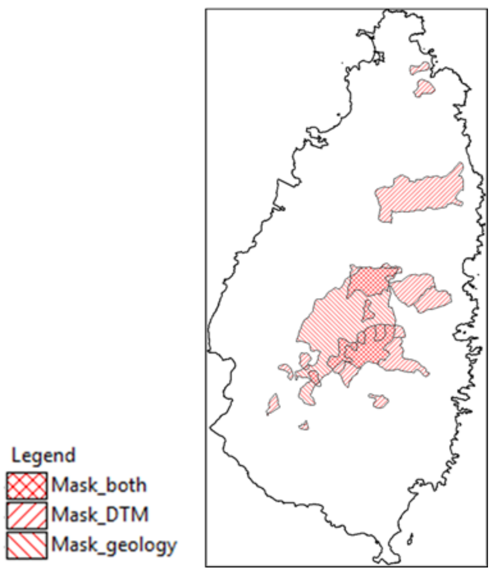


Figure 6-17: Areas where the quality of the landslide susceptibility map is less due to problems with the DEM, the geological map, or both.

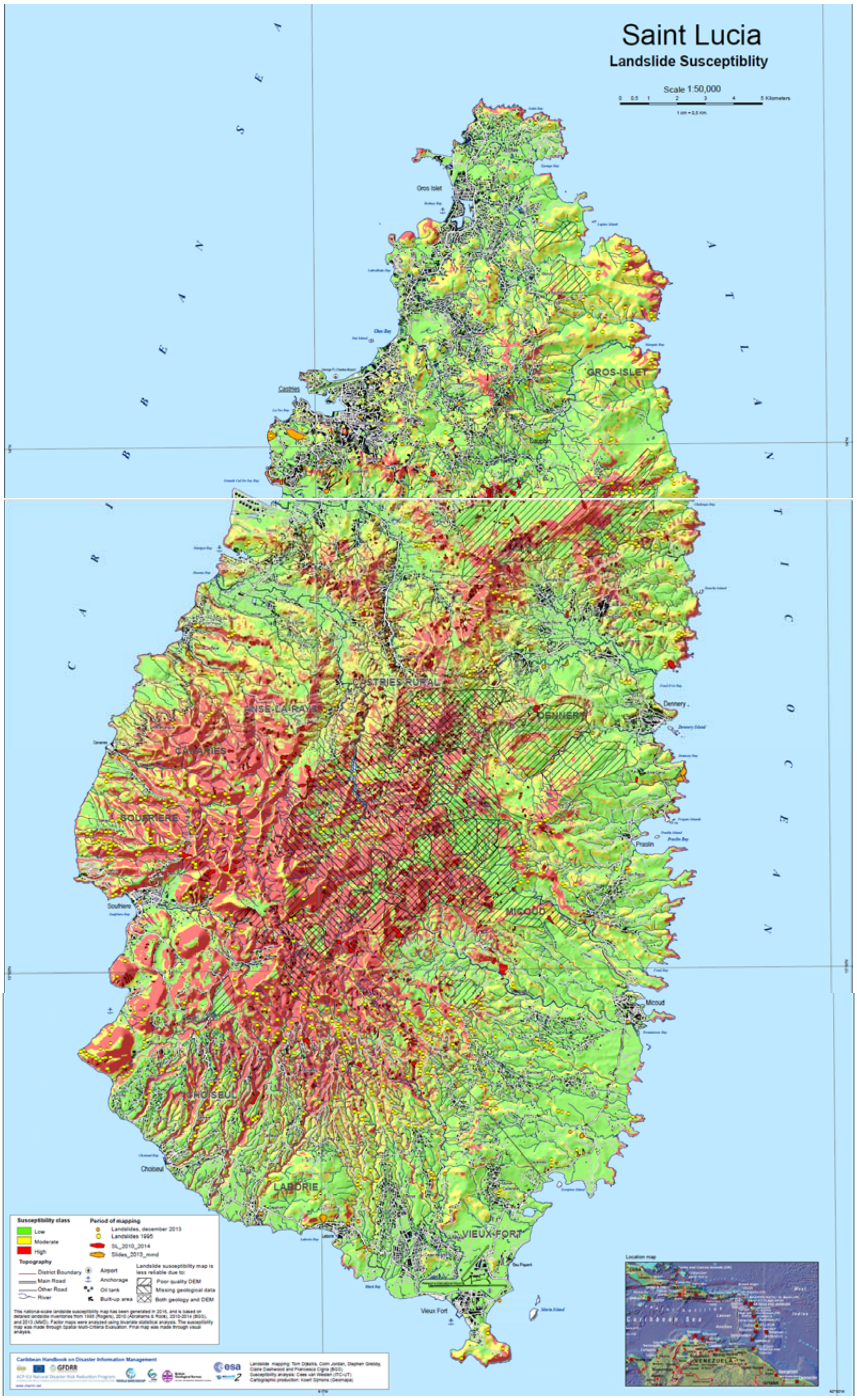


Figure 6-18: Final landslide susceptibility map for Saint Lucia. The full map can be downloaded as pdf from the following website: http://www.charim.net/stlucia/maps

7. Landslide susceptibility assessment along the road network

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

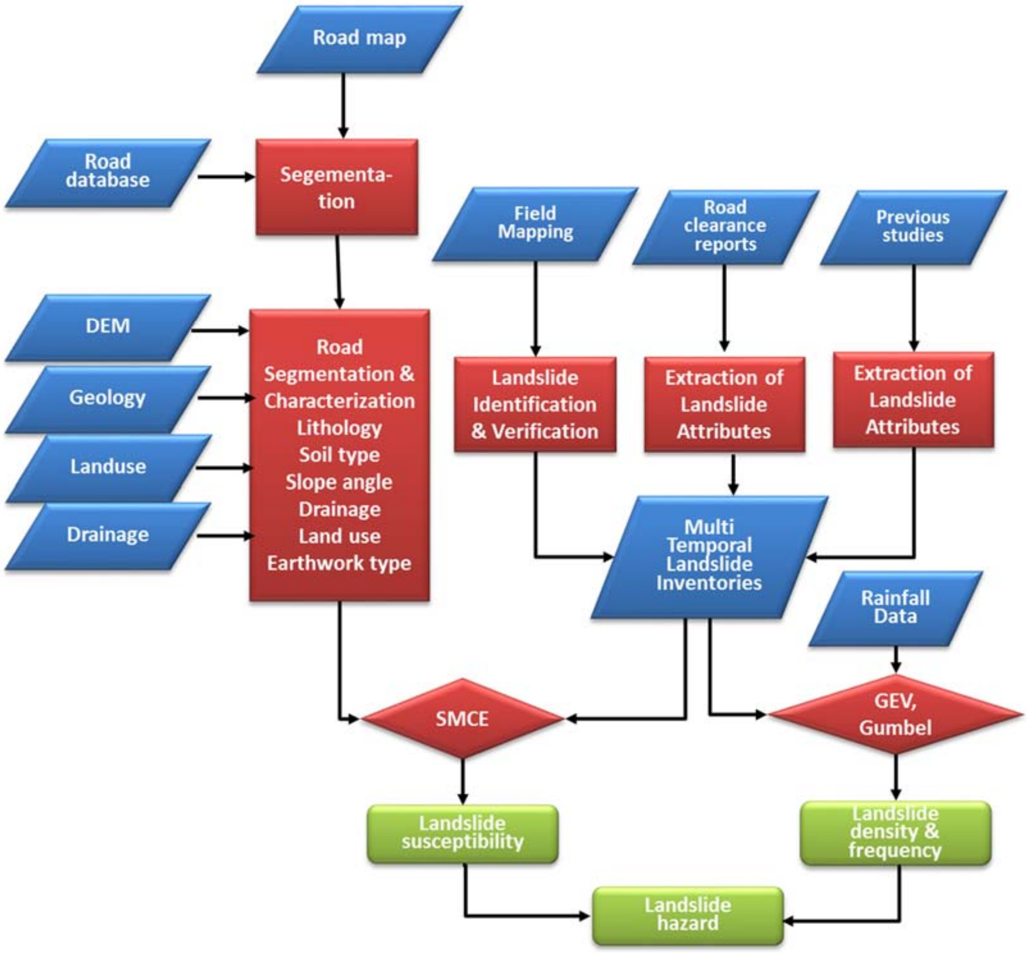


Figure 7-1: Method used for assessing the landslide susceptibility (and hazard) along the national road network in Saint Lucia. Landslide hazard is obtained by combining the susceptibility classification with the results of the density-frequency analysis.

7.1 Segmentation of the road network into homogeneous sections.

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

- Primary road
- Secondary road
- Tertiary road

For this study only the primary road network was considered. From the Ministry of Infrastructure, Port Services and Transport we obtained a database of the primary road network that was generated for another project (Mott MacDonald, 2013). This was the outcome of a large project related to the rehabilitation after hurricane Tomas in Saint Lucia. In the study they focused on the collection of previous works, analysed geology and seismicity, and carried out a landslide susceptibility assessment along the road network, and selected a number of sites for detailed slope stability measures. Figure 7-2 shows the landslide inventory map along the major roads of Saint Lucia, which was prepared by Mott MacDonald (2013). The inventory mainly contain landslides occurred during hurricane Allen (August, 1980) and hurricane Tomas (October, 2010). The road database has been updated after major changes in the road network.

We also obtained a report from BGC (2012) generated for the Government of Saint Lucia and Caribbean Development Bank on the preliminary landslide susceptibility assessment along the road network (Figure 7-2).

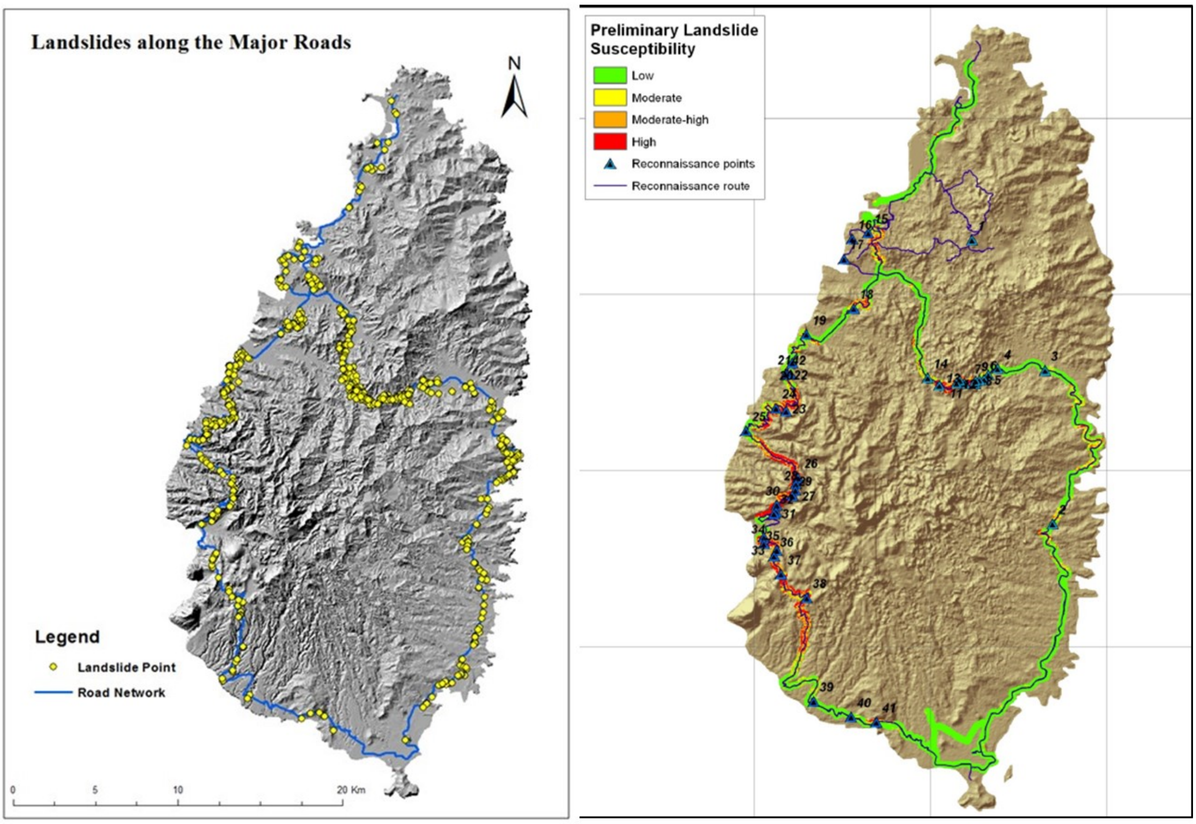


Figure 7-2: Left: Landslides along the Major roads of Saint Lucia. Source: Mott MacDonald (2013). Right: Preliminary landslide susceptibility map of the road network prepared by BGC (2012)

Besides the Mott MacDonald work, some road clearance and maintenance records from other landslide events like the Christmas Eve event (2013) were obtained. However, these records lack workable spatial reference and the number of landslides occurred were not mentioned (Table 3-1). Therefore, it was difficult to include them in the study. Field work was concluded by visiting major landslide prone areas along the road.

The GIS layer of the primary road network was used to subdivide it into units of 1 km length. The lithology, soil type and slope angle of the one kilometre road segments were extracted from the available geology map, soil map and digital elevation model (DEM) respectively. For this purpose buffer maps along the road network were prepared taking 50 m buffer distances on both sides. For each road segment the upslope-side buffer was identified based on the information obtained from the road database and image interpretation. Then, for each road segment the upslope side was selected and the other side was deleted from the buffer map. The buffer map was then crossed with the factor maps. Finally, the geology, soil type and slope angle were assigned for road segments, taking the predominant value (weighted by area) of each of the segment from the cross tables. These attributes were used by other authors for similar studies and they are proved to be significant factors for road related landslides (e.g., Das et al, 2010; Jaiswal et al, 2011; Jaiswal and Van Westen, 2013).

7.2 Generation of landslide inventories for specific events

We had several inventories for the road network that were already compiled by Mott MacDonald (2013). To assess the landslide susceptibility along the road network they used density analysis taking two storm events, namely hurricane Allen (August 3, 1980) and hurricane Tomas (October 31, 2010). The landslide inventory from hurricane Allen was taken from the inventory of DeGraff (1985) that was incorporated in the one by Rogers (1995). However, the inventory of Rogers (1995) also contains landslides caused by Tropical Storm Debby (1994) and therefore it is a mix of several events. The inventory of hurricane Tomas was taken from the one from Abraham and Rock (2010), and through fieldwork by Mott MacDonald (2013). During their analysis stage, they selected the landslides which they considered that directly affect the primary roads and made a different landslide datasets for both events. Then they totalled the number of landslide occurrences along a defined road section for each of the datasets and calculated a density per km of road section as shown in Figure 7-3. Road sections were defined based on the land morphology and locations of main towns. They supported the landslide inventories by field visit and verifying the landslide location and characteristics.

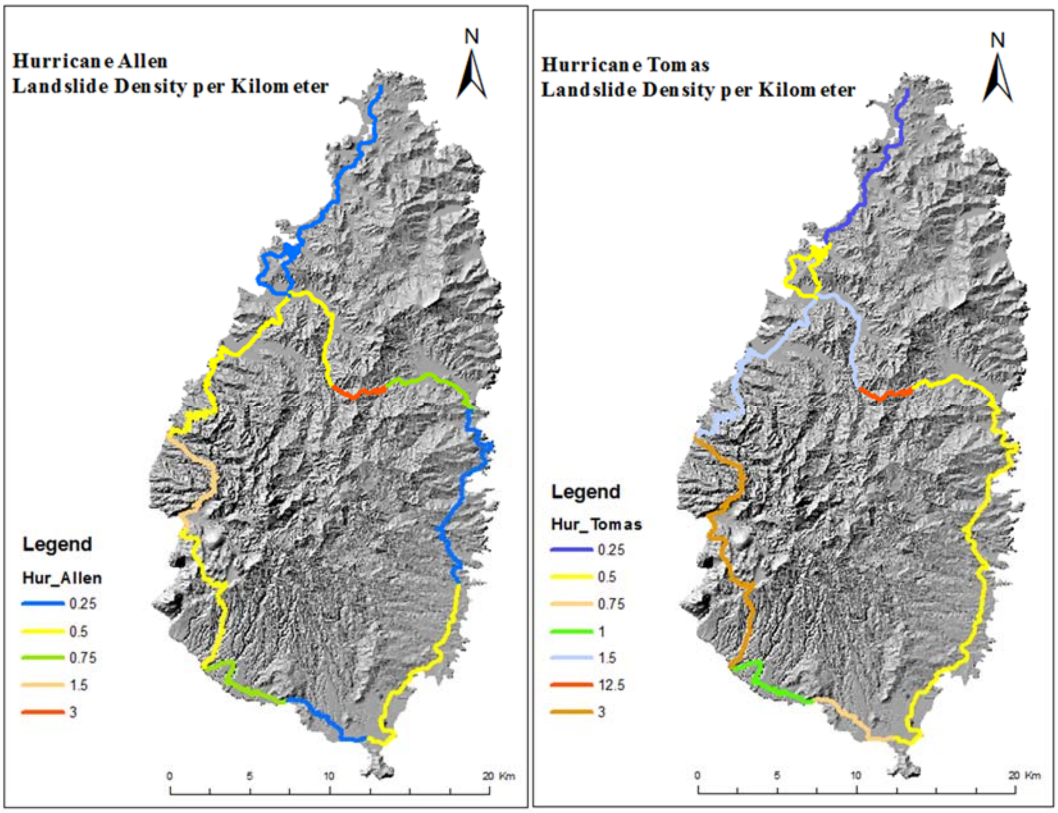


Figure 7-3. The results of the study by Mott MacDonald (2013) on landslide density per kilometer road. Post hurricane Allen (left) and post hurricane Tomas (right).

7.3 Landslide susceptibility assessment along the road network

The landslide susceptibility assessment along the road network was also carried out using Spatial Multi-Criteria Evaluation (SMCE). A criteria tree was made (Figure 7-4) with the following spatial factors: number of landslides, slope angle, erosion, geology and soil. The number of landslides factors represents the landslides points counted in each road segment. The landslide points were extracted from the landslide inventory made by (Mott MacDonald, 2013). The values of the number of landslide factor range from 0 to 14 and it was standardized as benefit using maximum value. The slope angle factor represents the upslope of the road segments and its values range from 0 to 49. This factor was also standardized as benefit using maximum value. The erosion factor represents the extent of erosion of the ground adjacent to the road segment, which was extracted from erosion map of island. It was classified qualitatively as: no apparent erosion, slight erosion, moderate erosion, severe erosion, very severe erosion and extremely severe erosion. These classes were given values between 0 and 1 for the standardization of the factor, no apparent erosion being 0 and extremely severe erosion being 1. The geology and soil factors were standardized based on the landslide density within each geologic unit and soil type unit respectively, which is discussed in section 5. The units were first ranked starting with the highest landslide density and then they were given values between 0 and 1 for the standardization.

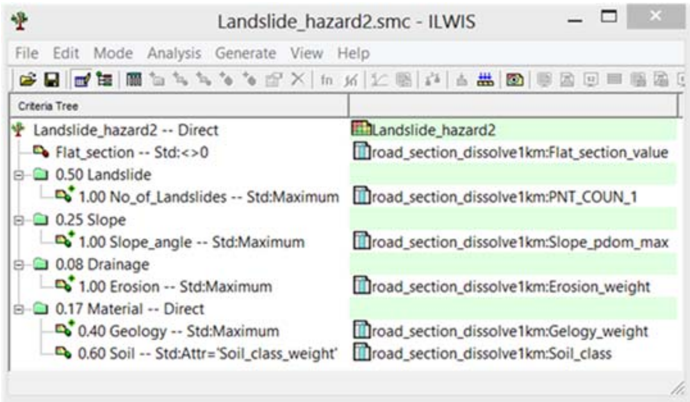


Figure 7-4: Criteria tree for analysing landslide susceptibility along the road network in Saint Lucia

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

The slope factor (considered independently) works in an ambiguous way in the case of road cuts. The steepest slopes do not correspond unequivocally to the more susceptible slopes and for that reason the weights to inclination ranges should not be considered in the same way as in the other soil types or natural slopes. More emphasis should be given to this in future projects on landslides susceptibility along roads.

The results obtained from the SMCE show that the road segments have landslide susceptibility scores ranging from 0 to 0.75 for Saint Lucia, representing road segments from the lowest to the highest susceptibility. To check the validity of the analysis result of Saint Lucia, a success rate calculation was made. The success rate was done using 214 landslide points along the major roads, 71 of these landslides were mapped during field work and the remaining were obtained from the landslide inventory dataset of the whole country presented earlier. Figure 7-5 shows the success rate graph of the susceptibility analysis for Saint Lucia. As the graph shows, about 80% of the landslides are located in 30% of the road segments with high susceptibility scores. Considering the relatively low quality and quantity of the data available for the analysis, we believe this is the best possible so far, although we hope in future such results could be improved when a consistent landslide database would be maintained on the island.

Based on the success rate result, the susceptibility map was classified into three classes of susceptibility level i.e. high, moderate and low. The boundaries of these classes were determined by considering the percentage of the landslides. It was found that 80% of the landslides are located within the high susceptible class, 15% within the moderate class and the remaining 5% within the low susceptibility classes of the road segments. The landslide susceptibility map along the major roads is shown in Figure 7-6. In the map, the known previous landslide locations are indicated with black dots.

Table 7-1 provides the summary information for the landslide susceptibility classes for the primary road network. The results show an almost equal percentage of the primary road network in high, moderate and low susceptibility classes. We also combined in GIS the road susceptibility map with the national landslide susceptibility map presented in chapter 6. From table 7-1 you can see that this depends on the method used.

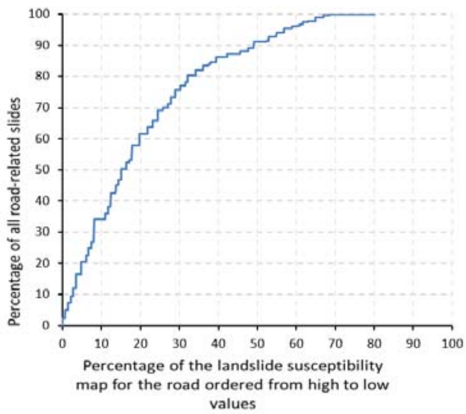


Figure 7-5: Success rate for the road-related landslide map.

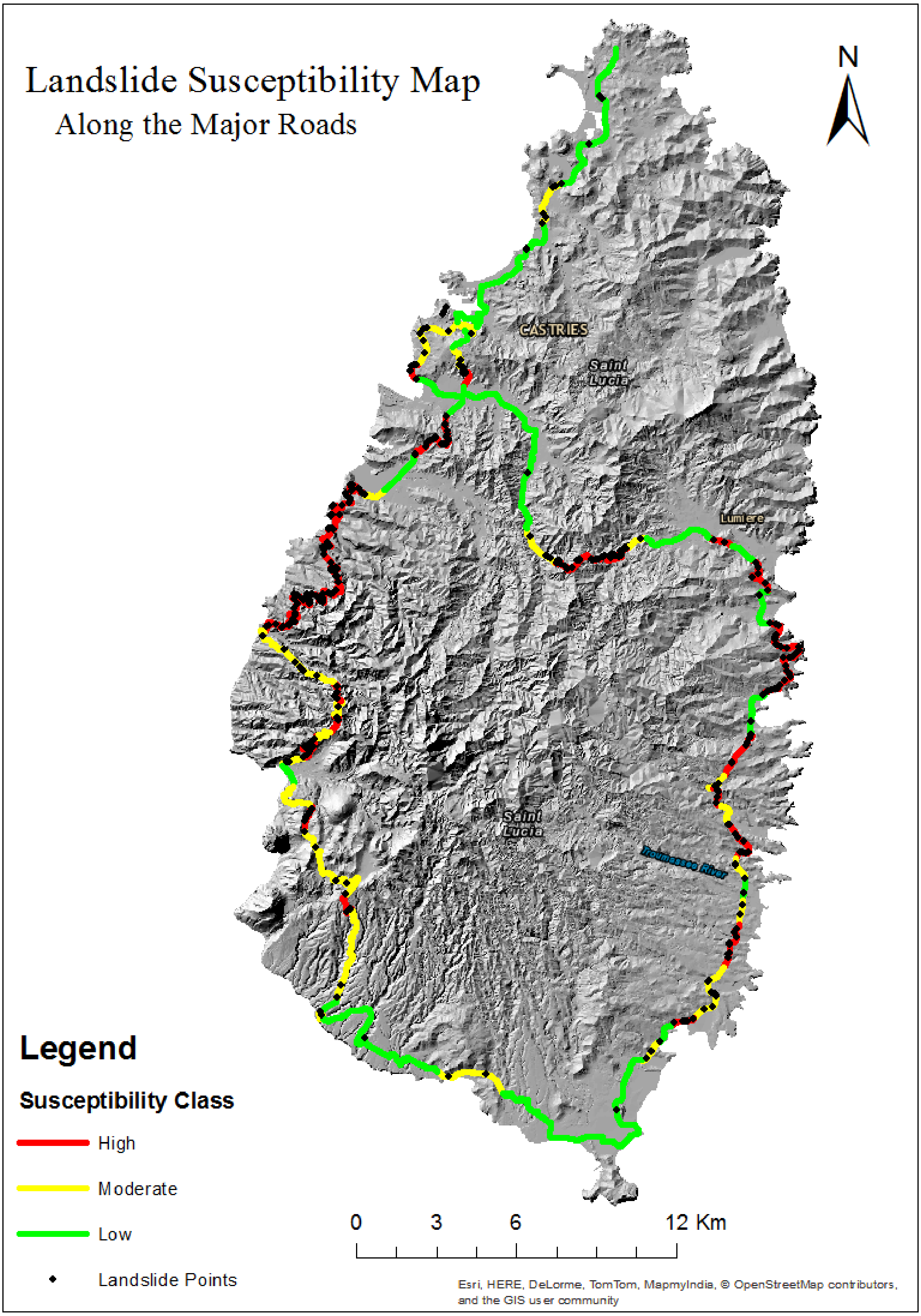


Figure 7-6. Landslide susceptibility map along the major roads of Saint Lucia.

If we take the predominant landslide susceptibility class for each of the 1 km road segments the results are very different than if we subdivide the road segments into smaller segments with the same landslide susceptibility, and then add up the length of all sub-segments within high, moderate and low landslide susceptibility. However, for both methods it is clear that there are more segments in the low susceptibility class when we use the national landslide susceptibility map, as compared to the specific road related landslide susceptibility map.
This shows that it is better to make a separate landslide susceptibility map for the road network. Although the method presented here has the potential of being useful on the long run, it is not so reliable still, mainly because of the problems involved in subdividing the road into meaningful segments, characterization of the road and most of all, collection of locations of landslides rather than using the number of landslides along broad stretches of the road, as was the case now. Road maintenance records should be converted into location maps by using GPS in the field during the clearing inspection of roads. Another improvement that should be made is in the criteria evaluation, where road cuts in different types of soil should be evaluated separately and slope shouldn't be an independent factor of soils in the analysis. However, this requires more detailed information on soils, and road cuts, based on detailed field data collection along the road network.

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

From road analysis	Landslide susceptibility class		
	Low	Moderate	High
Road length (km)	57.2	40.7	46.8
Percentage	39.5	28.1	32.4
From national scale susceptibility map			
When calculating intersections of road segments with susceptibility classes			
Road length (km)	98.6	24.3	21.8
Percentage	68.1	16.8	15.0
When taking the predominant susceptibility per road segment			
Road length (km)	112.7	12.7	19.3
Percentage	77.9	8.8	13.3

8. Characterizing the susceptibility classes

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

8.1 Density and frequency information

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

In the previous two chapters landslides susceptibility maps were presented for the entire island and for the road network. These maps show the relative likelihood that a certain area or road segment may be affected by landslides. However, for a hazard assessment it is also important to indicate how severe and frequent an area might be affected. In table 6-4 landslide densities were given for the various susceptibility classes, separately for different inventories. Later on we integrated the historical landslides within the landslide susceptibility map, so it is not possible to calculate landslide densities from the final susceptibility map anymore.

In this section we will try to indicate what the expected landslide densities are for various return periods. The result is shown in Table 6-1. It should be noted that these results are based on historical landslide inventories, but that values are largely based on expert opinion.

We started by analysing the different available landslide inventories and corresponding triggering events. Basically the following triggering events are represented:

- Hurricane Allen (1980): landslides (430) from this event are mapped by DeGraff (1985). The inventory is part of the inventory of 1995 from Rogers, but based on Table 4-2 we assume that 430 of the landslides are related to hurricane Allen.
- Tropical Storm Debby (1985): landslides from this event are mapped by Rogers (1995). However, from all the landslides in her inventory (713 as indicated Table 4-2) also a number were from DeGraff. She also indicated that the landslide mapping from Tropical Storm Debby was not complete.
- Hurricane Tomas (2010): landslides from this event were mapped by Abraham and Rock (2010) who mapped 1132 landslides and by the British Geological survey (BGS) who mapped 1025 landslides for this event. This is the best documented event, and we can assume that the landslide mapping is also complete for the island. The return period of Hurricane Tomas in Sa
- int Lucia is estimated to be in the order of 50-100 years, although some state the return period may be as high as 180 years (ECLAC, 2011).
- Christmas Eve 2013 event: for this event we also have several inventories. From the Damage and Needs Assessment survey 45 landslides were mapped, but the BGS mapped 459 active landslides of which 129 were new ones and the other reactivated landslides from Hurricane Tomas (Table 4-4). The return period of the 2013 event is considered much lower, in the order of 25-50 years.

It is quite difficult to determine the frequency of the landslide densities due to a lack of sufficient event-based inventories. Therefore as a summary we need to make an estimation as indicated in Table 8-1. These values are estimations based on the data from the various tables presented earlier, and from the description of the inventories a shown in Table 4.1. The spatial probability represents the chance that a landslide may occur in a single location. It is similar to the area density but now shown as probability, instead of percentage values. Also the number density is shown as the number of landslides per km^2. The return periods indicated in Table 8-1 are

pure estimations, and not based on actual calculations. Although we have calculated return periods for daily rainfall in section 3.1.3 (Figure 3-14), these are not useful either because we do not have the information on rainfall amounts for the specific triggering events, or because these rainfall amounts vary extensively with elevation and exposure (See Figure 3-13).
We have separated four types of events: frequent, moderate, large and major events. We selected landslide inventories with increasing densities to represent these four events.

The values shown in Table 8-1 are only indicative, showing that with increasing return periods, the number of landslides and area of landslides increases and that also the spatial probability and number density increase from frequent events to major events, and from low susceptibility to high susceptibility. The more information will become available on landslide inventories and on return periods of triggering events, the better these estimations can be made. Nevertheless we consider these values realistic estimations.

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

Event	**Frequency**	**Landslide inventory taken as example**	**Landslide probability for susceptibility classes**			
				Low	**Moderate**	**High**
Landslide susceptibility map			Area (km^2)	299.5	142.4	158.6
			Percentage	49.9	23.7	26.4
Frequent	<25 years	Trigger: Hurricane Allen (1980) Mapped by DeGraff (1985)	Landslide area	0.09	0.2	1
			Number of landslides	30	70	330
			Spatial probability	0.0003	0.0014	0.006
			Landslide density (nr/km^2)	0.1	0.5	2.1
Moderate	25 -50 years	Trigger: Debby (1994) 1995 Rogers inventory	Landslide area (km^2)	0.15	0.3	1.7
			Number of landslides	50	100	561
			Spatial probability	0.0005	0.0021	0.01
			Landslide density (nr/km^2)	0.2	0.7	3.5
Large	50-100 years	Trigger: hurricane Tomas 2011 BGS inventory	Landslide area (km^2)	0.68	0.88	3.29
			Number of landslides	90	129	806
			Spatial probability	0.0007	0.0041	0.02
			Landslide density (nr/km^2)	0.3	0.9	5.1
Major	>100 years	We take the data from all landslides	Landslide area (km^2)	0.3	0.85	6.3
			Number of landslides	126	183	1522
			Spatial probability	0.001	0.006	0.04
			Landslide density (nr/km^2)	0.4	1.3	9.6

8.2 Buildings located in the susceptibility classes

The final susceptibility classes can also be characterized by calculating the number of buildings located in the various classes. Building data was available for Saint Lucia. We only had a building footprint map without any further attributes.
The results of the building exposure analysis is shown in Table 8-2. The results show that in the entire country 2466 buildings (3.3 % of the total) are exposed to a high landslide susceptibility, 8499 (11.5 %) exposed to moderate and the remaining 63256 buildings exposed to low landslide susceptibility. When we evaluate these values per Parish, Castries has the highest number of buildings located in high susceptibility zones (1057), which is related to the unplanned areas East of the cities, but also some in the South (Figure 8-1). Also buildings located close to steep coastal cliffs which may show retrogressive failure are within the high landslide susceptible area. The second Parish with the highest number of buildings located in high landslide susceptible areas is Soufriere with 397 buildings.
One should be careful when using the national-scale landslide susceptibility and hazard map for evaluating the landslide hazard of individual buildings and critical infrastructure. The scale of this map is not appropriate to utilize it for local or detailed scale analysis. Other, more detailed landslide hazard methods should be used for these scales, which also require more detailed information on soil characteristics, such as soil depth, hydrological and geotechnical properties.
It is also possible to overlay the final susceptibility map with the roads, and agricultural fields and calculated the number, length or area per administrative unit, exposed to high, moderate and low susceptibility. However, given the extent of this report, we decided not to present that here.

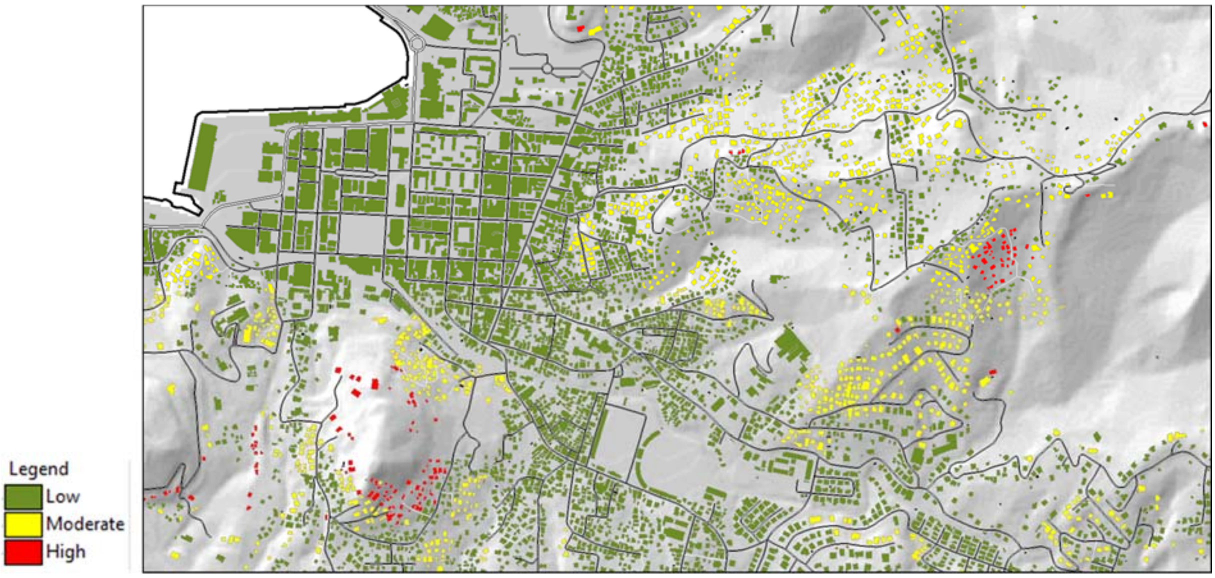


Figure 8.1: Landslide susceptibility of buildings in the area of Castries, based on the national scale landslide susceptibility map. Note: this map is not suitable for analysing local and site investigation scale

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

Parish	Characteristic	Landslide susceptibility classes		
		Low	Moderate	High
All	Nr of buildings exposed	**63256**	**8499**	**2466**
	Percentage of all buildings	**85.2**	**11.5**	**3.3**
Anse-La-Raye	Nr of buildings exposed	1035	245	82
	Percentage of all buildings	76.0	18.0	6.0
Canaries	Nr of buildings exposed	302	136	78
	Percentage of all buildings	58.5	26.4	15.1
Castries	Nr of buildings exposed	17948	4853	1057
	Percentage of all buildings	75.2	20.3	4.4
Choiseul	Nr of buildings exposed	3240	145	143
	Percentage of all buildings	91.8	4.1	4.1
Dennery	Nr of buildings exposed	5260	679	183
	Percentage of all buildings	85.9	11.1	3.0
Gros-Islet	Nr of buildings exposed	12888	1074	203
	Percentage of all buildings	91.0	7.6	1.4
Laborie	Nr of buildings exposed	3075	369	205
	Percentage of all buildings	84.3	10.1	5.6
Micoud	Nr of buildings exposed	7451	429	59
	Percentage of all buildings	93.9	5.4	0.7
Soufriere	Nr of buildings exposed	3162	364	397
	Percentage of all buildings	80.6	9.3	10.1
Vieux-Fort	Nr of buildings exposed	8879	204	56
	Percentage of all buildings	97.2	2.2	0.6

9 Conclusions and recommendations

9.1 Conclusions

The original aim of this study was to generate a national-scale landslide susceptibility map for Saint Lucia. 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 Saint Lucia 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, which was not an easy task. We were very fortunate to get the help of the British Geological Survey in this task. They generated a completely new landslide inventory using multi-temporal visual image interpretation, and generated an extensive landslide database for Saint Lucia.
- BGS also provided us with a new land use/ land cover map.

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

We applied a method for landslide initiation susceptibility assessment that is the best possible, given the availability of data. The bi-variate statistical analysis provided indications on the importance of the possible contributing factors, but the actual combination of the factor maps was done using a subjective expert-based iterative weighing approach using Spatial Multi-Criteria Evaluation. 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.

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

The final landslide susceptibility map, made after the above described procedure, is a much better susceptibility map than the one which was resulting from the bivariate statistical and multi-criteria evaluation. There are certain parts of the landslide susceptibility map, where the information is not adequate to a lack of reliable topographic and or geological data (Figure 6-17)

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.

We characterized the landslide susceptibility classes in terms of the expected landslide density (in area and number) for different frequencies, and also how many buildings are located in the various susceptibility classes. We therefore combined the landslide inventories for the different periods, with the final landslide susceptibility map. The result was shown in Table 8-1.

The national scale landslide susceptibility and hazard assessment should not be used to evaluate local scale or site-investigation problems. The analysis was done using raster maps with a spatial resolution of 5 meters, containing 8921 lines and 4455 columns. Most of the input data was obtained from 1:25000 or even 1:50000 scale maps. Also given the relatively poor quality of the factor maps (especially the Digital Elevation Model, the geological map and the land use map) the local variations are not properly depicted in the final map. For these scales the optimal approach is the use of physically-based landslide susceptibility assessment methods. These methods are based on modelling the processes of landslides using physically-based slope stability models. An overview of physically based models and their application for landslide susceptibility assessment is given in Brunsden (1999), Casadei et al. (2003), Van Asch et al. (2007) and Simoni et al., (2008). Most of the physically-based GIS models that are applied at a local scale (SINMAP, TRIGRS, SHALSTAB, STARWARS, PROBSTAB) make use of the infinite slope model and are therefore only applicable to modelling shallow translational landslides. At site investigation scale it is possible to apply 2-D Limit equilibrium methods with groundwater flow and stress analysis (E.g., SLOPE/W, SLIDE, GALENA, GSLOPE), 3-D slope stability analysis (e.g. CLARA-W, TSLOPE3, SVSLOPE) or numerical modelling (e.g. continuum modeling (e.g. finite element, finite difference) , like FLAC3D, VISAGE, or discontinuum modeling (e.g. distinct element, discrete element), e.g. UDEC).

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

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

Susceptibility	Explanation	Estimated landslide probabilities for different return periods			
		Frequent	Moderate	Large	Major
Low	This class generally is landslide free, although under special circumstances it may be possible that a landslide might occur in this zone, but the density and frequency will be low.	0.0003 0.1 landslides/km^2	0.0005 0.2 landslides/km^2	0.0007 0.3 landslides/km^2	0.001 0.4 landslides/km^2
Moderate	This class has some probability that landslides might occur, although not very frequent and not with a high density.	0.0014 0.5 landslides/km^2	0.0021 0.7 landslides/km^2	0.0041 0.9 landslides/km^2	0.006 1.3 landslides/km^2
High	This class has the highest density and frequency of landslides.	0.006 2.1 landslides/km^2	0.01 3.5 landslides/km^2	0.02 5.1 landslides/km^2	0.04 9.6 landslides/km^2

9.2 Recommendations

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

1. Establishment of a national landslide database.

Currently there is no single organizations responsible for generating and maintaining landslide data in Saint Lucia. The Ministry of Infrastructure, Port Services and Transport generates road clearance reports that could be easily converted into a landslide database. However, the current situation is that these data get lost after some years. The National Emergency Management Office receives information about emergencies, which also include landslide events. However, when we asked them for a database they were not able to provide one. Also the spatial planning division requires landslide data for generating land use plans, and for building permit issuing. The current practice is that landslide data is collected by external parties within international projects. 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 Saint Lucia is highly recommended, as they have reported many landslide events, with additional photo or video footage, which could be easily linked to a geolocation, and stored in such a database so that the information is not lost. It is very important to get better data on the location, type, damage and especially the date of landslide events, so that in future a correlation between rainfall characteristics and landslide incidences, and the establishment of rainfall thresholds, and frequency/magnitude relationships can be properly carried out. These reported events would be stored in a separate database, which is used by the national responsible organization for landslide inventory mapping, as the basis for checking. These are added to the actual database only after they have been checking by an expert. This will also allow the continuation of the landslide database in future. It is essential that there is a close collaboration between the various national organizations that have to deal with landslides. However, one organization should be the nodal agency responsible for setting-up the national landslide database.

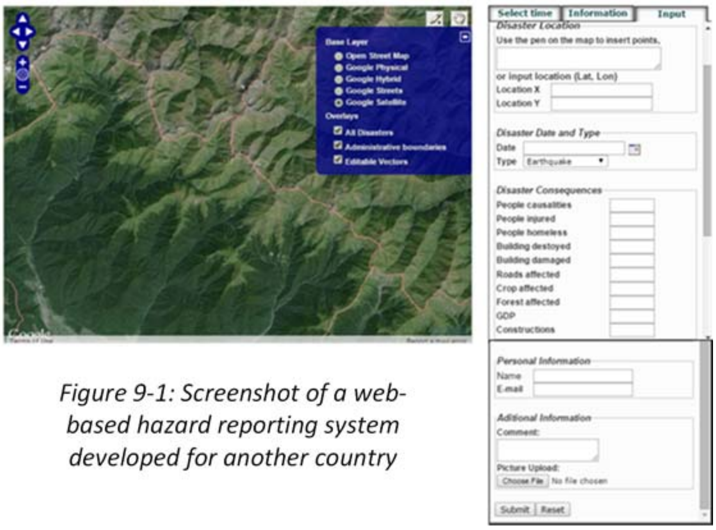


Figure 9-1: Screenshot of a web-based hazard reporting system developed for another country

2. Generating a national LiDAR survey.

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

3. Updated engineering geological map

The available soil map was made a long time ago without the new technology that is now available. The available map is also focusing on pedologic soils, which makes it less useful for landslide applications, where we are more interested in engineering soils and their characteristics. The existing geological map focuses on the description of the age and origin of the rocks rather than on their engineering characteristics. Therefore there is a need to generate an engineering geological map for Saint Lucia 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.

4. Carrying out a landslide run-out assessment.

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

For run-out assessment at the local scale an empirical run-out model Flow-R, developed by the University of Lausanne, could be used. Flow-R (Horton et al., 2013) is a modelling software that uses a GIS empirical distribution model to probabilistically estimate the flow path and run-out extent of gravitational mass movements at regional scales. Flow-R first requires the identification of source areas before the actual run-out can be modelled. Two parameters are required to model the run-outs for each return period in the Flow-R model: (1) the minimum travel angle and (2) the maximum velocity. These two parameters can be estimated based on literature review or back calibrated based detailed run-out models. The software calculates probably flowpaths from source points based on energy line calculations. The method doesn't require source volumes, or rheological parameters. It also doesn't consider entrainment. It can calculate the flowpaths from many different source zones at the same time. This makes the model suitable for use at a regional to medium scale. The results are indicative, but previous work has shown that the calculated distances correlate well with more detailed run-out models. The model can also be applied for different types of movement, e.g. debrisflows, flowslides, and rockfall, by varying the reach angles.

For run-out assessment at the site-investigation scale it is advised to use physically-based run-out models, such as Flow-2D or RAMMS. An overview of available models is given by Quan Luna (2012).

5. Incorporate possible landslide blockage in flash flood modelling

For the analysing of the maximum discharge in the design of bridges and culverts, it is also important to take into account the possible locations of damming landslides. Landslide dam susceptibility assessment is a difficult topic, but some interesting developments have been made by Fan et al. (2012; 2013). An analysis can be carried out of minimum landslide volumes required to dam a river, in relation with landslide susceptibility assessment. Historical information on landslide locations along the river network are very important for this. Another option is to develop an integrated modelling framework for extreme land surface processes, combining flash flood and landslide processes in the same model. For this, the OpenLISEM model will be altered to include sediment transport in flood water, slope stability and debris flows. Any interactions between these phenomena will be estimated on a physical basis and validated using field measurements. In the second phase, the equations that are used for individual flow domains, which are based on assumptions about flow characteristics, will be unified. In the third phase, the creation of a series of extreme climatic events will be investigated. Based on catchment properties and modelling, events with substantial influence on land surface processes will be selected.

6. Further training and discussion

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

7. 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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