Caribbean Handbook on Risk Information Management

World Bank LAC opportunities for all

ACP-EU Natural Disaster Risk Reduction Program

CHARIM

Caribbean Handbook on Risk Information Management

Report on methodologies for hazard mapping in the Caribbean

Suggested methods for analysis at various scales

Version 3

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1. Introduction

1.1. Purpose of this report

This report is an additional product of the CHARIM project. It has been drafted upon request of the World Bank and should form the basis of a technical discussion on

- the methodological framework as proposed for the methodology book,
- the national level hazard maps and
- the use case structure based on one example use case

The objective of the discussion is to make sure that

- the suggested methodologies are adequate and tailored for the Caribbean region
- all relevant methodological details for the national hazard maps are provided, and
- the structure, presentation and level of detail of the use cases is suitable.

In this report we describe the methodologies we propose for the assessment of flood and landslide hazard in the Caribbean region. The primary focus in this report is on the national scale hazard assessment.

For the other scales the role of the use cases will be very important as they will guide the user of the handbook through the first steps of selecting the appropriate method to solve a given problem at a certain scale and given constraints. This process will be further elaborated in the Methodology part of the Handbook where we foresee a section that provides more detail on the different methodologies and their appropriate application.

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1.2. 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 following sub-objectives are defined:

1. ***To make an inventory of the needs of each target country in terms of their capacity for spatial data collection, analysis and management, (landslide and flood) hazard and risk assessment, and integrate this information in spatial development planning and risk reduction planning*.**

   This was analysed during a series of workshops in the target countries in May/June 2014, and again during a regional workshop in October 2014. Detailed workshop reports were produced, which are available on
   ftp://ftp.itc.nl/pub/westen/Worldbank/

2. ***To make an inventory of the tools available worldwide in terms of technical training manuals linked with practical applications and in terms of methodologies applied for flood and landslide hazard and risk assessment at different scales, as well as open source modelling tools for these hazard types*.**

   This inventory was carried out and was reporting in the preliminary assessment report in June 2014, which can also be downloaded from the same site indicated above.

3. ***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*.**

   This report together with the report related to flooding are contributing to this objective.

4. ***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 floods.***

   This report states the method that is proposed for the national landslide and flood hazard assessments within the target countries. It will show first results.

5. ***To develop a handbook to support the generation and application of landslide and flood hazard and risk information.***

   A draft table of contents was included in the preliminary assessment report, which was discussed with the WB staff and was presented during the workshop in Saint Vincent in Early October. Also the platform for the handbooks (www.CHARIM.net) was presented.

6. ***To develop a number of use cases of the application of hazard and risk information to inform projects and program of planning and infrastructure sectors. The methodology provides the overall framework for the use cases.***

   The structure of the use cases was presented in a document in September 2014, and was also discussed during the workshop in Saint Vincent. The Table of Contents contains 6 use cases related to Land use Planning and Management, 13 use cases related to Critical Infrastructure, 2 related to emergency preparedness planning, 4 related to risk assessment, 6 related to vulnerability and exposure, 7 related to hazard assessment, and 6 related to data management. Currently the use cases are being developed by the consortium, and first results will be available by the end of November. Some of the use cases will also have GIS exercises.

7. ***To make the handbook, data and methodology available through a pdf document and through a web-based platform, consisting of web-based databases, and a Decision Support system set-up for risk reduction planning***

   A platform for the dissemination of the handbook is under development, through www.charim.net the structure of the platform was described in a document in September 2014, and discussed during the workshop in Saint Vincent.

8. ***To provide training courses based on the materials and the handbook, that is made available to the entire region through a web-based platform and distance education course in collaboration with the University of the West Indies;***

   An extensive training course is planned for one month in ITC, the Netherlands, in February 2015. Two participants from each country will attend the training course, where the use cases are presented, and a number of use cases are worked out in the form of GIS datasets together with the participants. Also plans for a follow-up distance education training course based on the CHARIM materials are currently under discussion with the WB team.

This report addresses specifically objectives 3 and 4.

2. Proposed method for national-scale flood hazard analysis of the 4 islands countries

Flooding in the Caribbean occurs relatively frequently, with a similar mechanism that causes flash floods for all 4 islands. The floods can be characterized as *flash floods*, which are characterized by a fast response to heavy rainfall, which leads to runoff that collects in flatter, low-lying areas. Each of the islands is basically a mountain ridge of volcanic origin which in terms of hydrology can be characterized as a central ridge with many small catchments that lead directly to the ocean. If the rainfall depth and intensity is such that not all can be absorbed in the soil, runoff will occur that is guided directly to the lower floodplains by means of natural river systems.

Each island consists of >50 catchments with rivers that are generally smaller than 20 km, and have natural channels for the most of their length. Only near the ocean on the floodplains, where there are towns and agriculture, are sometimes rivers canalized. Especially in the towns themselves the rivers are lined with concrete walls. There is very little baseflow in these streams, and often they are eroded to bedrock level, especially further upslope.

Note that this does not mean only the lower floodplains are subject to flooding, also higher up in the hill flatter areas may occur, which are inhabited. In fact, during a flash flood situation, flooding upstream often is positive for the flood dynamics downstream. If all discharge would be guided to the floodplain, reaction times would be decreased and flood extent would be increased.

It is of course impossible to protect all catchments on each island, or even every inhabited catchment on each island. People are however not completely unprepared as they experience floods several times in a lifetime. Also certain assets are vulnerable, such as transport corridors, bridges and culverts. Many buildings are constructed on stilts or platforms, or out of reach of the river. To assist in planning and emergency aspects, there is a lot of interest in early warning systems on the islands, which illustrates the nature of the flash floods.

Another specific characteristic of the flash floods is the high water velocities in the channels, and the erosive power of the discharge. Judging from the sediment left behind in the river channels downstream, there can be a lot of erosion and sediment transport during heavy rainstorms. Sometimes this is direct scouring of the river bed, although most rivers are eroded until bedrock level. More likely is that the sediment is derived from the many landslides that occur during an event, or have occurred during previous events and for a steady supply of sediment to the river. Also trees that are uprooted during one storm, can be found in the channels in the following storm. We have not done research into this aspect, and transport of boulders and trees in high velocity streams is more a topic for scientific research, than that there are easy methods available to include this in a hazard assessment.

2.1. Requirements and choice of flood models

There are three levels of flood hazard assessment that are generally applied on the islands:

1) GIS methods that combine geomorphology (DEM, relief) with factors related to runoff (land use, soils) to give a static assessment of flood hazard. Basically these methods divide the landscape in flood plains and contributing areas, with hazard levels derived from assumed flood extent based on rainfall amount. These methods give no information on flood dynamics (levels, timing). This has been applied in Grenada for instance.
2) A-priori selection of flood prone areas, based on governmental requests after flooding took place. The approach applied here is a combination of flood model that assumes a certain incoming discharge and simulates the spreading of this discharge on the floodplain (2D flood modelling). This can give a detailed assessment the flood process when floodplain data is collected (cross sections and elevations). Often a combination of HECRAS and HECHMS (US Army Engineering Corps) is used for this type of work. The flood simulation is relatively accurate, but the incoming hydrograph is often estimated with an assumed runoff coefficient. A common method to estimate runoff coefficients is with the SCS curve number method, which is well calibrated in the US under those conditions, but poorly defined for the small tropical catchments of the islands. Also these methods assumes that all runoff water reaches the downstream flood plain, but this is not the case in reality. For instance a well-known flood case of a school in Bexon (St Lucia) in 2013, is a flooding of a valley floor halfway the catchment, and not near the outlet. If these "halfway" floods are ignored, it is almost certain that the incoming hydrographs for the downstream flood models are not well calculated.
3) Integrated flood assessment, including both the upstream and downstream processes in one simulation, using a 1D-2D simulation approach. The advantage is that the full surface hydrology is simulated, without any a-priori selection of flooded areas. Also changes upstream or downstream (retention basins, protective barriers, or even changes in land use) can be simulated when they are translated into different input datasets. The disadvantage is that a large dataset is needed for this type of modelling with many hydrological parameters. Examples of this integrated flood models are FLO-2D (www.flo-2d.com), the BASEMENT model (ETH Zurich), the MIKE-SHE model suite (DIH), and openLISEM (ITC). There are technical differences but the datasets are essentially the same.

Based on the hydrological nature of the islands the following terms of reference for the flood hazard assessment are proposed:

1) Base the hazard methodology on full hydrological modelling, so that the particular nature of the islands is emphasized (extreme rainfall, tropical vegetation, small catchments).
2) Use the same logic and methodology on all scales and for all islands, so that per island a single dataset can be constructed, which only varies in the level of detail (scale/resolution). In this way there is only one methodology and skillset to understand, with more or less detail relevant to the scale.
3) Make sure that this methodology fits the available data, whereby data gaps are filled by knowledge and data pooled from the islands. Thereby we rely as little as possible on variables/constants/assumptions from general worldwide datasets, acquired in

environments that are very different. However not all islands have the same level of data, and there will be some shared datasets:

   a. Design storm shape and intensity will be derived from St Lucia data (1 minute rainfall available for 12 stations for 10 years). Note that the frequency/magnitude is derived from daily data and specific for each island.
   b. Soil physical data from the 2014 field investigation on Grenada (99 samples of hydraulic conductivity and porosity), which can be related to the soil classification system that is the same for all islands.

4) Based on field studies in Grenada, the generation of runoff from the interior of the islands is complex: soils are derived from volcanic parent material and are generally clayey. The clay forms very stable and strong small aggregates which results in very open and well-structured soils under natural vegetation. The infiltration capacity of the top soil is much higher than the literature suggests for clay rich soils. The subsoil is more massive and often stony, with much less structure. This is common in tropical soils where most root and micro-organism activity is in the top soil. This means that natural vegetated areas are capable of absorbing a considerable amount of water before they "overflow" while agricultural areas have a more immediate response.
5) There is a lot of interest in early warning systems. A hazard analysis can include information for that: for instance time to flooding start for any location in a catchment with respect to the beginning of the rainfall.

Based on these requirements we selected the integrated flood model **openLisem** (open source designed by the ITC), because it is designed to use geospatial data that can be derived from digitized general maps and satellite images, and the model results can be easily merged with known GIS systems. Also it produces the variables generally used in a flood hazard analysis: maps of flood extent, maximum depth, velocity, duration and start of the flooding per gridcell.

2.2. Methodology for the national scale hazard assessment

The flood hazard assessment will be based on flash flood modelling of all watersheds on the island. Using a spatial flash flood model, and the basic spatial databases available for the islands, the flash flood behaviour of individual complex rainstorms can be simulated, in high spatial and temporal detail. Fig 2.1 gives the methodology to create flood hazard maps.

The national scale flood hazard maps has the following steps:

1) A frequency magnitude analysis to select/create different rainfall events for different repetition times (for instance 5, 10, 20, 50, 100 years).
2) Simulating the effects of these events, using a spatial dataset of the landscape factors that has the highest possible resolution on this scale. Man-made structures are taken into account but generalized to some extent (explained below).
3) Translate the model outcome, i.e. flood water depth, flood duration, early warning time etc. to hazard classes.
4) Make a cartographic product of these hazard maps (e.g. a 100.000 scale map)

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National scales versus more detailed scales

The model system, i.e. flash flood model and model database, is capable of generating flood hazard information at both the national scale and on more detailed scales. It can be used for a detailed analysis of a particular situation if the input data is available. This is a matter of increasing the he level of detail of some of the data layers, and of course also of showing more details in the final map product. It is important to distinguish between these two aspects: the modelling on the one hand and the final cartographic product on a desired scale on the other. Table 2.1 gives the detail level of the data *used by the model*, that is needed at three levels of detail.

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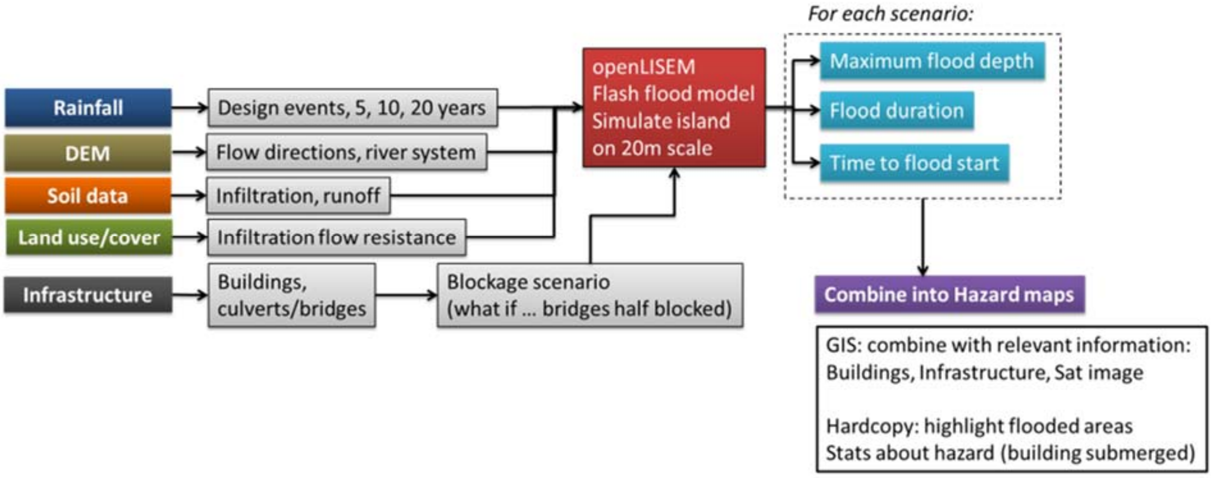


Figure 2.1. National scale flood hazard assessment methodology: basic information layers to the left are used for hydrological information that is given to the model. Rainfall for different return periods results in different flood simulation results. These are combined in hazard information databases, and also reproduced as cartographic products.

Table 2.1. Level of detail of the spatial information of the flash flood model, when used at different scales.

Data type	National scale	Intermediate	Case study
Resolution	20x20 m	20x20 m	10x10 m
Rainfall	Design event	Same as national	Same as national
Soils	Soil map	Same as national	Same as national + field info
Land use	Image classification	Same as national	Same as national + field info
DEM	National scale interpolation contour lines	Same as national	Re-interpolation with added GPS points, or LIDAR
Channels	Generalized width and depth, based on limited field observations. Blockages and sedimentation in channels ignored.	Actual channel dimensions of main streams, blockage and siltation by decreasing effective cross section.	Actual channel dimensions of main streams, blockage and siltation by decreasing effective cross section.
Bridges/culverts	Not included	Bridge cross sections and main/large culverts can be included.	Bridge cross sections and main/large culverts can be included.*
Roads	As fraction of gridcell	Same as national scale	Same as national scale
Buildings	Building density as fraction of a gridcell	Building density as fraction of a gridcell	Larger individual buildings as obstructions
Dikes and levees	Only major dikes, such as southern airport levee	Only major dikes, such as southern airport levee	Major local barriers influencing water flow can be included.

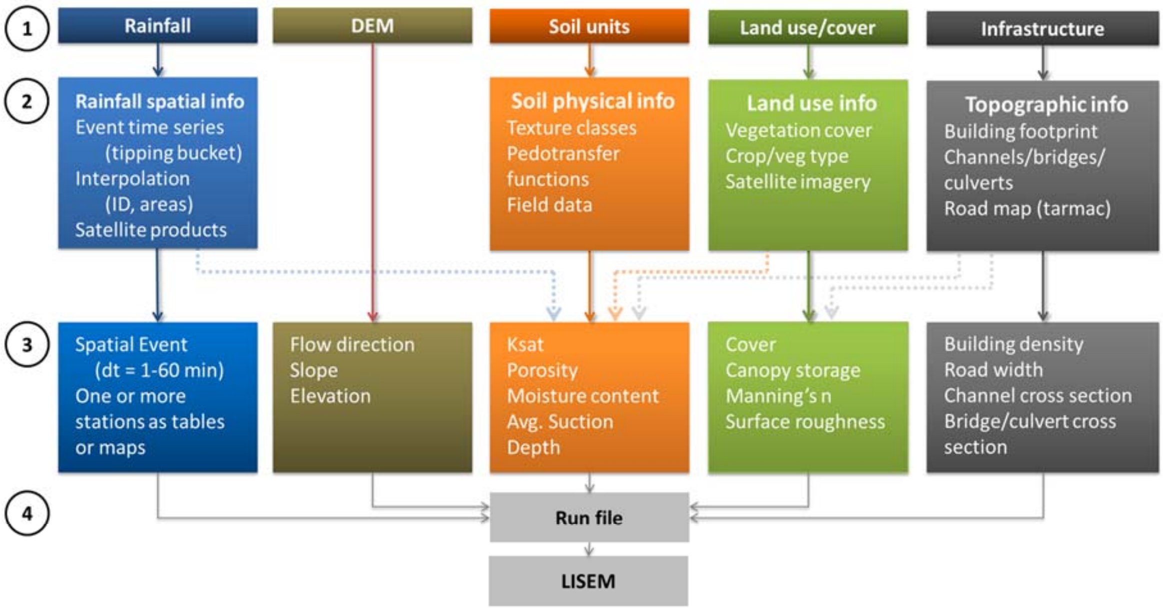
*=note that because of the numerical solutions in the model, the channel must always be smaller than the grid cell width.

The *hazard map* that is created in a GIS as a cartographic product will combine topographic information on the best level of detail with respect to the scale. A good example is the building information described below: the model uses a building density map, the hazard map combines the hazard information with the actual building polygons.

2.3. Model software – openLISEM

The method is based on the open source integrated watershed model **openLISEM**. This model is based on the well-known LISEM erosion/runoff model (see e.g. Baartmans et al., 2012), combined with the FullSWOF2D open source 2D flood package from the University of Orleans (REF). As a runoff model LISEM has been used in many environments, European humid and semi-arid areas, islands (Cape Verde), India, Indonesia and Vietnam. The flood part has been used in Kampala (Uganda). It can be downloaded from blogs.itc.nl/lisem.

openLISEM is a hydrological model based on the surface water balance. It uses spatial data of the DEM, soils, land use and man-made elements (buildings, roads, channels) to simulate the effect of a rainfall event on a landscape (see fig 2.3). The resulting runoff is derived from a Green and Ampt infiltration calculation for each gridcell, and routed to the river channels with a kinematic wave. The water in the channels is also routed with a kinematic wave (1D) but when the channels overflow the water is spread out using the full St Venant equations for shallow water flow. Runoff can then directly add to the flooded zone. Since it is an event based model, LISEM does not calculate evapo-transpiration or groundwater flow. Figure 2 shows schematically the steps in the model from runoff to flooding.



1. Basic maps needed, raster format, minimum resolution defined by user (min resolution wider than channel, no max area size)
2. Additional area information on rainfall distribution, soil and land use parameters, and infrastructure parameters. Derived from imagery, available maps, literature, field work, other models etc.
3. LISEM input database, generated automatically in PCRaster GIS (macro language script, combining base maps and knowledge to create maps for all input variables
4. Define a run file for the job, specifying all options and map names for this run.

Figure 2.2. Flow chart of the creatyion of an input database for openLISEM from 5 basic adta layers. The database is generated automatically in a GIS (PCRaster) with a script that is taylor made for each island.

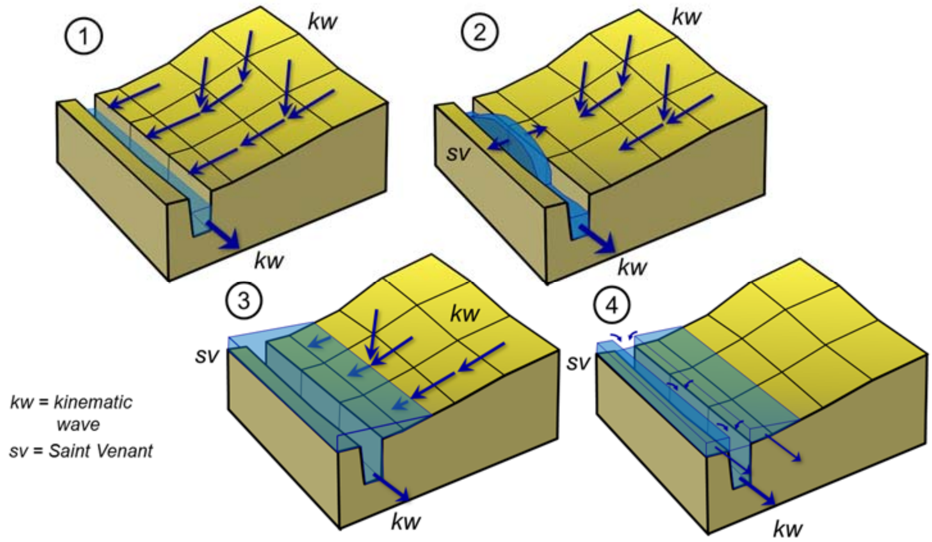


Figure 2.3. Schematic representation of flow processes from 1D kinematic wave runoff and channel flow (1), to overflow of channels (2), spreading out of water from the channels outward using 2D full Saint-Venant equations (3), and flowing back into the channel when water levels drop, most likely the runoff has stopped by now (4). Runoff continues to flow into the flood zone for a short distance.

Figure 2.4 shows how openLISEM deals with sub gridcell information. You can add layers with objects smaller than a gridcell, which are then defined as a fraction (buildings and vegetation) or by their width (roads and channels). Note that roads do not act as channels, and do not guide the water along the road, only if you make sure the flow direction is also along the road. Roads only influence infiltration (impermeable), runoff (smooth), and there is no interception and sediment detachment but there can be deposition.

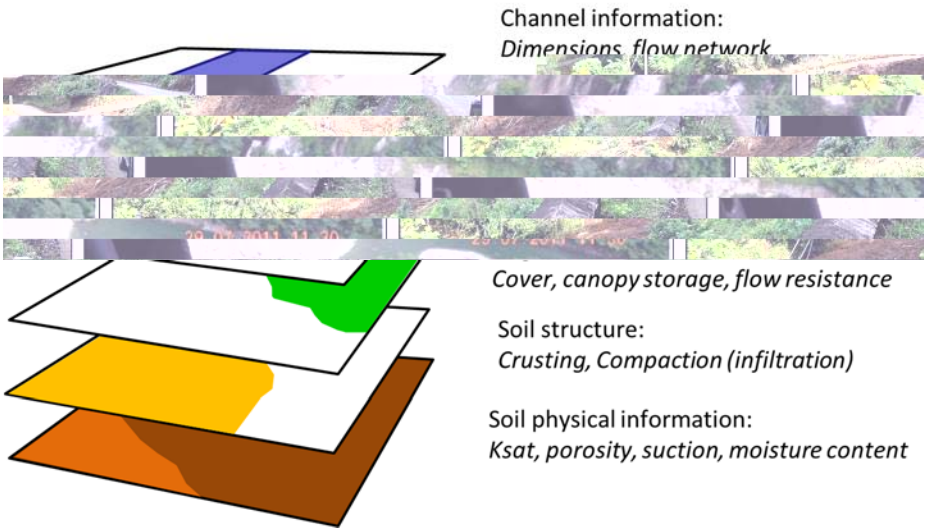


Figure 2.4. Different information layers are combined into one set of information per gridcell. Vegetation and building information is given as a fraction per cell, roads and channels are given as width in m. The soil layer is the base layer so that we always know what for instance the infiltration beside a road is.

2.4. Model calibration

Every model needs calibration to see if the choices in making the input dataset and translating basic data to model data have been done correctly. Normally this is done either by checking simulated discharges against measured discharges in a none flood situation, or checking flood extent and flood depth for a number of locations when there has been a flood.

None of the islands have measurements of discharge in a structured way. There are some river water levels measured during storm events, resulting in channel water level. However, the calibration is missing to translate these to discharges (water velocity is unknown). Neither is it known where exactly the discharge is measures, at which cross section, or the rainfall that lead to this rise in water level.

Calibration against known discharge was therefore not possible. It is strongly suggested to revive the gauging stations and establish calibration curves.

2.5. Rainfall data and return periods

openLISEM simulates the flash flood as a result of an extreme event. The model needs rainfall intensity in mm/h, preferably for small timesteps (<15min), so that it can calculate accurately infiltration and runoff. Many islands have daily data, sometimes hourly and sometimes minute data. This gives us the following approach (see fig 2.5 below). A frequency magnitude analysis is done on the maximum daily rainfall of each island. These will differ per island because of their north-south location with respect to hurricanes and tropical storms. Generally the southern islands experience lower maximum amounts of rainfall for the same frequency.

Important:

This approach means that the Flood Hazard maps do not show the frequency of the floods itself, but the flood that will occur with a given rainfall probability. A catchment with more storage capacity will have less flood hazard for the same rainfall return period, than a catchment with less storage capacity. Thus the same rainfall will have different effects on an island according to catchment characteristics. This is different from the Belize analysis in this CHARIM project as there the analysis is based on estimated discharges with return periods.

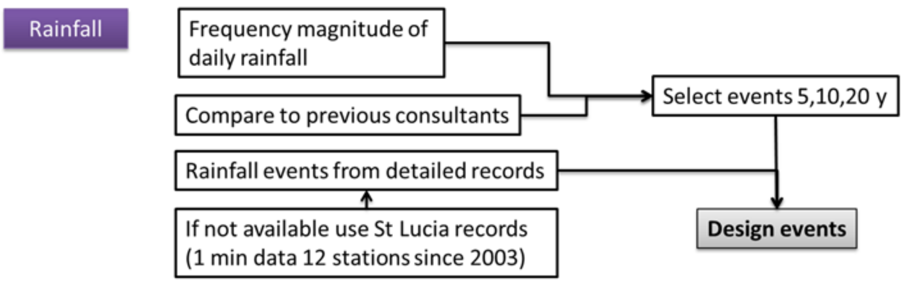


Figure 2.5. Workflow to derive design events for a certain frequency/magnitude

St Lucia frequency magnitude of maximum daily rainfall

There are 18 stations on St Lucia that have long records, mostly from 1955 to 2014. Not all stations have full records for the entire period (varying from 21 to 54 years with daily data). Many 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 600 mm/h).

These stations were each analyzed to isolate for each year the maximum daily rainfall. Subsequently for each station a curve was fitted. The freeware *easyfit* (Mathwave software) was used which fits 57 types of probability density functions on each dataset. In this dataset the "General Extreme value" (GEV) gave the best results. Figure 2.6 shows the equation of the GEV equation and parameters, the resulting GEV parameters for each station, as well as the calculated daily amounts in mm and their repetition times.

	k	sigma	mu	n
Vigie	0.366	25.654	81.892	21
Union Vale	0.219	37.316	83.506	30
Union	0.158	32.448	87.108	54
Troumasse	0.099	47.838	84.164	45
Soucis	0.284	23.707	69.456	36
Patience	0.069	29.968	82.618	52
Marquis de Bab.	0.120	39.638	86.645	47
Mamiku	-0.018	29.334	80.700	40
Mahaut	0.111	43.459	93.191	28
Hewanorra	0.129	39.399	86.826	21
GeorgeV Park	0.188	28.244	81.865	44
Errard	0.292	52.031	103.230	19
Edmund	0.240	57.252	113.080	21
Delcer	0.065	53.316	84.697	21
CARDI	0.481	19.880	74.476	21
Cap	0.156	38.194	82.341	44
Barthe	0.388	31.488	85.957	52
Barre de Lille	0.171	49.257	65.179	54
Average	0.179	38.738	85.439	

rainfall depth mm	return period (years)
152.1	5
192.7	10
237.2	20
304.0	50
361.8	100

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 2.6. Generalized Extreme distribution fitted to the daily maximum values of the stations. The average fitting parameters were used to derive the frequency/magnitude of daily rainfall for St Lucia (lower table).

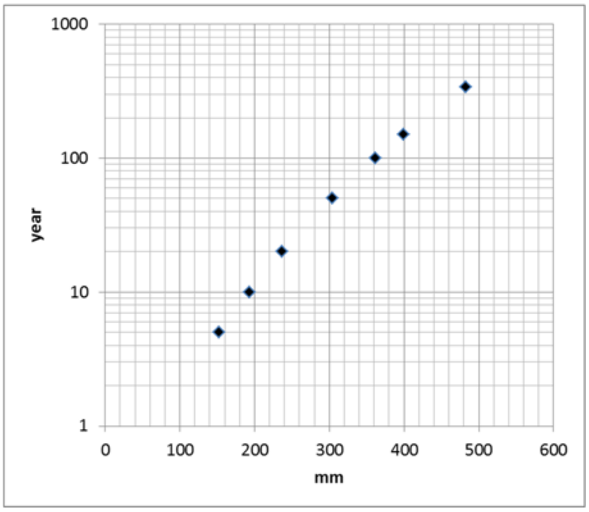


Figure 7. Frequency magnitude of daily max rainfall based on average GEV parameters.

Hurricanes

Normally the assumption is that the more extreme the event, as a result of extreme atmospheric conditions leading to storms, the more rare they are for a location. However, some of the extreme rainfall measured on the islands consists of "local depressions" while other are the result of hurricanes, that may or may not come near the island. Some stations show a clear difference in frequency/magnitude between the two, with a markedly different distribution, while others don't. Hurricanes have a certain trajectory when they cross the Atlantic, and the probability of hitting an island in full or not being near an island determines the amount of rainfall, and the influence of the hurricane on the local weather conditions. This might be a different probability altogether, that maybe should not be included in the same analysis. In other words a flood hazard analysis of the highest rainfall can be done but the frequency may not be that shown above. Notably amounts above 220mm associated with a return period of 50 years or more, might have a different (shorter) return period. Figure 2.89 shows a simple Gumbel analysis ranking all maximum daily amounts for all stations pooled, and suggests that the higher rainfalls have a different frequency. This difference is however not noticeable in a GEV analysis as done above.

It is therefore advised to consider all rainfall as one system and use one frequency magnitude analysis until more data is collected.

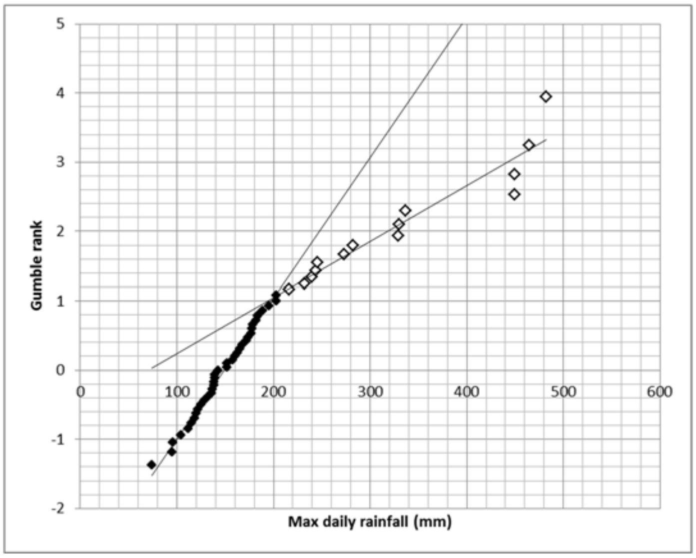


Figure 2.8. Gumbel rank and maximum daily rainfall, all stations pooled. The white diamond are mostly hurricanes and major tropical storms.

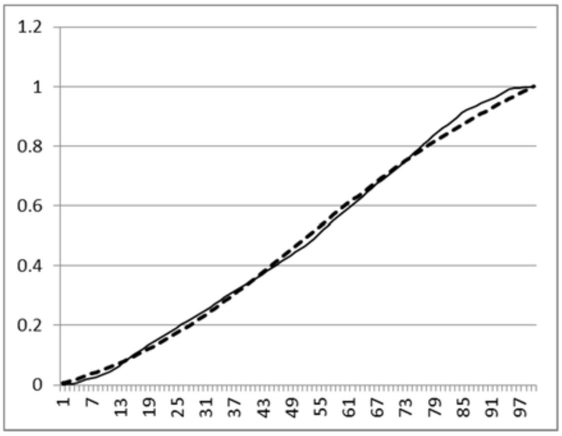
Design storms

THIS PART IS NOT FINISHED YET!

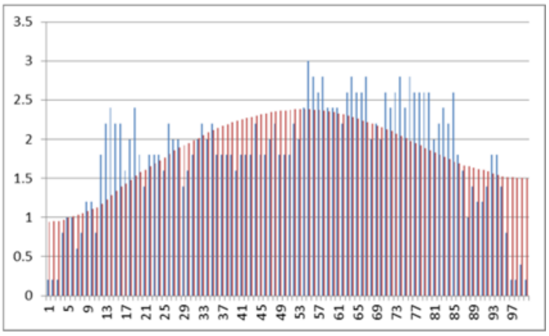
Design storms are based on IDF curves (Intensity-Frequency-Duration). Lumbroso et al. (2011) showed that good IDF curves are difficult to establish for the Caribbean islands.

Procedure:

standardize events of a magnitude close to the amount from the frequency magnitude analysis, e.g. 237 mm for 1:20 years. Fit a curve with the cumulative rainfall of this event, scaled between 0 and 1:



However, at the moment some analysis has to be done because the curve does not match the original well:



Most storms have already high maximum intensities, the higher rainfall amounts are usually more complex storms that have more volume, not necessarily higher peak intensities. So probably the result will be that storms with a lower return period are longer with more rainfall depth.

2.6. Spatial data

openLISEM uses input data directly to determine the hydrological processes that it simulates. There are very few built-in assumptions. For instance openLISEM does not handle units like "Maize" or "Forest". This information is broken down into hydrological variables related to interception of rainfall and resistance to flow. The user has to break these classes down into hydrological variables for cover, infiltration related parameters and surface flow resistance.

Nevertheless in this project scripts are made to create the 5 data groups for a model run, using a combination of field data and literature. These scripts are made in the freeware GIS PCRaster (pcraster.geo.uu.nl). The scripts read GeoTIFF raster maps (the basic layers shown in figure 2.2), and generates the input database automatically, so that the counterpart does not have to go through the GIS operations to create each layer separately. It is however advised the user has intimate knowledge of surface hydrology and flood processes.

Table 2.2 shows the basic data that is used for St Lucia, their origin, and the methods used to make them "hydrologically correct". All raster layers are produced on a 10m grid and resampled to a 20m grid, so that two detail levels are created for modelling.

Basic data	Created from	Method
DEM	From 3 contour shape files (FUGRO?): of the upper, middle and lower part of the island.	Kriging interpolated using with an exponential semivariogram to a 10m DEM, resampled to a 20m DEM using average.
Soil Map	Shape file. Origin 1966 soil map made by UWI Imperial College of Tropical Agriculture.	Interpreted the legend to standard USDA texture classes. Texture classes were used to derive soil physical properties, taking into account stoniness.
Land use map	Shape file. Thematic Mapper 1995. Date image not known. Classification procedure not known.	Used 15 classes for land use information, interpreted directly to cover fractions and manning's n.
Road map	Shape file of all roads (incl. highway).	Assumed all road to be tarmac/concrete slabs, narrow width (4m and 6m) and highway 10m wide.
Building map	Shape file from FUGRO digitized building information.	Rasterized to 1m resolution and resampled to 10m and 20m building density (m2 building/m2 cell)
River map	Shape file, two classes, natural and artificial. The natural streamlines follow the contour lines exactly and are assumed to be artificially generated in a GIS.	Select main streams from this network, using stream order. Stream order 1 and 2 (the lowest level branches) are eliminated. All rivers are connected to an outlet at the shore by hand, following the DEM or Google earth where necessary.

Table 2.2. List of main data layers for St Lucia and their origin and main gis operations

DEM

The DEM is used for flow directions and slope in the runoff part of the model, and elevation is used in flood modelling. The DEMs of St Lucia is created by Kriging interpolation from elevations lines using an exponential semivariogram. These elevation lines are 2 meters interval and generated automatically. It is not known when and how they were created, possibly as the result of a FUGRO project in 2009 (*? To be determined*). Because this results in a smoothed grid, and the density of points is very high, this map was combined with the original points using the average elevation for each cell where the original points exist. This gives some of the original detail back into the dem.

Rivers/Channels

A shape file with drainage lines exists in the St Lucia database, classified as artificial (small drains along the roads) and natural channels. The natural network is very dense, where every valley has a drainage line. For the flood hazard map mon a national scale only the major drainage lines are retained. Figure 2.9 shows the result of this process. For a detailed flood analysis this stream network should be checked on the field.

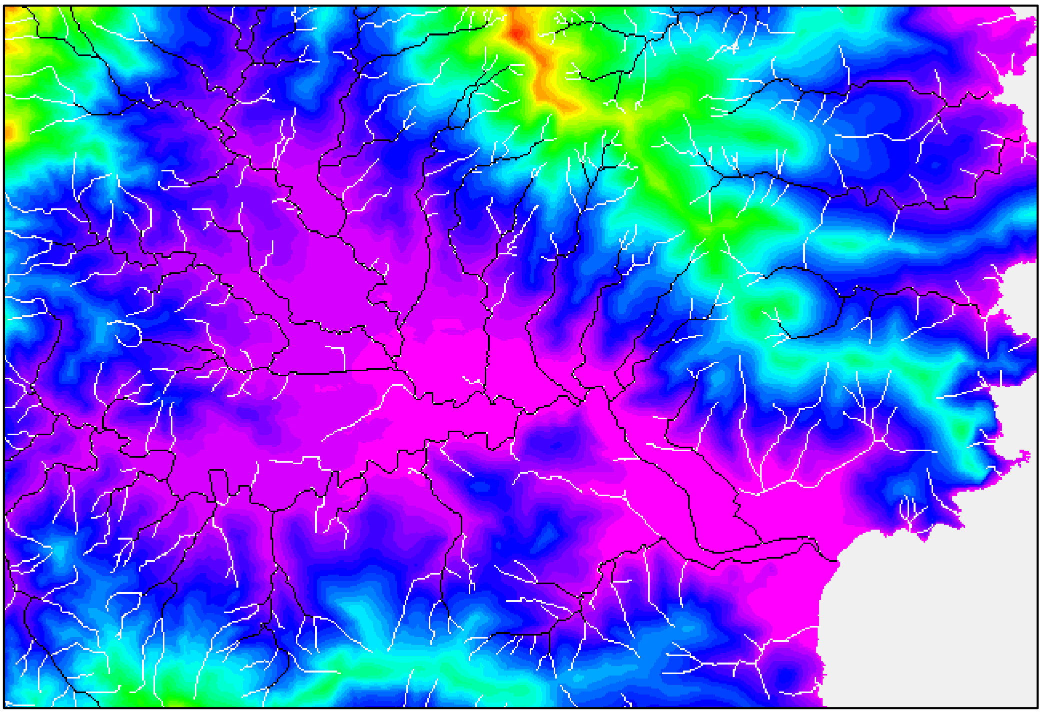


Figure 2.9. Stream network culling for flood hazard analysis on a national scale. White are the barnches not included (1st and 2nd order branches).

Soil map

This map originates from 1966 soil map made by UWI Imperial College of Tropical Agriculture. The soil Classification system is general for the islands, designed by the authors (Stark et al., 1966)) of these maps. The classification system follows the US convention of assigning "typical soil profile" and giving them a name based on the type location, such as "Anse Clay" or "Mabouya Silty Clay". Fig 2.10 shows the workflow of deriving soil physical properties from the soil classes and fieldwork data. Figure 2.11 and table 2.3 show the resulting map for openLISEM.

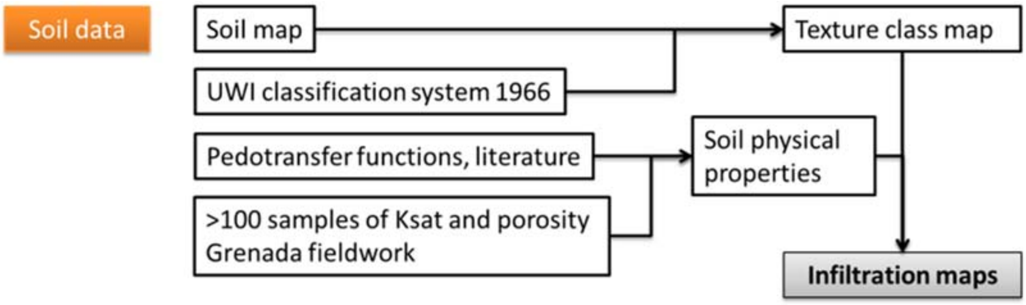


Figure 2.10. Workflow to derive soil phical data from soil classes and field data.

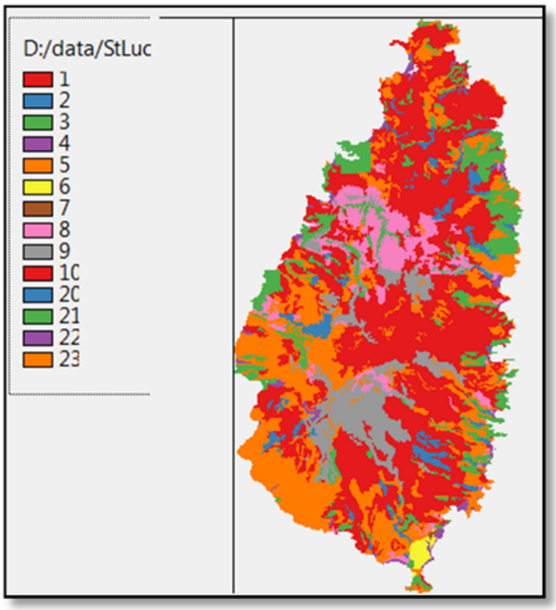


Figure 2.11. Soil map with main texture classes (1-10) and special classes (20-23)

		ksat	pore	psi
	text class	mm/h	cm3/cm3	cm
1	C	2.5	0.5	50.0
2	CL	4.2	0.5	50.0
3	L	18.5	0.5	40.0
4	S	112.0	0.5	20.0
5	SaCL	7.0	0.4	35.0
6	SaL	80.0	0.5	40.0
7	Si	42.0	0.5	40.0
8	SiC	13.0	0.6	40.0
9	SiCL	25.0	0.5	40.0
10	SiL	17.4	0.5	40.0
20	Water (W)	0.0	0.0	0.0
21	Urban (A)	0.0	0.2	40.0
22	Salt pans (m)	0.0	0.4	40.0
23	Rock/outcrops	0.0	0.1	40.0

Table 2.3. Main classes derived from the soil map and assumed saturated hydraulic conductivity (Ksat in mm/h), Porosity (pore in cm3/cm3) and Initial suction (psi in cm).

The soil physical parameters are derived from the pedotransfer functions of Saxton and Rawls (2006).

Normally a soil classification system is not based on the top soil as this is often affected by agriculture and building. This is also the case in this system. The texture indications are valid for both top soil and subsoil, but under natural vegetation the top soil has a much more open structure. The clayey soils, derived from weathered volcanic material, form strong and stable aggregates under natural conditions, that give the soil an open structure with a high porosity and saturated hydraulic conductivity (ksat). This means that the top soil can absorb quickly large amounts of water, depending on how dry it is. Under agricultural circumstances the tops soil is more massive during most of the year, for instance as in the frequently occurring Banana plantations. Trampling of the soil destroys its structure.

It is therefore assumed that under natural vegetation we are dealing with a 2 layer system in terms of infiltration, with the topsoil hhaving large values for porosity and ksat.

Soil depth

The max soil depth (figure 2.12) is created from the DEM and a number of assumptions regarding landscape evolution. It is assumed that steeper slopes have shallow soils because of constant erosion and landslides, and river valley have deeper soils as a result of accumulation. Nearer to the sea however, the soil becomes shallower, as the wider floodplain remains a one to several meters above sea level and is often fixed by human intervention. Deeper inland the rivers have cut down to bedrock level and have formed deep valleys. This is not always apparent from the DEM. The method used to create this map is based on Kuriakose et al., (2006) who generated a soil depth map in a mountainous tropical catchment in southern India.

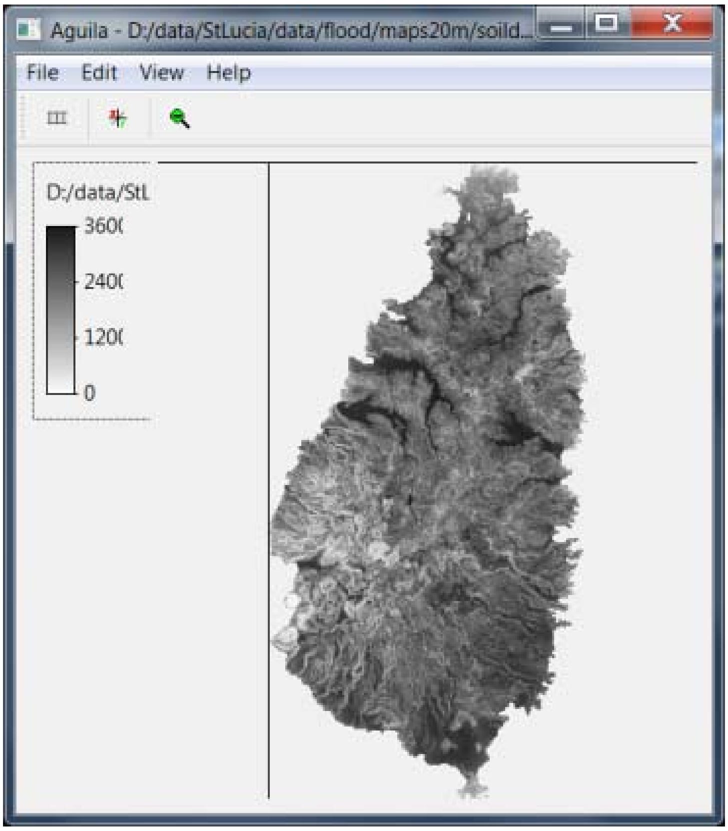


Figure 2.12

Land use map

The land use map is derived from a Thematic Mapper image (Date: ???). The land use table is shown in table 2.5. The variables derived from the land use are those affecting the soil surface structure and roughness, which affects the surface runoff. A continuous soil cover is assumed, which is of course not realistic for agricultural areas. For these areas the plant cover map could be created from NDVI satellite images, although series of images with a high temporal resolution are only available with a 250m resolution at best. Cover influences the interception of rainfall by the plant canopy. This is usually in the order of 1-2 mmm 9De Jong and Jetten, 2009) and therefore not an important factor when dealing with intense tropical storms. Other than that the cover only has an effect if the vegetation consists of grass, which slows down the surface runoff. This is determined by the Mannning's n factor. So an updated land use classification could have influence on the flood dynamics, but the expectation is that this does not have an extreme effect.

Note that the plant height is not used, it is only important when erosion is simulated.

	nr	Random Roughness	Manning's n	Height	Cover
		cm	-	m	-
Densely Vegetated Farming	1	1.00	0.10	20.00	0.95
Eroded Agricultural Land	2	2.00	0.10	8.00	0.95
Flatland Intensive Farming	3	1.00	0.05	10.00	0.95
Grasslands	4	1.00	0.10	5.00	0.95
Grasslands and Open Wood	5	1.00	0.15	2.00	0.95
Intensive Farming (25% Forest)	6	1.00	0.10	2.00	0.95
Mangrove	7	1.00	0.05	1.00	0.95
Mixed Farming	8	1.00	0.07	1.00	0.95
Natural Tropical Forest	9	1.00	0.03	1.00	0.95
Plantation Forest	10	2.00	0.03	0.50	0.35
Rock and Exposed Soil	11	0.50	0.02	0.20	0.35
Rural Settlement	12	0.50	0.02	0.20	0.10
Scrub Forest	13	0.50	0.02	0.00	0.10
Urban Settlement	14	0.10	0.03	0.00	0.00
Water	15	1.00	0.10	20.00	0.95

Table 2.5. Average vegetation parameters based on field observations.

Building density map

This map is derived from the building footprint (FUGRO, 2004). Fig 2.7 shows an example for the centre of Castries. The building density influences the interception of rainwater, infiltration (impermeable) and the flow velocity, but the influence of individual buildings cannot be simulated at this resolution (20m). This map is created by rasterizing the building polygons to a fine raster, and resampling that to 20x20m to a fraction of building density per cell (0-1 cover). The resulting flood hazard maps however are imported in the GIS system to be combined with building footprint.
Also roads and bridges have maps that are rasterized.

Figure 2.13. Rasterized bulding footprint at 2m (left) from the centre of castires. The 20m building density (right) as used in the model.

2.7. Island datasets

An analysis of the datasets of the other islands: in progress!

Grenada

Basic data	Created from	Method
DEM		
Soil Map		
Land use map		
Road map		
Building map		
River map		

St Vincent

Basic data	Created from	Method
DEM		
Soil Map		
Land use map		
Road map		
Building map		
River map		

Dominica

Basic data	Created from	Method
DEM		
Soil Map		
Land use map		
Road map		
Building map		
River map		

2.8. Model output and Hazard maps

Fig 2.14 shows a typical screen of openLISEM during a run, with flood depth (in m) and time to inundation (in min) after the start of the rainfall. Fig 2.9 shows a typical flood depth map directly imported in QGIS (reads model output directly) and combined with roads and housing footprint. The hazard maps show a different kind of information, this is just a to show what it will look like. Note that this is the result of the national scale flood modelling, zoomed in to a catchment where floods are reported to take place. The result has a similar resolution than other local consultancy studies that have been carried out.

This is just a first trial. Optimal representations will be made for depth distribution for different rainfall frequencies, duration, early warning, as well as statistics of buildings and roads flooded per catchment. The openLISEM model produces more information such as movies of the flood simulation, but this cannot only be represented in certain GIS systems (Ilwis, PCraster, or exported to a movie format). Figure 2.9 shows a detailed image. This type of information is available for the entire island but when displayed/printed on a large scale the information is lost.

The individual catchments can be easily retrieved, as the analysis is for the entire island in a single simulation. If the counterpart wants to do a simulation for a single catchment, this can be selected automatically from the database and the simulation can be rerun (for instance when changes in building footprint have occurred).

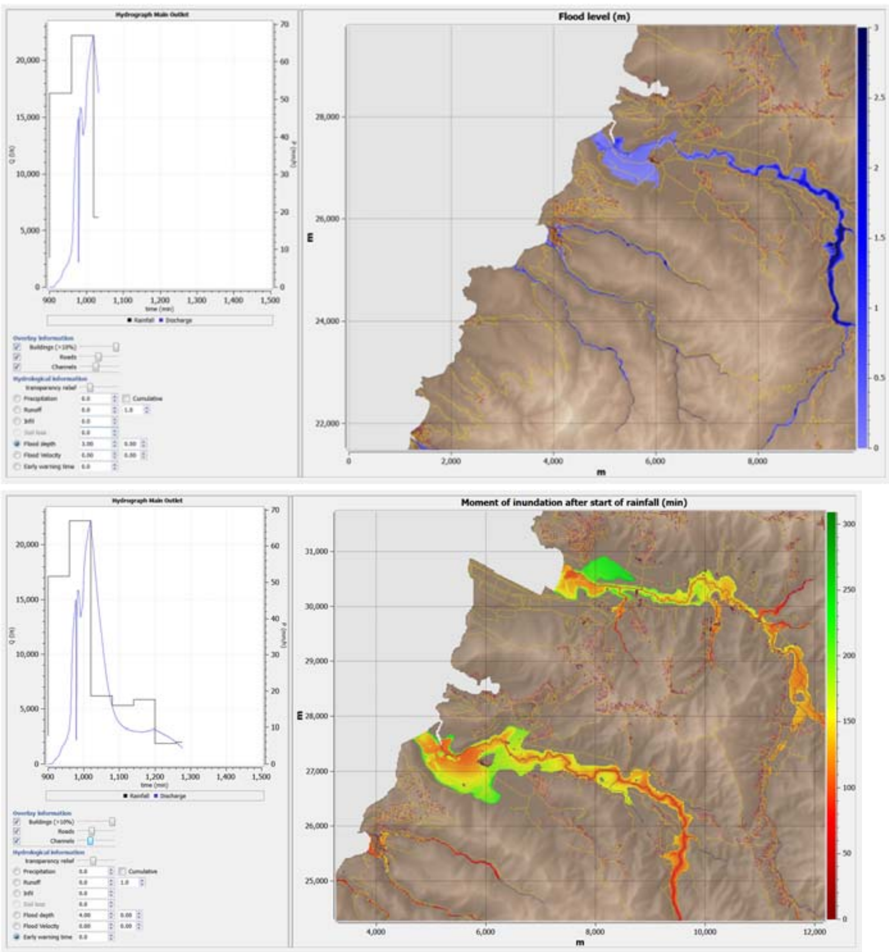


Figure 2.14. openLISEM screen: Flood Depth at the height of the rainfall (top), and Time to first inundation (min) at a location relative to the start of the rainfall (bottom). This and other information can be directly imported in a GIS.

There are different ways to translate the model outcome to hazard maps.

- The simplest is to show the flood extent: different return periods have different flooded areas and hazard levels 1, 2 and 3 are for instance related to return periods 5, 10 and 20 years. This is usually what is used for national scale flood assessment. Thereby all other information on floods are ignored, such as depth, velocity and duration. Usually a minimum level is assumed, for instance a the flood is only depicted when it is deeper than 0.05 m.

More complex hazard information can be generated without using full risk information. This uses the an underlying assumption of when a flood is considered a problem, and which levels are related to which problems. Examples are:

- A combination of depth and return period can result also in 3 or 5 hazard classes. The decision of what is considered low, medium or high hazards can only be done in discussion with the end users. A fire department may want to relate water depth to transport on foot or by car. In that case water depth levels are translated to being able to cross the water on foot, by car etc, or compare water depth to bridge height and road levels. On the other hand a planning or building company will want to relate water levels to legal building and safety standards.
-

		return period		
Flood hazard combined	**Depth**	**50 year**	**20 year**	**10 year**
	<0.5m	**Low**	**Low**	**Moderate**
	0.5-1.0m	**Moderate**	**Moderate**	**High**
	1.0 -1.5m	**Moderate**	**High**	**High**
	>1.5 m	**High**	**High**	**High**

- It is also possible to combine other factors for specific return periods: velocity and depth, early warning and depth etc. Meaningful levels are only possible in a local context.

		Reaction time		
Flood hazard of one return period level	**Depth**	**>90 min**	**45-90 min**	**< 45 min**
	<0.5m	**Low**	**Moderate**	**High**
	0.5-1.0m	**Moderate**	**Moderate**	**High**
	>1.0 m	**High**	**High**	**High**

- Finally and most complex is to combine all possible return periods and hazard related information into one spatial multi-criteria analysis. The result of this is a map with levels 0 - 1 from low to high hazard. It is not possible to determine *why* an area has a particular hazard level, it might be any combination of parameters that leads to this level. Also the outcome depends on how heavy the user weighs certain factors, depending on what is considered more important.

It is proposed to produce in any case flood extent for different return periods for all islands (hazard type 1), which is simple to interpret and comparable between the islands. It is also advisable to use the same system and criteria for all islands in case of more complex criteria, so that "high hazard" has the same meaning on all islands.

3. Belize National Flood Hazard Mapping

3.1. Background

This document has been produced in response to a request by the World Bank for further detail regarding our methodology for the Flood Hazard Modelling/Mapping for Belize under the CHaRIM project. This is the second version, with updates incorporated following discussions held with the World Bank on 24 and 25 November 2014. Cited papers in this report have been provided to the World Bank during the discussions.

3.2. Flood Hazard Types

Belize is exposed to the three major types of flood hazard: river flooding (fluvial), surface water flooding from extreme rainfall (pluvial), and coastal flooding from storm surges.

3.2.1. Fluvial (river overtopping)

This relates to prolonged rainfall across catchments and extremes often associated with hurricane or tropical storms. Headwaters in the Maya mountains where higher rainfall and steep slopes, leads to very rapid flood wave build and travel times, e.g. Macal River. When these flood waves arrive in the lower reaches of the river, where the terrain is very flat, bank overtopping occurs, leading to long duration ponded water flooding. These are essentially two very different flood mechanisms from the same flood but modified by local topographical context.

3.2.2. Pluvial (intense rainfall)

Tropical context leads to very high intensity, short duration rainfall events which results in rapid saturation, overland flow and localised ponding.

3.2.3. Coastal (storm surge)

This is associated with tropical storms and hurricane low pressure systems arriving at the coast. This leads to a 1-5 m water surge travelling inland, centred on the depression. Local tide range is small and timing with tide peaks is not an issue. (NOTE: this hazard was not identified in the ToR, but we will attempt to provide some modelling of a storm surge).

3.3. Addressing the Flood Hazards in Belize

For fluvial hazard (river overtopping), we will use a national scale 1D/2D model approach based on best available data. Return period flows for each river and reach are derived from regional flood frequency analysis.

For pluvial hazard, we will use a rain on 2D grid approach with extreme rainfall inputs derived from regional Intensity duration frequency curves (IDF) analysis.

For the coastal hazard, we will identify expected storm surge peaks and their spatial range along the coast from existing coastal modelling reports. We will derive the dynamics of the event from pressure measurements made of hurricane landfalls at Belize City. This will allow us to provide a spatially varying water boundary as a boundary condition to the 2D model domain to simulate landfall of the storm surge.

3.4.Methodology Objectives

A national scale flood hazard map is required to provide a large scale overview of flood risk across the entire country following a consistent methodology. Resolution must be good enough to enable the hazard map to be relevant to planners at a national, district and city scale in Belize.

The aims are to:

1. Identify the highest quality datasets available for Belize.
2. Use local knowledge and data to improve datasets where possible.
3. Employ state of the art modelling methods that can utilise high quality local data (where available) whilst being robust to poor quality data and/or data scarcity.
4. Create a ~100 m resolution national scale flood hazard map that incorporates the three dominant sources of flood risk.

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3.5.Process Overview

A simplified overview of the method is provided in Figure below. From this, it can be seen that there are four overall processes involved. The first two steps involve building the model geometry and generating the model inputs.

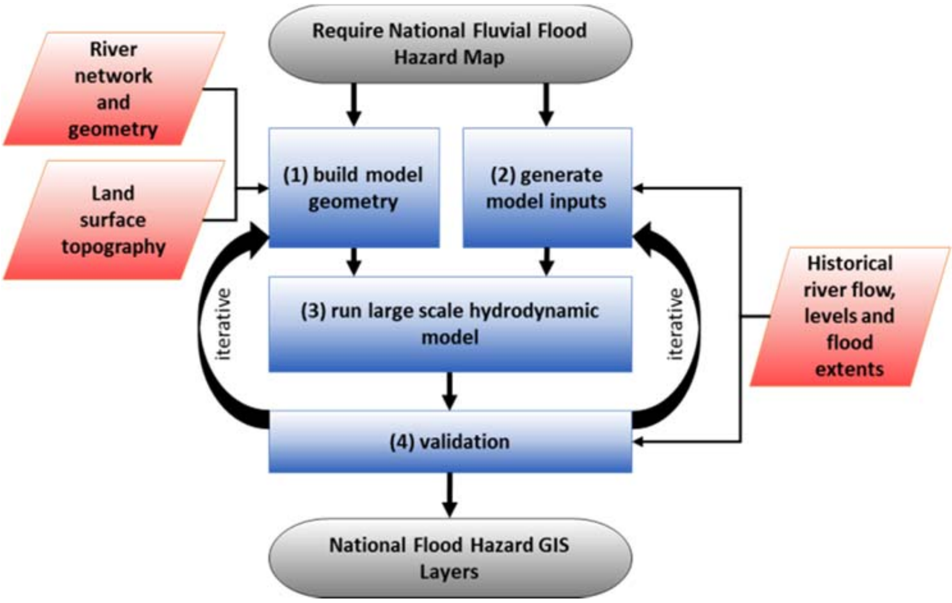

Figure 3.1 - Overview process diagram of National Flood Hazard Assessment for Belize

The model inputs define the quantity of water in the model at a particular time and the model moves this water in/through the model geometry provided to simulate channel and overland flow. The hydrodynamic model is the actual software used to simulate the flow physics required for realistic hydrodynamics (movement of water). The final validation step is an important part of the process used to test the model results, both to check for mistakes and to understand the scale of error that is inherent in all model results.

3.6. Data requirements

3.6.1. Digital Elevation Model (DEM) [Model Geometry]

The DEM should be bare earth and needs to have the same resolution as the final hazard map (~100m). Shuttle Radar Topography Mission (SRTM) has been identified as the best basic DEM for Belize. The ASTER DEM, while in theory is at a higher resolution (~30m), has been found to contain significantly more noise error, resulting in worse results when used for hydrodynamics modelling.

3.6.2. DEM correction data [Model Geometry]

Spatial urbanisation data (such as satellite luminosity data) and vegetation data (MODIS Vegetation Continuous Field (VCF)) are required to assess reduction of vegetation and urban biases in SRTM. These allow artefacts in the DEM due to vegetation and buildings to be removed, correcting the DEM to a bare earth DEM required for flow simulation.

3.6.3. River network [Model Geometry]

River network, upstream accumulating area, and geometry are all required for the modelling. The river network and upstream accumulating areas can be estimated in an automated fashion from the SRTM DEM (e.g. Hydrosheds), with subsequent manual validation and correction where necessary. It is also necessary to measure (or estimate) channel geometry (i.e. width and depth).

3.6.4. Flood defence standards [Model Geometry]

Knowledge of river defence standards can be incorporated into the model.

3.6.5. Discharge data [Model Inputs]

In order to construct design hydrographs for return period flood events on large rivers (e.g. the '1-in-100 year event'), local flow records are an advantage. Where discharge records do not exist, a regionalised flood frequency analysis (RFFA) is required to estimate appropriate discharges.

3.6.6. Rainfall data [Model Inputs]

As flooding along minor channels and away from floodplains is usually driven by intense local upstream rainfall, local rainfall records should be used to estimate intensity-duration-frequency (IDF) curves for the region. If local rainfall data is not available, regionalised IDF curves can be used.

3.6.7. Storm surge data [Model Inputs]

Local tide buoy records of water level changes during historical storm surges (if available) allow an understanding of the magnitude and duration of storm surges that might be experienced along the coast. Ideally there will also be a coastal bathymetry model to determine the spatial pattern of this storm surge along a heterogeneous coastline.

3.7. Analysis steps

The National Flood Hazard Layer for Belize has been generated using a state of the art Global Flood Hazard framework, improved with local data where such data is available. A detailed breakdown of its application in Belize is shown in Figure and explained in the subsections below. The full framework contains many modules and sub-modules, and the full structure is shown graphically in Figure for completeness, although Figure should be sufficient for understanding its application to Belize.

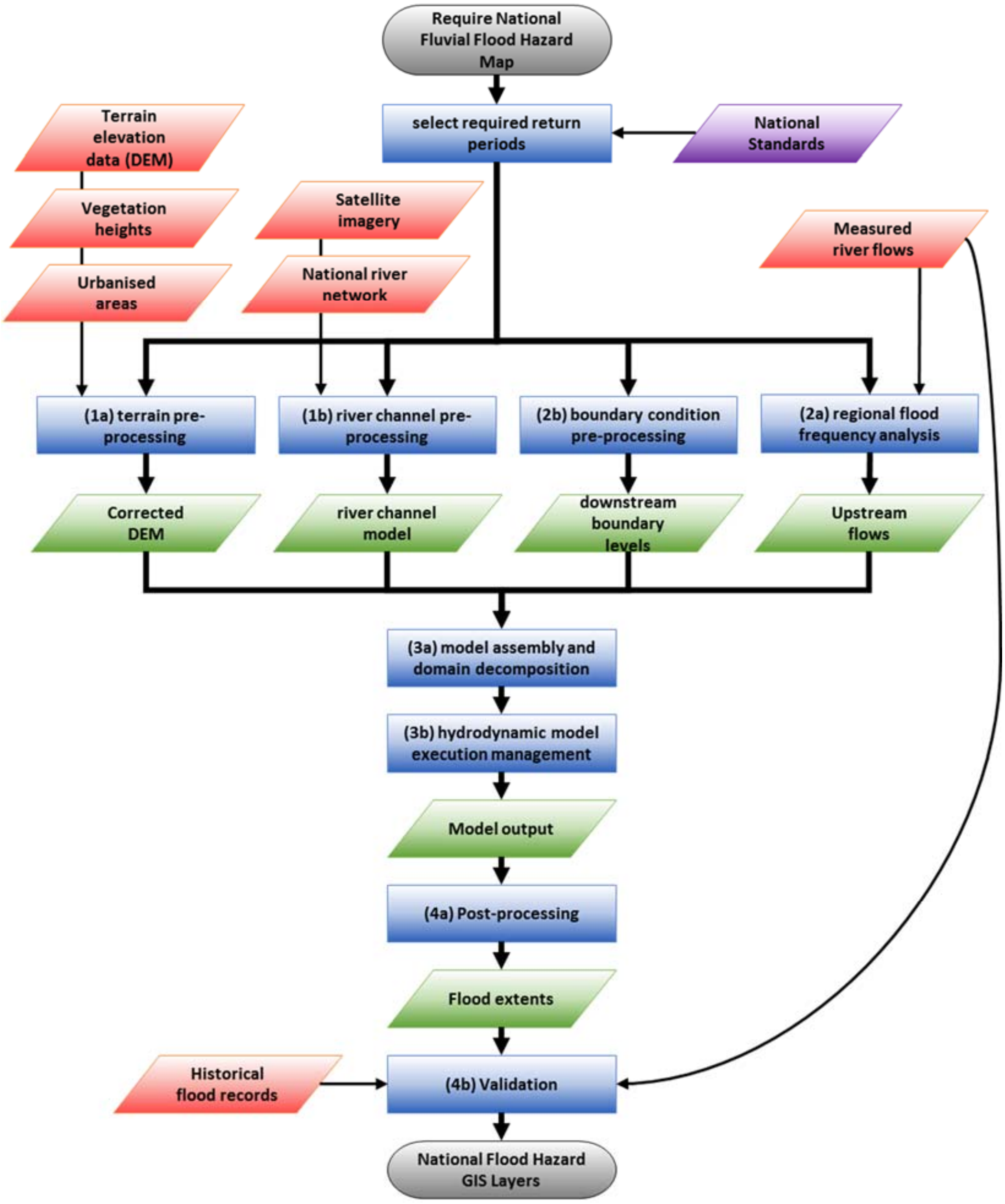

Figure 3.2 - Detailed process diagram of National Flood Hazard Assessment for Belize

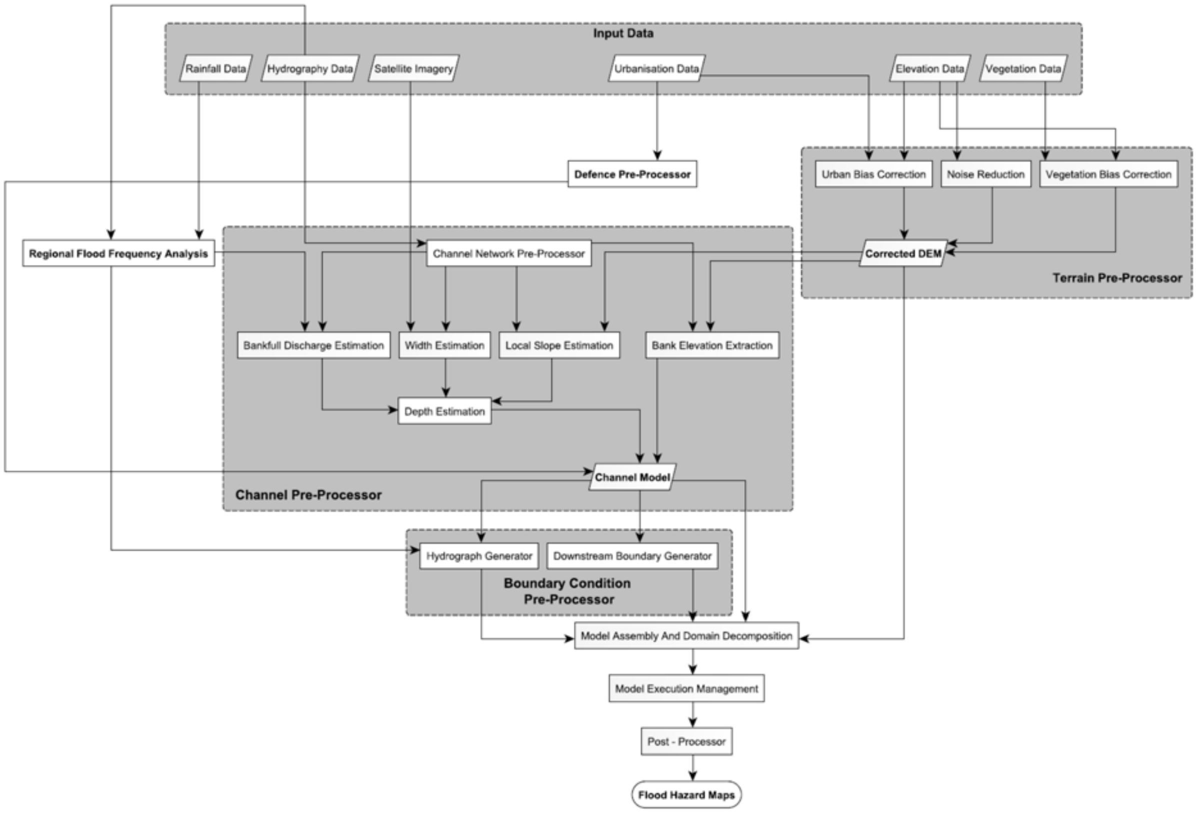

Figure 3.3 - Full process diagram of SSBN Global Flood Hazard Modelling methodology

3.7.1. (1a) Terrain Pre-Processor

- The relevant 3 arc second SRTM terrain tiles are extracted and joined to create a continuous DEM of the entire country.
- Urban areas are identified using satellite night time luminosity data (Elvidge et al., 2007).
- Depending on the degree of urbanisation, a filter of varying strength is applied to the SRTM data to remove local high points (which represent building roofs) and reconstruct the surface by interpolating between the remaining lower points.
- Vegetation bias is reduced using an algorithm based on MODIS VCF.
- A feature preserving smoothing algorithm is applied to the entire DEM to reduce the noise inherent to SRTM data (Gallant, 2011)

-

3.7.2. (1b) Channel Pre-Processor

- It is critical to explicitly model river channels within flood models as most water is conveyed across the land surface within them; their omission leads to severe over estimation of flood hazard.
- The channel network is generated using GIS-based hydrological analysis tools; the basic network used here was created as part of the Hydrosheds project (Lehner et al., 2008). The Belize network has been validated manually, with corrections made where necessary.
- Simple models of river width can be built by surveying using aerial and satellite photography and relating measured width to upstream accumulating area. The model can then be used to estimate an appropriate width for all river channel cells within the model.
- River depth can be estimated using the Manning's equation given that bankfull discharge can be estimated using the RFFA. Width can be estimated using the width model and slope can be calculated using the DEM.

-

3.7.3. (2a) Regional Flood Frequency Analysis

- The RFFA (Smith et al., 2014) has been developed to enable return period discharges to be estimated anywhere on Earth based only on Köppen–Geiger climate classification, upstream area and upstream annual rainfall. By making an assumption of bankfull return period (typically ~ 1 in 2 years), it is possible also to estimate bankfull discharge using the RFFA.
- Local data is quality assessed and used to validate RFFA flows where available.
- Flows estimated via the RFFA approach have been validated by comparing with observed flows for the stations in which flows were judged to be reliable.
- Not all stations were used in this process as some of the data were clearly erroneous at higher flows.
- Validation involved comparing estimates of the Mean Annual Flood and the Q100 (100 year recurrence interval) event. More broadly, flood frequency curves estimated from observations and from the RFFA method were compared.
- The RFFA operates for channels with an upstream area of >~40 km^2. For channels below this size, intense rainfall is simulated within the hydraulic model. The rainfall intensity for an event of given duration and return period is estimated using IDF curves generated from local rainfall data if available, else using regional IDF curves.

-

3.7.4. (2b) Boundary Condition Pre-Processor

- Simple hydrographs are generated based on the rational method, where time to concentration is used to estimate the period of rising and recession limbs. The time to concentration is estimated by using Manning's equation to calculate velocities along the length of the river network to the furthest point. The peak discharge is taken from the RFFA.
- River network is decomposed into reaches, with each reach having its own hydrograph simulated.
- Reach decomposition is dependent on change in bankfull discharge: the maximum difference in bankfull discharge between boundary condition points along a river is 5%.
- Downstream boundary conditions are set to sea level if terminating in the ocean, or at DEM elevation if terminating inland or at model domain.

-

3.7.5. Coastal Storm Surge Analysis

The coastal storm surge analysis is effectively a specialised version of (2b) Boundary Condition Pre-Processor. Here we need to define the water levels experienced at the coast, allowing the model to simulate what would happen as this surge spreads over the coastal topography.

Storm surge amplitude

The Caribbean Disaster Mitigation Project (CDMP) created the Atlas of Probable Storm Effects in the Caribbean Sea. In brief, this used the conditions of 973 tropical cyclones in the region to force a numerical storm surge model. It provides estimates of storm-tide elevations accounting for tide, pressure, wind and wave influences upon the ocean (but not run-up) over a 1 km resolution grid. From the ensemble of simulations, return period water levels were calculated (10, 25, 50, 100 year) for each cell in the domain. Interpolation between points enables representation of spatial variability in surge characteristics along the coastline (Figure).

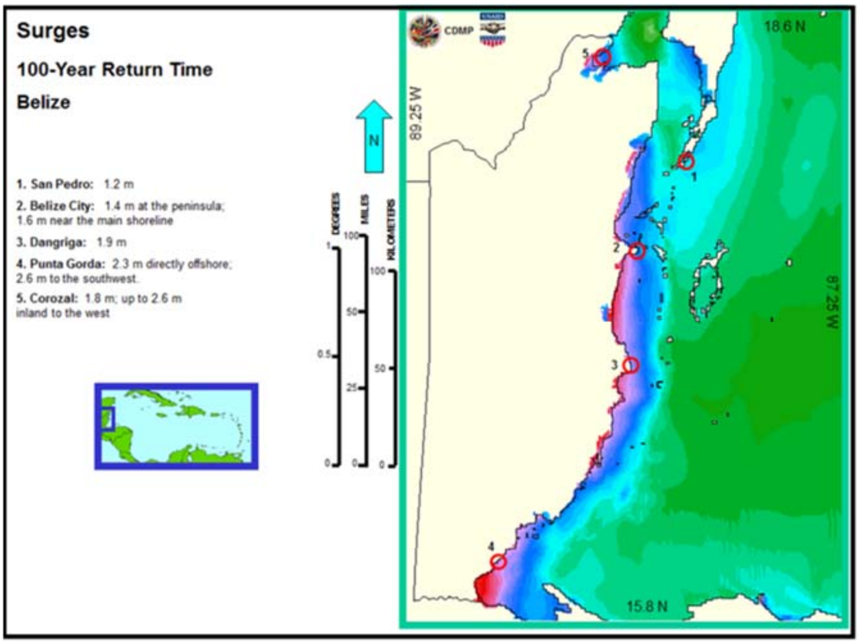

Figure 3.4 – Spatial variation of 100 year surge along Belize coastline from Atlas of Probable Storm Effects (CDMP)

Storm surge time series

Due to a lack of tide gauge data, past data can be used to infer a relationship between atmospherics and surge. For instance, Figure below shows the water level and pressure time series at 2 gauges along the coast of the USA during hurricane Rita in 2005. This infers that we can at least make an approximation of the time series of extreme surge events based on historical pressure charts where we have no water level data.

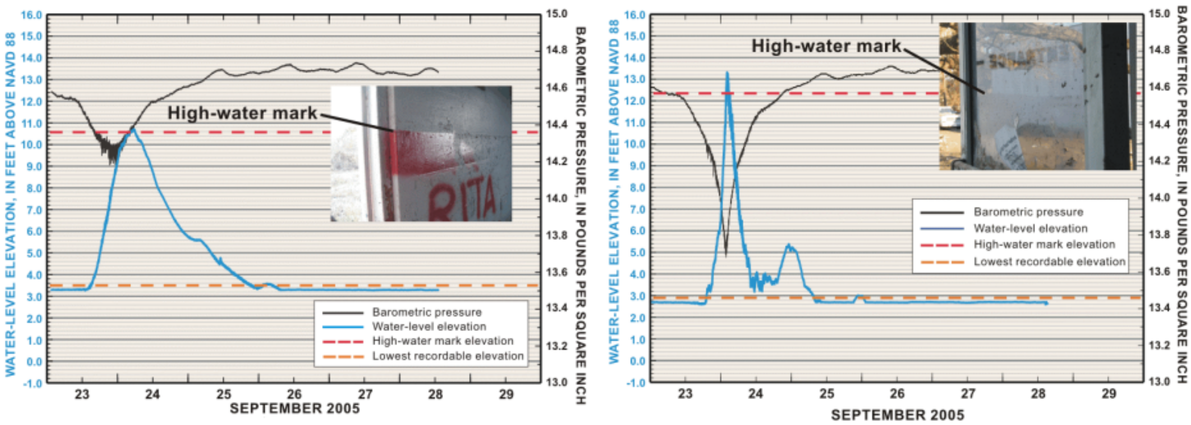

Figure 3.5 - Water level and pressure at 2 gauges along the coast of the USA during hurricane Rita in 2005

Pressure records at Belize during hurricane Hattie will be used as a first approximation of extreme event time-series. This event could be characterised by a triangular function in which a linear interpolation is used from the peak (100% of the surge peak magnitude) to 0% at approximately 6 hours either side, derived from pressure records for hurricane Hattie at Belize City in 1961 (Figure).

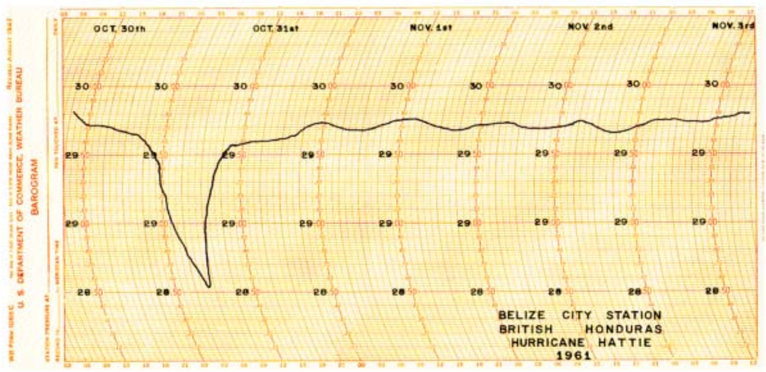

Figure 3.6 - Pressure records for hurricane Hattie at Belize City in 1961

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3.7.6. (3) Hydraulic Model

- The models are executed using a full 2D hydraulic model based on a simplified momentum-preserving variant of the shallow water equations (Bates et al., 2010).
- The model explicitly models channels using a subgrid scheme (Neal et al., 2012) that decouples the channel geometry from the model grid, allowing channels of all sizes to be represented.
- A surface water routing scheme is incorporated into the model to handle situations where the assumptions underlying the shallow water equations are violated. This usually applies to areas of very steep or discontinuous terrain. The routing scheme moves water downslope at a velocity that is dependent on slope gradient; the velocity-gradient relationships were developed from empirical studies of surface water flow velocities (Sampson et al. 2013).
- Large rivers are modelled at 30 arc second resolution, as a coarser grid produces a more stable simulation of water surface elevation on large flood plains. This is because resampling the DEM reduces the noise present in SRTM terrain data.
- Small rivers and pluvial simulations are simulated at 3 arc second resolution as the higher resolution is necessary to resolve the small scale topographical features that constrain the flow of smaller channels.

-

3.7.7. (4a) Post Processor

- 30 arc second simulations of large rivers are re-projected onto the 3 arc second DEM by interpolating between water elevations at the centre of each 30 arc second cell to create a smooth 2D surface of water elevations at 3 arc second resolution.
- Simulations of individual reaches are combined to create a continuous flood hazard map.
- Fluvial / pluvial / coastal simulations can also be merged to create composite flood hazard maps if required.

3.7.8. (4b) Model Validation

The validation of a flood hazard map is challenging as such a map does not attempt to describe any single real event but instead attempts to describe the areas affected by all events of a certain magnitude. However, we can test the following:

1. The underlying methods are sound and robust
2. Generalisations and regional values with local information, where available
3. Compare results with other studies and event data sets

-

Assumptions to test with Validation

The following assumptions will be tested explicitly during the validation:

1. SRTM with correction represents actual topography.
    - Raw random noise error ~5-6 m, resampled to 1km resolution ~0.5 m.
    - Vegetation/urban bias. Assume removable.
2. Regional flow method provides reasonable estimates for ungauged catchments locally.
3. Regional rainfall depth duration relationship is appropriate locally.
4. Hydrosheds drainage network represents actual river network.

-

Validate river network against national network data

The national river network vector data set provided by the Belize Government will be used to check the model river network derived from SRTM topography.

Quality of SRTM corrected DEM

LIDAR (1 m resolution) topography has been obtained from the University of Florida for a 1,200 km^2 region of Western Belize. This will be used to assess whether vegetation bias in SRTM has been usefully reduced by the use of vegetation-type correction factors based on a MODIS VCF data.

Validation of river flows and rainfall

Data was collected from the Belize Government for all available river and met gauging stations. This will be processed to extract rare high magnitude events for extreme value analysis (Figure). The results of this local data analysis will be compared directly to the regional values used in the model at the station locations.

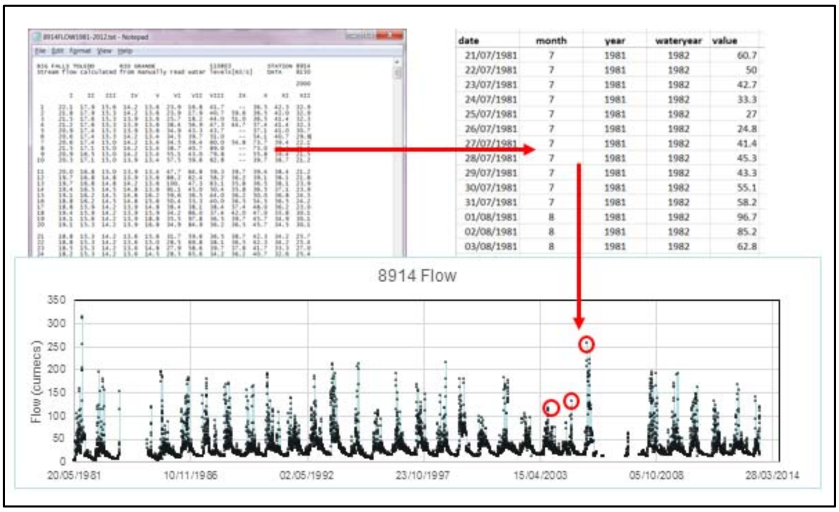

Figure 3.7 - River flow data processing and annual maxima analysis

Comparison to existing flood hazard information

An important part of the validation process is to compare the results of the national flood hazard map (NFHM) to existing data that is available to the Belize Government. This is not just a numerical comparison exercise, but also serves as an important part of the credibility acceptance of the output by the users of the hazard information within the Belize Government. Therefore we have produced draft model output for the Belize Government personnel to comment on and feedback initial thoughts and ideas for the validation phase. This draft output also serves the purpose of preparing the users for the final output and begins the process of thinking about how best to integrate the new hazard information in their work. There are also two primary existing datasets that are available for direct comparison to the draft NFHM (Meerman October 2008 Landsat extent; Kings et al., 1992 – Geomorphological assessment). Comparison maps for these datasets were also provided to the Belize Government and World Bank at the St Vincent Workshop (Figure). While neither dataset is the same as a return period based nationwide hydrodynamic model output, they can still provide valuable information as to what might be expected.

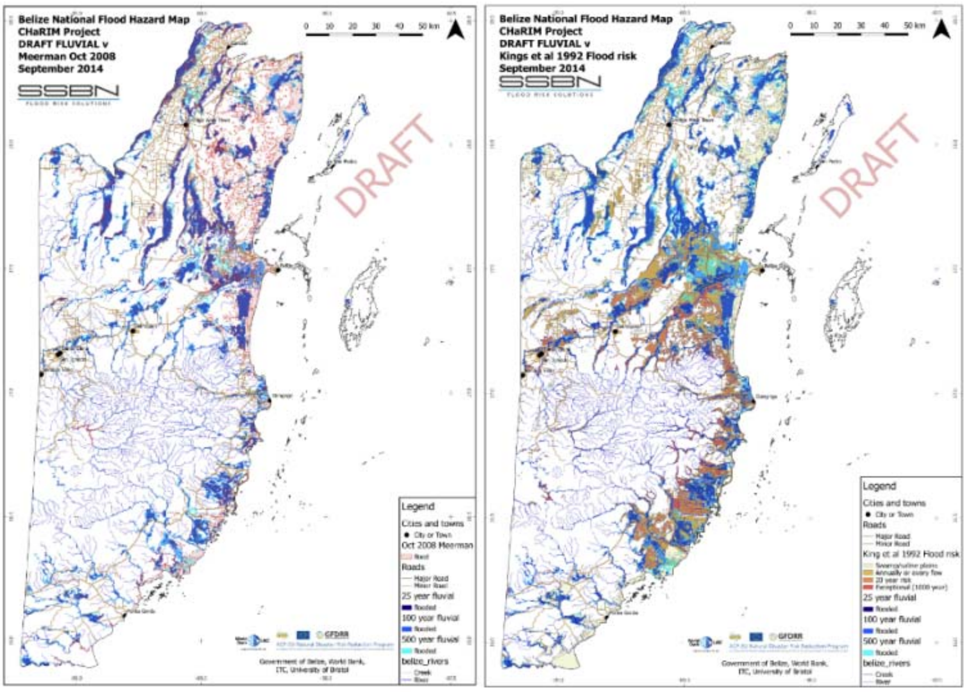

Figure 3.8 - Draft NFHM compared with Oct 2008 Landsat (Meerman) and King et al 1992 study.

3.8. Preliminary Results and Validation

3.8.1. Drafts of fluvial results for feedback

Draft NFHM results in map form were produced for inspection and feedback and were provided to the Belize Government and World Bank at the St Vincent Workshop (September 2014). These were provided in PDF map format shown in Figure .

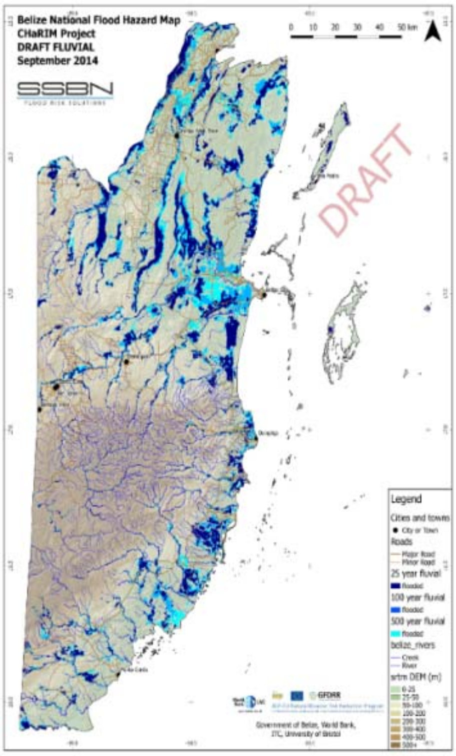

Figure 3.9 – Draft Fluvial Hazard results for Belize.

We are currently providing the latest model results in live interactive web format, URL [mgo.ms/s/73r7n](mgo.ms/s/73r7n) (now including pluvial hazard), see Figure below.

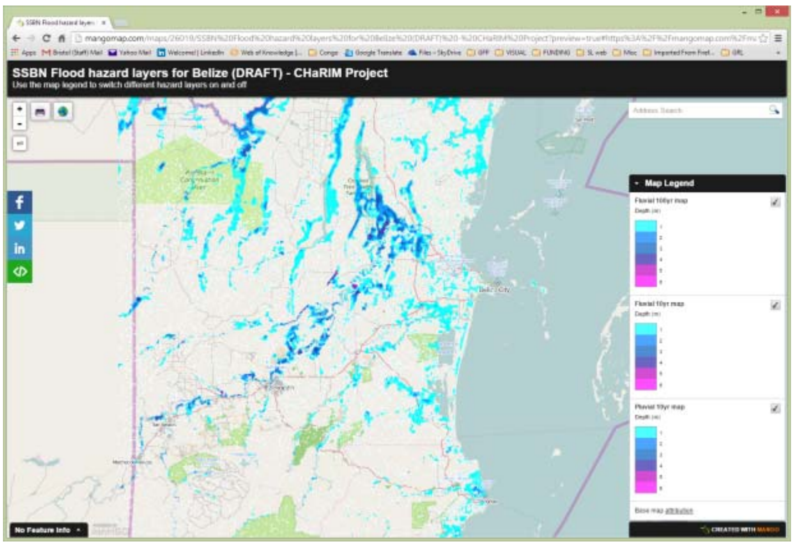

Figure 3.10 – Draft Belize results in live interactive web format

3.8.2. Validation of global model framework

Model Hydraulics and data scarce regions

The University of Bristol Hydrology Group has produced many research papers since Bates et al. 2001, detailing and validating the underlying hydrodynamic model physics. This hydrodynamic approach has been used in UK national assessment incorporated in JFLOW by JBA consultants. There are also extensive published model validations, including the Environment Agency benchmark testing against commercial full shallow water models, August 2013 (http://evidence.environment-agency.gov.uk/FCERM/Libraries/FCERM_Project_Documents/SC120002_Benchmarking_2D_hydraulic_models_Report.sflb.ashx).

A core science research focus of the Hydrology Group at Bristol over the last 5 years is the application of these hydrodynamic methods using globally available datasets in data scarce regions.

SSBN have developed the modelling framework to apply this approach in a practical and rapid manner to anywhere globally by semi-automatically building the model structure. They have also developed the regional approaches to allow flows and rainfalls to be estimated anywhere, for any catchment (Smith et al. in review), and added the pluvial overland flow components (Sampson et al. 2013).

Global model framework

SSBN are in the process of publishing a global validation of their approach against National Flood Hazard Maps developed with LiDAR DEMs with surveyed bathymetry and full engineering modelling frameworks. This comparison explicitly compares the global approach with UK and Canada flood hazard maps (Sampson et al. in preparation).

The global model is shown to capture 2/3 to 3/4 of the area determined to be at risk in the benchmark data without generating excessive false positive predictions. When aggregated to ~1 km, mean absolute error in flooded fraction falls to ~5%. Comparison plots for the Severn and Thames catchments in the UK are shown in Figure and Figure .

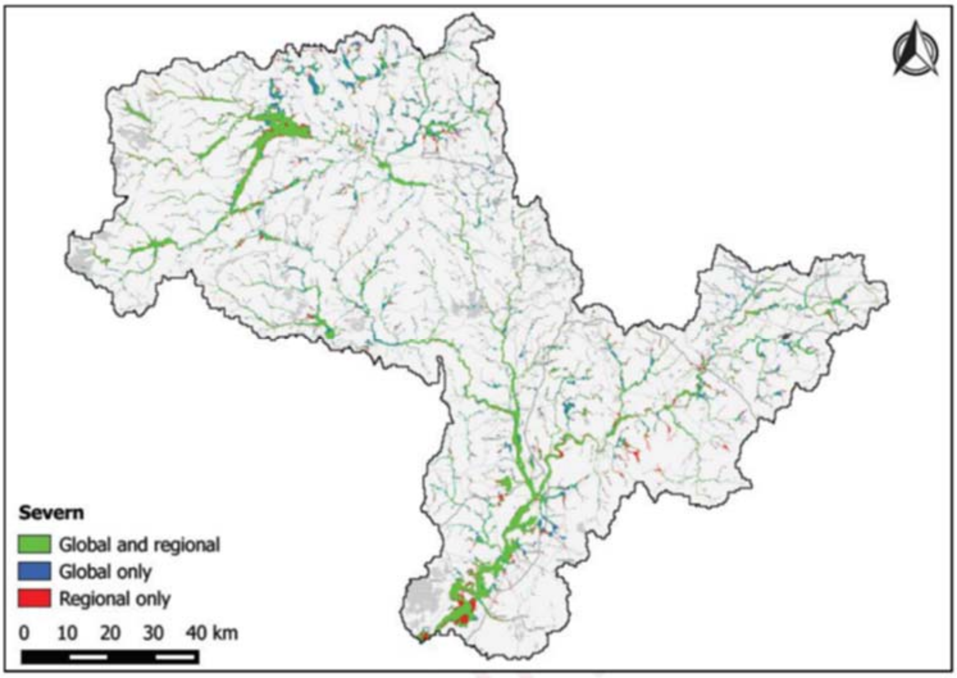

Figure 3.11 – Test of Global model against UK NFHM, Severn catchment

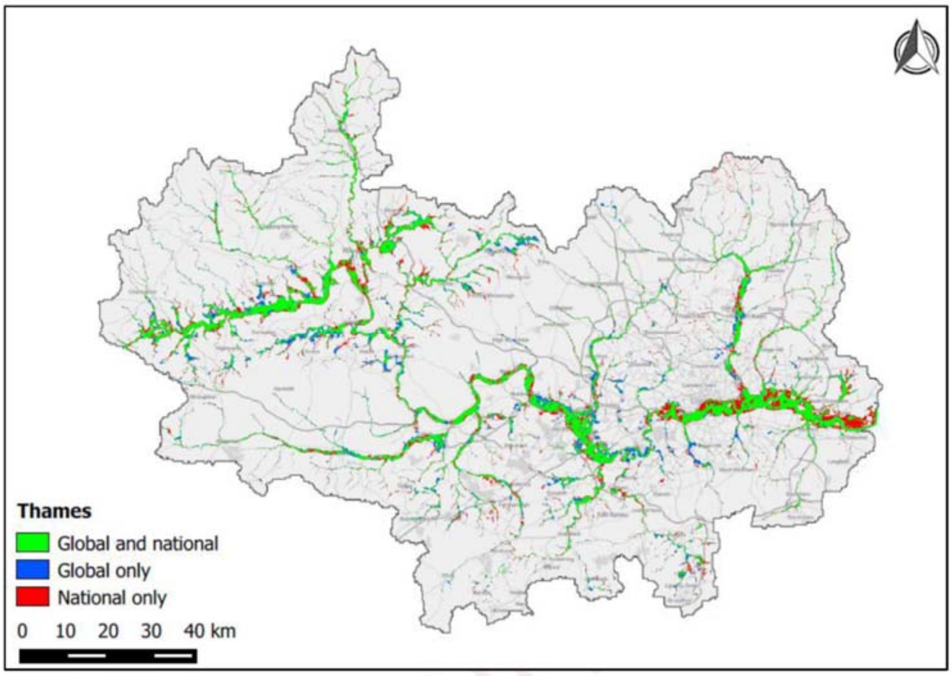

Figure 3.12 – Test of Global model against UK NFHM, Thames catchment

3.8.3. River Network Validation

The Hydrosheds dataset (Lehner et al., 2008) provided the basic river network for the Belize flood model, but as the data is derived from spaceborne radar (SRTM), it is particularly susceptible to errors in dense tropical forest. The Hydrosheds network was therefore manually validated against both the national river data (vector format) and satellite imagery using GIS, and corrections were made where necessary. The network was generally accurate; the most significant error was the connection of the upper half of Monkey River catchment to Deep River (the next river to the south). This was corrected, using the national vector dataset to guide channel location in the forested area.

3.8.4. SRTM Vegetation processing

SRTM is not a bare earth DEM. Where there is vegetation, the radar did not fully penetrate. This means that without extra processing, the SRTM elevations include some of the vegetation height (~50%). We normally process SRTM to remove the vegetation height by removing 50% of the vegetation height as presented in the Simards global vegetation height dataset [*Simard et al., 2011*] after the method developed by *Baugh et al.,[2013]*. However, one of the limitations of this approach is the fact that the actual penetration of the vegetation canopy by the SRTM Radar depends upon the canopy density. Recently Dr O'Loughlin at the University of Bristol has been pioneering a new approach which includes a vegetation density dataset (DiMiceli et al., 2011) to provide this missing information. This allows us to assign a penetration factor (rather than blanket 50%) derived from the relationship between vegetation density (VCF) and ICESat altimetry measurements. We have applied this method in Belize and validated it against the LiDAR data that we have for part of the country. Results are very promising, significantly reducing the vegetation bias in flatter areas. Results are shown in Table 3.4 and Figure 3.1315 & Figure below.

Note that the vegetation correction does not remove the errors that SRTM suffers in steep sloped areas, seen in the residual red and blue in the mountainous areas (opposite sides of the valleys) in the vegetation corrected SRTM comparison in Figure 3.1315b. However, as most of our floodplains are not in these steep terrain sloped areas, these residual errors are not important to the national flood hazard map. The conclusion is that the vegetation correction method employed for Belize significantly improves the resulting bare earth DEM used for the hydrodynamic modelling.

Table 3.4 - Validation statistics for comparison of SRTM with LiDAR data

Comparison metric (units metres)	All elevations	Elevations<100 m
Raw DEM RMSE	17.1	10.1
Veg processed DEM RMSE	9.1	4.7
RAW DEM bias	15.8	9.8
Veg processed DEM bias	0.1	1.16

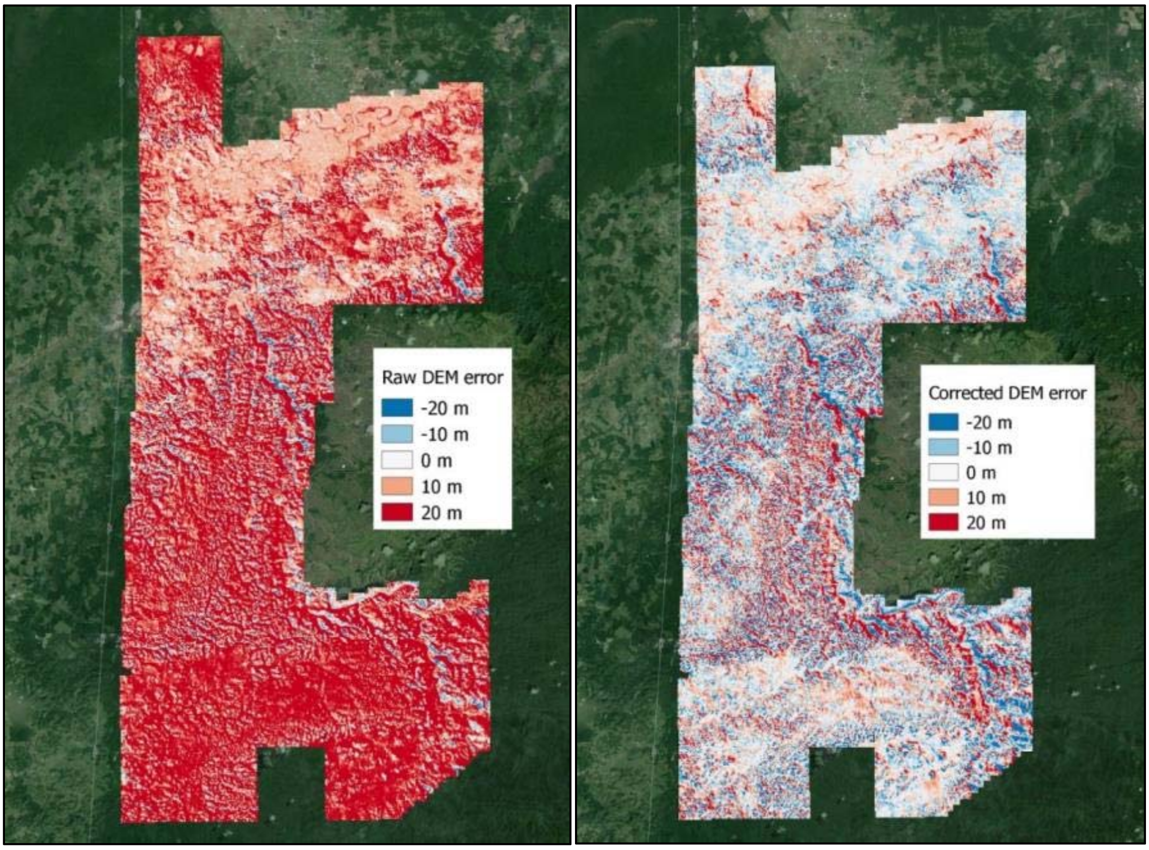

Figure 3.1315 – (a) Comparison of raw SRTM DEM to LiDAR for Western Belize, and (b) comparison of vegetation corrected SRTM with LiDAR

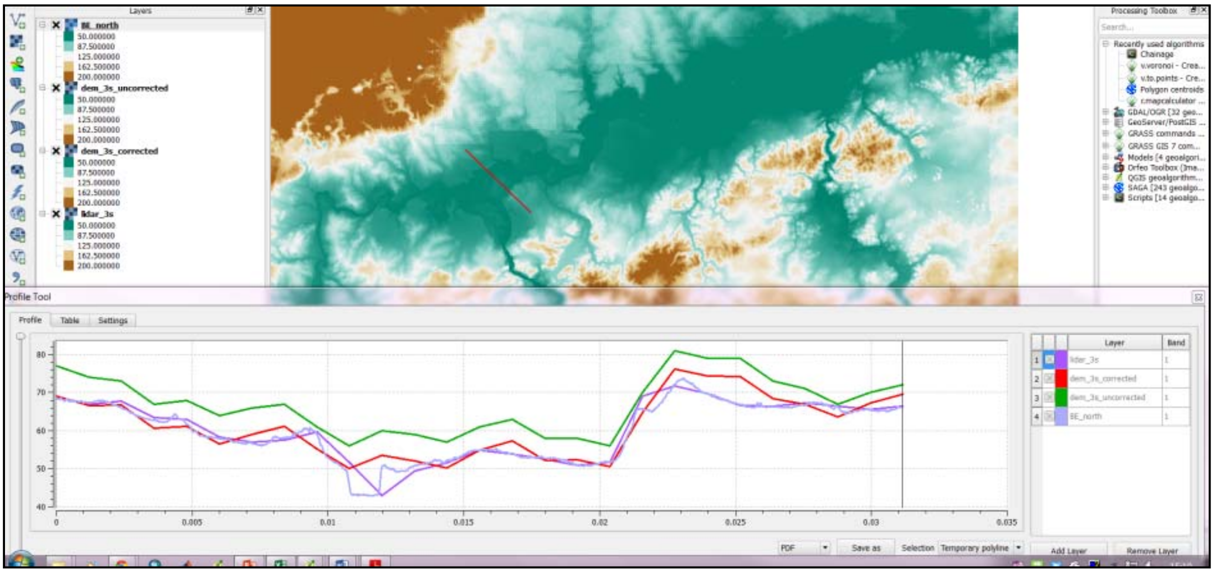

Figure 3.14 - Cross-section through Belize River valley comparing different DEMs

3.8.5. Validation of regional flood frequency analysis (RFFA)

The Regional flood frequency analysis (RFFA) applied by the modelling framework is validated against the discharge data available in Belize. This is undertaken in two stages:

Data was collected from the Belize Government for all available river gauging stations. There were approximately 50 stations with some kind of data (levels/flows/rainfall) from hydro services. Of these only 13 stations had flow data available (Figure). This data was pre-processed to produce time series data for the extraction of Annual Maxima Series. Extreme value analysis is then undertaken with the extracted Annual Maxima for each station to generate flood growth curves.

Assessment of local flow data availability and quality

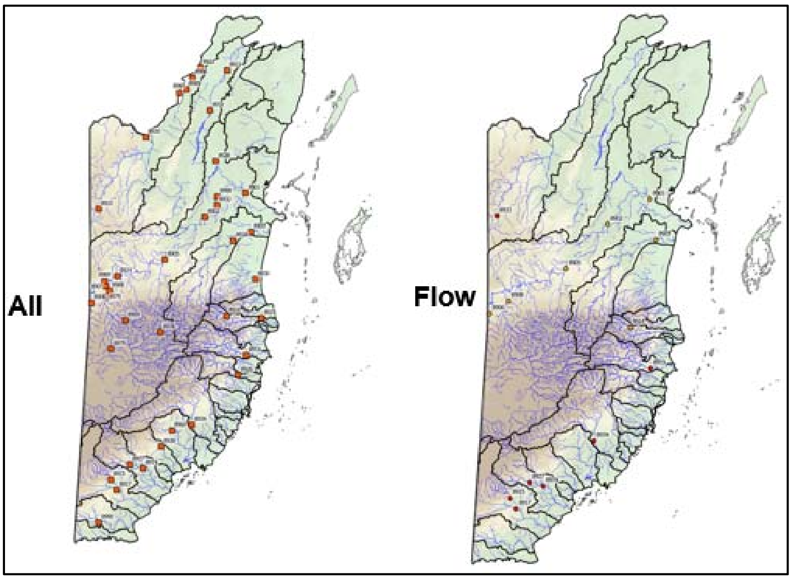

Figure 3.15 - River Gauging stations for Belize and those with flow data

Conclusions

- There are insufficient flow data (number of years or spatial extent) to be used for direct input to national flood hazard assessment.
- For some of the gauges in smaller catchments, the once daily recording interval may “miss” the true peak flows resulting in an underestimation of extreme flows.
- There are some issues with a number of stations with the extreme end of the stage discharge relationship, e.g. overestimates due to influence of bridges and possible underestimates due to bypass flows.
- The data we do have is still useful to ensure the regional curves applied across national scale make sense, by direct comparison of model flows with the gauged data.
- We would recommend a full river gauging station review for extreme flow and high intensity rainfall measurements. The current setup appears to be focused on mean water resources measurement purposes rather than extreme flow recording.
-

Comparison of station growth curves to RFFA

The RFFA is a flood frequency analysis applied to a global dataset; the full methodology is outlined by Smith et al. (2014 in review). The validation procedure compares the flood frequency (FF) relationships defined by the observed data against the FF relationships defined by the RFFA. In addition to the comparison of FF relationships, the observed data will also be analysed to assess its accuracy. This will be undertaken by firstly using expert knowledge to assess whether the recorded extreme flows are realistic, given the specific catchment characteristics. A cross-station comparison will also be undertaken, using stations within the same catchments to draw conclusions as to the accuracy of the observations. For the stations judged to contain reliable discharge data, a comparison of the observed and simulated FF relationships can then be undertaken. This comprised a comparison of the mean annual flood (MAF), FF distribution and the Q100 event (100 year event). Conclusions can then be drawn as to the suitability of using the RFFA to generate flows for the hydrodynamic model of Belize.

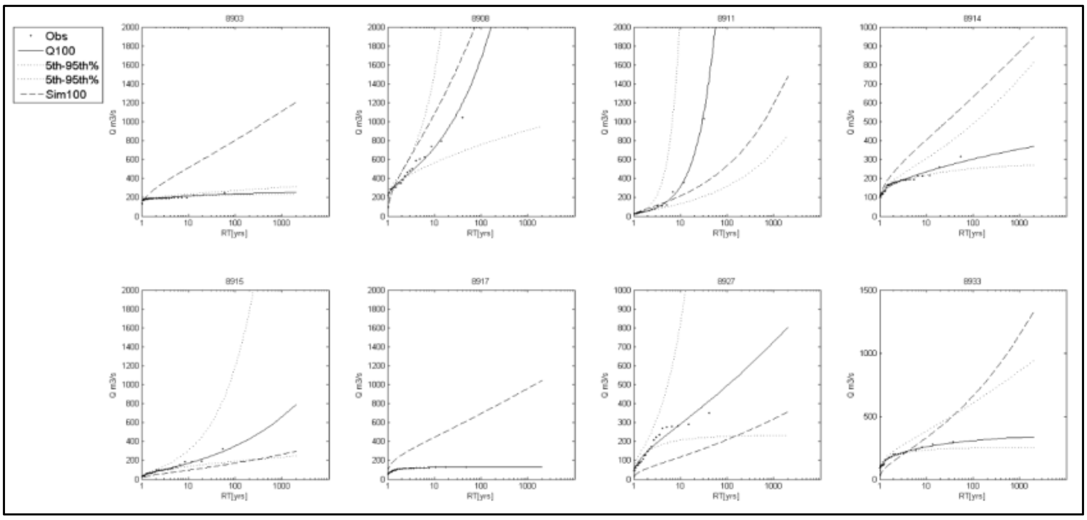

Figure 3.16 - Extreme flow analysis results with Generalised Extreme Value curve fits to Annual Maxima Data for 8 of the Belize flow stations

Initial Results

Flow station comparison results can be divided into three groups.

(1) RFFA is a good fit. The regional curve provides a good fit to measured flows and the derived growth curve. Mainly upper catchment stations.
(2) RFFA higher than measured. This seems to be related to measurement stations with very flat growth curves (unrealistically so – singular matrix issues fitting EVA). Assumption is that station SDE is not calibrated for high flows and therefore not providing a true estimate of out of bank flows due to bypass flow. However, the national model explicitly includes river and topographical storage that would simulate out of bank conditions for these reaches anyway.
(3) RFFA lower than measured. Suspicion of bridge afflux effects on some stations due to shape of growth curve, e.g. Monkey River 10,000 cumecs flow. Physically unfeasible!

We will report on each station in the final report, and provide our interpretation based on what data we have, but we would recommend a full station review, particularly for extreme flows. Our conclusion is that where we have reliable gauged data, the regional approach is providing meaningful estimates of ungauged flows.

3.8.6. Validation of Regional Rainfall IDF values

Estimates of extreme rainfall derived from local data are compared against the estimates produced by the modelling framework. The regionalised Intensity Duration Frequency (IDF) curves used in Belize are also compared to IDF relationships that have been derived in other similar climatic regions.

Assessment of local rainfall data availability and quality

Data was collected from the Belize Government for all available rain gauging stations. A total of approximately 55 stations were provided by the National Met services. Mostly these were data at a daily recording interval. Of these stations, only 7 had any shorter duration intensity data available (Figure). This was for a period in the mid 1980s-2000, but none are currently functional. The longest historical rainfall intensity record was available for the airport with 15.7 years of data (1983-2002), the rest of the stations only have between 11 and 1 years of data. This data was pre-processed to produce time series data for the extraction of maxima recorded rainfall intensities for a range of durations.

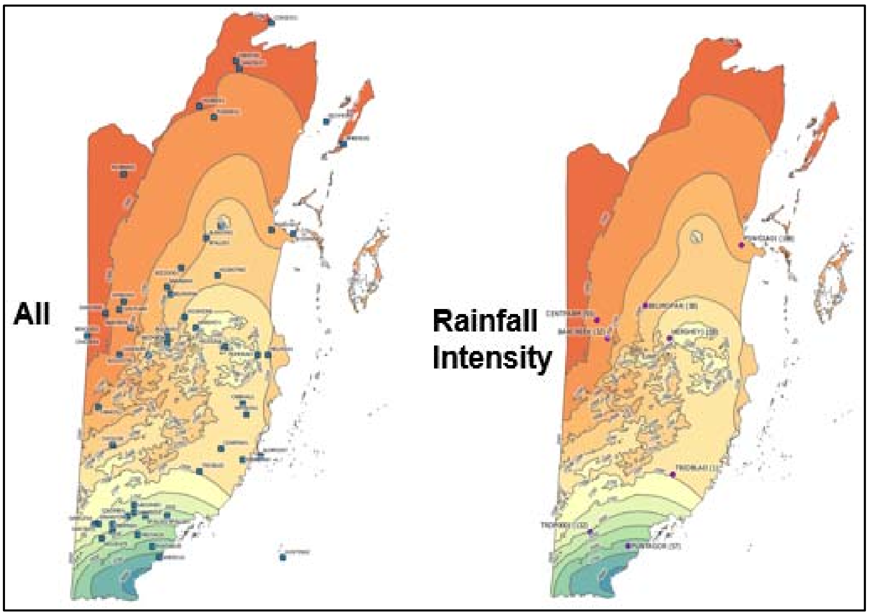

Figure 3.17 - Rainfall Gauges for Belize and those with intensity data

Conclusions

- There is insufficient rainfall intensity data (number of years or spatial extent) to be used for direct input to national flood hazard assessment.
- The data we do have is still useful to ensure the regional IDF curves applied across national scale make sense, by direct comparison of rainfall intensities flows with the gauged data.
- Using relationships from analogue countries may provide a useful approach, especially as we have some evidence from the local data that they may be appropriate.
- We would recommend a long-term reinstatement of rainfall intensity measurement at strategic sites across the country to overcome the data for hazard assessments such as this.

Initial Results

Maximum recorded intensities durations for the available stations are shown in Figure , together with IDF curves for 2, 10, 50 and 100 year return periods for Miami (Climatically similar and similar hurricane incidence). For some of the very short durations, 5 min and 10 min data is lower than expected and does not follow the expected behaviour of higher intensity for shorter duration. On close inspection of the records, this is because the recording device was overwhelmed at these high intensities and therefore missed the very high intensity short duration events. For durations between 15 min and 12 hours, data follows the expected behaviour. However, for most of the stations, the intensities recorded are quite low due to their very short records not capturing enough high intensity events. Only two of the stations appear to have enough data for further investigation. PSWGIA01 and TRDP0001.

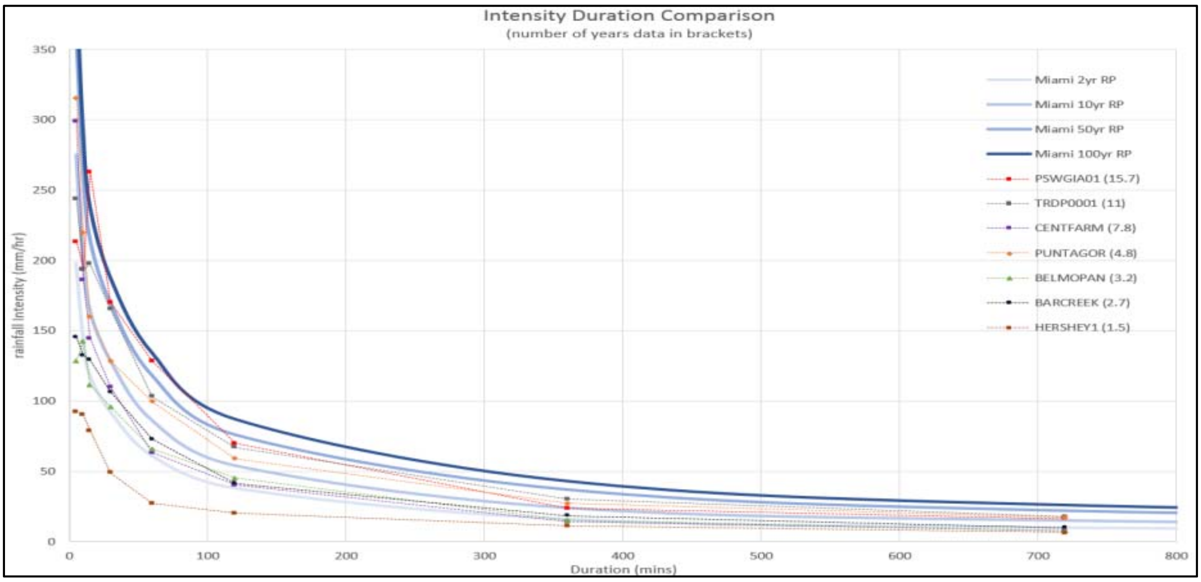

Figure 3.18 - Maximum rainfall intensities measure in Belize at 7 stations compared to Miami IDF relationships

Carrying out extreme value analysis (EVA) on the two stations with the longest time series provides expected intensities for given return periods. The fitted EVA curves show the behaviour of data does not follow expected depth to duration relationships observed globally for durations longer than 60 minutes as shown for the airport station in Figure . This relates to the fact that the longer the duration we need to estimate intensities for, then the longer the record we need for a reliable estimate, i.e. there is a bigger sample of 15 minute durations than there are 12 hour durations in a 10 year record.

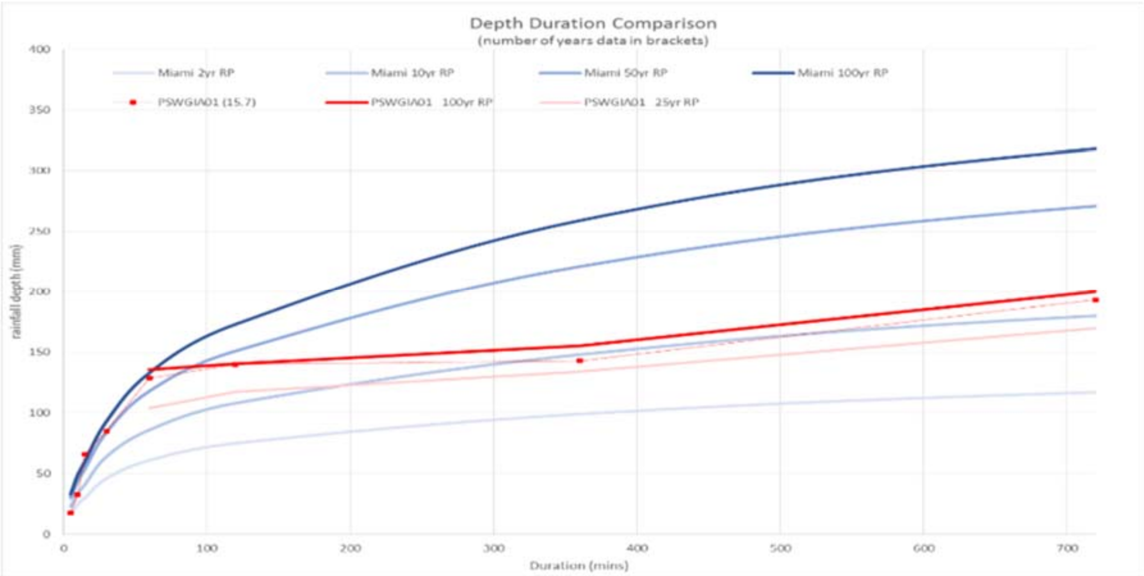

Figure 3.19 – Depth duration comparison for airport station compared with Miami DDF curves.

Comparison of station IDF curves to Regional Model values

We compare the regional rainfall depth values to the two stations (PSWGIA01 and TRDP0001) and Miami for the 60 minute (Figure) and 6 hour duration (Figure 3.2116).

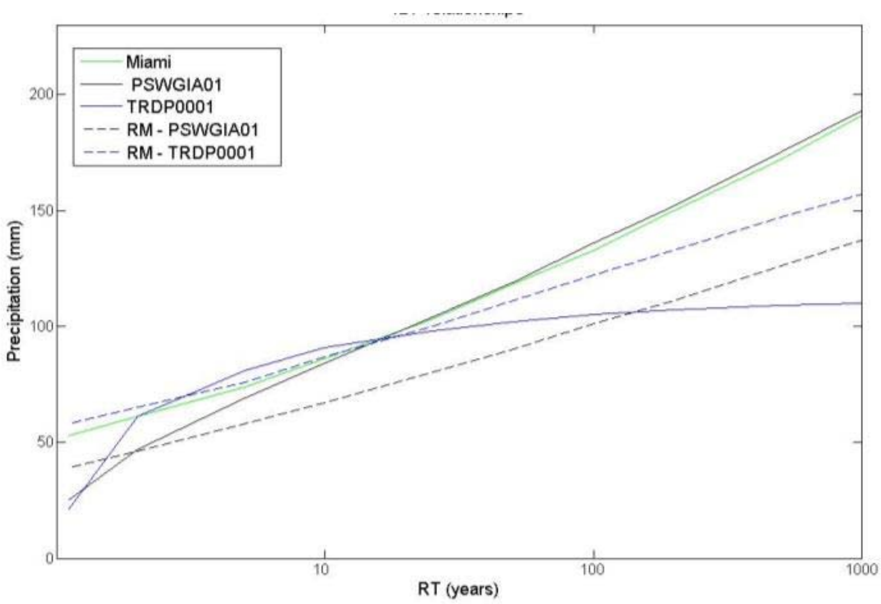

Figure 3.20 - 60 minute duration values for regional model (RM), Belize stations (PSWGIA01 and TRDP0001) and Miami

The Belize Airport gauge data is a good match to Miami for the 60 minute duration for most of the range of return periods. The TRD gauge is a poor fit and shape, probably due to insufficient data to provide robust estimates. Regional model curves are a little lower than Miami.

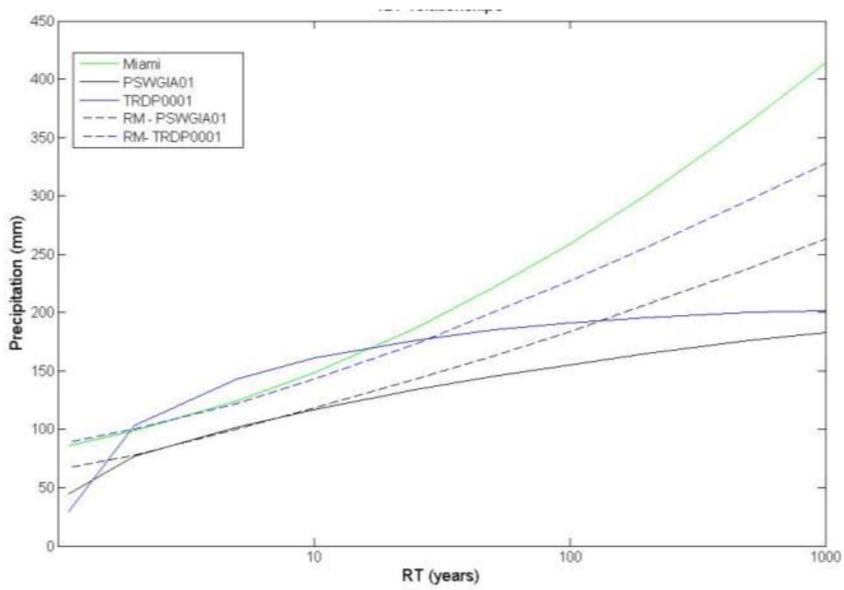

Figure 3.2116 – 6 hour duration values for regional model (RM), Belize stations (PSWGIA01 and TRDP0001) and Miami

The Belize Airport gauge and TRD gauge are a poor fit and shape to Miami for the 6 hour duration, probably due to insufficient data to provide robust estimates. Regional model curves again are a little lower than Miami.

Our conclusion is that the Miami IDF curves are a good proxy for Belize and that our regional curves need to be adjusted upwards slightly to match this higher intensity in the model.

3.8.7. Comparison with existing flood information

Comparison of the draft fluvial results was undertaken with the flood extent derived from a Landsat image of the October 2008 event by Meerman. This shows broadly similar inland flood areas to the draft NFHM. The NFHM does not show all of the same coastal inundation that was experienced in the event but the draft output is for fluvial hazard only, so would not be expected to show this. There is also some concern that vegetation will mask some of the flood extent on the Landsat image, therefore underestimating the actual flood extent. Never-the-less, it provides a valuable dataset to compare to.

The King et al 1992 study, contains an element of flood risk information based on a geomorphological assessment of rivers and floodplains. The actual methods used, criteria applied, as well as metadata regarding the final categories, is not available. However, we can assume that site visits were undertaken across wide parts of the country that probably identified flood deposits and erosions evidence to infer historically active floodplain areas. This of course will overestimate the current risk as it will include all geologically historical events rather than what is possible now, given the current terrain etc. It is a useful dataset with which to understand the river systems. Again the draft NFHM compares reasonably well and identifies similar areas at risk. The King et al study tends to show wider areas at risk, but this is likely to be due to the broader geomorphologically based definition of risk used.

3.9.Results Output: Format, limitations and sensitivity

3.9.1. Return periods/categories

The modelling framework allows hazard output from 2 to 1000 year return periods. Currently planned output will be at 10, 25, 50, 100, 250, 500, 1000 year RP. Feedback from the World Bank is that we should stick to a return period definition rather than the strictly more correct annual exceedance probability for simplicity. Feedback from the Belize Government indicates that for planning purposes, it would be easier to incorporate a low, medium and high hazard categorisation.

3.9.2. Definition of scenarios and meaningfulness of statistics

There is a large uncertainty in flows and DEM without good local data, and even with good local data, there are still huge uncertainties above 25 year return period. Uncertainty increases with increasing return period. Results from a range of return periods can provide a sense of how sensitive the results are, by showing where there are threshold changes and where large areas may be exposed at higher return periods (Figure), we just can't be exactly sure it will be at that particular return period.

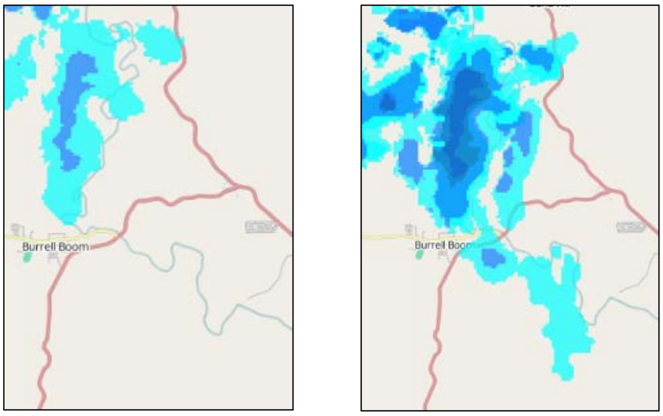

Figure 3.22 – examples 10 year RP and 100 year RP flood extents indicating a threshold change in flood across the road area.

3.9.3. Limitations

The SRTM DEM representation of the topography is one of the biggest limitations for the Belize hazard map. Whilst we get reasonable results at the national scale, this coarse scale DEM prevents a more detailed scale of application. Given the scale of DEM and modelling, we suggest a scale limit of not less than 1 km^2.

Uncertainty in ungauged flow inputs is a limitation of the regional modelling approach. This will be tested with an explicit sensitivity test given the known uncertainty in the regional approach.

The Belize hazard maps will not include extreme flood risk due to dam failure. From previous reports and our understanding of extreme events in Belize, this risk should not be underestimated for the three hydroelectric dams on the Macal River.

For the coastal hazard, the spatial variation of storm surge amplitude may be too simple. In addition, the results of the coastal hazard modelling will be particularly sensitive to SRTM errors as it is mainly flat vegetated coastline.

3.9.4. Modelling approach to structures

Some structures/constructs with a topographical component may be implicitly incorporated in the DEM, e.g. large embankments.

Capacity of culverts and bridges is assumed to be the same as bank full capacity of the watercourse that is being crossed, i.e. allows stream capacity flow through embankments. Otherwise not explicitly included, as this would require considerable topographical survey detail to build correctly into the model. It would also rely on the surveyed detail to be to the same datum as the SRTM DEM.

For dams, we have no knowledge of the operating rules and assume they are full in extreme events. Therefore, they will overflow as if they are contain no storage.

In the global methodology, flood defences are automatically added to the model based on the assumption that NASA nightlights dataset is an indication of assets requiring protection. This may not be the case in developing countries and given the low light intensities in Belize, this is not activated in the model. We have also not received any explicit information regarding, or observed, of any flood defences in Belize.

3.9.5. Sensitivity/uncertainty Analysis

A sensitivity analysis will be conducted on the flood modelling framework used to derive the national scale flood hazard maps. The analysis was conducted by varying the fluvial river flows that are generated for the regional flood frequency analysis (RFFA); aside from the uncertainty in the terrain data, which cannot be overcome at this stage, the estimation of extreme discharge values represents one of the primary sources of uncertainty in the modelling framework. The RFFA used to drive the model was described by Smith et al. (in review). Along with the method for deriving extreme discharge, the paper also presented the standard errors found when applying the RFFA to estimate extreme discharge across a number of climate zones. For tropical climates, such as in Belize, the standard error found in the 100 year event was around 70%. Therefore, a sensitivity analysis will be applied be vary the estimate 100 year flows by -70 and +70%. The implications of the uncertainty in discharge estimation can then be explicitly explored.

3.10. References

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4. Proposed method for national-scale landslide hazard mapping

The aim of this report is to present the proposed methodology for the landslide susceptibility and hazard assessment for the 4 island countries (Dominica, Saint Lucia, Saint Vincent and Grenada).
It will do so by first discussing the criteria for selecting the method used, then by presenting the landslide inventory data which is essential for assessing the landslide susceptibility, followed by a discussion on the factor maps used for the susceptibility assessment, and finally the analysis method for the susceptibility and hazard assessments. The susceptibility and hazard assessment methods will be different for landslides occurring along the main road network, and for those occurring in the rest of the area. The report will end by discussing the critical points in relation to the available data and suggestions for additional data collection.
It is important to state here that the assignment for the national scale landslide hazard maps was based on the use of existing data, with only limited possibilities for additional data collection. Nevertheless efforts have been made in collecting new data, focusing mainly on landslide inventories, and not on the generation of new factor maps (as this would require substantial efforts in data collection that were not foreseen in the TOR). Landslide inventories were generated for Saint Lucia and Grenada by the British geological survey, as part of a contract between the World Bank and the European Space Agency (which focused on the use of European satellite data from 2010 or later). Also landslide inventories were generated by MSc students involved in the project, focusing on road related landslides for Saint Lucia and Dominica, and on image interpretation of landslides in other locations in saint Vincent and Dominica.

4.1. Definitions

The terminology used in this report follows that of the Guidelines for landslide susceptibility, hazard and risk assessment and zoning, produced as Deliverable D2.4 of the EU FP7 Research Project SAFELAND, Living with landslide risk in Europe: Assessment, effects of global change, and risk management strategies, which can be accessed through: http://www.safeland-fp7.eu/results/Documents/D2.4.pdf The guidelines were also published as:

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

This study was based on a number of sources, among which Fell et al (2008), TC32, UN-ISDR (2004):

For this project 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.

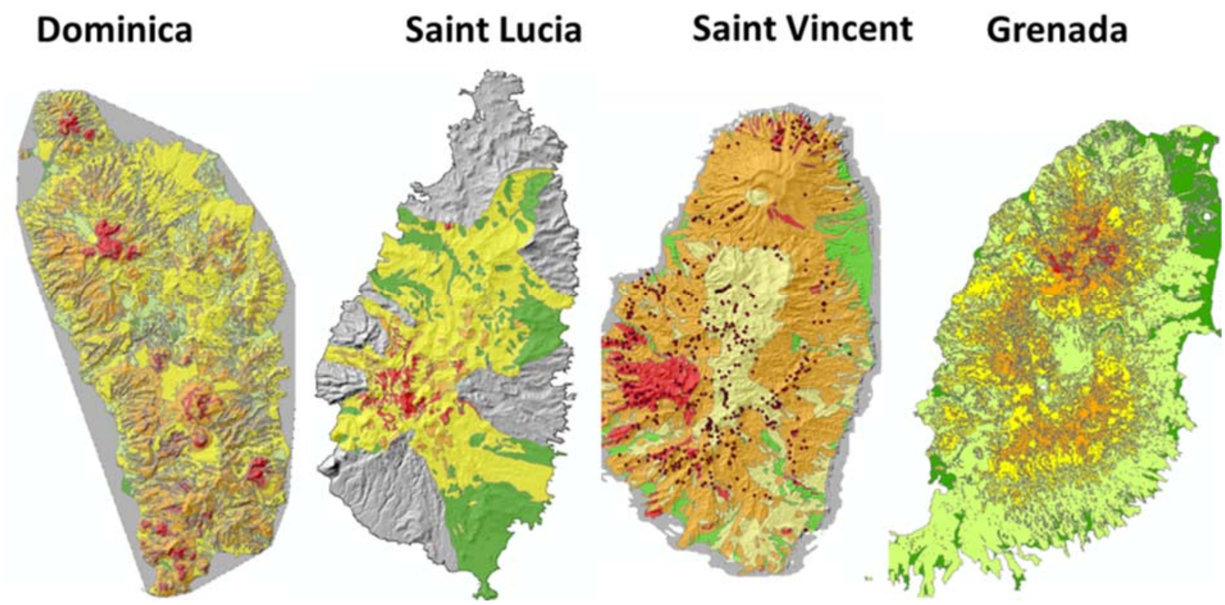

Figure 4.1: Available landslide susceptibility maps for the four island countries generated in previous projects. Dominica: study carried out by CIPA for USAID in 2006, as part of a multi-hazard mapping project. Saint Lucia: debrisflow susceptibility map generated by C. Rogers in 1995. Saint Vincent: Susceptibility map generated by DeGraff in 1988; Grenada: susceptibility map generated in 2006 for CDB and CDERA. All maps are qualitative susceptibility maps, generated with limited landslide inventories using a weighted approach, with the same types of factor maps.

4.1.1. Reflection on the definitions in relation to the objectives

Based on these definitions and the situation in the four island countries, the methodology should lead to landslide susceptibility maps at the national scale, which might not be actual landslide hazard maps according to the above definitions. It is questionable whether it would be possible to represent spatial, temporal, size and run-out probability for landslides for an entire island at a scale of around 50.000.
However, we would like to go a step further then the available national scale susceptibility maps for the four islands (See Figure 4.1).

At a national scale it may be more logical to aim at 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 would be 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.

4.2. Criteria for selection the proposed method

In order to determine the optimal method used for the national scale landslide susceptibility/hazard maps for the four Caribbean island countries we first need to look at a number of criteria. These criteria are displayed in Fig. 4.2, and are discussed in this section.

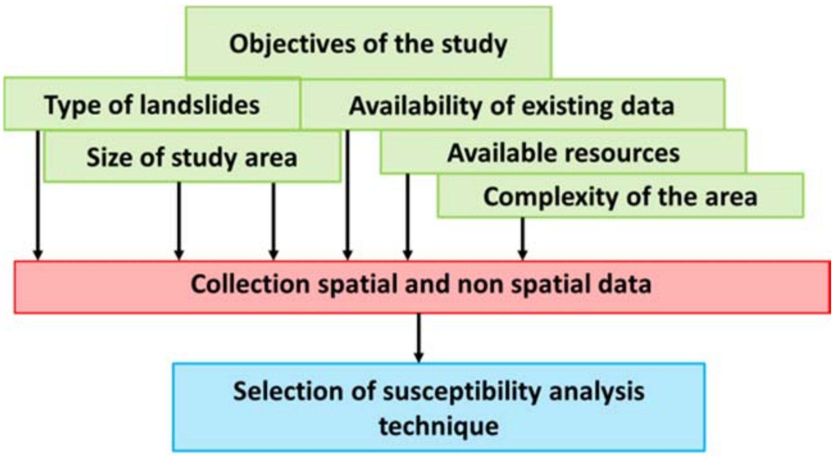

Figure 4.2: Criteria that determine the selection of the optimal landslide susceptibility method for the national scale in the four Caribbean island countries.

These criteria are interrelated, as one criterion also determines other. For instance the objective of the study will determine the scale and the size of the study area.

4.2.1. Scales of analysis

Landslide susceptibility assessment can be performed at different scales. For this project the following scales of analysis are considered:

- National scale : 1:50.000. Given the relatively small size of the islands this is in fact considered as a medium scale in other studies.

- Local scale: 1:10.000.
- Site investigation scale: >1: 5.000

Scale in this context refers to the end products (maps) that we will produce for the end-users. And the scale is also determined by the scale of the input data that is used in the analysis. The notion of scale is a bit less relevant when working with GIS, as it is more relevant to evaluate the spatial resolution of the data that will be used in the analysis.
We propose the following spatial resolutions:

- National scale: 5 meter pixelsize. This results in the following sizes of the input (raster) maps

Country	Rows	Columns
Dominica	9583	5347
Saint Lucia	8921	4455
Saint Vincent	6100	4556
Grenada	5540	4554

- Local scale: 1 meter pixelsize
- Site investigation scale: 1 meter pixelsize.

The four Caribbean countries are all relatively small in size, ranging from 306 km2 (Grenada) to 754 km2 (Dominica). In comparison to other countries this is actually very small for a national scale assessment and would be comparable to a regional scale assessment for other countries. This means that it is possible to collect information at scale ranging from 1:25.000 – 1:50.000. An advantage of the relative small size is that the individual islands can be captured mostly within a single frame of a high resolution satellite image, although several images are generally needed to cover an island due to the constant cloudiness in the elevated centres' of the islands.
For the national scale hazard maps it was decided to focus on the main islands, and exclude the other small islands that are part of the countries of Saint Vincent and the Grenadines and Grenada. The Bequia Island, located near St. Vincent. has significant coastal erosion problems. However, we do not include this in the study.

4.2.2. Objectives of the study

First of all the objectives of the study are quite important for selecting the best method. The national scale susceptibility maps are intended as baseline studies covering the entire territory of the islands.

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Such national scale maps are intended to be used by the governments to:

- Include them as a factor in national scale land use planning, by outlining the zones that are most susceptible to landslides;
- Include them as a factor in local development planning;
- Include them as a basis for restrictive zoning as a basis for building control, together with other hazard maps;
- Identify the areas where more detailed investigations are required for the planning of critical infrastructure;
- Form the basis for identification of the strategies to make the national road network more resilient;
- Be used as the basis for a national scale multi-hazard risk assessment, by integrating these with hazard maps from other types of hazards (e.g. flooding, windstorms, coastal hazards, volcanic, and earthquake) in combination with asset information (e.g. building exposure, or community vulnerability assessment in combination with census data aggregated by enumeration district).
- Be used as a risk communication tool for the local population;

Table 4.1 gives an overview of the objectives for the three scales outlined above.

With respect to the required contents of such national scale maps, the following information should be obtained from them:

- Landslide inventories. The locations that have been affected by landslides in the past. Specifically it is important to indicate this for triggering events with different magnitudes, so they can get an idea on:
    - The locations that had landslides during major triggering events, such as a hurricane or storm, which we would identify as a worst case scenario, characterized by a rare event when a hurricane or tropical storms fully hits the island.
    - The locations that have been affected by minor events , which are generally less severe tropical storms, or storms passing further from the islands, and also intensive rainfall events that occur outside of the actual hurricane season.
- Zones where landslides have a higher chance of occurrence in future events, characterized by the:
    - Density of landslides that are expected for
    - Triggering events with different return periods. These return periods should be obtained from the available rainfall records, which are correlated with known landslide events;
- Zones which may be affected by the run-out of landslides and debrisflows in future events.
- Road segments of the national primary road network that have been affected by landslides in the past, indicating the density of landslides that might be expected.

Table 4.1: Characteristics of the 4 islands relevant for the landslide susceptibility assessment

Scale	Indicative range of scale	Objectives
National	1:25.000 – 1:50.000	Baseline information Public awareness and risk communication Policy support: national land use policies Prioritization of regions Analysis of triggering events Implementation of national programme Strategic environmental assessment Insurance Land use zoning
Local	1:25,000 to 1:5,000	Detailed land use zoning, Restrictive zoning Planning of critical infrastructure Early warning system (based on rainfall thresholds) Environmental Impact Assessment
Site-specific	> 1:5,000	Design of risk reduction measures Early warning systems (movement related)

4.2.3. Complexity of the study areas

The islands also have a relatively small population, ranging from 72,000 (Dominica) to 182,000 (Saint Lucia). The population is concentrated mostly along the coast, due to the steep centres of the islands.

Therefore the population density figures in Table 4.2 are not representative for the actual settlement areas. The urban centres in most of the countries are relatively poor developed, with many unused buildings. Development of residential areas takes place in the hills surrounding the capitals, which lead to building constructions in landslide prone areas. Since building control is relatively weak or absent, there is no consideration of optimal sites for construction with respect to natural hazard avoidance. The islands have road networks that have very limited redundancies. Primary road networks generally follow the coastlines, passing a number of flood and debris flow prone gulleys, and passing stretches below steep cliffs next to the coast line. Some stretches that pass the higher parts of the islands (e.g. Dennery to Castries in Saint Lucia, Airport road in Dominica) are specifically landslide prone.
All island are volcanic origin with a series of volcanos in the centre part of the island, some of which are considered active (especially Sourfriere volcano in Saint Vincent, and 9 in Dominica). Soufriere volcano in Saint Vincent has produced a series of volcanic debrisflows in historic times. The submarine Kick-em-Jenny volcano, north of Grenada has produced several tsunamis in historic times.

Table 4.2: Characteristics of the 4 islands relevant for the landslide susceptibility assessment

	Dominica	**Saint Lucia**	**St. Vincent and the Grenadines**	**Grenada**
Surface Area	754 km^2	617 km^2	390 km^2 Saint Vincent: 342.7 km^2 Bequia: 17.00 km^2 Union Island: 7 km^2 Mustique: 5.70 km^2 The other 28 islands are smaller than 1.5 km^2	348.5 km^2 Grenada main island: 306 km^2, Carriacou : 34 km2 Petit Martinique: 2.37 km2 Ronde island: 2.07 km2 the other 15 islands are smaller than 1 km2
Coastline	148 km	158 km	84 km	121 km
Terrain	Rugged mountains of volcanic origin, 9 potentially active volcanos. Max. elevation: 1,447 m	Volcanic and mountainous with some broad, fertile valleys. Max. elevation: 950 m	Volcanic, mountainous. Max. elevation: 1,234 m	Volcanic in origin with central mountains. Max elevation: 840 m
Volcanic activity	9 potentially active volcanos. Seismic swarms in South of the island	Qualibou volcano is potentially active	Active volcano Soufriere in the north of the island.	Mt saint Catherine is considered potentially active. Kick-ém-Jenny is an active submarine volcano near North which has produced tsunamis.
Economy	(Eco) tourism, bananas, other agricultural products Export: 37 M US$ Import: 220 M US$ Debt: 379 M US$ 70% of GDP	Tourism, bananas, other agricultural products Export: 175 M US$ Import: 670 M US$ Debt: 1,062 M US$	Tourism, significant clandestine marihuana trade. Export: 45 M US$ Import: 360 M US$ Debt: 533 M US$	Tourism, spices, agricultural products Export:35 M US$ Import: 345 M US$ Debt: 894 M US$
Road network	Complex network , partly circular, partly crossing. Few very import5ant stretches	Limited to no redundancy, circular network	No circular network. Leeward ad windward road.	More redundancy in the road network. Circular roads and roads crossing the island.
Population	72,301 (2014)	182,273 (2013).	105,897 Of which > 100,000 on main island	109,373 Of which 100,930 on main island
Population density	105/km2	294/km2	307 km2	313 km2

The geology of the islands 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 in any of the islands. As can be seen in Figure 4.3 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 (See Figure 4.3). These deposits may sustain near vertical road cuts which are stable, however, when future weathering is taken into account such road cuts may cause problems in future.
The large heterogeneity of volcanic deposits is unfortunately not portrayed in the available maps for the islands. The geological maps are rather general and do not focus on the specific volcanic deposits (See for example Figure 4.4). The soil maps are more detailed and show a large differentiation, but they are focusing on pedologic soil characteristics for agriculture purposes.

Figure 4.3: Examples of outcrops in volcanic deposits indicating that the differentiation between rocks and soils is often arbitrary due to the relative degree of consolidation of the volcanic deposits, their heterogeneity and the effect of weathering.

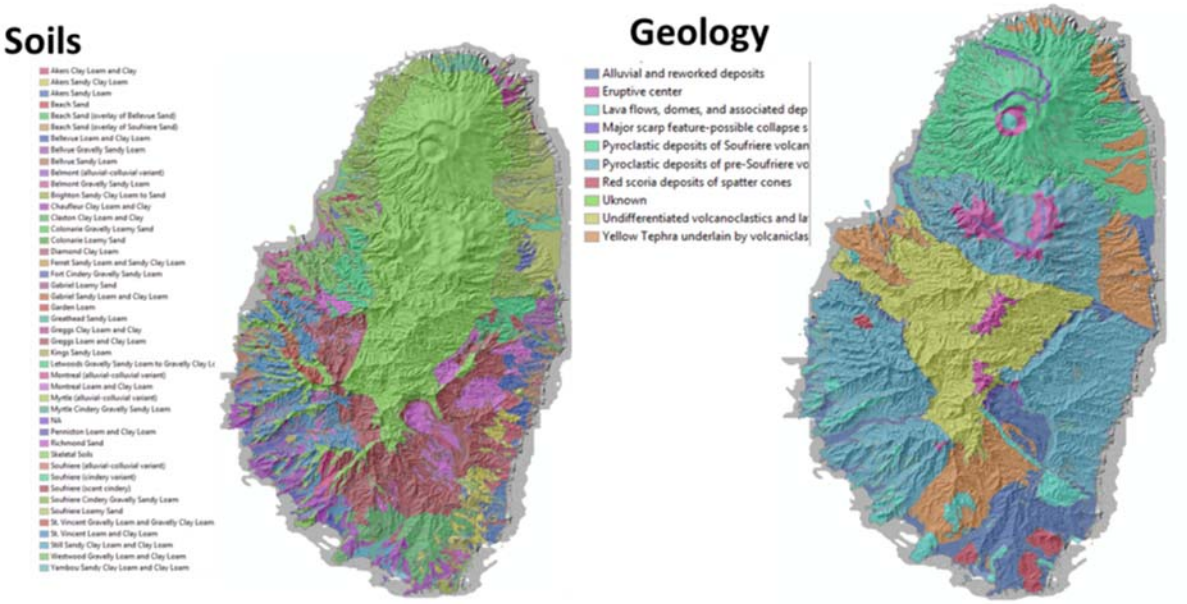


Figure 4.4: Examples of soil and geological maps for one of the islands (Saint Vincent). The soil maps focus on the upper decimetres and are intended for agricultural applications. They do not descrie the volcanic origin of the soils and do not contain related geotechnical information or information on soil depth. The geological maps are rather general, and do not differentiate between the various volcanic deposits.

4.2.4. Landslide characteristics

The landslides in the islands are predominantly shallow soil slides and flow slides, which may turn into debrisflows, or hyper concentrated flows that affect buildings and bridges located in the rover channels. Landslides occur mostly in the soil cover, which is of varying thickness, and doesn't seem to be related to one particular type of soil. Landslides may occur in different land cover types, and also landslides occurring in tropical forests or plantation areas are quite common in the area. Most of the landslides seem to be first time failures, and relatively few are reactivations of older landslides.
Although the main type of landslide is shallow soil slides, rock falls are also quite common along the steep cliffs and may affect roads in several of the islands (e.g. Stowe area in Dominica). Deep seated landslides are relatively rare. One of the most spectacular ones is located in Dominica (See Figure 4.5).

Due to the tropical climate the vegetation recovery within the areas affected by landslides is extremely fast. For instance, the landslide that killed one person in a relocated settlement in Manning village in December 2013, was already completely vegetated by September 2014. This forms one of the major obstacles in the landslide inventory mapping from images. Unless the images are taken within a few months after the triggering event, it becomes very difficult to recognize them as such.
Landslides are very common along the road network (See Figure 4.7). They are in most of the cases related to failures upslope of the road with landslide materials covering the road. However, also quite some examples are found where landslide occurs below the road, due to poor drainage, and where roads are undercut by landslides. There are relatively few examples where the road is on an active moving landslide (most examples are found along the airport road in Dominica).

It is important to carry out an extensive analysis of the various landslide types. Table 4.3 gives an overview based on the available inventories that have a classification of landslide types.

Figure 4.5: Several landslide examples that have caused destruction in the target countries. Upper left: A landslide at Rose Bank on South Leeward island in St. Vincent and the Grenadines; Upper right: Deep-seated landslide which caused the damming of Mathieu river in Dominica, leading to a devastating debris flow in 2011 along Layou River. Lower Left: Shallow flow slide killing a family and obstructing the road along the leeward road in Saint Vincent. Lower right: Debris flow at Fond St. Jacques during Hurricane Tomas in 2010.

Figure 4.6: Google Earth image showing the large landslide on the confluence of Mathieu River and Layou River in Dominica that created a dammed lake which broke out catastrophically later.

Figure 4.7: Examples of landslide problems along the road corridors. Upper left: A landslide at the tunnel entrance in St. George, Grenada that happened 21/9/2014. Upper right: A landslide affecting the road from Roseau to the airport, Dominica. Lower Left: Landslide that destroyed primary road in Belmont area, Saint Vincent. Lower Right: Rockfall in road to Stowe, Dominica

Table 4.3: Summary of landslide types from available landslide inventories.

SlideType	*Dominica*	*Saint Lucia*	*Saint Vincent*	*Grenada*
Debris Flow	*484*	*619*	*90*	*3*
Debris Slide	*318*	*28*	*45*	*35*
Earthflow	*-*	*41*	*-*	*-*
Rockfall	*8*	*22*	*5*	*35*
RockSlide	*-*	*-*	*52*	*43*

Note: these data are derived from available landslide inventories. Within this project ITC has generated a series of new landslide inventories with many more landslides.

4.2.5. Available data and resources

As this national hazard assessment component under the CHARIM project is to be carried out primarily with existing data, with only relatively small resources for additional data collection, the available data is one of the most important factors that will determine the method for susceptibility and hazard assessment used.

Therefore the last criteria that will be discussed here relates to the available data in terms of:

- Landslide inventory data;
- Triggering events;
- Factor maps.

The number and quality of the available landslide inventory maps is perhaps the most crucial factor that determines the method of analysis. If sufficient landslide inventories are available the analysis could be carried out primarily using statistical methods. Chapter 5 focuses on the analysis of the available landslide inventories. As we will see there is a large difference between the 4 countries.

Saint Lucia has by far the largest number of inventories, both for road related landslides as well as for inventories for the whole country. Grenada has only one inventory. Here we will have to complement the inventory by analysing possible old landslides through interpretation of the LIDAR hillshading image. We will also use older satellite images that were available after Hurricane Ivan in 2004 to map landslides caused by this event. This will not allow us to characterize the triggering event, and we will not be able to generate event-based landslide inventory maps. This means in the susceptibility assessment we have to rely more on expert opinion and estimations.

It is also important if inventories from different triggering events are available, because then it is possible to characterize the susceptibility classes with the expected landslide densities that could occur with triggering events with different return periods. Ideally we would like to have a worst case scenario for each of the island: what would happen in terms of landslide density if the island would be hit by a major hurricane or tropical storm. In the next chapter we will analyse the available data for the triggering events, based on collection of disaster events per island for the past 150 years. In this chapter we will also analyse the available rainfall data. If rainfall data covers a substantially large period of time during which these major triggering events have occurred, we can use the data to calculate the return periods. Also the spatial distribution of the rainfall stations is important in order to model the spatial distribution of rainfall during these triggering events. The distribution with different altitude zones on the leeward and windward sides are also very important for analysing the relation between landslide distributions and rainfall distributions.

Later on we will also make an evaluation of the available factor maps for landslide susceptibility assessment. Here we are faced with several problems, related to the spatial, thematic and temporal accuracy of the data. Spatial accuracy is a major problem for several of the islands, as many of the available factor maps do not spatially match, due to differences in coordinate systems, and the fact that the conversion factors for some of the coordinate systems are not well defined. Therefore it was difficult to overlay the data with the satellite images that we obtained, but also several of the factor maps from the same country provided by different organizations had severe problems in spatial matching. Another aspect related to spatial accuracy is the large variation in mapping scale of the input data. Some of the data was obviously digitized from very general base maps, where others are much more detailed.
Thematic accuracy relates to the accuracy of the content of the factor maps. From our analysis it became clear that several of the critical layers for landslide susceptibility assessment are very general. For instance lithological maps are generally very general, and lack the detail that would be required to match the landslides with specific volcanic deposits. The same is true for the available soil maps, which are generally almost useless as a factor map for the slope stability assessment. Also Digital Elevation Models are quite different in quality. Some of the DEMs seem to have been derived from other products, with strange artefacts and angular contour lines, as was the case for the DEM in Saint Lucia.

Finally also the temporal accuracy is a point, specifically for the land cover maps, which are generally rather old, and should be updated. Fortunately we can make use of the updated and more detailed land cover maps that are provided by the British Geological Survey.

4.3. Landslide triggering characteristics

One of the key factors for the generation of landslide susceptibility and hazard maps is information on when landslides occurred in the past, and by which triggering events. For the four islands intense rainfall events are considered the most important triggering events. Even though there might be earthquakes occurring in the island, their expected intensity is generally not considered to be high

enough to cause substantial landslide problems. Also human interventions may trigger landslides, e.g. through deforestation, clear cutting, improper drainage practices, or slope cutting, but still a rainfall trigger would be required to actual cause the landslides.
Therefore a study was carried out using various literature sources to reconstruct the major disaster events in the history of the islands. First of all we visited the Office of Disaster Management/ NEMO/NadMA. One of the best data on historical disaster events came from Saint Vincent, where someone carried out a study using newspaper records for the past decades. In some of the cases they had very limited information on historic disaster occurrences. For instance in Grenada the information is very limited. We also collected information from various sources on the internet. One of the best sources for older information was 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.
The preliminary results of the data collection on disaster events are presented in Tables 4.4 to 4.7 for the four islands. The data cover a long period starting mostly in the 19th century. As can be seen there is a large difference in the detail of the historical data sets between the four countries. Most data is available for Saint Lucia, and for Grenada there is much less information available.
For many of the historical events it was possible to reconstruct the date of occurrence. This is important as we intend to correlate these dates of occurrence with rainfall data for the same period, in order to determine rainfall thresholds for the occurrence of landslide events, where we would like to subdivide them according to the severity of landslides that were triggered during the event. Once we can subdivide the triggering events according to the severity of landslides caused, we intend to calculate the return periods of these events, and represent landslide densities for these triggering events in order to characterize the areas with higher probability of occurrence of landslide events. The procedure is illustrated in Fig. 4.8. The further back in time, the less landslide inventories, and also less rainfall data will be available, which will make it difficult to determine what would be the relations between triggering rainfall and landslides.
Rainfall data were also collected for the four islands. An overview of the data that was collected is shown in Table 4.8. As can be seen from this table there are many problems with respect to the rainfall data. Most of the stations data are only available for limited periods of time, and they often present data gaps. Many of the rain gauges that were previously maintained on the various estates have become dysfunctional. Hourly data is available for only a limited number of stations and for a short period of time. Therefore it will not be possible to use the data for the generation of intensity-frequency-duration curves, and we will try to use the daily rainfall data for the stations to correlate with the landslide occurrence dates.

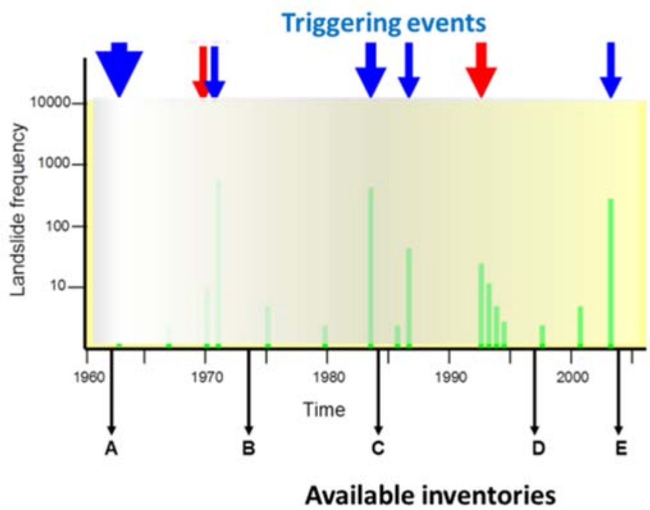


Figure 4.8: Schematic representation of the importance of collecting landslide inventories of specific triggering events. The larger the trigger, the more landslides. Therefore it is important to reconstruct the inventories caused by the main triggering events, and to correlate these events with the rainfall characteristics, which can then be used in a magnitude-frequency analysis in order to estimate return periods of triggering events.

Table 4.4: Historical disaster events in Dominica collected from different sources (NI = No Information).

Year	Day	Events	Notes	Information available
1806	09/09/1806	Hurricane	Landslides and Flooding	
1813	23/07/1813	Hurricane	Flooding	
1813	25/08/1813	Hurricane	Flooding	
1834	10/09/1834	Hurricane	NI	
1834	20/09/1834	Hurricane	Landslides and Flooding	
1851	NI	Hurricane	NI	
1916	28-8-1916	Hurricane	Landslides and Flooding	
1920	NI	NI	Landslides and Flooding	
1921	NI	Hurricane	NI	
1924	NI	Hurricane	NI	
1926	24-7-1926	Hurricane	Landslides and Flooding	
1928	12-9-1928	Hurricane	NI	
1930	1-9-1930	Hurricane	Landslides and Flooding	
1948	NI	Tropical Storms	Landslides and Flooding	
1949	set-49	Tropical Storms	NI	
1960	NI	NI	Landslide Bellevue Chopin	
1963	28-9-1963	Hurricane Edith	Landslides and Flooding	
1966	jun-66	Tropical Storms	Landslides and Flooding	
1970	20-8-1970	Hurricane Dorothy	Landslides and Flooding	
1977	NI	NI	Landslide (Bagatelle Disaster)	
1979	29-8-1979	Hurricane David (Category 5)	Landslides	
1980	NI	Hurricanes Federick & Allen (Cat1)	NI	
1983	NI	NI	Landslide Bellevue Chopin	
1984	NI	NI	Landslides	
1984	6-11-1984	Hurricane Klaus	Debris Down	
1986	11-11-1986	Several days of heavy rainfall	Landslide Good Hope	
1986	12-11-1986	Several days of heavy rainfall	Landslide Castle Bruce	
1988	NI	Hurricane Gilbert	Landslides' Mathieu and Layou River	
1989	NI	Hurricane Hugo	NI	
1995	25-8-1995	Hurricane Luis	NI	
1995	4-9-1995	Hurricane Iris	Large landslides Mathieu River	
1995	16-9-1995	Hurricane Marilyn (Cat 1)	Flooding	
1997	18-11-1997	NI	Debris Flow Mathieu River	Location known
1997	25-11-1997	NI	Landslides Mathieu River	
1997	28-11-1997	NI	Landslides Mathieu River	
1999	apr-99	Hurricane Lenny	Landslides in the north	
2003	NI	NI	Carholm landslide	
2003	9-12-2003	NI	Landslide Bellevue Chopin	Location known
2004	nov-04	NI	Series of Landslides'	
2004	21-11-2004	earthquake	NI	
2007	NI	NI	Landslide Campbell	Location known
2007	NI	NI	Landslide Bellevue Chopin	Location known
2007	aug-07	Hurricane Dean (Cta 2)	Flash Flooding	
2008	okt-08	Hurricane Omar	NI	
2009	jul-09	NI	Flooding	
2010	24-5-2010	Heavy rains Overnight	Saint Sauver Slide	Location known
2011	28-7-2011	NI	Miracle Lake Flooding	
2011	29-7-2011	NI	Landslide Soufriere	Location known
2011	sep-11	Storm Ophelia	NI	Inventory along roads
2012	29-8-2012	Tropical Storm Isaac	landslides'	
2013	apr-13	NI	Landslides	Inventory along roads
2013	5-9-2013	NI	Landslide Morne Prosper	Location known
2013	24-12-2013	Christmas Eve trough	landsides and Flooding	Inventory along roads, image interpreted inventory

Table 4.5: Historical disaster events in Saint Lucia collected from different sources (NI = No Information).

Year	Day	Events	Notes	Information available
1872	09-20/09/1872	Hurricane	NI	
1875	08-18/09/1875	Hurricane	NI	
1876	01/11/1876	Hurricane	NI	
1879	09-16/10/1879	Tropical Storm	NI	
1880	15-20-08/1880	Hurricane	NI	
1886	15-27/08/1886	Hurricane	NI	
1887	08/08/1887	Tropical Storm	NI	
1887	11-22/09/1887	Hurricane	NI	
1888	01-08/11/1888	Tropical Storm	NI	
1891	18-25/08/1891	Hurricane	NI	
1894	11-20/10/1894	Tropical Storm	Landslides and Flooding	
1895	22-30/08/1895	Hurricane	NI	
1896	11/09/1896	Tropical Storm	Landslides and Flooding	
1898	05-20/09/1898	Hurricane	NI	
1901	04-13/07/1901	Hurricane	NI	
1903	06-16/08/1903	Hurricane	NI	
1916	10-22/07/1916	Hurricane	NI	
1916	12-20/08/1916	Hurricane	NI	
1916	06-15/10/1916	Tropical Storm	NI	
1917	20-30/09/1917	Hurricane	NI	
1918	09-14/09/1918	Tropical Storm	NI	
1921	10-9-1921	Tropical Storm	Landslides and Flooding	
1924	16-18/08/1924	Hurricane	NI	
1928	19-9-1928	Tropical Storm	Landslides and Flooding	
1931	10-21/08/1931	Tropical Storm	NI	
1938	21-11-1938	Tropical Storm	Landslides and Flooding	
1938	22-11-1938	Tropical Storm	Landslides Ravine Crebiche and Flooding	
1939	7-1-1939	Tropical Storm	Landslides Ravine Poisson and Flooding	
1940	7-8-1940	Tropical Storm	Landslides and Flooding	
1941	23-30/09/1941	Hurricane	NI	
1942	21-31/08/1942	Hurricane	NI	
1942	15-22/09/1942	Tropical Storm	NI	
1943	11-18/10/1943	Hurricane	NI	
1948	1-9-1948	Tropical Storm	NI	
1949	3-9-1949	Tropical Storm	NI	
1951	5-9-1951	Hurricane Dog	NI	
1954	12-12-1954	Tropical Storm	Landslides Ravine Poisson and Flooding	
1958	4-7-1958	Tropical Storm	Landslides and Flooding	
1958	6-9-1958	Hurricane Ella	NI	
1960	10-7-1960	Hurricane Abbey	NI	
1963	24-9-1963	Hurricane Edith	NI	
1965	27-9-1965	Hurricane Betsy	NI	
1965	25-10-1965	Tropical Storm	Landslides and Flooding	
1966	jun-66	Tropical Storm	Landslides and Flooding	
1966	27-30/09/1966	Tropical Storm Judith	NI	
1967	8-9-1967	Hurricane Beulah	NI	
1967	26-9-1967	Tropical Storm Edith	NI	
1969	25-27/07/1969	Tropical Depression	NI	
1970	17-23/08/1970	Tropical Storm Dorothy	NI	
1970	2-10-1970	Tropical Depression	Landslides and Flooding	
1971	18-25/08/1971	Tropical Storm Chole	NI	
1976	03-12/10/1976	Tropical Depression	NI	
1979	19-24/06/1979	Tropical Storm Ana	NI	
1980	3-8-1980	Hurricane Allen	Widespread landslides particular Barre de l'isle	
1981	nov-81	Storm	Landslides	
1983	23-7-1983	Storm	NI	
1984	24-26/07/1984	Tropical Depression	NI	
1988	11-9-1988	Tropical Storm Gilbert	Landslide	1985 map De GRaff
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	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	
2001	14-22/08/2001	Tropical Storm Chantal	NI	
2001	04-09/10/2001	Tropical Storm Jerry and Hurricane Iris	NI	
2003	07-17/07/2003	Hurricane Claudette	NI	
2004	03-14/08/2004	Tropical Storm Bonnie	NI	
2004	26-9-2004	Seismic Event	Landslides Tapion	
2005	1-7-2005	Heavy rainfall prior to the failure	Landslide Windjammer Landing Beach Resort	
2007	13-23/08/2007	Hurricane Dean	NI	
2010	30-31/10/2010	Hurricane Tomas	Many landsides Colombette, Fond St Jacques, along the Barre De L'ile, Millet and on the hills east and south of Castries	
2004	26-9-2004	Seismic Event	landslides' Tapion	
2005	1-7-2005	Heavy rainfall prior to the failure	Landslide Windjammer Landing Beach Resort	
2007	13-23/08/2007	Hurricane Dean	NI	
2010	30-31/10/2010	Hurricane Tomas	Many landslides' Colombette, Fond St Jacques, along the Barre De L'ile, Millet and on the hills east and south of Castries	
2013	24-12-2013	Christmas Eve trough	Several landslides along the roads	

Table 4.6: Historical disaster events in Grenada collected from different sources (NI = No Information).

Year	Day	Events	Notes	Information available
1856	13/08/1856	NI	Hurricane	NI
1894	09/1894	NI	Tropical Storm	Flooding
1895	NI	NI	Tropical Storm	Flooding
1896	27/11/1896	NI	Tropical Storm	Flooding
1897	NI	NI	Tropical Storm	Flooding
1915	NI	NI	Tropical Storm	Landslides and Flooding
1921	NI	NI	Tropical Storm	Landslides and Flooding
1954	7-10-1954	NI	Tropical Storm	Flooding
1955	22-9-1955	NI	Hurricane Janet	Landslides and Flooding
1963	24-9-1963	NI	Hurricane Edith	NI
1963	1-10-1963	NI	Hurricane Flora	Landslides and Flooding
1964			Hurricane Cleo	NI
1978	7-8-1978	NI	Tropical Storm Cora	NI
1979	NI	NI	Hurricane David	NI
1980	NI	NI	Hurricane Allen	NI
1985	11-9-1985	NI	Tropical Depression	NI
1988	10-10-1988	NI	Tropical Storm	NI
1999			Hurricane Lenny	
2004	7-9-2004	NI	Hurricane Ivan	NI
2005	4-7-2005	NI	Tropical Depression	NI
2007	31-8-2007	NI	Hurricane Felix	NI

Table 4.7: Historical disaster events in Saint Vincent collected from different sources (NI = No Information).

Year	Day	Events	Notes	Information available
1874	09/09/1874	Tropical Storm	Landslides and Flooding	Heavy Rain
1876	01/01/1876	Tropical Storm	Landslides and Flooding	Heavy Rain for 2 days
1884	16/08/1884	Tropical Storm	Landslides and Flooding	NI
1886	15/08/1886	Tropical Storm	NI	NI
1887	30/07/1887	Tropical Storm	NI	NI
1887	11/09/1887	Tropical Storm	NI	NI
1895	06/09/1895	Tropical Storm	Landslides and Flooding	NI
1895	15/09/1895	Tropical Storm	Landslides and Flooding	NI
1896	28/10/1896	Tropical Storm	NI	Heavy Rain
1897	NI	Tropical Storm	Flooding	Cyclone
1898	11/09/1898	Hurricane	NI	NI
1902	8-5-1902	Earthquakes and volcanic activity	Landslides	NI
1916	okt-16	Tropical Storm	Flooding	Heavy Rain
1955	23-9-1955	Hurricane Janet	NI	NI
1954	9-10-1954	Tropical Storm	Flooding	
1957	30-5-1957		Landslide	
1963	5-7-1963	Storm	NI	NI
1963	24-9-1963	Hurricane Edith	NI	NI
1962	1-9-1962	Heavy rain	Landslide	Heavy Rain
1962	25-6-1962	Tropical Storm	NI	NI
1967	17-9-1967	Hurricane Behulah	Landslides and Flooding	18'' of rain in 12 hours
1974	13-5-1974	Heavy rains	Landslides and Flooding	heavy Rains
1974	2-10-1974	Tropical Storm	Landslides and Flooding	Heavy Rains
1977	18-10-1977	Heavy Rains	Flooding	Heavy Rains
1978	19-10-1978	NI	Landslide	NI
1980	11-8-1980	Hurricane Hallen	NI	NI
1981	1-5-1981	Tropical Storm	Landslides	NI
1986	8-9-1986	Tropical Storm Daniel	Landslides and Flooding	NI
1987	21-9-1987	Hurricane Emily	Landslides and Flooding	NI
1987	nov-87	NI	Landslides'	NI
1988	22-08-1988	Previous Heavy Rains	Rockslides	Heavy Rains
1988	22-10-1988	Heavy Rains	Landslides	Heavy Rains
1990	28-09-1990	Heavy Rains	Landslides and Flooding	Heavy Rains
1991	26-08-1991	Heavy Rains	Flooding	NI
1991	24-10-1991	Torrential Downpours	Landslides	NI
1992	21-09-1992	Heavy Rains	Flooding	NI
1995	26-08-1995	Tropical Storm Iris	Landslides and flooding	NI
1996	08-09-1996	Incessant Rain	Flooding and Landslides	NI
1998	08-01-1998	Torrential rainfall	Flooding	NI
1999	17-11-1999	Hurricane Lenny	Flooding	NI
2000	29-11-2000	Torrential Downpours	Flooding	NI
2001	4-10-2001	Tropical Depression Iris	NI	NI
2002	24-9-2002	Tropical Storm	Landslides and flooding	NI
2004	8-9-2004	Hurricane Ivan	Landslides and Flooding	NI
2004	24-11-2004	Tropical Storm	NI	NI
2005	14-7-2005	Tropical Storm	NI	NI
2010	29-10-2010	Hurricane Tomas	NI	NI
2011	11-4-2011	Tropical Storm	Landslides	NI
2013	24-25/12/2013	Tropical Storms	Flooding	Heavy Rain 200 to 300 mm in two hours

Table 4.8: Available rainfall data for the 4 islands

Island	Number of stations	Period of data	Characteristics
Dominica	Canefield airport	1982 to present	Daily data only
	Melville Hall airport	1975 to present	Daily data only
	DOMEX	2007 to present	Hourly data for 10 stations arranged in a transect over the country http://www.domex2011.com/rain-gauge-network
Saint Lucia	19 stations	Longest period 1955 - 2005	Daily rainfall data
	19 stations	Longest period 2003 - 2010	Hourly data but with many interruptions
	Canelles, Deglos Mabouya	2012 -2013	Rainfall data (continuous) and water levels measurements.
Grenada	Botanic Gardens	2003-2012	Hourly
	Mirabeau	2003-2009	Hourly
	Pearls	2005-2006	Hourly
	Cardi	2003-2009	Hourly
	Kubalal C & W	2003-2009	Hourly
	La Sagesse Agriculture Station	2011	Hourly
	59 stations	Variable periods from mid 1900's	Monthly data for estates, but very irregular in terms of time period. Data probably in inches
	2 stations	1986-2014	Hourly data
Saint Vincent	7 stations	Longest period 1957 - 2008	Monthly data
	28 stations	Few years only	Daily rainfall data
	1 station	1986-2009	Daily data

4.4. Landslide inventory mapping

Landslide inventories are the basis for assessing landslide susceptibility, hazard and risk. 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 they happened. The conditions under which landslides happened in the past analyzed and the relevant combinations are used to predict future ones. Therefore 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. This means 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 difficult to interpret from images. 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.

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:

- Image interpretation
- (Semi) automatic classification
    - Based on spectral information
    - Based on altitude information
- Field investigation
- Community reporting
- Archive studies
- Dating methods
- Monitoring networks

Often there is no single agency that has the responsibility for maintaining a landslide database. This is one of the major problems in the 4 target countries. No agency feels responsible to collect landslide locations and dates, and keep a database up-to-date. This is the case both for mapping landslides in the rural areas, as well as for collection landslide data along the road network. Only very limited landslide data could be obtained from the Ministries of Public works and transport, although 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, with the exception of the 2010 Hurricane Tomas landslide inventory in Saint Lucia which was made by Adriana Abrahams and Rebecca Rock.

For collecting landslide information in the four islands the following approaches are considered most useful:

- Image interpretation from high resolution satellite imagery;
- Collection of landslide data in the field by different agencies, e.g. road engineers, forestry staff etc.
- To communicate to the public those landslide occurrences should be reported to the National Emergency management organization.
- To involve the District Disaster Committees in the reporting of landslide events.

The National Emergency Management Organization seems also the most appropriate one to store the landslide data in an incident database, including the location information in a simple GIS and maintain it.

For the acquisition of satellite images and the expertise for landslide inventory mapping the countries will remain dependent on outside support. But the maintenance of a national landslide database should be the taken up by a national agency.

4.4.1. Method followed for collection of landslide inventories

Within this project we have collected the available landslide inventories. But, as these were in most cases not sufficiently, reliable or available, we also decided to collect landslide inventories ourselves. This was done using image interpretation and field work.

Image interpretation can be defined as the study of the imaged objects of the earth surface, the extraction of those features relevant to the object of study, the analysis of the selected features with the objective to come to a deduction of their significance for the specific field of study.

Stereoscopic image interpretation is important tools to recognize and map landslides. The interpretation of images is an empirical and subjective process. It is a systematic scanning of a stereo model assisted by logical and scientific evidences. Stereo image interpretation (API) is an art as much of a science, and it requires well trained, experienced investigators.

After hearing that the British Geological Survey, as part of a project between the World Bank and the European Space Agency, would also be involved in landslide inventory mapping, we decided to divide the work, and asked the BGS to carry out landslide image interpretation for Saint Lucia and Grenada, while we did it for Saint Vincent and Dominica.

We obtained through the EU FP7 Copernicus project INCREO (http://www.increo-fp7.eu/) the possibility to order very high resolution satellite images (Pleiades images, with 0.5 m spatial resolution for panchromatic and 2 m multi-spectral) for the four island countries (See Table 4.9). We received the images that were obtained in the first months of 2014. In December 2013, several of the islands were hit by a high intensity rainfall event (the so-called Christmas-eve trough). This allowed us to map the landslides caused by this event.

For the interpretation the following simple procedure was proposed: mapping the landslides as polygons, separating between scarp and body, assigning a unique identifier to each landslide and describe each landslide with a number of attributes. This is illustrated in Figure 4.9 and Figure 4.10.

Landslide inventories were checked in the field during a fieldwork period of 3 weeks in September-October 2014. During the fieldwork several of the features that were identified through image interpretation as potential landslides, were actual bare field or other features. As the stereo-image interpretation focused not only on the absence of vegetation in potential landslide areas, but more on the morphological characteristics of old landslides, many more landslides were interpreted than the ones caused by the 2013 Christmas eve event. However, for these older ones, it was difficult to establish the age. During the fieldwork we also obtained some additional satellite images that still need to be interpreted in the coming period.

Table 4.9: Available satellite images for the four island countries

Country	Satellite	Date	Type	Columns, Rows
Dominica	Downloaded from google Earth	Various covering the island, but all with very high resolution	Colour image	35120, 63354
	Digital Globe	13 FEB 2014	Cloud cover 3.6 % pixel size 2 meters	6983, 30999
	Pleiades	2014 03 08	0.5 meter panchromatic 2 meter multispectral. Covers North west part of the island	43814, 80743
	Pleiades	2014 01 17	0.5 meter panchromatic 2 meter multispectral. Covers middle part of the island	7009, 18049
	Pleiades	2014 03 08	0.5 meter panchromatic 2 meter multispectral. Covers Northwest part of the island	10921, 20183
	Pleiades	2014 01 17	0.5 meter panchromatic 2 meter multispectral. Covers east part of the island	47246, 101040
Saint Lucia	Pleiades	2014 02 25	0.5 meter panchromatic 2 meter multispectral. Covers whole island, except extreme west coast	10676, 23943
	Pleiades	2012 11 20	0.5 meter panchromatic 2 meter multispectral. Covers south part of the island	41149, 42418
Saint Vincent	Pleiades	2014 02 23	0.5 meter panchromatic 2 meter multispectral. Covers whole island	12507, 16250
Grenada	Digital Globe	2010	1 meter, only of SE part	16384, 15700
	Ikonos	2004	1 meter, Only of the SE part. Entire island except SE corner	8269, 5797
	Pleiades	2013 08 06 About 5 % clouds	0.5 meter panchromatic 2 meter multispectral. Entire island except SE corner	45354, 65909
	Pleiades	2013 11 17	0.5 meter panchromatic 2 meter multispectral. SE corner of the island	49947, 48707

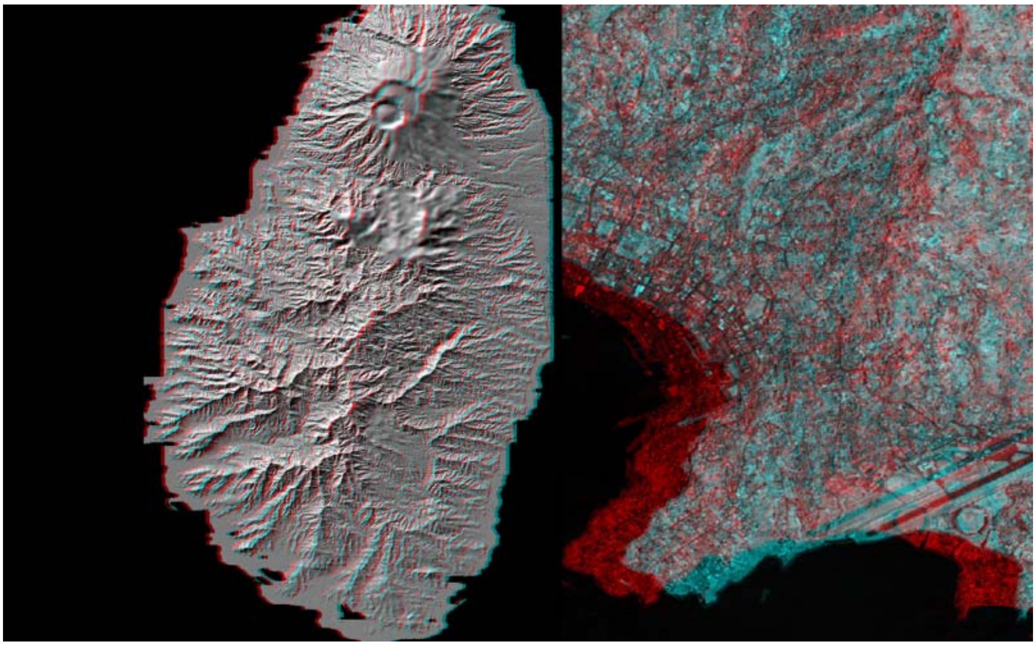


Figure 4.9: Example of a stereo image for Saint Vincent, displayed as anaglyph image. Use red-green glasses for stereo viewing.

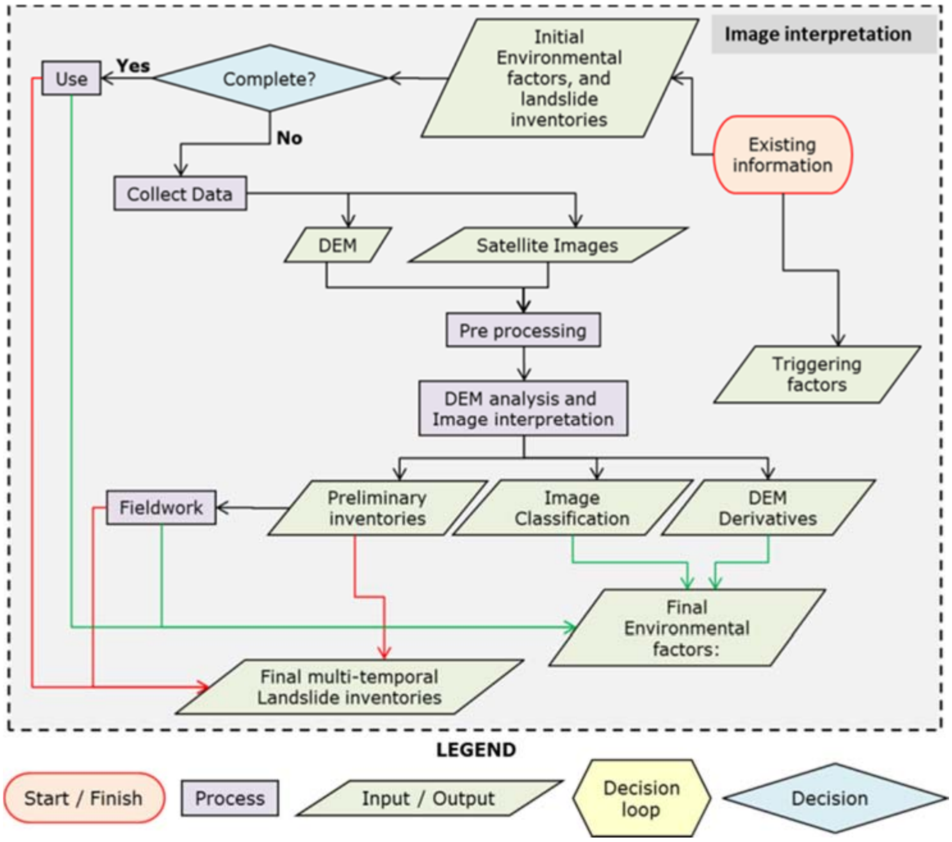


Figure 4.10: The procedure followed for stereo-image interpretation.

During the fieldwork also specific emphasis was given to the collection of landslide inventories along the road network. For this purpose landslide data was collected through the following means:

- Image interpretation of landslides along roads, and subdivision of roads into segments with different characteristics in terms of cut slopes, upslope and downslope terrain, and geology.
- In the countries fieldtrips were carried out together with the road engineers in order to know the locations where landslides have occurred in the past;
- Road maintenance records were collected from which information related to the number, data and volume of landslides was extracted for a number of triggering events.
- The road segments identified through image interpretation were checked in the field, and additional information on road characteristics was obtained. Some of the countries had road databases, with information on each road section. However, they were not geo-located and this proved to be a difficult work.
- Finally also reports related to landslide studies along the roads were collected. This was specifically successful for Saint Lucia, where recently a large study was completed by a consultant (Mott Macdonald).

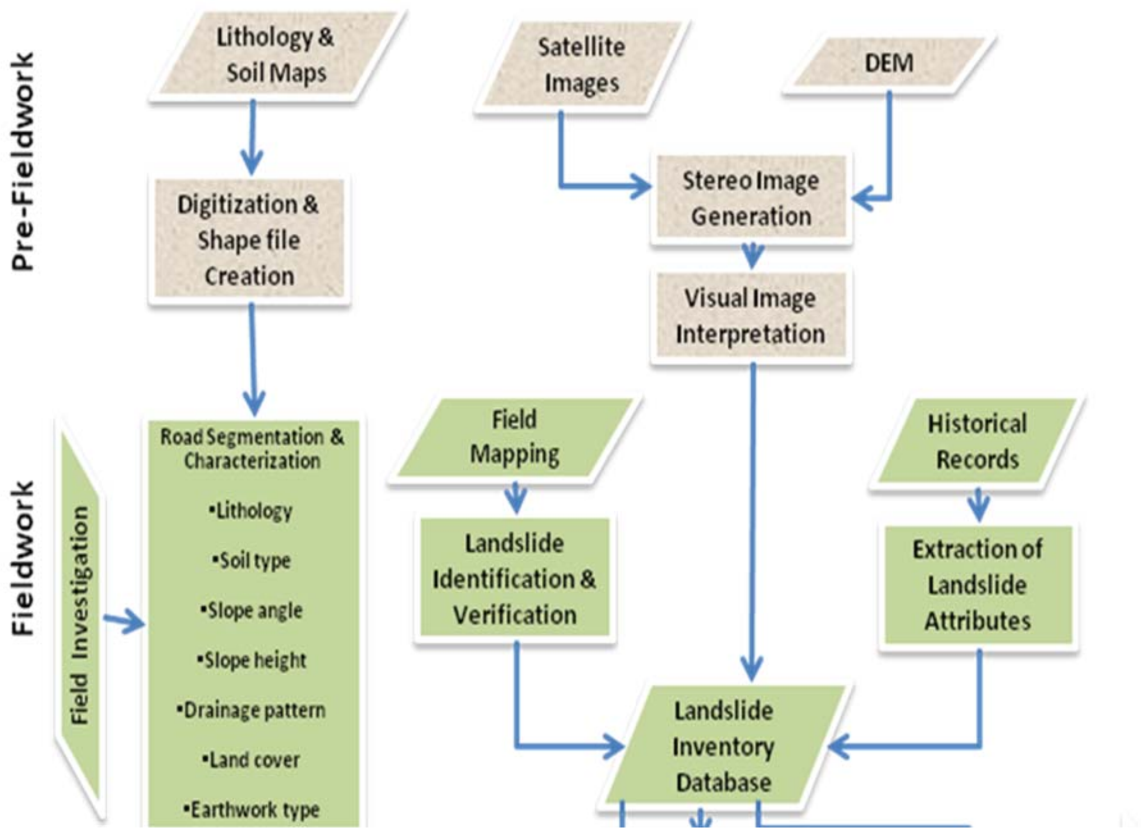


Figure 4.11: The procedure followed for collection of road-related landslide data.

4.4.2. Available landslide inventories

With the method described above a number of inventories were generated, next to the inventories that were obtained from previous studies and from the parallel BGS landslide inventory project. The number of available landslide inventories differs very much from island to island. For Saint Lucia a large number of inventories were obtained, whereas for Saint Vincent and Grenada we were less successful.

Dominica

For Dominica there are only a limited number of landslide inventories available (See Table 4.10). The base line study, as in most of the countries is the work carried out by J. DeGraff from the US Forest Survey for the OAS in the late 1980's. He carried out detailed image interpretation of landslides using the available black and white aerial photographs. He differentiated between landslide types. I the mapping by DeGraff was not related to a specific triggering event.

Later on under a USAID programme, a multi-hazard assessment was carried out for Dominica in 2006. This included a landslide susceptibility assessment, which also incorporated a limited data collection for new landslides. However, these were concentrated mostly along the roads, and do not cover a specific triggering event. The maps generated by this project still hang on the wall of the Physical Planning Office, but the planners indicated that the detail of these maps is not high enough to use them in the planning processes.

We carried out a landslide inventory mapping for Dominica with two MSc students. They did a digital stereo image interpretation of a very high resolution Pleiades image from 2014, and carried out a field work of 1.5 weeks in Dominica. During this fieldwork they also worked together with the road engineers from the department of works, and with staff from the department of Physical Planning, to map the location of known landslides.

We also obtained a road database from the department of works, which describes the roads segments in terms of road conditions, number of bridges and culvert, drainage, road cuts etc. Unfortunately this database has no spatial connection, and the segments of the roads are from one junction to the next. Work is needed to geo-locate these segments and generate a road segment map.

From the department of works also a number of reports were obtained with information of damage caused by several triggering events in the past five years. Unfortunately no information was available for earlier events.

If we compare the available inventories with the list of triggering events shown in Table 4.4 we can conclude that it will be difficult to link one of the inventories to a major triggering event, such as hurricane. Detailed landslide information for the latest hurricanes (e.g. Dean in 2007, Lenny in 1999, David in 1979) is not available. Therefore we might not be able to apply the proposed method for the conversion of susceptibility maps into hazard maps due to the lack of sufficient event-based landslide inventories.

Table 4.10: Landslide inventories for Dominica.

Year	Author	Characteristics
1987	DeGraff	For OAS. The report presents maps of landslides detected through interpretation of 1:15000 scales black and white aerial photography taken before 1987 combined with field study in selected areas... Inventory contains type classification.
1990	DeGraff	He made an update of the landslide inventory map a few years later, and added a number of landslides to the existing inventory. This is not available in digital form yet.
2006	CIPA USAID	Under the UASAID COTS programme a multi-hazard assessment was done for Dominica. This included a landslide hazard map. Limited fieldwork was carried out and only landslides along the main roads were added.
2014	ITC	Landslide inventory based on image interpretation of very high resolution Pleiades images from 2014, and fieldwork.
2009	ITC	Landslide along road network caused by a triggering event in September 2009
2011	ITC	Landslide along road network caused by a triggering event in November 2011
2013	ITC	Landslide along road network caused by a triggering event in April 2013

We carried out an extensive interpretation of landslides using different sets of satellite images, and also using historical imagery from Google Earth Pro. We were able to map a large number of landslides, many more than in any of the previous inventories. We incorporated in our inventory also the landslides from the previous inventories and made a complete classification for all landslides. Also the mapping of coastal landslides was carried out. The resulting map is shown in figure 4.13.

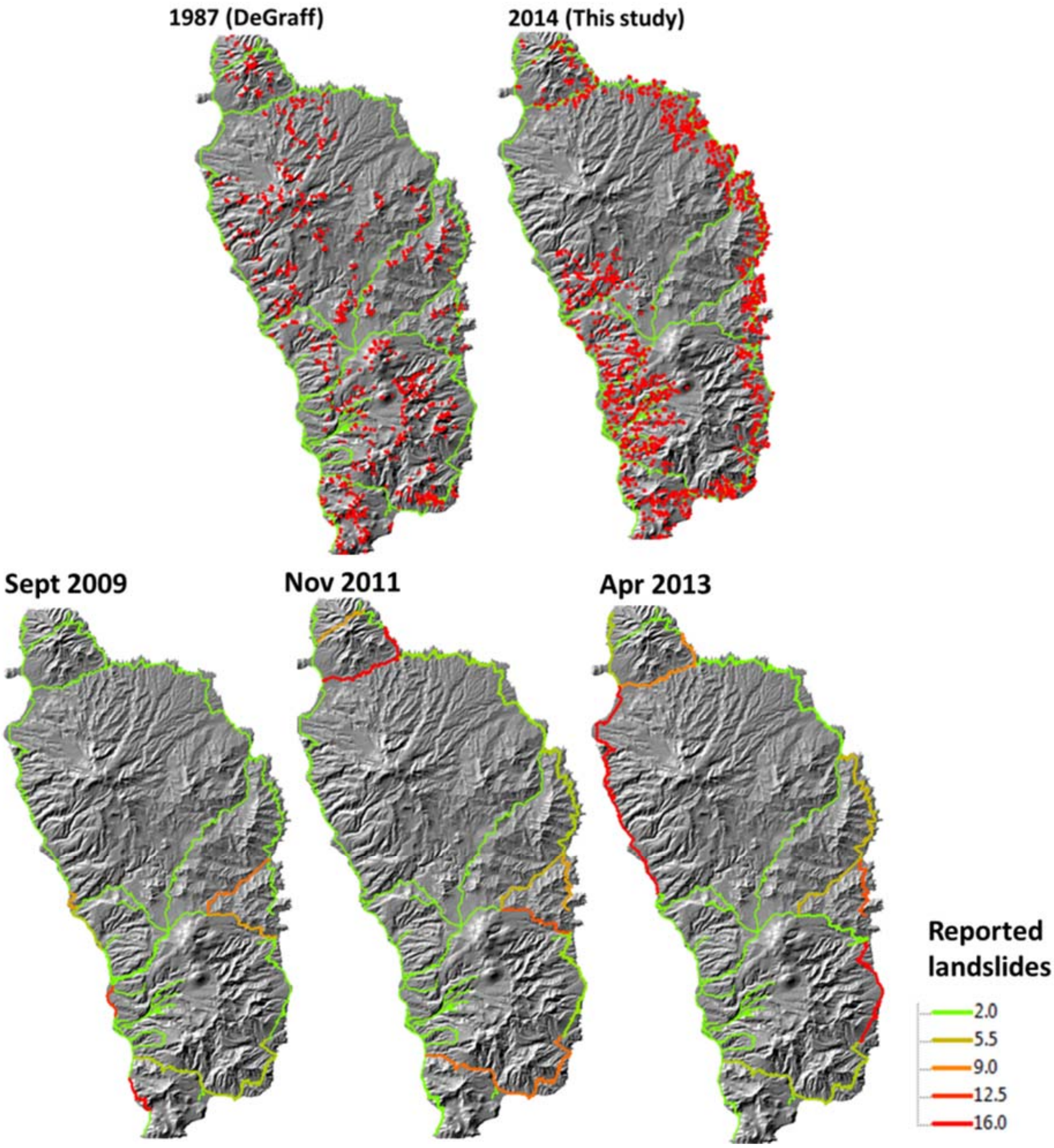
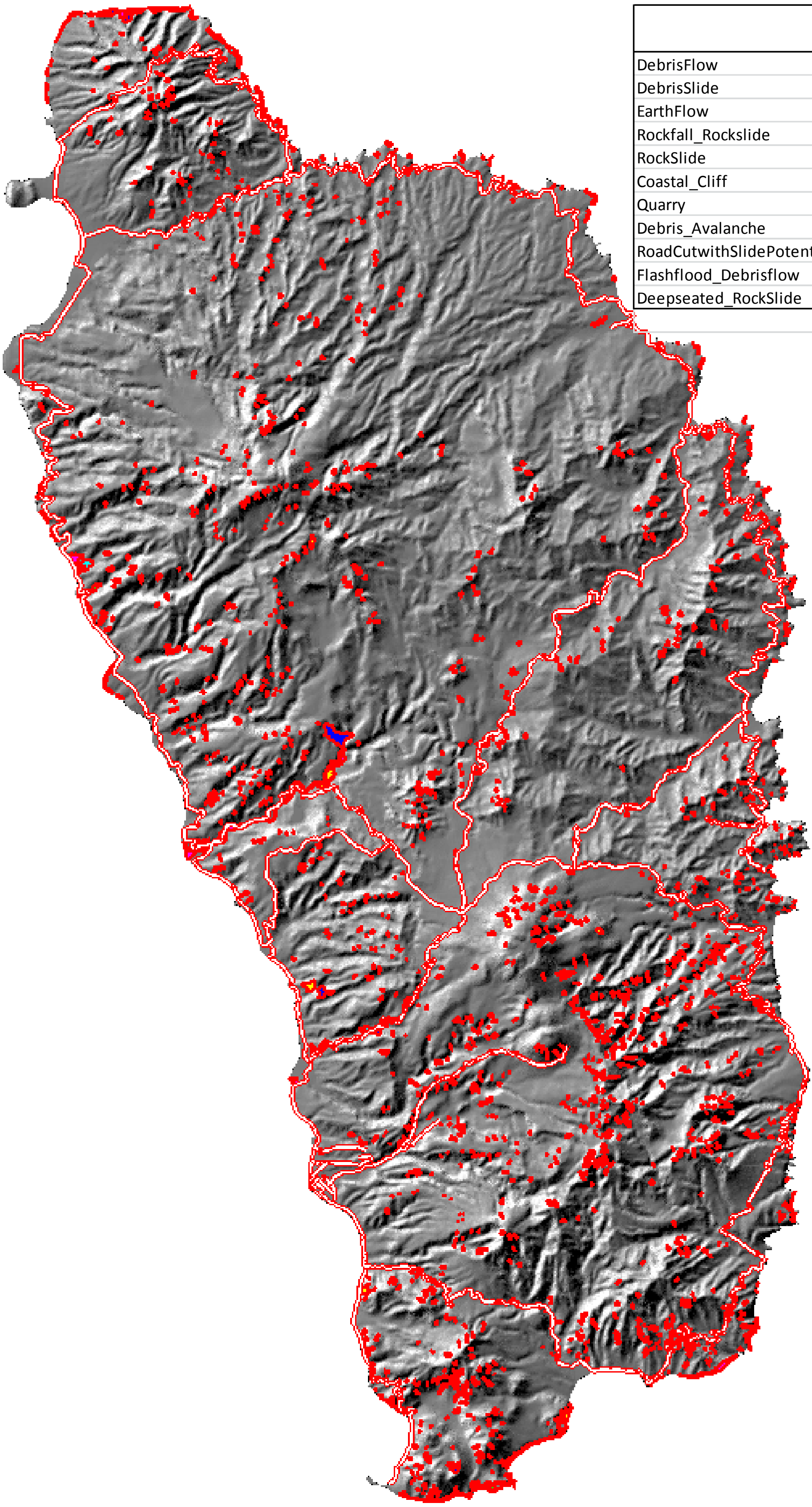


Figure 4.12: Landslide inventories that are available for Dominica. Above: Landslide inventory made by De Graff in 1987 and the landslide inventory made through this project in 2014. Below: reporte4d number of landslides for three recent triggering events based on data from the Ministry of works. No location information was available.



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

Figure 4.13: Final landslide inventory map generated through extensive image interpretation for Dominica. The map incorporates the limited previous inventories. The database contains landslide types for all landslides, and includes coastal landslides. Also debrisflow channels were mapped.

Saint Lucia

For Saint Lucia a large number of landslide inventories are available. Table 4.11 gives a list of the landslide inventories that we were able to collect. It is not clear whether Saint Lucia has much higher landslide problems than the other islands, has been unfortunate to be hit be major triggering events in the past decades or whether it is favoured by donors for funding landslide studies.

Table 4.11: Available landslide inventories for Saint Lucia

Year	Author	Characteristics
1985	DeGraff	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.
1995	C. Rogers	Post Tropical storm Debby landslide hazard assessment study
1998	Hunting Technical Services and Mott MacDonald	Watershed and Environmental Management Plan Phase II Final Report. Proposed by the World Bank following Tropical Storm Debbie. 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	Project done for the World Bank. Strangely enough no one we spoke seemed to know this project… 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 new book recently published in January 2013
2006	CDB/CDERA	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.
2012	P. Quinn and Alex Strouth for BGC	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	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	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 1250 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.

Figures 4.14and 4.15 give examples of the landslide inventories that are available. For road related landslide the recent work carried out by Mott MacDonald can be considered the baseline study. For the island wide landslide inventory the work carried out by BGS in 2014 is also such a baseline study.

We therefore can use these inventories that are linked to major triggering events in our method to convert susceptibility maps into hazard maps. It is important here that we have landslide for different major event, such as the Hurricane Tomas (2010), Debby (1994) and the 2013 Christmas Eve trough.

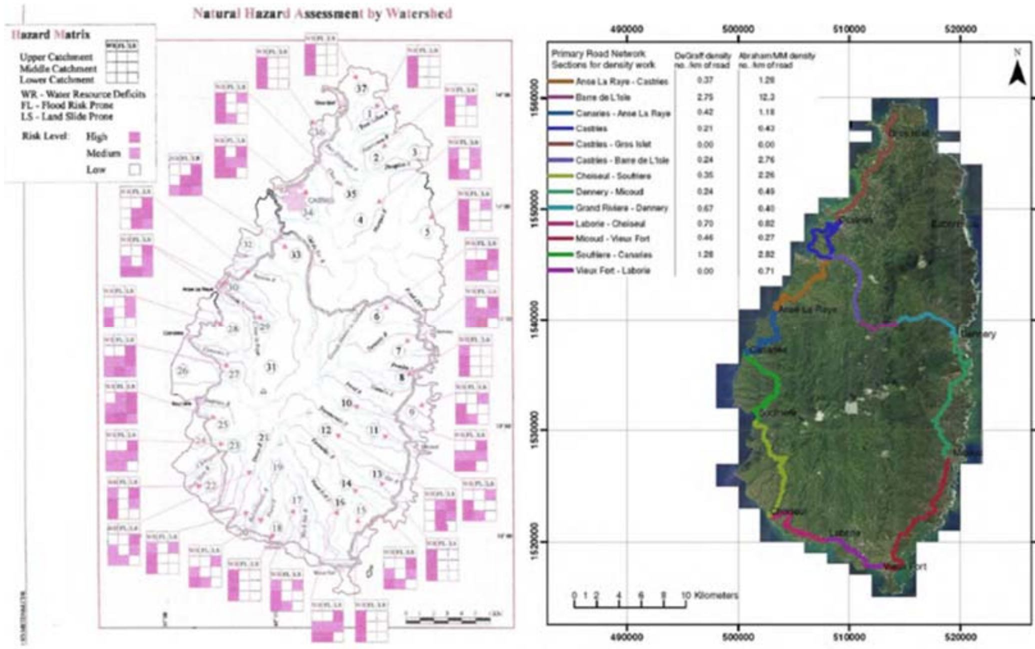


Figure 4.14: Left: Landslide assessment by Huntington and Mott Macdonald in 1998. Right: Landslide risk study along the national road network by Mott Macdonald in 2014.

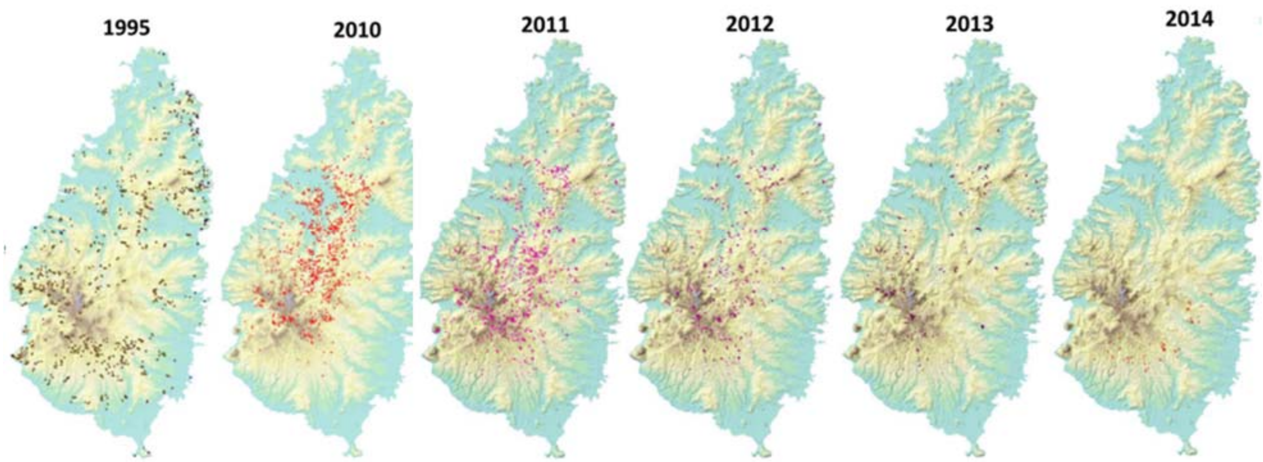


Figure 4.15: Landslide inventory maps for Saint Lucia. 1995: Cassandra Rogers, 2010: Abrahams & Rock map of hurricane Tomas landslides, 2011: Hurricane Tomas landslide inventory mapping by BGS, 2012 – 2014: Annual landslide inventory maps by BGS.

Given the large number of available inventories we didn't make a new inventory for Saint Lucia. However, we discovered fairly large discrepancies between the inventories mapped by BGS , MMD and Abrhams for the 2010 situation. Also many of the landslides were not classified in types.

Saint Vincent

For Saint Vincent we only found the landslide inventory made by De Graff (1988), with 475 landslides (See Figure 4.16). We also obtained a list of events, including landslide events based on the analysis of historical newspaper records.

Therefore we decided also to generate a new landslide inventory based on digital stereo image interpretation of a very high resolution Pleiades image from 2014. However, as there has not been a recent major landslide triggering event in the past years, it was difficult to map out recent landslides. We were able to differentiate the landslides caused by the 2013 Christmas Eve trough. This event caused many damage related to flood events, but we also found several locations with landslide and debris flow problems. The map below indicates the preliminary map. The final map will have fewer landslides as it was found in the field that many of the image-interpreted landslides did not have sufficient field evidence.

Unfortunately we do not have sufficient event-based landslide inventory maps of different triggering events (e.g. Hurricane Iva in 2004) to be able to use the proposed method for converting the susceptibility map into a hazard map. We also have only limited information on landslides along the road network to be able to make a quantitative analysis.

We carried out an extensive interpretation of landslides using different sets of satellite images, and also using historical imagery from Google Earth Pro. We were able to map a large number of landslides, many more than in any of the previous inventories. We incorporated in our inventory also the landslides from the previous inventories and made a complete classification for all landslides. The resulting map is shown in figure 4.17.

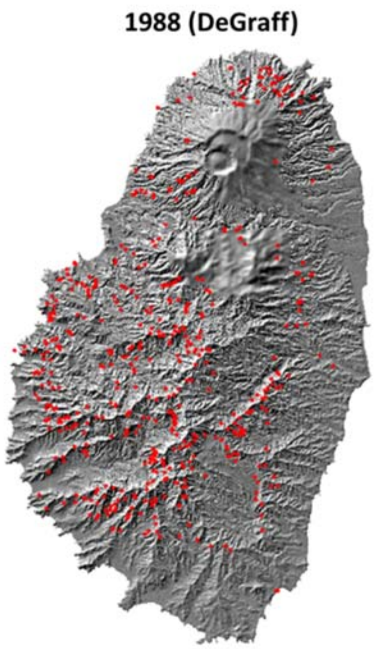


Figure 4.16: Landslide inventory maps for Saint Vincent. Left: the map generated by De Graff in 1988. Right: preliminary map made through this project.

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

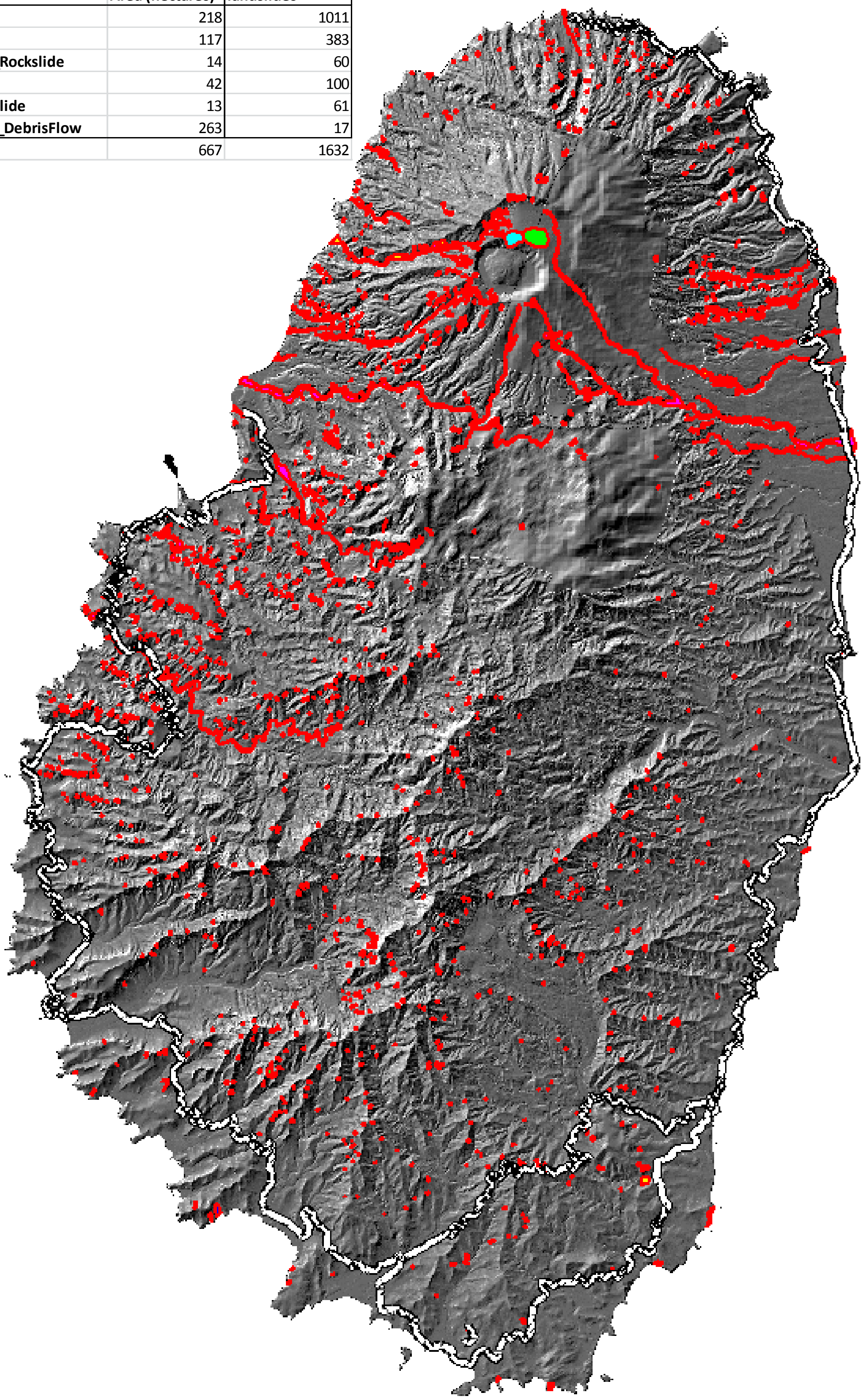


Figure 4.17: Final landslide inventory map generated through extensive image interpretation for Saint Vincent. The map incorporates all previous inventories. The database contains landslide types for all landslides, and includes the landslides mapped by DeGRaff in 1988. Also debrisflow channels were mapped. Apart from the landslides mapped from satellite images also a separate datset was made of landslides mapped from the LIDAr hillshading image.

Grenada

For Grenada we have found only one landslide inventory map generated in the 2006 by CIPA/CDB. The Caribbean Development Bank (CDB) through the Disaster Mitigation Facility for the Caribbean (DMFC), and the Caribbean Disaster Emergency Response Management Agency (CDERA) through the Caribbean Hazard Mitigation Capacity Building Program (CHAMP), have collaborated on a multi-phased project to support the development of national hazard mitigation plans in Grenada in 2006. No image interpretation was carried out for this study. Field reconnaissance along the roads was carried out for five days in early September of 2005. This was within one year after the occurrence of Hurricane Ivan in 2004. However, they collected two hundred and forty five (245) landslide points for Grenada. The inventory is shown in Figure 4.18.

In 2014 the British Geological Survey carried out a landslide inventory mapping based on image interpretation of very high resolution satellite images from 2010 to 2014. Unfortunately they indicated that they could not map any existing landslides. Their landslide inventory contains only 1 landslide.

No one seems to have mapped landslides caused by Hurricane Ivan based on image interpretation. We have tried to get satellite images pre- and post-Ivan from the government agencies, but these only cover a part of the island. We also obtained some landslide locations from the engineers of the ministry of works. We are planning to carry out extensive image interpretation for landslide mapping in Grenada.

We carried out an extensive interpretation of landslides using different sets of satellite images, and also using historical imagery from Google Earth Pro. We were able to map a large number of landslides, many more than in any of the previous inventories. We incorporated in our inventory also the landslides from the previous inventories and made a complete classification for all landslides. The resulting map is shown in figure 4.19.

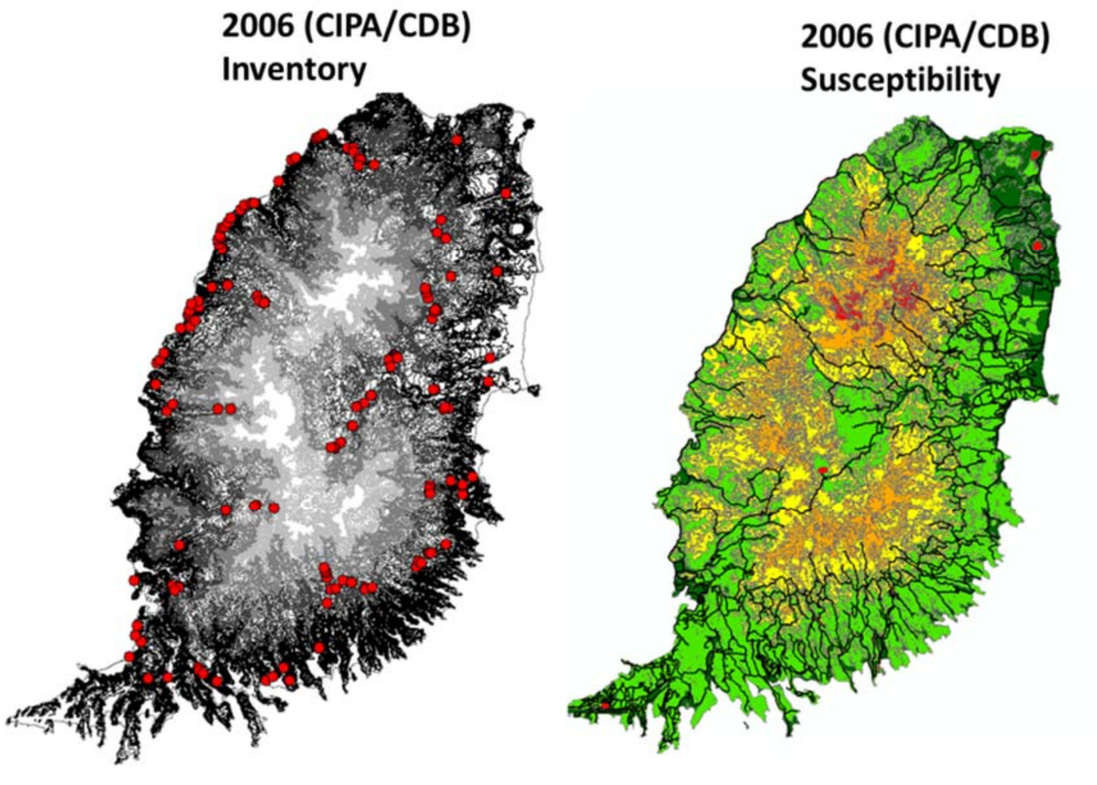


Figure 4.18: Landslide inventory maps for Grenada Left: the map generated by CIPA in 2006. Right: landslide susceptibility map made by CIPA in 2006.

	Area (hectares)	Number of landslides
Creep	5	7
Debris_avalanche	153	307
Debris_slide	121	364
Debrisflow	2	8
Rockfall	6	14
Rockslide	3	3
Rotational_Slide	24	80
Stream_Flood_DebrisFlow	70	4
Subsidence	1	2
Coastal_cliff	33	28
	418	817

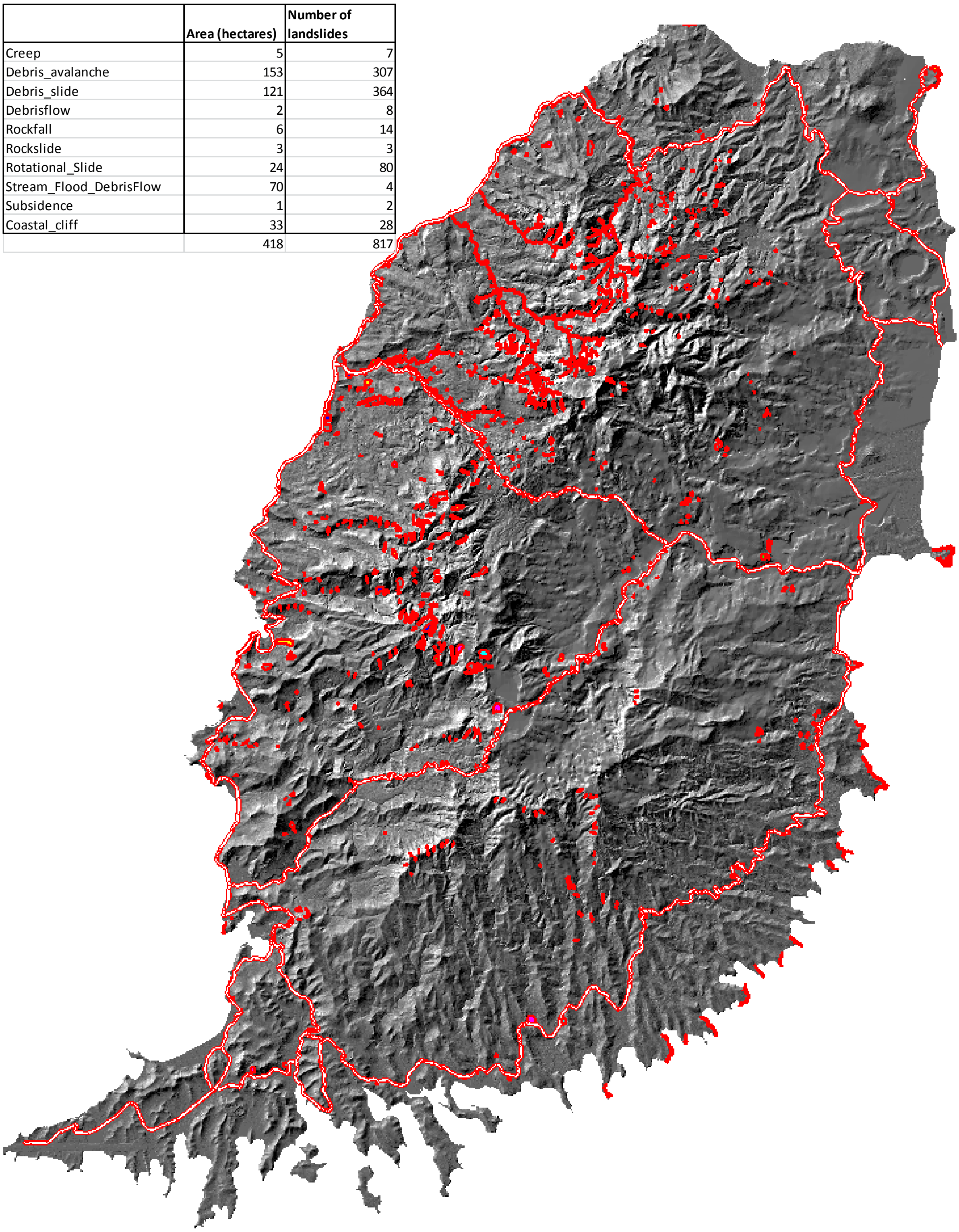


Figure 4.19: Final landslide inventory map generated through extensive image interpretation for Grenada. The map incorporates the limited previous inventories. The database contains landslide types for all landslides, and includes the landslides mapped by GRN in 2006. The landslides triggered by Hurricane Ivan are also included. Also debrisflow channels were mapped. Apart from the landslides mapped from satellite images also a separate datset was made of landslides mapped from the LIDAr hillshading image.

Table 5.12: Summary of available landslide inventories

Country	Author	Captures event?		Completeness	Classification
Saint Lucia					
1985	DeGraff	Tropical Depression (1984)? And Hurricane Allen (1980)		complete	Basic
1995	Rogers	Tropical Storm Debby (1994)	712 points	Not complete	Yes
2010	Abrahams and Rock	Hurricane Thomas	392 points		None
2011	BGS	Hurricane Thomas	?	complete	Complete ?
2012	BGS	None	?	complete	Complete ?
2013	BGS	None	?	complete	Complete ?
2014	BGS	December 2013 storm	?	complete	Complete ?
Dominica					
1987	DeGraff	Nov. 1986 storm, Hurricane Klaus (1984)	800 Polygons	Covers entire island	Yes: Debrisflow Debris slide Rockfall Rockslide
1990	DeGraff	Hurricane Gilbert (1988) and Hurricane Hugo (1989)	Not digitized	Covers entire island. But is not digital	Basic
Sep 2009	ITC	Sep 2009		Roads only	None
Nov 2011	ITC	Nov 2011		Roads only	None
Apr 2013	ITC	Apr 2013		Roads only	None
2014	ITC	Dec 2013	1086 Polygons	Whole island	Yes
Saint Vincent					
1988	DeGraff	Emily (1987) and Daniel (1986) combined	500 points	Seems complete	Partly
2014	ITC	December 2013	2364 points	Difficult to map recent landslides	Partly
Grenada					
2006	CIPA/CDB	Hurricane Ivan (2004) and tropical storm (2005)	146 points	Roads only	None
2014	BGS	There is no recent event related to this inventory	?	No recent landslides mapped	Complete ?

4.5. Landslide conditioning factors

For the landslide susceptibility assessment at scale 1:25,000 - 1:50.000 the factors that are considered to contribute to landslide occurrence have also been collected. These may differ from area to area, but the most important ones are:

- Topographic layers:
  - Digital Elevation Model
  - Altitude zones.
  - Slope steepness
  - Slope aspect
- Drainage related factors
  - Eroding sections of main rivers
  - Closeness to eroding streams
  - Distance from stream initiation
- Geological layers
  - Lithological map
  - Faults and lineaments map
- Soil types
  - Soil type map
- Land cover related layers
  - Land cover (existing)
  - Land cover (previous period)
  - Land cover changes
  - Road cuts

Not all these data layers are equally important, and they also vary a lot for area to area. However, based on the experience of landslides in the Caribbean and the availability of information the list indicated in table 6.1 can be used as guideline.

Soils and Land cover are determinant for susceptibility assessment. In tropical environments (and in the special volcanic environments) soil layers are very different in their stability characteristics. Landslides have occurred on these soil layers due to their different composition and degree of weathering.

From the methodological point of view is important to consider the relevant intrinsic characteristics relevant for the development of landslides. On the other hand, for the practical application in the generation of national scale landslide hazard maps for the fours island, we need to take into account the data availability and the data quality as well. Therefore, table 4.13 gives an overview of the available data for the four countries and also indicates the quality in green (good) and yellow (lees good).

Table 4.13: Overview of input maps for landslide susceptibility assessment, with indication of their quality of the data for the islands in green (good) , yellow (less good), and orange (not available).

Group	Factor	Availability and quality of the data in the 4 island countries.			
		Dominica	Saint Lucia	Saint Vincent	Grenada
Topographic factors	Digital Elevation Model	Poor. Available contour lines have been smoothed quite a bit.	Moderate. Available contour lines have problems.	Good, except for upper part of the island, where we had to fill it with an ASTER GDEM	Good, LIDAR derived, and also contour lines for missing part
	Altitude zones	Good	Good	Good	Good
	Slope steepness	Moderate	Moderate	Good	Good
	Slope aspect	Good	Good	Good	Good
	Upslope contributing areas	Poor	Moderate	Good	Good
Drainage factors	Eroding sections of mains rivers	Some problems with fitting of drainage to DEM	Some problems with fitting of drainage to DEM	Good, but incomplete in the upper part of the islands	More or less OK, although some problems with fitting to DEM
	Distance from stream initiation	Can be generated	Can be generated	Can be generated	Can be generated
Geological factors	Lithological map	Too general to be of much use for landslide work	Too general to be of much use for landslide work	Too general to be of much use for landslide work	Too general to be of much use for landslide work
	Fault map	Not available	Not available	Not available	yes
	Geomorphological map	Not available	Not available	Not available	yes
Soil mao	Soil type map	Detailed map. Extensive legend. No clear relation with topography and lithology	No clear relation with topography and lithology	No clear relation with topography and lithology	Unclear legend. No clear relation with topography and lithology
Land cover factors	Land cover existing	From BGR	From BGR	Latest one from 2005 Poor quality	From BGR
	Land cover (earlier)	Two maps, not clear what date. General.	Unclear what the date is	2000	1982 2000 2009
	Road cuts	Moderate	Good	Good	Moderate

The data collection and compilation for the four countries is now nearly complete. Data was obtained in many different formats, and several different projections, from many different persons and organizations in the countries. All the data was transformed to UTM WGS84 projection, and is now available as shape files, GeoTIFF, and in ILWIS format. When the missing data from the BGS will be incorporated we can start with the actual susceptibility assessment.

4.6. Landslide susceptibility assessment

Overviews and classification of methods for landslide initiation susceptibility assessment can be found in Soeters and Van Westen (1996), Carrara et al. (1999), Guzzetti et al. (1999), Aleotti and Chowdury (1999), Dai et al. (2002), Cascini et al. (2005), Chacon et al. (2006), Fell et al. (2008), Cascini (2008) and Dai et al (2008). The selection of the optimal method depends on the size of the study area, the amount of available data, the scale of analysis and the experience of the susceptibility analysts, as indicated in chapter 1.

Figure 4.20 gives an overview of the available methods. For the landslide susceptibility project in the Caribbean island at a national level, we would like to use input data ranging in scale between 1:25,000 and 1:50.000, and raster maps with a pixel size of 5 meters.

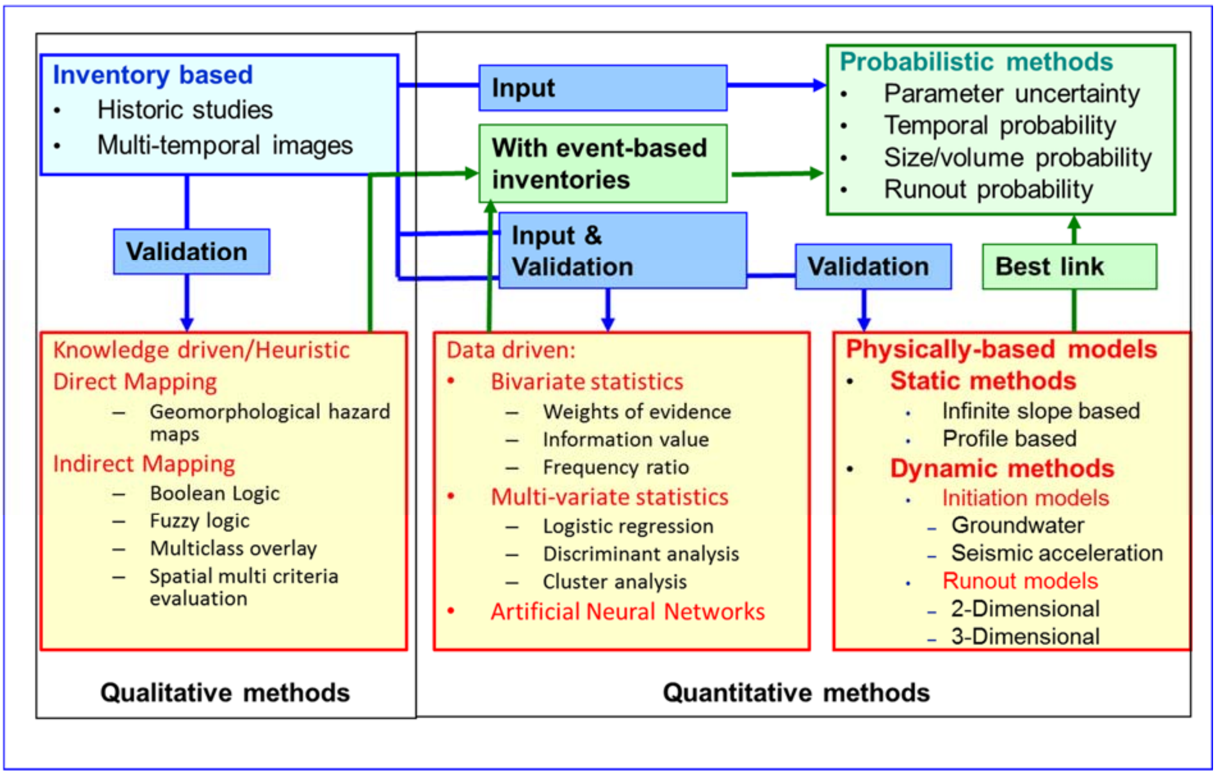


Figure 4.20: General classification of methods that can be used for landslide susceptibility assessment. In this case we suggest using a combination between Knowledge driven and data driven methods for initiation susceptibility assessment.

For the three scales of analysis different landslide susceptibility methods are proposed:

- National scale (1:25.000 – 1:50.000)
  Detailed inventories. Combination of statistical methods with Spatial Multi-Criteria Evaluation. Separate for road network.
  Methods: Weights-of-Evidence, FLOW-R, SMCE
- Local scale (1:10.000)
  Detailed mapping. Soil mapping. Simple physically based modelling approach, with hydrological component and infinite slope modelling component (e.g. TRIGGRS, STARWARS-PROBSTAT, RAMMS, FLO2D, DAN3D)
- Site investigation (>1: 5.000)

Geotechnical assessment. Detailed slope stability analysis, run-out modeling. Site-specific analysis using specific software (e.g. SlopeW, CHASM, Rockyfor3D, FLO2D, DAN3D) .

4.6.1. National scale susceptibility assessment

For this scale the use of physically-based modelling is not possible, as the parameterization of such models is not feasible for such large areas, due to the absence of reliable soil thickness information. Although there are soil maps available for most of the study areas, these are pedologic soil maps, and not engineering soil map, and do not contain information on soil thickness distribution or on the geotechnical and hydrological parameters required to carry out physically-based modelling. If we would still apply physically-based modelling using software such as SINMAP, SHALSTAB, TRIGGRS or STARWARS/PROBSTAT, this would be rather meaningless, as the slope angle distribution would completely dominate the analysis in the absence of the relevant factor maps.

For a statistical approach we require a sufficiently large landslide dataset that is related to different failure mechanisms, and contains different landslide types. Although the overall number of landslides per country is reasonable, there is a very large difference between the 4 countries, and the landslide inventories cover a large number of years, during which the causal factors might have changed (e.g. land use/land cover).

One of the main difficulties is that the triggering rainfall distribution that caused the landslides in the various landslide inventories is not known, as we do not have a sufficient amount of rainfall data to model the rainfall distribution for the specific event. It may be that certain triggering events produced much more rainfall in one part of the country, and if there are more landslides in the same area, this will overrule the importance of the topographic, lithological and other factors. Also the rainfall stations are mostly along the coast, and the variation of rainfall with elevation and orientation is difficult to assess. For that we intend to further study the DOMEX results from Dominica where a network of 10 rain gauges was used in a transect over the island. However, it is questionable whether the same relation could be applied to the other islands directly.

Another difficulty is that many of the earlier landslide inventories are not covering the entire country. For many of the inventory it is difficult to find out what the exact method of mapping was, and which criteria were used for the mapping. A number of inventories focus on landslide mapping along the roads, due to the lack of suitable imagery or skill for image interpretation.

Since the majority of the existing landslides that have been mapped in the field are located along the roads, the use of a statistical method would have resulted in a very large susceptibility along roads and a low susceptibility elsewhere, as the factor “close to roads” would have dominated very much over the other factors.

One major difficulty is when we would also include the scarps of the photo-interpreted landslides into account in the statistical analysis; we do not know the relative age of these and therefore would not use the current land use to correlate with the landslide occurrence. Land cover change as a factor would probably be much better.

For several countries we do not have sufficient event-based landslide inventories that relate to a particular triggering event. For many areas the date information is still rather incomplete and needs to be further improvement before it can be used in a temporal frequency analysis.

Given these considerations we propose the following approach, as illustrated in Figure 4.17 (black lines):

- Landslide initiation assessment.
    - For landslides along the roads: based on road segments, combination of statistical and expert-based methods
    - For landslide in the rest of the area: combination of statistical and expert-based methods. Separation per main types of landslides.
- **Landslide run-out assessment**: regional scale empirical run-out modelling.
- **Landslide susceptibility assessment**: using combination of initiation and run-out.
- **Landslide hazard assessment**: characterize the susceptibility classes with landslide density for specific return periods.

4.6.2. Landslide initiation assessment using statistical analysis

The best approach for landslide initiation susceptibility assessment at a scale of 1:25,000 - 1:50000 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 only used the landslides to check the statistical relation with the factor maps, but generate the actual landslide initiation susceptibility map using Spatial Multi-Criteria evaluation. A combination of statistical methods and expert-based methods should be used, in which the emphasis is on either one of the two, depending on the knowledge of the contributing factors, and the availability of sufficient landslide information.

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. There are several useful tools available that can be used with a conventional GIS system, without the need of external statistical models. Some of these tools are shown below. 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)

Frequency ratio method

$$FR = \frac{\text{Area of landslides in Class / Area of all Landslides}}{\text{Area of Class / Entire map}}$$

Hazard Index method

$$FR = LN \left[\frac{\text{Area of landslides in Class / Area of Class}}{\text{Area of all landslides in the map / Area of Entire map}} \right]$$

Weights of evidence method

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

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

Landslide susceptibility assessment using statistical methods is considered attractive methods by many researchers, as it is an objective method, which is also reproducible. This means that the same results could be obtained if it was repeated by other persons. However, this is not really true, as the method very heavily depends on the quality of the landslide inventory maps, and the contributing factor maps. And even more so it depends on the knowledge of the person that carries out the assessment. Such methods cannot be automated. They will also require a very substantial expert-based input, in deciding which factors (or combinations of factors) contribute to the occurrence of landslides.

Black box methodologies are very dangerous, and should be avoided. Expert-knowledge is essential, and high quality input data is essential.

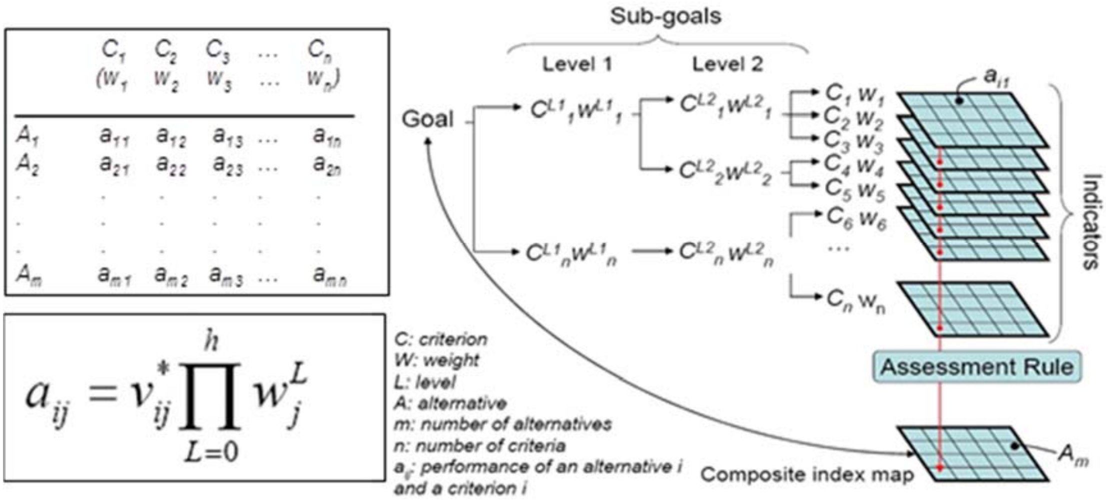
4.6.3. Landslide initiation assessment using SMCE

Spatial multi criteria evaluation is a technique that assists stakeholders in decision making with respect to a particular goal (in this case a qualitative risk assessment). It is an ideal tool for transparent decision making, using spatial criteria, which are combined and weighted with respect to the overall goal. For implementing the analysis in the countries, the SMCE module of ILWIS will be used. The input is a set of maps that are the spatial representation of the criteria, which are grouped, standardized and weighted in a criteria tree. 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 4.21

From a decision-making perspective, multi-criteria evaluation can be expressed in a matrix as shown in the figure 4.21. The matrix A contains the criteria in one axis (C1 to Cn), and a list of possible alternatives, from which a decision has to be taken on the other axis (A1 to Am). Each cell in the matrix (aij) 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 (W1 to Wn) 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. a11 to a1n for alternative A1).

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 (Cj) becomes a raster layer, and every pixel (or set of pixels) of the final composite index map eventually becomes an alternative Aj. The goal (risk index) has been decomposed into criteria levels CL1 and CL2. The intermediate levels are often indicated as sub-goals or objectives (e.g. in level 1, the sub-goals are a 'hazard index' and a 'vulnerability 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 (aij) and the alternative (Ai) will be identified for particular raster cells.



$$a_{ij} = v_{ij}^{*} \prod_{L=0}^{h} w_j^L$$

Figure 4.21: Schematic procedure for spatial multi-criteria evaluation based on the analytical hierarchical process

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 4.21).

In this equation, vij refers to the standardised value of criterion (Cj) for alternative (Ai), and weight wLj refers to the weight of criterion (Cj) 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.

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**.

An example of a possible criteria tree is shown in Figure 4.22. The actual criteria trees that we will use for the 4 countries will be different, as the selection of factors will be different per country, and also the standardization and weights will be different. We will also generate different criteria trees for different types of landslides, e.g. for shallow flow slides, rock falls and deep seated landslides separate criteria trees are made with different factors and weights, and the resulting maps will be combined.

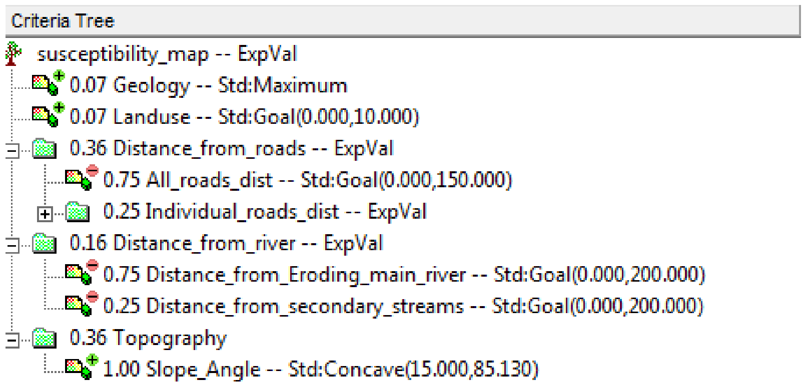


Figure 4.22: Example of a criteria tree used for landslide initiation assessment.

It is very 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 map sheet the experts that does the analysis should decide what the main contributing factors are, what their relative importance is, and assign the weights.

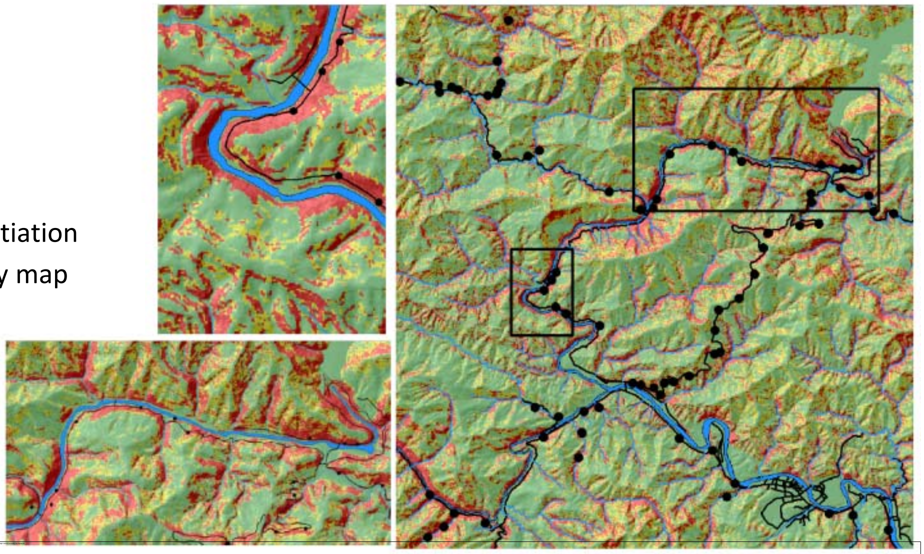
The method is transparent, as the stakeholders (e.g. the engineers and planners from the four countries) and other consultants can consult the criteria trees and evaluate the standardization and weights, and make adjustments.

We intend to classify the landslide initiation susceptibility maps into 3 – 5 classes (high, moderate and low). Figure 4.23 shows an example of the resulting susceptibility map for another study area in a tropical country (Vietnam) that we generated recently.

In the final susceptibility map also the historical landslides should be included, as these are the locations where landslides have actually occurred.

We intend to make different landslide susceptibilities for different landslide types, as they might be related to different combinations of causal factors. For instance: different susceptibility map for debris flows, deep seated landslides, and rock falls. We can also differentiate the initiation and accumulation susceptibility. If we do that the susceptibility classes would have a code indicating the type of landslide, and the erosion/accumulation part.

Landslide initiation susceptibility map



Landslide run-out susceptibility map

Combined landslide susceptibility map

Figure 4.23: Example of an initiation susceptibility map (Above), landslide run-out map (Middle) and combined susceptibility map (Below) for another test site in a tropical environment (Vietnam).The run-out areas are smaller than the initiation areas, as they are concentrated along the valleys.

4.6.4. Landslide run-out assessment

After generating the initiation susceptibility map, and classifying it into a number of classes, we will extract the high susceptible areas, and used these in a regional scale run-out model (Flow-R developed by the University of Lausanne). The national scale run-out modelling will be carried out using Flow-R (Horton et al., 2013), 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 (Flow path assessment of gravitational hazards at a Regional scale) is a distributed empirical model for regional susceptibility assessments of debris flows, developed at the University of Lausanne. It was successfully applied to different case studies in various countries. Flow-R first requires the identification of source areas before the actual run-out can be modelled. Two parameters are required to model the run-outs for each return period in the Flow-R model: (1) the minimum travel angle and (2) the maximum velocity. These two parameters can be estimated based on literature review or back calibrated based detailed run-out models. We aim to use different travel angles and maximum stopping velocity for different return periods, assuming that larger triggering events will result in larger landslides with longer travel angles.

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

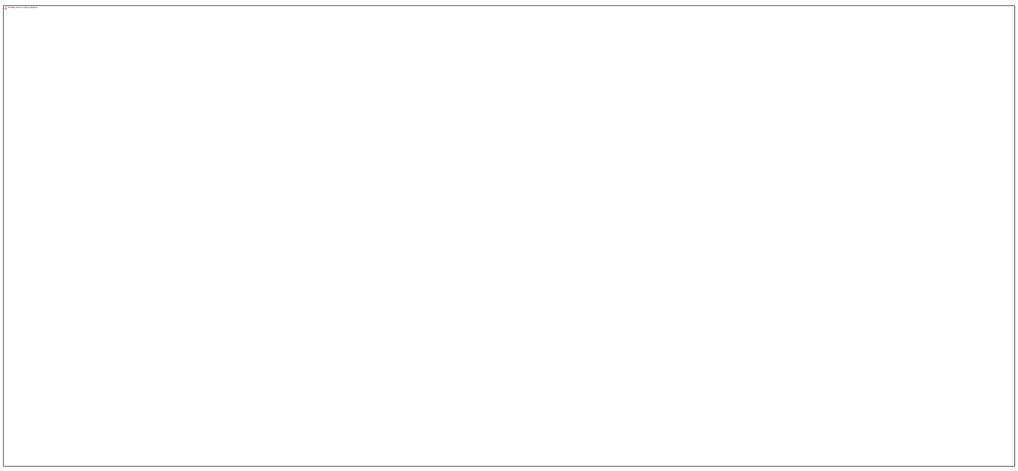


Figure 4.24: Principle of the energy calculation in the FLOW-R software. At the start (a), a source has a certain energy potential. Then during the spreading, a part of this energy is dissipated according to the chosen algorithm (b). The limit of kinetic energy intervenes, if it is activated, from a certain energy threshold (c). The flow stops when the energy becomes zero (d)..

Figure 4.25: Openings screen and input screen of the Flow-R software for regional scale run-out modelling

The result of the Flow-R model is two maps:

(1) a map showing the run-out probability for each pixel in the map;
(2) a kinetic energy map

Generally the first map is used and is classified into 3-5 classes.

4.6.5. Landslide susceptibility assessment along the road

As mentioned earlier, a separate susceptibility assessment is carried out for the road network, based on the road segmentation and characterization of the road segments with respect to landslide occurrence and road characteristics, like cut slopes, closeness to rivers, geology etc.

Based on the landslide inventory and the fieldwork, the road network is subdivided into homogenous road segments, with variable length using the following attributes: landslide occurrence, lithology, soil type, road side slope and height, drainage pattern (from above the road, along the road and below the road), land cover above the road and earthwork type(cut or fill). The lithology and soil type will be extracted from available geology maps and soil maps respectively together with field verification. These attributes were used by other authors for similar studies and they are proved to be significant factors for road related landslides (e.g., Anbalagan, 1992; Budetta, 2004; Das et al., 2010). Most emphasis will be given to the characterization of cut slopes (cut slope height, slope and length) and fill areas.

The landslide database and the road segment database will be digitized in GIS and will be the input for the landslide susceptibility and hazard assessment.

For assessing the landslide susceptibility statistical analysis will be used with road segments as mapping units, landslide frequency per unit length as dependent variable and the various terrain and material factors mentioned above as independent variables. Also Spatial Multi- Criteria analysis will be used to derive the final classification. This technique was used by Jaiswal et al., 2010 for a similar study.

4.6.6. Final Susceptibility map

The final susceptibility map will be made by combining the individual maps: the initiation susceptibility map and the run-out susceptibility map. This combination could be done using a two dimensional table:

		Initiation susceptibility		
Run-out susceptibility		**low**	**Moderate**	**High**
	Low	**Low**	**Moderate**	**High**
	Moderate	**Moderate**	**Moderate**	**High**
	High	**High**	**High**	**High**

Also the road susceptibility will be included in the final map. The final susceptibility map can be overlain with the parishes and enumeration districts to calculate the area and the percentage of high, moderate and low susceptibility per administrative unit. This information can be used to display as bar charts or table next to the map.

It is also possible to overlay the final susceptibility map with the buildings, roads, and agricultural fields and calculated the number, length or area per administrative unit, exposed to high, moderate and low susceptibility.

In order to avoid that the final susceptibility map has a large number of individual pixels with different susceptibility levels, it is advisable to apply a majority filter to the susceptibility map for a few times. The majority filter select for a group of 3 by 3 cells, the majority of the classes in the 9 cells and assigns this to the central cell. When this is done a few times isolated pixels with different susceptibility classes than the surroundings are removed.

Generation of a susceptibility map is an iterative process. It needs to be done in several stages:

- Generate an initial map
- Compare the results with the existing landslide pattern
- If there are sufficient landslides, generate a success rate curve
- Analyse where the resulting susceptibility map shows anomalies, and which contributing factors might be responsible for that.
- Adjust either the number of contributing factors, or combine some of the factors to make them more focused, or adjust the weighting of the contributing factors;
- Generate a new version of the susceptibility map
- Repeat the procedure

4.6.7. Validation of the final susceptibility map

Once the landslide susceptibility maps are generated they will be validated. There are several ways to validate the results:

- The simplest way of validation is to analyse the susceptibility values for the existing landslides. The susceptibility values are obtained for each landslide. They can then be plotted or arranged from high to low values.
- Another approach is to use the same operation after classification of the susceptibility map into the three classes. With this method it is possible to directly obtain the number of

landslides in the various susceptibility classes, and also to calculate which percentage of the landslides is in the high, moderate and low classes.

- The third option is to generate 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.

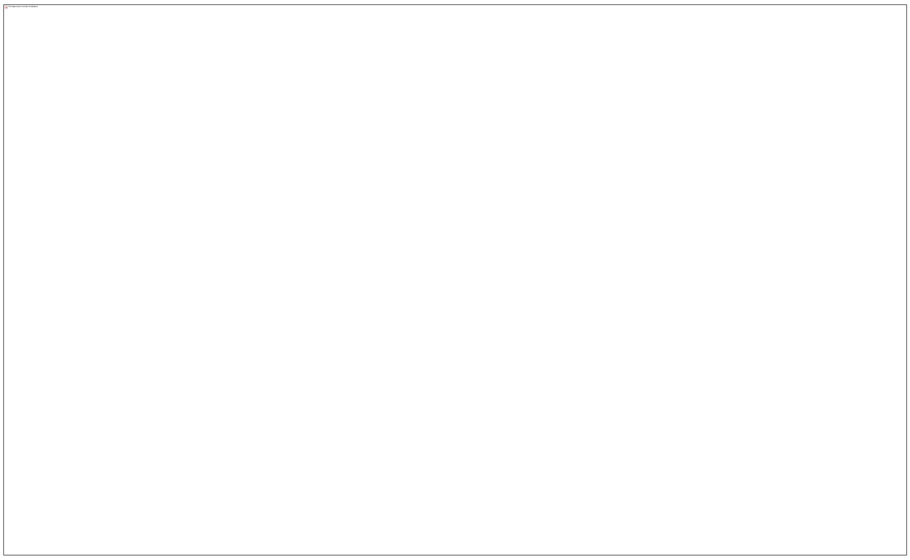


Figure 4.26: Success rate curve for the validation of the landslide susceptibility map.

When the validation is done with the same dataset that was used in a statistical model, we call the resulting curve a success rate curve, because what is tested is only whether the model explains the landslides that were used to make it. When you use a landslide data set that is different from the data set used for making the model, we can actually test the prediction capability of the map, and the resulting curve is called a **prediction rate curve**.

We would use the landslide datasets from the different triggering events, so that we can check whether a susceptibility map is capable of predicting new landslides. However, care should be taken here, as the conditioning factors (in particular land cover, or roads) might have changed which then makes that the prediction rate will be much less than the success rate.

When different susceptibility maps have been generated for different landslide types, it is also possible to generate success rate curves for the various maps. It may be that for certain types of landslides there is a much better prediction than for others. A better prediction means that a smaller part of the susceptibility map with the highest values contains most of the landslides, in order words that the majority of the landslides are within the highest susceptibility values.

Success rate curves can also be used to classify the susceptibility maps into the required number of classes. The curves can be used to select predefined levels for the percentage of the landslides and the corresponding area of the map. This is illustrated in the Table 4.14.

	Weights	Percentage landslides	Percentage area
High	>0.4	90 %	5.2 %
Mod	0.2-0.4	9 %	2.6 %
Low	<0.2	1 %	91.7 %

Table 4.14: Example of a table showing the classification of a susceptibility map based on the percentage of landslides and the percentage of the area.

The landslide validation methods explained above should not be taken as absolute. It often occurs that the historical landslide points are actually in low susceptibility zones, but in the immediate vicinity of high susceptibility zones. This is not shown when making the success rate curves. So in practice it is also equally important to carefully check the susceptibility map where the landslide points are overlain.

4.7. From susceptibility to hazard

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 done using antecedent rainfall analysis, for which the availability of a sufficient number of landslide occurrence dates is essential. An example for Dominica is shown in the Figure below.

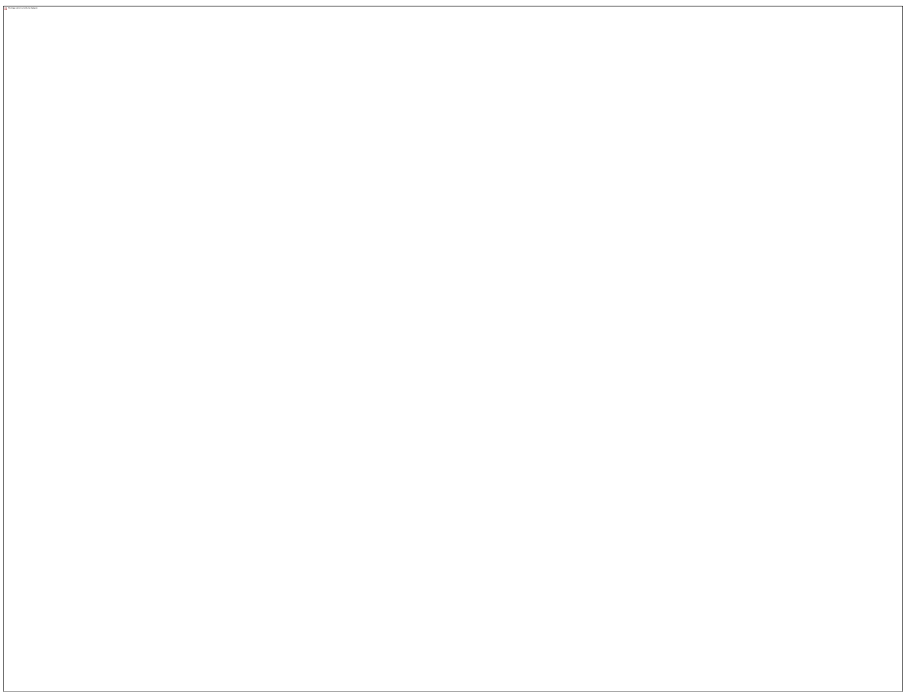


Figure 4.27: First results of rainfall threshold analysis for Dominica. Red dots indicate known landslide events, and blue dots represent other events.

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 converting the landslide susceptibility map into a landslide hazard map. 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.
The percentage of all landslides within the map sheet. Ideally high susceptible areas should have at least 75% of all landslides, the moderate areas maximum 25 % and the low susceptible areas should have less than 2 % of all landslides. We should define this for all the maps sheets, so that these rules apply everywhere.
The density of landslides per unit area (km2). The legend of the final map should explain the expected landslide density for each of the legend units. The highest susceptibility class should also have the highest density. We probably cannot use fixed thresholds for this for the entire country, as there are areas that have a much higher landslide density than others.

Legend classes	Explanation	Percentage of all landslides	Landslide density: Major event Return Period:	Landslide density moderate event Return Period:	Landslide density Minot event Return Period:
Existing landslides	With suffixes indicate: - Type of landslide - Activity (relative age) - Scarp/accumulation areas				
High susceptibility	Limited areas that should be avoided in spatial planning due to their high landslide occurrence	>75%			
Moderate susceptibility		Max 25%			
Low susceptibility	As large as possible area, that have no or only a few landslides. Can be considered safe for spatial planning	< 2 %			
Not susceptible	Areas with certainty that no landslides are likely to occur	0 for certain			

Table 4.15: Legend classes of the landslide susceptibility map, and the additional columns calculated using event-based inventories for different triggering events, with different return periods will also be used to characterize the classes with respect to landslide densities

If there are sufficient landslides along the road segments the method proposed by Jaiswal & van Westen (2009) will be used for determining the temporal probability of landslide events. The method uses the probability of exceedance of an empirically derived rainfall threshold and the probability of occurrence of landslides related to the rainfall threshold for the analysis. Rainfall thresholds will be determined empirically using combinations of daily and antecedent rainfall. Based on the threshold values, its exceedance probability will be determined using Poisson probability model which gives the probability of having one or more landslides. Landslide frequency probability will then be estimated on a condition that the threshold has been exceeded. The temporal probability will finally be calculated by multiplying the two probability values.

4.8. Suggested methods for landslide susceptibility assessment at the other scales

As was mentioned in section 4.1 landslide susceptibility assessment aims at subdividing the terrain in zones that have a different spatial likelihood that landslides of a particular type may occur in future. The previous chapter explained in more detail the method proposed for the national scale landslide susceptibility and hazard assessment. This chapter will highlight methods that can be used at the local and site investigation scale.

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 models that are applied at a local scale make use of the infinite slope model and are therefore only applicable to modelling shallow translational landslides. They can be subdivided in static models that do not include a time component, and dynamic models, which use the output of one time step as input for the next time step. Physically-based models for shallow landslides account for the transient groundwater response of the slopes to rainfall and or the effect of earthquake acceleration. The transient hydrology component is incorporated assuming a slope parallel flow either in its steady state as a function of slope and drainage area (called steady-state models) or by dynamically evaluating the entire process from rainfall to the transient response of the groundwater (called dynamic models).

Dynamic models are capable to run forward in time, using rules of cause and effect to simulate temporal changes in the landscape. A dynamic landslide susceptibility model addresses the spatial and temporal variation of landslide initiation. They are therefore also applicable in the landslide hazard assessment. However, the resulting maps show the Safety Factor for each pixel for a given scenario. It is still complicated to determine the possible landslide size, although this is done by grouping pixels with the same low Safety Factors into potential landslide polygons. Physically-based models are also applicable to areas with incomplete landslide inventories. The parameters used in such models are most often measurable and are considered as state variables having a unique value for a given moment in time and space. Most physically-based models are dynamic in nature, implying that they run forward (or backward) in time constantly calculating the values of the state variables based on the equations incorporated. If implemented in a spatial frame work (a GIS model) such models are also able to calculate the changes in the values with time for every unit of analysis (pixel).

The results of such models are more concrete and consistent than the heuristic and statistical models, given the white box approach of describing the underlying physical processes leading to the phenomena being modelled. They have a higher predictive capability and are the most suitable for quantitatively assessing the influence of individual parameters contributing to shallow landslide initiation. However, it is often more time consuming and resource intensive to derive the necessary data required for physically-based models. The parameterization of these models can be complicated, in particular the spatial distribution of soil depth, which plays a decisive role. The advantage of these models is that they are based on slope stability models, allowing the calculation of quantitative values of stability (safety factors). The main drawbacks of this method are the high degree of oversimplification and the need for large amounts of reliable input data. The methods are applicable only over larger areas only when the geomorphological and geological conditions are fairly homogeneous and the landslide types are simple. The methods generally require the use of groundwater simulation models. Stochastic methods are sometimes used for selection of input parameters.

Apart from GIS-based models for slope stability assessment, there is also a range of detailed 2-D and 3-D models that normally are applied on a site investigation scale (e.g. Slope/W, SLIDE, CLARA etc.). These require detailed information on geotechnical parameters, soil/rock layers, failure mechanisms, hydrological situation and seismic acceleration.

Numerical modelling applications can be subdivided in continuum modelling methods (e.g. finite element, finite difference, with software such as FLAC3D, VISAGE) and discontinuum modelling (e.g. distinct element, discrete element, with software such as UDEC). Limit Equilibrium Methods do not allow the evaluation of stress and strain conditions in the slope and are incapable to reproduce the crucial role played by deformability in slope movements (Bromhead, 1996; Van Asch et al., 2007). Finite Elements Methods and Finite Difference Methods are able to handle material heterogeneity, non-linearity and boundary conditions, but due to their internal discretization they cannot simulate infinitely large domains and the computation time can be problematic. Boundary Element Methods require discretization at the boundaries of the solution domains only, which simplifies the input requirements, but they are impractical when more than one material must be taken into account. It is the most efficient technique for fracture propagation analysis. Distinct Element Methods represent a discontinuous medium as assemblages of blocks formed by connected fractures in the problem domain, and solve the equations of motion of these blocks through continuous detection and treatment of contacts between the blocks. Handling large displacements including fracture opening and complete detachments is therefore straightforward in these methods although they are less suitable to model plastic deformation.

Hence, any numerical simulation will contain subjective judgements and be a compromise between conflicting detail of process descriptions and practical consideration. It is essential to define guidelines for the development of physically-based models that perform satisfactorily for a given problem (Van Asch et al., 2007).

Table 4.16: Recommended methods for physically-based landslide suscepibility assessment

Type	Method	References
GIS-based limit equilbrium methods	Static infinite slope modeling (e.g. SINMAP, SHALSTAB)	Pack el al. 1998; Dietrich et al., 1995
	Dynamic infinite slope modeling with rainfall trigger (e.g. TRIGRS, STARWARS +PROBSTAB	Baum et al, 2002; Van Beek, 2002; Casadei et al. 2003; Simonie t al., 2008
	Earthquake induced infinite slope modeling (e.g. Newmark)	Jibson et al., 1998
Kinematic analysis for rockslopes	Stereonet plots, GIS based analysis of discontinuities (e.g. SLOPEMAP, DIPS)	Gunter, 2002;
2-D Limit equilibrium methods	2-D LEM with groundwater flow and stress analysis. E.g., SLOPE/W, SLIDE, GALENA, GSLOPE	GEO-Slope, 2011;
3-D Limit equilibrium methods	3-D slope stability analysis, e.g. CLARA-W, TSLOPE3, SVSLOPE	Hungr, 1992; Gilson et al, 2008
Numerical Modeling	Continuum modeling (e.g. finite element, finite difference) , FLAC3D, VISAGE	Hoek et al, 1993; Stead et al, 2001
	Discontinuum modeling (e.g. distinct element, discrete element), e.g. UDEC	Hart, 1993; Stead et al., 2001

4.8.1. Selecting the best method of analysis

Not all methods for landslide hazard zonation are equally applicable at each scale of analysis. Some require very detailed input data, which can only be collected for small areas at the expense of a lot of efforts and costs.

Therefore a selection has to be made of the most useful types of analysis for each of the mapping scales, maintaining an adequate cost / benefit ratio. Table 8.2 gives an overview of the methods for landslide hazard analysis and recommendations for their use at the three scales of analysis.

There are several aspects that should be considered:

- Selection of a method should suit the available data and the scale of the analysis. For instance, selecting a physical modelling approach at small scales with insufficient geotechnical and soil depth data is not recommended. This will either lead to large simplifications in the resulting hazard and risk map, or to endless data collection.
- In the case of lacking or incomplete landslide inventories, heuristic methods can still be applied.
- Different landslide types are controlled by different combinations of environmental and triggering factors, and this should be reflected in the analysis. The landslide inventory should be subdivided into several subsets, each related to a particular failure mechanism, and linked to a specific combination of causal factors. Also only those parts of the landslides should be used that represent the situation of the slopes that failed.
- Use of data with a scale or detail that is not appropriate for the hazard assessment method selected should be avoided.
- One should take care not to select factor maps because they can be easily obtained, such as DEM derivatives on a regional or local scale, or the use of satellite derived NDVI values as a causal factor instead of generating a land cover map.
- Methods should take into account the specific characteristics of the Caribbean islands, in terms of their volcanic soils, high weathering degree, intense rainfall, and tropical vegetation cover.

Table 4.17 Important aspects in the use of the main methods for landslide susceptibility assessment a tht ethree scales of analysis. Colours indicate: green: best, yellow: useful as supporting tool or alternative, Orange: not applicable.

	Important aspects	**Applicability at the defined scales of analysis**		
		National scale	**Local scale**	**Site investigation scale**
Inventory methods	• Limited to knowing the spatial and temporal distribution. • Can be carried out at all scales of analysis. • Difficult to apply at small scales (it is quite time consuming to map landslide distribution over large areas, using image interpretation). • Used in combination with a heuristic or statistical method at larger scales.	Yes, but difficult to obtain event-based landslide inventories due to the rapid vegetation growth and unavailability of high resolution images after major events in the past. Emphasis should be given on the local collection of landslide data in the islands.	Important supporting tool for the analysis at this scale is to map out in detail the landslides, also using community-based approaches.	Important supporting tool for determining local hazard. Detailed mapping is required.
Heuristic methods	• A dominant role for the expert opinion of the analyst. • Can be used at all scales of analysis. • Increasing detail of the input data, going from small to large scales. • Highly subjective, depending on the skill and experience of the analyst, but may result in the best output results, since they do not lead to generalization.	Best method at this scale. Causal factors and triggering factors can be weighted. In combination with statistical methods.	In case physically based models turn out to be too complicated, this is the other alternative to be used at this scale.	In case physically based models turn out to be too complicated, this is the other alternative to be used at this scale.
Statistical methods	• The relative importance of the causal factors for landslides is analysed using bivariate or multivariate statistics. • These methods are objective, since the weights for the different factor maps contributing to slope instability are determined using a fixed method. • They may lead to generalizations in those cases where the interplay of causal factors is very complex	Best method for this scale. Correlating past landslides with combination of factors, in combination with heuristic methods	Not so applicable at this scale due to the limited spatial variability of the input factors.	No, not enough spatial variability of input factors.
Physically-based modelling	• The hazard is determined using slope stability models, resulting in the calculation of factors of safety and failure probabilities. Provides the best quantitative information on landslide hazard. • Can be used directly in the design of engineering works, or the quantification of risk. • Requires a large amount of detailed input data, derived from laboratory tests and field measurements. • Suitable only over small areas at large scales.	No, too difficult to parameterize the models. There is not enough information available on soil depth, geotechnical properties and hydrological properties of soil materials to do this.	Yes, best method for this scale. But only if the area if fairly homogeneous, and it is possible to generate soil maps which indicate the soil thickness and geotechnical & hydrological properties.	Yes, best method for this scale. Different approaches can be selected, depending on the landslide type. Detailed ruinput modelling is also possible for specific sites. Should serve as basis for design of engineering measures.

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