

## Caribbean Handbook on Risk Information Management



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# CHaRIM Project

## Saint Lucia National Flood Hazard Map

### Methodology and Validation Report

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# 1 National flood hazard map St Lucia

## 1.1 Caribbean flash floods

The Caribbean islands are frequently plagued by floods as a result of heavy rainfall during tropical storms and hurricanes. These floods are termed “flash floods”, from their rapid onset and relatively short duration, and are directly caused by runoff produced during a rainfall event. The islands mostly consist of a central mountain range, with small catchments ranging from the center part of the island to the sea. These catchments can be anything from 5 to 50 km<sup>2</sup> in size. Hydrologically speaking, each island is made up of up to 50 larger catchments, with various types of land cover and soils, determining the hydrological behavior.

In tranquil conditions the rivers have a low baseflow level, fed by local groundwater bodies constrained to the valleys. During a tropical storm, the soils on the slopes quickly saturate and literally overflow, or the rainfall intensity can be so high that the infiltration capacity of the soil is not sufficient. Hence severe overland flow and erosion may take place, leading to flooding along the river channels. The water level can rise from 0.5 m to more than 4 m at given locations, within 2 hours' time (sometimes much less) from the start of the rainfall. Since many valleys are inhabited, especially near the coastline, these flash floods can cause great damage and casualties. The shape and condition of the river channel has a large influence of the flood behavior: small and narrow channels quickly overflow, or channels that have a decreased size because of sediment may overflow much more quickly.

Flooding circumstances can be aggravated by man-made decisions or behavior such as:

- channels that are blocked by debris (e.g. at bridge locations) and are not regularly cleaned;
- channels that are diverted to circumvent habitation, leading to unnatural bends and flow paths that cannot handle extreme discharges;
- culverts and bridges at road crossings may be under-dimensioned, leading to backflow and rising water levels;
- Individuals extend their property into the river channel flood plain, thus narrowing the potential flow path.

It is a mistake to think that only the lowest areas in a catchment, i.e. the villages on the coastline, are subject to flooding. Also in the upstream valleys in the hills flooding occurs, which are often inhabited and the major valleys have important transport corridors that allow you to cross over the island. Moreover, upstream flooding may actually be considered positive if a valley is uninhabited, as the temporary retained flood water would otherwise contribute to the hazard downstream. It is therefore important to consider flood hazard as part of an integrated catchment analysis, and not focus on single isolated occurrences.

Given these conditions where the flood hazard is directly related to the rainfall-runoff processes in the catchments, a national flood hazard map for the islands should be based on a flood hazard model that takes these into account.

## 1.2 The national flood hazard map

The national flood hazard map shows the *potential* flood hazard of all the catchments and locations on the island where flooding may take place. The information shown is *flood extent* only, water depth information is not included in this map. At this scale and resolution, water depth information is not accurate enough to make a hazard classification combining depth and extent. The flood extents relate to design rainfall events that have a return period of 1:5, 1:10, 1:20 and 1:50 years. The map is produced on a scale of 1:50,000 based on GIS raster data layers used in the flood model with a gridcell resolution of 20x20m.

This effectively means that the map can only be used as an indication of where flood may occur, and be used to check which settlements and areas are exposed to floods. The infrastructure and buildings are deliberately shown in a generalized way, as is common with 1:50000 scale maps.

In chapter 6 of this report, a quality analysis is done based on a visual inspection and evaluation by the stakeholders in this project. Also the results are compared to two detailed flood hazard analysis projects that were done before. Based on this it can be concluded that:

The CHARIM national flood map of 2016 has been evaluated by government representatives and according to their judgement it offers a reasonable amount of detail. It correctly indicates places that are flooded regularly. It is consistent with earlier hazard analyses executed in St Lucia, and at times even very similar to detailed site analysis that were performed in those studies, especially in the floodplains near the coast. In the upper reaches of the catchments, the flood analyses may be somewhat exaggerated, as the accuracy of the DEM and the presence of an actual stream channel determines the flood hazard.

As such, the national flood hazard map is a tool to gain more understanding on flood hazard on an island level, as an input for national planning, risk reduction and disaster preparedness. The map gives an indication of exposure of built up areas and infrastructure to flood hazard. It can be used to judge which communities should prepare themselves for a given hazard magnitude.

However, at this scale it has inherent uncertainties due to reasons explained below (in points 3 and 4). Therefore, the map and associated information is indicative and cannot be used to provide details for individual properties or engineering design. It can be used as a first approximation, and serve as guidance to locate where a more detailed site investigation should be done to reduce local risk.

The methodology is based on the following considerations:

1. **Rainfall:** the frequency and magnitude of the floods is assumed to be the same as the frequency and magnitude of the rainfall that causes it. In the model simulations, the island is subjected to a rainfall event that covers the entire island at the same time, without spatial differences. These are statistically derived artificial rainfall events (so called design storms), that do not resemble the dynamics of a real storm with a moving weather front and erratic variations in intensity. Therefore this map does **not** show what will happen exactly during a real event of a comparable magnitude. The return periods used are 1:5, 1:10, 1:20 and 1:50 years. In the rainfall analysis (chapter 4) it is shown that the extreme rainfall with higher return periods (above approximately 1:30 years) is due to category 4 and 5 hurricanes and large tropical storms. These storms seem to be in a separate category compared to local weather conditions (they do not fit well in the probability density function). Further extrapolation to 1:100 years or more was not considered statistically sound given the rainfall database.

2. **Land use and soils:** the differences in flooding between the catchments for a given rainfall are caused by differences in relief, land use/land cover and soils. Especially soil moisture storage capacity and infiltration rates determine how a catchment reacts to rainfall). The initial moisture content on the entire island is set to 85% of the porosity, which is generally half way between field capacity and saturation. These conditions apply in the wet season when most hurricanes and tropical storms occur.
3. **Buildings and infrastructure:** on a national scale, certain details cannot be simulated, such as the effect of bridges and culverts, as well as the presence of debris and excessive sediment from previous storms in the river channel.  
Also the fact that some roads are elevated and may act as temporary barriers is not included. The only known flood barrier included is the barrier that protects the Hewanorra international airport in the south of the island.  
The effect of buildings is included to a certain extent (explained in section 5.3).
4. **Spatial data quality:** the quality of the model results depends to a large extent on the quality of the input data. Care has been taken to use the existing data as much as possible, so that the results are close to the island circumstances. Where needed literature values are used, or values measured on the other islands in the CHARIM project (for instance soil hydrological data on Grenada).

### 1.3 Return periods

It is important to realize what exactly a return period (or recurrence interval) of 1:X years actually means. A 1:5 year storm means that **on average** over a long period, a storm of a given magnitude and duration **is exceeded** once every 5 years. This does **not** mean that a 5-year storm will happen regularly every 5 years, or only once in 5 years, despite the connotations of the name "return period". In any given 5-year period, a 5-year event may occur once, twice, more, or not at all.

This can be explained as follows. Statistically the probability of a 1:5 year storm occurring is 0.2 per year, and therefore each year it has a probability of 0.8 of **not** occurring. If the storm hasn't happened several years in a row, the probability that it will occur in the following year increases. If it hasn't happened in 2 years, the probability of not occurring is reduced to  $0.8 \times 0.8 = 0.64$ . If it hasn't happened 5 years in a row, the probability of the storm not occurring has reduced to  $0.8^5 = 0.33$ , and so forth. The probability that it will occur after 5 years of not occurring is  $1 - 0.33 = 0.67$ . In other words, there is a 67% chance that a 1:5 year storm occurs after the next 5 years. Continuing this reasoning it is 99% certain that such a storm will happen within the next 20 years.

### 1.4 The 2015 Draft version of the national flood map

A draft flood hazard map was created with LISEM simulations in 2015 and discussed with the partners from Saint Lucia (Water Resources Management Authority). A second set of simulations were done based on these discussions, field visits with the Water Resources Management Agency (WRMA) to the Bois d'Orange watershed, and the request of the World Bank to use the latest land cover maps. The following changes were made to the database:

- The 2015 map was created using as input the 2004 land cover map (shape file) and certain assumptions on the channel dimensions. The latest land cover map is created by the British Geological Survey based on a supervised classification of high resolution images (2m resolution).

The land use directly influences soil physical parameters in the modelling setup (explained in this report).

- A relation was found in literature to derive channel dimensions from catchment size (Allen and Pavelsky, 2015), which seem to fit field observations better. A field visit and channel cross section measurement for a HECRAS exercise done with the WRMA, showed that the channels in the first database were generally too narrow. Section 5.1 explains in more detail how the channel dimensions (width and depth) are created.

## **1.5 Calibration and verification**

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.

Unfortunately, Saint Lucia does not 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). Hence the flood water level shown, depict mostly the channel depth (bank full conditions). Since the river channel cross sections may change rapidly because of sedimentation and erosion, the water level cannot be used, even when the location is known. Calibration against known discharge was therefore not possible. It is strongly suggested to revive the gauging stations and establish calibration curves. There are a number of early warning systems active that monitor river water level, these could be used easily.

The flood extent maps were verified in a discussion with counterparts from the WRMA and other agencies in 2015. In general all known flood locations were considered to be correct, but the draft version of the map from 2015 was considered to give too much flood hazard, in locations that normally did not flood in the experience of the agencies. Also several other flood hazard maps were created for St Lucia. These are compared to this flood hazard analysis in chapter 6 of this report.

## **2 Methodology**

### **2.1 Requirements for the flood model**

Based on the physiography and topography of Saint Lucia, the following terms of reference for the flood hazard assessment were used:

- 1) There is no viable discharge data, therefore rainfall is used to simulate the flash flood process. This means that a flood model has to be able to simulate the surface hydrology of entire catchments, both upstream and downstream areas. Since settlements are also spread out over the islands, flooding occurs not only near the coast (where the largest villages are) but also in higher valleys.
- 2) The flood model has to be able to use the existing national spatial datasets, so that when better data becomes available, simulations can be done again relatively easily. Formats used are standard GeoTIFF. Data gaps are filled by knowledge and data pooled from the islands



and from literature. Thereby we rely as little as possible on variables/constants/assumptions from general worldwide datasets, acquired in environments that are very different.

Based on these requirements we selected the integrated flood model **LISEM** (freeware and open source developed at the Utrecht University (1992-2006) and subsequently by the ITC (2006-current), in the Netherlands. LISEM is a model that was initially developed to simulate the effect of land use changes at farm level for sustainable land management, to combat erosion and desertification. Recently a 2D flood module was added to enable integrated flood management. It is an spatial event based model that operates at timescale of < 1 minute and spatial resolutions of < 100m grid cells. It does not model groundwater and evapotranspiration because it focuses on the consequences of single rainfall events.

## 2.2 National scale hazard assessment methodology

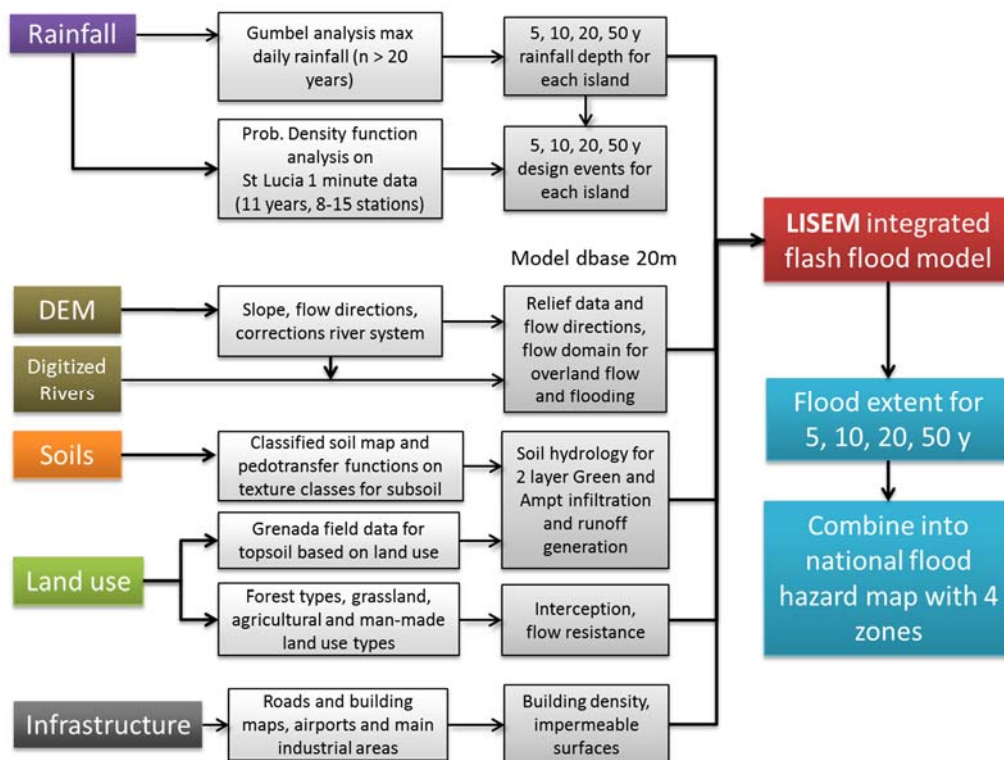
Figure 1 shows the framework that is used to create the flood hazard map (each step is explained in detail in subsequent sections):

- A frequency magnitude analysis of daily maximum rainfall of all stations that had 20 years or more of daily rainfall data. Generalized Extreme Value distributions were fitted to these datasets to determine the daily rainfall with return periods of 5, 10, 20 and 50 years.
- Design events were created using the network of 8 tipping bucket rainfall stations on Saint Lucia, which have datasets between 5 and 11 years. Using the rainfall depth from the maximum daily values, and duration and intensity data from the tipping bucket stations, design curves were created using a Johnson Probability Density Function.
- The DEM was created from existing elevation isolines in the national GIS database. From these lines a continuous surface was interpolated using block kriging, for a 10m grid. This was then resampled (averaged) to a 20m resolution for the modelling. The DEM boundary was used as coastline and very small islands and peninsulas were eliminated. The DEM was used directly in the modelling but also to correct the vector based river network.
- The land use map and soil class map were used to derive a number of soil physical and vegetation parameters used for the surface water balance of the model.
- The infrastructure, i.e. the road network and buildings were taken from the shape files in the national database.
- The model output consists of the maximum flood level reached during the event, the maximum water velocity the duration of the flood, the time since the start of the rainfall when a pixel is first inundated, and statistics about the total surface of buildings in different flood depth classes. From this data the extent was used for the flood hazard map. Note that pixels with less than 10 cm of water were not counted as flood pixels. The 4 flood extent maps were combined into a hazard map with 4 zones (corresponding to areas flooded with the 4 design events).

## 3 Model software – LISEM

The method is based on the open source integrated watershed model LISEM. This model is based on the well-known LISEM erosion/runoff model (see e.g. Baartmans et al., 2012, Hessel et al., 2003, Sánchez-Moreno et al., 2014), combined with the FullSWOF2D open source 2D flood package from the University of Orleans (Delestre et al., 2014). As a runoff model LISEM has been used in many

environments, European humid and semi-arid areas, islands (Cape Verde), East Africa (cities of Kampala and Kigali), India, Indonesia, Vietnam and Brazil.



**Figure 3.1. 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.

LISEM is a hydrological model based on the surface water and sediment balance (see fig 3.1). In CHARIM only the water processes are used, erosion and sedimentation is not simulated. 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. Above ground processes are interception by vegetation and roofs, surface ponding and infiltration. The resulting runoff is derived from a Green and Ampt infiltration calculation for each gridcell, and routed as overland flow to the river channels with a 1D kinematic wave. The routing takes surface resistance to flow into account. 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. Figure 3.2 shows schematically the steps in the model from runoff to flooding. Since it is an event based model, LISEM does not calculate evapotranspiration or groundwater flow.

Figure 3.4 shows how LISEM deals with sub gridcell information. Layers with objects smaller than a gridcell can be added, which are then defined as a fraction (buildings and vegetation) or by their width (roads and channels). Roads, houses and hard surfaces (e.g. airports runway) are considered impermeable, smooth and have no vegetation interception. Houses are impermeable but have roof interception and to some extent obstruct the flow. LISEM ‘looks’ vertically along all the information layers to determine the hydrological response of each gridcell.

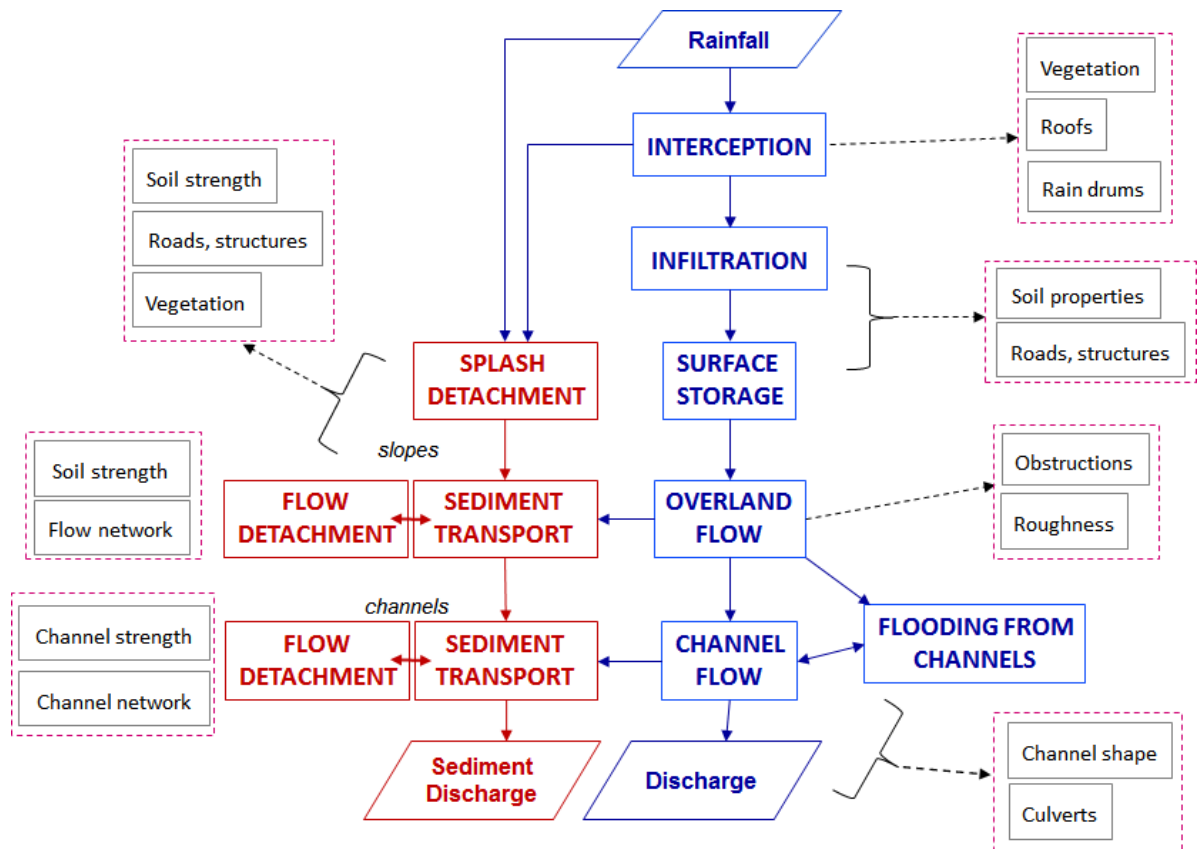


Figure 3.2. Flowchart of the water and sediment processes in LISEM. In dashed lines the main parameters are given. In CHARIM only the water processes are used (in blue).

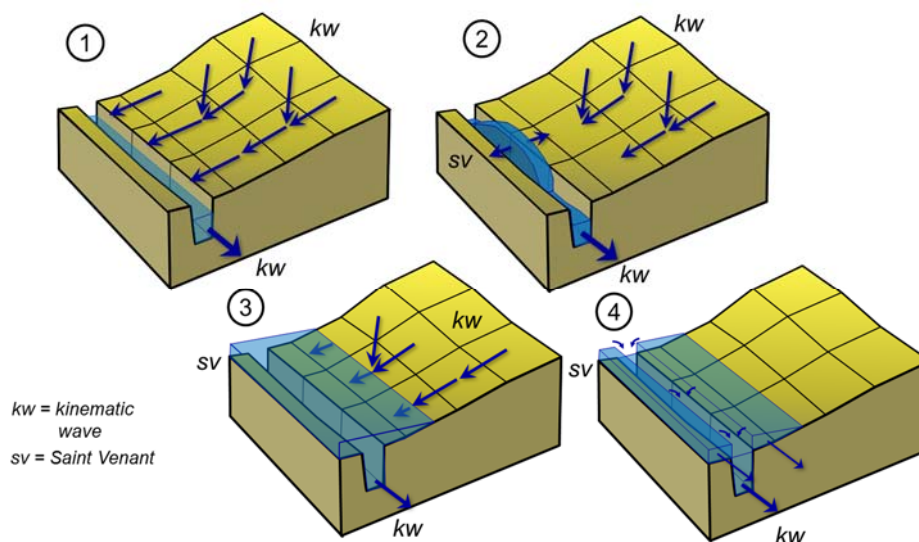
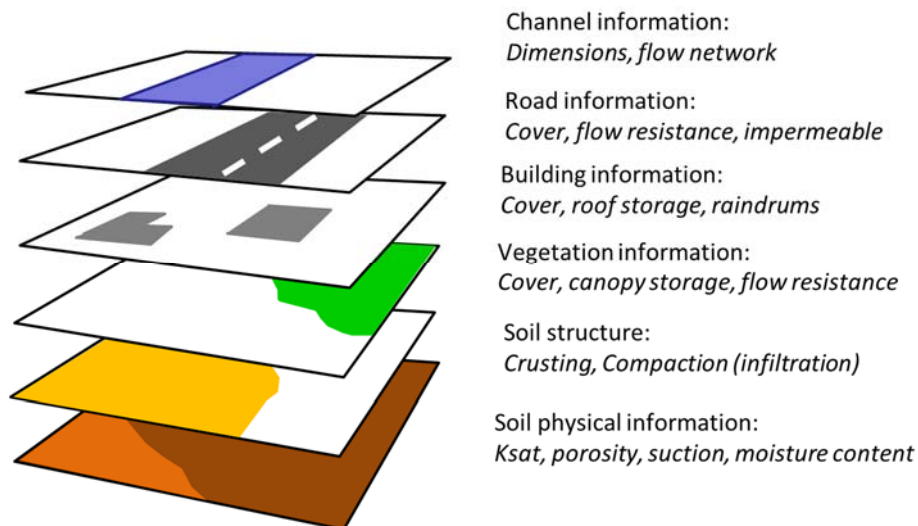


Figure 3.3. Schematic representation of flow processes from 1D kinematic wave runoff and channel flow (1), to overflow of channels (2), spreading out of water from the channels outward using 2D full Saint-Venant equations (3), and flowing back into the channel when water levels drop, most likely the runoff has stopped by now (4). Runoff continues to flow into the flood zone for a short distance.



**Figure 3.4.** 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 or house is. Infiltration and flow resistance are determined as a gridcell weighted average response.

This setup needs a lot of data, because in a raster GIS, that is essentially what LISEM uses, each property is defined in a new map layer. For instance the channel is characterized by 7 maps, for width, depth, angle of the channel sides, bed slope, flow resistance, and areas with imposed maximum flows (for bridges and culverts). The total number of input maps for LISEM looks daunting at a first instance, but they are all derived from 6 basic maps and several tables with soil and vegetation properties. This is explained in detail below. In the CHARIM project, a GIS script is created to do this automatically. The GIS used is the freeware GIS PCRaster developed at the Utrecht University, the Netherlands ([pcraster.geo.uu.nl](http://pcraster.geo.uu.nl)). This is just for convenience, in principle LISEM can use data from other GIS systems if it is in GeoTIFF format.

## 4 Rainfall data analysis, return periods and design storms

LISEM 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. Saint Lucia has an extensive network of daily total rain gauges, and also automatic tipping bucket rain gauges, that give 1 minute intensities data since 2003 (but not operational 100% of the time).

A frequency magnitude analysis is done on the annual maximum daily rainfall of all stations. This gives us the maximum daily rainfall for different recurrence intervals. Subsequently, design storms are created with 5 min intensities that have a total rainfall depth corresponding to the daily maximum values.

### 4.1 Recurrence intervals

There are 18 stations on St Lucia that have long records, mostly from 1955 to 2014. These stations are shown in Figure 4.2 (yellow dots are stations with long records). Not all stations have full records for the entire period (varying from 21 to 54 years with daily data, see fig 4.1 for an impression of the quality of the stations). Years with less than 60% of the days with valid records were excluded.

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

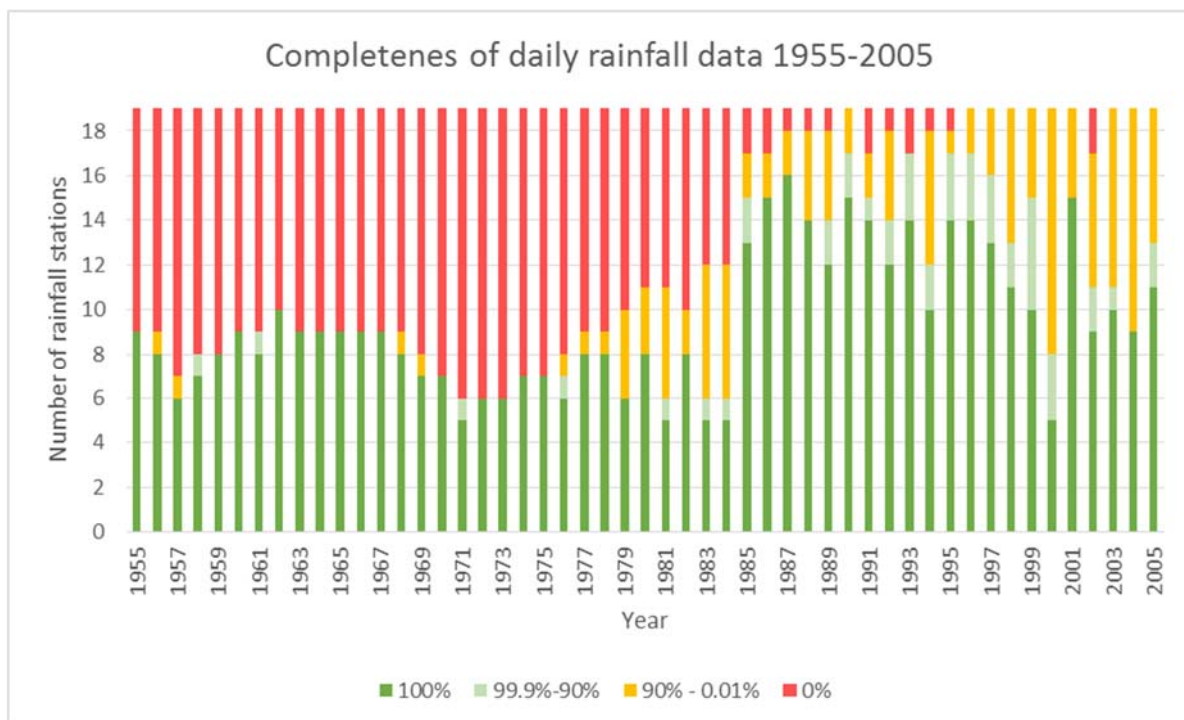


Figure 4.1. An impression of the Station record quality, with 0% = missing data. The 18 stations are given in fig 4.2 as yellow dots.

The next step is to look at the extremes, but this cannot be done by regarding each station as a separate entity, independent of the others. A major rainfall event should influence many or all



stations on the same date to some extent and it is assumed that a large daily rainfall cannot occur in one station only. However, not all stations always record an event on the same day, sometimes a value is the sum of several days, see figure 4.3. This is an example of Hurricane Debbie (9/9/1994). It shows that for some records, the instrument has not been read for a number of days, and the rainfall is therefore an accumulated reading (stations Cap and Hewanorra). It was therefore assumed that the maximum recorded daily rainfall in a 10 day period is from the same storm event.

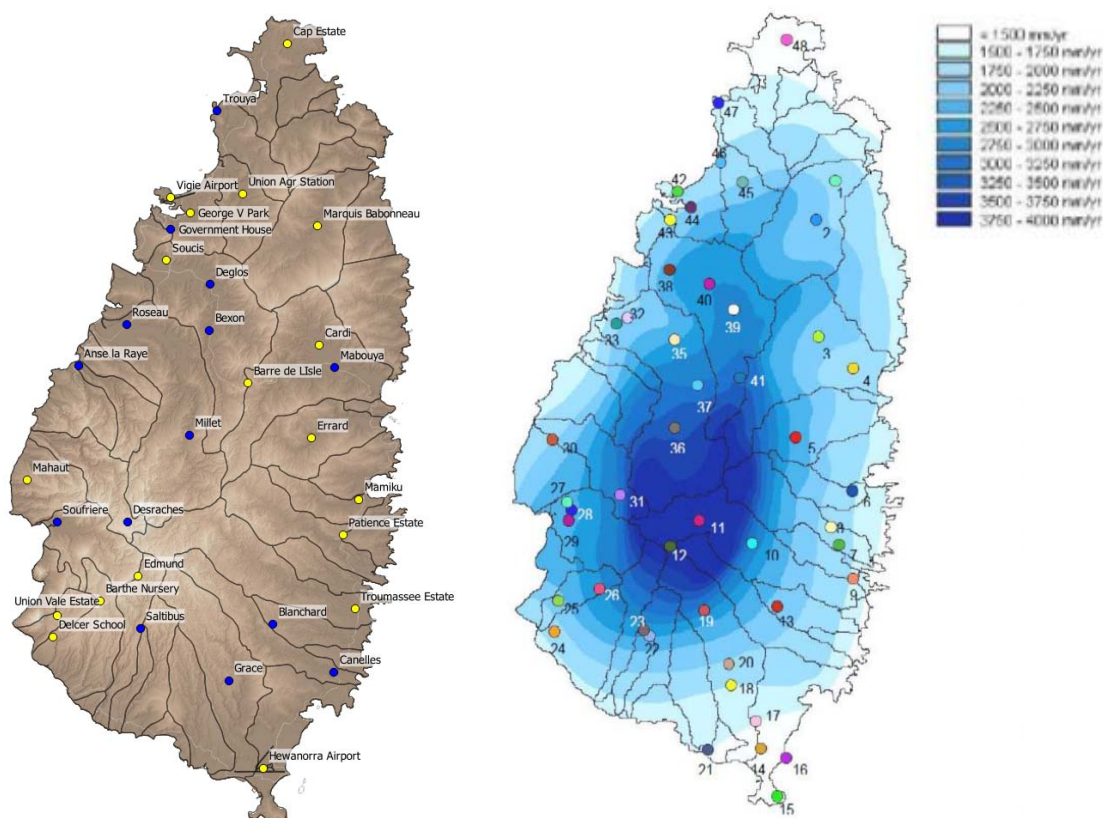


Figure 4.2. Rainfall stations on St Lucia. Left: stations represented as yellow dots are used in the frequency magnitude analysis (1955-2005). Right: average annual rainfall, ranging from 1500 mm/year (white) to 4000 mm/y (dark blue), by Marmagne and Fabrègue (2013)

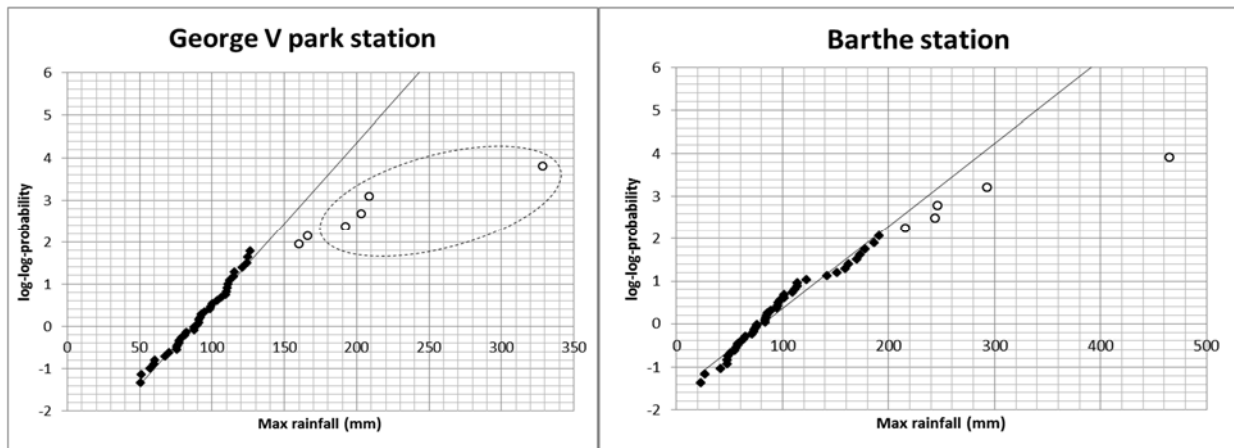
Day	Month	Year	Soucis	Barre De Lisle	Barthe	Cap	Delcer	Errard	Hewanorra	Troumasse	Union	Union Vale	Vigie
8	Sep	1994	19	14.8	14.6	0	9.3	7.2	1.5	2.8	6.2	9.1	11
9	Sep	1994	230	450	280	0	244.9	323.6	0	184.1	275.6	259	238
10	Sep	1994	20.8	0	30	0	17.2	17.7	212	78.2	30.1	20	10.3
11	Sep	1994	0	0.1	1.2	0	2.2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

Figure 4.3. Example of station recordings for hurricane Debbie on 9 Sep 94. Arrows show likely delayed readings.

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

Initially Gumbel distributions were fitted to each station. A Gumbel distribution is a special case of Generalized Extreme Value distributions, suitable for right hand skewed datasets (such as rainfall,

that cannot be less than 0, but can have extreme maxima). The Gumbel distribution assumes a double logarithmic relation between the maximum rainfall  $R$  and the return period  $T$ . The return period is the inverse of the probability  $P$ . As an example, Figure 4.4 shows the Gumbel analysis of George V Park in Castries. The station is close to Bois d'Orange river and Choc river, that are both known to flood occasionally. It can be seen that a Gumbel analysis linearizes a part of the data, but the 6 highest values are not on the same line. When searching for the dates corresponding to these days, it appears that the 4 largest at least are known class 5 hurricanes (NOAA Hurricane Database, <http://www.nhc.noaa.gov/>).



**Figure 4.4.** Example Gumbel analysis of maximum daily values of Barthe station and George V park station (1955-2005). The four encircled highest values for George V park correspond from low to high to category 5 hurricanes: Aug-Sep 1960 –Donna; Aug-Sep 1980 –Allen; Sep 1988 –Gilbert and Sep 1967 –Buela. For Barthe the highest values correspond with: Oct 1970 – Tropical depression 19, hurricanes Buela and Gilbert and May 1987 tropical depression 1.

Two conclusions are drawn from this:

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

It was decided to abandon Gumbel and use a Generalized Extreme Value (GEV) distribution fit. The equation has more parameters that allow for a better linearization of the data (see e.g. Coles, 2001). Each station was fitted with a GEV distribution. The parameters of the distribution are given in Figure 4.5. The stations are grouped with respect to their location on the island: the near coastal stations in the east (E), the near coastal stations in the west (W) and the stations further from the coast towards the center of the island (C). This grouping was done to explore if there are differences relative to the position of the station. According to Klein Tank et al. (2009),  $\mu$  and  $\sigma$  are location parameters that are surprisingly stationary and can be averaged for different stations, while  $k$  is a shape parameter that has a more local nature. Figure 4.6 shows the curves using the averages of the fit parameters  $k$ ,  $\mu$  and  $\sigma$ : it can be seen that the east and west of the island show very little difference in return periods structure, while the center of the island has much higher daily maxima for the same return period values.

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

Station	k	sigma	mu	n	max P	nr days active	loc.	Generalized Extreme Value Distribution
Edmund	0.2	57.3	113.1	21	450.0	6325	C	<b>Parameters</b> $\hat{k}$ - continuous shape parameter $\sigma$ - continuous scale parameter ( $\sigma > 0$ ) $\mu$ - continuous location parameter  <b>Domain</b> $1 + k \frac{(x - \mu)}{\sigma} > 0$ for $k \neq 0$ $-\infty < x < +\infty$ for $k = 0$  <b>Probability Density Function</b> $f(x) = \begin{cases} \frac{1}{\sigma} \exp(-(1 + kz)^{-1/k}) (1 + kz)^{-1-1/k} & k \neq 0 \\ \frac{1}{\sigma} \exp(-z - \exp(-z)) & k = 0 \end{cases}$  <b>Cumulative Distribution Function</b> $F(x) = \begin{cases} \exp(-(1 + kz)^{-1/k}) & k \neq 0 \\ \exp(-\exp(-z)) & k = 0 \end{cases}$ where $z \equiv \frac{x - \mu}{\sigma}$
CARDI	0.5	19.9	74.5	21	403.0	4841	C	
Barthe	0.4	31.5	86.0	52	482.6	17991	C	
Barre de Lille	0.2	49.3	65.2	54	464.8	16862	C	
Errard	0.3	52.0	103.2	19	429.2	6453	C	
Vigie	0.4	25.7	81.9	21	270.1	7670	E	
UnionVale	0.2	37.3	83.5	30	268.5	8629	E	
Union	0.2	32.4	87.1	54	293.4	18237	E	
Soucis	0.3	23.7	69.5	36	249.2	11019	E	
GeorgeV Park	0.2	28.2	81.9	44	328.9	14421	E	
Delcer	0.1	53.3	84.7	21	244.9	7150	E	
Cap	0.2	38.2	82.3	44	304.8	15258	E	
Troumasse	0.1	47.8	84.2	45	336.3	12739	W	
Patience	0.1	30.0	82.6	52	343.8	17286	W	
Marquis de Bab.	0.1	39.6	86.6	47	345.2	14454	W	
Mahaut	0.1	43.5	93.2	28	280.9	9116	W	
Hewanorra	0.1	39.4	86.8	21	245.3	7670	W	

Figure 4.5. Left: GEV distribution fit parameters for 19 stations. The indication E, W and C corresponds to stations near the east coast, near the west coast and closer to the center of the island. Right: GEV equations.

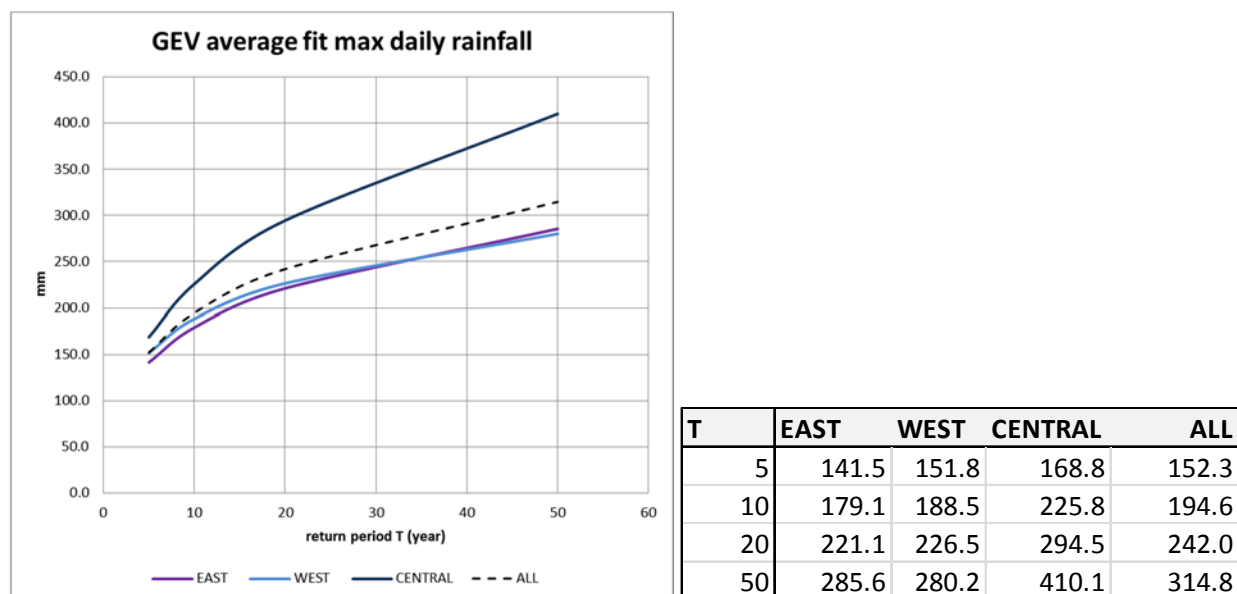


Figure 4.6. Left: GEV analysis of stations in fig 4.5. The coastal zone stations for the east and west side of the island are not significantly different. Right: the corresponding return period T and average daily maximum values used in the hazard analysis.

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



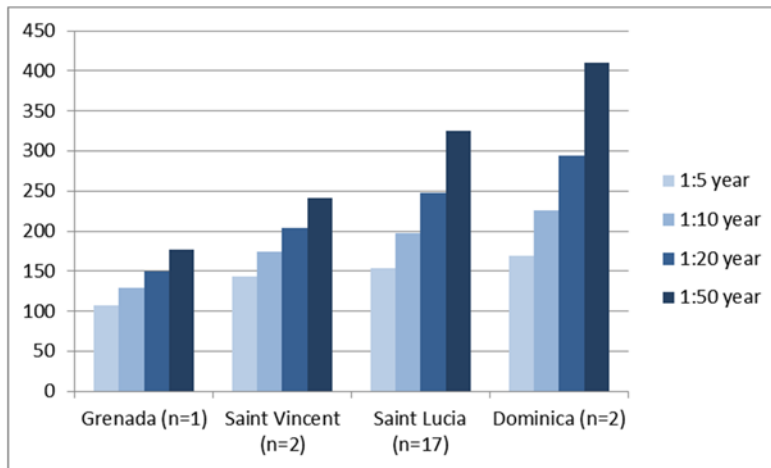


Figure 4.7. Return periods and daily maxima from GEV analyses of rainfall stations at the 4 islands in CHARIM.

## 4.2 Design storms

A hazard analysis cannot be done on actual rainfall events because this would make the comparison between events of different magnitude impossible, if they are spatially very different. Design rainfall event have to be used. Design storms are used mostly in civil and construction engineering to calculate proper dimensions of channels, culverts and bridges. These are events that correspond to a certain shape, size and duration for each return period that is needed (in this case 5, 10, 20 and 50 years). The total size of the design events (the rainfall depths) should be identical to the GEV analysis sizes in Figure 10.

A common way to create a design event is from intensity-duration-frequency curves, or IDF curves. A few such curves exist for the region, but mainly for the northern part of the Caribbean. Lumbroso et al. (2011) constructed IDF curves for the Bahamas (fig 4.8). IDF curves also exist for the Florida but those are considered not representative as they are too far north and the climate might be dominated by the US landmass.

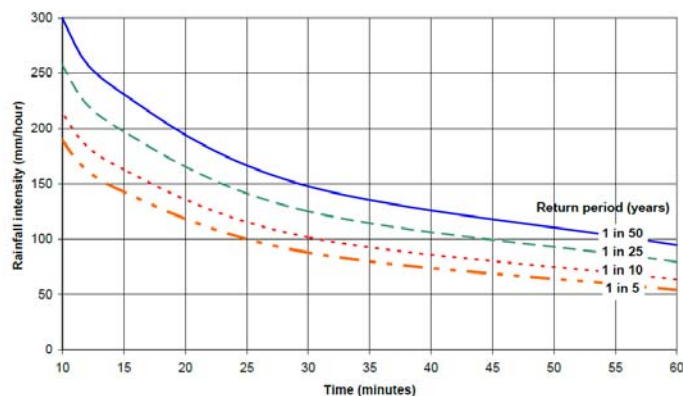


Figure 4.8. IDF curves for the Bahamas (Lumbroso et al., 2011).

Of the Saint Lucia high resolution weather stations that are operational since 2005, 3 had a consistent continuous rainfall record that enabled the construction of IDF curves, for 5 and 10 years (fig 4.9). Curves for longer return periods cannot be created because the series are not large enough. It can be seen that Bexon station has higher rainfall intensities. This could be because of its elevation, but Cardi is in a similar position and has much lower intensities. Bexon station curves resemble the

Bahamas curves of Lumbroso et al. (2011), but the difference between 5 and 10 year is more pronounced for the higher intensities.

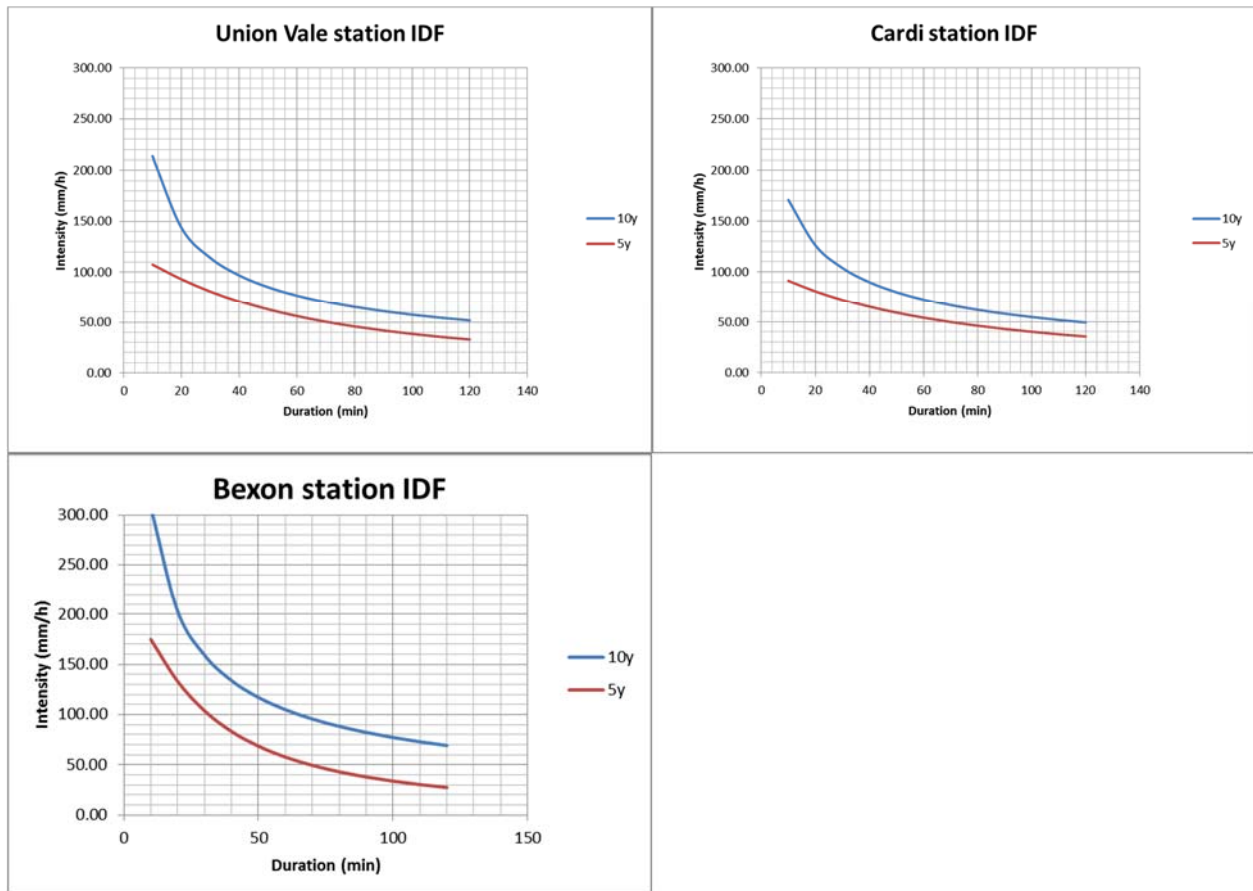


Figure 4.9. IDF curves for 3 stations that have 10 years of intensity data.

From IDF curves design storms can be created using the alternating block method (Chow et al., 1988). The design storms are shown in Figure 4.9. Unfortunately, the rainfall derived from the IDF curves do not have the correct depth compared to the GEV analysis (the rainfall events are all approximately 50% smaller). A possible explanation is the short time series that is at the basis of this analysis, within 10 years the range of intensities that are captured by the 3 stations does not resemble the intensities of the larger dataset of the 17 stations of the GEV analysis. Moreover the detailed data does not exist for the other islands in the CHARIM project.

We therefore decided not to use the IDF data but analyze the rainfall events directly. In total 35 rainfall events existed of 90 mm and larger, based on the 1 minute intensity data of 15 stations over a period of 3 to 10 years (depending on the station). These events were grouped according to total depths. Of course the larger events only have a few realizations, a summary is given in Figure 4.11. Average depth and duration are well correlated, while the average maximum intensity does not show any correlation with event size. In other words, larger rainfall events are longer in duration, but not necessarily more intense. In reality they are very complex with temporal and spatial variability.

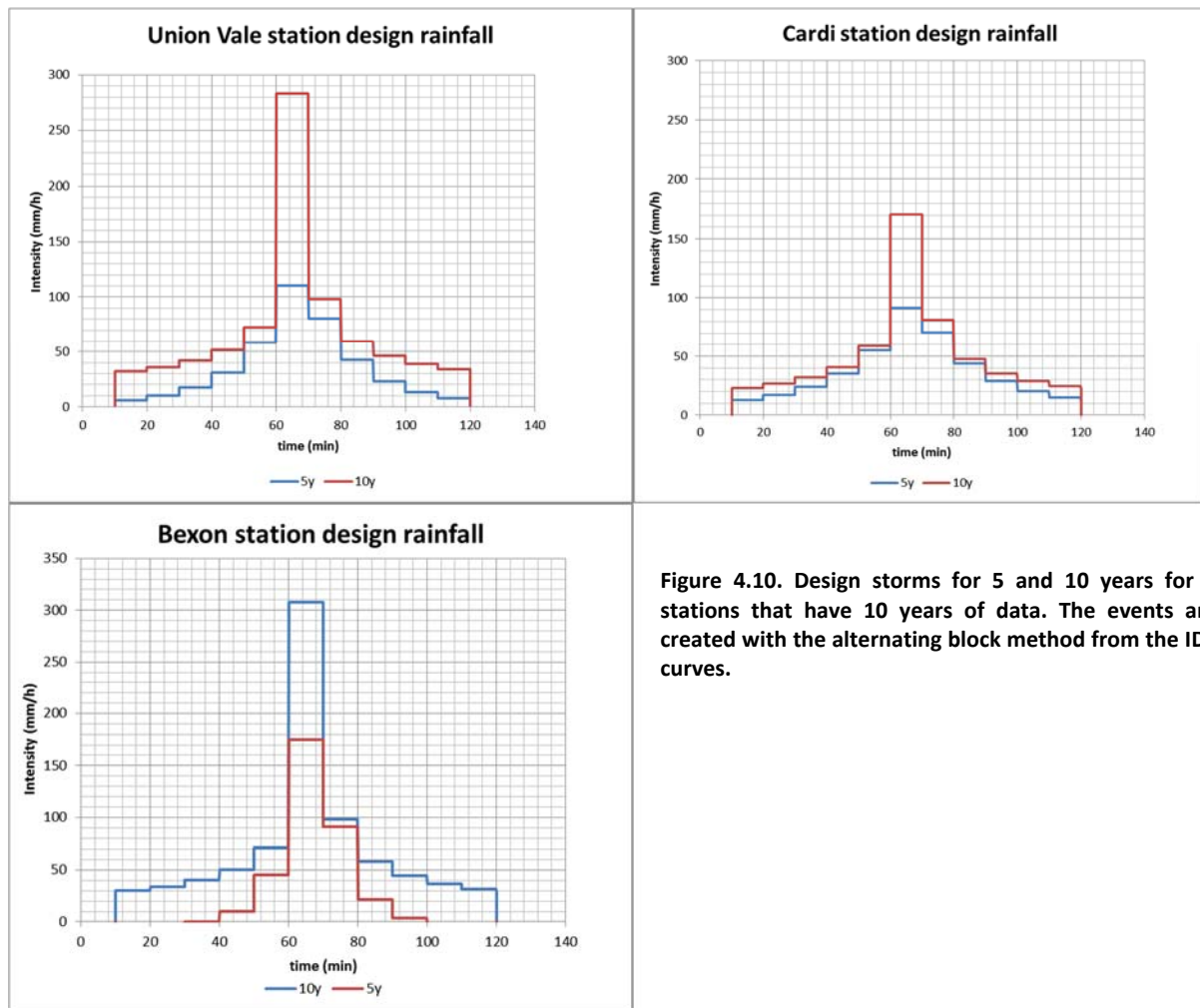


Figure 4.10. Design storms for 5 and 10 years for 3 stations that have 10 years of data. The events are created with the alternating block method from the IDF curves.

Event	average size	min	mm/h	n
350-550 mm	463.7	1481.5	144.0	4
250-300 mm	258.6	837.6	172.8	5
200-250 mm	202.1	870.0	132.0	2
150-200 mm	160.2	628.3	147.0	4
100-150 mm	119.3	388.6	150.0	8

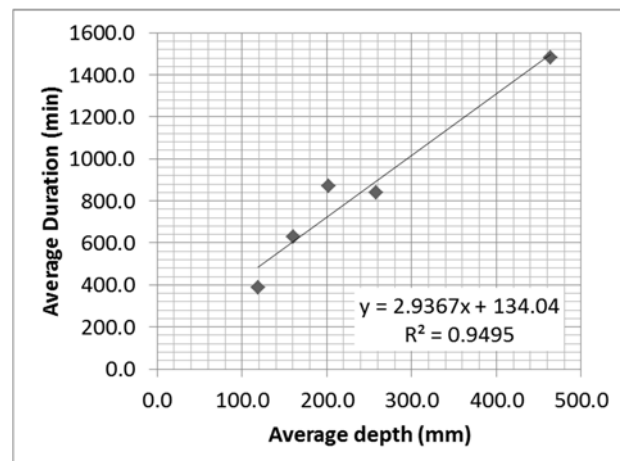


Figure 4.11. Summary characteristics of the 23 largest events, from 15 stations in 10 years. Average depth and duration are well correlated, while the average maximum intensity does not show any correlation with event size.

Within each class the events were fitted with a probability density function, for which a Johnson SB distribution was used. To do this events were from all stations in each class and converted to relative cumulative data (relative rainfall depth versus relative duration). This allows all events to be fitted with a similar set of parameters. The procedure also has a smoothing effect compared to the more erratic real rainfall distribution of an event. Figure 4.12 shows an example from Cardi station.

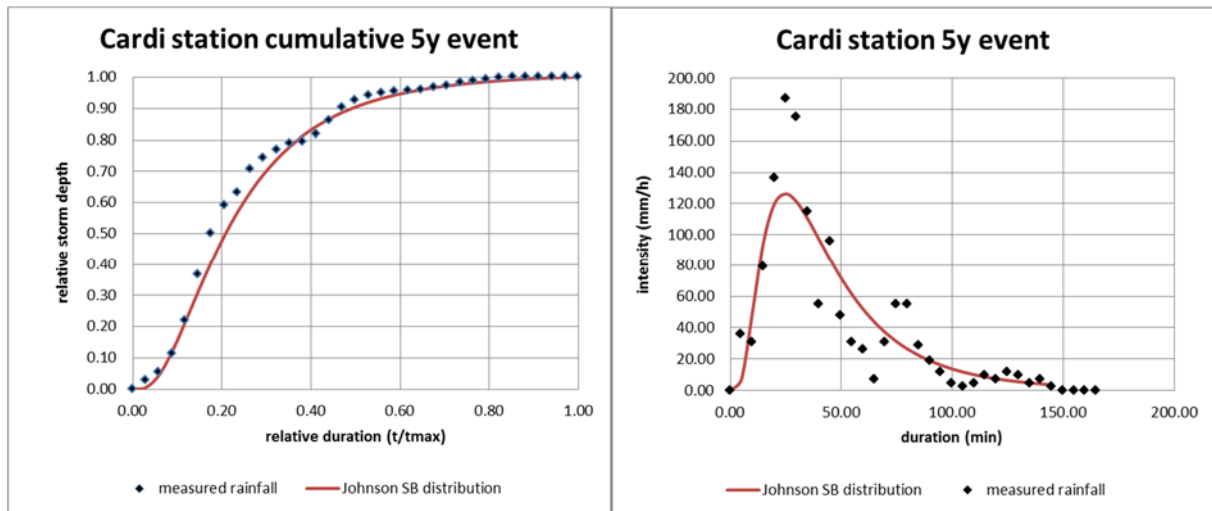
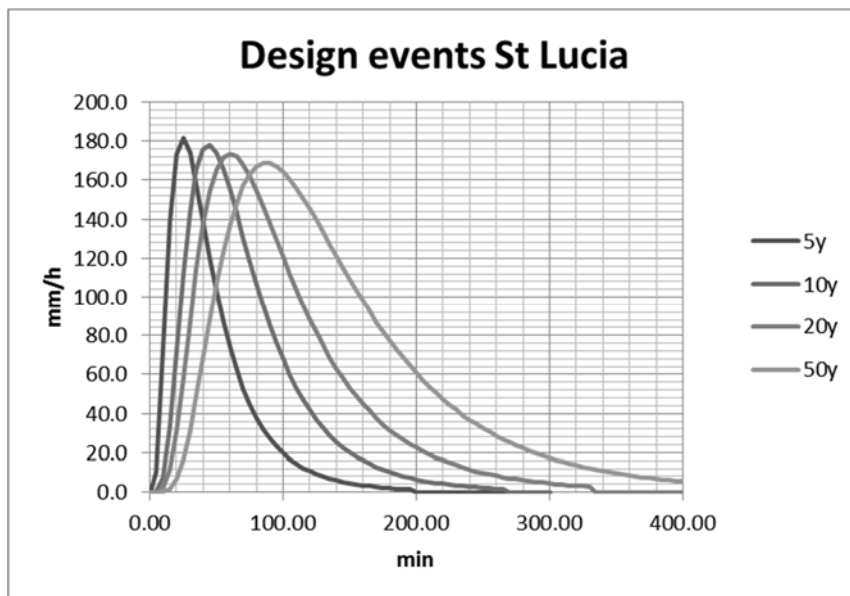


Figure 4.12. An example of fitting a Johnson SB probability density function to an event from Cardi station. Left: relative cumulative event used for fitting; right: the real event and design event shape.

This resulted in a set of Johnson SB distribution parameters for each class. These were then scaled up so that the curve describing the rainfall event has a depth and intensity close to the measured average maximum intensities. This resulted in the design events shown in fig 4.12. There is a gradual decrease in peak intensity from 5 to 50 years return period, and a larger storm depth. The duration of the design storms is considerably shorter than the real average duration as shown in Figure 4.11, which is because in the real events there are frequently short periods with low amounts of rainfall while the design events is a single closed event.



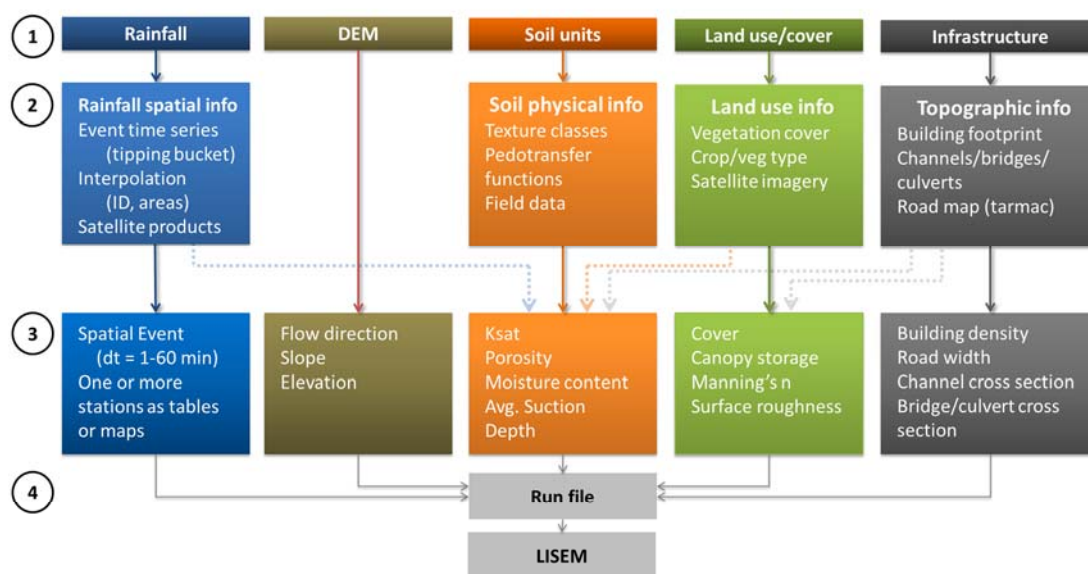
	1:5 y	1:10 y	1:20 y	1:50 y
Depth (mm)	154.0	197.8	247.4	325.3
Max Intensity (mm/h)	181.8	178.2	173.5	168.5
Duration (min)	195	265	330	400

Figure 4.13. Design storms for St Lucia for 4 return periods, based on a Johnson SB distribution fit to representative rainfall events in the classes shown in fig 4.11.

## 5 Spatial database

LISEM uses input data directly to determine the hydrological processes that it simulates. There are very few built-in assumptions. For instance LISEM 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 a PCRaster script is made to create the 5 data groups for a model run (columns in fig 5.1), for which basic maps are needed (row 1). Using a combination of field data and literature (row 2) the input database for the model is created (row 3). Table 5.1 describes briefly the main base maps, their origin if known, and how they are used in LISEM.



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 5.1.** Flow chart of the creation of an input database for LISEM from 5 basic data layers. The database is generated automatically in a GIS (PCRaster) with a script that is tailor made for St Lucia.

Basic data	Created from	Method
<b>DEM</b>	From contour shape files with 2m intervals (origin unknown).	Kriging interpolated using an exponential semivariogram to a 10m DEM, resampled to a 20m DEM using 2x2 window average.
<b>Soil Map</b>	Shape file. Origin 1966 soil map made by UWI Imperial College of Tropical Agriculture.	The legend includes a texture class indication using USDA texture classes. These were used to derive soil physical properties, taking into account stoniness.
<b>Land cover map</b>	Based on classified images 2014, Pleiades and RapidEye images, British Geological Survey.	Has 18 classes for land cover information, interpreted directly to hydrological parameters.
<b>Road map</b>	Shape file of all roads in 3 classes (incl. highway).	Assumed all roads to be tarmac/concrete slabs, narrow width (4m and 6m) and highway 10m wide.
<b>Building map</b>	Shape file from FUGRO digitized building information.	Rasterized to 1m resolution and resampled to 10m and 20m building density (m <sup>2</sup> building/m <sup>2</sup> cell)
<b>River map</b>	Shape file, two classes, natural and artificial. Consists of many separate disconnected branches.	Combine the digitized natural river channel information in the coastal zone, with automatic DEM generated river channel location in poorly visible (inland under vegetation cover).

**Table 5.1. List of main data layers for St Lucia, their origin and main operations for hydrological database preparation.**

## 5.1 DEM and derivatives

The DEM is used for overland flow directions and slope in the runoff part of the model, and the elevation is used directly in flood modelling. The DEM of St Lucia is created by a Kriging interpolation from elevations lines using an exponential semivariogram. The elevation contours have 2m spacing, and the interpolated map was produced on a 10m resolution. This was then resampled to a 20m resolution using the average of 2x2 cells. It is not known what the origin of the contour lines is. They seem to be generated automatically from another source but the meta data is not available. Nevertheless they do contain some detail in the flood plain as can be seen in fig 5.2. The resampling did not significantly change the level of detail.

The absolute accuracy of the DEM is not known, but a good check is if the digitized river (derived from air photos or images), follow the DEM depressions (see figures 5.4 and 5.5). This is an indication that the natural depressions and small variations in the flood plain, with elevation details of less than 0.5 m, are faithfully reproduced.

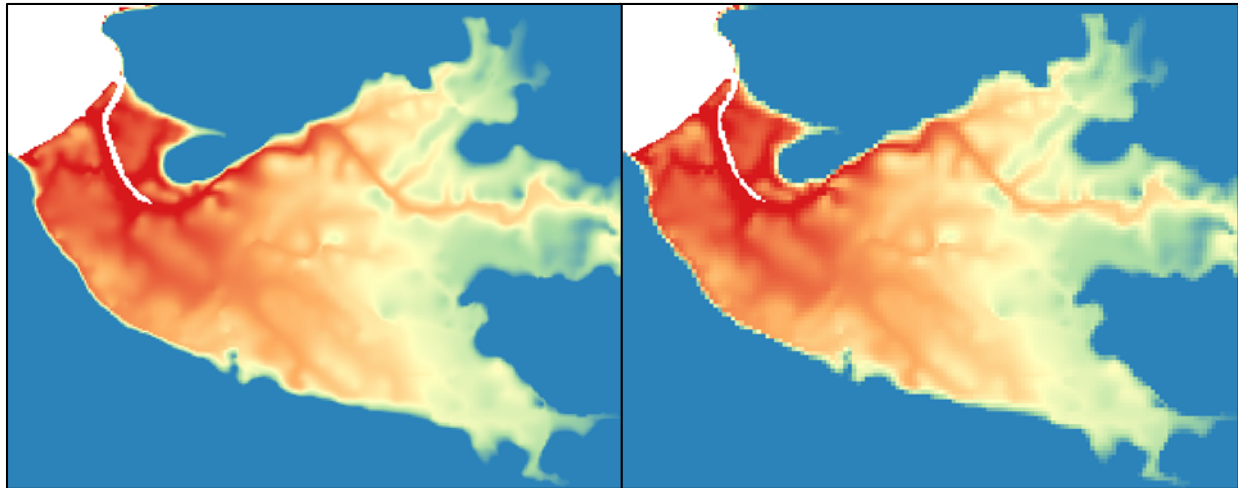


Figure 5.2. DEM in 10m resolution (left) and 20m resolution (right) based on Kriging of the elevation lines. The area shown is Roseau river floodplain and bay on St Lucia. The elevation scale is scaled from 0 (red) to 10m (blue) to show the detail in the flood plain. The section shown is 3750m in width.

### Soil depth

The soil depth is unknown and in spite of the simplicity of the parameter, it is not well studied and few algorithms exist to generate a soil depth map. Kuriakose et al., (2009) generated soil depth for a mountainous catchment in the southern India, in the Ghats mountains. The research was part of a landslide research where soil depth was one of the more important parameters. The situation is very similar to the Caribbean islands: tropical wet climate (Monsoon driven), soil formation due to weathering, although not from volcanic origin, and rapid denudation that causes slopes with thin soils and valleys that are filled up with debris over time, by erosion and mass movement. Derived from this research, the following GIS operation was used to create a soil depth map (in m):

$$\text{Soil depth} = a((1-S) - b D_{\text{river}} + c D_{\text{sea}}^d)^e$$

where:

$S$  = terrain slope (bounded 0-1)

$D_{\text{river}}$  = is the relative distance to the river channel (0-1)

$D_{\text{sea}}$  = the relative distance to the sea (0-1)

Scaling parameters:  $a=1.5$ ,  $b=0.5$ ,  $c=0.5$ ,  $d=0.1$ ,  $e=1.5$

The logic is that steeper slopes have shallower soil, closer to the river the soil depth increases, and closer to the sea the soil depth decreases. Visual field checks have been limited to observations of river depth (surface to bedrock) along Bois d'Orange river, Choc river, Roseau river and the rivers near Dennery and Castries. Fig 5.3 shows the soil depth for the areas shown above. The river depth is simply the soil depth in the channel pixels.



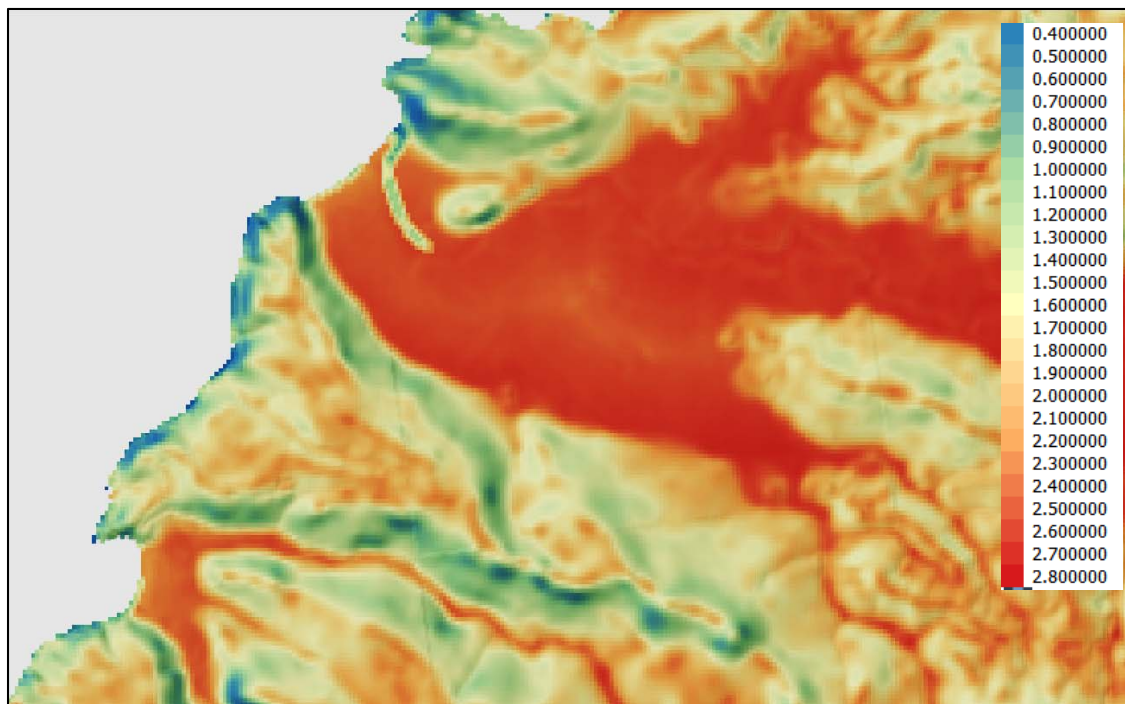


Figure 5.3. Example of soil depth (in m) generated from the DEM, river system and proximity to the sea.

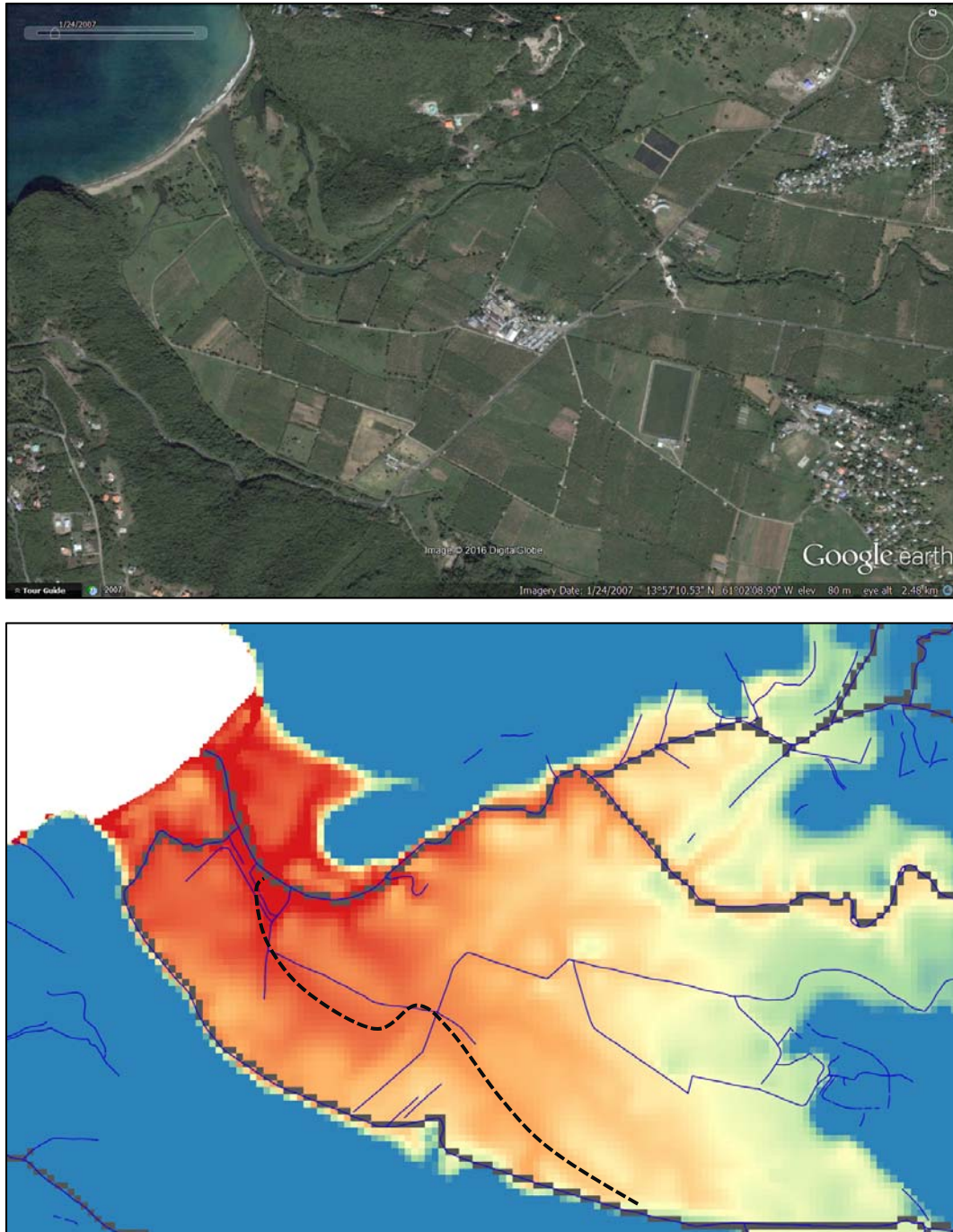
### *Rivers network and river dimensions*

A shape file with drainage lines exists in the St Lucia database, classified as artificial (small drains along the roads) and natural channels. The latter class, the natural channels, have been used in the flood model, because at the national scale drainage along roads cannot be modelled. However, the hydrological quality of the digitized map is not very high, almost all river sections are digitized separately and there is no connectivity, so the river network shape file does not constitute a continuous flow network. Also under vegetation the rivers are not easy to spot and are sometimes not visible at all. This also lead to network fragments, and moreover these flow lines are not always in the deepest part of the valleys. It is impossible to use this network directly in the model (or any model) as flood water that overflows will flow into the deepest points of the valley and cannot drain from there. The simulated flood hazard would be more severe than it is in reality.

In contrast in the flat coastal plains and river mouths, the DEM does not have enough information to generate a valid flow network, but there the rivers can be well seen on high resolution imagery and the digitized river networks are of a higher quality.

The final river network was created by combining the visible coastal plain sections with an automatically generated river network based on the DEM for the upstream areas. There is no automatic procedure for this. All rivers were corrected and checked by hand, and a river channel mask map was produced on a 10m and a 20m resolution. Fig 5.4 shows a comparison of Roseau bay. For example hand corrections were made to the entire lower branch that borders the agricultural fields, which does not flow into the sea but turns northward to join the main channel. The man made channels are not included in the national flood hazard map, as their dimensions are very small and the line elements in the GIS database are fragmented channel lines that do not form a network.





**Figure 5.4.** Stream network example of Roseau bay, with a high res image (24 Jan 2007) from Google Earth (top) and the digitized stream network (blue lines) and 20m raster river network used in the flood model (dark grey). The dashed line shows the original channel derived from the DEM.

From the river network at 20m, the channel dimensions are derived automatically. It is assumed that the river dimensions increase from the source to the outlet near the see. Note that LISEM has the restriction that the river channel cannot be wider than the gridcell, because the flow is a 1D kinematic wave in the converging channel network. The algorithm used is based on Allen and Pavelski (2015) who show that for large North American river systems there is a good correlation between total river length and river width. They further extrapolated their data to smaller river systems, using the total river surface area, and correlated that to river width ( $r^2 = 0.996$ ,  $p < 0.001$ ):

$$\text{Area} = 3.22e4 * W^{-1.18}$$

This equation is used in the dataset, whereby the river area is approximated as the accumulation of cell area from the river source to the outlet. Fig 5.5 shows the effect for the Roseau river mouth.



**Figure 5.5.** Example of the river width algorithm near L'Anse la Raye. The river mouth is wider than results from the algorithm but the river widths several 100m from the coast line are close to the estimated values (between 6 and 7 m in the top red circle and 9 and 10m in the bottom red circle).

Everywhere it is observed that the river has eroded until bedrock, apart from the last kilometer or so near the mouth, where sedimentation takes place and the river widens. This river depth was estimated by using the soil depth as river depth. The soil depth is generated from the DEM as explained below.

**Important: at the national scale sedimentation of sand and debris in the river beds is not included. Occasionally this may cause obstruction of culverts and bridges, or greatly decrease the storage capacity of the channels. Hence the flood map shows the situation with clear rivers with maximum capacity, using the assumptions of dimensions as explained above.**

The river network in LISEM is characterized by two more parameters: the slope of the river bed and the resistance to flow (Manning's  $n$ ). The slope of the river bed is obtained by taking the slope of the DEM in its steepest downstream direction. The Manning's  $n$  is taken from comparing observations in the field with literature values. Morgan et al. (1998) has compiled a large number of values for different surfaces, and the USGS websites provides visual references: <http://wwwrcamnl.wr.usgs.gov/sws/fieldmethods/Indirects/nvalues/>. Generally the riverbeds are either sedimented or rocky with boulders, which gives a Manning's  $n$  of 0.03-0.04, and the banks are overgrown with abundant natural vegetation, so the value was increased to 0.05.

## 5.2 Soil map and derivatives

The island is of volcanic origin with an active volcanic site comprising near surface hydrothermal hot spots with geothermal energy potential. St. Lucia can be described as geologically young not exceeding 50 million years with rocks such as rhyolite, andesite and various basalts (Towle et al, 1991, in WRMU, 2001). The rock formations present are classified into three series:

- Northern Series (Early Tertiary- Eocene) – older rocks predominantly basaltic in composition, heavily folded and of Eocene age. In some areas in the north one can find Andesite Porphyry and Rhyolite.

- Central Series (Middle Tertiary – Miocene / Pliocene) – the central ridge (Barre D'Isle) and the rocks underlying the eastern coast were formed thirty to forty million years ago due to an extended sequence of volcanic activity which generated extrusions of younger andesite, basalts, agglomerates and tuffs.
- Southern Series (Mid to Late Pleistocene)- the southern region in the area of the pitons, the volcano as well as Mount Gimie (the highest peak) can be found the newest (geologically) dacite segment. The region near the volcanic crater evolved when there was volcanic activity with dacite and pyroclastics after a series of thirty-three consecutive eruptions, which triggered avalanches of andesite pumice on the adjacent slopes.

The soils that came into existence from this volcanic parent are generally fertile and rich in clay and silt. The valley floors are generally filled with material from erosion and mass movement from the slopes, and can be more sandy in nature because of the lateral sorting process, where clay in suspension is washed out. Near the coast the material is also more sandy. All soils are gravelly to some degree, the gravel resulting from weathering processes of the parent material.

The soil 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. It is important to note that the soil mapping was primarily based on topography, drainage, parent material and not according to pedology which emphasizes how the soils originated. The approach taken by the surveyors reflected the need to produce a survey that would be of most use for the agricultural community, not for its potential use in geotechnical investigations (CDERA, 2006). The classification system follows the US convention of assigning a "typical soil profile" and giving them a name based on the type location, such as "Anse Clay" or "Mabouya Silty Clay". Each of these units has a texture class indication according to the USDA texture class triangle, and the class average grain size distribution was assumed. Based on the texture class the soil physical parameters Saturated Hydraulic Conductivity ( $K_{sat}$  in mm/h), Porosity ( $cm^3/cm^3$ ) and average initial matric suction (kPa) were derived, using the pedotransfer functions of Saxton and Rawls (1986), see fig 5.6. This results in the values in table 2.2.

The pedotransfer functions are largely texture based, with effect of stoniness and organic matter. The stoniness is information given for each soil class in the soil map which causes a small effect on  $K_{sat}$  and somewhat larger on porosity (Saxton and Rawls, 1986):

$$K_{sat_{eff}} = K_{sat} * (1 - stone) / (1 - 0.85 * stone)$$

$$Pore_{eff} = Pore * (1 - stone)$$

It is known however that the soil structure has a large effect on the  $K_{sat}$  and porosity. Normally a soil classification system is not based on the top soil as this is often affected by agriculture and building activities. 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 high saturated hydraulic conductivity. This means that the top soil can absorb quickly large amounts of water, depending on how dry it is. Under agricultural circumstances the top 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.

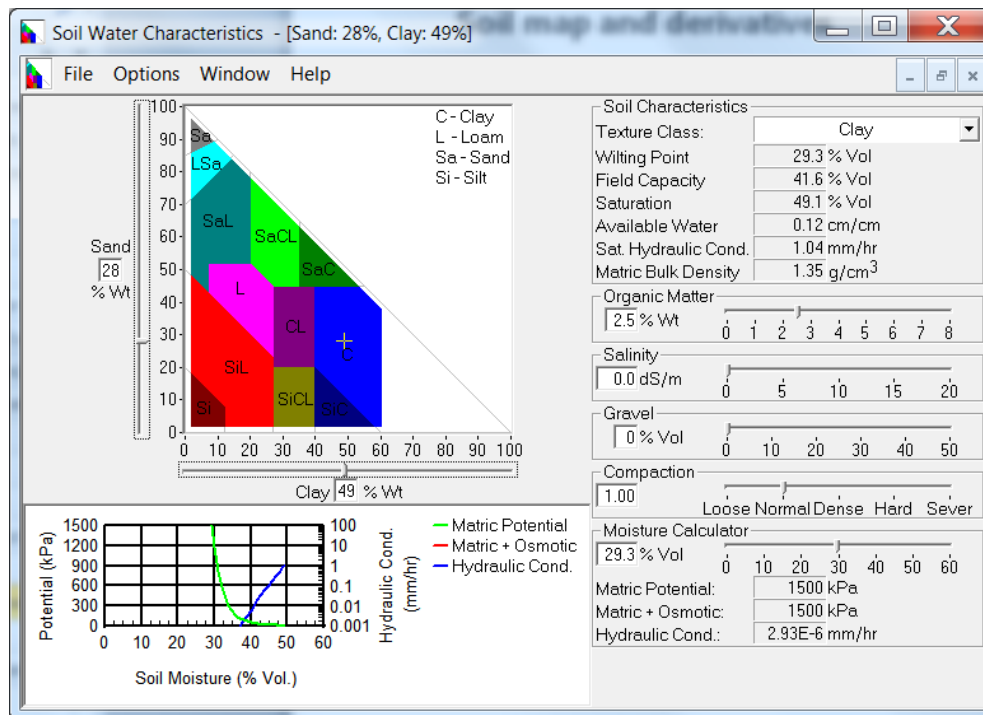


Figure 5.6. Pedotransfer functions by Saxton and Rawls (1986) used in SPAW model software.

As is common in tropical environments, the organic matter rapidly decreases with depth because of the high degree of decomposition. This was confirmed by Pratomo (2015), who determined the saturated hydraulic conductivity from 64 sample rings and porosity from 72 sample rings on Grenada, in the Gouyave and St John watersheds as part of a comparative catchment study in the CHARIM project. It is clear from figure 5.7 and table 5.2, that the  $k_{sat}$  under natural vegetation is a lot higher than the statistical values for the clays and silty clays in the area (table 5.3). This is attributed to the high organic matter content and open structure of the forest soils. The agricultural area was clearly closer to the statistical values found by Saxton and Rawls (1998), although there is a large spread as is also common for conductivity. The porosity values are generally high which is also common to clay rich soils and there is much less variation.

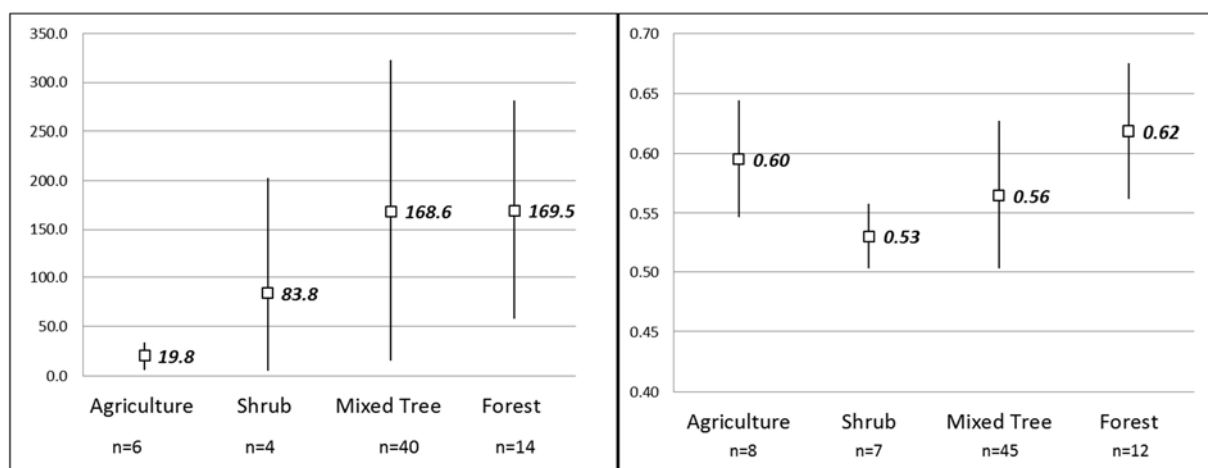


Figure 5.7. Left: saturated hydraulic conductivity (mm/h) and right: porosity (-) organized per main land cover type. The measurements are from Grenada, taken in the Gouyave and St John watersheds (Pratomo, 2015). The values in bold are the average, the lines show one standard deviation around the mean.

	Ksat (mm/h)				Porosity (cm <sup>3</sup> /cm <sup>3</sup> )			
	Mixed				Mixed			
	Agriculture	Shrub	Tree	Forest	Agriculture	Shrub	Tree	Forest
min	5.4	5.4	10.7	21.4	0.50	0.50	0.44	0.53
-std	6.1	5.3	14.5	57.4	0.55	0.50	0.50	0.56
avg	<b>19.8</b>	<b>83.8</b>	<b>168.6</b>	<b>169.5</b>	<b>0.60</b>	<b>0.53</b>	<b>0.56</b>	<b>0.62</b>
+std	33.5	202.5	322.6	281.6	0.64	0.56	0.63	0.68
max	42.9	257.1	492.9	321.4	0.65	0.57	0.70	0.70
n	6	4	40	14	8	7	45	12

Table 5.2. Basic statistics of soil physical parameters measured in Grenada in the Gouyave and St John catchments, in clays and silty clays (Pratomo, 2015).

It was therefore decided to use a two layer Green and Ampt infiltration model in LISEM, whereby the top layer of 15 cm, has larger values of Ksat and porosity than the second layer for all land cover types that consist of natural vegetation (see table 5.4, column 4 and 5).

The advantage of this approach is that the forested areas have a larger buffering effect than would be evident from the soil texture alone. Also land use changes have a larger effect on the hydrology and flood dynamics than if soil units are directly used, which is assumed to reflect the reality better.

nr	Unit	Ksat mm/h	Pore -	Field Capacity -	Wilting Point -
1	C	9.0	0.56	0.40	0.25
2	CL	16.0	0.54	0.35	0.20
3	L	74.0	0.48	0.25	0.10
4	S	161.0	0.45	0.11	0.06
5	SCL	31.0	0.43	0.28	0.15
6	SL	102.0	0.45	0.18	0.06
7	Si	73.0	0.46	0.30	0.06
8	SiC	15.0	0.56	0.41	0.24
9	SiCL	22.0	0.50	0.38	0.18
10	SiL	48.0	0.48	0.30	0.09
20	Water (W)	1.0	0.00	0.00	0.00
21	Urban (A)	15.0	0.40	0.30	0.06
23	Rock/outcrops (R)	1.0	0.30	0.11	0.06

Table 5.3. Main classes derived from the soil map and assumed saturated hydraulic conductivity (Ksat in mm/h), Porosity (pore in cm<sup>3</sup>/cm<sup>3</sup>), field capacity and wilting point (cm<sup>3</sup>/cm<sup>3</sup>), after Saxton and Rawls (1986).

The Green and Ampt infiltration process in LISEM needs the matric suction at the wetting front, based on the initial moisture content that is assumed.

All simulations of the flood hazard use an initial moisture content ( $\theta_i$ ) of 0.75 of the porosity ( $\theta_s$ ), which is approximately at field capacity ( $\theta_{fc}$ ) or slightly wetter. Since the porosity is adapted to the presence of natural vegetation, the initial moisture content is adapted as well. The matric suction ( $\psi$ )



in kPa) is calculated directly from the initial moisture content using the following set of equations (Saxton and Rawls, 1986):

$$psi = a \theta i^{-b}$$

where:

$$b = (\ln(1500) - \ln(33)) / (\ln(\theta_{fc}) - \ln(\theta_{wp}))$$

$$a = \exp(\ln(33) + b \ln(\theta_{fc}))$$

1500 and 33 = matric suction for resp. wilting point and field capacity (kPa)

## 5.3 Land use and infrastructure

### *Land cover map and hydrological parameters*

A 2014 land cover map of St Lucia was created by the British Geological Survey as part of the framework of the European Space Agency (ESA) “Eoworld 2” initiative. The following description is provided (CHARIM Data management book, section basic data collection):

“The satellite data comprised Pleiades imagery (acquired between 2013-2014) and RapidEye imagery (acquired 2010-2014). These datasets have a spatial resolution (pixel size) of 2m and 5m, respectively, for the multispectral waveband images. Additionally, the Pleiades datasets includes a very high-resolution 0.5m panchromatic image. To enable the most detailed information to be resolved, the Pleiades imagery was used as the primary dataset for generation of the new land use/land cover maps for the three AOIs; thus achieving a spatial resolution of 2m, which is equivalent to a mapping scale of 1:10,000. For each of the AOIs, land use/land cover was mapped using a combination of automated image classification, rule-based refinement and manual digitization. The existing 30m maps were used to define the different land use/land cover types and identify representative areas in the imagery to help guide the initial automated classification and to subsequently validate the mapping. Water features and the basic road networks were manually digitized at 1:10,000-scale from Pleiades imagery that had been pan-sharpened to 0.5m resolution using the panchromatic image. Wherever available, existing vector layers were utilized as baseline information during mapping.

The land use/land cover maps were validated using a standard remote sensing approach, which involves comparing the land use/land cover class identities of a sample of pixels in the map with their ‘true’ land use/land cover class. The ‘true’ land use/land cover classes of these pixels were determined using a combination of the pan-sharpened Pleiades imagery and existing maps. Consequently, the maps for St. Lucia, Grenada, and St. Vincent and the Grenadines were found to have accuracies of 84.9%, 84.8% and 80.8%, respectively; which are within the desired target accuracy of 80-90%. Additional validation of the maps for St. Lucia and Grenada was achieved using point-sampled field observations at a number of locations.”

The land cover types are reclassified according to their hydrological characteristics. For event based surface hydrology only the major land cover types are important. The 2014 land cover types have therefore similar values if they are hydrologically similar (such as Evergreen forest and Semi-deciduous evergreen forest). The parameter values used in LISEM are shown in in table 5.3.

The parameters derived from the land cover are those affecting the soil surface structure, which affects infiltration, and roughness, which affects the surface runoff. Also the canopy storage for

interception is derived from the land cover type. A soil cover that does not change in time is assumed, which is less realistic for agricultural areas. Cover influences the interception of rainfall by the plant canopy. This is usually in the order of 1-2 mmm (De Jong and Jetten, 2007). The variables *Ksat\_nat* and *Pore\_nat* (table 5.4) are used for the top layer Ksat and porosity under natural vegetation (see section 5.2).

Land Cover Type	Roughness	Manning's n	Cover	Ksat_nat	Pore_nat
Elfin and Sierra Palm tall cloud forest	1.0	0.10	0.95	168.4	0.62
Evergreen forest	1.0	0.10	0.95	168.4	0.62
Mangrove	2.0	0.10	0.95	n.a.	n.a.
Wetland	2.0	0.10	0.95	n.a.	n.a.
Semi-Deciduous, coastal Evergreen and mixed forest or shrubland	1.0	0.10	0.95	83.3	0.53
Lowland forest (e.g. Evergreen and seasonal Evergreen)	1.0	0.10	0.95	83.3	0.53
Golf course	1.0	0.15	0.95	n.a.	n.a.
Woody agriculture (e.g. cacao, coconut, banana)	1.0	0.07	0.95	n.a.	n.a.
Pastures, cultivated land and herbaceous agriculture	1.0	0.03	0.95	n.a.	n.a.
Buildings	0.5	0.02	0.2	n.a.	n.a.
Concrete pavement	0.5	0.02	0	n.a.	n.a.
Roads and other built-up surfaces (e.g. concrete, asphalt)	0.5	0.02	0.5	n.a.	n.a.
Bare ground (e.g. sand, rock)	0.5	0.02	0.1	n.a.	n.a.
Quarry	0.5	0.02	0	n.a.	n.a.
Water	0.1	0.03	0	n.a.	n.a.

**Table 5.4. Average vegetation parameters based on field observations. From left to right: roughness is the surface microroughness (cm) for surface storage, Manning's n is the flow resistance (-), Cover is the vegetation canopy cover (used in interception), Ksat\_nat (mm/h) and Pore\_nat (cm<sup>3</sup>/cm<sup>3</sup>) are top soil values under natural vegetation.**

The values that are used for anthropogenic cover (built up area, concrete, roads etc.) represent the value of soils adjacent to a house or road. As explained in figure 3.3, LISEM uses different layers with information on houses, roads, parking lots etc. as fractions of surface occupied, and the model needs to know the hydrological characteristics of the surface in between these structures, or next to the road in a cell.

### **Building density map**

The building density map is derived from the building footprint (FUGRO, 2004) that is available in the national GIS database as a shape file. Fig 5.8 shows an example for the center of Castries. The building density influences the interception of rainwater, infiltration (impermeable) and the flow velocity in overland flow and floods, but the influence of individual buildings cannot be simulated at this national scale. This map is created by rasterizing the building polygons to a 2m raster, and resampling that to 20x20m to a fraction of building density per cell (0-1).



**Figure 5.8. Rasterized building footprint at 2m resolution (left) from the center of Castries. The 20m building density (right) is used in the model.**

### *Roads, bridges, dikes*

The road shapefile has three types: 1 is the main highway, 2 are primary roads and 3 are secondary roads. All roads in the shape file are tarred roads or paved with concrete slabs. Therefore they are hydrologically smooth, impermeable and have no virtually surface ponding. The roads are reclassified to the LISEM input map according to their width. The highway is assumed to be 10m wide, the primary roads 6m wide and the secondary roads 4m wide.

Note that at the national scale, the road drainage channels are not included, as they are too small. Also the fact that at some locations the road is elevated above the flood plain like a dike, is not included, as that information is not available.

## 6 Model output and Hazard maps

### *Hydrological response*

The hydrological response of the model with respect to the rainfall is such that the areas that are built up (roads, paved surfaces) generate runoff first, then the soils with a high clay content under non-natural vegetation, and finally the forested areas contribute (see fig 6.1). The overall runoff fraction (average of the island) of a 1:5 year event is 15% and increases to 20% for a 1:50 year event.

All major valleys have flooding effects upstream in the hills. While this is of course dangerous for locations where there are settlements, there is also a hydrological effect of these flooded areas. Flooding upstream generally decreases and slows down the streamflow decreasing the flood hazard downstream near the coast. Site investigations that are based on models that need an incoming discharge to operate, should take this into account. Catchment models that generate a discharge as input for flood models overestimate the discharge when this is not taken into account.

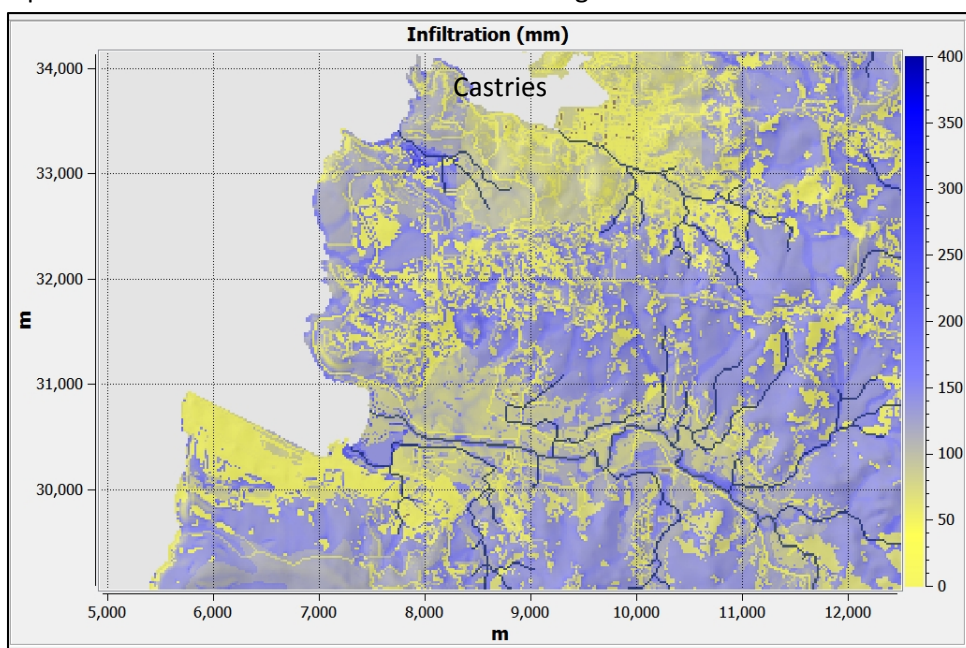


Figure 6.1. Example of the hydrological response: cumulative infiltration approx. 2 hours after the start of the 1:5 year design rainfall event (in mm). To the north is Castries, south west is the Oil terminal. Built up area and roads show little infiltration, forested areas have an infiltration above 200mm at this moment. Flooded areas have increased infiltration because of the flood water pressure, in spite of the clay rich soils.



## 6.1 Summary flood hazard statistics

Figure 6.2 shows the summary statistics for the flood hazard for 4 return periods. In total the area flooded increases from 11.5 to 34 km<sup>2</sup>, while the flood volume increases from 4.8 to 26.7 million m<sup>3</sup>.

Note that for these statistics, areas inundated by less than 5 cm were not flooded. The level of accuracy of the modeling system and the database were not considered sufficient for that level of detail. The flooded area is the “flood extent” on which the national flood hazard map is based.

The average building size in the national flood database is approximately 75 m<sup>2</sup>, LISEM does not deal with individual buildings, only with built up area per grid cell area. Based on this average number, the approximate number of buildings flooded is 3200 for 1:5 years and rises to 9800 for 1:50 years. This analysis gives no indication of the flood depth at the location of these buildings, which can be anything from 0.1 to over 3 meters.

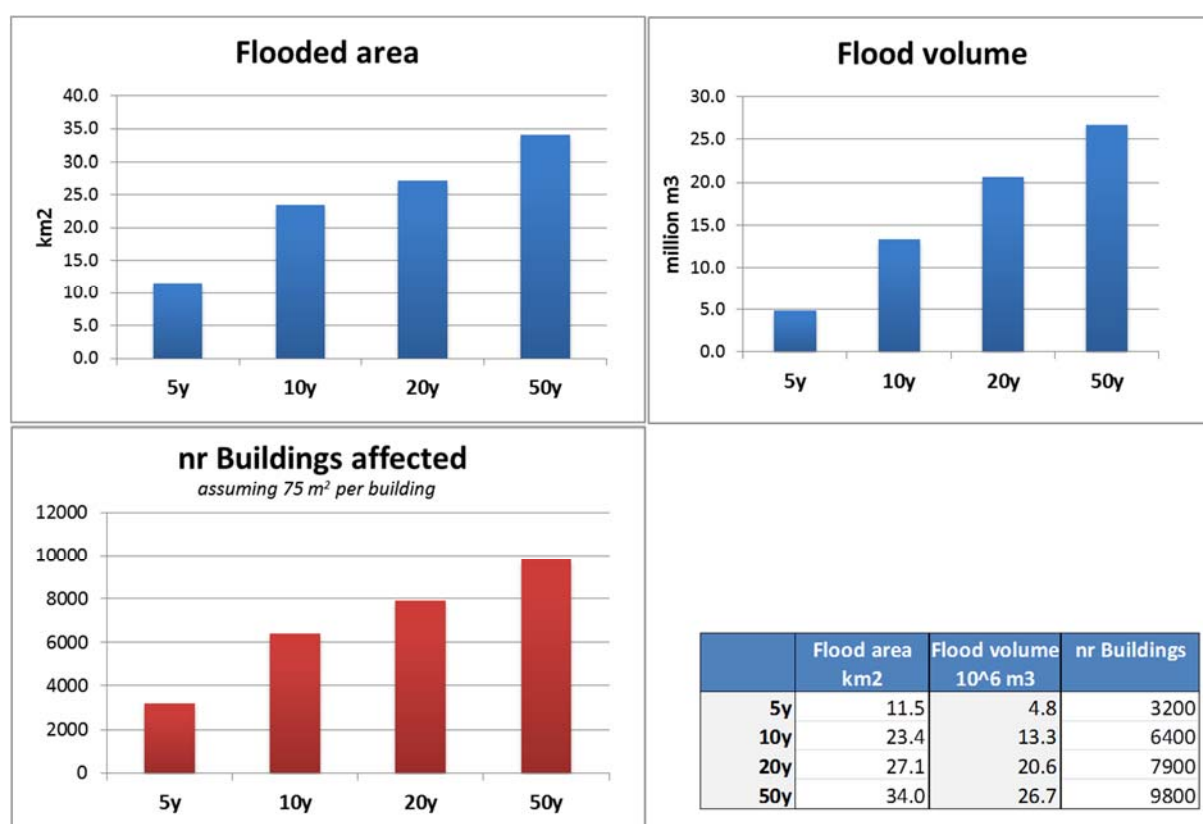


Figure 6.2. Summary statistics of the national flood hazard map for the 4 return periods. Note that the building nr affected is an approximate number based on an average building size of 75 m<sup>2</sup>.

## 6.2 Stakeholder evaluation of Draft Flood hazard map

The 2015 draft flood hazard map was discussed with the Water Resources Management Agency. In this section the evaluations and differences between the 2015 draft and the final 2016 flood hazard maps are discussed. Using the BGS land cover map and improvement of the river width and depth, and corrections to the river network pattern (see section 1.4), caused differences in flooding relative to the 2015 draft map. Since the land cover influences the infiltration rates and therefore the amount of runoff generated, while the channel dimensions determine whether the discharge overflows, there are significant differences between the first draft and the final version.

Morne Serpent evaluation (upstream Bois d'Orange river): "Due to the elevation at some locations it is not believed that flooding will occur". The new and old flood hazard maps are the same in this location. Note however that the duration (< 2 hours) and flood depth levels (< 0.2 m) are low in this area. So some flooding may occur, but it may not be experienced or recognized as severe. An explanation might also be that LISEM uses channels as a source of flooding. If in an area there are no real channels, but the ones generated from the DEM are not really there, a flood might be simulated where there is only surface runoff in reality (see fig 6.3).

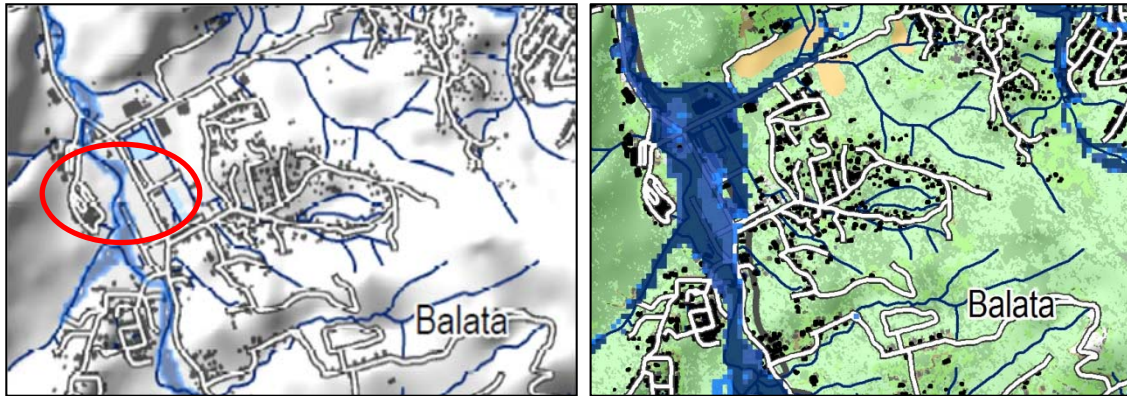


Figure 6.3. Choc river upstream area. Left 2015 draft flood hazard map, right final 2016 flood hazard map.

Balata area evaluation (upstream Choc river): "The flood representation should be extended to include the area circled in red" (red circle fig 6.4). The final flood hazard represents the experienced flood pattern much better.

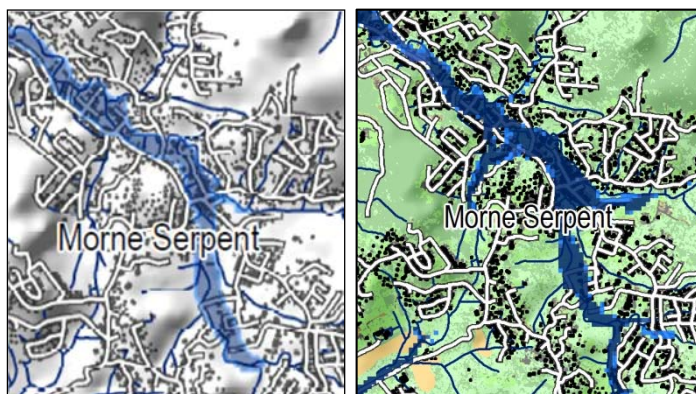


Figure 6.4. Bois d'Orange river upstream area. Left 2015 draft flood hazard map, right final 2016 flood hazard map.

Cul de Sac flood plain evaluation: "The flood representation should be extended to include either side of the highway and adjacent low lying areas such as Souci." (red circles fig 6.5). The final flood hazard represents the experienced flood pattern much better: the highway is indeed flooded although the Soucis area is not recognized as hazardous. Note that the highway in this area might be elevated and there are man-made drainage channels that are not included in at the national scale, which may influence the flow patterns of the flood water.

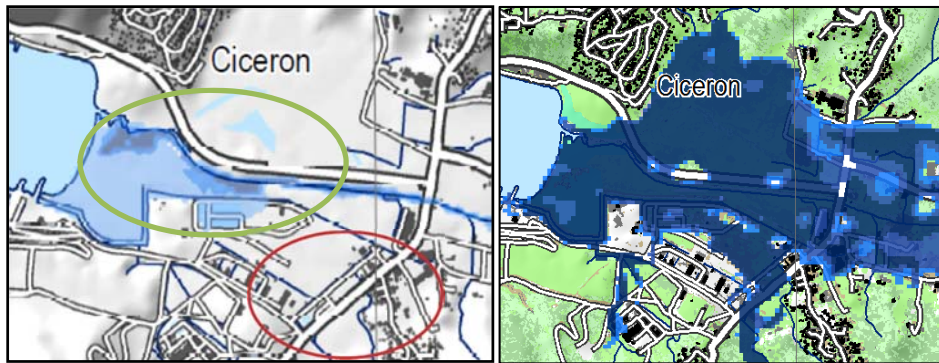


Figure 6.5. Cul de Sac flood plain. Left 2015 draft flood hazard map, right final 2016 flood hazard map.

Hewanorra airport evaluation: “The flooding near the Hewanorra International Airport should include the runway and adjacent areas.” (red circle fig 6.6). This was indeed a mistake in the draft flood map. The effect of the barrier protecting the airport combined with the Vieux Fort river being assumed deep and wide (without sediment) resulted in the airport not being flooded. In reality figure 6.7 shows the channel north of the airport and the fact that there is no storage capacity because of sedimentation. The final flood hazard map shows more clearly that the airport is in fact subject to flood hazard. However it should be noted that the final map may exaggerate this effect because the flooding originates at the very top of the barrier, combined with excess water that does not drain sufficiently fast from the runways (the drainage system in place may not be well represented). This area needs a careful site investigation in view of its importance.

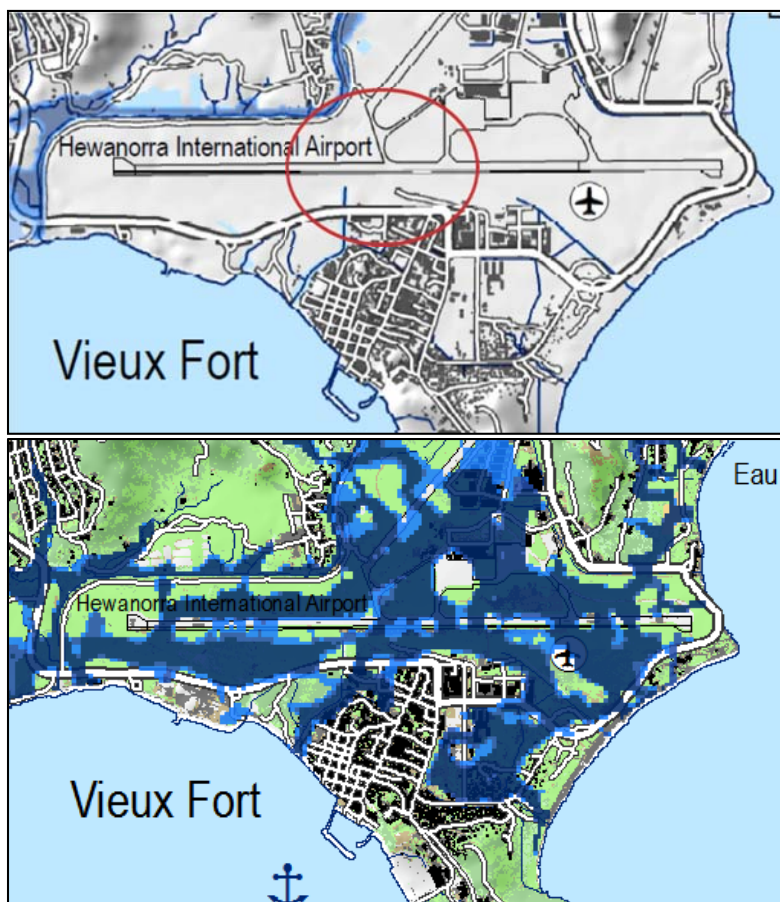


Figure 6.6. Hewanorra airport. Top 2015 draft flood hazard map, bottom final 2016 flood hazard map.





**Figure 6.7. Channel north of the airport looking west. The rise to the left is the dike protecting the airport. It can be clearly seen that the channel is filled with sediment.**

### 6.3 Evaluation against existing flood hazard assessments

After a literature search, two studies were found that were done in the past and offer more insight in flood hazard and that can be used to further evaluate the flood hazard map.

#### *Castries*

Cooper and Opadeyi (2006) assessed flood hazard in Castries. They produced a method for the entire island based on a GIS indicator method, where parameters related to floods are combined into a susceptibility map. Unfortunately, the map itself is not included in the report. They also looked at the flood hazard of Castries, for a 1:10 year event using the integrated model FLO-2D. This is a model similar to LISEM in scope and detail. Unfortunately they did not explain what parametrization they used, nor which hydrological conditions they used to run FLO-2D.

The result is expressed as a hazard combining water level and velocity, geared towards evacuation and the ability of people to pass the inundated area. For a 1:10 year event almost the entire city has color code yellow - low hazard (see fig 6.8 top). The entire area is very flat and the obstacles (buildings) will cause most of the center to have very low velocities (fig 6.8 bottom), consequently the hazard will always be low and people are able to pass. There are two areas that have higher velocities: one related to the northern channel entering the city, which is also shown by the LISEM simulations. The central red area in the map by Cooper and Opadeyi (fig 6.8 top) cannot be found back in the LISEM simulation. There is no channel here in the LISEM database so there will be no river flash flood. Possibly the area is poorly drained and excessive rainfall gives problems, but that is not considered in LISEM.

It should be noted that LISEM is configured in such a way that the buildings are only partly obstructing the flow and have a high resistance (Manning's  $n$ ). The water flow through built-up cells but slower. The FLO-2D simulation was configured in a much higher resolution, where the buildings are real impermeable obstacles. This gives different results in flow velocity, and hence differences in detail for the two models. LISEM gives a much higher effect of the river located on the southern boundary of the center, which is not visible in the FLO-2D simulation. It seems that river may not have been included in the FLO-2D simulation to start with, which is not explained clearly in the report of Cooper and Opadeyi. Omitting that river would be a mistake, as it is a known source of flood problems (discussions with the WRMA). The LISEM simulation shows that the effect of a 1:10 year rainfall might be devastating for Castries. The city is known for its poor surface drainage of rainfall, which frequently causes problems. A 1:5 year storm and above should pose a serious hazard for most of the center. This is confirmed by the report of Wright et al. (2014), describing the consequences of the December 2013 Christmas Trough (which had an average estimated recurrence period of 1:35 years). The areas flooded in Castries are described as extensive. Because it is a flat poorly drained area, hemmed in by hills, the flood extent for different return periods is not very different for different return periods (the flood depth is different). We conclude that given the differences in detail, the LISEM simulation is very similar, with details that can be logically explained, to the hazard assessment of Cooper and Opadeyi, 2006.

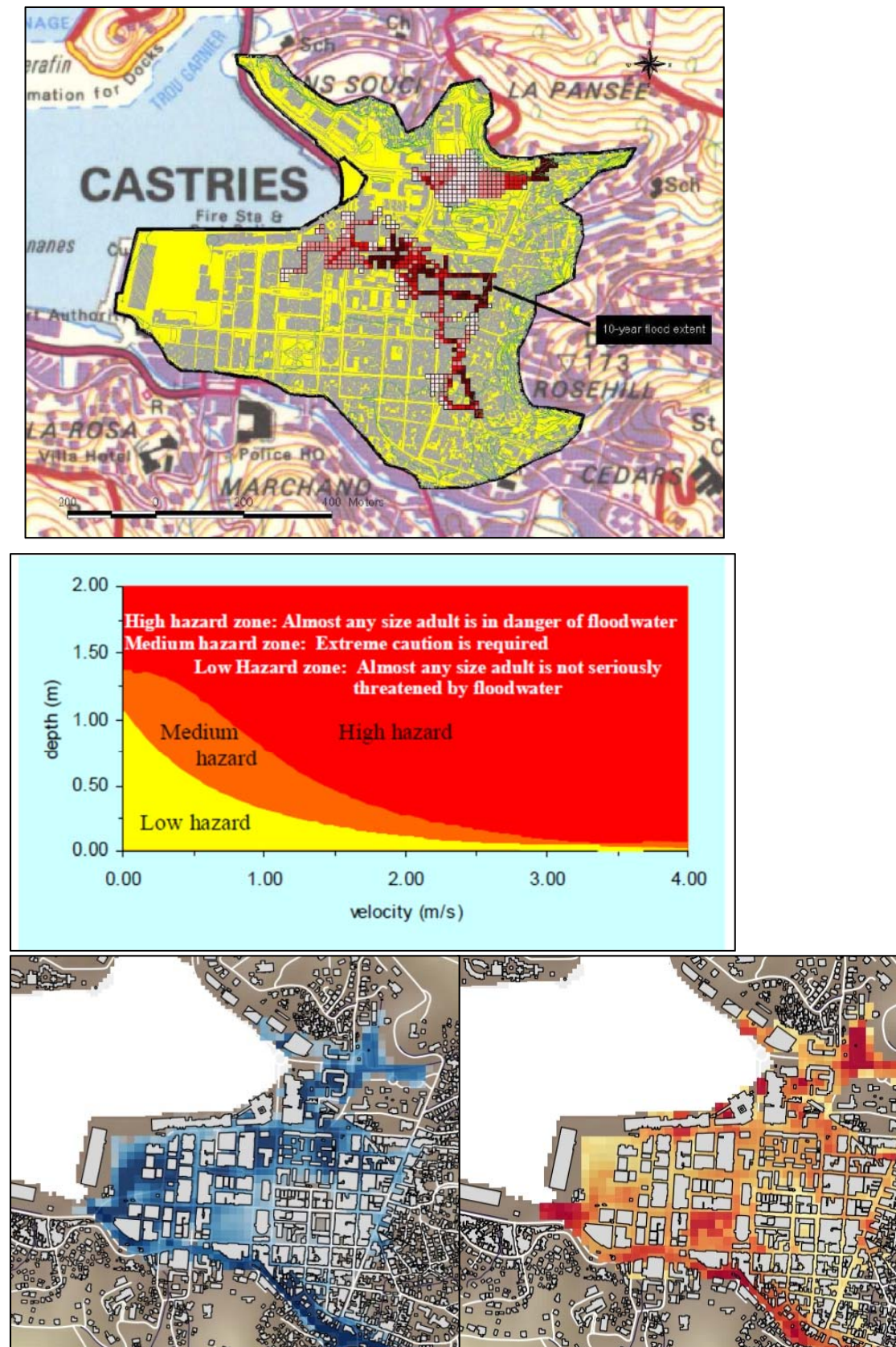


Figure 6.8. Comparison of the Cooper and Opadeyi 2006 flood hazard assessment for Castries center (top) and the hazard classification used based on depth and velocity (middle). The 1:10 year flood hazard output from LISEM in flood depth (scaled from, light blue to dark blue, 0-1 m) and flood velocity (from yellow to red, 0-1m/s) for the 1:10 year design event.



*EGISEau analysis of Soufrière, Fond St Jacques and Dennery*

Marmagne and Fabrègue (2013) did a flood risk assessment for the communities of Soufrière, Fond St Jacques and Dennery. Their assessment was stakeholder oriented, based on many interviews. An extensive analysis was done in each community to analyze the hydraulic situation of the rivers and drainage channels and identify weak spots. They used a method based on a 1:10 year return period discharge. This is a detailed site analysis, which cannot be directly compared with the national flood hazard map. Nevertheless they also made a potential flood extent map for Soufriere and Fond St Jaques, which is compared to the national flood hazard map.

The result for Soufrière is very good. The 1:5 year flood hazard extent is smaller but the 1:10 year hazard area is almost the same, including the exact boundary in the northern part of the village where the road remains just outside the flooded area, and the unaffected (higher elevated) area in the mid right part of figure 6.9 (black arrows).

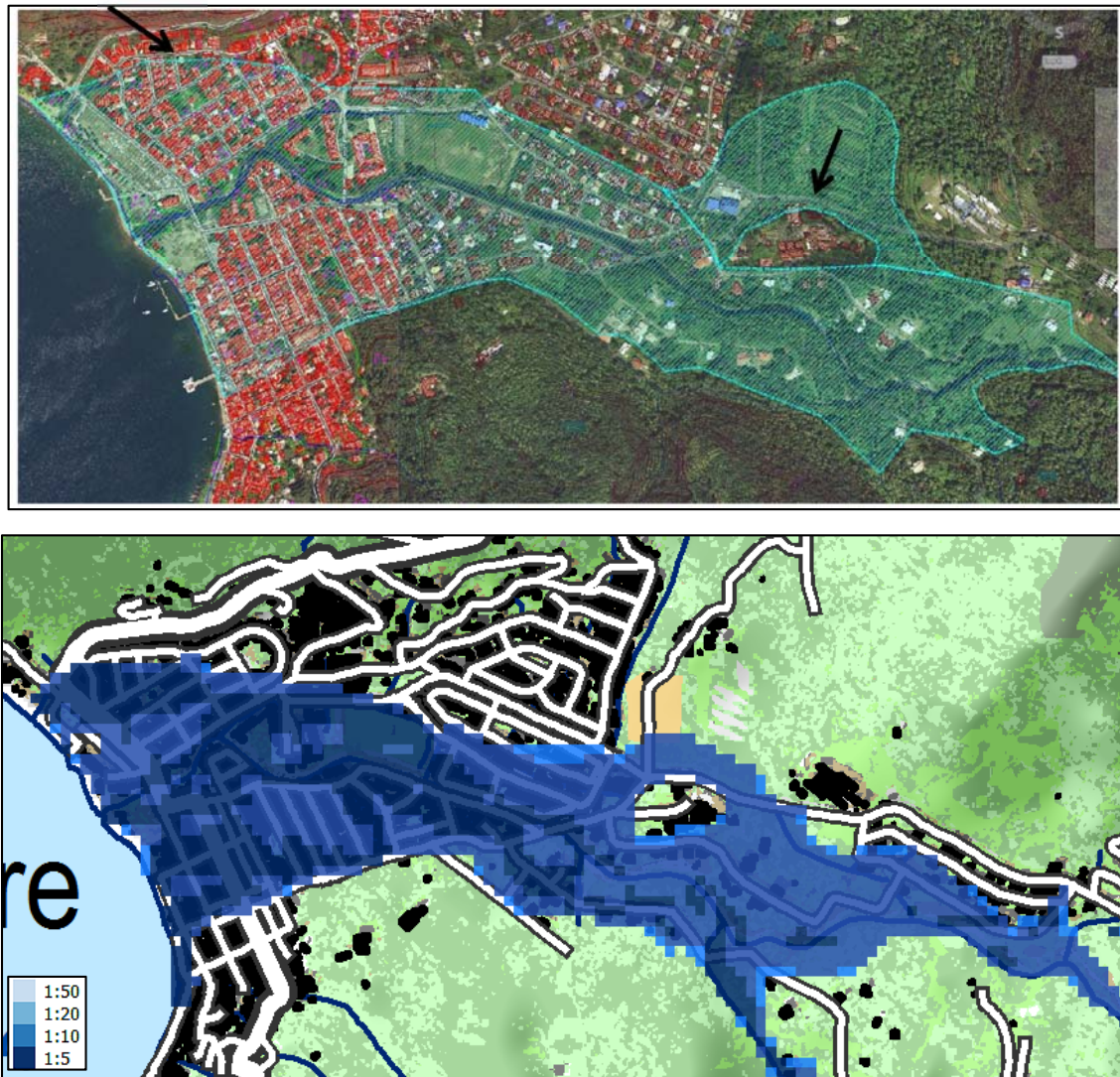


Figure 6.9. Comparison of the EGISeau 2013 flood hazard assessment (top) and the national flood hazard map (bottom), for Soufrière.

The results for Fond St Jacques (indicated on the national flood hazard map as Migny, fig 6.10 bottom), is reasonable but at the limit of what the flood hazard map can do in terms of resolution. In this location the flood hazard is simply determined by the steep terrain and the narrow valley. The valley around the river fills up during a flood, so the flood extent is entirely determined by the DEM quality. With this consideration, the national flood hazard map is very similar, but possibly too narrow in certain locations. However, the same parts of the village are affected in both assessments (fig 6.10).

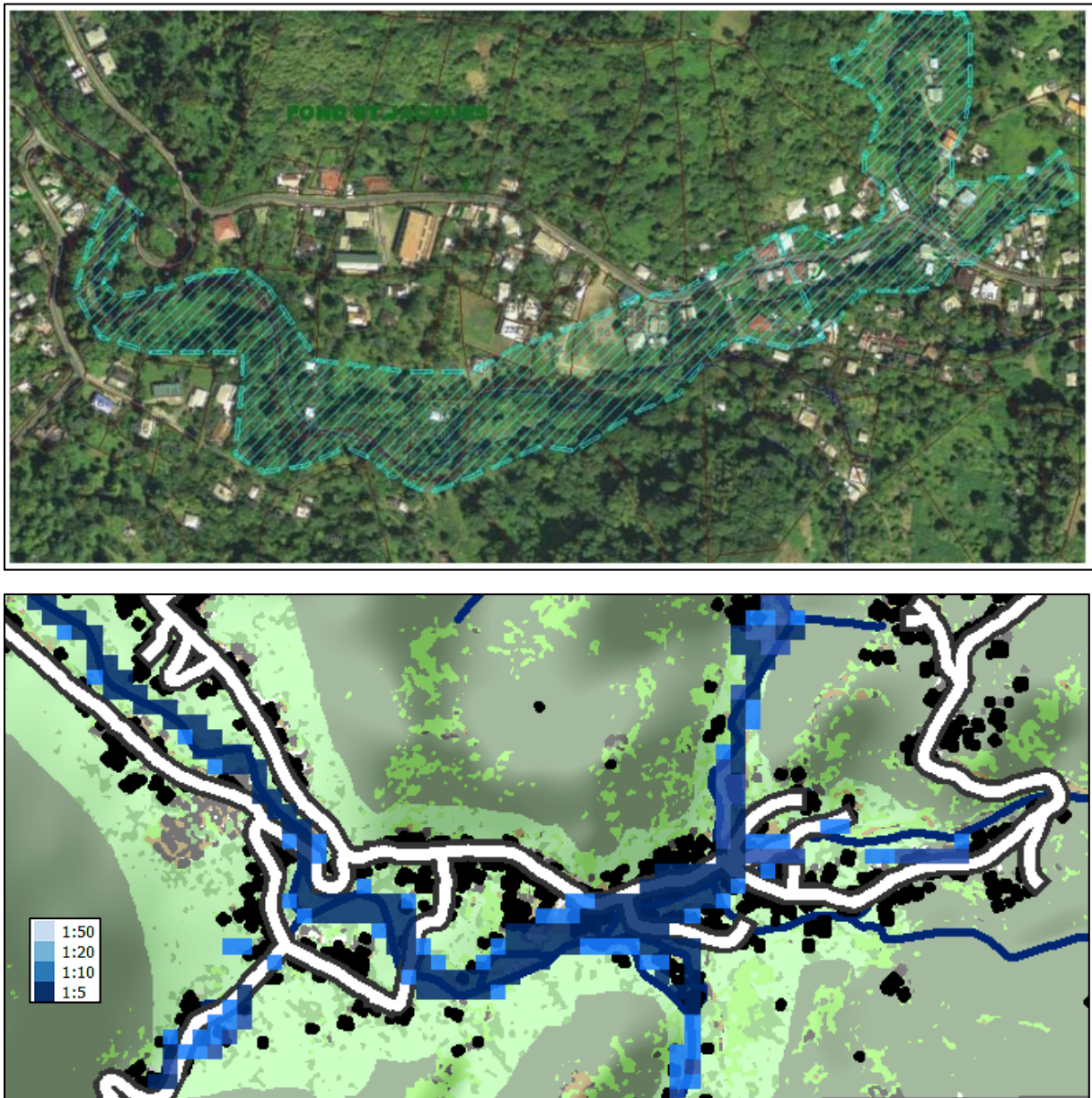


Figure 6.10. Comparison of the EGISeau 2013 flood hazard assessment (top) and the national flood hazard map (bottom), for Fond St Jacques (Migny).



## 7 Recommendations

### Flood hazard and IWM recommendations

- The flood model LISEM for national and watershed scale works well with the current dataset composition but is essentially uncalibrated. The first priority must be to collect data to calibrate and validate the model.
- All consultants until now just make an assumption on discharge conditions during a flood, without any backup data. They all use their own principles and assumptions, so that reports and results are not intercomparable.
- People may have a false sense of security from the FEW systems, because they operate on mere assumptions.

Select Locations: while island wide inventories are of course good to work on, they are also maybe a task too large to execute (taking too much manpower). Concentrate on the catchments in which you have a flood early warning system installed (FEW system), and collect the following data from these catchments. In other words: establish three catchments per island on which you concentrate these efforts with the goal to test and validate any tool you want to use. Establish a database for these catchments.

### Skill improvement WRMA and others

GIS: The agencies who deal with watershed management and have to operate tools such as the LISEM model, need a to have better GIS and possibly remote sensing skills. They are involved in the acquisition of spatial data, but are not fully equipped to transfer this data into a model dataset, nor can they easily transfer model outcome into a GIS environment for reporting. The data improvements suggested are only useful if the people in the agencies know how to improve the model data set with what they collect from the field.

Database: many data is collected and stored, predominantly in excel files, but metadata is not well described. The persons handling these datasets are very knowledgeable and know what they are doing, but if they should somehow be no longer involved in the process, a lot of knowledge will be lost. Establish a hydrological database, according to international standards.

Soils and Hydrology: many counterparts have followed hydrological courses that focus on operating a certain technology (a method or model). In these courses engineering assumptions are used that are not always site specific (runoff curves, peak discharge estimates etc.). The knowledge to understand and collect basic soil hydrological data and soil data related to soil erosion could be improved. Often a soil lab is seen as something related to fertility and agriculture, while it forms also the basis for hydrology and flooding.

### Data improvement

Measuring storm discharge data must have absolute priority!

- In several location early warning systems are installed with ultrasonic sensors that check water levels for a sudden rise. Known water level sensors are on st Lucia (at least 3 locations) and Grenada (at least 3 locations). This equipment is not used to actually collect river water level data, as far as we know. This should be relatively easily changed. The following steps are advised:

- A continuous time series of water level will help to understand the water balance, as the baseflow data is related to groundwater activity and peak flow data is related to storm runoff from the slopes. So store and collect the water level at all locations where a FEW system is installed to start with.
- Check these readings with a level staff that is constructed on the side of the channel, possibly at a bridge. Note: baseflow levels are generally very low and uninformative, so a weekly visit to a river is not very useful, as all variations in water level are missed. A continuous short time interval series should be captured, preferably at a 10 min interval.
- On these locations the water velocity and channel cross section must be measured, to be able to convert the water level to a discharge (create a stage-discharge relationship).

### **Rainfall data**

St Lucia has a very good set of rainfall measurements and this network is being maintained constantly. Nevertheless the data collected still has impossible values, a rigorous check is needed to clean the available data. If more data with a short time interval is collected, eventually better design rainfall curves can be collected.

The other islands do not have detailed rainfall data, only daily data and only from a few stations. An investment should be made to improve the rain gauge network on Grenada, St Vincent and Dominica. Without this data flood modelling cannot be done.

### **Hydrological data**

- Channel dimensions: measuring channel dimensions is a simple task in the context of hydrological modelling at the watershed scale. This doesn't have to be done with a full elevation level equipment. Average width and depth is on every 100 m along the channel is sufficient. This should be done for the main rivers that are known to be flooded.
- Estimate/measure other elements that interfere with surface flow: elevated roads, bridges, culverts etc.
- Soil data: based on the soil and land use map, a series of simple soil tests should be done for selected catchments. In each catchment about 50 samples should be taken in different classes of land use and soils. Gradually this will lead to a database of pedotransfer functions, that can be used on the entire island. Taking sample rings and processing them is not much work, about two weeks per catchment for 1 person.

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## Annex: national Flood Hazard map St Lucia



