An OpenLISEM Flooding Risk Assessment for the Tropical Volcanic Island of Réunion

*The village of Cilaos on the French island of R*éunion (Source: réunion.fr)

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Abstract

The island of Réunion is prone to natural hazards such as flooding and mass movements due to frequent tropical storms. The island is an overseas French territory in the Indian Ocean and one of the fastest growing regions in the EU with a population growth rate of 0.8%. Réunion holds various rainfall world records including most precipitation for 12, 24, 72 and 96 hour periods. These events and other tropical storms are responsible for considerable damage to property and people. In January 1980, Cyclone Hyacinthe, the wettest tropical cyclone worldwide struck claiming 25 lives and leaving 7,000 homeless. Cyclone Gaméde also broke rainfall records when it struck in February 2007 resulting in 2 fatalities and 90 severely wounded. If this growth trend persists and if more tropical storms are to be anticipated and produce record rainfall it is imperative to identify the degree of flooding hazard and subsequent risks. The objective of this study is to identify areas at risk of flooding and the potential water depth of flood prone regions.

This study utilizes the hydrological erosion model OpenLISEM to simulate a 1 in 10 year storm event derived from 25 years of precipitation data. The most heavily impacted region is the floodplains of the Riviére du Mât where flood heights exceeding 4 meters were found to inundate 940 structures, placing them at extreme risk. Flood heights of 0.5 to 4 meters inundate the fourth most populated city of Le Tampon, home to 70,000 residents. When compared to a risk survey by the BRGM, this study differs in that it determined a much greater flooding risk on the eastern side of the island most likely to differences in methodology when creating the design storm and classification of risk based on flood heights.

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1. Introduction and Objectives

Throughout the world the frequency of hazards has been increasing. The number of natural disasters has more than tripled in the period from 2000-2010 than from 1980-1990 (Leaning et al., 2013). This increase is due to weather related events which made up an overwhelming 90% of disasters in the past 20 years. Weather related disasters include storms, heatwaves, floods as well as several other weather related events. Of all weather related disasters, flooding accounted for 47% of events from 1995-2015 affecting more than 2.3 billion people (CRED, 2015). Extreme precipitation events often trigger other hazards such as landslides which in their turn may block rivers causing flooding upstream and the risk of breakthrough resulting in flash floods downstream. This is especially true for areas in subtropical regions as these areas are often battered by tropical storms (Pohl et al., 2016). With the anticipated global warming and rapid urbanization these hazards are only going to increase in frequency and in magnitude (IPCC, 2014). Improved understanding of these hazardous processes, modelling of these processes and the creation of hazard zonation maps will help to mitigate the negative effects of these natural hazards.

1.1 Flooding

Flooding is defined as the overflowing by water of the normal confines of a watercourse or water body and the accumulation of drainage water over areas that are not normally submerged (WMO, 2012). The most prevalent cause to flooding is water from rain or snowmelt that accumulates faster than soils can absorb it or rivers can carry it away. There are three common types of floods which occur in subtropical regions: coastal, river and flash. Coastal floods or storm surge is an abnormal rise in water level in coastal areas caused by forces generated from a severe storm’s wind, waves, and low atmospheric pressure. River floods occur when water rises above the banks of a river due to excess rainfall. Flash floods are the rapid rise of water in a stream or other low lying areas. Flash floods differ from regular floods in that they strike within 6 hours of a significant rainfall event such as a cyclone or an intense storm (WMO, 2012). The rapid discharge from flash flood events are powerful with enough strength to roll boulders, tear out trees, and destroy roads and bridges. The speed at which they occur in combination with their power makes them a major hazard as there can be little to no warning. On steep terrain floods can weaken soil and trigger catastrophic land movements that can damage homes, roads and property.

1.2 Historic Record of Hazards on Réunion

There are several terms that should be addressed to assess the risk of hazards. ‘’Hazards’’ can be defined as any threat that can potentially cause damage to people, property or other elements (Dewan , 2013). They can be natural (flooding), technological (pollution), or man-made (war). Risk refers to the degree of loss from a specific hazard on a specified element (Dewan, 2013). Vulnerability can be broadly defined as the potential for loss. These terms are central to hazard assessment studies.

As a result of its geological makeup and of its geographical location, La Réunion is especially susceptible to natural hazards. The high rainfall intensity (up to 6m/yr) and the prevalence of tropical cyclones contribute to erosion, land instabilities, urban and coastal flooding (MeteoFrance, 2017). This is of primary importance since much of the island is heavily urbanized and has a high average population density of 346 inhabitants per square kilometer (INSEE, 2018). Réunion is an island that is rapidly growing and with the acceleration of climate change the risks of flooding hazards are only going to get greater.

With its history of hazards it is no surprise that the French Geological Survey or BRGM has conducted hazard assessments of La Réunion in the past. A full island survey was conducted from the period of 2010 to 2016 in order to identify risks for an assortment of hazards including volcanic eruptions, earthquakes, hurricanes, tsunami, flooding and landslides. The resulting document, The Dossier Départmental des Risques Majeurs (or DDRM) is an extensive hazard assessment established by the BRGM in collaboration with the local government of La Réunion. It was among the first extensive surveys to be carried out on La Réunion and reached completion in the middle of 2016. The document is intended to increase the general knowledge about natural hazards to the general public, not to act as a regulatory document. The document highlights the island's volcanic history and how it's shaped the local geology such as steep reliefs which are subject to rapid erosion and ground movements with torrential rains. The DDRM stresses the risk of these hazards to the network of water resources, transport and energy which could deter assistance to the Reunionese people. The coastal road that goes around the island is essential to the movement of people and goods and is strongly disturbed by hazards.
The DDRM also documents the history of major hazards on Réunion shown below in Table 1.

Date	**Hazard**	**Damage**
1875	Catastrophic Landslide of Grande Sable at Salazie	63 people buried
Jan 1948	Cyclone	165 dead and huge loss of food crops throughout the island
Jan 1980	Cyclone Hyacinthe	25 dead, considerable damage from flooding on the entire island
Mar 2006	30,000m^3 landslide on the coastal road	2 dead
Jan 2014	Collapse of 10-15,000m^3 at Cilaos	0 Casualties but permanent evacuation of nearby homes

Table 1: Major Disasters at La Réunion (DDRM, 2016)

While the DDRM covers the various natural hazards present on La Réunion, several areas of the island that were difficult to survey especially in Les Hauts and the Piton de la Fournaise were omitted from the study because of their rugged topography and limited accessibility. Through the use of remote sensing and modelling, such areas can be more easily observed and analyzed for risk.

Furthermore the DDRM doesn't publicly explain the methodology that went into producing their thematic hazard maps for landslides and flooding. The risk of flooding appear to not have been determined with defined rainfall events in consideration. The flooding risk map produced by the DDRM can be found below in Figure 3 (DDRM, 2016). The DDRM distinguishes itself as a broad introduction to the all the hazards on La Réunion rather than an in depth thematic hazard assessment. It focuses on the importance of awareness of the hazards and their surveillance. This study evaluates the work of the DDRM through the use of satellite imagery and by comparing the outcome of the OpenLISEM runoff model. rainfall event.

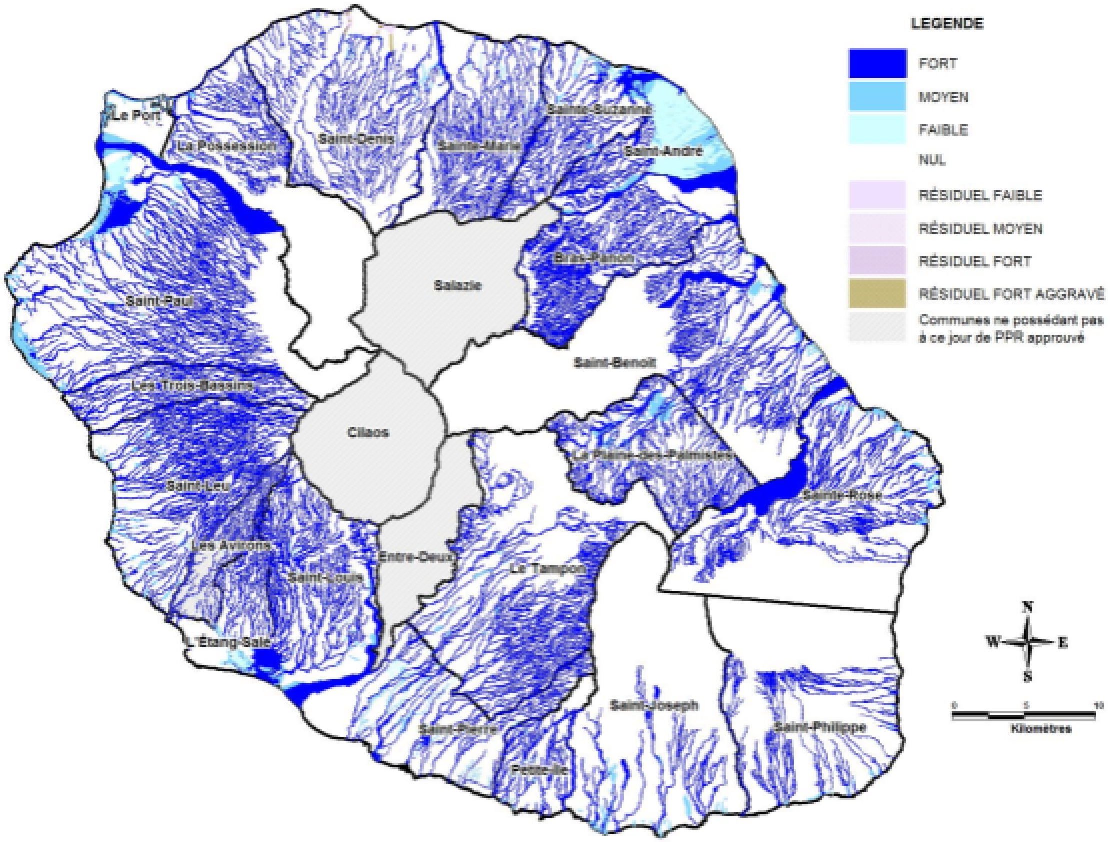

Figure 1: DDRM Map for Flood Risk (DDRM, 2016)

1.3 Objectives and Research Questions

La Réunion is one of the fastest growing regions in the EU with a growth rate of 0.8% (United Nations, 2017). If this growth trend persists and if more tropical storms are to occur and produce record rainfall it is crucial to have a detailed and preferably quantitative map of the area at risk for flooding. It was determined that the island would be tested by OpenLISEM model simulations for a 24 hour rainfall event as Réunion is known for its long periods of intense rainfall from tropical cyclones. The objective of this study is to identify the risk of flooding for the island of La Reunion through the development of a hazard zonation map. Under this objective, this study will investigate the extent of the area at risk and the potential water depth of flood prone areas. The anticipated output will be

1. Hazard zonation map/Elements at Risk Map for flooding given a 10 year storm event
2. Quantitative map for flood frequency and water depth during flood events based on OpenLISEM model scenarios
3. Intermediary maps for cumulative rainfall, interception, infiltration, and maximum flooding velocity.

In working towards addressing the main objective, this study also aims to accomplish a series of sub objectives in the process including: identify a 10 year design storm derived from ground meteorological stations present on La Réunion, calculate the percentage of buildings at risk, and compare the results from this study to the flood risk map produced by the DDRM. The final sub objective would be to test the capacity of OpenLISEM, as prior to this study, it was unusual for LISEM to be run on a catchment at the scale of Réunion. Earlier studies only tested LISEM for catchments up to several hundred km^2 and for shorter storm events less than a day long. This study will exert LISEM beyond previous runs and will examine the results to check for feasibility to see if the program is truly capable of modelling a catchment and storm of such large scale.

2. The Study Area: Island of Réunion

2.1 The Island of Réunion

The island of Réunion is selected for this study due to its vulnerability for a range of natural hazards and its location in the ocean and tropical climate.

La Réunion is a French Overseas Territory part of the Mascarene archipelago in the western Indian Ocean this can be seen in Figure 1 (right). This volcanic island is located 175km east of Madagascar near the densely populated Mauritius. La Réunion is the most populated of the French Overseas Department as it is home to 870,000 people as of 2017 and is expected to reach 1 million by 2030 (Claude-Valentin et al., 2012). Despite being among the poorest regions of France, the island is one of the most prosperous areas in the Indian ocean. Prior to becoming a French Department in 1946, the island's economy was almost entirely dependent on agriculture, which is responsible for destroying up to 65% of the natural forest cover (Petit et al., 2008). Since 2000, tourism has become the major industry that sustains the island's economy with the number of foreign visitors reaching record numbers of 426,000 in 2015. Visitors often flock to the island to witness its rugged terrain and varied landscapes.

Figure 2: Map of La Réunion (Le Masson et al., 2011)

2.2 Geography and Topography

La Réunion (21°S, 55°E) is a small mountainous island with a total area of about 2,511 km^2 (Réchou et al., 2014). The island is composed of two volcanoes: Piton de La Fournaise (2632m) in the southeast and the Piton des Neiges (3070m) in the center of the island (Réchou et al., 2014). The Piton de la Fournaise volcano is amongst the most active volcanoes in the world, having erupted more than 100 times since 1640 (Lénat et al., 2012), most recently in July of 2017. The Piton des Neiges is the highest point of the island and is surrounded by three steep calderas (or Cirques): Mafate to the northwest, Salazie to the northeast, and Cilaos to the south. The landscape of Réunion is very steep and rugged away from the coast as the volcanic rock has endured intense erosion due to heavy precipitation from tropical rainfall (Pohl et al., 2016). The most populated city in La Réunion, Saint Denis, also functions as the capital and resides in the furthest point of the north coast with 145,238 people as of 2012 (INSEE, 2018). Most of the dense population centers are located on the low elevation coastal areas since much of the center of the island is too steep and rugged to be easily developed on: Saint Paul (101,023 people) in the east, Saint Pierre (75,265) in the south and Saint André (51,964) in the east. These natural settings in combination with the high population number makes the island an excellent study case for hazard mapping.

2.3 Climate

In La Réunion the climate is tropical but features a variety of microclimates due to the island's topography (MeteoFrance, 2017). The temperature is mild throughout the year and fluctuates between 12 and 26 degrees Celsius. There are two distinct seasons in Réunion: the rainy season from January to March and the dry season from May to November. The windward side of Réunion sees easterly onshore winds and is wet tropical while the western side of the island lies in the rain shadow of the volcanoes. The high terrain of the island, particularly the Piton de la Fournaise and the Piton des Neiges are responsible for the high spatial variability of precipitation between the west and the east. Precipitation is generally higher on the higher elevation terrain than on the coast. Even during the dry season, precipitation remains high on the eastern part of the island. Figure 2 (left) reveals the great spatial variability of precipitation for La Réunion.

La Réunion holds most world records for intensive rainfall amounts for time scales ranging from 12hrs to 15 days due to the influence of tropical cyclones (Breña-Naranjo et al., 2015). The tropical cyclones are capable of producing these extreme precipitation events due to enhancements from orographic forcing (Pohl et al., 2016). These high precipitation events produce flash floods, landslides and increased river and sediment flows that regularly produce fatalities and significant damage to infrastructure and crops.

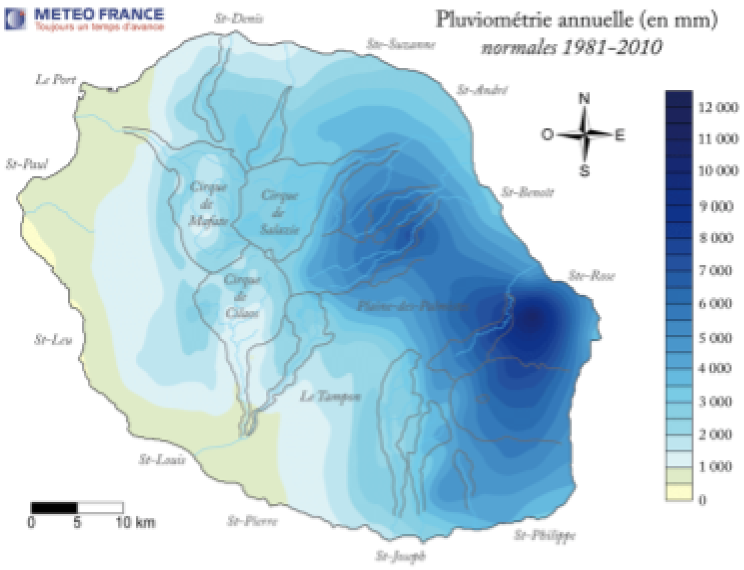

Figure 3: Average Annual Rainfall in La Réunion 1981-2010 (MeteoFrance, 2017)

2.4 Tropical Cyclones

The numerous world record precipitation events on La Réunion are the result of tropical cyclones which are capable of releasing sustained intensive precipitation over a period ranging from hours to 15 days (MeteoFrance, 2017). Cyclones are defined as tropical storms with a sustained wind speed exceeding 33m/s or 64 knots and which occur in the Southwest Indian Ocean. There are three principal dangers of cyclones: the strength of the winds, the storm surge and the rainfall. The force of the winds and their abrupt changes in direction and intensity are responsible for considerable damages. Storm surge or the rise in mean sea level and the swells flooding coastal plains can cause intensive damage to coastal areas, fortunately the bathymetry of Réunion features a rather deep seabed so the island tends to resist damages from storm surge. Perhaps the most damaging effect of the tropical storms is the torrential rainfall as it often leads to several hazards such as floods, flash floods, landslide, and mudslides (Rappaport, 2014). The intensity of the precipitation is not related to the intensity of the storm as the Saffir-Simpson Hurricane Wind Scale as well as many other classification types only consider the strength of the wind when determining the intensity of a cyclone event. Tropical depressions can produce more rainfall than mature cyclones. Tropical storm events are important to be aware of when determining the frequency and risk of flooding and landslide hazards.

3. Methods and Data

3.1 The OpenLISEM Model

The Limburg Soil Erosion Model (LISEM) is a physically-based numerical model designed to simulate runoff, flooding and erosion (OpenLISEM Manual, 2018). LISEM breaks down the processes involved in these events into two categories, Hydrological and Sediment. As the principal focus of this study is flood hazard, the sediment processes are omitted during the program run. Hydrological processes are made up of: precipitation, interception, infiltration, surface storage, overland flow, channel flow, and flooding flow. LISEM was selected as the model for this study for its capacity to run larger catchment sizes and its compatibility to run with most datasets.

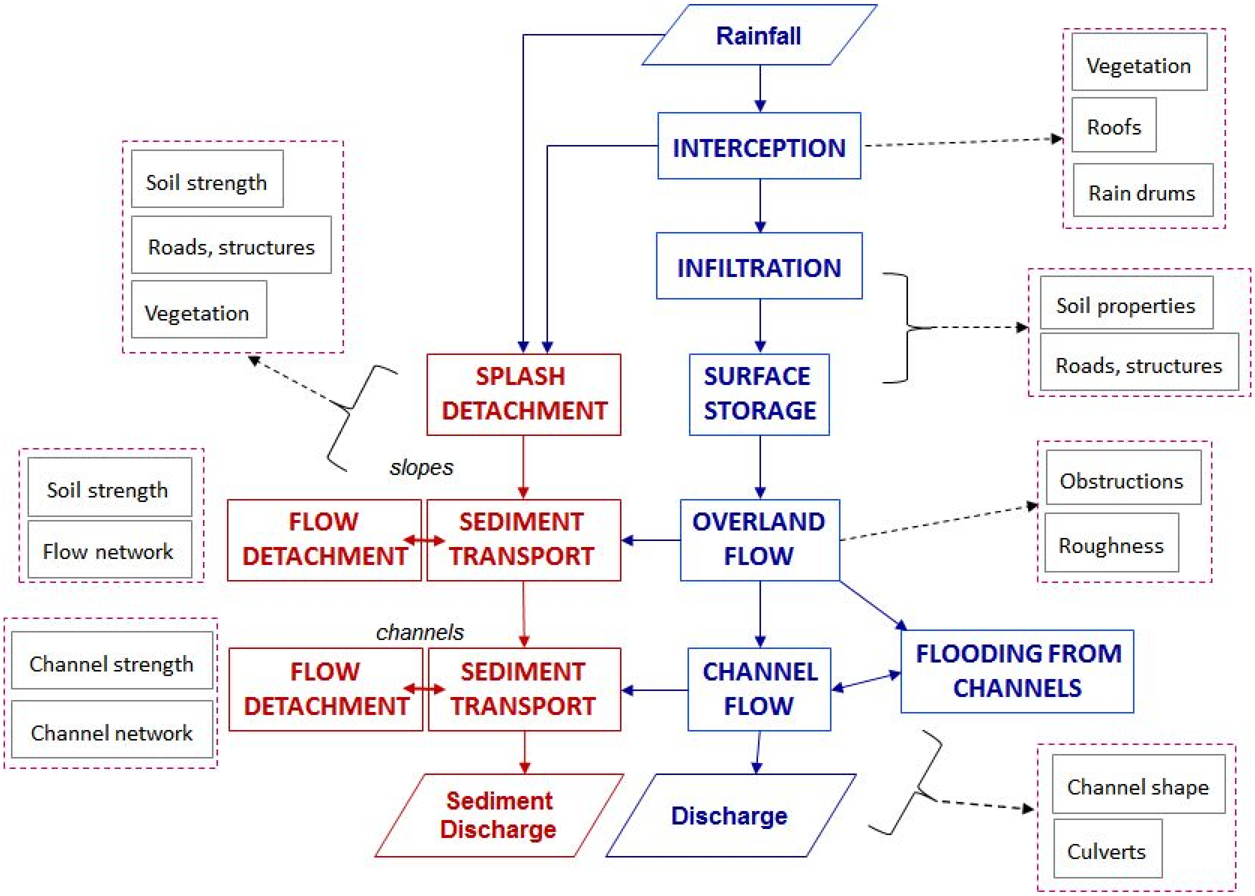

Figure 4: Summary of how LISEM simulates various process from the hydrological cycle and how it impacts sediment processes (OpenLISEM Manual, 2018)

Precipitation is modelled from rainfall intensity which varies spatially and temporally and serves as a crucial input for the model as it deposits water onto the surface. Interception refers to precipitation that does not reach the surface but is captured by surfaces other than the soil such as buildings and vegetation. Infiltration occurs when water on the ground surface percolates into the soil. Surface storage refers to water stored in the micro depressions at the surface, only when the water level in these depressions reach a certain threshold can runoff begin. Overland flow refers to the flow of water at the surface into a channel. This accumulation of water in a channel causes channel flow. Only when the channel overflows is flooding flow initiated. The channel acts as the main link between the various flow domains. Sediment processes include: splash detachment, sediment transport, and flow detachment deposition. Splash detachment is the loosening of soil on impact from rainfall due to its kinetic energy.

Sediment transport occurs when water with a concentration of sediment is transported. Flow detachment deposition is the process where materials are transported by channel flow.

LISEM divides the study area into a grid of square cells where each cell is subject to all the aforementioned processes at any given timestep. The program requires the input of several maps each modelling a different variable. The maps are treated as layers so that the same cell can contain several properties. A gridcell can contain bare soil, compacted soil, vegetated surface, a road, a house, and a channel. This is possible by integrating the cells as different layers as fractions of total cell area. The soils map acts as a base layer with its hydrological characteristics and additional maps are input to represent other hydrological processes.

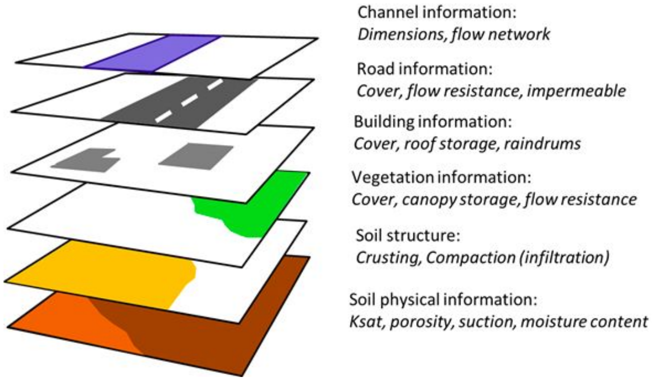

Figure 5: Representation of how LISEM integrates input data as layers per gridcell (OpenLISEM Manual, 2018)

LISEM uses these maps and differential equations to solve for runoff flow, channel flow, channel flooding, erosion, sediment transport, and multiclass sediment. The program, LISEM requires a minimum of 24 maps in order to run. The maps required can be structured into 8 categories: Topography related maps, Rainfall maps, Surface cover maps, Soil surface maps, Infiltration related maps, Erosion maps, Channel maps, and Tile drainage maps. All the required maps were derived from 5 basics sources: rainfall intensity, topography map, land cover map, soil map, and an infrastructure map.

3.2 Data Collection

3.2.1 Rainfall Intensity

In order to identify flooding risks for La Réunion it is first necessary to collect rainfall data in order to determine rainfall parameters. Rainfall data was collected from MeteoFrance, the French national meteorological service. MeteoFrance manages a vast network of 56 ground meteorological stations distributed throughout the island. Ten of these stations were selected to be part of this study based on their location, altitude, and periods of activity. The stations as well as their coordinates can be found in Table 2 below:

Station ID	Station Name	Altitude	Latitude	Longitude
97418110	GILLOT-AEROPORT	0008 m	-20.892	55.528
97424410	CILAOS	1197 m	-21.134	55.471
97419350	GROS PITON SAINTE-ROSE	0181 m	-21.179	55.828
97417360	LE BARIL	0115 m	-21.359	55.732
97407520	LE PORT	0009 m	-20.946	55.282
97422440	PLAINE DES CAFRES	1560 m	-21.209	55.572
97406220	PLAINE DES PALMISTES	1032 m	-21.136	55.627
97415590	POINTE DES TROIS-BASSINS	0005 m	-21.105	55.247
97404540	PONT-MATHURIN	0020 m	-21.259	55.374
97410238	SAINT-BENOIT	0043 m	-21.058	55.719

Table 2: MeteoFrance Precipitation Station Information (MeteoFrance, 2017)

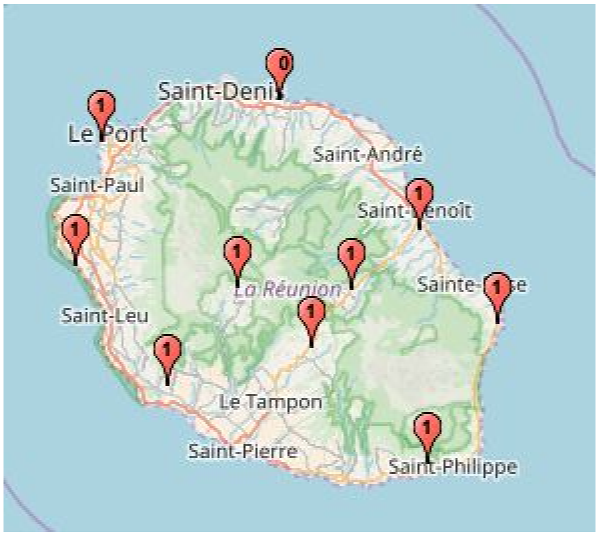

Figure 6: Location of MeteoFrance rainfall stations on La Réunion (Source: GoogleMaps)

A design storm is a temporal and spatial precipitation pattern which serves as input for the hydrological system. It consists of a defined rainfall magnitude and frequency such that a 10 year storm event is a storm with a probability of occurrence of 1 in 10 in any given year.

In order to identify 10/50/100 year rainfall events for Réunion, the first step was to retrieve daily precipitation data which was pulled from the MeteoFrance Publithèque portal (Données Publiques De

Météo-France, 2017).The daily precipitation was gathered for a 25 year period from the 1st of January 1992 to the 1st of January 2017. This period was selected as it was the time that most stations were active in collecting precipitation data. This information was used to create an frequency analysis for rainfall intensity which states the probability that a given average rainfall event will occur for a given recurrence period (Deltares, 2008). The frequency curves were created for each of the 10 sampled stations by first identifying periods where the stations were not operating and filling in the “N/A” values with no rainfall. The hourly rainfall data was then averaged under a 24 hour moving average which means that each rainfall value was averaged with the 12 hourly rainfall values preceding and following it. This process creates a 24 hour moving window in which rainfall values are averaged with the surrounding values. The purpose of this process is to smoothen the data and rid of minute abnormalities or errors.

The next step involved in creating the frequency curve was to find the recurrence interval for every rainfall value. This was done by assigning a rank for each rainfall value and then dividing the given rank by the total number of observations. By retrieving the inverse of this value yields the return period for each rainfall value in ascending order. The rainfall values were matched with their respective return periods to create the frequency curve. The next step was to create a trendline in order to extrapolate for extreme rainfall events beyond the 25 years of rainfall data collected. To incorporate all of the rainfall values into the trendline would require a largely inaccurate logarithmic curve. Therefore it was decided that the trendline would be better fit if only the larger rainfall events were included. As a result, only rainfall values with a return period greater than 0.1 were considered in the trendline. An example of the resulting linear trendline can be found below in Figure 6:

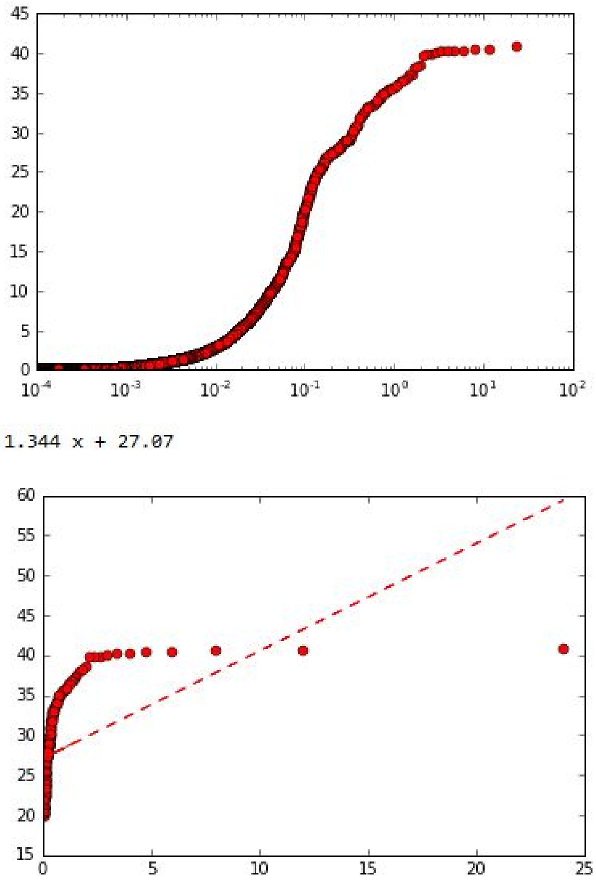

Figure 7: Example Frequency Analysis for the station of Cilaos with respective trendline

The trend lines were used to extrapolate 50 and 100 year rainfall events. The following step was to establish the 24hr design storm window. This was achieved by isolating the 24 hour periods with the rainfall rate which matched with the 10 year scenario. These rainfall events were then averaged based on their orientation on the island into West, Central and East. Réunions topography casts a significant rain shadow on the island causing a significant disparity in rainfall westward. The stations in the West include: Le Port, Pointe Des Tres Bassins, Pont Mathurin, and Gillot Aeroport. The stations in Central include: Cilaos, Plaine Des Cafres and Plaines Des Palmistes. The stations on the East include: Saint Benoit, Gros Piton, and Le Baril. The stations were averaged by region in order to keep the design storms spatially continuous/consistent. To directly combine the different 10yr storm events would be flawed as some of the selected rainfall events are different stages of different storms and by averaging the rainfall events by region, the abnormalities will be minimized. Since there is not enough rainfall observations for a 50 year event, the regionally averaged 10yr rainfall data was scaled up according to the trendline to fit the 50 and 100 year events. By replicating the temporal distribution of the rainfall and scaling it up we can assure that we retain a realistic rainfall event/scenario. This process was replicated for each of the three regions of the island (West, Central and East). A map of the rainfall stations was then assembled in order to create a spatial time series of rainfall of Réunion from the created design storm events.

3.2.2 Topography

In order to model the hazards on Réunion, a detailed model of the topography is essential and an understanding of the role of topography with respect to hazards is paramount. The steep terrain in combination with the high rainfall scenarios are responsible for the high hazard risk particularly in regards to landslides. The Institut Géographique National (IGN), the French state establishment for geographical information, has a geographical database for all of mainland France and its overseas territories (IGN, 2018). To properly model the topography, the ALTI RGE dataset was retrieved from the IGN portal. This particular digital elevation model (DEM) was selected as it provided the highest spatial resolution (5m) for the entire island of Réunion. The ALTI RGE series was collected as part of an ambitious renovation program initiated in 2009 to create elevation data for all French territory. The data was collected from airborne LIDAR surveys.

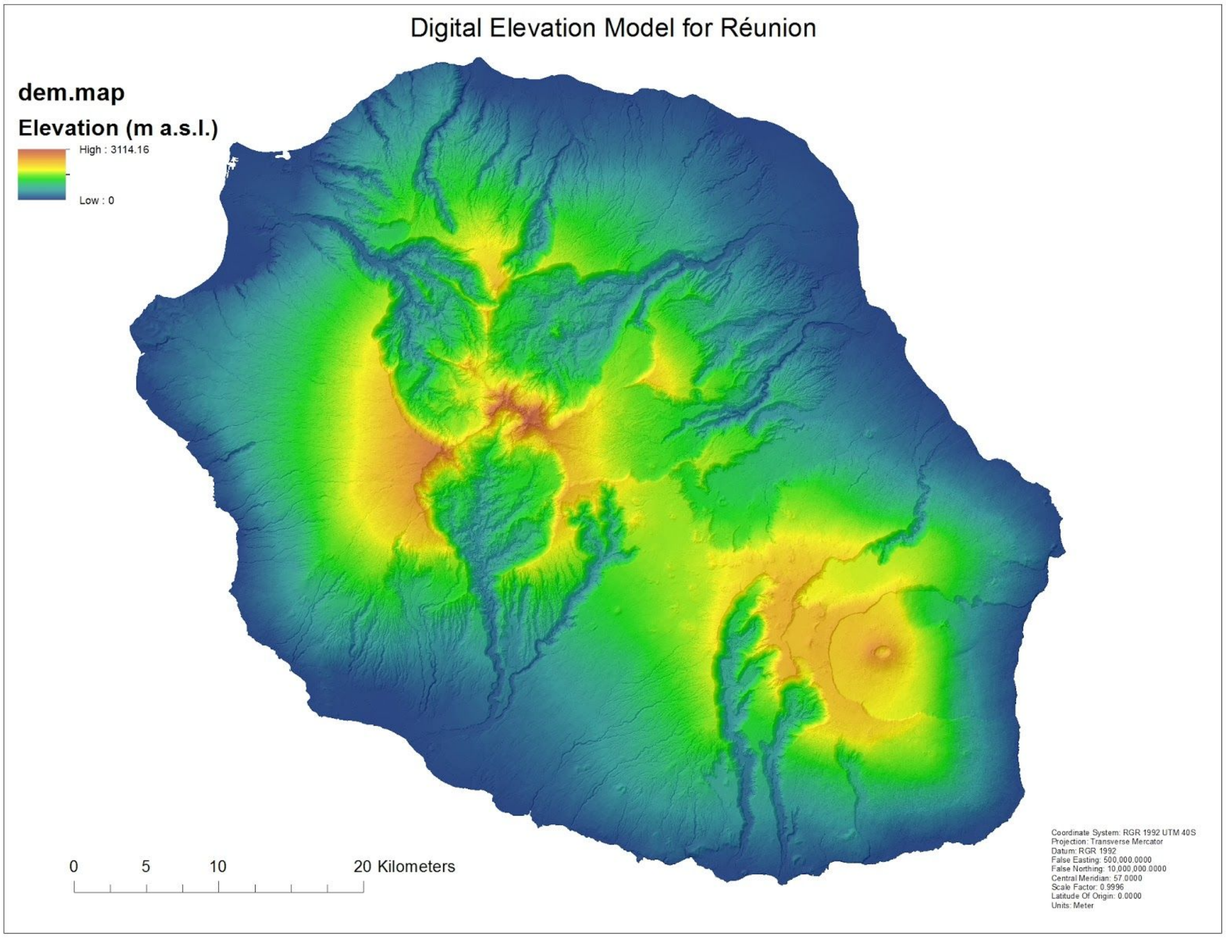

Figure 8: Digital Elevation Model (DEM) for Réunion with a grid size of 25m and elevation range of 0 to 3154m. Source:(Institut Géographique National, 2018).

The DEM is used to create a local drainage direction (LDD) map which indicates where water should flow at any given point and is used to identify channels and catchments. This in turn is used to identify possible flood prone regions. The transformation from the DEM to create the LDD was performed using PCRaster, spatio-temporal environmental modelling software most commonly used in applications of hydrology, ecology and land use. PCRaster is a python based GIS program developed at Utrecht University which is an excellent tool for manipulating raster maps (Karssenberg et al., 2010). The ‘lddcreate’ function was applied to the DEM and calculates an 8 point pouring algorithm to identify its steepest downslope neighbor for every cell to create the LDD. If a cell has all of its neighbors with a local drainage direction flowing into it and it doesn’t have a neighbor at a lower elevation, a pit is formed. The ‘lddcreate’ function was used with the ‘lddin’ option which assures that there are no pits at the edge of the map. This limits the number of catchments to larger outflow points. The lddcreate function operates with four different arguments: max local depression outflow depth (m), max local depression outflow volume (m^3), max local depression area (m^2), and max rainfall (mm) needed to fill depression. These arguments are used to determine the threshold to determine where pits are formed. In this study, the outflow depth, core volume, core area, and precipitation were all set to arbitrary high values ($1x10^8$) to limit the number of catchments to a reasonable number, capable of being processed. The LDD is among the most important inputs in the LISEM program as it is the mask under which all the other maps are run.

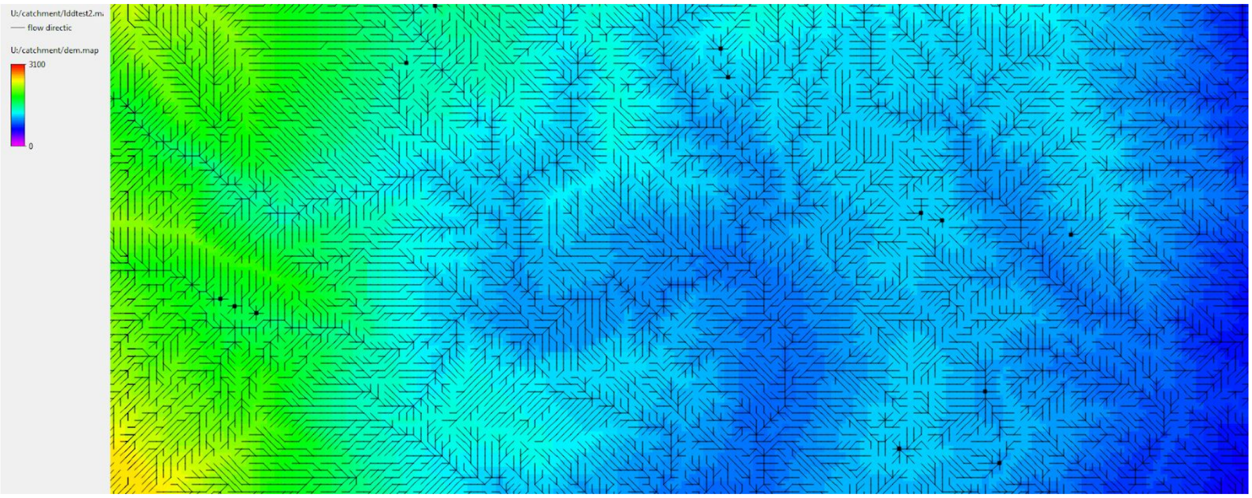

Figure 9: Example of pits (shown as black dots) overlayed on the DEM. Pits are important indicators for determining the number of catchments that will be simulated for discharge in OpenLISEM.

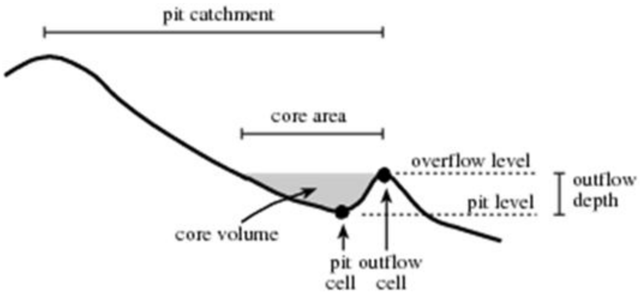

Figure 10: Example of arguments used in pit definition (OpenLISEM Manual, 2018)

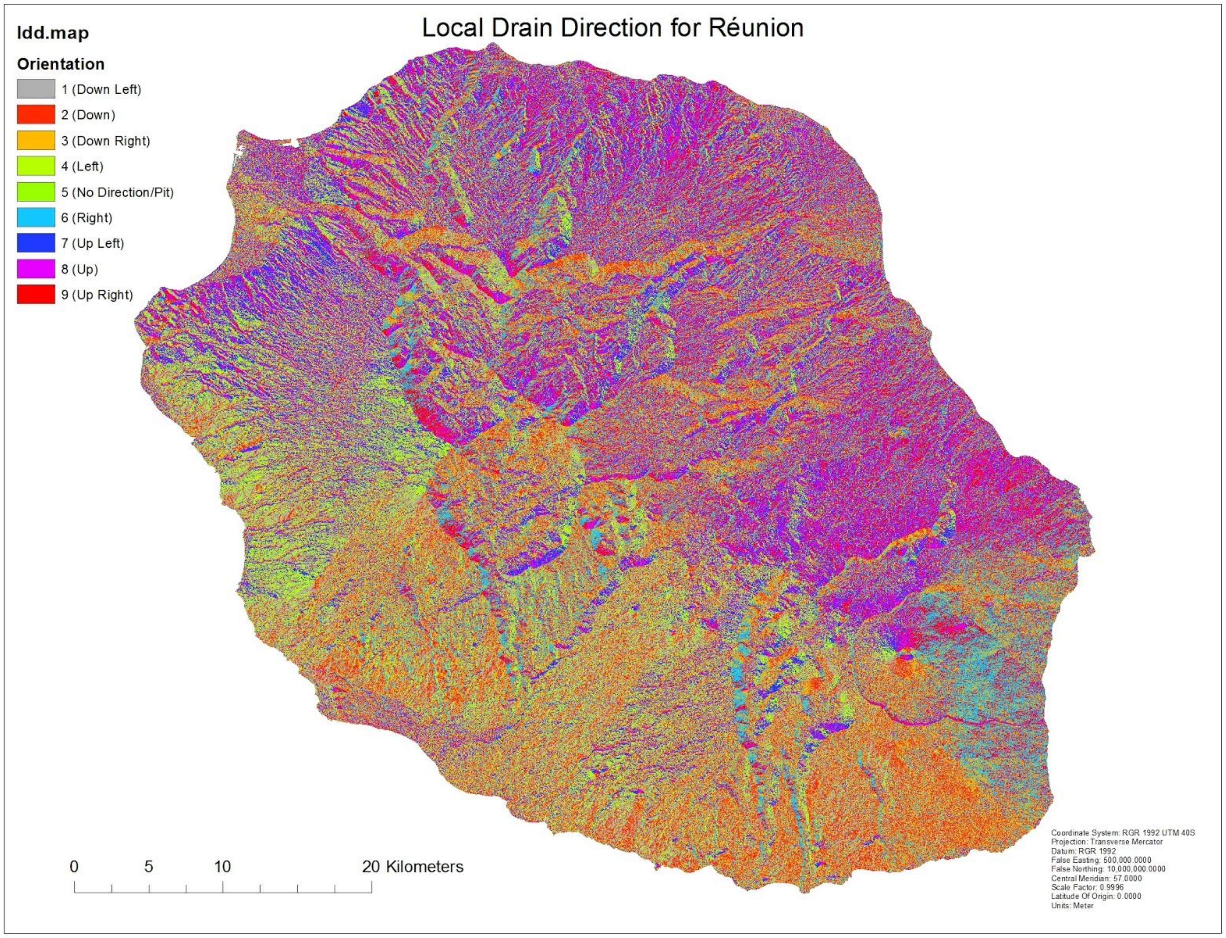

Figure 11: Local Drain Direction (LDD) for Réunion where each numerical value indicates a flow direction. The flow directions correspond to the numbers on a numerical keypad where 2 is South, 4 is West, and 5 is a pit or the absence of flow direction

In combination with the 10 meteorological stations of Réunion, the DEM was incorporated to make a topography based rainfall map shown below in figure 10. The ‘spreadzone’ function of PCRaster uses a slope map derived from the DEM as a friction base and then calculates the shortest distance to each meteorological station. This in turn created topography based rainfall zones that when applied with the tables of various rainfall events can be used to form spatially and temporally consistent design storms.

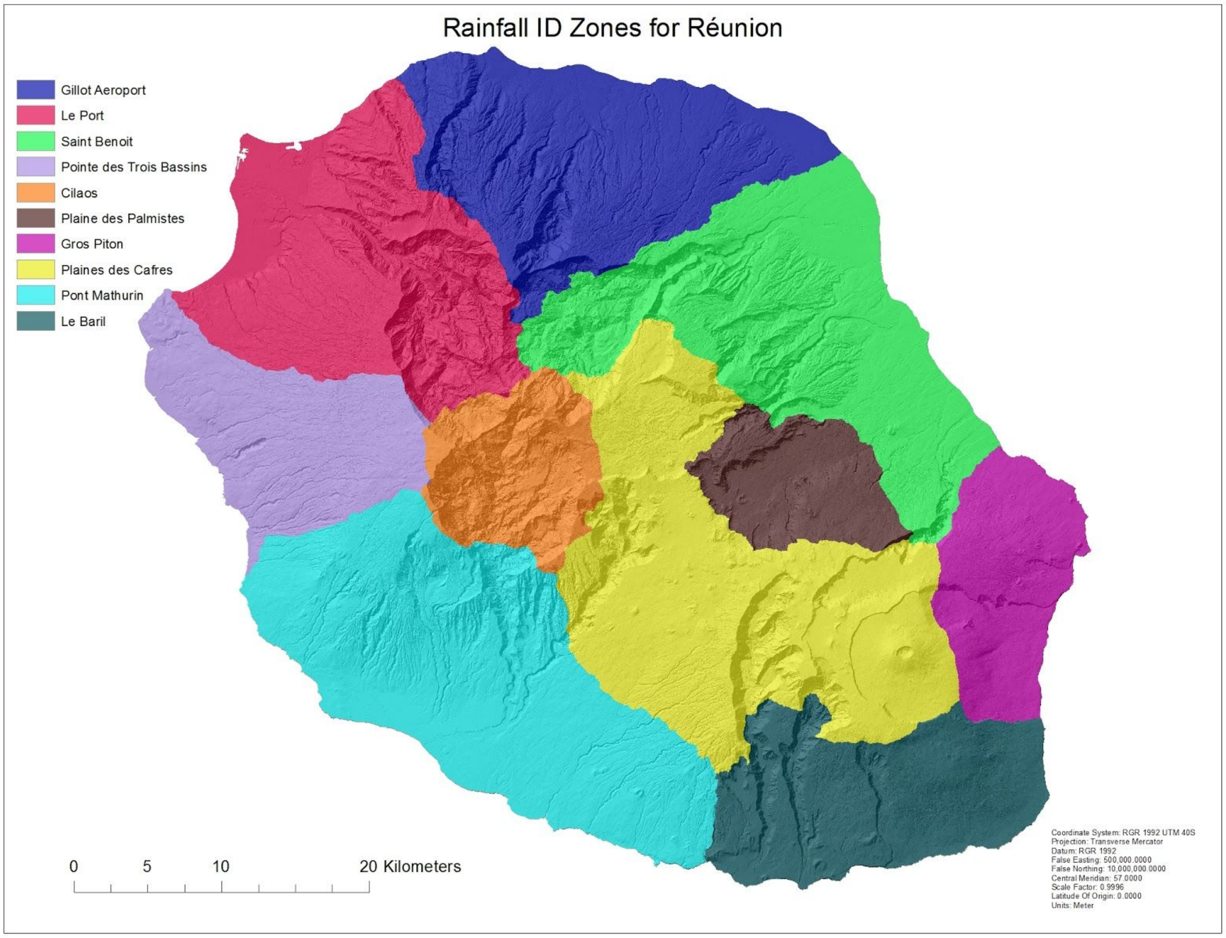

Figure 12: Rainfall Zonation map for Réunion derived from the DEM

3.2.3 Soil Properties and Soil Cover

An important component of the water balance is the soil as water is stored, drained, and evaporated from the soil. Information on soils is especially crucial for infiltration as it is used for determining the degree of factors such as overland flow, channel flow, and flooding. Furthermore soil properties such as soil cohesion are used to determine sediment transport and potential erosion risk. The map for soil cover was provided from CIRAD (2018), the French Agricultural Research Center for International Development. The organization addresses issues of food security, climate change, and natural resource management for tropical less developed regions of the world. CIRAD provided a soil map from Michel Raunet (1991) which recognized soil typology on a scale of 1:50,000. On Réunion, soils are made from the volcanic lavas from the two shield volcanoes. The lavas are disproportionately weathered based on their location, from factors such as altitude, rainshadow, and erosion. Raunet used the weathering gradient to classify soils in the French classification. The data collected identified 8 primary soil types on Réunion under this French soil classification system, all of which are quite clayey in nature. The soils were then converted into the most similar FAO soil classification based on their properties provided in the dataset. The list of soil conversions as well as their properties can be found in the Appendix B. From the soil cover, the erosion maps and infiltration maps can be derived. Erosion maps include cohesion, aggregate stability and median grain diameter. Cohesion refers to the shear strength of soils and can be reimagined as the attraction between soil particles and ability to resist external forces like erosion. Aggregate stability is the ability of soil aggregates (groups of soil particles which bind to each other more strongly than adjacent particles) to resist disruption from outside forces are applied (usually with water or wind) (Carter et al., 1991). Median grain diameter is the midpoint of grain size distribution where 50% of the sediment is coarser and 50% is finer (Bowles, 1979). Median grain diameter (d50) is used to find the settling velocity which in turn is used as an indicator for the degree of detachment and deposition. Infiltration maps include saturated conductivity, average suction at the wetting front, porosity, and initial moisture content. Saturated conductivity (Ksat) relates to permeability and describes the ease with which a fluid can move through pore spaces or fractures in the saturated soils (Bowles, 1979). Average wetting at the suction front refers to soil water pressure differentials which drives water from regions of high pressure (where water is held tightly to grains) to low pressure typically vertically downwards (Bowles, 1979). Porosity is a measure of the empty spaces in the soil and typically decreases as particle size increases. It is measured as the fraction of empty space over the total volume. Initial moisture content refers to the quantity of water contained in the soil prior to the design storm. It is an important indicator for the capacity of infiltration as more saturated soils will absorb less rainfall and contribute more to runoff. All of the aforementioned maps were constructed in PCRaster the 'lookupscalar' function. The 'lookupscalar' function creates new scalar maps with the expression provided in a given table. Provided with a soil type map and a soil properties table, this function was used to create all the erosion and infiltration maps by attributing property values to the soils mask.

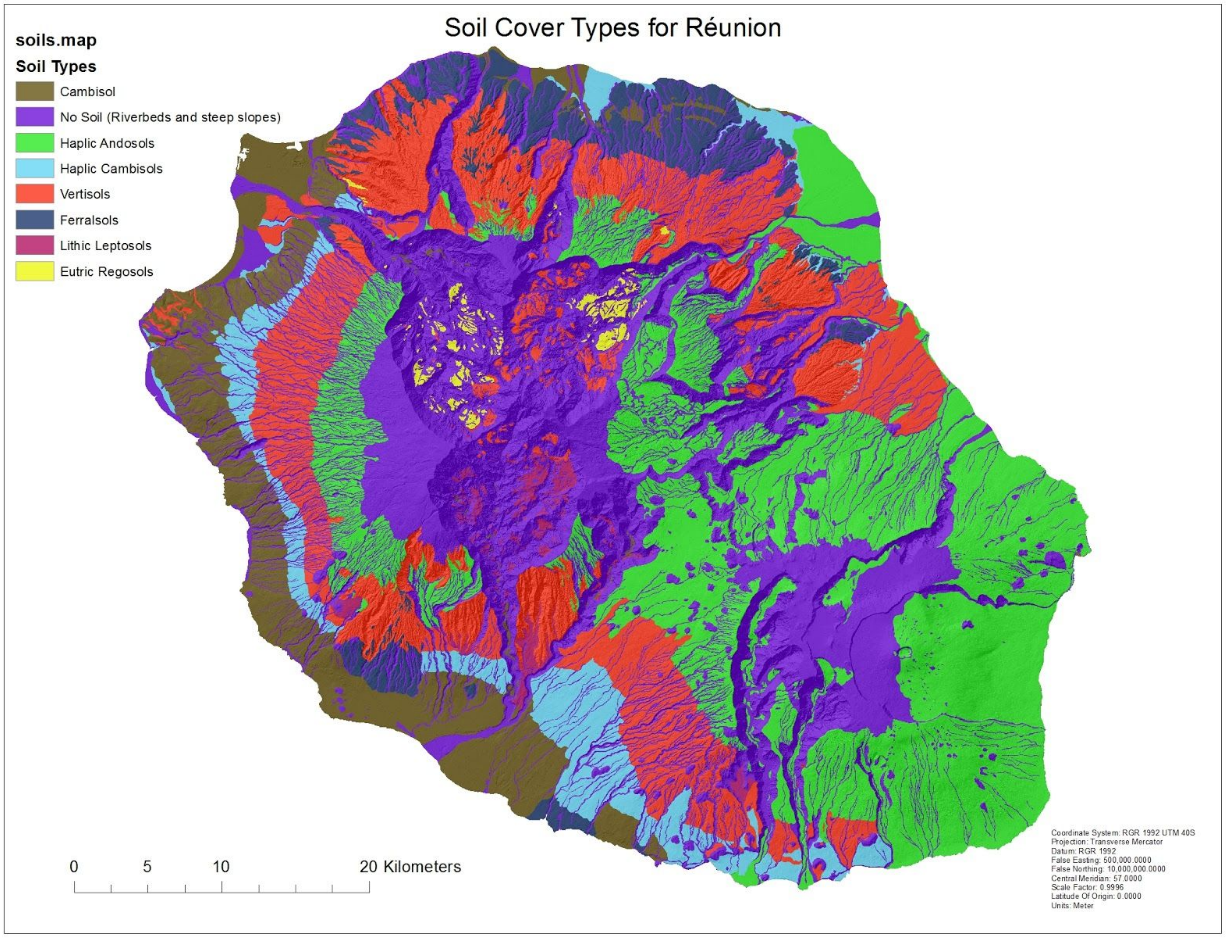

Figure 13: Soil Cover map for Réunion (Source: Michel Raunet, 1991)

3.2.4 Land Use, Land Cover, and Infrastructure

Sufficient knowledge of the land use is vital for the vulnerability and risk assessment of Réunion. Once the spatial distribution of flooding and landslides are determined, it's important to know how the extent of the hazards compares relative to the location of communities and buildings. Land use plays an important role in the water balance especially in the process of interception as forests and urban areas have varying levels of vegetation. In addition, the land use also identifies where homes and other significant buildings are located, which is important to consider in respect to flooding. The land cover map was also retrieved from the IGN portal. The BD TOPO series (established in 2007) consists of 10 land use types: shrubland, open water, urban area, forest, marshlands, grasslands, rock, sand, orchards, and areas of public utilities like airports and harbors.

This land use dataset was selected for it contained the most comprehensive list of land classes which covers the diverse terrains present on the island. However the dataset was not without its shortcomings. The land use failed to capture the diversity of forests present such as low lying coastal forests and tropical montane cloud forests. These forests vary vastly in their height and their canopy storage so it was necessary to update the land use map to capture these differences. The forest extent of the map was extracted and overlaid with the DEM. The forest extent was then reclassified based on elevation in order to distinguish the three final forest classes: Coastal Forest (0-100m), Tropical Lowland Forest (100-1200m) and the Tropical Montane Cloud Forests (1200-3000m). The altitude conditions for various forest types were pulled from the Laboratoire des Sciences du Climat et de l'Environnement in a paper about tropical rainforest classification based on LIDAR measurements (Shang et al. 2016).

From the land use maps the surface roughness and Manning's surface roughness coefficient are derived which gives valuable information about the amount of rainfall storage possible at the soils surface and indicates when runoff begins. Surface roughness is part of the surface texture and is defined as the irregularities of the surface caused by vegetation cover, land use, and rock fragments. Manning's surface roughness coefficient functions the same way with the exception that it is often applied to channels. The land use maps are also used to derive maps for vegetation cover fraction, Leaf Area Index, vegetation height, and maximum canopy storage. Vegetation cover is the fraction of a cell that is covered with vegetation. Leaf Area Index (LAI) is a ratio of total projected leaf area per unit ground area. Vegetation height is simply the average height of vegetation within a given cell. Maximum canopy storage is the capacity for vegetation to store rainfall and is calculated from the LAI. There are several canopy storage equations that are used to determine max canopy storage based on the type of vegetation (De Jong et al., 2007). The island of Réunion contains crops, broadleaved forests, and clumped grasses and each formula was applied to its respective land use type.

Vegetation Type	Maximum Canopy Storage Formula	Source
Crops	$S_{max} = 0.935 + 0.495\,LAI - 0.00575\,LAI^2$	Von Hoyningen Huene (1981)
Broadleaved Forest	$S_{max} = 0.2856\,LAI$	Aston (1979)
Clumped Grasses	$S_{max} = 0.59\,LAI^{0.88}$	Domingo et al. (1998)

Table 3: Maximum Canopy Storage Vegetation Types with their respective formula

Values for surface roughness, LAI, vegetation height and S_{max} are assigned to map units using the PCRaster command 'lookupscalar'. These variables are used in calculating the influence of interception and splash detachment processes.The list of land use types as well as their properties can be found in the Appendix C

The BD TOPO series (2007) also provides a coverage map for the variety of different roads and buildings on Réunion which are the elements at risk in a hazards assessment study. Next the infrastructure coverage is used to calculate the potential for interception and infiltration. For this reason only paved roads were considered in the roadwidth maps as they are considered impermeable. Buildings and roads are also used for interpreting the degree of damages caused by the flooding events.

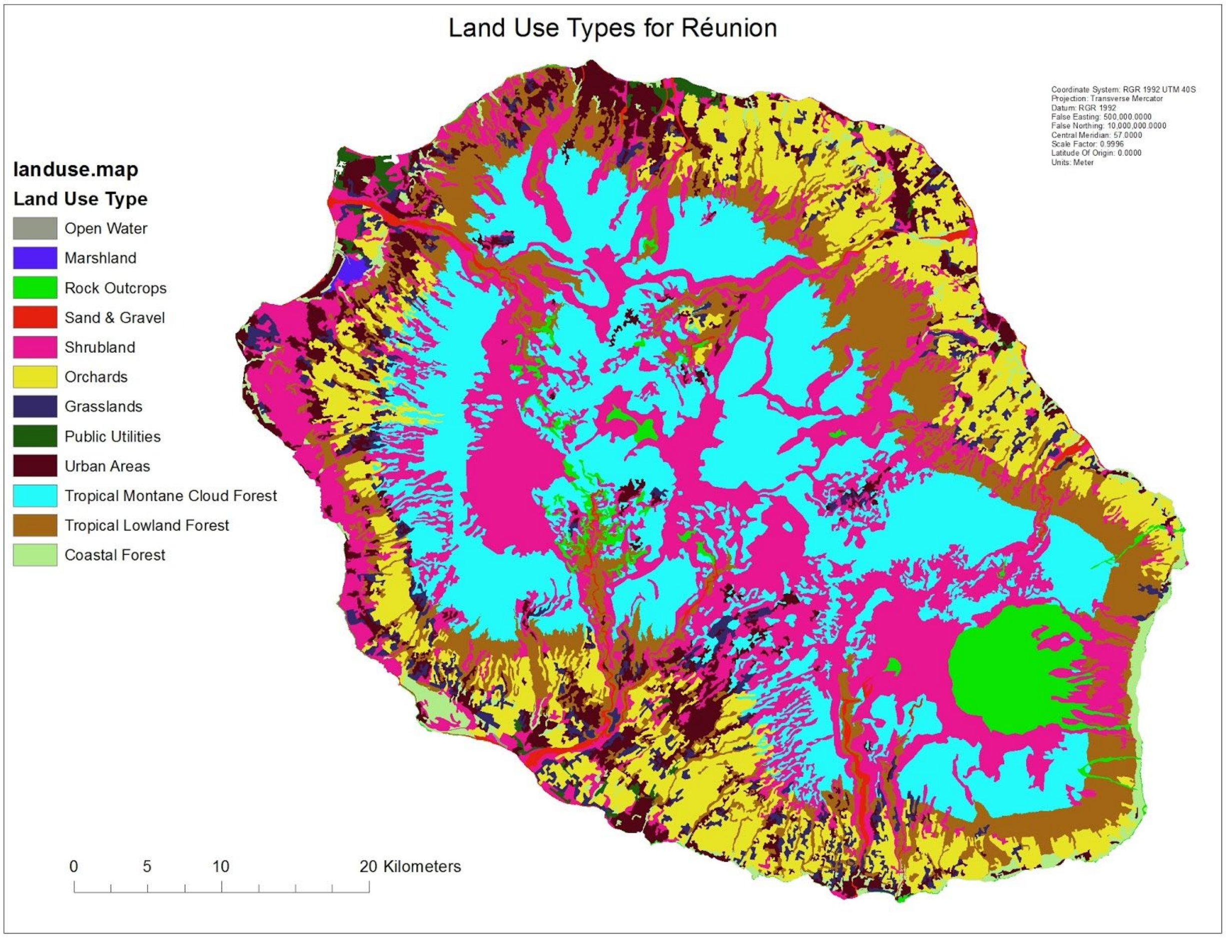

Figure 14: Land Use cover map for Réunion as of 2007. Source:(Institut Géographique National, 2018).

3.2.5 Soil Depth

Soil depth is an important component of LISEM as it determines how far water can infiltrate into the soil and how much water can be stored in the soil before runoff begins. OpenLISEM input uses soil depth and volumetric relative water content therefore changes in the soil depth are reflected in the potential for infiltration. Information on soil depth is very scarce on Réunion. There are several papers about sugarcane root depth such as Choppart et al. (2010), which lightly touches upon the depth of soil but only for a few sites such as Saint Pierre and Saint Benoit. Due to limited soil depth data, it was necessary to use soil depth equations to make a best estimate. A paper by Saulnier et al. (1997) produced several depth equations based on the processes of rock weathering, soil production, and soil transport.

$$h_{soil} = h_{soil_{min}} + \left(h_{soil_{max}} - h_{soil_{min}}\right) * \frac{z - z_{min}}{z_{max} - z_{min}}$$

$$h_{soil} = h_{soil_{min}} + \left(h_{soil_{max}} - h_{soil_{min}}\right) * \frac{s - s_{min}}{s_{max} - s_{min}}$$

$$h_{soil} = h_{soil_{min}} + \left(h_{soil_{max}} - h_{soil_{min}}\right) * \frac{AC - AC_{min}}{AC_{max} - AC_{min}}$$

$$h_{soil} = h_{soil_{min}} + \left(h_{soil_{max}} - h_{soil_{min}}\right) * \frac{Dist_{chan} - Dist_{chan_{min}}}{Dist_{chan_{max}} - Dist_{chan_{min}}}$$

Equation 1: Saulnier equations to derive soil depth where h_{soil} refers to the soil depth, z refers to the elevation, s refers to slope, AC refers to the profile curvature and $Dist_{chan}$ refers to the channel distance. Source: (Saulnier et al., 1997)

These equations use assumptions regarding the DEM to find soil depth in every cell provided max and minimum soil depth parameters. The first assumes that soil depth is a decreasing function of elevation. Weathering increases soil depth at lower elevations as gravity and precipitation transport sediment to lower elevations. Furthermore the equations assume that soil depth decreases at steeper slopes. The Saulnier equations also rely on the curvature of the surface. The profile curvature is negative when convex and this is indicative of deeper soils. The final assumptions are that soil depth increases near channels, flood plains and lower elevations due to erosive processes which accumulate sediment. The assumptions were put together in a model in PCRaster to create the final soil depth for the island.

Each of the parameter values were then calibrated to fall between the range of soil depth represented in the Chopper et al., (2010). So that the regions with gentle slopes or at lower elevations feature deep soils which reach up to 7 meters while steep higher elevations feature much more shallow soils around 1 meter or less.

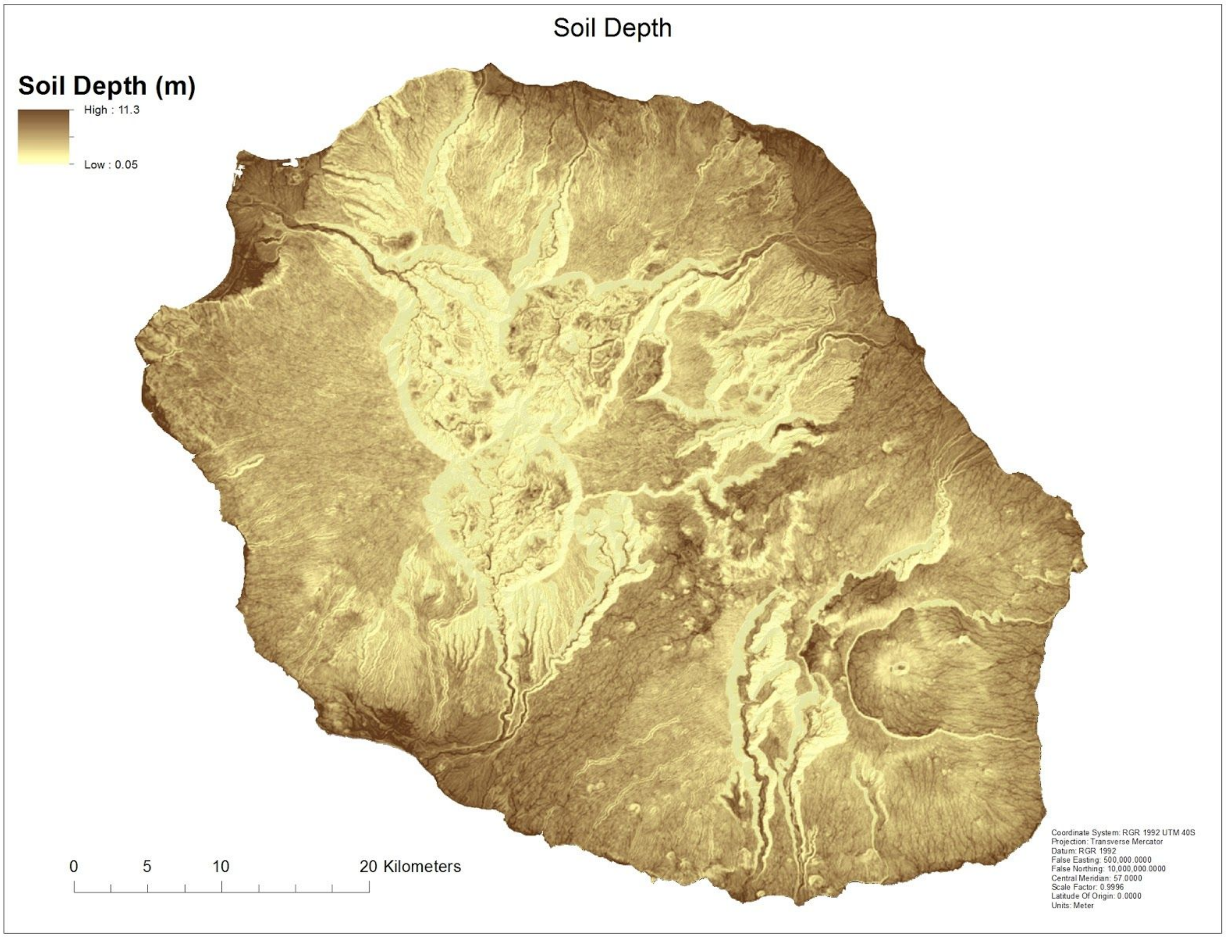

Figure 15: Soil Depth map for Réunion (derived from Saulnier equations)

3.3 OpenLISEM Parameters

OpenLISEM operates by solving the water balance and simulating outflow. First, precipitation is initiated and deposits water on the surface. Vegetation may intercept some rainfall while the rest is stored in the soil. Once the maximum soil water capacity is reached, runoff can begin. Overland flow refers to the flow of water at the surface into a channel. This accumulation of water in a channel causes channel flow. Only once the channel overflows is flooding flow initiated. This process is handled at every cell so it is important that settings are adjusted properly.

OpenLISEM requires several important decisions to be determined by the user. Among the most significant of these is the option to select the cell grid size and the timestep. It is important for the cell size to be the smallest possible in order to achieve the highest resolution. This study had initially planned to run the model under 5m resolution however after several runs it became apparent that this resolution takes too long to run especially since the island measures a massive 2512 square kilometers. To counteract this, all the maps were resampled in ArcGIS to 50m resolution. Unfortunately this was also not without problems. Although the model was able to run significantly faster, under this grid size several assumptions made during calculations were inaccurate and yielded unusual results. The final resolution was settled to be 25m. Under this resolution all the assumptions made in the LISEM calculations are still met and the cell size is as big as it could be to accelerate the processing time.

Following the cell size, the next significant parameter is the simulation times. As a general rule the duration of each timestep, that is the rate at which each variable is used, should be similar to grid size. For this reason, it was determined that a timestep of 30 seconds would be most fitting as it was the maximum timestep that would yield accurate results while also limiting the simulation time. The duration of the simulation is also an important parameter. The design storm lasts for 24 hours or 1440 minutes, this study decided that the model will simulate for 3000 minutes in order to allow for runoff to flow to the outlet points out of the catchment. In doing this, it is possible to see where large amounts of water will pool and aggregate damage over longer periods of time following the end of the storm.

There are seven main categories of simulation options in OpenLISEM, made up of: Global, Interception, Infiltration, Flow, Erosion, Sediment transport, and Calibration (OpenLISEM Manual, 2018). However since processes involving sediment are omitted, the options in categories Erosion and Sediment transport are of no use. In the Global tab, the first of the parameters to decide is the type of flow considered in the model. LISEM presents three different varieties of overland flow: kinematic wave using the LDD flow network (1D), diffusive wave using the DEM (2D), and dynamic wave using the DEM (2D). Kinematic wave using the LDD network makes two big assumptions that lead to unrealistic runoff water heights: (1) there are only 9 possible directions for overland flow to move and (2) the discharge of a cell always flows into the single next connected cell. These assumptions cause overland runoff height that in reality would be spread out to be focused into fewer cells. For the same reason, discharge is also unrealistically high and since the soil surface beneath the flow is smaller, infiltration is generally lower than what would be expected. Kinematic waves inability to allow the runoff to diffuse or dissipate was why this study opted not to model overland flow with this method. Diffusive waves using the DEM is an option designed for shallow waters as it does not incorporate the conservation of momentum and does not properly model flood behavior. Therefore it was determined that Dynamic waves would be the most realistic option for modelling the runoff and flooding on Réunion. The second parameter pertained to sediment and was ignored as to not include erosive processes. These processes drastically slow down the progress of the model. Channels and rivers were included in order to get a hydrograph for each outlet point. The effects of infrastructure, buildings and road systems, were also included in order to get account for the effects of their interception or their lack thereof.

The Interception tab was mostly left to the default values. The canopy openness factor is a variable that describes the open area between leaves in the canopy that contribute to direct throughfall and was left at 0.450. The option to include litter interception was ignored as the effects would be negligible when applied to the entire island. The final option was to define a canopy storage equation to be applied to all the vegetation types. However, since Réunion features such a diverse range of landuse it was opted to use a custom maximum canopy storage map that the study had produced earlier from the LAI of various vegetation types.

The Infiltration tab contains one of the more important settings, the type of infiltration model. There are four options: Green & Ampt (1911), Smith & Parlange (1978), SWATRE multilayered soil water (1996), and no infiltration model. The Green & Ampt model is a 1 or 2 layer infiltration based on the simplified Darcy equation. The Smith & Parlange is a 1 or 2 layer infiltration based on an exponential solution to the Darcy equation. The SWATRE model is a 1D finite difference multilayer scheme based on soil water balance from the Richard equations. SWATRE requires a large database of information including water retention curves and water repellency for each soil type. The large data input was one of the main reasons why the study did not opt for this model. The Green & Ampt and Smith & Parlange models are similar in that they incorporate the Darcy equation for vertical soil water balance although in different ways (Mishra et al., 2003). However the Green & Ampt model is more commonly accepted and used among the scientific community and for this reason it was the chosen model for this study. With the Green & Ampt approximation we can estimate the infiltration rate based on the depth of the wetting front and soil moisture content of the rest of the soil. This model runs on two assumptions, the first being that the wetting front moves parallel to the soil surface downwards. The second assumption is that above the front, the soil is completely saturated and that below the front, the soil is dry. The Green & Ampt model was also run with the option for percolation from the lower soil boundary. The soil water can leave the soil by a flux based on the saturated hydraulic conductivity (K_{sat}) and an exponential decrease in soil moisture.

The flow tab was left entirely to the default values. There were no flow barriers so that category was omitted. The coupling of overland flow and channel is only relevant for kinematic or diffusive flow. The dynamic wave numerical scheme was left unchanged as they are mostly designed to adapt to the flow conditions of smaller catchments at higher resolution.

3.4 Risk Assessment

Upon completion of the OpenLISEM run, the next step is to conduct a risk analysis in order to identify the areas subject to damage at the given flood event with regard to water depth and flow velocity. The land use map contains a buildings map at a spatial resolution of 1m. The housing map will be overlayed with the map of flood height. The flood height map needs to be reclassified so that it can be converted from a raster into a vector format. Regions that fall into a given flooding class were then selected and isolated by their given attribute. The next step selects housing units given that they fall completely within the flooding class and then extracts them. For example, housing units that fall within areas of flooding greater than 4m were deemed to be extreme risk and were extracted to create a map of extreme risk housing. The divisions were made as follows: housing that falls within regions less than 0.5m of flooding are no risk zones, houses with less than 2m of flooding are at moderate risk, homes with less than 4m are at high risk, and houses with flooding greater than 4m are at extreme risk.

Risk Level	**Description**
No Risk	< 0.5m
Moderate	0.5 - 2.0m
High	2.0 - 4.0m
Extreme	> 4.0m

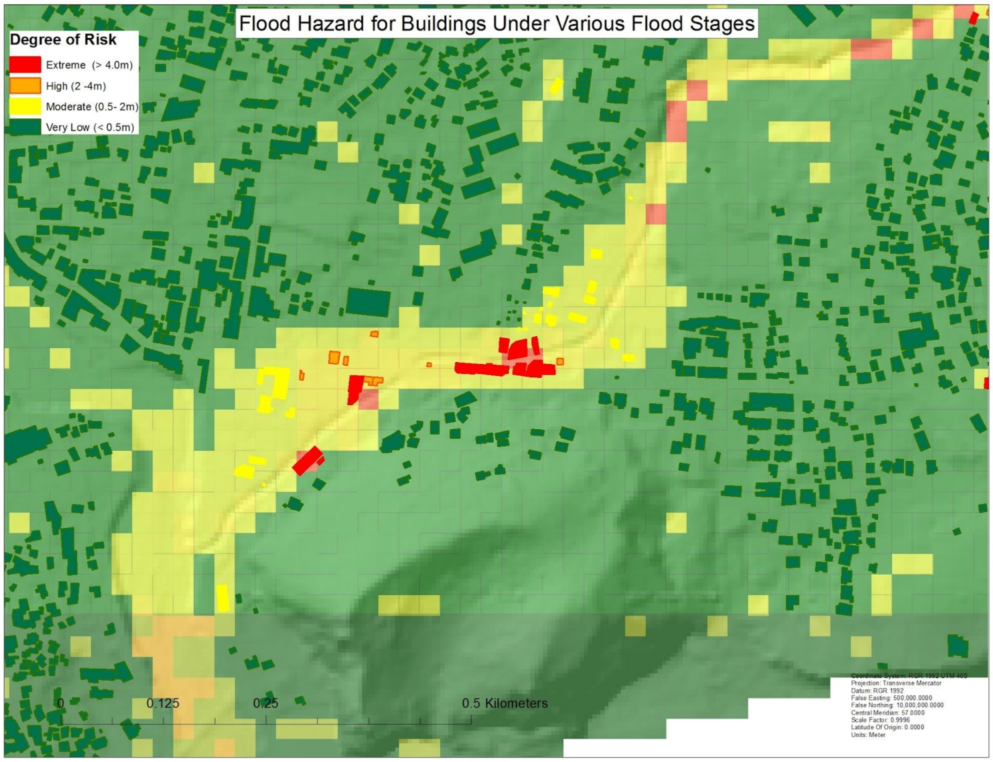

Figure 16: Divisions of risk levels for buildings according to water depth

4. Results

OpenLISEM produces results in a series of maps which highlight the various processes at work throughout the water balance simulation. This study will examine the processes at each map for patterns of significance based on the distribution or percent cover of various features. Under this analysis for regions of significance, the study will analyze the maps in relation to each other to create a more complete overall view for the storm event.

4.1 OpenLISEM Outputs for a 10 Year Rainfall Event

Under the aforementioned parameters and given thee computational demand of the model, LISEM was run for a 10 year design storm event. The program produced six maps: cumulative rainfall, cumulative interception, cumulative infiltration, cumulative runoff, maximum flooding velocity, and the maximum water height. These maps are presented below and discussed in detail.

4.1.1 Cumulative Rainfall

The first step to simulating rainfall and the first output is the cumulative rainfall map. The cumulative precipitation map shows the total amount of precipitation that has fallen during the 24 hour rainfall period.

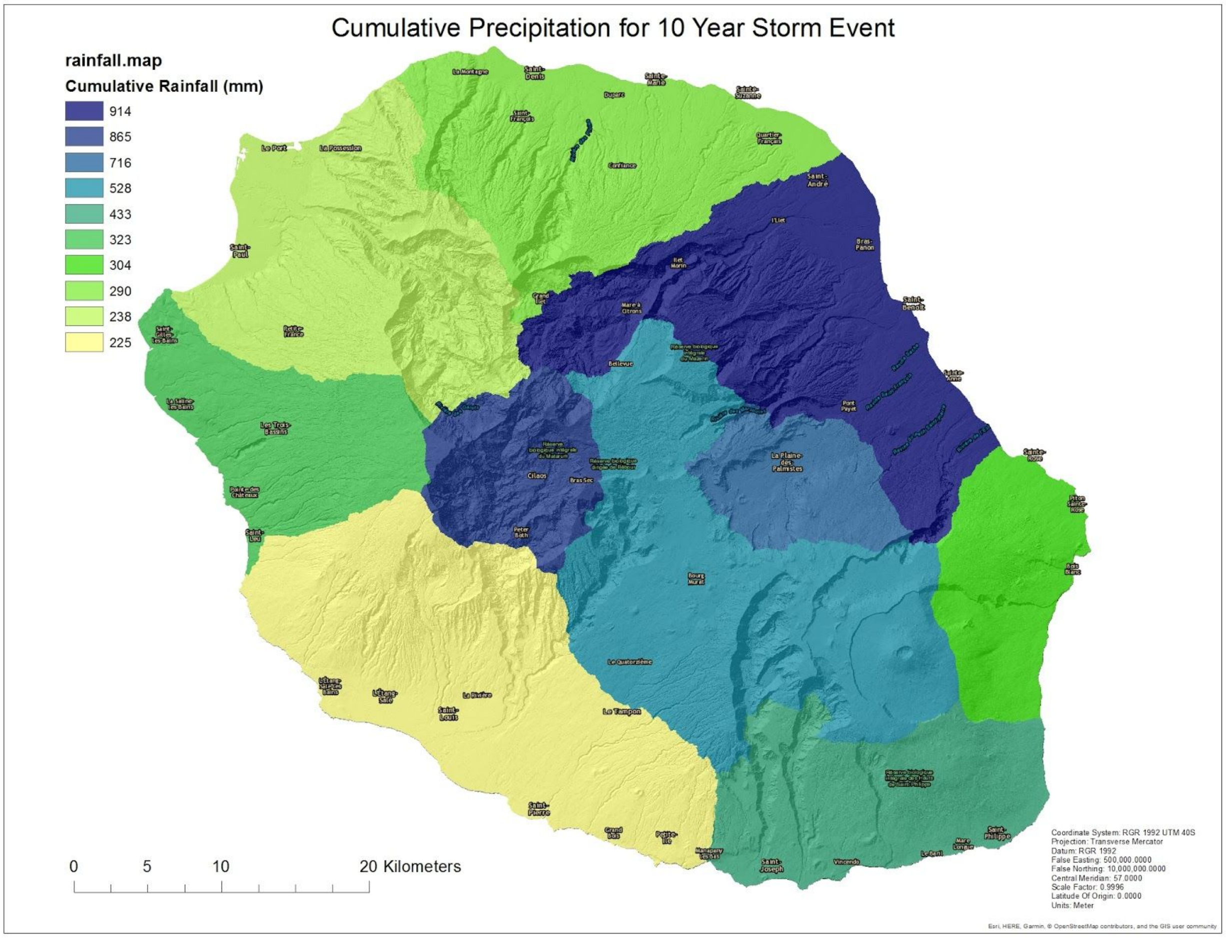

Figure 17: Cumulative Precipitation map for 10 year storm event. The large differences between the east and west side of the island are well illustrated.

The map reflects the same spatial pattern as the rainfall zonation map produced by Thiessen Polygon interpolation from the 10 meteorological stations as the 10 different cumulative precipitation values are identical as the 10 rainfall zonation map areas. This is to be expected as the rainfall zonation map was used to distinguish varying levels of precipitation within the island. The map is a result of the meteorological station analysis and primarily serves as input for the simulation. The highest amounts of precipitation (greater than 850mm) fall on the regions of Cilaos and Saint Benoit. On the opposite side of the spectrum, Pont Mathurin experiences just 225mm of rainfall. The regions of Saint Denis, Le Port, Pointe de Trois Bassins, and Gros Piton fall towards to lower end of rainfall range around the 300mm mark. The regions of Le Baril, Plaines des Cafres, and the Plaines de Palmistes reveal a rainfall at the higher end of the spectrum measuring 433mm, 527mm, and 714mm respectively. Most of the rainfall tends to fall on the eastern part of the island as shown by the frequent presence of rainfall greater than 400mm with the exception of Gros Piton. The western side of the island including: Pont Mathurin, Pointe de Trois Bassins, Le Port and Saint Denis has experienced a significantly drier storm event.

4.1.2 Cumulative Interception

The cumulative interception map shows the total amount of precipitation to have been intercepted prior to making contact with the soil surface, usually captured by vegetation or building cover. The amount of interception ranges from 0mm to 4.2mm.

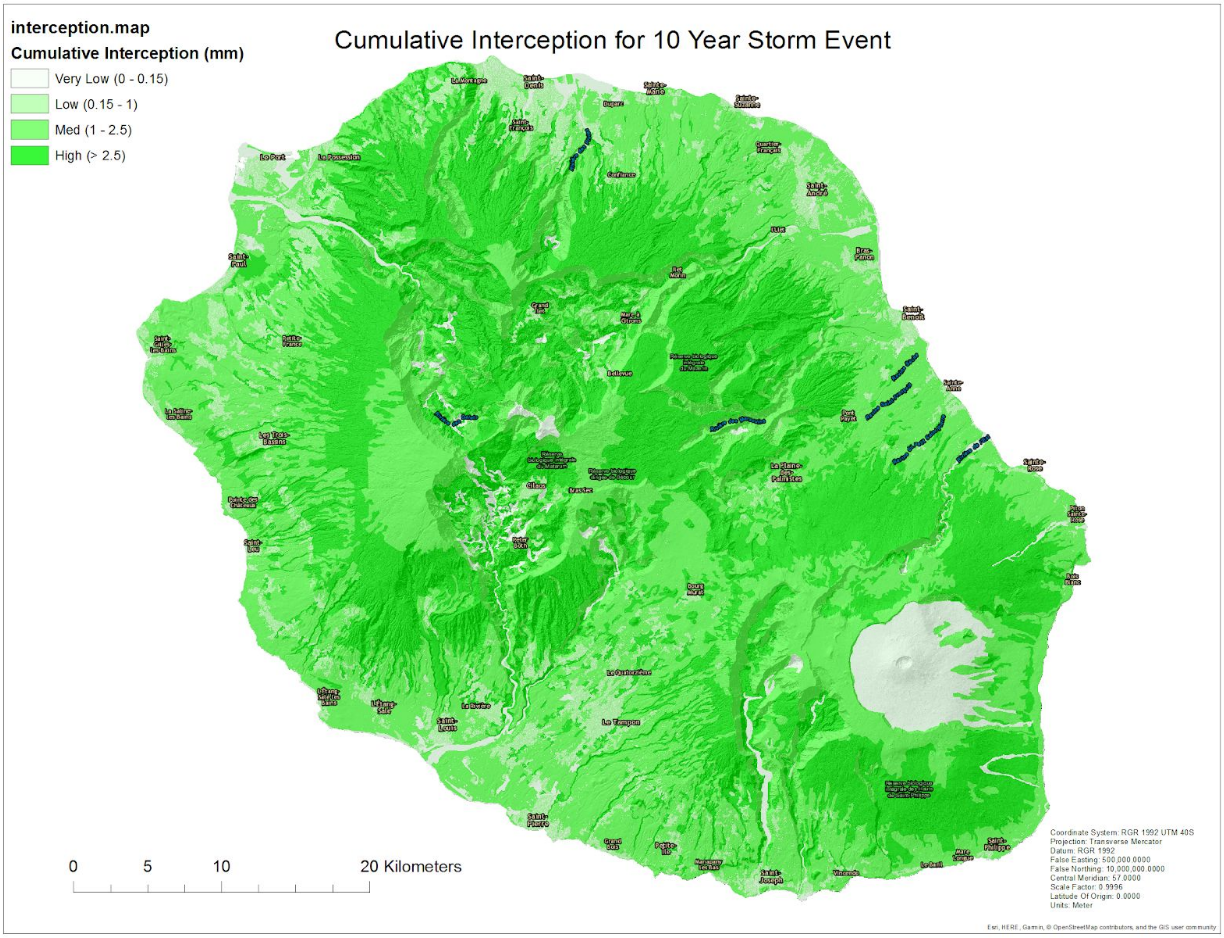

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Figure 18: Cumulative Interception map

The most distinct region with very low interception is the Piton de la Fournaise and the surrounding area on the eastern flank which consist of 71 km^2 of the island. Interception is very low in the rocky areas such as the volcano, channels and regions of high elevation like the Piton des Neiges. The channels of the Riviére de Remparts in the south, Bras de Cilaos and the Bras de la Plaine in the southwest, the Riviere des Galets in the northwest, and the Riviére du Mât in the northwest, and the Riviére de l'Est in the east all feature lower interception values around 0mm. These regions make up only 6.5% of the island or 163.7 km^2, most of which is made up of the Piton de la Fournaise.

Low interception values less than 1mm are found in urban centers such as the capital Saint Denis, the industrial Le Port, and Le Tampon. These regions are primarily on the coast and also only make up 6.2% of Réunion or 156.5 km^2.

The medium interception values in the 1.0mm to 2.5mm range are much more widespread. These values tend to reside in the low lying inland areas such as marshes and orchards and in the high altitude tropical montane cloud forests and scrublands. These types of vegetation and land classes are more sparsely concentrated and tend to not be able to intercept as much precipitation. These regions make up 46.7% of the island or 1174.4km^2.

The coastal and tropical lowland rainforests regions are more dense and tend to capture more rainfall which tends to put them in the high infiltration range from 2.5mm to 4.2mm. The high infiltration areas also make up a significant part of Réunion as it covers 40.5% of the island or 1016.8km^2.

Classification	**Percent Cover (%)**	**Total Area (km^2)**
Very Low (0-0.15)	6.52	163.7 km^2
Low (0.15-1)	6.23	156.5 km^2
Med (1-2.5)	46.75	1174.4 km^2
High(2.5-4.2)	40.48	1016.8 km^2
	100	2512 km^2

Table 4: Distribution of Interception classes

4.1.3 Cumulative Infiltration

The cumulative infiltration map reveals how much precipitation entered the soil during the duration of the storm event. The degree of infiltration varies greatly throughout the island ranging from around 0mm to 1432mm where less than 200mm of infiltration is classified as low, 200-400mm is classified as medium, 400-600mm is classified as high, and greater than 600mm is classified as extreme.

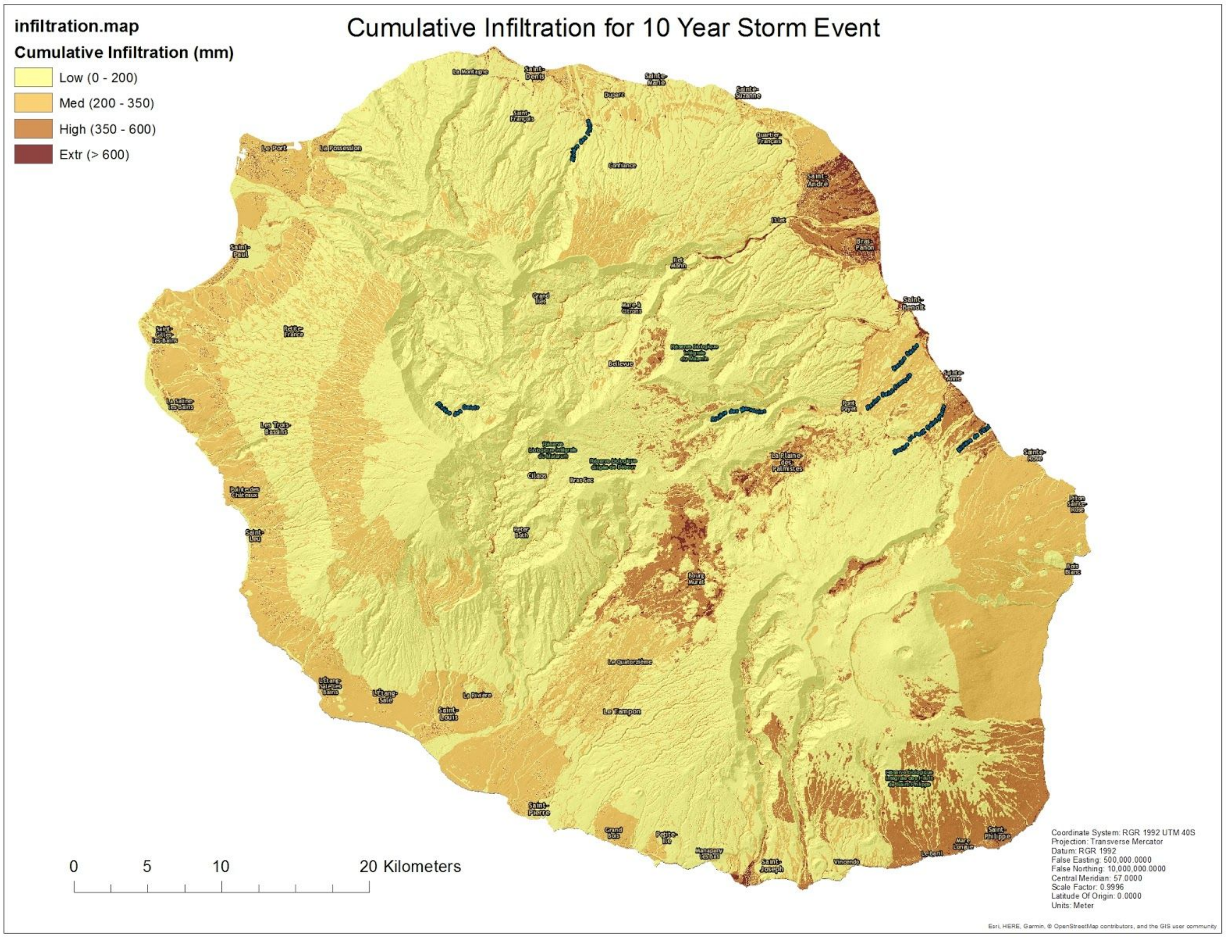

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Figure 19: Cumulative Infiltration map for Réunion

The vast majority of the island falls between 0mm to 200mm of infiltration. This is apparent as 68.2% of the island or 1713.4km^2 falls within this class. Most of the infiltration less than 200mm occurs in the center of the island in the regions of the Piton des Neiges and the three surrounding calderas as well as the forest regions surrounding the Piton de la Fournaise on the western flank. The 30km between Le Port and Saint André in the northern area of the island also feature low infiltration values less than 200mm.

There is an interesting pattern for the medium infiltration range of 200mm to 400mm as it resides predominantly on the coastline. The medium infiltration area covers the entire west coast from Le Port to Saint Joseph (67km). Smaller regions with this infiltration range include the cities of Saint Denis, Saint André, as well as the region from Saint Rose to the volcanic runoff area East of the Piton de la Fournaise. There is one final area with the medium infiltration window which is located inland on the western side of the Mafate and Cilaos calderas and contours the coastline for about 20km. Overall, these areas make up 24.6% of the island or 616.9km^2.

The high tier of infiltration ranges from 400mm to 600mm and can be found in several locations on the eastern side of the island including the floodplains by the mouths of the Riviére du Mât and the Riviére de l'Est in the northeast, the Plaine des Cafres and Bras des Calumets in the middle of the island, and the entire coastline of the Saint Philippe commune in the south west. At the mouth of the Riviére du Mât, the high infiltration values branch out to the surrounding low lying floodplains for 4km towards Saint André in the North and down 2km towards Bras Panon in the South. In total, this region accumulates 28 km^2 of high infiltration. Rather unusually, only the area surrounding the Riviére du Mât a is high infiltration zone. The river itself reverts from an extreme infiltration level to a medium one where the surrounding area is high. The Saint Philippe commune has 15km of coastline which consistently has an infiltration of about 430mm. The Plaine des Cafres and Bras des Calumets have high infiltration values spread throughout the flat plains. This low lying region region falls between the high altitude of the calderas of the northwest and the Piton de la Fournaise volcano in the southeast. In total, high infiltration rates make up 6.4% of the land cover or 161.5km^2.

Infiltration regions greater than 600mm qualify as extreme. These tend to occur adjacently to the high infiltration zones such as at the Riviére du Mât, the Plaine des Cafres and Bras des Calumets. As previously mentioned, at the mouth of the Riviére du Mât is surrounded by approximately 28 km^2 of high infiltration floodplains. Within these flood plains extreme infiltration can be found in 8 km^2 of neighboring channels breaking away from the Riviére du Mât. The region of extreme infiltration starts at the exit of the Salazie caldera until it reaches the low lying plains 5km from the coastline. This is the largest region of continuous extreme infiltration, however there are smaller regions thinly spread throughout the island. The Plaine des Cafres and Bras des Calumets have sparse regions of extreme infiltration ranging from 600-100mm lying within the high regions. These areas lie within depressions in the already low lying flat plains. The city of Saint Joseph in the south is situated at the mouth of the Riviére des Remparts and experiences approximately 900mm of infiltration. The Riviére de l'Est has a basin approximately 12km from the coast with an infiltration also around 900mm. Infiltration at this degree is scarcely found on the island with only 0.8% of Réunion or 20km^2 being present.

Classification	**Percent Cover (%)**	**Total Area (km^2)**
Low (0-200)	68.21	1713.4 km^2
Med (200-400)	24.26	616.9 km^2
High (400-600)	6.43	161.5 km^2
Extreme (600-1432)	0.79	20.0 km^2

Table 5: Distribution of Infiltration classes

4.1.4 Cumulative Runoff

Cumulative runoff map shows how much excess stormwater flows over the surface that couldn’t be intercepted or infiltrated.

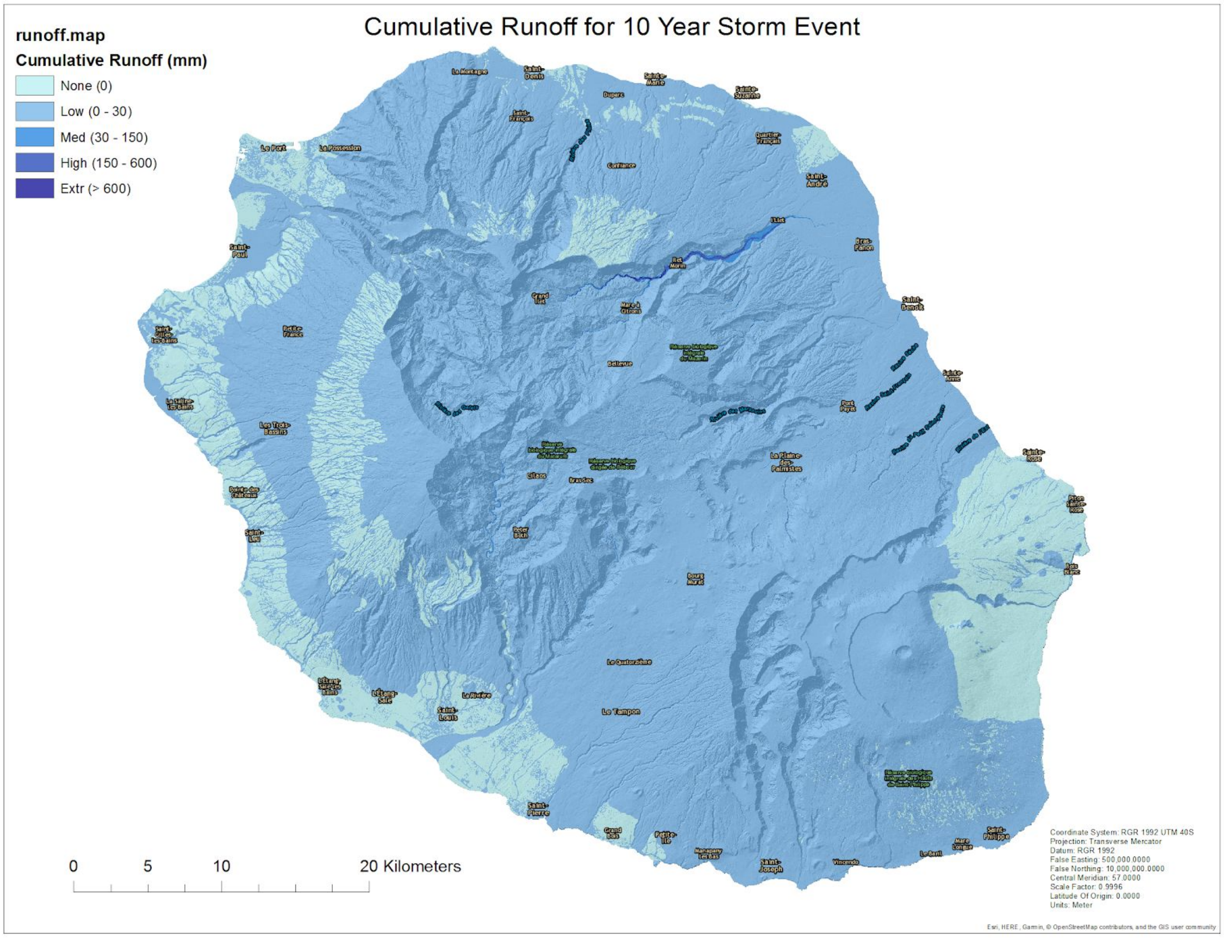


Figure 20: Cumulative Runoff map for Réunion

A significant 14.8% or 371km^2 of the island experience no runoff. These dry regions make up the entire west coast from Le Port to Saint Pierre, a distance of 67km that extends approximately 3km inland consisting of 223km^2. The next largest area with no runoff is the region of Sainte Rose to the eastern flank of the Piton de la Fournaise which measures 130km^2. The final patch of land without runoff lies on the western side of the Mafate and Cilaos calderas and contours the coastline for about 20km.

The vast majority of the island falls into the low runoff category. A total of 2131.9 km^2 or 84.9% of the islands surface experiences less than 30mm of runoff. Low runoff is widespread throughout the island from the high altitude calderas in the northwest and the Piton de la Fournaise in the southeast to the low lying Plaines de Palmistes and Plaines des Cafres between them.

There are only two regions of medium degree runoff. The first is within the Cilaos caldera where the Bras de Cilaos resides. The river begins about 2km northwest from the city of Cilaos and to Îlet Grand. It runs for 8km due south and accumulates 40-100mm of runoff. Bras de Cilaos has 2 branching channels which also have medium runoffs of 50mm. Throughout the eastern side of the island there are several small channels with runoff in the medium range however they are quite faint as they are intermittent and do not last for long. Only 0.3% of the island cover or 6.5km^2 has medium tier runoff.

The area with the largest runoff is the Riviére du Mât. The river flows northeastward from Grand Ilet within the Salazie caldera towards Saint Andre for 24km. It also runs adjacent to the tributary, Riviére des Fleurs Jaunes, which joins after 5km at the edge of the Salazie caldera.

Prior to the confluence at the Plateau Wickers, each of the rivers experience varying runoffs. The Riviére du Mât displays medium tier runoff while the Riviére des Fleurs Jaunes displays a range of medium to extreme tier runoff as it reaches Plateau Wickers. High runoff is exhibited about 4km into the Riviére des Fleurs Jaunes and continues as it merges with the Riviére du Mât until it reaches the city of Saint André. High runoff makes up 2km^2 of Réunion or 0.077% of the island.

Extreme runoff is also found intermittently in the Riviére du Mât, especially near the confluence. The Riviére des Fleurs Jaunes has several regions of extreme runoff around 1300mm while the extreme runoff after the confluence reaches 700-900mm. The extreme runoff regions are quite intermittent and occur irregularly from the last 2km of the Riviére des Fleurs Jaunes to 3km after Plateau Wickers. Overall, extreme runoff only covers 0.0077% of the island or 0.2km^2.

Classification	**Percent Cover (%)**	**Total Area (km^2)**
None (0)	14.8	371
Low (0 - 30)	84.87	2131.9
Medium (30 - 150)	0.26	6.5
High (150 - 600)	0.077	2
Extreme (600-1484)	0.0077	0.2

Table 6: Distribution of Cumulative Runoff classes

4.1.5 Maximum Water Height

The maximum water height map reveals the greatest flood depth to occur throughout the duration of the design storm. The maximum water depth map is the most important indicator for determining the degree of damage to infrastructure.

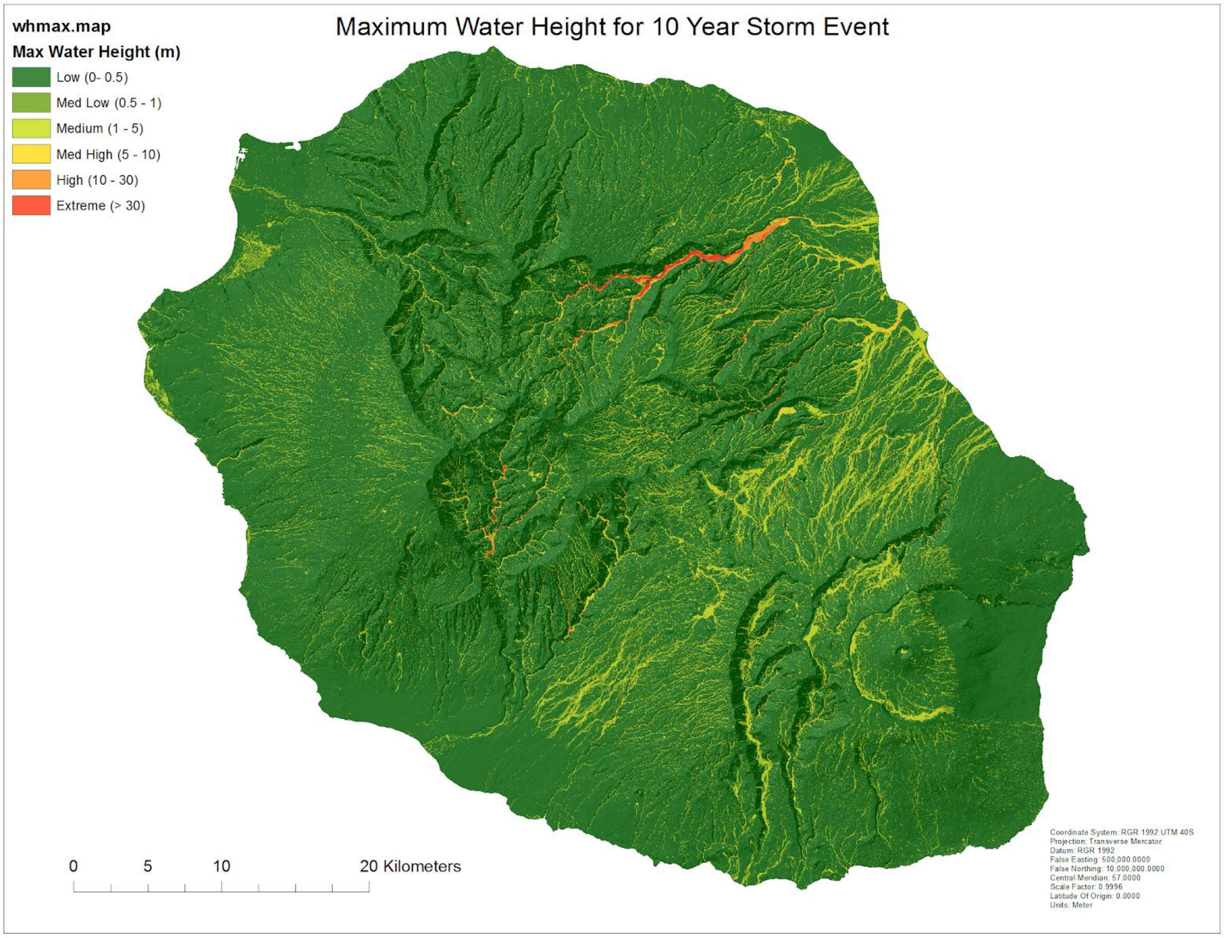


Figure 21: Maximum Water Height map of Réunion

The vast majority of the island, 86.6% or 2176km^2, demonstrates a low flood level. Most of the island does not flood at all while other areas in low flooding tend to have a max water height of 0.05m. Areas with low flood level are widespread and make up most of the high altitude regions inland as well as the lower coastal regions. There are two significant zones which are clear of any flooding. The first would be the area made up of eastern flank of the Piton de la Fournaise and Sainte Rose which contains 126km^2. The second would be the at the mouth of the Riviere Saint Etienne where both sides of the river are devoid of flooding and make up an area of 90km^2.

The medium low range of flood height is also widespread throughout the island. This level of flooding is found on most of the smaller channels that run off the calderas and volcano into the ocean. The most noteworthy zone of medium-low flooding is in the Plaine des Palmistes and the Plaine des Cafres. These low lying regions are riddled with widespread flooding around 1m deep. The largest region with flooding of this degree would be the marshland on the west coast by the city of Saint Paul which amasses 4km^2. Overall this level of flood height covers 6.7% of the island or 167.5km^2.

The medium tier flood height is just as prominent as the medium low tier range as it covers 6.3% of the island or 157.8km^2. Whereas the ML tier occupied most of the smaller channels, the medium tier represents most of the larger rivers throughout the island. The Riviere des Galets (21km), Riviere Saint Etienne (12km), Riviere des Remparts (15km), Riviere de l'Est (18km) all demonstrate continuous flood heights of around 2m. Flooding of this degree also occupies much of the plains between the calderas and the volcano. Small channels run through the commune of Le Tampon in the southwest producing 1.5m of flooding. In the northwest of the plains there are several ravines spread throughout the Plaines des Palmistes such as the Ravine Saint Francois, Ravine du Petit Saint Pierre, and the Ravine Saint Anne. All of the ravines have flood heights on the higher end of the medium range around 2.5 to 3m. The city of Saint Benoit is surrounded with 1.5 to 2m of flooding. The Piton de la Fournaise caldera also features 2m of flooding near the boundaries on the western flank.

Flooding at the 5 to 10m range is quite rare and only makes up 0.8% of the surface or 20km^2. The only occurrence of medium high flooding in the west side of the island is on the Bras de la Plaine which runs along the base of the Cilaos caldera on the southeast side. The Bras de la Plaine experiences 6 to 8m of flooding for a period of 5km or approximately 40% of its entire length. On the eastern side of the island there are four principal regions which fall into the medium high tier. The first is the Riviére du Mât which has 8m of flooding near the city of l'Llet and again for a period of 2km as the river reaches 2km from the coast. The second is the lake of Grand Etang which is 3km north of the Plaine de Palmistes. The lake is about 0.5km^2 and it experiences a flooding of 6m. Another region of medium high flooding is the Riviere des Roches which runs through the coastal city of Bras Panon. Medium high flooding is experienced for 3km from the ocean and there is even an unnamed tributary with a similar degree of flooding which runs for 1.7km. The final region of MH flooding is the Riviere des Marsouins which runs through the city of Saint Benoit. The river flows with flooded conditions of 8m for approximately 3km before relieving into the coast.

There are four noteworthy locations where high flood heights reside. The most striking is the Riviére du Mât where the river rises above the banks to flood up to 450m from the original boundaries in some spots such as over the city of l'Llet. The river drastically spreads out for approximately 5km between l'Llet and the Salazie caldera exit and covers approximately 2km^2 with 20m of flooding. The second significant high flooding zone is the Bras de Cilaos in the Cilaos caldera. The Bras de Cilaos does not experience as much overflow as the Riviére du Mât but it still overflows 50 - 100m from the banks as it nears the Cilaos caldera exit. The Riviére des Marsouins is also distinguishable as it experiences high degrees of flooding for 7km, part of which is near the city of Saint Benoit. The final noteworthy region of significant high flooding is Riviére des Roches near Bras Panon which undergoes flooding for 6km, most of which is in the upstream more highly elevated areas. Overall high flood heights make up 0.5% of the islands surface or 12.6km^2.

Extreme flooding greater than 30m is rare and covers only 0.1% of Reunion or 2.5km^2. The Bras de Cilaos and the Riviére du Mât are the only prominent regions to undergo such severe flooding. The Bras de Cilaos has 4.5km of intermittent extreme flooding. Most of the sections of extreme flooding fall around 32m water depth. This is only exceeded as the Bras de Cilaos approaches a tight bend near the exit of the Cilaos caldera where at this point the river reaches depths of 50m. The Riviére du Mât features the most striking water height on the island. The extreme flooding proceeds continuously for 12km on the the Riviére du Mât and extends for another 7km on the adjacent tributary the the Riviére des Fleurs Jaunes. Extreme flooding burst out of the banks by 250m such as near Ilet Morin. The Riviére du Mât features much greater water heights than the Bras de Cilaos. Water heights vary between 50 to 90m while at the Bras de Cilaos water heights rarely reach 50m.

Classification	Percent Cover (%)	Total Area (km^2)
Low (0 - 0.5)	86.64	2176.3
Medium Low (0.5 - 1)	6.67	167.5
Medium (1 - 5)	6.28	157.8
Medium High (5 - 10)	0.8	20
High (10 - 30)	0.5	12.6
Extreme (> 30)	0.1	2.5

Table 7: Distribution of Maximum Water Height classes

4.1.6 Maximum Flood Velocity

The maximum flood velocity map presents the greatest speed that the floodwaters travel. Flow velocity is not a significant influencer on structural damage for building infrastructure and will not largely be considered in the study yet it is a product of LISEM and aids in creating a grander picture of the flood event (Kreibich et al., 2009).

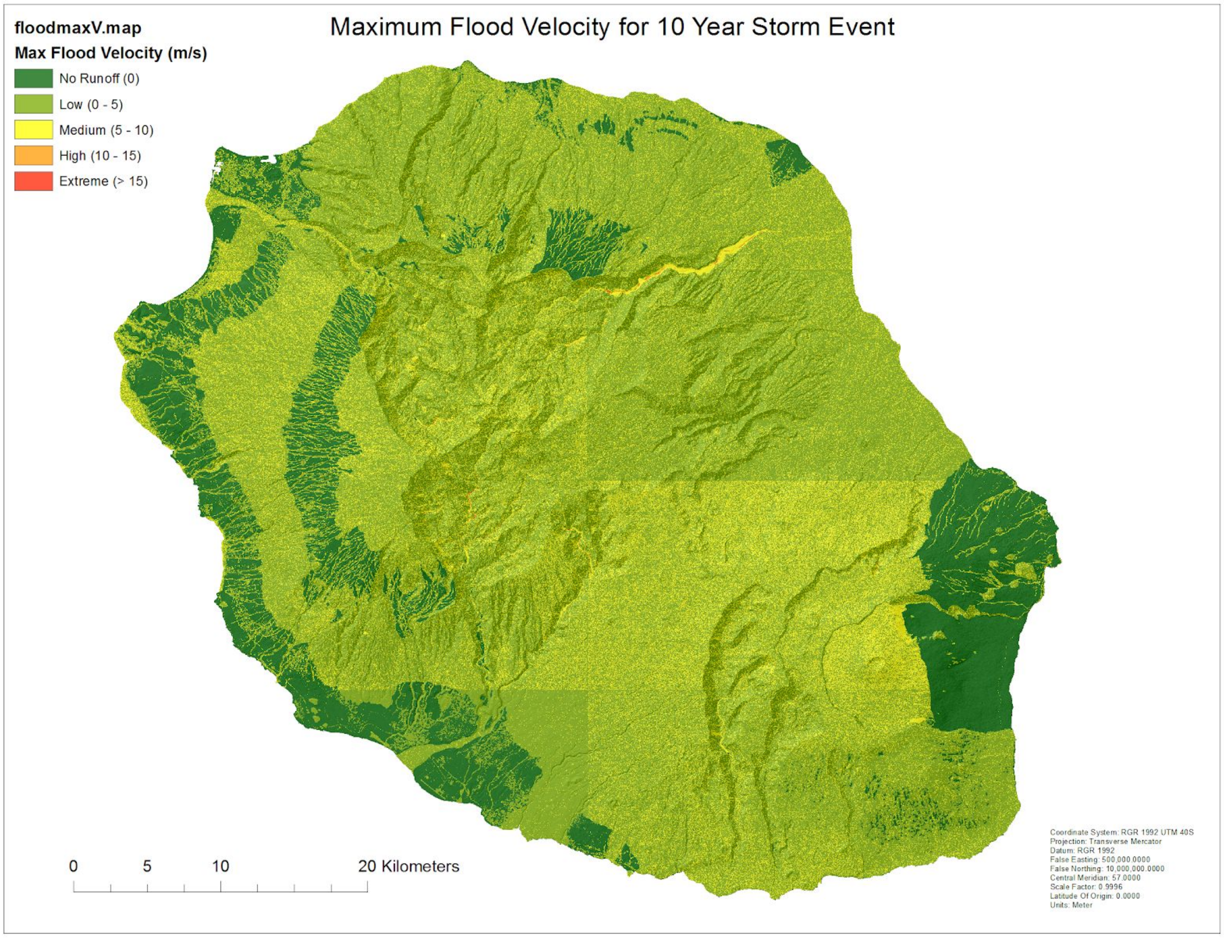


Figure 22: Maximum Flood Velocity map for Réunion

The areas with no runoff are also incapable of producing a flood velocity so these regions are still set to 0m/s. As for the regions where there is runoff, results are difficult to interpret. The map produced appears to contain quite a bit of noise. The entire island looks to be covered with random noise as there is no discernible pattern within any of the flood velocity classes. Furthermore, there appears to be striping as there are several noticeable rectangle blocks that run directly through the middle of the map.

The majority of the island, 66%, experiences low flood velocity however it is thoroughly mixed with the medium flood velocity class which occupies 19% of the surface. The two classes are unable to be distinguished from each other as no clear spatial pattern or extent can be found. The only three regions where some spatial pattern arises is within the Riviére du Mât, the Bras de Cilaos, and the Bras de la Plaine.

The Riviére du Mât experiences a flood velocity greater than 5m/s consistently for 18km. There are sections of the river where the flood velocity rises to around 12m/s such as the region near Ilet Morin but these regions are sparse. The tributary the Riviére des Fleurs Jaunes experiences the greatest max flood velocity on the island of 18m/s.

The Bras de Cilaos experiences a flood velocity greater than 5m/s consistently for 8km. Similar to the Riviére du Mât, the Bras de Cilaos also displays sections of high and extreme flood velocity, however these regions are not as expansive and are even more sparse.

The Bras de la Plaine is also observable however it is broken up into two 3km segments. Both segments undergo approximately 7m/s of flood velocity throughout them. This is most likely due to the quality of the resampled DEM as drastic changes in elevation are the likely cause of this rapid water speed. The river does not manage to exceed 15m/s.

Classification	**Percent Cover (%)**	**Total Area (km^2)**
No Runoff (0)	14.8	371.8
Low (0 - 5)	66	1657.9
Medium (5 - 10)	19.1	479.8
High (10 - 15)	0.05	1.3
Extreme (> 15)	0.0004	0.1

Table 8: Distribution of Maximum Flood Velocity classes

4.2 Flood Risk

The most important output of this study is the flood hazard map linking the locations of predicted flooding to the proximity of people and buildings. This map shows the degree of risk that each building in Réunion might undergo on the basis of OpenLISEM simulation giving a rainfall event with a 10 year return period. As previously mentioned, The divisions were made as follows: housing that falls within regions less than 0.5m of flooding are very low risk zones (in green), houses with less than 2m of flooding are at moderate risk (in yellow), homes with less than 4m are at high risk (in orange), and houses with flooding greater than 4m are at extreme risk (in red).

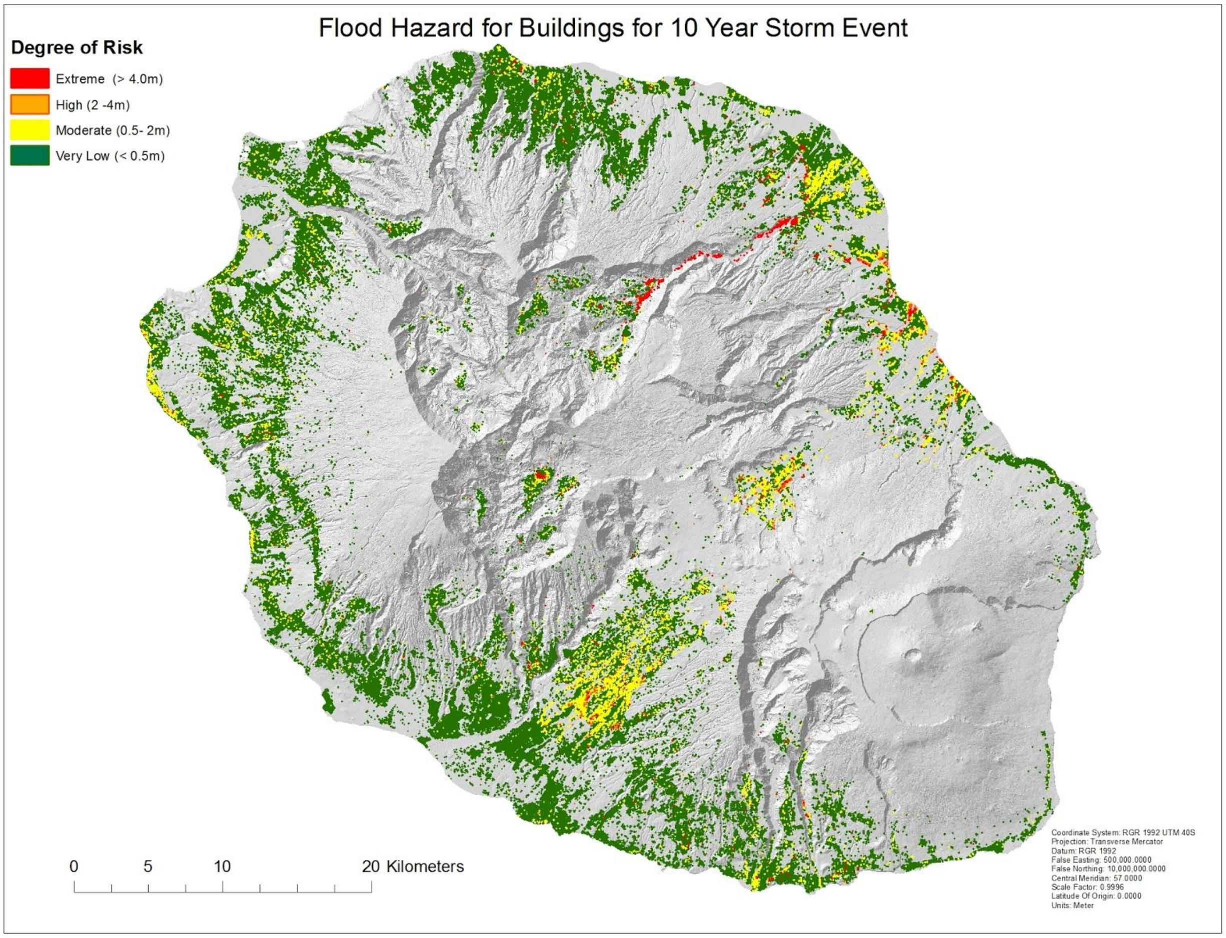


Figure 23: Flood Hazard map for Réunion

It is clear at first glance that most buildings fall into very low risk. The entire east coast from Saint Denis to Saint Pierre features many clusters of buildings with very low risk, typically only experiencing 0.1m of flooding. The 283,580 structures which make up this category consist of 94.1% of all buildings on the island.

Moderate risk affects approximately 15,080 settlements or 5% of the total on Réunion. Most of the buildings impacted reside in Le Tampon, Bras des Calumets, and Saint Andre. Approximately a third of moderately affected buildings will be in Le Tampon. All the buildings in these cities are in low lying regions at the base of mountains. These buildings will be subject to flood waters below 2 meters.

Buildings at high risk are rather rare with only 1,080 or 0.3% of all buildings being impacted. The buildings at this risk are more widespread and are sparsely found in Le Tampon, Bras des Calumets, and in Saint Benoit. Structures with this degree of risk are prone from 2 to 4 meters of flooding.

Extreme risk establishments are built in regions subject to over 4m of flooding. Extreme risk makes up 1,706 buildings or 0.5% of the total on Réunion. The highest concentration of extreme risk buildings on the island are found by the Riviére du Mât. The floodplains of the river are expected to impact 940 buildings. The remaining extreme risk buildings are dispersed in the each of the cities of Cilaos, Bras Panon, and Saint Benoit.

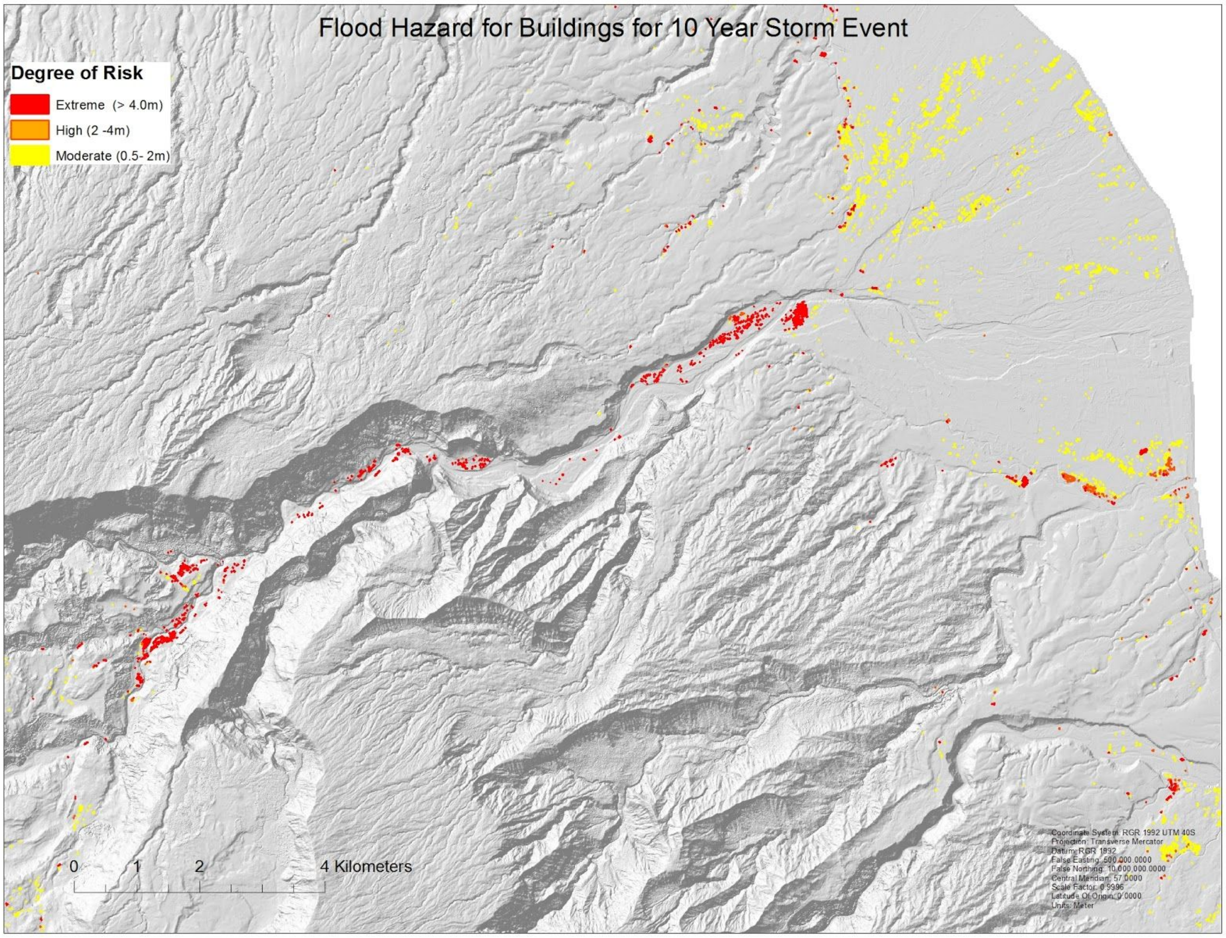


Figure 24: Flood hazard map for the Riviére du Mât featuring the most impacted buildings

Degree of Risk	**Total Number Impacted**	**Percentage of Buildings (%)**
Very Low (< 0.5m)	283,580	94.1%
Moderate (0.5 - 2m)	15,080	5.0%
High (2 - 4m)	1,080	0.3%
Extreme (>4m)	1,706	0.5%

Table 9: Distribution of flood hazard classes

5. Discussion

The most significant preliminary result would have to be the design storm created the simulate rainfall intensity throughout the island. Daily precipitation was collected for a 25 year period from the 1st of January 1992 to the 1st of January 2017 as it was the time that most stations were active in collecting data. Despite being the best time series available, a 25 year period is short for computing recurrence time. Longer time series are required to establish accurate recurrence intervals. The frequency analysis yielded sensible recurrence intervals for the 10 years rainfall scenario, however when extrapolated to 50 and 100 year events the results overestimate the rainfall volume and intensities. The extrapolation of 50 years yielded a rainfall volume of 1989mm for Cilaos and 2484mm for Saint Benoit which is plausible given that the world record for most rainfall in 24 hours belongs to Cilaos on January 7th, 1966 in which 1825mm of precipitation fell during Tropical Cyclone Denise (MeteoFrance, 2017). Unfortunately the 100 year extrapolation produced a drastically high rainfall volume where half of the stations on the island exceeded 2000mm. The station of Saint Benoit would have anticipated 4510mm of rainfall which exceeds the world record for most rainfall in 72 hours (3929mm fell on Commerson, Réunion on February 24-27 2007(MeteoFrance, 2017)). While the extrapolation for 50 years was sensible, extrapolation for 100 years was drastically overestimated and will require longer time series to establish more reliable recurrence intervals and design storms.

The cumulative rainfall and interception maps closely resemble their inputs maps. The cumulative rainfall map reflects a combination of the inputs rainfall zonation map and the 10 year design storm precipitation file. The cumulative rainfall map shows the disparity between rainfall on the west side of the island to the east. Over the duration of the design storm, the eastern region of Saint Benoit receives 914mm of rainfall while the western region of Pont Mathurin receives 225mm. The exception to the spatial pattern of dry west and wet east is the region of Gros Piton. Gros Piton resides on the western coast and experiences a rainfall of 304mm which is an amount expected to be found on the east coast. This is unusual as it appears to indicate an unusual pathway for a tropical storm event to clash with the island. The cumulative infiltration map is simply the distribution of the rainfall interception (S_{max}) map derived from the vegetation.

The cumulative interception map reflects the LAI map derived from the landuse map. Very low interception is found in areas designated as volcanic or rocky gullies. Low interception is found in regions of agriculture, marshland and scrubland. Medium interception is representative of coastal forests and high altitude montane cloud forests. High interception is found in tropical lowland forests. Overall the amount of interception better reflects the type of vegetation and its respective LAI more than the amount of rainfall. It was anticipated that there would be more interception in the east given the drastic amount of rainfall, however this appears not to be the case. The amount of interception appears rather negligible in the context of the 10 year design storm as the maximum cumulative interception to occur is 4.2mm. In the meantime, the driest part of the island receives 225mm of rainfall.

The cumulative infiltration reflects a combination of the saturated conductivity, initial soil moisture content, porosity, and the soil depth. Given that the porosity and soil moisture are fairly consistent throughout the island, the variables with the biggest impact on the infiltration appear to be the saturated conductivity and the soil depth. All the zones that are capable of absorbing more than 200mm of precipitation consisted of Haplic Andosols or Cambisols soils. These soils contain a high saturated conductivity around 18mm/hour making water more likely to drain deeper into the soil profile. The cumulative infiltration capacity is highly dependent on the soil depth as the deeper the soil profile, the more water can permeate downward and be stored. The soil type and its respective saturated conductivity determine where water can permeate the soil, and the soil depth determines the degree of how much water can be stored. For example, the three calderas consist of primarily of rock and have very low soil depths which render them incapable of infiltrating vast amounts of rainfall. Most of the medium infiltration zones on the west coast have the potential for high infiltration as they have soil depths of 3 to 4 meters as well as the high saturated conductivity to absorb plenty of precipitation, however the west coast remains rather dry relative to the east. Saint Philippe in the southeast experiences all the optimal conditions for high infiltration as it contains a soil profile of 3 to 4 meters of high saturated conductivity soil in a region with high rainfall. The same goes for the Plaines des Cafres and Plaine des Palmistes in the middle of the island as these regions contain the same conditions except with 528mm and 716mm of precipitation respectively. This triggers the aforementioned areas to develop small regions of extreme infiltration. The most prominent region of high infiltration is the mouth of the Riviére du Mât and the surrounding city of Saint Andre. In addition to a high K_{sat} value, this region receives the most rainfall found on the entire island at 914mm and also some of the deepest soil profiles that extend from 5 to 7 meters. In summary, higher cumulative infiltration is anticipated more frequently in the East due to higher rainfall and regions of abnormally deep soil.

The cumulative runoff map appears to reflect the spatial pattern of the infiltration map. The large regions with no runoff such as the west coast and the eastern flank of the Piton de la Fournaise are the regions that experience medium infiltration of 200 to 400mm. These regions experience 323mm of rainfall at most, so they are rather dry in the context of the whole island. Therefore, it appears that these regions have had all of their precipitation absorbed by the soil so that cumulative runoff is zero. The regions with less than 323mm are Pont Mathurin, Pointe des Tres Bassins, Le Port, Gillot Aeroport, and Gros Piton, if there is low infiltration within these area, there will also be low cumulative runoff. For areas that receive greater than 323mm of rainfall, such as the regions of Cilaos, Saint Benoit, Le Baril, Plaine des Cafres and Plaine des Palmistes, they all experience at least low runoff even in the presence of extreme infiltration levels. These areas receive so much precipitation that there is bound to be runoff as the soil has exceeded its max storage potential. In Cilaos, the Plaines and Saint Benoit there are several gullies with medium runoff. Water is channeled in from higher altitudes, however they often dwindle away after a couple km making them more akin to elongated lakes rather than streams. This is most likely due to erroneous blockages within the DEM. Were this not the case, one would expect that there be streams of cumulative runoff that flow to the coast.

The blockages within the DEM are a result of the resample method implemented to change the resolution from 5m to 25m. Upon reclassification, some of the more smaller channels were lost and a lot of the channels with narrow widths were closed off due to averaging the surrounding cells. This is quite problematic as many of the larger rivers are located at the base of huge valleys and when cell size is redetermined to include their surroundings quite a few important details can be lost. Consider a channel that run through narrow cliffs, the base of the river is averaged with the peak of the cliff so that the resulting cell elevation is somewhere in between. The process itself isn't flawed but it requires channel definition by burning in the river system into the DEM so that cliffs surrounding a river don't become obstructions to the flow of the channel. The result is streams that don't manage to flow out to the ocean. This is most apparent for larger rivers such as the Riviére du Mât. It is the only part of Reunion that experiences high and extreme levels of cumulative runoff capable of exceeding 600mm. The effects of the resampled DEM and the resulting blockages are most apparent in the water height map.

The water height map reveals the most significant problem of having obstructions to channel flow. Flood heights vary greatly and reach up to 150m in some locations. The Riviére du Mât consistently maintains a water height greater than 10m for 12km. The water height map appears to overestimate the degree of flooding due to the inability of the water to leave the catchment through the coastline. This is especially true in the Riviére du Mât, the Bras de Cilaos and the Bras de la Plaine, where these rivers become deep lakes exceeding depths of 10m. All of these rivers fall within the regions of the most extreme rainfall greater than 700mm, however there are other rivers within these regions such as the Riviére des Marsouins which runs through Saint Benoit into the ocean without being dammed. The Riviére des Marsouins reaches a max flood height of approximately 6m. If the Riviére du Mât, the Bras de Cilaos and the Bras de la Plaine were to flow properly,it is anticipated that they should experience similar maximum flood heights. The water height map also highlights the spatial extent of depressions throughout the island as they are the first to be filled with floodwater. The caldera of the Piton de la Fournaise, the marshland next to Saint Paul, and the many gullies which run through the Plaines des Cafres and Palmistes all sustain approximately 1 to 2m of flooding.

5.1 Most Extreme Areas

The most extreme damages occur in regions that are sparsely populated. The Riviére du Mât runs from Hell Bourg in the Caldera Salazie to the coastline of Saint Andre yet most of the extreme flood heights and buildings impacted are in between the two cities. The region where the river exits the caldera contains the most concentrated area of buildings at extreme risk. 940 buildings are at extreme risk along the 13km segment of the river. A similar situation befalls the city of Cilaos. The Bras of Cilaos overflows its banks by the city and a cluster of 127 buildings are put at extreme risk. This cluster of buildings all fall within a 1km^2 area.

5.2 Most Impacted Populations

It is also important to recognize risks in relation to city size. For example, Bras des Calumets in the Plaine des Palmistes sustains moderate to extreme risk in 1117 buildings, however the village only contains a population of 2000. The land mostly consists of agricultural fields. On the other end of the spectrum is Le Tampon which also resides nearby in the Plaines des Cafres. Le Tampon is home to a population of around 70,000 residents. The islands fourth most populated municipality has 5590 structures subject to medium to extreme flooding risk. Compared to Bras des Calumets, Le Tampon poses a greater overall threat to the people of Réunion given the higher population. The other highly populated municipality with many affected buildings is Saint Andre. Saint Andre has 2746 buildings at medium to extreme risk and is home to 48,000 inhabitants making it the fifth most populated city. The cities of Le Tampon and Saint Andre sustain the most buildings damaged throughout the island.

5.3 No Risk Areas

While the flooding may reach extreme levels in some areas, the most important factor is the hazards proximity where to people live and work. This study decided to use buildings as a proxy for urban development and people. Results from the risk map highlight the spatial extent of flood risk for all buildings on the island. The produced risk map reveals that 94.1% of all the islands buildings are at little risk. An important aspect to consider is the disparity in development as approximately ⅔ of all the buildings on the island are situated on the west coast from Saint Denis to Saint Joseph. This is also where the highest density of safe (low risk) buildings reside which isn’t too surprising given that the three most populated cities of Saint Denis (137,000), Saint Paul (99,000), and Saint Pierre (76,000) are located here. The high density of low risk buildings also agree with what is expected as rainfall in the West is rather low in comparison to the East. All the main transport hubs on the island are also classified to be low risk such as the main port in Le Port as well as the main airports, Gillot Aeroport in Saint Denis and the Pierrefonds in Saint Pierre.

5.4 Comparison to DDRM

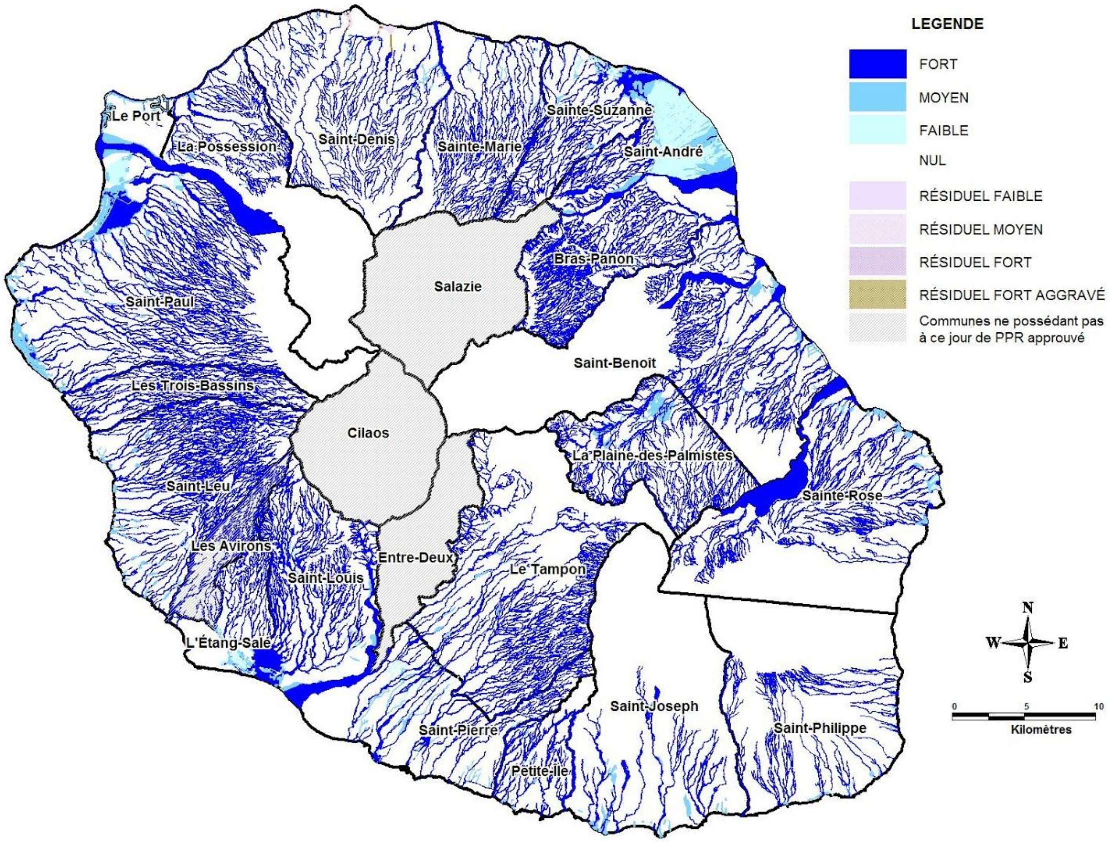


Figure 25: Flood Hazard map produced by the DDRM

The DDRM was the largest natural hazard assessment to ever be conducted on Réunion. The BRGMs (French Geological Survey) goal was to increase knowledge of floods zones throughout the island for the sake of increasing awareness of floods among citizens rather than act as a regulatory document, however some of the more difficult to survey regions in the Hauts were omitted from the assessment. Furthermore It is also unknown how the assessment was carried out and what the criterion were for varying degrees of risk. The LISEM assessment conducted in this study used a combination of remote sensing and literature to get a more complete picture of the state of flood risk on Réunion. The most striking aspect of the LISEM study revealed that some of the most extreme areas at risk are located in the areas omitted from the DDRM assessment such as the calderas of Cilaos and Salazie where flood heights tend to exceed 4 meters in the Bras de CIlaos and the Riviére du Mât. The DDRM features high flooding in all the communes surrounding the calderas, even on the western face which is typically quite arid. Among the biggest differences between the two studies is the presence of highly concentrated flood risk on the western side of the island. The Riviere des Galets in Le Port and the Riviere Saint Etienne in Saint Pierre do not tend to experience much flooding in LISEM, however the risk proposed by the DDRM appears to anticipate wide spread high risk which is concerning as these river run through populated cities. The marshland next to the second most populated city of Saint Paul also has a strong flood risk. The DDRM appears to have applied a design storm event that precipitates more on the western side of Réunion. Interestingly enough, while the degree of flooding on the western side appears to show quite some variance between the two studies, on the eastern side of the island the studies tend to agree in their risk assessment. The floodplains at the mouth of the Riviére du Mât are low to moderate risk while the main body of the river is high risk in both the assessments. High risk of flooding is also present in both assessments for the Riviere des Roches in Bras Panon and the Riviere des Marsouins in Saint Benoit. The only discernible difference on the western side of the island is the regions surrounding the Piton de la Fournaise. In the LISEM analysis, flood water tends to pool in the base of the depression/caldera surrounding the volcano, this is not present in the DDRM. The DDRM has the Riviere de lÉst is at a much higher and widespread flood risk when compared to the LISEM analysis. This might be because in the LISEM analysis, the river falls under the regions of rainfall from Gros Piton which is rather low when compared to the surrounding areas. The difference in rainfall between the two regions is quite drastic so the flooding in the river wasn't able to manifest as well as it could have in that area.

In general, the DDRM does not appear to function strongly as a document for policy makers in regards to the flood risk map. When the entire island is covered in high flood risk, it makes it difficult to decide where to concentrate efforts as the areas that are most impacted are not clearly identified. Certain regions should be more prioritized or highlighted in their assessment. While the LISEM analysis appears to exaggerate flood heights in some regions due to blockages in the DEM, the risk classification remains true. The risk classification done in this study were carried out so that the areas with the highest flood height are at the most risk. Overall the LISEM study is an excellent complement to the risk analysis carried out by the DDRM and despite some differences adds to complete the picture of flood risk for Réunion.

5.5 OpenLISEM Capacity PERFORMANCE

Over the duration of this study, OpenLISEM was pushed to its limits in terms of temporal and spatial extent as well as its processing power. As previously mentioned, prior LISEM runs were often used for much smaller catchments for shorter storm events. The original intent for this risk analysis was to utilize the 5m resolution maps collected from the IGN and to run the model for multiple recurrence time of precipitation events. However in order to lower the processing time, the maps were resampled to 25m. Yet even when the lower resolution files were used as input, LISEM took a period of 25 days to run to completion for a 48 hour storm event. This makes the process of calibrating results for the island difficult as it is very time intensive.

5.6 Looking Forward

A storm of this scale requires immediate intervention to be prepared for the risk. The 10 year flood event created in this study is useful for showing what the island should already be prepared to endure. Most of the structures subject to the worst damage reside nears the Riviére du Mât. The river extends beyond its banks by 450 meters in some parts, especially in the region near l'Llet. Although constructing larger levees would be a possibility, it does not make much sense given the number of people that live there. Perhaps it would be best to just remove constructions and future development in the Riviére du Mât as the extreme flood depth is widespread and the number of people are few. It might be more meaningful to focus efforts and increase flood resilience where the more impacted populations lie such as the fourth most populated city of Le Tampon where 5590 structures are at risk. In addition to improving surveillance and flood warning systems, Le Tampon would greatly benefit from the introduction of drainage systems to channel water away and the flood proofing of buildings. The area is already heavily urbanized so these forms of mitigation may prove difficult however it would be in the communes best interest to prepare for such an event. Future studies are recommended in order to better determine the risk in these regions as well as to determine the most appropriate form of mitigation.

5.7 Recommendations

While the study was able to successfully reach definite conclusions regarding regions at risk of flooding in Réunion, it wasn't without its shortcomings. A number of these issues are discussed in detail below with possible solutions and recommendations for further studies.

One of the more obstructive issues of the experiment was the unrealistic high flood heights caused by blockages in the DEM which did not allow for water to flow out of the catchment. This was a result of the resampling process when changing the resolution for all the maps from 5m to 25m. This in turn increased extreme flooding in rivers at the base of high cliffs. Among the first recommendations to be made based on this study would be to use the 5m resolution or at least the highest available for LISEM. If the resampling method cannot be avoided and a lower resolution must be used, perform channel definition on the DEM to ensure that rivers can flow out to the coast without obstruction. This should allow for more realistic flood heights and risk analysis.

Among the difficulties of the study was the long processing time for LISEM to simulate the entire island of Réunion. As a result of this long computational time, several of the original objectives had to be omitted, primarily the design storms for 50 and 100 year events. The addition of these scenarios on the LISEM program would aid in creating a more complete picture for the state of flood risk in Réunion and also to anticipate the worst event possible. The 10 year flood event created in this study is useful for showing what the island should already be prepared to endure. The 50 and 100 year events are important for representing worst case scenarios that the island of Réunion should work to prepare for in the coming years. In order to properly simulate sensible rainfall intensity and volume projections, longer time series for precipitation are required as the current 25 year period of daily rainfall produces overestimated results. A longer time series will yield more just recurrence times and projections.

One goal that had to be eliminated for the sake of time was the option to utilize LISEMs ability to simulate erosion and landslides caused by rainfall. Mass movements and heavy precipitation events are closely linked and simulating the processes together through LISEM could yield interesting results given Réunion's varied and steep topography.

Throughout the process of creating the inputs for LISEM, it became apparent that there were several maps that could be improved on. The rainfall maps feature various zones of distinct rainfall based on where the closest meteorological station lies. Rather than have 10 distinct rainfall amounts, perhaps it would be better to perform an inverse distance weighted interpolation between the station to smoothen out the disparity between regions. This would make the process of precipitation to be more realistic because as it is now, adjacent regions of rainfall have some drastic differences. Another map with room for improvement would be the soil depth map. As previously mentioned, the soil depth is crucial for determining the potential storage of the soil yet there is very little information on soil depth for the island. The soil depth map created in this study was calibrated using information of the root depth of sugarcane for 3 sites on the island as well as images provided from Google Earth streetview. However for the most accurate perspective on infiltration and the subsequent effects on flooding, it would be beneficial to have more sites tested for soil depth throughout the island.

6. Conclusions

With a population rapidly approaching 1 million people, it is becoming increasingly crucial for Réunion to be cognizant for the degree of flood risk throughout the island. This study set out to identify the extent of areas prone to flooding as well as to determine the degree of flooding. Given a 1 in 10 year storm event, 94.1% of buildings (283,580) would be deemed safe or low risk. Of the 301,446 structures on Réunion, 1,706 fall within regions subject to extreme flooding and are vulnerable to flood heights exceeding 4 meters. The remaining 16,160 structures fall somewhere in between and would be subject to varying degrees of flooding from 1 to 4m. The most impacted area would be the communities around the Riviere du Mat (shown in figure 24) as it undergoes the most extreme water heights as well as the most widespread extent of damage. Approximately 940 buildings are at risk in this region however not many people reside in this area so efforts should be focused to build protective constructions in more populated areas at risk such as Le Tampon. Under the design storm utilized in this study, the eastern side of Réunion is much more likely to experience flooding hazard when compared to the risk assessment conducted by the DDRM. The DDRM appears to be a difficult to interpret document as it lacks the description of its creation to the point that it is difficult to consider a stand alone document for risk assessment. This study complements the work laid out by the DDRM to create a more complete and comprehensive picture for the state of flood risk in Réunion.

Cyclone Gamede (2007) was among the last big record breaking rainfall events which claimed 2 lives and left 90 severely wounded. As tropical storms increase in frequency and magnitude (IPCC, 2014) it will be increasingly important for there to be better floodplain management to influence future developments and to determine appropriate land uses. This study concluded that rather than fortify and floodproof the structures at extreme risk by the Riviére du Mât, it would be better to focus efforts and funds towards more populated urban centers at risk. Le Tampon is home to approximately 70,000 residents and has structures subject to medium to extreme risk. This urban center should be prioritized and treated to enhanced drainages systems and floodproofing. Furthermore, future studies are required to determine the most appropriate form of mitigation whether it be to remove existing structures in high risk areas, to construct dykes to hold back the water from exceeding the banks, or to retrofit the existing structures in order to make them more flood resistant.

Further risk assessments are also suggested in order to insure the safety for the inhabitants of Réunion. Although this study did not account for landslides and other erosive properties triggered by rainfall, the most extreme flood heights occur in regions with high cliffs and steep slopes so mudslides could be a real threat. It is strongly recommended that future studies run flood simulations for 50 and 100 year rainfall events for a more complete picture of flood risk. These rainfall events require longer time series in order to accurately determine recurrence intervals and project more realistic design storms. This study had to lower the resolution of the maps from 5m to 25m to be input into LISEM as the available computational power took a month to run. However, this resulted in blockages in the DEM so water could not flow freely to the coasts and would pool resulting in unrealistic flood heights exceeding 30 meters in the Bras de Cilaos as well as the Riviére du Mât. Future studies should be cautious to make that sure that the DEM is of the highest resolution available and that if there are blockages to burn in channels so water can flow.

In summary, as the population of Réunion continues to grow and the effects of climate change increase storm intensity, it becomes increasingly important to become more aware of the risk of flooding on the island so that adaptations and mitigations measures can be carried out.

7. References

Asner, G.P., Scurlock, J.M. and A Hicke, J., 2003. Global synthesis of leaf area index observations: implications for ecological and remote sensing studies. *Global Ecology and Biogeography*, *12*(3), pp.191-205.

Aston, A.R., 1979. Rainfall interception by eight small trees. *Journal of hydrology*, *42*(3-4), pp.383-396.

Breña-Naranjo, J.A., Pedrozo-Acuña, A. and Rico-Ramirez, M.A., 2015. World's greatest rainfall intensities observed by satellites. *Atmospheric Science Letters*, *16*(3), pp.420-424.

Bowles, Joseph E. 1979. "Physical and geotechnical properties of soils."

Carter, Michael, and Stephen P. Bentley. 1991. *Correlations of soil properties*. Pentech press publishers.

Centre for Research on the Epidemiology of Disasters (CRED) and United Nations of Office for Disaster Risk Reduction., 2015. The human cost of weather related disasters: 1995-2015. 27 pages

Claude-Valentin, M. and Jean-Louis, R., 2012. Demographic and migration trends in the outermost regions: impacts on territorial, social and territorial cohesion. Institut National D'Études Démographiques (INED). 16 pages

Chopart, J.L., Azevedo, M.C.B., Le Mezo, L. and Marion, D., 2010. Sugarcane root system depth in three different countries. 8 pages

De Jong, S.M. and Jetten, V.G., 2007. Estimating spatial patterns of rainfall interception from remotely sensed vegetation indices and spectral mixture analysis. *International journal of geographical information science*, *21*(5), pp.529-545.

Deltares, 2008. "05 IDF Relations." Oyster Reefs and the Pacific Oyster - Building with Nature - Deltares Public Wiki. Accessed June 13, 2018. https://publicwiki.deltares.nl/display/HYMOS/05 IDF Relations.

Dewan, A.M., 2013. Hazards, risk, and vulnerability. In *Floods in a Megacity* (pp. 35-74). Springer, Dordrecht.

Domingo, F., Sánchez, G., Moro, M.J., Brenner, A.J. and Puigdefábregas, J., 1998. Measurement and modelling of rainfall interception by three semi-arid canopies. *Agricultural and forest meteorology*, *91*(3-4), pp.275-292.

Données Publiques De Météo-France., 2017. Catalogue Des Données Publiques De Météo-France Avec Ou Sans Redevance. Accessed June 12, 2018. https://donneespubliques.meteofrance.fr/.

Geotechdata.info. (2013). Geotechdata.info - Database of geotechnical information. [online] Available at: http://www.geotechdata.info/index.html [Accessed 19 Jun. 2018].

IGN, 2017. "IGN - Espace Professionnel | L'information Grandeur Nature." Accueil. Accessed June 13, 2018. http://professionnels.ign.fr/.

INSEE., 2018. Estimation de population par région, sexe et grande classe d'âge - Années 1975 à 2018. Available at: Insee.fr [Accessed 27 January 2018].

IPCC, 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pages

Karssenberg, D., Schmitz, O., Salamon, P., de Jong, K., and Bierkens, M. F. P. 2010. A software framework for construction of process-based stochastic spatio-temporal models and data assimilation, Environmental Modelling & Software 25(4), pp. 489-502.

Kreibich, H., Piroth, K., Seifert, I., Maiwald, H., Kunert, U., Schwarz, J., Merz, B. and Thieken, A.H., 2009. Is flow velocity a significant parameter in flood damage modelling?. *Natural Hazards and Earth System Sciences*, *9*(5), p.1679.

Le Masson, V. and Kelman, I. 2011. Disaster risk reduction on non-sovereign islands: La Réunion and Mayotte, France, *Natural Hazards*, 56(1), pp. 251–273.

Leaning, J. and Guha-Sapir, D., 2013. Natural disasters, armed conflict, and public health. New England journal of medicine, 369(19), pp.1836-1842.

Lénat, J.F., Bachèlery, P. and Merle, O., 2012. Anatomy of Piton de la Fournaise volcano (La Réunion, Indian Ocean). *Bulletin of volcanology*, *74*(9), pp.1945-1961.

Mishra, S.K., Tyagi, J.V. and Singh, V.P., 2003. Comparison of infiltration models. *Hydrological processes*, *17*(13), pp.2629-2652.

MeteoFrance., 2017. CLIMAT LA REUNION - Descriptions, records de pluie, record de vent, ... [online] Meteofrance.re. Available at: http://www.meteofrance.re/climat/description-du-climat [Accessed 28 Sep. 2017].

Raunet, Michel. 1991. "Le milieu physique et les sols de l'île de la Réunion. Conséquences pour la mise en valeur agricole." 555 pages.

OpenLISEM Manual, 2018. Available at: https://blog.utwente.nl/lisem/ [Accessed 4 March 2018]

Petit, J. and Prudent, G., 2008. *Climate change and biodiversity in the European Union overseas entities*. IUCN.

Pohl, B., Morel, B., Barthe, C. and Bousquet, O., 2016. Regionalizing Rainfall at Very High Resolution over La Réunion Island: A Case Study for Tropical Cyclone Ando. *Monthly Weather Review*, *144*(11), pp.4081-4099.

Préfecture de la Réunion and BRGM, 2016. *Dossier Départemental des Risques Majeurs De La Réunion (DDRM).* pp. 2-57.

Rappaport, E.N., 2014. Fatalities in the United States from Atlantic Tropical Cyclones: New Data and Interpretation. *Bulletin American Meteorological Society*, 95(1), pp. 341–346.

Réchou, A., Rao, N., Bousquet, O., Plu, M. and Decoupes, R., 2014. Properties of rainfall in a tropical volcanic island deduced from UHF wind profiler measurements. *Atmospheric Measurement Techniques*, *7*(2), pp.409-418.

Saulnier, G.M., Beven, K. and Obled, C., 1997. Including spatially variable effective soil depths in TOPMODEL. *Journal of hydrology*, *202*(1-4), pp.158-172.

Shang, Xiaoxia; Chazette, Patrick; Totems, Julien; Dieudonné, Elsa; Hamonou, Eric; Duflot, Valentin; Strasberg, Dominique; Flores, Olivier; Fournel, Jacques; Tulet, Pierre. 2016. "Tropical Forests of Réunion Island Classified from Airborne Full-Waveform LiDAR Measurements." *Remote Sens.* 8, no. 1: 43.

United Nations, 2017. World Statistics Pocketbook 2017. 5th ed. New York: United Nations Publications.

USDA, N., 1998. Keys to soil taxonomy. *USDA, Washington DC Google Scholar*.

Von Hoyningen-Huene, J., 1981. Die Interzeption des Niederschlags in landwirtschaftlichen Pflanzenbeständen. Arbeitsbericht Deutscher Verband für Wasserwirtschaft und Kulturbau, DVWK.

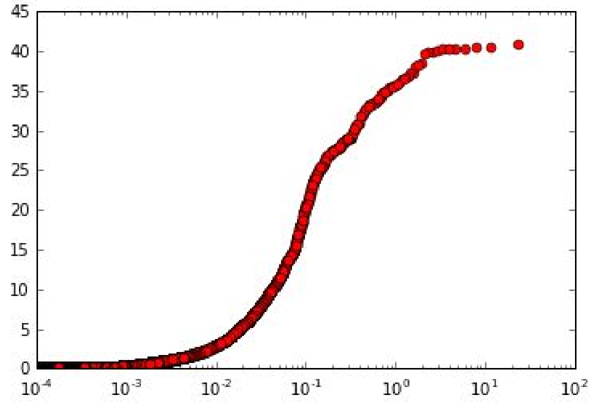
Von Hoyningen-Huene, J. 1983. Die Interzeption des Niederschlags in landwirtschaftlichen Pflanzenbeständen. Z. *Pflanzenernaehr. Bodenk*., 154(1), pp. 153-156.

WMO, 2012. International glossary of hydrology. *World Meteorological Organization Bulletin* 385(1), pp. 1-461.

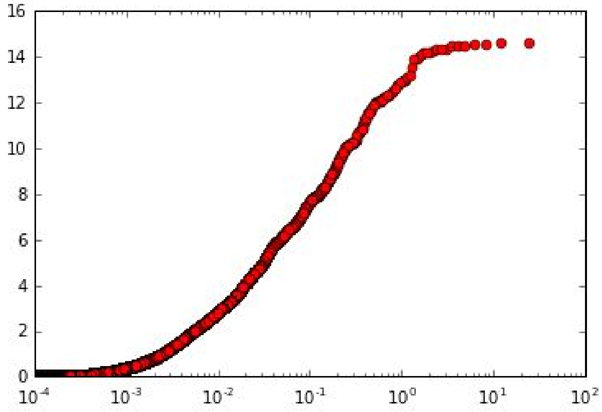
8. Appendix

Preliminary Results

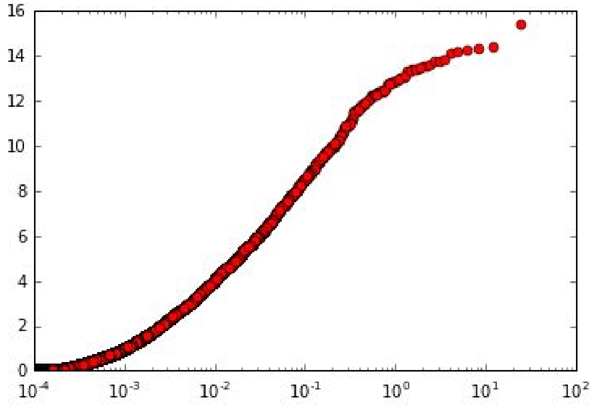
A. Frequency Analysis Curves for the 10 MeteoFrance Stations of La Réunion



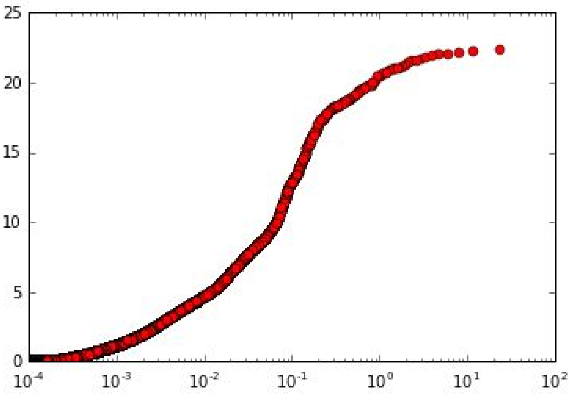
Cilaos



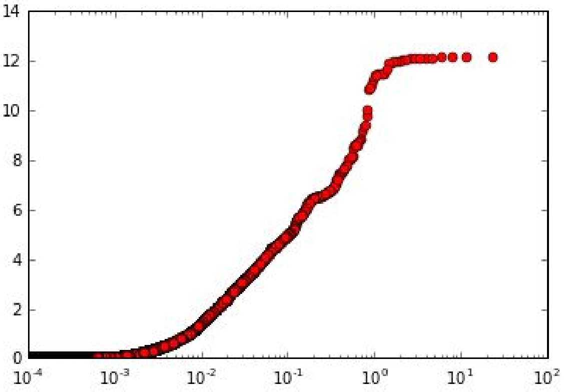
Gillot Aeroport



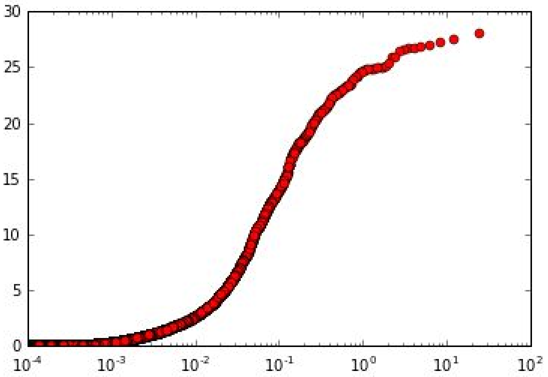
Le Port



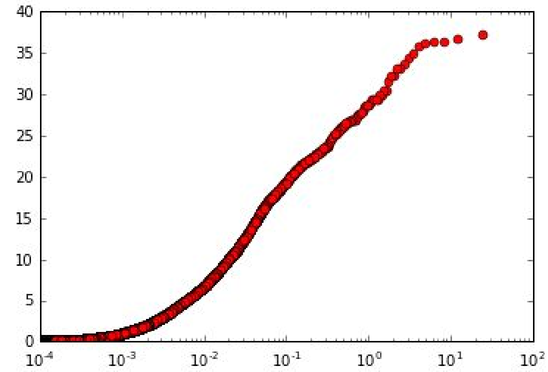
Le Baril



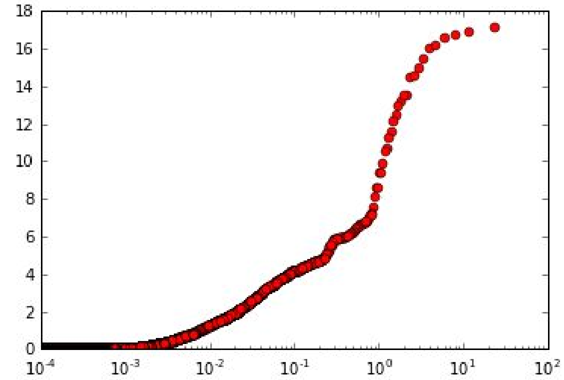
Pont Mathurin



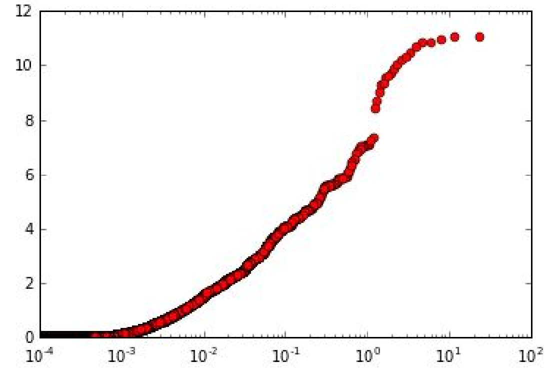
Plaine Des Cafres



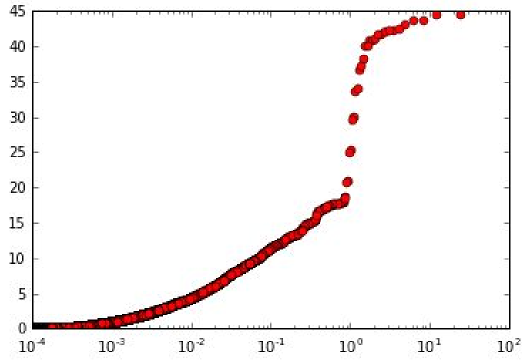
Plaine Des Palmistes



Pointe des Trois Bassins



Gros Piton



Saint Benoit

B. Soil Properties Table (Geotechdata.info, 2013)(USDA, 1998)

Soil Types	**Soil Texture Reclass**	ksat (mm/hr)	porosity (cm3/cm3)	psi (cm)	Initial Moisture Content (cm2/cm2)	Soil Density (drybulk density) (kg/m3)	Internal Friction Angle	D50 - Median Grain Diameter	Soil Cohesion (kPa)	Extra Soil Cohesion	Aggregate Stability	Rock Fraction
Sol Brun (Cambisol)	Loamy to Clayey (L)	18.5	0.5	40	0.34	1700	30	0.05	65	1.6	2	0.4
Inculte (No Soil= riverbeds gullies and steep slopes)	No Soil (Outcrops)	1,5	0.25	40	0.1	1400	22	0.2	250	1	2	0.9
Andique Perhydrate (Haplic Andosols)	Silt Loam (SiL)	17.4	0.5	40	0.4	1550	28	0.028	75	2	2	0.5
Brun Andique (Cambisol)	Clay Loam	4.2	0.5	50	0.4	1650	25	0.047	85	1	2	0.42

	(CL)											
Vertique (Vertisol)	Clay (C)	2.5	0.5	50	0.4	1400	23	0.001	90	4	2	0.45
Ferraltie (Ferralsols)	Clay (C) (perhaps ClayLoam)	2.5	0.5	50	0.4	1400	24	0.001	90	3	2	0.4
Brun Cilaos (Lithic Leptosols)	Clay Loam (CL)	4.2	0.5	50	0.5	1650	26	0.047	85	1	2	0.55
Brun Salazie (Eutric Regosols)	Loam (L)	18.5	0.5	40	0.5	1700	30	0.05	65	1	2	0.55

C. Land Use Properties Table (Asner et al., 2003)(OpenLISEM Manual, 2018)(Shang et al. 2016)

Land Use Type	Random Roughness (cm)	Mannings n	Plant Height	Fraction Covered by Vegetation	Leaf Area Index	Max Canopy Storage	Fraction Covered by Houses
Coastal Forest (0-100)	1	0.1	16.2	0.95	3.5	2.6	0
Tropical Lowland Forest (100-1200)	1	0.15	15	0.95	7.5	4.34	0
Tropical Montane Cloud Forest (1200-3000)	1	0.1	13	0.95	5	3.28	0
Buildings (Urban)	0.5	0.05	7	0.2	1	1.42	0.8
Public Utilities (Airports & Harbor)	0.5	0.015	1	0.05	1	1.42	0.95
Grasslands or Meadow	0.5	0.1	2	1	1	1.42	0
Orchard or Vineyard	1	0.13	3.5	0.8	4.2	2.92	0
Scrub or Brush or	0.5	0.1	0.5	0.8	2	1.9	0

Bushes							
Sand Gravel	0.5	0.02	0	0	0.1	0.93	0
Rock or Scree	0.5	0.01	0	0	0.1	0.93	0
Marshland Bog	1	0.1	3	1	3.3	2.51	0
Open Water	0.1	0.05	1	0.9	0.1	0.98	0

D. Design storms scenarios for 10, 50 and 100 year events

1. 10 Year Event (Precipitation in mm/hr)

Time	GillotAeroport	LePort	SaintBenoit	PteDes3Bassins	Cilaos	PlaineDesPalmistes	GrosPiton	PlaineDesCafres	PontMathurin	LeBaril
0	0	0	0	0	0	0	0	0	0	0
60	12.89	11.43	38.18	9.38	38.02	17.82	12.73	15.11	7.33	13.07
120	13.53	11.43	40.08	9.86	38.50	20.66	12.97	17.22	8.71	13.68
180	13.95	11.46	40.76	10.69	39.85	23.01	13.08	18.94	9.26	15.24
240	14.18	11.98	42.30	11.54	40.28	24.53	13.29	19.04	9.54	16.47
300	14.26	12.07	43.03	12.44	40.48	24.98	13.38	18.97	9.69	17.29
360	14.33	12.02	42.46	13.22	40.30	27.29	13.48	20.32	9.85	18.66
420	14.41	12.09	40.86	13.53	39.85	32.18	13.53	20.91	10.00	19.69
480	14.48	12.08	40.98	14.48	40.02	34.35	13.46	22.64	10.18	19.78
540	14.43	12.08	41.67	16.01	40.21	35.67	13.55	25.11	10.45	20.66
600	14.77	12.11	42.11	16.54	40.49	36.38	13.73	28.39	10.85	21.84
660	14.45	12.10	43.68	17.16	40.93	37.23	14.37	28.00	10.82	22.51
720	14.61	12.14	44.44	17.13	40.75	37.23	15.39	27.44	11.04	22.32
780	14.49	12.14	44.83	16.89	40.26	36.34	15.53	27.18	11.04	21.01

840	14.31	12.14	44.44	16.73	39.67	36.58	14.06	26.62	11.06	20.02
900	13.88	12.13	43.69	16.18	38.23	36.12	14.18	25.83	10.94	19.59
960	12.56	11.95	42.18	15.43	37.22	34.90	14.21	24.80	10.68	18.17
1020	11.10	11.20	41.57	14.98	35.95	33.55	13.76	24.14	10.31	18.06
1080	10.59	9.78	40.08	14.53	34.99	33.14	14.27	23.38	9.60	17.90
1140	9.53	7.75	37.23	13.52	33.18	31.37	13.82	22.67	9.31	17.33
1200	8.92	6.35	34.03	12.97	31.03	29.80	12.25	22.18	9.02	17.33
1260	8.28	5.73	29.52	12.15	28.88	27.47	10.84	21.39	8.40	17.31
1320	7.34	3.52	24.93	11.26	27.38	25.68	7.93	19.83	7.23	17.31
1380	6.16	1.84	20.57	10.53	25.28	25.31	7.04	18.24	6.42	17.31
1440	5.14	1.29	17.04	9.42	22.38	24.67	6.46	16.75	5.58	17.18
1500	0	0	0	0	0	0	0	0	0	0
Total	292.60	238.81	920.64	326.54	874.08	726.23	307.27	535.11	227.29	439.72

2. 50 Year Event (Precipitation in mm/hr)

Time	GillotAeroport	LePort	SaintBenoit	PteDes3Bassins	Cilaos	PlaineDesPalmistes	GrosPiton	PlaineDesCafres	PontMathurin	LeBaril
0	0	0	0	0	0	0	0	0	0	0
60	36.61	32.47	102.96	26.65	86.37	40.48	34.34	34.33	20.80	35.24
120	38.43	32.47	108.08	28.00	87.47	46.94	34.97	39.12	24.73	36.90
180	39.62	32.54	109.93	30.36	90.54	52.27	35.26	43.04	26.29	41.11
240	40.28	34.03	114.08	32.78	91.50	55.74	35.85	43.26	27.10	44.41
300	40.49	34.27	116.06	35.33	91.96	56.76	36.07	43.09	27.52	46.64
360	40.71	34.13	114.51	37.54	91.56	62.01	36.34	46.16	27.97	50.32
420	40.92	34.34	110.19	38.41	90.54	73.12	36.50	47.50	28.40	53.11
480	41.13	34.29	110.51	41.11	90.92	78.04	36.30	51.44	28.92	53.36
540	40.99	34.32	112.38	45.46	91.35	81.03	36.54	57.05	29.68	55.72
600	41.94	34.39	113.57	46.98	92.00	82.64	37.02	64.51	30.81	58.91
660	41.04	34.36	117.81	48.73	92.98	84.58	38.75	63.62	30.72	60.70
720	41.49	34.48	119.86	48.66	92.58	84.59	41.51	62.35	31.36	60.19
780	41.16	34.48	120.92	47.97	91.47	82.57	41.87	61.76	31.36	56.66

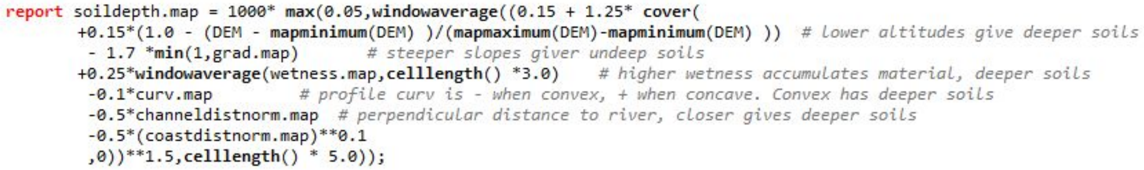
840	40.64	34.48	119.86	47.50	90.12	83.10	37.92	60.47	31.41	53.98
900	39.41	34.44	117.84	45.94	86.85	82.06	38.23	58.69	31.07	52.84
960	35.67	33.94	113.75	43.83	84.56	79.29	38.32	56.35	30.32	49.00
1020	31.52	31.81	112.11	42.55	81.68	76.23	37.11	54.85	29.28	48.70
1080	30.08	27.76	108.10	41.25	79.50	75.30	38.48	53.13	27.26	48.28
1140	27.07	22.01	100.40	38.39	75.37	71.27	37.26	51.50	26.44	46.75
1200	25.32	18.03	91.79	36.83	70.51	67.71	33.04	50.40	25.61	46.75
1260	23.52	16.28	79.61	34.51	65.60	62.40	29.24	48.60	23.86	46.68
1320	20.85	9.99	67.25	31.97	62.21	58.33	21.37	45.06	20.54	46.68
1380	17.49	5.23	55.47	29.89	57.42	57.50	18.99	41.45	18.22	46.68
1440	14.60	3.67	45.96	26.74	50.84	56.04	17.42	38.06	15.83	46.34
1500	0	0	0	0	0	0	0	0	0	0
Total	830.98	679.22	2484.97	930.38	1989.92	1655.00	834.70	1222.77	653.51	1194.94

3. 100 Year Event (Precipitation in mm/hr)

Time	GillotAeroport	LePort	SaintBenoit	PteDes3Bassins	Cilaos	PlaineDesPalmistes	GrosPiton	PlaineDesCafres	PontMathurin	LeBaril
0	0	0	0	0	0	0	0	0	0	0
60	66.08	58.61	186.90	48.10	147.88	69.31	62.34	58.77	37.55	63.97
120	69.37	58.61	196.21	50.53	149.77	80.36	63.48	66.97	44.64	66.99
180	71.51	58.74	199.55	54.81	155.02	89.50	64.02	73.68	47.46	74.62
240	72.70	61.43	207.10	59.16	156.67	95.43	65.08	74.07	48.91	80.62
300	73.09	61.85	210.69	63.78	157.45	97.19	65.48	73.78	49.68	84.66
360	73.47	61.60	207.88	67.75	156.77	106.16	65.97	79.03	50.49	91.35
420	73.86	61.98	200.04	69.33	155.02	125.19	66.26	81.33	51.26	96.41
480	74.24	61.90	200.61	74.20	155.66	133.62	65.89	88.08	52.20	96.86
540	73.99	61.94	204.00	82.06	156.41	138.74	66.34	97.67	53.57	101.14
600	75.69	62.07	206.16	84.79	157.51	141.50	67.20	110.44	55.62	106.94
660	74.07	62.02	213.87	87.95	159.20	144.81	70.34	108.92	55.45	110.20
720	74.88	62.24	217.59	87.83	158.52	144.84	75.36	106.75	56.60	109.26

780	74.28	62.24	219.50	86.59	156.60	141.37	76.01	105.74	56.60	102.86
840	73.34	62.24	217.59	85.73	154.30	142.28	68.83	103.54	56.69	98.00
900	71.12	62.15	213.91	82.91	148.70	140.49	69.40	100.49	56.09	95.92
960	64.37	61.26	206.49	79.11	144.77	135.76	69.56	96.47	54.72	88.94
1020	56.90	57.41	203.51	76.80	139.85	130.51	67.36	93.91	52.84	88.41
1080	54.29	50.11	196.25	74.46	136.12	128.92	69.85	90.96	49.21	87.64
1140	48.87	39.73	182.25	69.29	129.05	122.02	67.65	88.17	47.71	84.86
1200	45.71	32.55	166.63	66.47	120.72	115.92	59.98	86.29	46.22	84.86
1260	42.46	29.39	144.51	62.28	112.32	106.85	53.08	83.21	43.06	84.74
1320	37.63	18.03	122.07	57.71	106.52	99.88	38.80	77.15	37.08	84.74
1380	31.57	9.44	100.69	53.95	98.32	98.45	34.48	70.96	32.89	84.74
1440	26.36	6.62	83.44	48.27	87.04	95.95	31.62	65.16	28.58	84.13
1500	0	0	0	0	0	0	0	0	0	0
Total	1500.87	1226.13	4510.46	1677.85	3405.18	2831.05	1511.38	2089.57	1174.10	2162.89

E. Modified soil depth model implemented to create soil depth map and adapted to fit Réunion (Source: ITC & Saulnier et al., 1997)



```
report soildepth.map = 1000* max(0.05,windowaverage((0.15 + 1.25* cover(
       +0.15*(1.0 - (DEM - mapminimum(DEM) )/(mapmaximum(DEM)-mapminimum(DEM) ))  # lower altitudes give deeper soils
        - 1.7 *min(1,grad.map)       # steeper slopes giver undeep soils
       +0.25*windowaverage(wetness.map,celllength() *3.0)    # higher wetness accumulates material, deeper soils
        -0.1*curv.map         # profile curv is - when convex, + when concave. Convex has deeper soils
        -0.5*channeldistnorm.map  # perpendicular distance to river, closer gives deeper soils
        -0.5*(coastdistnorm.map)**0.1
        ,0))**1.5,celllength() * 5.0));
```