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June, 2015

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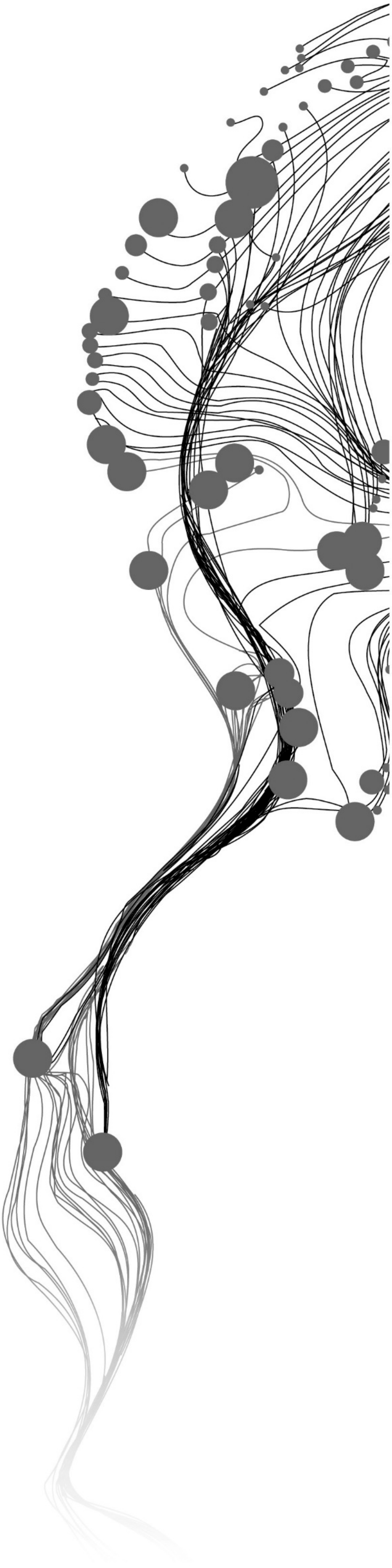

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ANDREAS CHRISTOFFER LUNDEGAARD
Enschede, The Netherlands, June, 2015

Thesis submitted to the Faculty of Geo-Information Science and Earth Observation of the University of Twente in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation.
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ABSTRACT

The study is conducted on Saint Lucia in the Caribbean Sea to assess the Hydro-Estimator as a rainfall product for early flood warning. The Hydro-Estimator is compared to rain gauges and flood events for Hurricane Tomas and the December trough in 2013 are modelled based on the different rainfall products. The results shows that the Hydro-Estimator in general has a time bias and overestimates the rainfall compared to the rain gauges. This results in higher modelled flood levels and earlier flood times than the flood model results based on the rain gauges.

The flood events were created based on the Hydro-Estimator from NOAA/NESDIS and the rain gauges and was modelled with openLISEM. The flood levels and timing were compared for the two rainfall events.

Though the Hydro-Estimator greatly overestimates the total amount of rainfall for Hurricane Tomas, the rainfall pattern looks close to the gauges. There are however only four ran gauges to base the comparison on. For the December trough the total rainfall amount for the Hydro-Estimator is very close to the records for many of the rain gauges. The spatial pattern for the whole December trough has noticeable local differences when comparing the Hydro-Estimator and the rain gauges. For the December trough the 15 rain gauges to evaluate against, gives a better chance to spot rainfall differences, than for Hurricane Tomas where only four rain gauges were available.

ACKNOWLEDGEMENTS

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABRIVIATIONS

CDEMA	Caribbean Disaster Emergency Management Agency
CHARIM	Caribbean Handbook on Risk Information Management
EFAS	European Flood Awareness System
EWS	Early Warning System
FFG	Flash Flood Guidance
FFGS	Flash Flood Guidance System
FFT	Flash Flood Threat
HE	Hydro-Estimator 1 hour records
HDRFFGS	Haiti-Dominican Republic Flash Flood Guidance System
JICA	Japan International Cooperation Agency
MIPST	Ministry of Infrastructure, Port Services and Transport
MOU	Memorandum of Understanding
MPDE	Ministry of Physical Development, Housing & Urban Renewal (Saint Lucia)
NEMO	National Emergency Management Organisation (Saint Lucia)
NESDIS	The National Environmental Satellite, Data, and Information Service (U.S.)
NOAA	National Oceanic and Atmospheric Administration (U.S.)
RG5	Hourly rainfall intensities based on 5-minute rain gauge records
RG60	Hourly rainfall intensities based on 60-minute rain gauge records
USAID	United States Agency for International Development (U.S)
WMO	World Meteorological Association
WMO-FFI	World Meteorological Association Flood Forecasting Initiative

1. INTRODUCTION

As a case study in the CHARIM project, this thesis will evaluate rainfall records from both the Hydro-Estimator and rain gauges on Saint Lucia for flash flood forecasts and warning. Saint Lucia has a long record of extreme flood events (NEMO Secretariat, 2011). During the 20th century, thousands of people have lost their lives because of natural hazards in Small Island Development States (SIDS) (Pelling & Uitto, 2002). Hurricanes have a long track record in the Caribbean Sea and are an increasing problem in the region (Caviedes, 1991). In recent years, hurricanes have caused severe human and economic losses in the Caribbean Sea (Records et al., 2005). Rescue and relief efforts, by the international community, can be difficult due to the isolated location and limited infrastructure (Wright, 2013). To improve the capacity building in relation to natural hazards for development states in the Caribbean, the World Bank has initiated the CHARIM project (Caribbean Handbook on Risk Information Management) in which ITC participates. The purpose of CHARIM is to create an online handbook for planners and developers in the Caribbean, to help applying hazard and risk information for landslides and flooding.

One of the problems caused by heavy precipitation is flash floods, which is defined by World Meteorological Organisation (WMO) as (World Meteorological Organization, 2009):

> “Flash floods are rapidly rising flood waters that are the result of excessive rainfall or dam break events. Rain-induced flash floods are excessive water flow events that develop within a few hours – typically less than six hours – of the causative rainfall event, usually in mountainous areas or in areas with extensive impervious surfaces such as urban areas. Although most of the flash floods observed are rain induced, breaks of natural or human-made dams can also cause the release of excessive volumes of stored water in a short period of time with catastrophic consequences downstream. Examples are the break of ice jams or temporary debris dams.”

Most recently, severe flash floods hit several Caribbean Island from the 23rd to 24th of December 2013. The states Dominica, Grenada, St. Vincent and the Grenadines, and Saint Lucia were affected. Heavy rainfall was caused by a small low level depression. During the 12 to 24 hour event, rainfall as high as 406 mm were recorded in Burton, Saint Lucia, 156 mm in Grenada and 109 mm in St. Vincent and the Grenadines (Caribbean Disaster Emergency Management Agency, 2013). The infrastructure was hit severely in St. Vincent & the Grenadines where 28 bridges were destroyed or damaged (CDEMA, 2013). There is no specific information about the number of damaged bridges on Saint Lucia, but the damage reports following the event requests 10 temporary bridges (French, 2013). In 2010, Hurricane Thomas caused losses worth 43 percent of the GDP in Saint Lucia. In 2004, hurricane Ivan devastated Grenada causing damages worth 200 percent of its GDP (Kentish, 2014), damaging or destroying 90 percent of the buildings on Grenada and killing 39 people (WORLD METEOROLOGICAL ORGANIZATION, 2005). Heavy precipitation in relation to hurricanes is a major contributor to flood damage.

Due to these intensive rainfall events, there is an urgent demand for disaster management solutions and reconstruction in relation to flash floods caused by hurricanes and tropical storms (The World Bank, 2014). The awareness among locals in St. Vincent and the Grenadines has increased, but people are worried if existing protection at the river embankments are able to withstand extreme situations as the hurricane season approaches (Kentish, 2014).

According to WMO and the Global Water Partnership an effective system for real-time flood forecasting consists of three main component in (The Associated Programme on Flood Management, 2013): (1) providing specific rainfall forecasts (both quantity and timing) using numerical weather-prediction models; (2) establishing a network of manual or automatic hydrometric stations linked to a central control by some form of telemetry and (3) flood forecasting model software connected to the observing network and operating in real time.

The warnings are distinct from forecasts since they are issued when an event is imminent or already occurring. Flood warnings must be issued to a range of users and for various purposes. According to WMO these purposes include (The Associated Programme on Flood Management, 2013): (a) readying operational teams and emergency personnel; (b) warning the public of the timing and location of the event; (c) warning of the likely impacts on roads, dwellings and flood defence structures, among others; (d) giving individuals and organizations time to prepare; (e) in extreme cases, to enable preparation for undertaking evacuation and emergency procedures.

Over the years, different approaches have been developed to warn against flash floods. In 2003 WMO started the WMO Flood Forecasting Initiative (WMO-FFI), which focusses on improving the capacity of meteorological and hydrological services to deliver more accurate and timely flood forecasts and warnings. One of the goals of the initiative is to implement a Flash Flood Guidance System (FFGS) with world wide coverage (WMO, 2013b).

A study by an expert team established by WMO, shows that the cyclone frequency is likely to decrease or stay the same. Though the total storm count is not increasing, the strongest tropical cyclones are expected to occur more frequent (Knutson et al., 2010).

It is very important to get the timing and intensity right for the used precipitation products, when using them in a warning system. If the rainfall is captured and delivered too late, the flood will occur before the rainfall data has been transmitted and used for flood modelling. On the other hand, a bias towards a too early estimate of the rainfall, makes it possible to run the flood model earlier and therefore increase the warning time. Saint Lucia has the most complete rainfall data set within the CHARIM project with daily rain gauges measurements dating back to 1955 and broadly implemented minute records since 2003, which gives a good basis for comparison. With an increasing number of available meteorological satellite products, the possibilities for using remote sensed data for areas without ground measurements has become increasingly improved in relation to the spatial resolution, temporal and intensity estimates. When new products are introduced, it is important to evaluate them against ground truth, to assess how well they perform before they are used for in flood modelling and flood warning systems.

Rain gauges with broadcasting capabilities, ground based radar, and meteorological satellite products are often used for flood modelling for flood warnings. However, the spatial resolution for many satellite products used for precipitation estimates is low compared to the small size of many of the Caribbean islands. The area of Saint Lucia is 617 km^2 in comparison to the TRMM precipitation estimates which are delivered in a resolution of 0.25 degrees (equal to ~27 km at Castries), making each pixel around 729 km^2 and therefore bigger than Saint Lucia itself. Most of them are therefore not useful to estimate the local differences in precipitation on an island like Saint Lucia with dramatic elevation changes from a volcanic terrain with steep mountainsides climbing up to elevations around 960 meters. This makes the Hydro-Estimator, with a spatial resolution of 4-5, km and rain gauges more interesting as rainfall products.

1.1. Problem statement and Objectives

The challenge in Saint Lucia arises from the small river catchment size, which quickly can produce severe flooding due to the steep terrain and narrow valley bottom, which results in rapid flooding with only a short time frame for the communities to prepare. This is especially a challenge for the Cul-de-Sac catchment, which has the only two road connections between the Capital Castries in the north and the communities and the main airport in the south.

To address the flash flood challenges, National Emergency Management Organisation (NEMO) is interested in the possibilities of flood early warning systems on the island. As a case study for a hydro-meteorological flood warning system, the flood dynamics for the Cul-de-sac catchment needs assessment.

There is currently only one physical early warning system in Saint Lucia. It is located in the Choc watershed between Castries and the touristy Rodney Bay north of the Capital. It was installed by Japan International Cooperation Agency (JICA) in 2012. During the December trough in 2013 it was not functioning, because the batteries had been stolen from the device.

NEMO is interested in the possibilities for better flood warnings in Cul-de-Sac, near Bexon, because previous flood events have been very severe in those areas and affected the mobility on the island greatly.

1.1.1. Objectives and research questions

The objective of the research is to evaluate a theoretical rain gauge based warning detection system versus a meteorological indicator based weather forecast model.

Objective 1: Compare the rainfall of the Hydro-Estimator with the rain gauge measurements on Saint Lucia:

- Is there a systematic bias (difference) in the HE data compared to RG data?
- Is there spatial variation in the correlation between the rainfall products?
- Is there a temporal variation in the correlation between the rainfall products?
- How does the applied interpolation technique influence the rainfall layer?
- Are there differences in correlation between the rainfall products between different storms?

Objective 2: Evaluate the suitability of the rainfall products for flood modelling

- Which major flood events have happened on Saint Lucia?
- Which major flood events have taken place between 2007 and 2014 which is the overlapping time span with available data for the Hydro-Estimator and the rain gauges.
- How do model runs using the 5 minute and 1 hour RG data compare to runs performed with the HE data?
- How does rainfall data influence the flood depth and flood time?
- Do the results differ for different storms?

1.2. Study area

The study area covers Saint Lucia, in the Caribbean Sea, with focus on the two small river catchments at Anse la Raye and a bigger one at Bexon and Marc. A full map can be found in appendix A.

The historic events has mainly taken place during or after the hurricane season, which is from the 1st of July to the 30th of November.

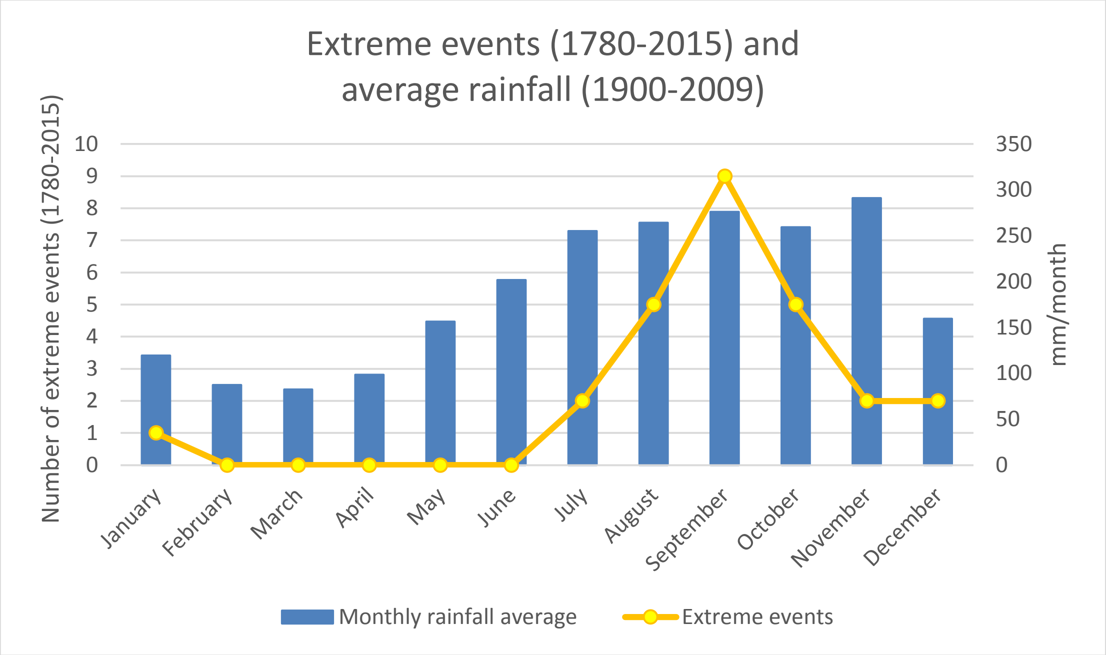


Figure 1 - extreme events and rainfall on Saint Lucia in the Caribbean Sea (The World Bank, 2015) and (Dillon Consulting, 2014).

The tropical climate and steep terrain on Saint Lucia means high precipitation rates, with a yearly average of 2249 mm. The hurricane season runs from the 1st of June to the 30th of November, which also are the months with the highest precipitation.

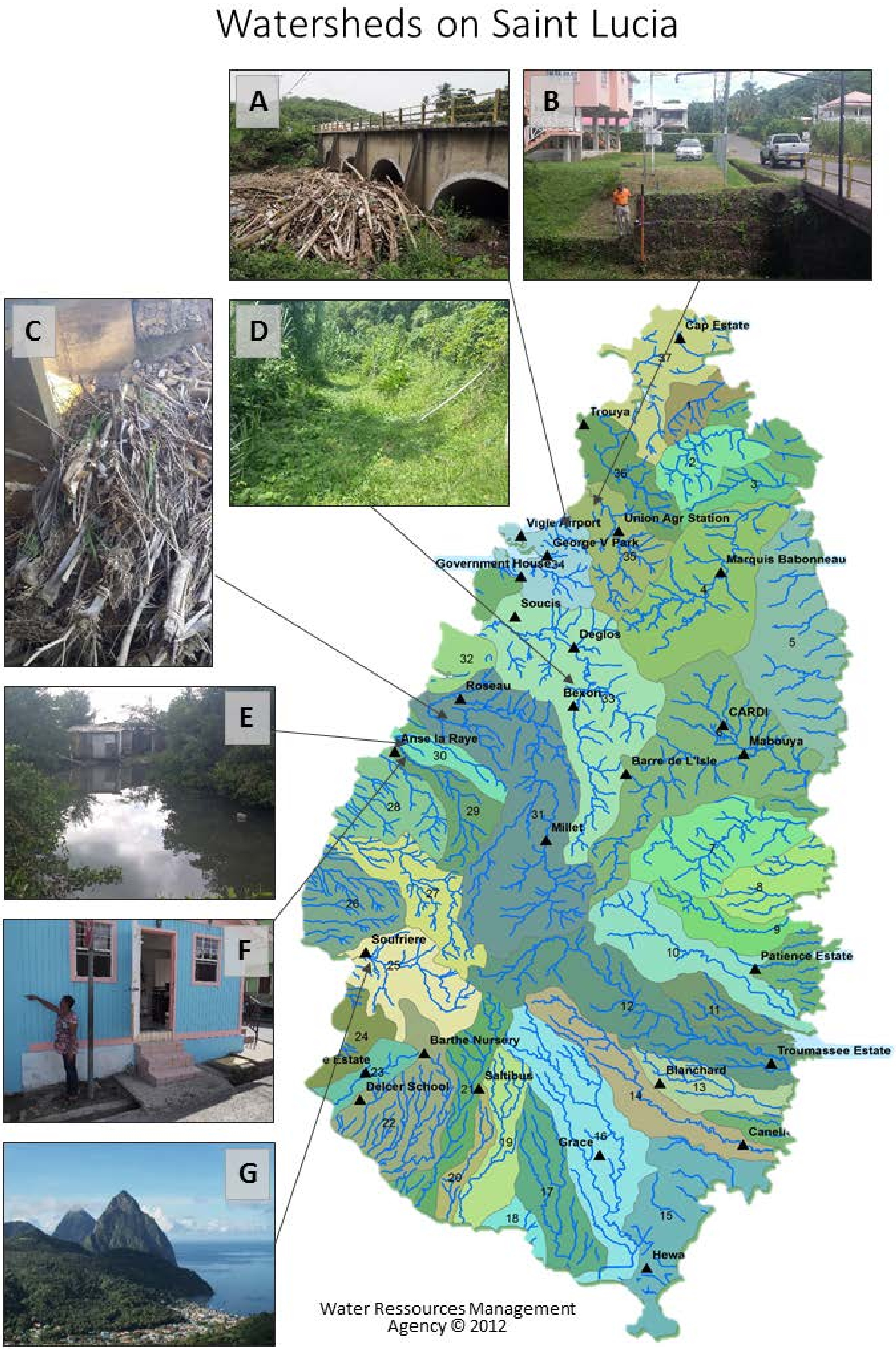


Figure 2 – pictures from the fieldwork: A) debris at Choc river, B) flood warning system, C) debris near Roseau, D) overgrown cleared sediments from the river, E) river at Anse la Raye, F) flood level Anse la Raye and G) Soufriere. The named triangles represents rain gauges and the differnet colours represents watersheds.

Below are the most significant hydrological disasters in Saint Lucia listed.

Table 1 - know severe flood events. Adapted from (NEMO Secretariat, 2011) and (Dillon Consulting, 2014).

Year	date	Deaths	Damage (million $)	Name (if named)
1780	11-12 Oct	800 Deaths	ND	Great Hurricane
1831	8-11 Aug	10-12 Deaths	ND	Hurricane
1894	3 Oct	11 Deaths	ND	Gales and floods
1897	11 Sep		ND	
1898	11-12 Sep	13 Deaths	ND	Hurricane
1908	25 Sep	1 Deaths	ND	Considerable damage
1921	ND	15 Deaths	ND	Considerable damage
1928	ND		ND	Considerable damage in Roseau
1938	21-22 Nov	120 Deaths	ND	
1939	7 Jan	100 Deaths	ND	Three villages destroyed
1940	7 Aug	ND	ND	Roads swept away. Cul-de-Sac valley particularly badly hit.
1954	12 Dec	ND	ND	Ravine Poisson badly hit by landslides
1960	10 Jul	6 Deaths	$4	Hurricane Abby
1963	24 Sep	ND	$4	Tropical Storm Edith
1966	1 Aug	ND	$4	Tropical depression
1967	7 Sep	18 Deaths	$2	Tropical storm Beulah
1980	3 Aug	9 Deaths	$250	Hurricane Allen
1988	10 Sep	ND	ND	Hurricane Gilbert
1994	9-10 Sep	4 Deaths	$230	Tropical storm Debby (Debbie)
1996	26 Oct	ND	$12	Tropical wave
1998	21 Oct	1 Deaths	$0.62	Tropical wave
1999	19 Nov	ND	$16.9	Hurricane Lenny
2002	22-23 Sep	ND	$20.3	Tropical Storm Lili
2003	7 Jul	ND	$3.07	Tropical Wave
2004	9 Sep	ND	$6.98	Hurricane Ivan
2007	17 Aug	1 Deaths	$6.4	Hurricane Dean
2010	30 Oct	14 Deaths	$900	Hurricane Tomas
2013	23-24 Dec			December trough

1.3. Fieldwork

The fieldwork took place on Saint Lucia in the Caribbean Sea from the 20th of September 2014 to the 18th of October 2014. Contact to the local authorities was established through the CHARIM project. On arrival, a meeting and presentation was hosted by the local authorities to present the project and the thesis topics, which would be used as extra case studies for the project. We had presentations at the Ministry of Physical Development, Housing & Urban Renewal (MPDE) and at the Ministry of Infrastructure, Port Services and Transport (MIPST).

To get a better understanding of their data management in relation to planning, we met with the Survey and Mapping office at MPDE, where it became apparent that most of the data management in the planning department is done by physically updating the old paper maps. GIS data does exist, but the impression was that it only was used to a limited degree in the everyday planning tasks.

At MIPST, we became aware of a digitizing project which was updating the current GIS products for the island. Unfortunately it was only a pilot project so far and covered around 20% of Saint Lucia. The project was mainly updating infrastructural elements like road names and driving direction. However, it also included information on landslides along the road. A file with data for bridge properties and bigger culverts was collected, but the locations were unfortunately only defined as the distance driven along the road, which did not give a good enough indication of the actual location of the road elements. Some visits to the bridges with MIPST showed a limited effort to remove debris at the bridges though we already were in the middle of the rainy season (Figure 2 – A and C).

The Water Resources office was visited to obtain hydrological info. We obtained data from the rain gauges and their locations. A request was also made for the discharge measurements for the rivers, however these turned out to be limited and unsuitable to calibrate for extreme events. We also got a map of rivers and channels, which mainly appeared to be directly derived from the DEM. Some extra digitized channels did exist, but not all river mouths matched the actual river mouth location.

To get an understanding of the disaster management system on Saint Lucia, meetings were hosted with the National Emergency Management Organisation (NEMO). Here we got an agreement to visit three of the local Disaster Communities most exposed to flooding: Canaries, Anse la Raye, and Bexon. We also got an agreement about visiting the only currently installed flash flood warning system on Satin Lucia at the Corinth Grand Riviere north of Castries (Figure 2 - B).

The Disaster Communities gave a tour of the neighbourhood where they indicated the water levels on the buildings which were measured in relation to the ground level (Figure 2 - F). The low lying area in between the two rivers, at Anse la Raye, makes it very prone to even small flood levels (Figure 2 - E). Existing mitigation work which had been breached during the most recent flood events was also showed. People's memory was best for the most recent flood event, and limited for events dating further back.

2. LITTERATURE REVIEW

Flood management depends on cooperation between many unique departments with different specialisations, a complex interaction between policy makers, planners, hydrologists and meteorologists. An effective flood management system relies on good cooperation between these departments. The Flash Flood Guidance (FFG) and Flash Flood Threat (FFT) are the two key concepts within the Flash Flood Guidance System (FFGS). The FFG is the rainfall needed of a given duration over a small basin to create a minor flood at the outlet of the stream basin. The FFT is the amount of rainfall for a given duration in excess of the corresponding FFG value (WMO, 2013a).

2.1. Precipitation and tropical weather systems

Since 1842, 15 hurricanes have passed within 65 nautical miles of Saint Lucia according to the historical record from National Oceanic and Atmospheric Administration (NOAA). Most recently, Hurricane Thomas in 2010 and Hurricane Dean in 2007. Tropical and subtropical storms have occurred 42 times within the last 150 years (NOAA, 2015).

2.2. Flash flood forecasting

The main reason for flood forecasting is to increase the lead-time for issuing warnings to prepare for the flood event. Depending on the type of event the lead-time will differ. A number of countries does already have implemented forecasting, monitoring, and warning systems. The European Flood Awareness System (EFAS) is an example of an integrated system which provides 3-10 day forecasts in a 5 km grid in Europe (Thielen, Bartholmes, Ramos, & de Roo, 2009). EFAS is however focussed on bugger river systems. Specifically on flash floods in Europe the HYDRATE project has been working on enhancing the capabilities of flash flood forecasting for ungauged river networks (Borga, Anagnostou, Blöschl, & Creutin, 2011).

After the earthquake in Haiti, January 12 2010, a Haiti-Dominican Republic Flash Flood Guidance System (HDRFFGS) was implemented as a part of the relief efforts in July 2010. In October the same year Hurricane Tomas hit. An evaluation of the flash flood warnings based on the Hydro-estimator in Haiti after hurricane Tomas showed good results (Shamir et al., 2013). The current system is delivered as an experimental advisory product with 3-hour mean area precipitation, modelled average soil moisture for every hour and a flash flood guidance indicating the needed rainfall, for bank full flows at the mouth of the catchment.

The development of a world wide FFGS was taken a step closer in February 2009 with a memorandum of understanding (MOU) between WMO, NOAA, U.S. Agency for International Development/Office of U.S. Foreign Disaster Assistance and the Hydrologic Research Center. So far, Haiti and the Dominican Republic had the FFGS implemented under the MOU as the only nation in the Caribbean Sea (WMO, 2013a). An evaluation of the real time forecasting was made for the FFGS in Haiti based on Hurricane Tomas in November 2010. It highlighted awareness of the shortcomings of the forecasting and the precipitation measurements by satellite, which resulted in an underestimations of the flash flood impacts. It displays a need to include the uncertainty of the forecast in the delivered real-time forecasting products (Shamir et al., 2013). Other countries in the region uses the flash flood guidance as well. In cooperation with NOAA and USAID the Central America Flash Flood Guidance (CAFFG) has been set up to cover Belize, Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua, and Panama (Hydrologic Research Center, 2004).

Trends are going towards a more global early warning system (EWS). The available remote sensing products from satellites plays an important role in the possibility of early warning. Meteorological satellites play a crucial role in weather forecasting e.g. the geostationary satellites METEOSAT, GOES 8 and 10, GMS, the Indian INSAT and the Russian GOMS as well as the polar orbitals such as SSMI and NOAA (NOAA 15). When looking at storms extra parameters are necessary compared to ordinary meteorological satellites. Example surface temperature, air humidity, surface wind speed, rain estimates. For the Caribbean, and the tropical region in general, especially TRMM is important, besides DMSP/SSMI, TRMM, ERS, QuikScat, AVHRR and RADARSAT. The radar in the TRMM is especially important to assess how the intensity of the tropical storms varies spatially (United Nations Environment Programme (UNEP) Global Environmental Service (GEAS), 2012). The TRMM is used for a global heavy rain, flood and landslide estimate.

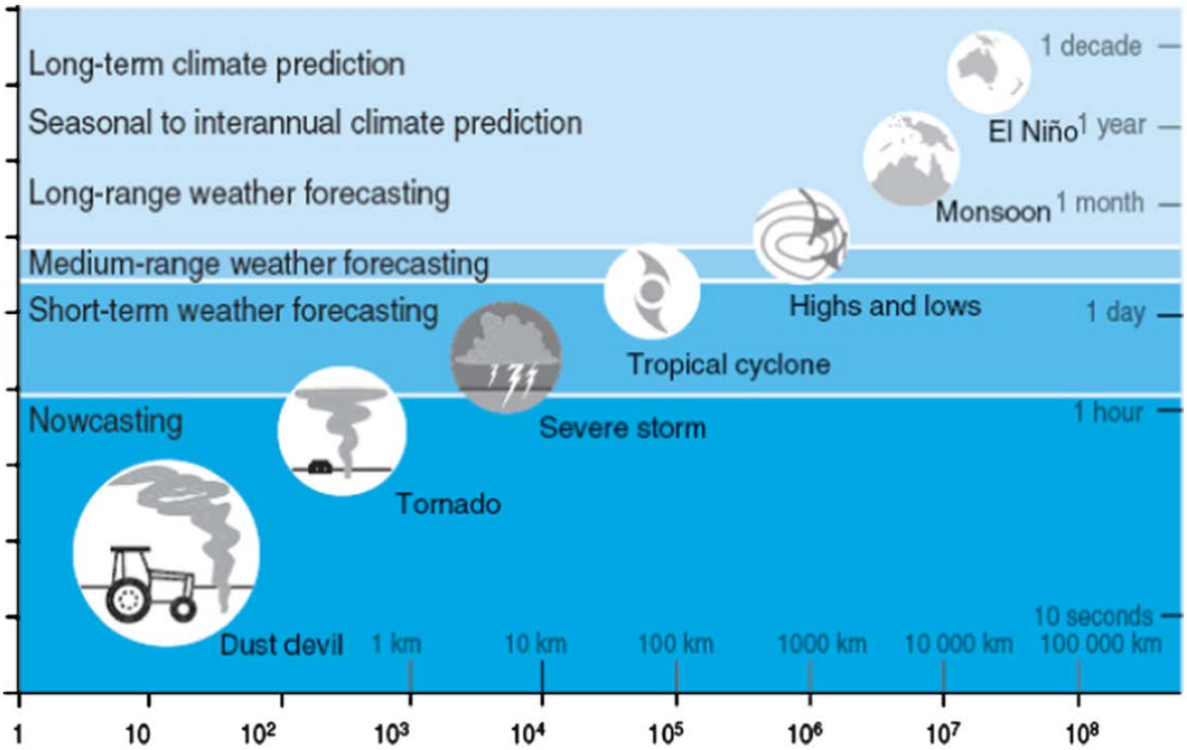


Figure 3 - the relation between the area of impact and the early warning time (United Nations Environment Programme (UNEP) Global Environmental Service (GEAS), 2012).

Most of the flood causing rainfalls in Saint Lucia (Figure 3) are severe storm or tropical cyclones (Hurricanes), but though they usually are spotted on meteorological satellites days in advance, it can be difficult to estimate the exact amount of rainfall.

2.3. Flash Flood Guidance

The flash flood guidance (FFG) used by NOAA uses the rainfall forecast for the following day, and runs it for assumed durations of 1, 3, 6, 12 and 24 hours, as an indicator of the likelihood of a flash flood event to happen within the next day (Norbiato & Dinale, 2009). The approach appears less data intense and require less access to advanced technology than other real time monitoring systems like the high-resolution and quantitative precipitation forecast in Taiwan, which has a close to real time warning update every 10th minute based on radar and rain gauge measurements delivered in a 500 – 1000 meter resolution (Navon, 2009).

For Haiti in the Caribbean a flash flood forecasting system based on the FFG is in use and can delivers up to 36-hour forecasts for catchments of around 70 km^2. It was evaluated based on the floods created by Hurricane Tomas in 2010. They have proved to be useful in understanding the spatial distribution of the flooding, but also highlighted the need for explaining the uncertainties related to the forecast product (Shamir et al., 2013).

To use the FFG, a continuous hydrological model is required for the initial soil water content. It could also be replaced with a more scenario based approach, assuming different initial soil saturation stages. The FFDI is seen as a possible step towards creating a European protocol for flash flood warnings (Borga et al., 2011). The success rate of the FGG can be based on historic meteorological forecasts (if available) or using the actual rainfall data, assuming a perfect forecast. For comparison purposes, an optimised location of a river level sensor will be assessed to compare to possible differences in warning time and success rate for the physical river level sensor versus the hydro-meteorological warning approach.

Flash floods are frequently described as a rapid increase in water level. It is usually related to heavy rainfall, but can also be related to dam failures, blocked rivers or drainage issues in cities (Sene, 2013).

Looking at flash floods there are four main phases, which they can be described: monitoring, forecasting, warning and preparedness (Flash flood forecasting and warning p. 12) .

Within NOAA they work with first the hydrologic outlook, the flash flood watch and flash flood warning. Thereafter there is the flood statement where a decision is made about the possible extension and status change of the flood warning.

2.4. Satellite and precipitation data

Accurate precipitation data with a high temporal resolution is important for precise flood modelling and forecasting. Different means of data acquisition can be used for remote sensing or direct collection of rainfall. Some important aspect to be aware of when looking at remote sensed precipitation products are the capture to product time and the temporal and spatial resolution. Though some satellite products can deliver data with daily or hourly precipitation measurements, the data is not delivered as a live or near-live product.

Remote sensed precipitation is usually measured based on ground based RADAR and satellite data. There are different types of satellite products with a variation of temporal and spatial resolution.

Satellite information can also be divided in two major product types. Raw precipitation estimates and ground validated satellite products. The TRMM has two different products. A precipitation estimate and a ground validated product. The challenge with precipitation is to get an accurate estimate in areas where there are no stations for ground measurements. By nature, the rainfall station represents point data. It is therefore important with a good interpolation technique. The above satellites can be good to get precipitation estimates for regions where there are no precipitation ground measurements.

Global rainfall products based on the geostationary and polar orbiting satellite constellations, are important for flood monitoring and prediction. The Hydro-Estimator (HE) by NOAA/NESDIS gives hourly rainfall estimates. The Tropical Rainfall Potential (TRaP), also by NESDIS, gives 24 hour precipitation forecasts of landfilling tropical cyclones. The HE product is delivered in 4-5 km resolution with worldwide coverage every hour. It is based on a combination of top of cloud temperature estimates compared with the surrounding pixel temperatures (Kuligowski, 2006).

An evaluation of the accuracy of remote sensed precipitation from Typhoon Maroka in Taiwan showed a general underestimation compared to the rainfall measured by rain gauges. They conclude that ground based radar gives the best remote sensed estimate though it is -18% to -36%. The satellite CMORPH had -61% and PERSIANN-CSS had -28%. However, they still find the gauge station to deliver the best rainfall product (Chen et al., 2013).

2.4.1. Hydro-Estimator background

The Hydro-Estimator has been evaluated in a study in north-west Mexico and another for the United States, Northen Europe and Australia. The study in Mexico evaluated the Hydro-Estimator with and without orographic correction for a two month period from August to September in 2002 and 2003. Some elevation dependent biases were found, which were characterized by underestimation of light precipitation at high elevations and an overestimation of the occurrence of precipitation at lower elevations. The elevations were in six classes of 500 meters from 0 to 3000 meters above sea level, and a temporal resolution of one hour was used for the Hydro-Estimator. There are significantly more events with lover precipitation than high precipitation within the studied period. An important result is that the Hydro-Estimator significantly underestimates the rain probabilities for threshold values greater than 37 mm/hour in 2002 and 33mm/hour in 2003. Their findings suggests a continued improvement of the orographic correction used by the Hydro-Estimator to advance the quantitative precipitation estimation in complex terrains (Yucel, Kuligowski, & Gochis, 2011).

The satellite precipitation products are in general most accurate during the summer periods at the lower latitudes. When the precipitation regime trends towards deep convection the satellite estimates becomes more accurate. It is mentioned that small local islands often has a strong local influence on the precipitation compared to estimates over the open ocean. Algorithms which only uses IR (which includes the Hydro-Estimator), underestimated the mean summer rainfall with up to 50% in the eastern United States and overestimated with 50%-100% in the entire United States during winter (Ebert, Janowiak, & Kidd, 2007).

3. DATA AVAILABILITY AND PREPARATION

The data limitations and the availability will be explained in this chapter. Starting with the rainfall and river discharge data and ending with the base data for the flood model.

3.1. Rainfall products

In order to perform flood modelling, precipitation data is needed. Two different rainfall products have been selected to be evaluated for a flood warning system. Ground data from rain gauges and satellite estimates from the Hydro-Estimator. A priority for the satellite based product is that it should be a near real time product, otherwise it does not fit the purpose of flood modelling. There are inconsistencies between the two products from the, inconsistencies exist between these two sources. In this chapter a comparison will be made between the different sources and a method will be developed how to estimate the correct amount of precipitation for the flood modelling.

Satellite bias is the fact that this data Hydro-Estimator only uses the top of cloud temperature in relation to the surrounding pixels. If no correction is conducted it will overestimate the amount of flooding.

The ultimate aim of this work is to see how the flood output base on the two satellite data sets compares and see if there are trends which makes bias correction possible for the Hydro-Estimator.

3.1.1. Data availability for rain gauges

The rain gauge data has been retrieved from the Department for Water Resources in Saint Lucia through the CHARIM project. One dataset consists of daily measurements from 1955 to 2005, with up to 19 rain gauges. The first two rain gauge with tipping buckets which records minute data are set up in 1998. The number of rain gauges with minute data is increased in 2003 after a period with pilot measurements.

For the December trough 15 rain gauges are used, which record rainfall every minute.

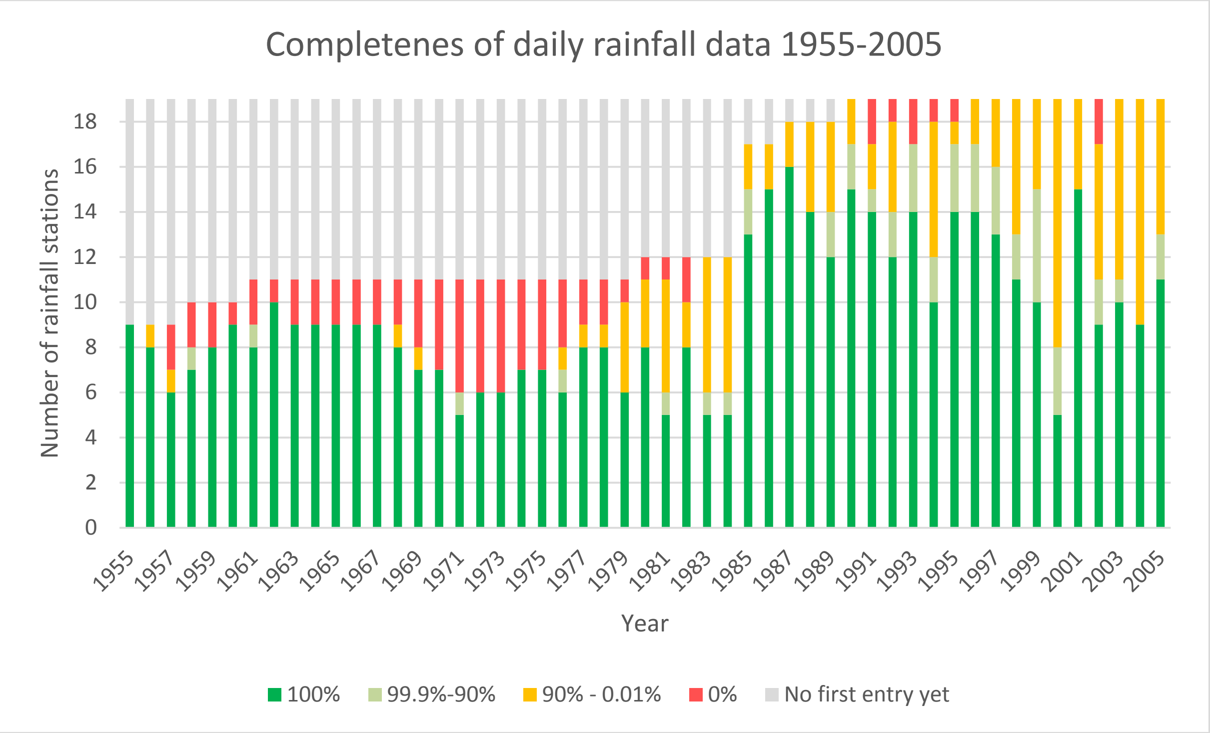


Figure 4 - data completeness from rainfall stations on St. Lucia 1955-2005.

The data set for the daily rainfall contains error codes to identify whether zero rainfall values represents days with no rainfall or a malfunction. The same is not the case for the newer stations with tipping buckets. It only records every time there has been at least 0.2 mm of rain, but the data set does not provide error codes to identify down time. The evaluation of available data is therefore based on counting the months with records instead of counting percentage of days, which is the case for the daily rainfall dataset.

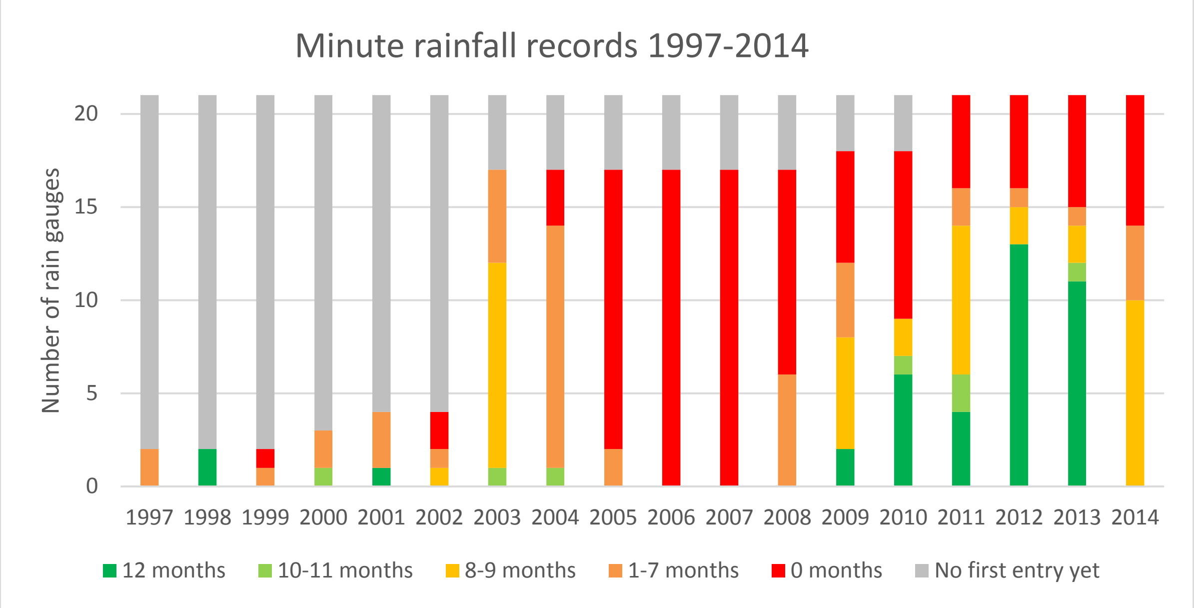


Figure 5 - data completeness based on the rain gauges with minute records. Months are counted if they have at least one rainfall entry. For 2014 records were only available from January to July.

The three most recent severe tropical weather events are only partially covered by the data. The December trough in 2013 has available rainfall record from 15 rain gauges and Hurricane Tomas in 2010 has records from 4 rain gauges, though the graph showing the rainfall records indicates that 6 stations have at least one rainfall from all months. Hurricane Dean in August 2007 is not represented at all in the records.

3.2. River level and discharge

To evaluate how accurate the flood model reflects reality, ground truth is required. For rivers, it would be preferred to have automated measurements of water level, velocity and discharge with a high continious temporal frequency. For Saint Lucia river measurements are only available to a limited extent. They are limited in duration and frequency because they are done manually. At best they are done on a bi-weekly basis.

The watershed Cul de Sac (33) has 302 discharge measurements from Bexon, Ferrands, Deglos and Miama. The maximum number of yearly measurements were in 2013 with 41.

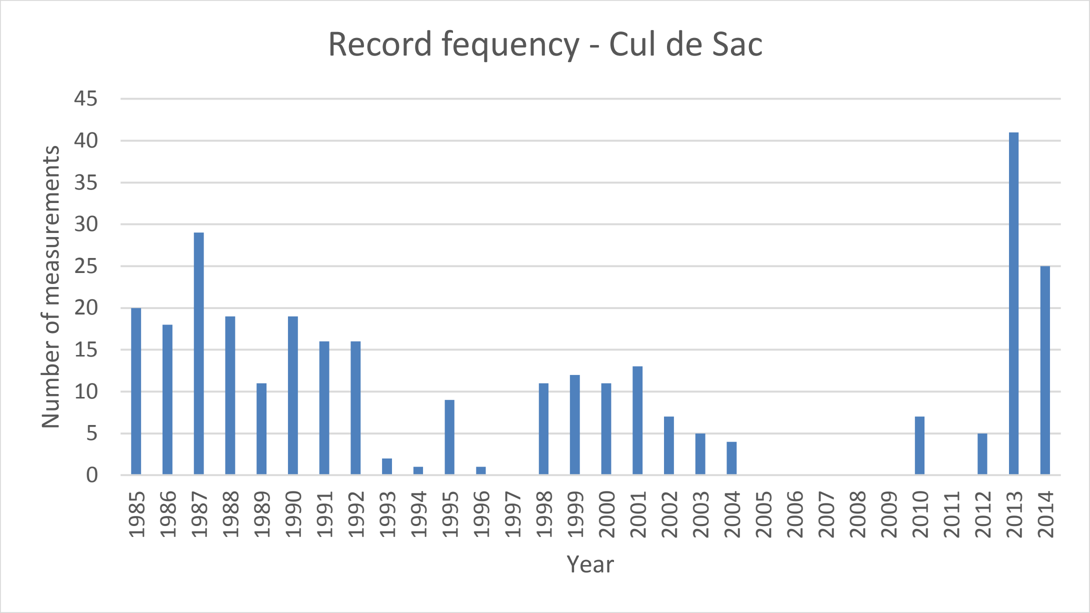


Figure 6 - river discharge measurement frequency for Cul de Sac, St Lucia

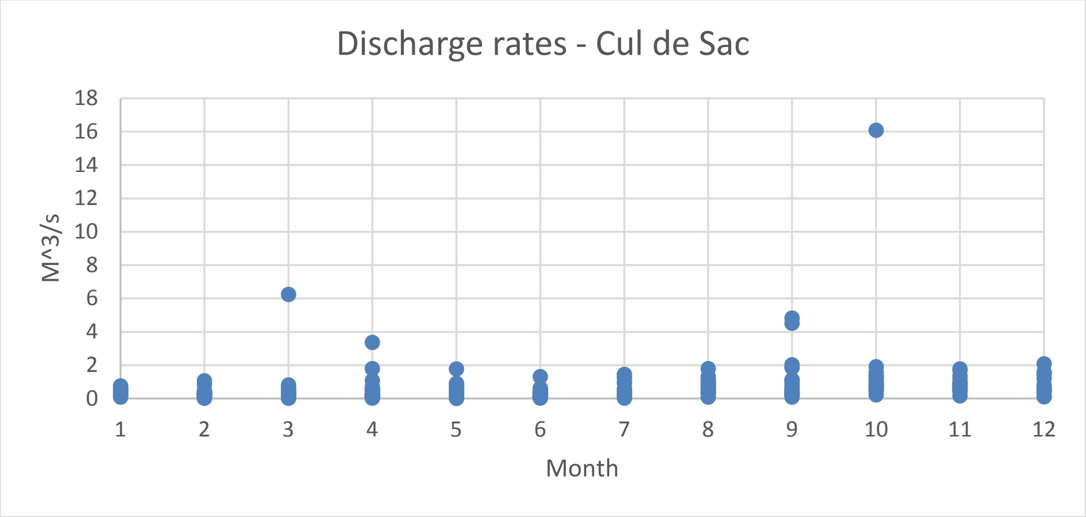


Figure 7 - measured discharge rates for Cul de Sac, St. Lucia

Most of the discharge rates are below 2 m^3/s. The highest measurement is 16.0 m^3/s taken at 10:00 am 28/10/1985. This is also the highest recorded discharge of all the watersheds. On the day of the highest discharge measurement (16 m^3), the highest recorded daily rainfall in Cul de Sac was 90.1 mm, but the rainfall is only recorded per 24 hours, so it is not possible to make a good temporal correlation with the river discharge. This is significantly lower than the extreme rainfall events I will assess. For these reasons, the river measurements are not useful to help calibrating a flood model for extreme rainfall events.

Table 2 - the recorded rainfall on the day of the highest measured river discharge at Cul de Sac, St. Lucia

Day	Month	Year	Soucis	Barre De Lisle
26	Oct	1985	11.3	3.1
27	Oct	1985	3.2	11.5
28	Oct	1985	90.1	43.5
29	Oct	1985	32.9	6.1

The watershed G. Riviere at Anse la Raye has 64 measurements from 1995 to 2014.

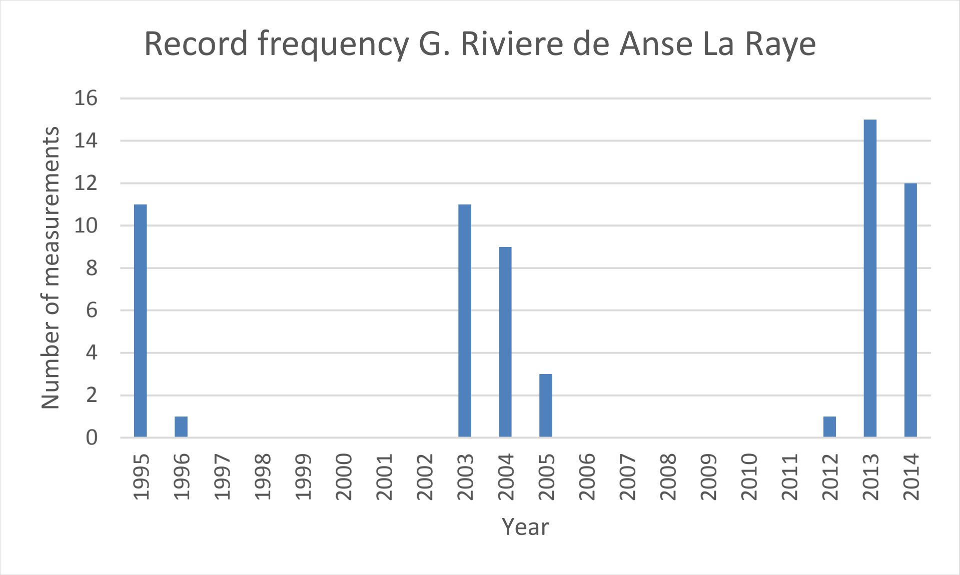


Figure 8 - river discharge measurement frequency for G. Riviere de Anse La Raye, St. Lucia

The highest measured discharge rate at Anse la Raye is 0.96 m³/s. The other watershed at Anse la Raye only has one record and has not been included.

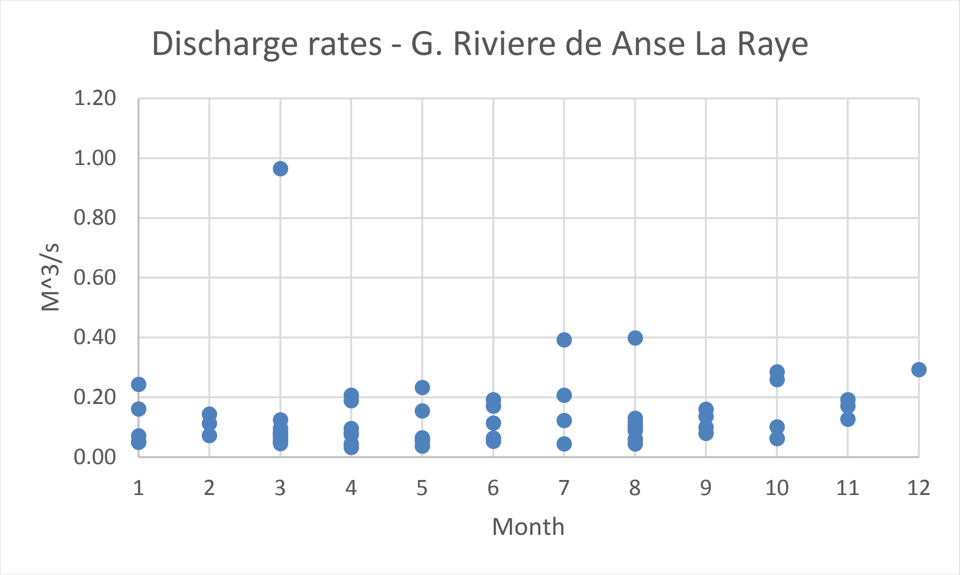


Figure 9 - measured discharge rates for G. Riviere de Anse La Raye, St. Lucia

The measurements from Anse La Raye represents very low discharges and can be seen as base flows which is not useable for the calibrating flood models for extreme events.

Since September 2012 the rainfall station in Deglos in the Cul de Sac watershed has recorded the water level in the river and minute rainfall data. That makes it possible to make a comparison between the timing of the rainfall and the changes in river level. Unfortunately, Barre de L'Isle further upstream does not have record from December 2 2013 and onwards.

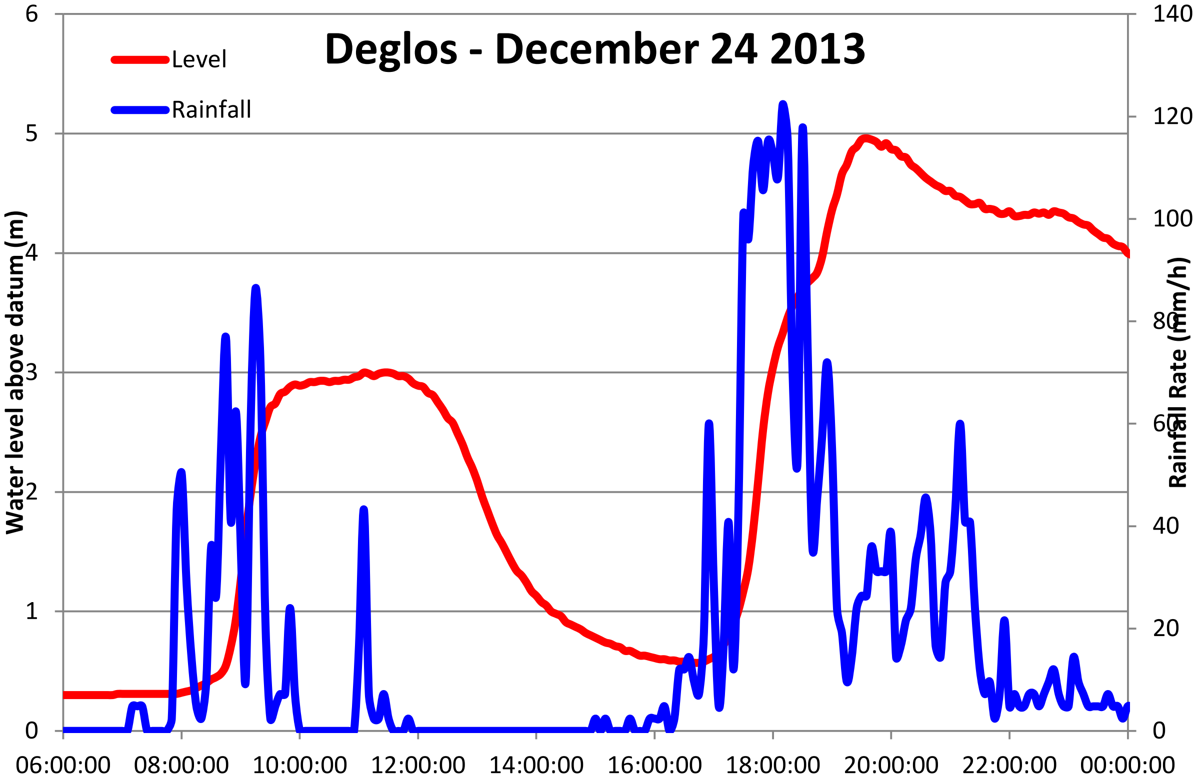


Figure 10 - water level and rainfall rate for Deglos at the flash flood December 24 2013

4. METHODS

4.1. Overall flow chart

Below is the general flow chart of the proses for the rainfall preparation and the flood modelling.

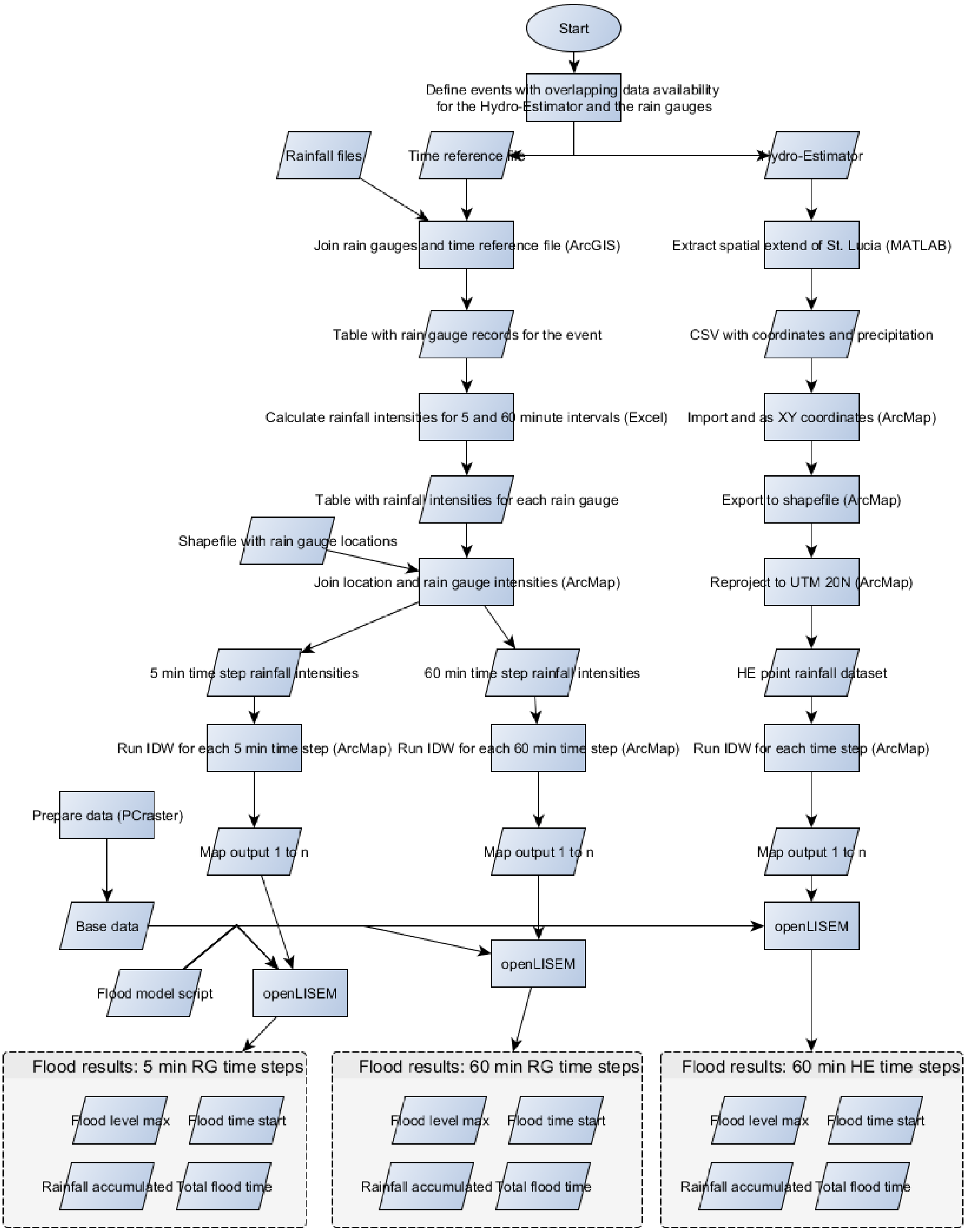


Figure 11 - flow chart of the main components of my workflow from the rainfall to flood model output.

4.1.1. Rain gauges

First the availability of data for the rain gauges was checked including their temporal resolution. Rainfall data was received both from the Department of Water Resources and from the meteorological institute. Based on the known historical rainfall and reported extreme events from NEMO the December trough in 2013 and Hurricane Tomas in 2010 were identified as the only extreme event with overlapping data availability for the Hydro-Estimator and the rain gauges.

The rainfall is recorded with a maximum temporal frequency of a minute. The precision is 0.2 mm per tip and tips are accumulated for every minute. There are only records if there has been rainfall, which makes it difficult to identify now rain periods from downtime periods. To match all the records from the rain gauges on a temporal basis a reference list is created for the two extreme rainfall events with the time and date as an identifier. All the rain gauges are joined to the reference list to select the rainfall record within the time defined for the event.

To generate hourly rainfall intensities to compare with the Hydro-Estimator the rainfall is accumulated on and hourly basis. The rainfall records are also accumulated on a 5-minute basis, and multiplied with 12, to define the hourly rainfall intensities for the 5-minute intervals.

4.1.2. Hydro-estimator

NOAA Center for Weather and Climate Prediction makes hourly data sets available from the Hydro-Estimator. The ACSII files are described as a matrix of 8001 columns and 3111 rows with world coverage from 60N to 60S. In practise the files are forward running rows 3111 x 8001 = 24,891,111 and the precipitation and the corresponding coordinates are in two different files. There is one reference file with coordinates which refers to all the files with the precipitation entries (NOAA Center for Weather and Climate Prediction (NCWCP), 2014).

The size of the file makes it a challenging data set to handle both regarding the 24.89 million rows and the size of around 170 MB per file, which is one hour of rainfall. To pair up the coordinates and the rainfall a conditional statement is made as follows to identify the desired rows.

$$Degrees\ North = \ Coloumn\ 1 > 12.8\ \&< 14.6$$
$$Degrees\ West = \ Coloumn\ 2 > 57.8\ \&< 63.0$$

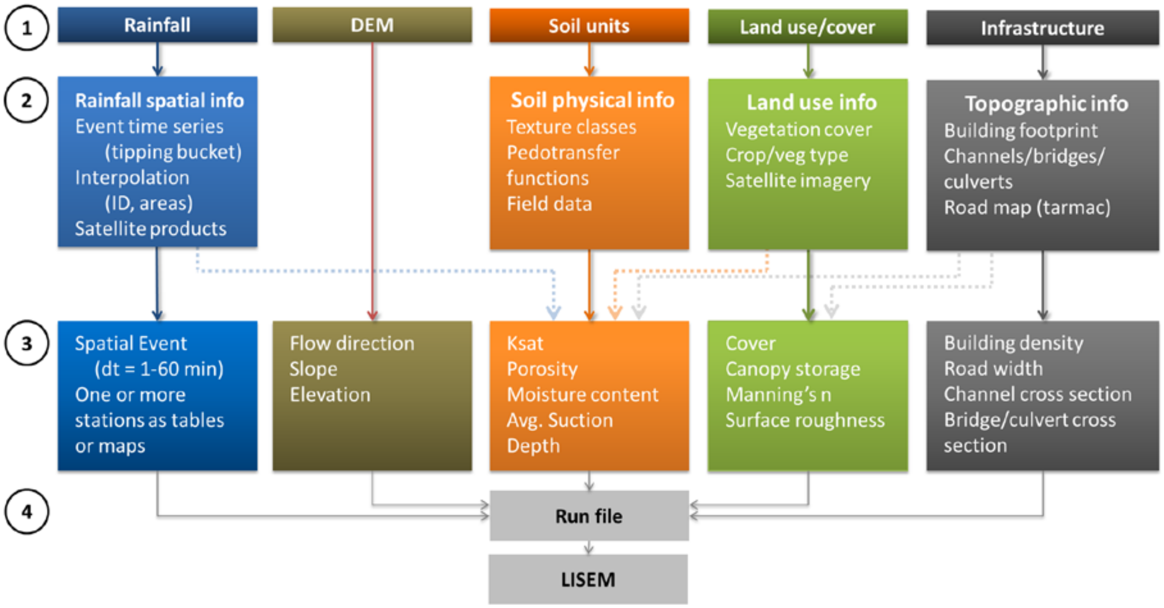
It is important to note that the degrees West is written positive, which is inverse compared to the normal notation. A list with row numbers and corresponding coordinates with corrected longitude (by multiplying with minus one) is exported as a csv-file based on the conditional statement above.

Using the row numbers as identifiers the rainfall with the desired geographic coverage now be extracted. The rainfall is exported to individual csv-files with coordinates based on the hourly temporal resolution of the Hydro-Estimator.

The csv-files are imported to ArcMap and converted to shapefiles. Before converting to raster, inverse distance is performed on the shapefiles.

4.2. Flood modelling

The flood modelling is done with openLISEM, which is based on the known erosion and runoff model LISEM (Baartman et al. , 2012 & Sanchez-Moreno et al., 2012) in combination with the open source 2D flood package, FullSWOF2D, from The University of Orléans (Delestre et al., 2014). The openLISEM model is event based and simulates three flow processes: (1) Overland flow, based on an flow network extracted from the DEM, (2) Channel flow, based on a defined channel network with extra maps defining the channel properties and (3) channel overflow, simulating flood when the channel is full. The flood direction is calculated as a kinematic wave using on a flow direction network following the steepest slope. The required input for openLISEM is rainfall, DEM, soil units, land use/cover, and infrastructure (Figure 11). A limitation of the model is that it does not include evapotraspiration and groundwater flow. The inputs are spatial maps representing the input layers in the desired resolution. (Westen et al., 2014).



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

Figure 12 - inputs needed for the flood model openLISEM (Westen et al., 2014)

All the input used for the model were raster in a resolution of 20x20 meters covering the entire mainland of Saint Lucia. The water flow and rainfall is calculated in steps of usually 1-60 second. The flood runs for the December trough ran with a setting of 60 seconds, but for Hurricane Tomas a setting of 120 seconds was used, after several tries at lower time settings where openLISEM crashed.

4.3. Flood model evaluation

To evaluate the results of the flood model two different data sources are used. River measurements and interviews for flood level assessments.

The three flood maps based on HE, RG60 and RG5 are reclassified and given a new code.

	Hydro-Estimator (HE)	Rain gauge 60 (RG60)	Rain gauge 5 (RG5)	Water level
Reclassification codes	900	090	009	> 0.10 m
	500	050	005	> 0.5 m
	100	010	001	> 1.0 m
	600	060	006	> 1.5 m

	200	020	002	> 2.0 m
	300	030	003	> 3.0 m

The reclassified values are added to generate a map showing the difference in flooding based on the three different rainfall products.

Accumulated	Hydro-Estimator (HE)	Rain gauge 60 (RG60)	Rain gauge 5 (RG5)
Reclassification code	X00	0X0	00X
XXX	X	X	X
XX0	X	X	
X0X	X		X
0XX		X	X
X00	X		
0X0		X	
00X			X
000			

Six different reclassification sets were created based on the maximum flood levels for entire Saint Lucia. The reclassification shows where the flood model outputs agrees, based on the three different rainfall inputs. This gives

5. RAINFALL SCENARIOS AND FLOOD MODELLING RESULTS

To evaluate the difference in flood outcome from the rain gauges and the Hydro-Estimator the flood dynamics for the December trough 2013 and for Hurricane Thomas 2010 will be analysed. For both events a rainfall will be In order to do this chapter will describe both input datasets (4.1), and will compare the data for (4.2) and will come up model with a correction method for the satellite data (4.3).

5.1. Historical review of rainfall extremes

The intensity of the yearly rainfall events differs depending on the location on the island. For two of the stations in the watershed Cul de Sac, the maximum daily rainfall differs with almost 300 mm, for the most extreme events, and around 100 mm for a 5 year event. Only years with at least 95% complete rainfall records has been used.

Berra De L'Isle is located in the most central location on Saint Lucia. The four highest rainfalls in one day are Hurricane Emily in 1987 (464.8 mm), Hurricane Debbie in 1994 (450 mm), Hurricane Tomas in 2010 (403 mm) and the December trough in 2013 (321.4 mm).

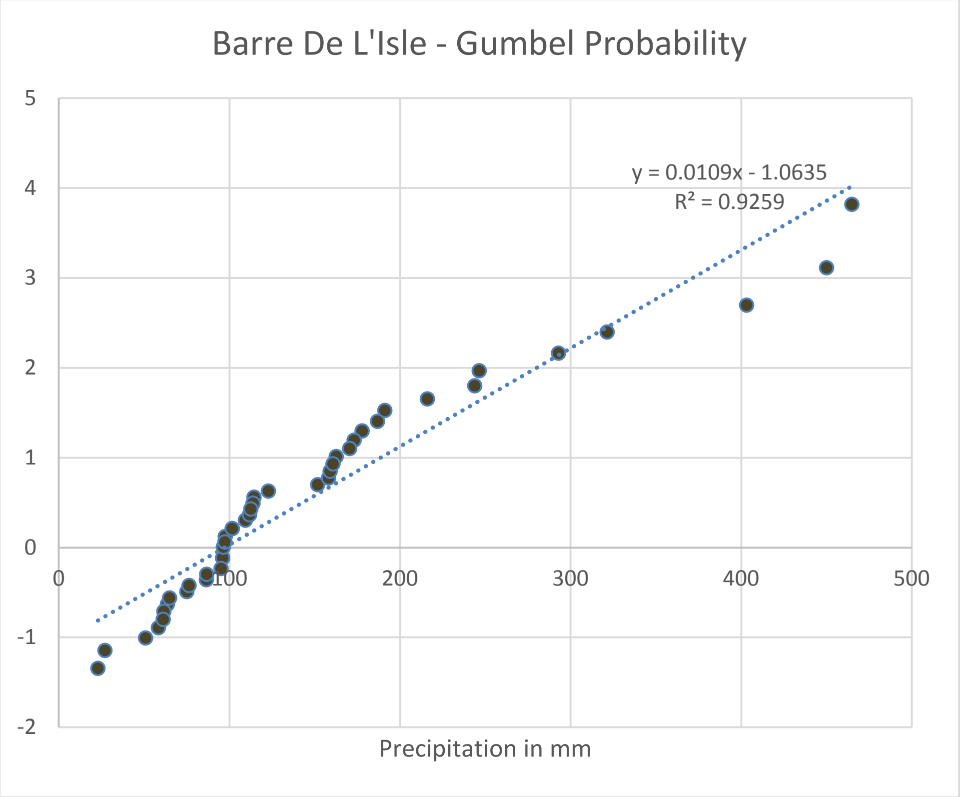


Figure 13 - rainfall return periods for Barre De L'Isle from 1955-2005 for years with at least 95% of the rainfall records. The rain gauge was discontinued since 2005. Therefore data from the two nearest stations Cardi, Bexon and Millet have been added in the period 2009-2013 where data was available.

The result of the calculated return periods (Figure 12) shows that the Hurricane events does not fit that well with the calculated return periods. It could be suggested to calculate the return periods based on the type of weather system, because it looks like the hurricanes does not fit well with the general trend of the smaller rain storms. It should be pointed out that Huricane Dean in 2006 is not included, because no record were found for that year, which would make the return period for heavy rainfall more frequent. Hurricane Ivan in 2004 has records of zero with error codes or daily precipitation of around 1 mm, which is unlikely low for a hurricane pass.

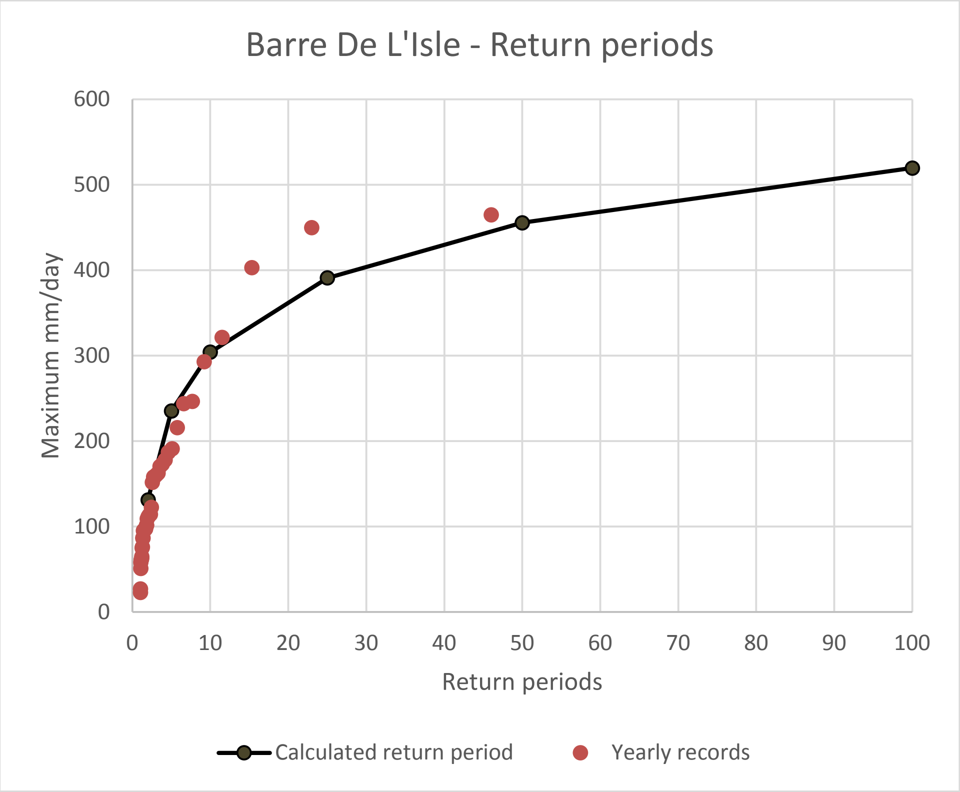


Figure 14 - Calculated return periods compared with the actual records

5.2. Comparison of the spatial distribution of rainfall

The available rainfall gauges differs between the December trough in 2013 and Hurricane Tomas 2010, which makes the comparison challenging. Below is a map with the spatial distribution of rain gauges on Saint Lucia.

For the December trough the best correlation is to the North at Cap Estate, Trouya and Soucis. For Roseau slightly further to the South, the Hydro-Estimator underestimation the rainfall. The same is the case for Soufriere and Union Vale Estate in the Southwest corner. The biggest offsets between the rain gauges and the Hydro-Estimator are at Desraches located at a high elevation of 570 meters to the Southwest. In the South-eastern corner the Hydro-Estimator overestimates the rainfall at Grace, Blancherd and Troumassee Estate. At the East-central part of the Island Cardi has the second biggest offset with an overestimation of the rainfall by the Hydro-Estimator.

Hurricane Tomas does only have three rain gauges with complete measurements for the event. The only rain gauge that overlaps with the December event is Cardi, which again shows a higher value for the HE compared to the rain gauges, though less significant.

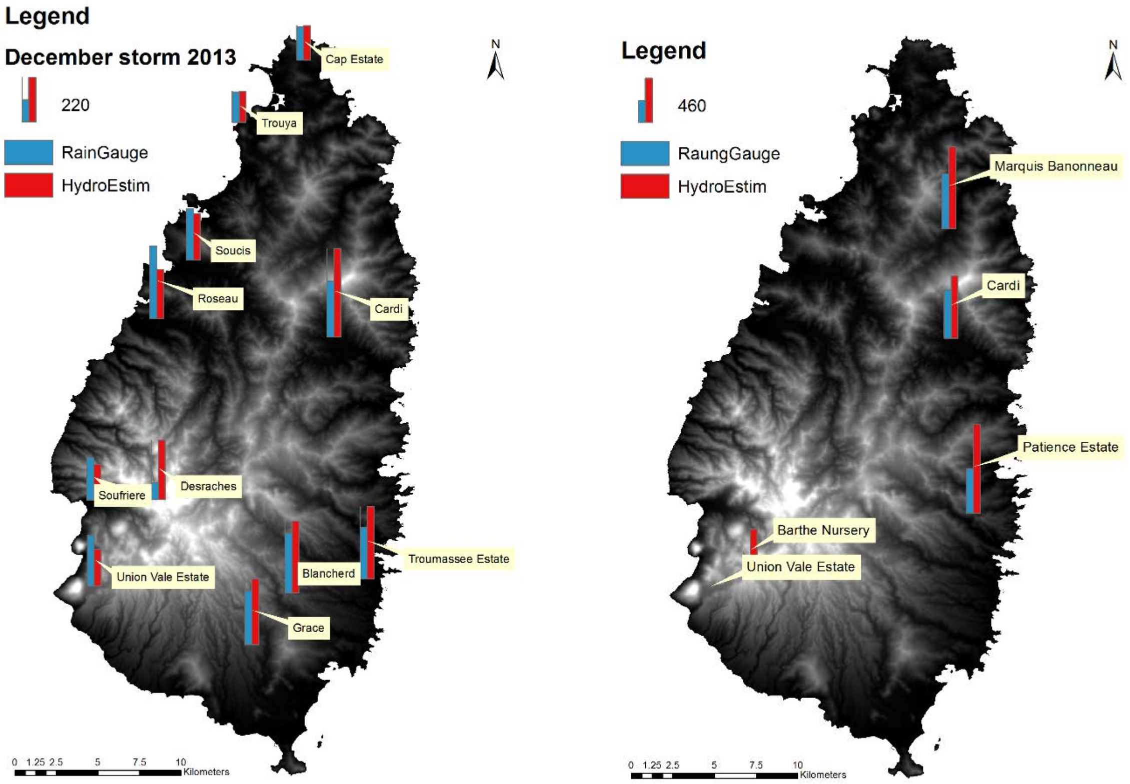


Figure 15 - Location of rain gauges combined with the estimate from the Hydro-Estimator at the same locations in mm for the December trough to the left and Hurricane Tomas to the right. Graph shows the total rainfall for the event in mm. Only a selected number of rain gauges for the December through is showed.

5.2.1. Accumulated rainfall difference

The rain gauges and the Hydro-Estimator (HE) does not show a consistent difference (Figure 14). At six of the positions the HE is highest, at four positions the rain gauge is highest and at one position they are very close to the same. In comparison the average rainfall in December is 160 mm (Figure 1).

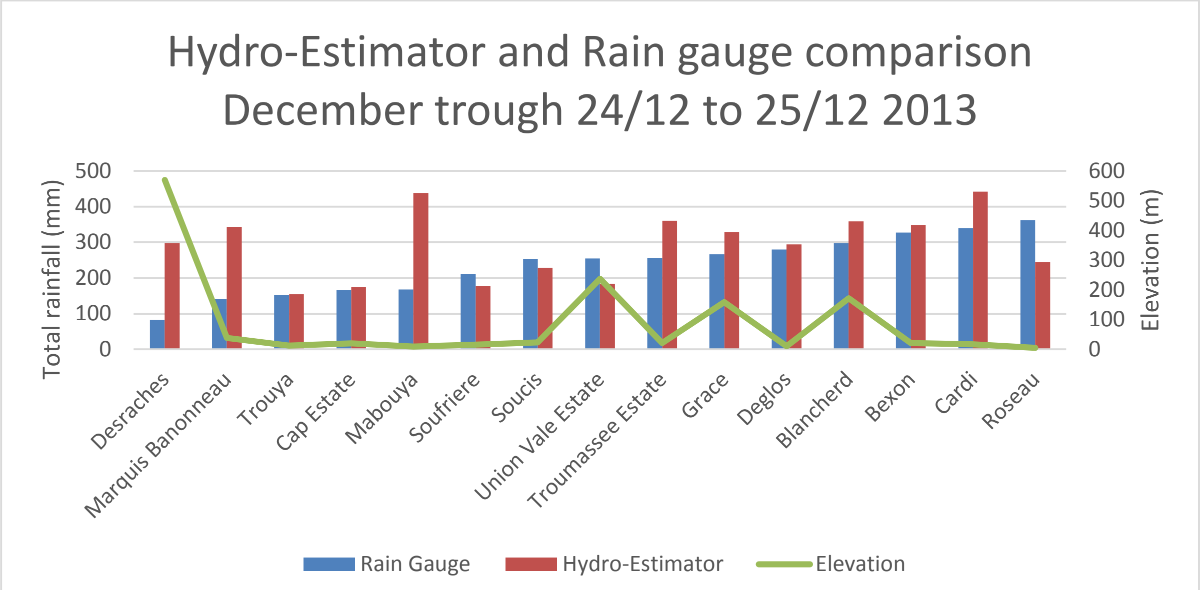


Figure 16 - total precipitation from 6:00 24/12 to 5:59 25/12 2013 including the elevation of the rain gauge. 24 hour comparison.

Hurricane Tomas (Figure 15) has a lot fewer available records and unfortunately only one rain gauge which also is available for the December trough 2013. The Hydro-Estimator is consistently overestimating the amount of rainfall during the event and it is important to notice that Hurricane Tomas, when overestimating, refers to maximum values of 920 mm compared to 440 mm at the December trough. In comparison the average rainfall in October and November is 260 mm and 291 mm (Figure 1).

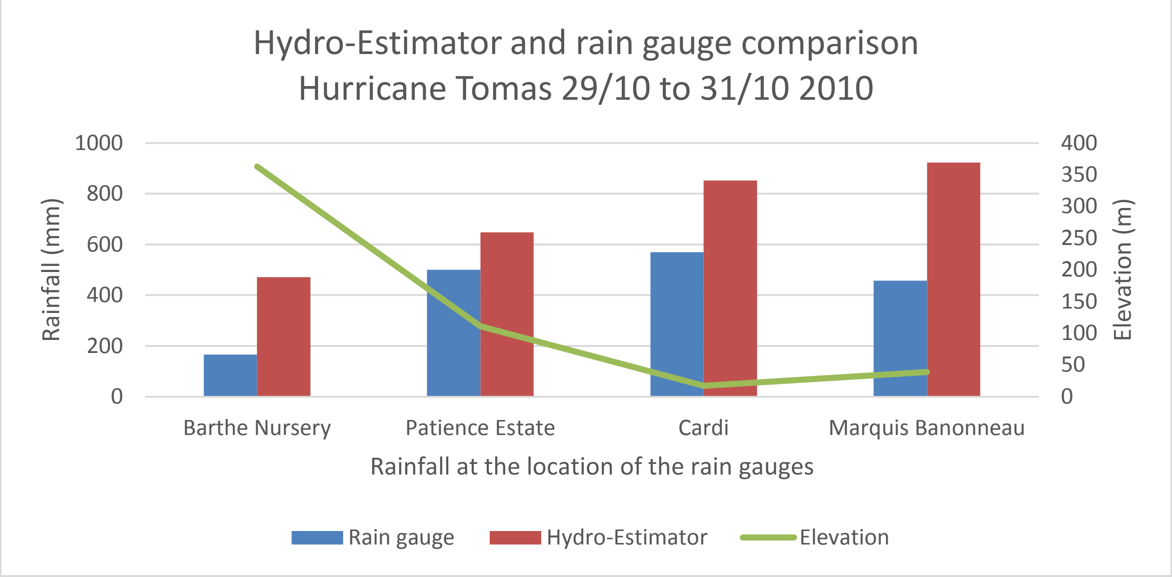


Figure 17 - total precipitation from 21:00 29/30 to 19:59 the 31/30 2010 including the elevation of the rain gauge. 48 hour comparison.

5.2.2. Interpolated accumulated rainfall

The accumulated rainfall used for the flood events for the December trough 2013 and Hurricane Tomas 2010 are showed below based on the Hydro-Estimator and the rain gauges.

The spatial pattern is rather similar, but with only data from four working rain gauges, it is difficult to truly evaluate how well the rainfall pattern of the Hydro-Estimator matches the rain gauges. It is important to notice that the maximum rainfall for the Hydro-Estimator is around 800 mm and almost 550 mm for the rain gauges for Hurricane Tomas it is. the Hydro-Estimator does overall have some rather high overestimates compared to the rain gauges.

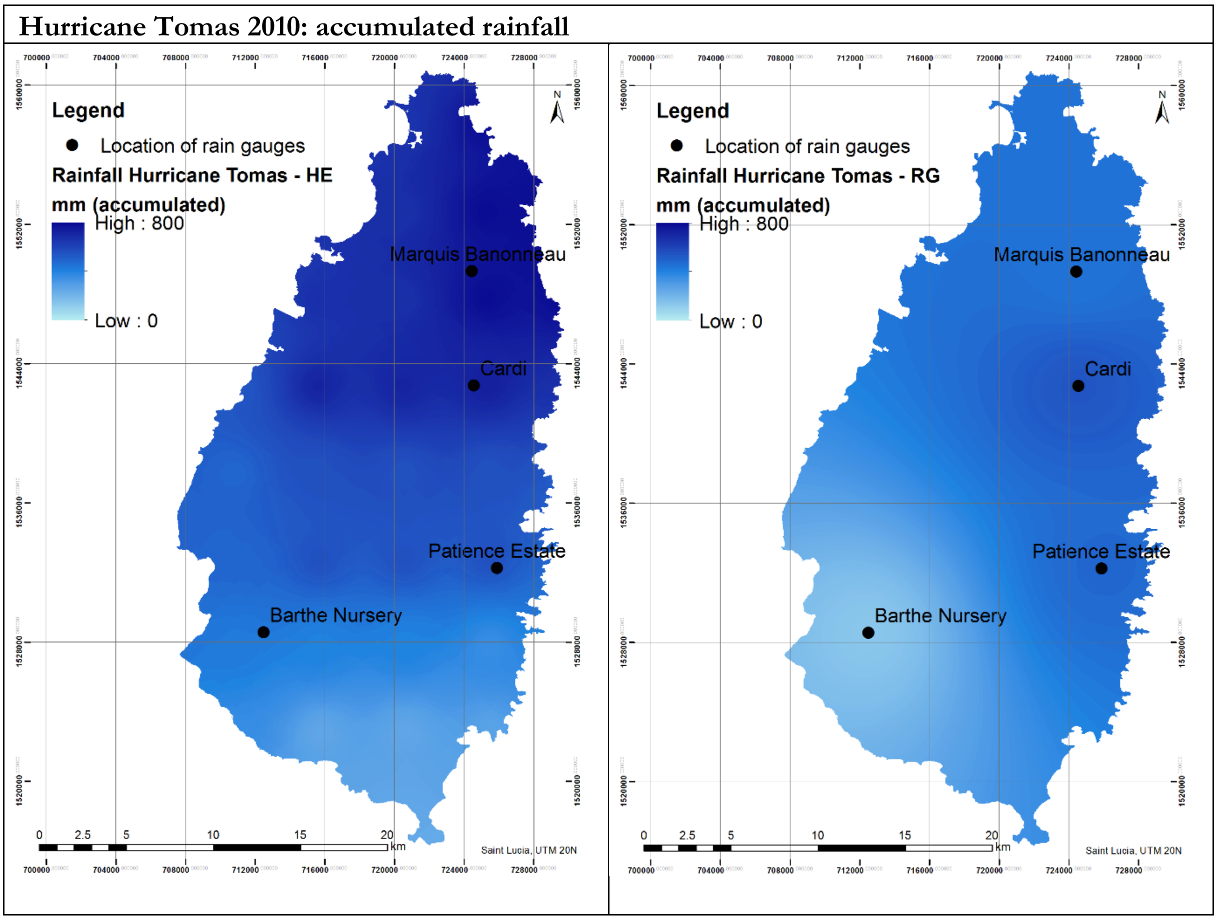

Hurricane Tomas 2010: accumulated rainfall

Figure 18 - Accumulated rainfall used for the flood modelling for Hurricane Tomas. The HE to the left and the RG5/RG60 to the right

For the December trough 2013 the are available records from 15 rain gauges which gives a better base for comparison with the Hydro-Estimator.

December trough 2013: accumulated rainfall

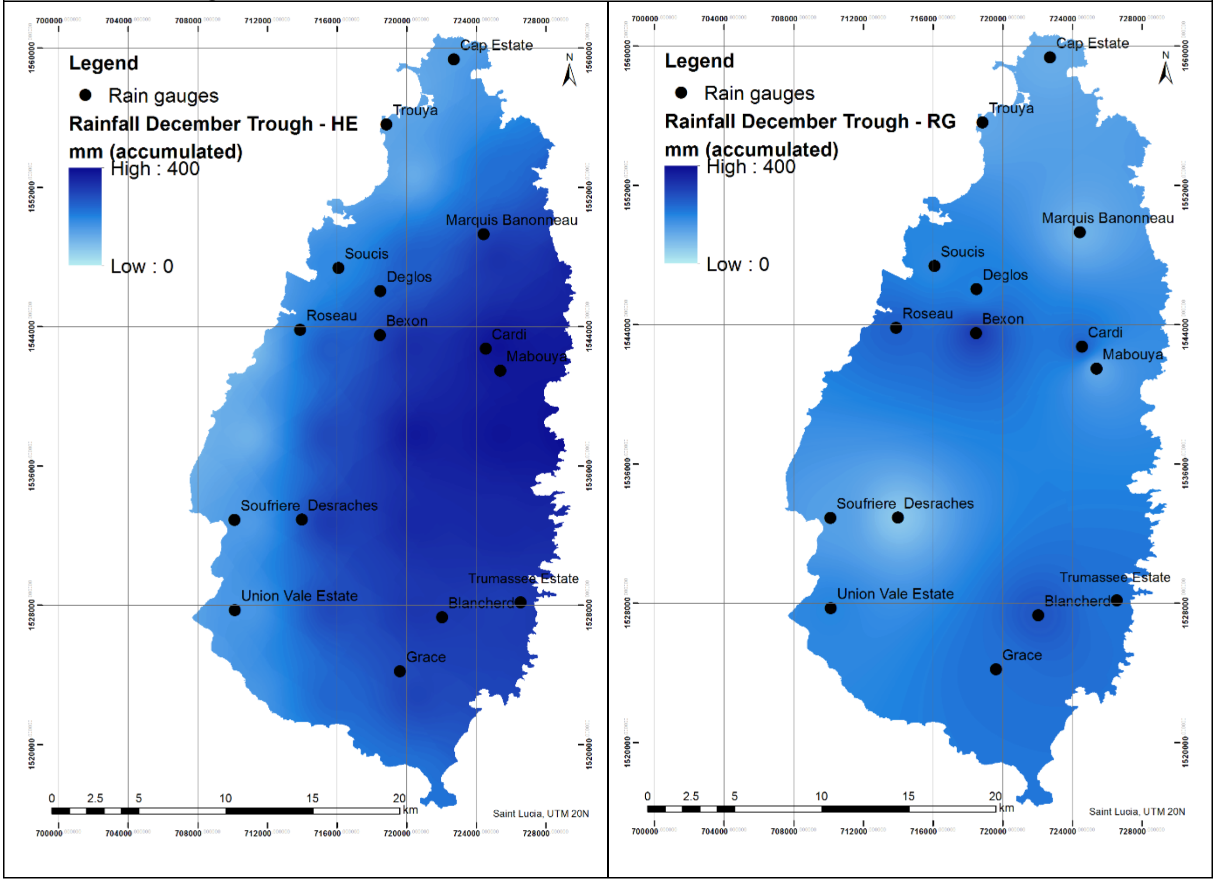


Figure 19 - Accumulated rainfall used for the flood modelling for the December trough in 2013. The HE to the left and the RG5/RG60 to the right.

5.2.3. Temporal rainfall difference for the December trough

One hour rainfall intensity comparison between the Hydro-Estimator (HE) and the rain gauges (RG). The combined width of the HE 60 min and the RG 60 min represents an hour of the rainfall scenario. Within each hour there are 12 five minute representations (RG 5). All values are hourly rainfall intensities.

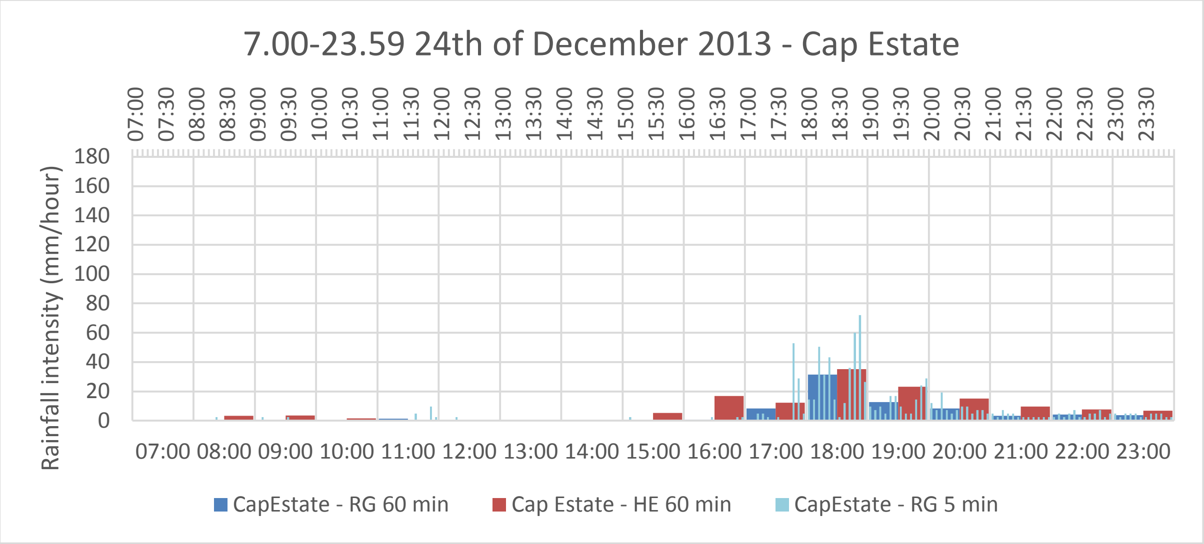


Figure 20 - Hourly rainfall intensities for the December trough. HE is the Hydro-Estimator, RG60 is the hourly average intensity from the rain gauges, and the RG5 is the hourly rainfall intensity based on 5-minute intervals - Cap Estate

Cap Estate (Figure 20) has low rainfall intensities. The HE is over estimating from 15-17. From 18 the correlation is a little better, but it is still overestimating though a few RG 5 min peaks are higher than the HE.

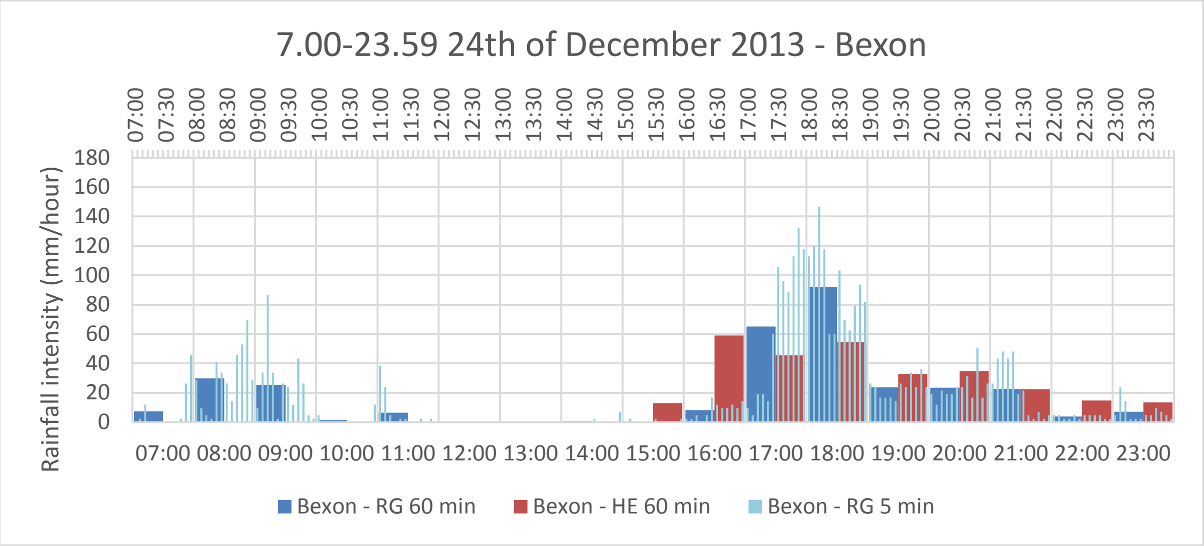


Figure 21 - Hourly rainfall intensities for the December trough. HE is the Hydro-Estimator, RG60 is the hourly average intensity from the rain gauges, and the RG5 is the hourly rainfall intensity based on 5-minute intervals - Bexon

In the morning (Figure 21) from 7-11 the HE does not pick up on this intensive rainfall with intensities exceeding 90 mm/h. The HE is overestimating at 15-16, and underestimating from 17-18.

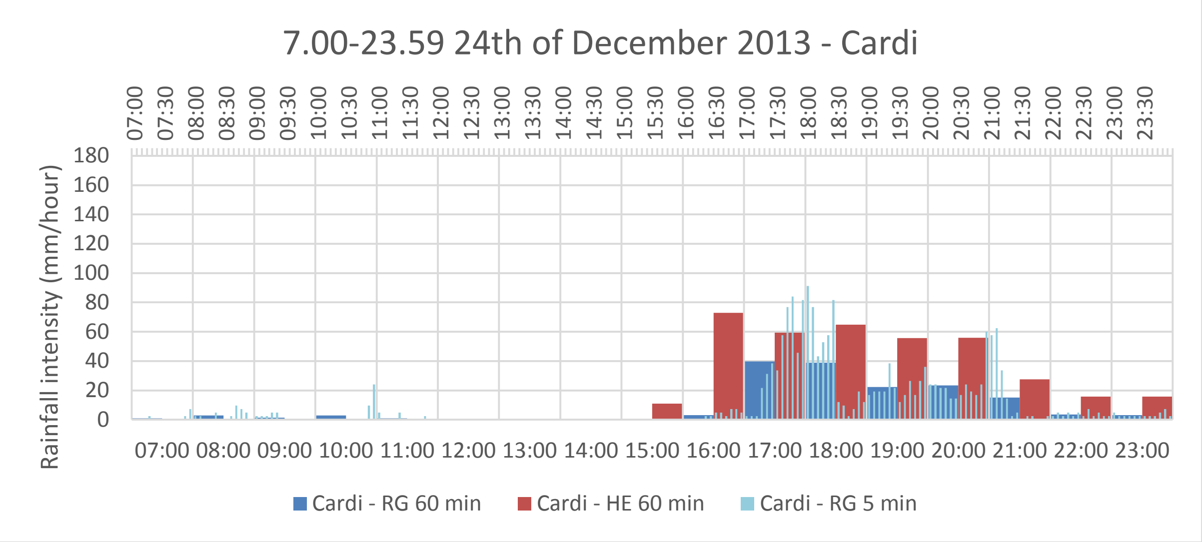


Figure 22 - Hourly rainfall intensities for the December trough. HE is the Hydro-Estimator, RG60 is the hourly average intensity from the rain gauges, and the RG5 is the hourly rainfall intensity based on 5-minute intervals - Cardi

A small amount of rain in the morning (Figure 22) which the HE does not pick up on. The HE is overestimating from 15-23, with a few RG 5 min peaks exceeding the HE around 17-18 and 21.

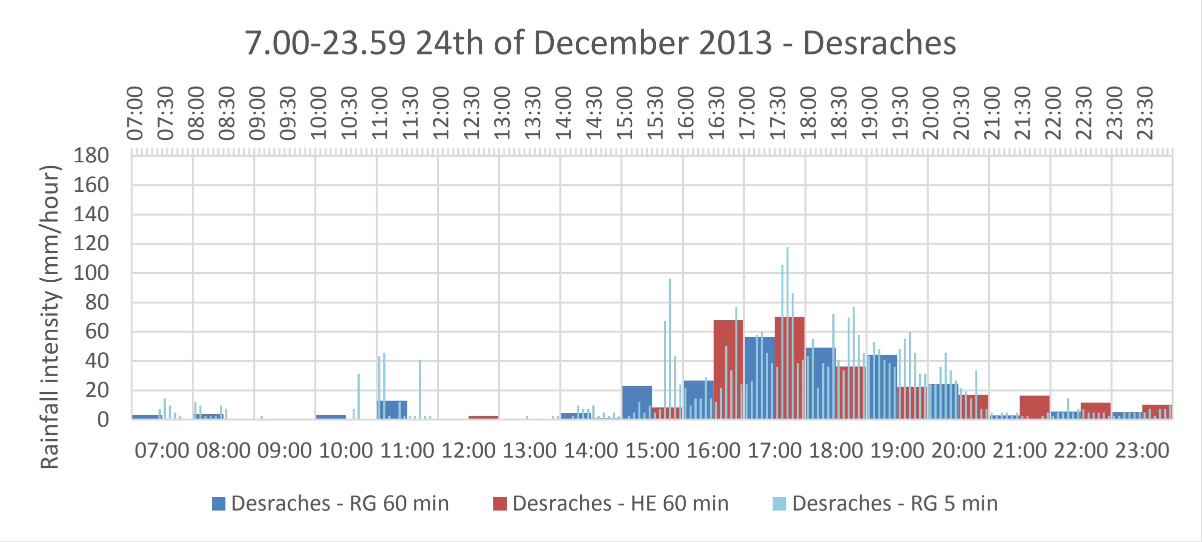


Figure 23 - Hourly rainfall intensities for the December trough. HE is the Hydro-Estimator, RG60 is the hourly average intensity from the rain gauges, and the RG5 is the hourly rainfall intensity based on 5-minute intervals - Desraches

A little rain in the morning (Figure 23) which the HE does not pick up on. The HE is underestimating at 15 and 18-20. It is overestimating a from 16-17.

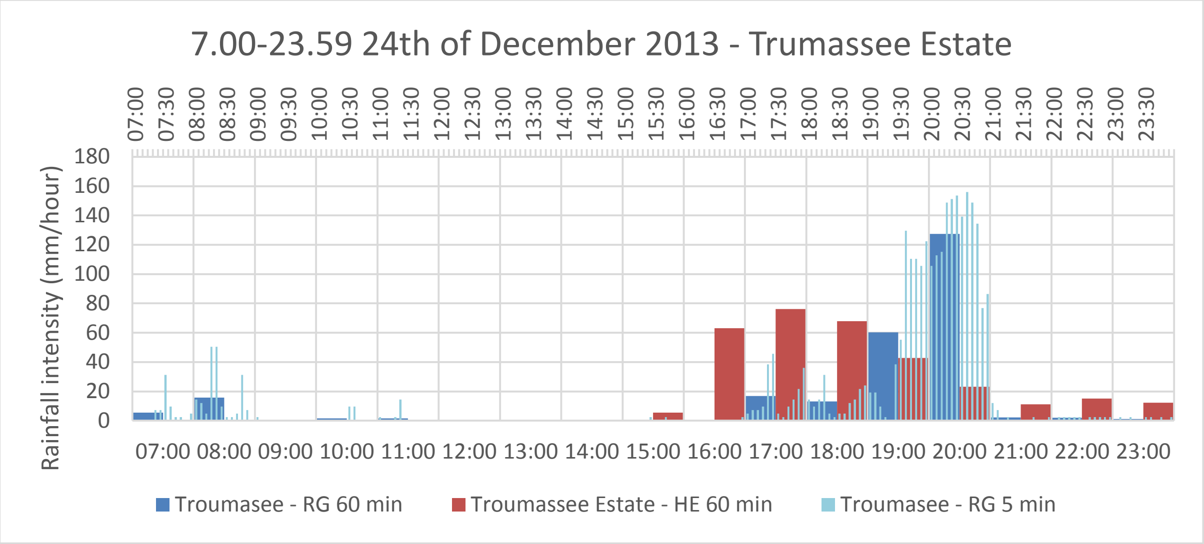


Figure 24 - Hourly rainfall intensities for the December trough. HE is the Hydro-Estimator, RG60 is the hourly average intensity from the rain gauges, and the RG5 is the hourly rainfall intensity based on 5-minute intervals - Trumassee Estate

Rain in the morning (Figure 24) which the HE does not pick up on. The HE is overestimating the rainfall from 15-18. From 19-20 the HE is greatly underestimating the rainfall.

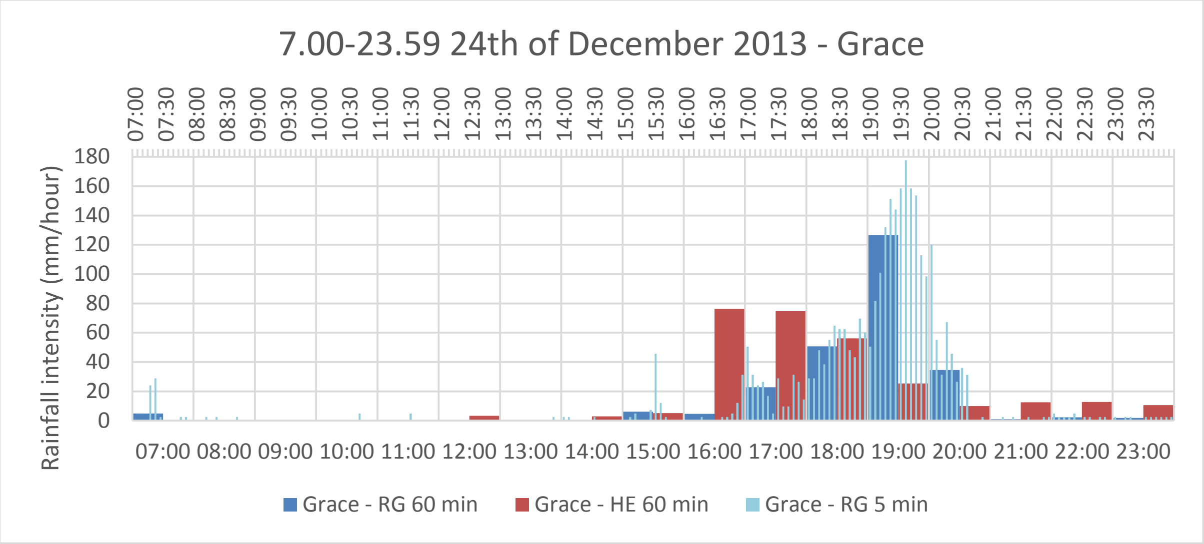


Figure 25 - Hourly rainfall intensities for the December trough. HE is the Hydro-Estimator, RG60 is the hourly average intensity from the rain gauges, and the RG5 is the hourly rainfall intensity based on 5-minute intervals - Grace

The records (Figure 25) shows very light rain in the morning which the HE does not pick up on. The HE is overestimating from 16-17. At 18 the HE is about right. From 19-20 the HE is greatly underestimating.

The graph below shows the temporal difference between the rain gauges and the HE. The positive values shows that the HE estimates more rain than the rain gauges recorded at during that hour of the day. Negative values represents hours where the HE estimate is lower than the records from the rain gauge. For the temporal distribution it is obvious that the Hydro-Estimator estimates the rainfall 2-4 hours ahead of the rain gauge measurements.

5.2.4. Temporal rainfall difference for Hurricane Tomas

The following comparison shows the data from the four available rain gauges during Hurricane Tomas.

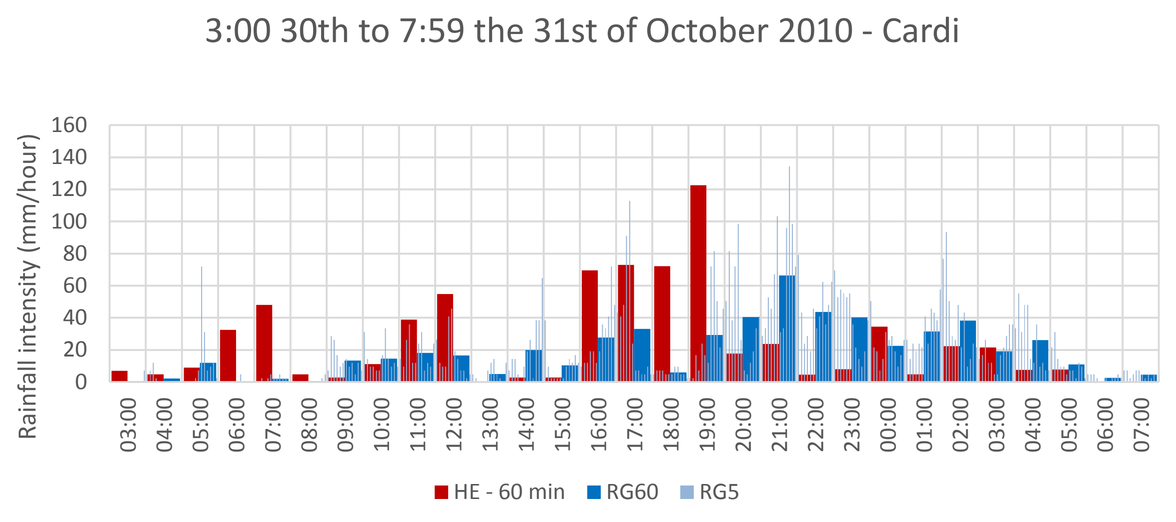


Figure 26 - Hourly rainfall intensities for Hurricane Tomas. HE is the Hydro-Estimator, RG60 is the hourly average intensity from the rain gauges, and the RG5 is the hourly rainfall intensity based on 5-minute intervals - Cardi

At Cardi (Figure 26) the Hydro-Estimator overestimates the rainfall from 5.00-7.00, at 12.00 and from 16.00-19.00. From 20.00 and onwards the Hydro-Estimator is underestimation the rainfall.

z

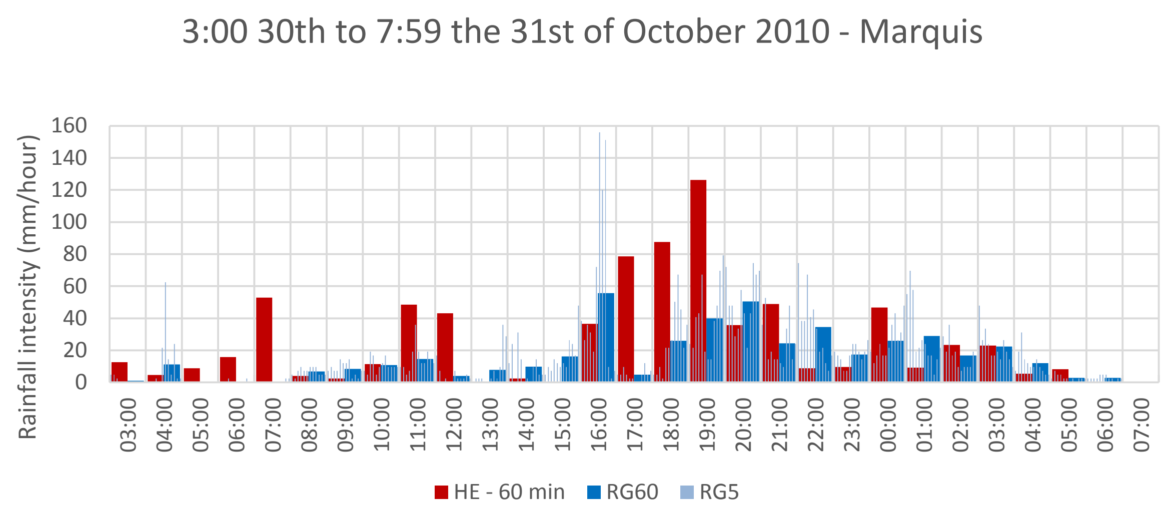


Figure 27 - Hourly rainfall intensities for Hurricane Tomas. HE is the Hydro-Estimator, RG60 is the hourly average intensity from the rain gauges, and the RG5 is the hourly rainfall intensity based on 5-minute intervals - Marquis

At Marquis (Figure 27) the Hydro-Estimator overestimates the rainfall from 6.00-7.00, 11.00-12.00 and from 17.00-19.00. From 20.00 and onwards the Hydro-Estimator and rain gauges shows relatively the same rainfall intensities.

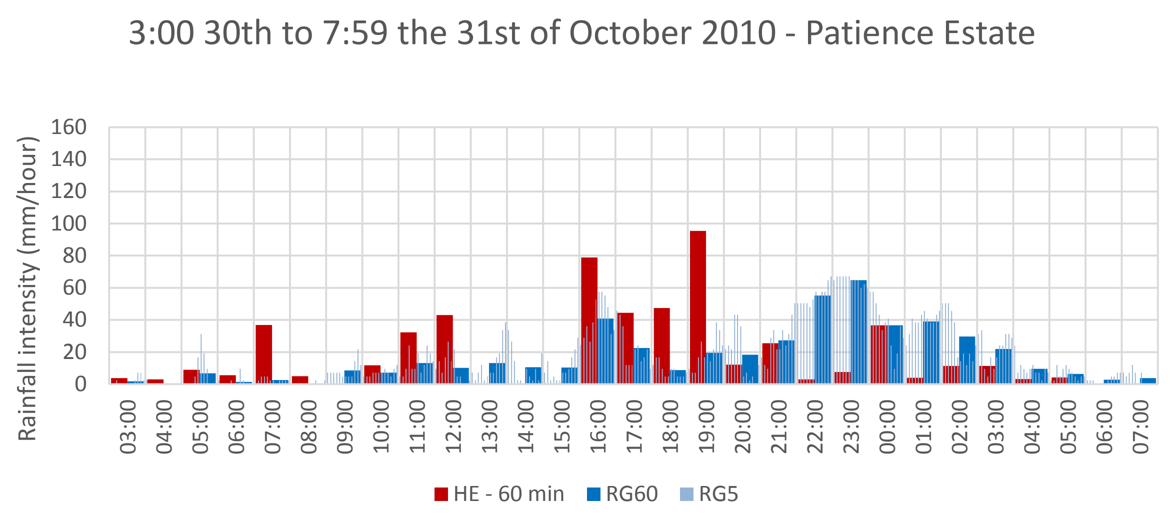


Figure 28 - Hourly rainfall intensities for Hurricane Tomas. HE is the Hydro-Estimator, RG60 is the hourly average intensity from the rain gauges, and the RG5 is the hourly rainfall intensity based on 5-minute intervals - Patience Estate

At Patience Estate (Figure 28) the Hydro-Estimator overestimates the rainfall at 7.00, 11.00-12.00 and from 16.00-19.00. From 22.00 and onwards the Hydro-Estimator underestimates the rainfall intensities compared to the rain gauges, except for midnight at 00.00.

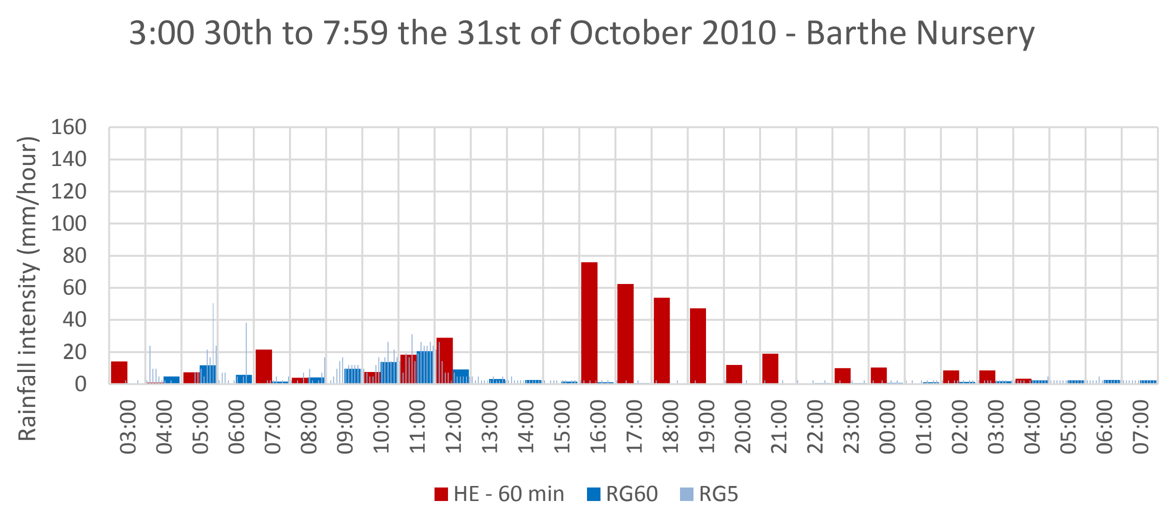


Figure 29 - Hourly rainfall intensities for Hurricane Tomas. HE is the Hydro-Estimator, RG60 is the hourly average intensity from the rain gauges, and the RG5 is the hourly rainfall intensity based on 5-minute intervals - Barthe Nursery

At Barthe Nursery (Figure 29) the Hydro-Estimator overestimates the rainfall at 7.00, and from 16.00 and onwards where the rainfall station shows as good as no rainfall. Though the records from the rain gauges are really low they are not complete missing. It could be that Hurricane Tomas did not give much rainfall to this corner of the island. In that case the Hydro-Estimator shows a high intensity of rain at a time where clearly was not raining.

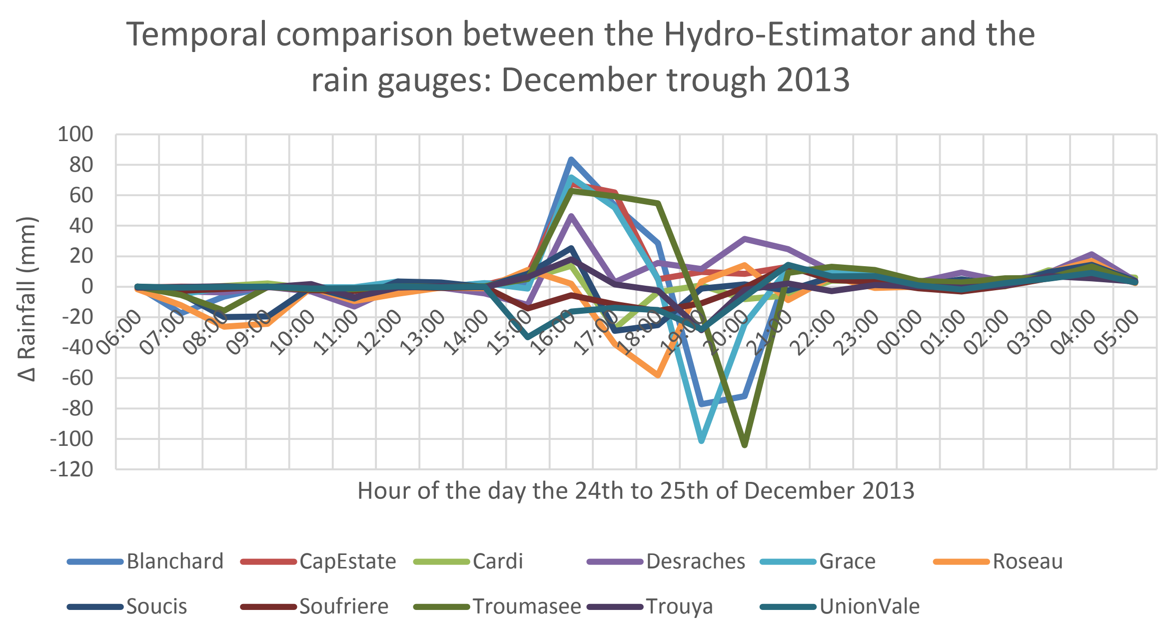


Figure 30 - Δ Rainfall (mm) shows the temporal difference in the over- and underestimation for the Hydro-Estimator compared to a selected number of rain gaugesthe rain gauges. A positive value is an overestimate and a negative value is an underestimation.

The temporal comparison for the December trough (Figure 30) shows a time bias in the rainfall estimates by the Hydro-Estimator. The tendency is that the Hydro-Estimator estimates rainfall earlier than it is picked up by the rain gauges.

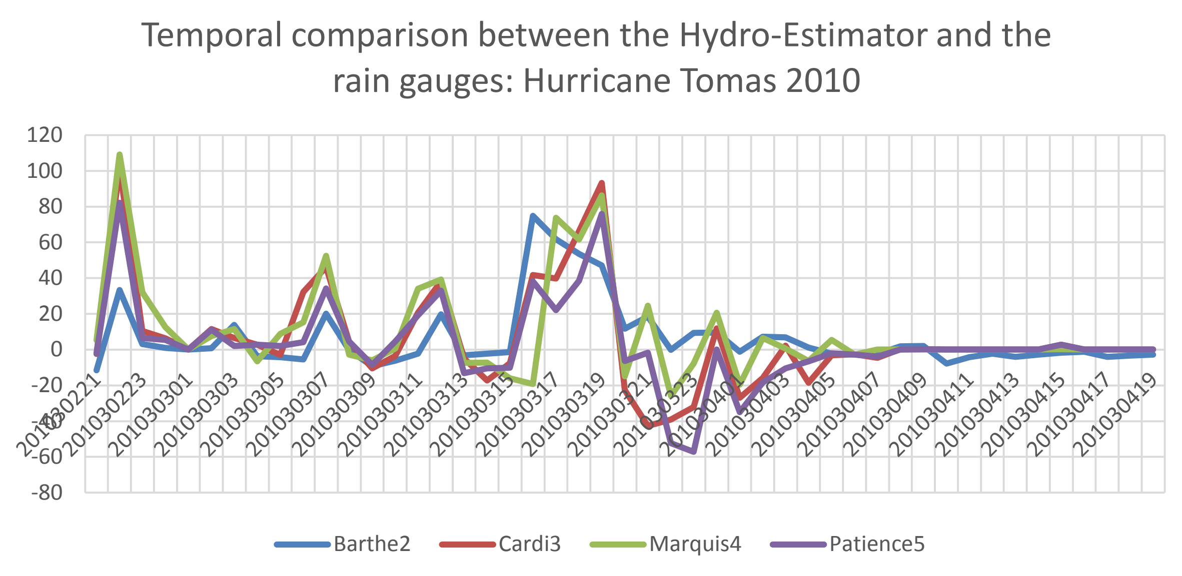


Figure 31 - temporal rainfall comparison for Hurricane Tomas 2010. They y-axis shows the year, day of year and hour of the day.

The rainfall comparison (Figure 31) shows that the Hydro-Estimator greatly over estimates the rainfall intensities around multiple times from 21.00 (day 302) to 21.00 (day 303). After 21.00 there is a tendency for the Hydro-Estimator to underestimate compared to the rain gauges.

5.3. Method of correction

Previous studies Puerto Rico (Ramirez-beltran et. al., 2008) have showed that the Hydro-Estimator underestimates the amount of rainfall (Figure 19), unfortunately I do not have a clear pattern in the same way for the December trough. I have therefore decided not to perform a correction. There does also appear not to be a clear relation between the elevation and the differences in rainfall estimates (Figure 14), there are not enough rain gauges located at higher elevations to create a good basis for comparison.

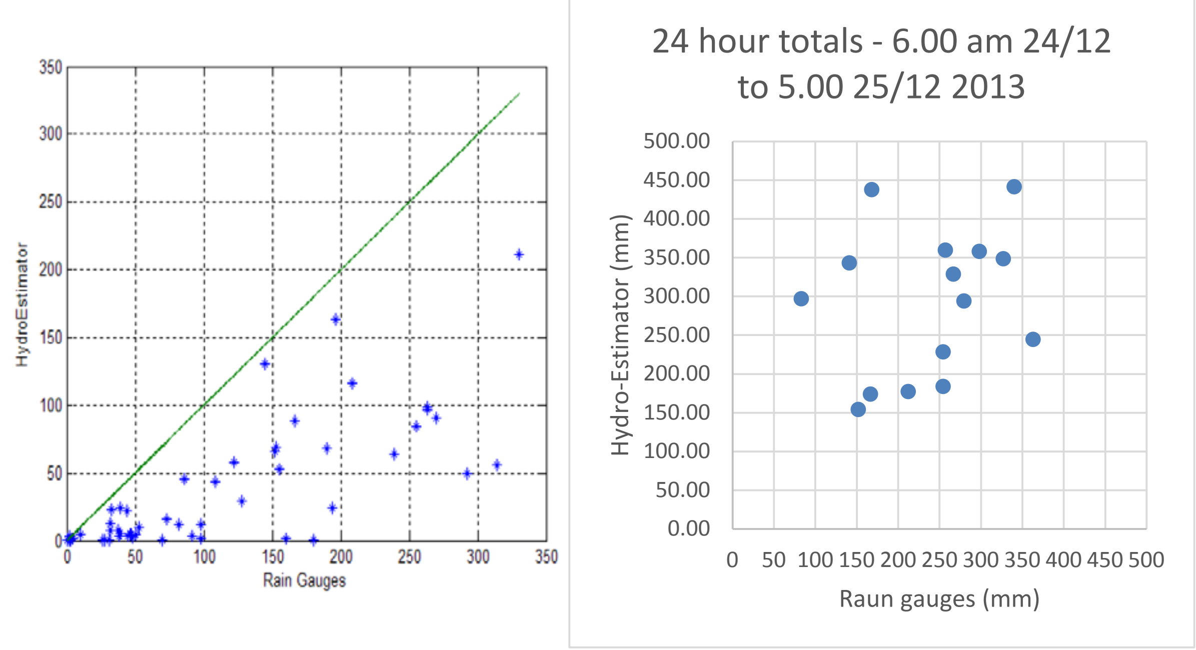


Figure 32 - to the left: a rain gauge comparison of the Hydro-Estimator and rain gauges in Puerto Rico for a flood event. To the right: a comparison for the raingauges on Saint Lucia for the December trough 2013.

Cardi and Marquis are the only rain gauges with records for both Hurricane Tomas and the December trough.

Table 3 - correction based on the two rain gauges which has records from both events. All measurements in mm.

	Cardi					**Marquis Banonneau**			
	HE	RG	Delta	Calculated Factor		HE	RG	Delta	Calculated Factor
Hurricane Tomas	852	570	282	1.49		923	457	466	2.02
December trough	442	340	102	1.30		344	141	203	2.44
Corrected	HE	RG	Delta	Applied factor				Delta	Applied Factor
Hurricane Tomas	655	570	86	1.30		378	457	-79	2.44
December trough	295	340	-44	1.49		170	141	29	2.02

If a correction factor is made based on the two rain gauges which are available (Table 5) the rainfall in mm for the Hydro-Estimator, will get closer to the measurements for the rain gauges. If it was applied on those rain gauges which has already has a good fit, it will decrease the correlation . It could however be wrth investigating with differences between the rain gauges and the Hydro-Estimator can be calculated based on a mask, which is dependent on local physical parameters.

6. FLOOD MODELLING

6.1. Flood differences

The total flood affected area differs depending on the rainfall product. For the December through

Table 4 - the total flood area (in ha) in relation to the water depth for the December trough depending on the rainfall product.

	> 0.10 m	> 0.50 m	> 1.0 m	> 1.50 m	> 2.0 m	> 3.00 m
HE	1886.84	1149.36	670.32	404.6	195.04	58.20
RG60	1122.12	488.72	193.16	78.92	32.64	6.28
RG5	1155.44	535.72	187.28	77.80	28.88	4.92

The flood model results based on the Hydro-Estimator does clearly affect a bigger area than the two rain gauge results. At a flood level of 0.5 meter the hydro-estimator has flooded twice as much as the rain gauge flood model results and factor difference keeps increasing with the flood level.

Table 5 - Flood areas (in ha) with water levels greater than the defined value. The green X's marks classes where the HE, RG60, or RG5 rainfall products have overlapping flod areas.

HE	RG60	RG5	> 0.10 m	> 0.50 m	> 1.0 m	> 1.50 m	> 2.0 m	> 3.00 m
0	0	X	14.08	5.52	2.80	0.96	0.32	0.00
0	X	0	9.40	5.84	3.64	2.00	1.16	0.64
0	X	X	86.96	43.00	20.72	9.12	3.80	1.04
X	0	0	788.96	639.24	489.52	327.16	165.24	53.28
X	0	X	72.12	70.24	12.00	9.64	2.12	0.32
X	X	0	43.48	22.92	17.04	9.72	5.04	1.04
X	X	X	982.28	416.96	151.76	58.08	22.64	3.56

6.2. Flood affected area

Below is the development in the flood affected area:

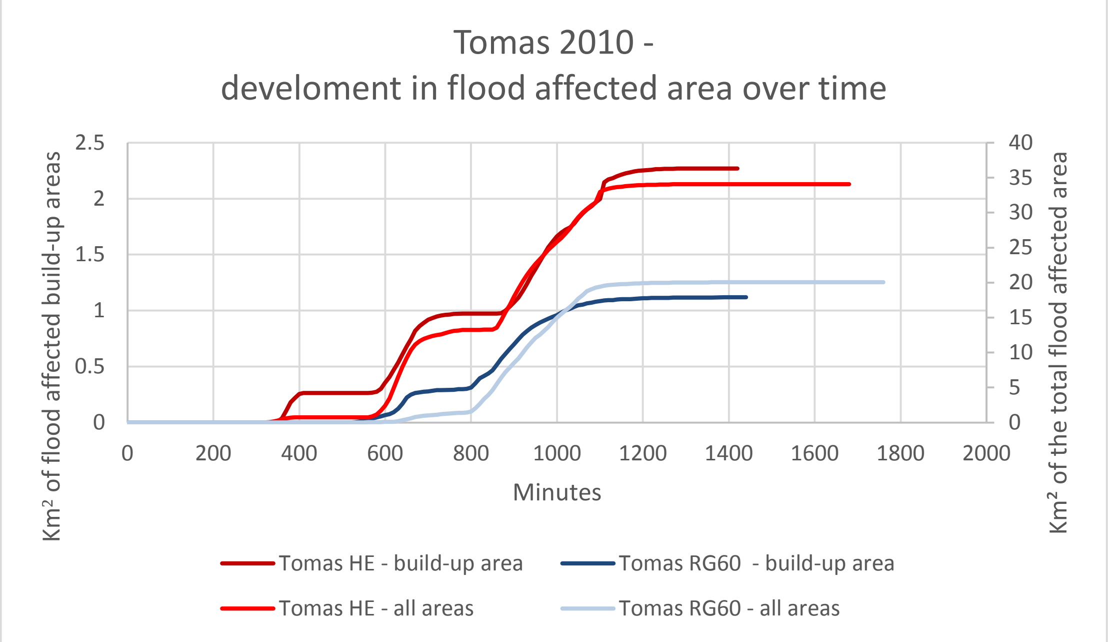


Figure 33 - difference in temporal flood development

For Hurricane Tomas the amount of flood affected areas increases faster with the Hydro-Estimator than with the rain gauges (Figure 33). The same goes for the flood affected areas which is occupied by buildings.

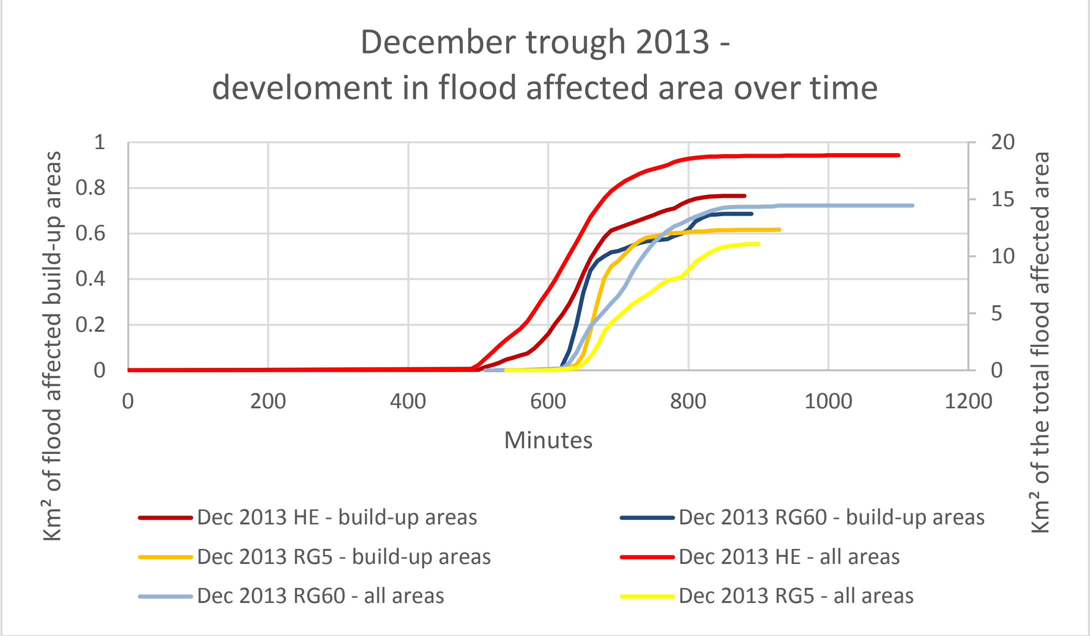


Figure 34 - difference in temporal flood development

For the December trough 2013 the amount of flood affected areas increases faster with the Hydro-Estimator than with the rain gauges (Figure 33). The same goes for the flood affected areas which is occupied by buildings.

6.3. Flood level evaluation

Flooding level comparison for the December trough 2013.

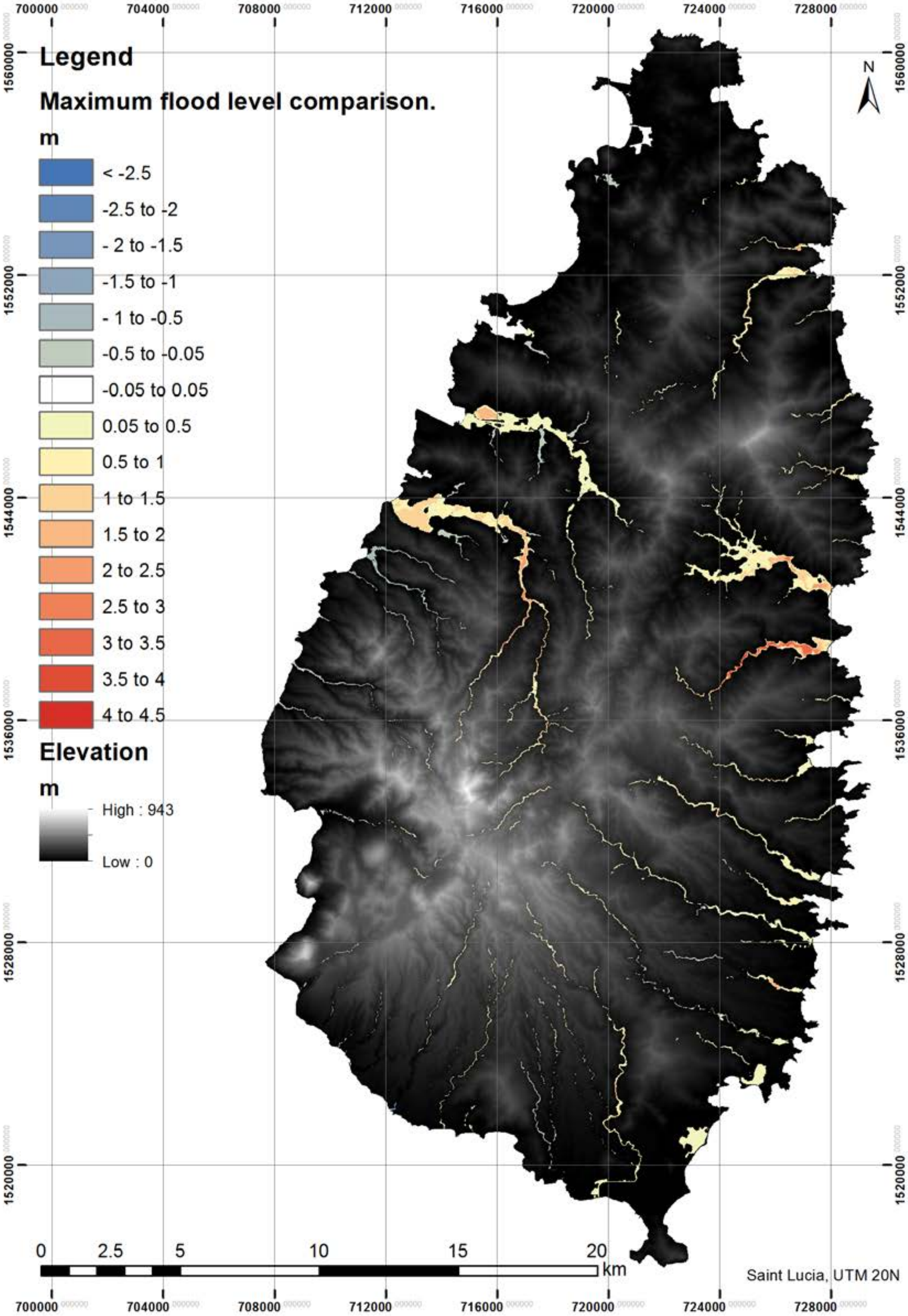


Figure 35- Maximum flood depth for the December trough 2013 based on HE 60 minutes minus maximum flood depth based on the 5-minute rain gauges data. A positive value mean that the modelled maximum water level from the HE is higher than the the result based on the 5-minute rain gauges. A negative value means that the 5-minute rain gauges model result had a higher maximum flood level than the Hydro-Estimator.

The Hydro-Estimator does generate significantly higher floods than the result based on rain gauges. Only in some of the small catchments to the West is the modelled flood level higher based on the rain gauges.

Based on the ground data collected through interviews during field work the water level of the December trough in 2013.

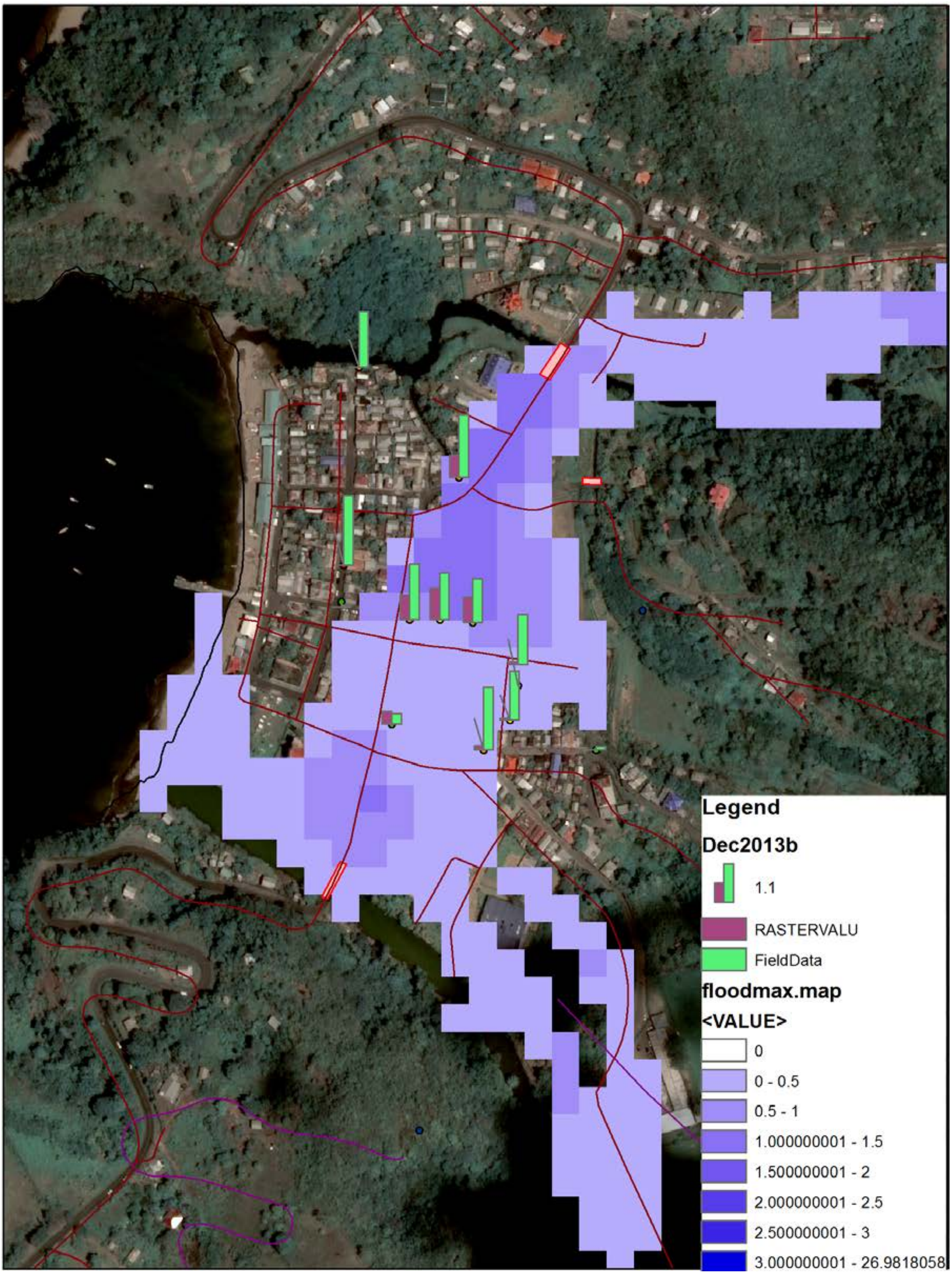


Figure 36 - map of Anse laRaye. Comparing the field flood measurements with the flood output based on the Hydro-Estimator

6.4. Flood extend difference

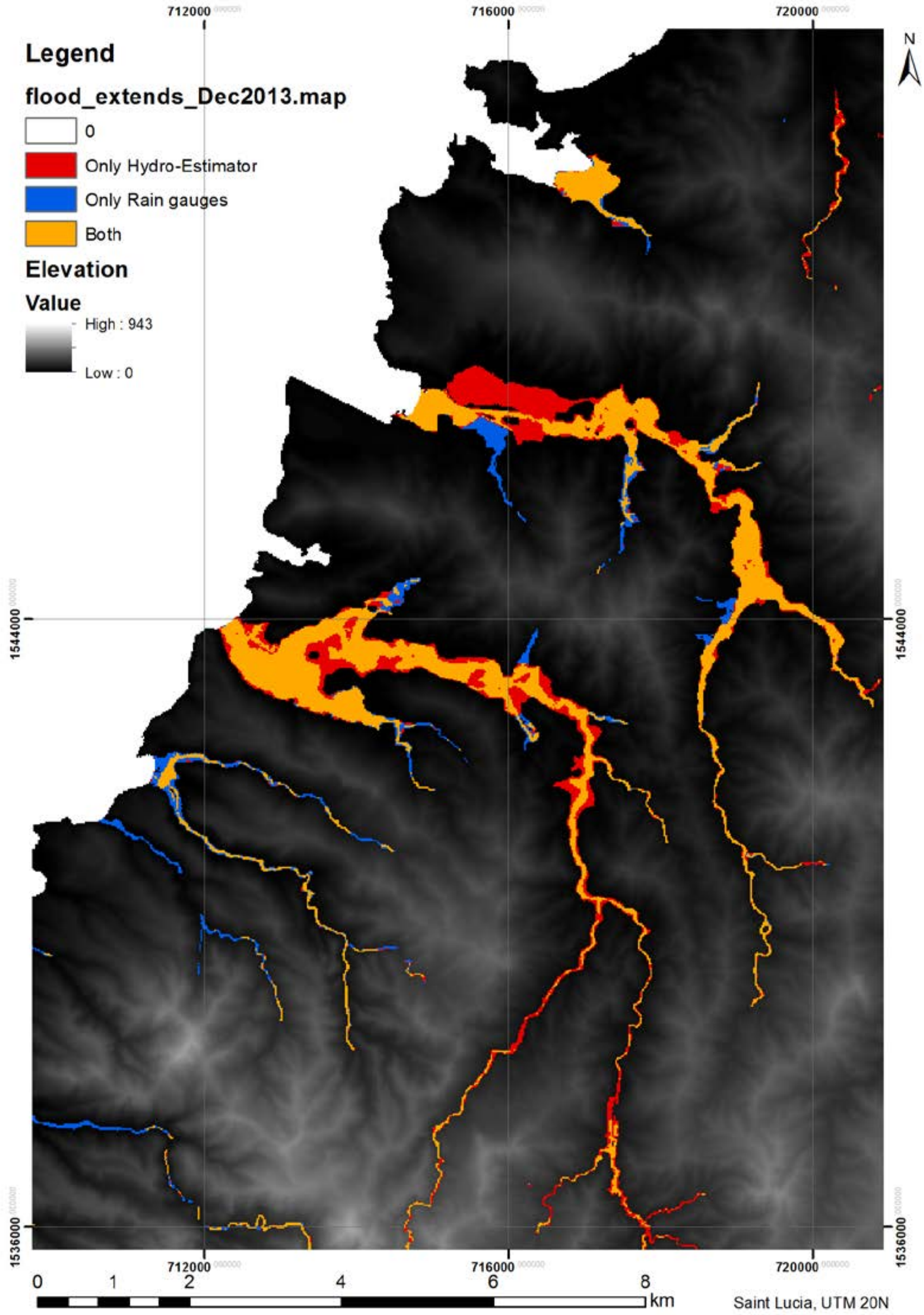


Figure 37 - Flood extend difference. Hydro-Estimator and 5-min rain gauge.

6.5. First flood time

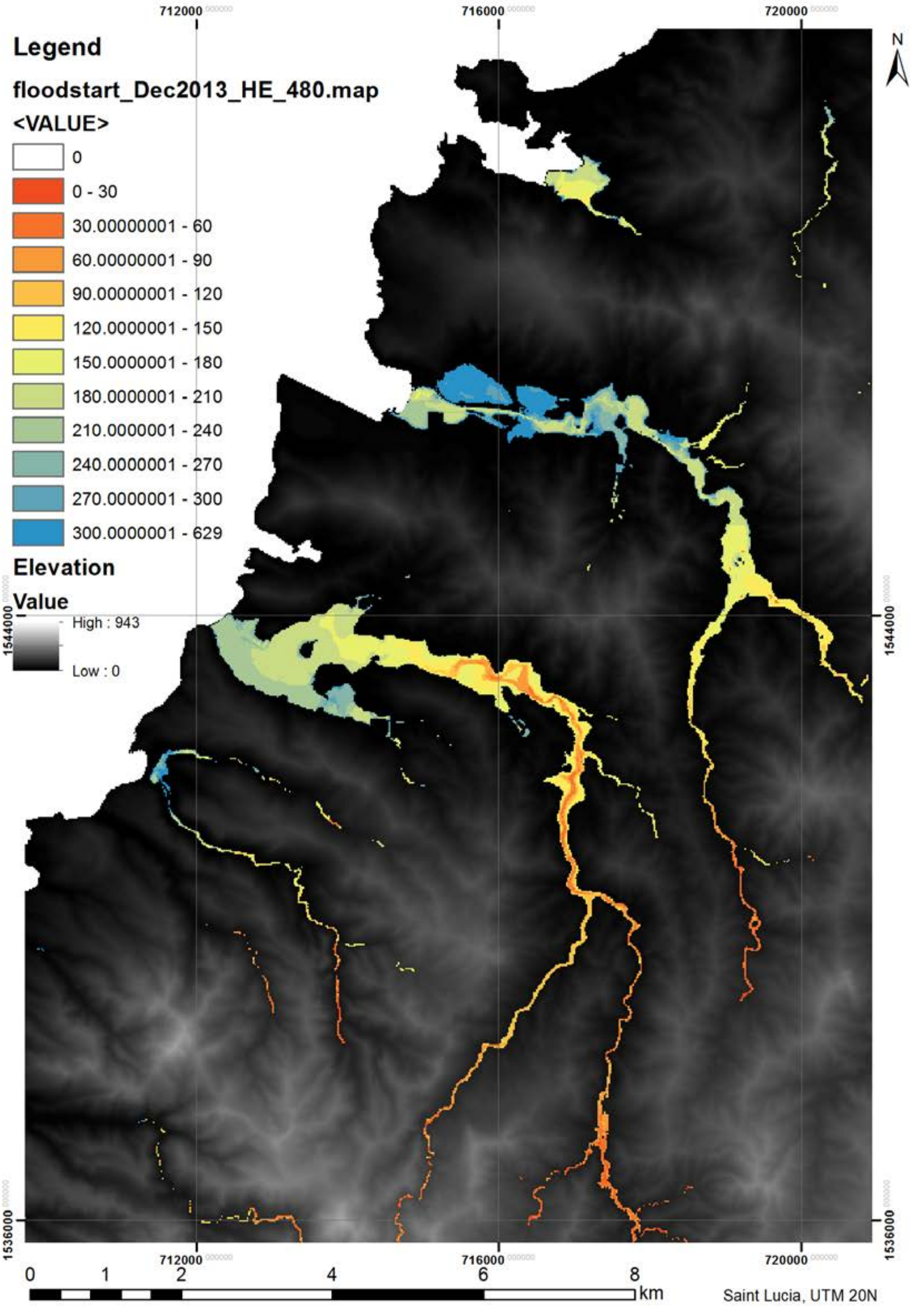


Figure 38 – Hydro-Estimator: Flood start time after rainfall in minutes after 15.00 the 24th of December 2013.

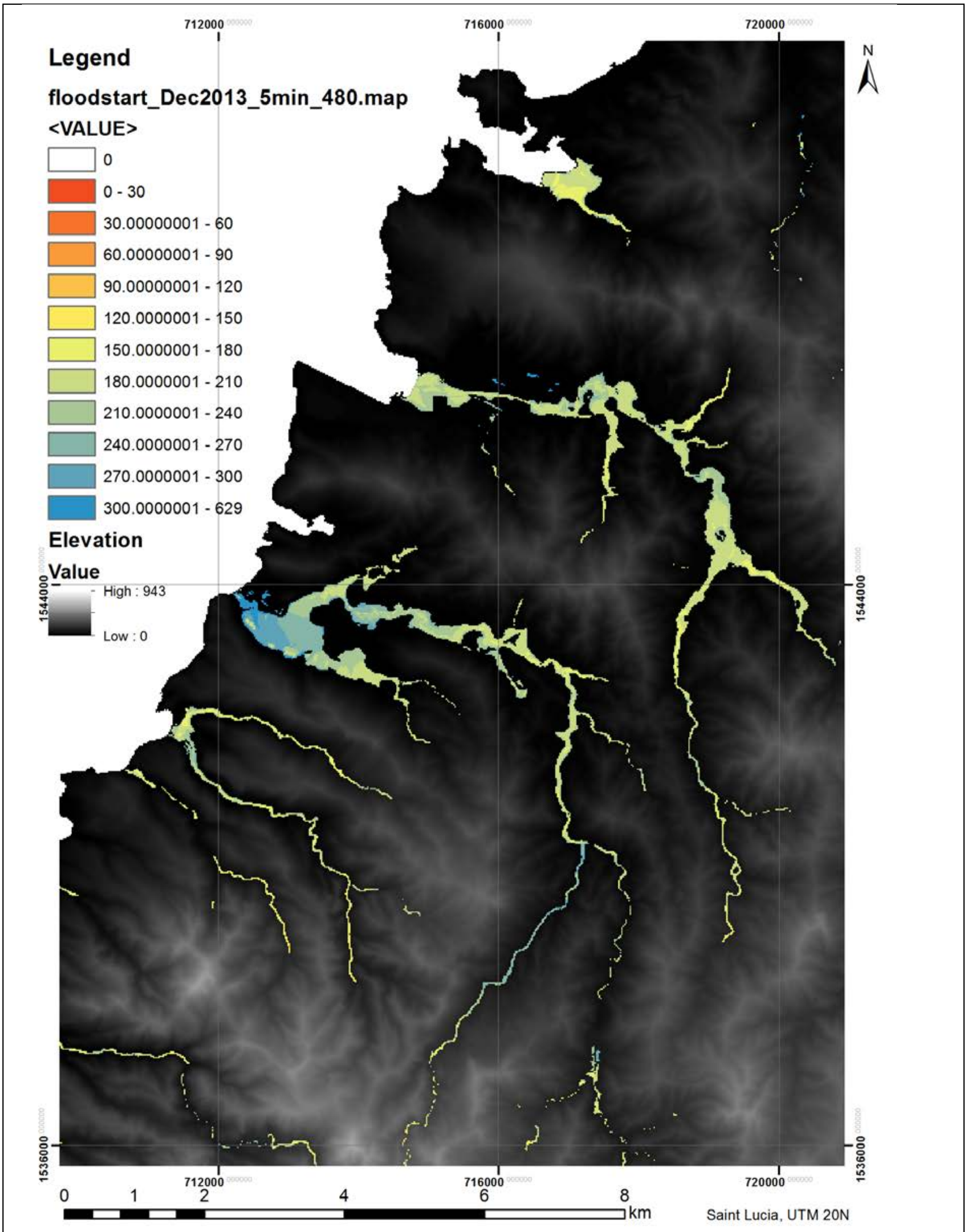


Figure 39 – Rain gauge 5-minute: Flood start time after rainfall in minutes after 15.00 the 24th of December 2013.

7. CONCLUSION

The Hydro-Estimator shows a general time bias and overestimation of rainfall compared to the rain gauges. This results in higher modelled flood levels and earlier flood times than the flood model results based on the rain gauges.

For Hurricane Tomas the Hydro-Estimator overestimates the amount of total rainfall compared to the four available rain gauges. For the December trough, the Hydro-Estimator results are more spread with overestimates for four of the fifteen stations. The Hydro-Estimator shows a temporal bias both during the December trough and Hurricane Tomas towards estimating the rainfall earlier than the rain gauges has records.

Though the Hydro-Estimator greatly overestimates the total amount of rainfall for Hurricane Tomas, the rainfall pattern looks close to the gauges. There are however only four ran gauges to base the comparison on. For the December trough the total rainfall amount for the Hydro-Estimator is very close to the records for many of the rain gauges. The spatial pattern for the whole December trough has noticeable local differences when comparing the Hydro-Estimator and the rain gauges. For the December trough the 15 rain gauges to evaluate against, gives a better chance to spot rainfall differences, than for Hurricane Tomas where only four rain gauges were available.

However, two events are too little to draw a general conclusion about the performance of the Hydro-Estimator. More events should be evaluated, including events with low rainfall amounts, to get a better understanding of the differences in rainfall intensity, temporal occurrence and total rainfall amounts.

The floods modelled for both Hurricane Tomas show higher flood levels with the Hydro-Estimator than for the rain gauges. For the December trough it is slightly different. Here does the areas furthers to the West show higher flood levels with the rain gauges, where the rest of Saint Lucia has highest flood levels based on the Hydro-Estimator.

For both flood events the Hydro-Estimator does in general estimates the flood to happen at an earlier point in time, which is an advantage for warning purposes.

The current available elevation model does not represent elevation changes well in the bottom on the valleys. This makes it difficult to compare known flood levels with those generated by the flood model. It also means that the way the flood develops in the bottom of a valley might not be represent that well.

It would be interesting to further explore the radar on Martinique north of Saint Lucia to investigate how it can be used to improve the current remote sensed results.

8. DISCUSSION

Models will always be a representation of reality and it will never perform better than the data it is using. A challenge with the available data from Saint Lucia is that the elevation model is interpolated from 2.5 meter contour lines. It means that the bottom of the valley only to a limited degree reflects the actual elevation differences around the river bed some places. The modelled flood dynamics could be greatly improve in regards to the actual water level and the early stage spatial distribution of the flood. It would be worth to consider getting a LIDAR which greatly will improve the accuracy of the elevation model, especially in the vegetated areas. It could also be considered to invest in a drone for mapping from which point clouds can be generated for elevation models.

The overestimation of rainfall by the Hydro-Estimator during Hurricane Tomas shows that the HE does not show sufficient precision on the rainfall measurements. Previous studies have showed that the HE was a good indicator for flooding during Hurricane Tomas on Haiti. It is therefore important to note which way the HE results are used to indicate a flood scenario. On Haiti the HE was used to model if the rivers would breach the banks of river based on the estimates from the HE. In the approach I am using I aim at using the rainfall output for a spatial analysis, to identify which areas will be flooded when the river breaks its banks. When using a model which simulates a spatial extent the result becomes more sensitive to the exact rainfall estimates, because a water flow and level is calculated outside the defined riverbed.

A limitation of the research is that the floods scenarios I ran is using rainfall data which represents the entire event. In that manner it is difficult claim at what point in time the flood model will have reached its maximum flood level. However, the hydrographs does still represent the discharge for the selected location for the rainfall up until that point in time. The curve of the discharge can be an indicator if the discharge is still increasing or levelling off.

The FFGS requires continuous soil moisture modelling which can work as a synergy for the assessment of draught for the water department

The overall goal of a flood warning system is to warn people in the areas at risk and reduce the human and physical impact of the flooding. The more precise the warning can be in terms of location, time and intensity, the easier it becomes for public agencies and the public to prepare themselves.

Cost efficient solutions are often in demand in developing countries. In that way the Hydro-Estimator is interesting because the data itself is made available for free by the STARS project at NOAA/DESDIS. It also makes the warning system depended on access to the data, and that the project will be continued for a long time. Luckily the Hydro-Estimator is based on the GOES satellites, for which the next generations of satellites are about to be launched.

There is a temporal difference between the two products. The HE is a near real time product, but because the data is an hourly average there is a natural delay in the information which for smaller catchments may mean that the information will be available too late.

A system based on rain gauges has the advantage of a higher temporal frequency, which means that the information will reach the end user faster, and make it possible to run a flood model earlier and earlier get a result a warning can be based on.

Another approach could be to pre-run a series of scenarios and map decisions tables for each catchment based on modelled flood depth and time. That reduces the technical needs for running the flood models on the fly and saves time.

A better DEM based eg. World DEM, LiDAR, Drones, would greatly improve the accuracy of the flood results..

Development of a national spatial database to gather intelligence on previous disasters, would be a great asset for future development and flood model callibration.

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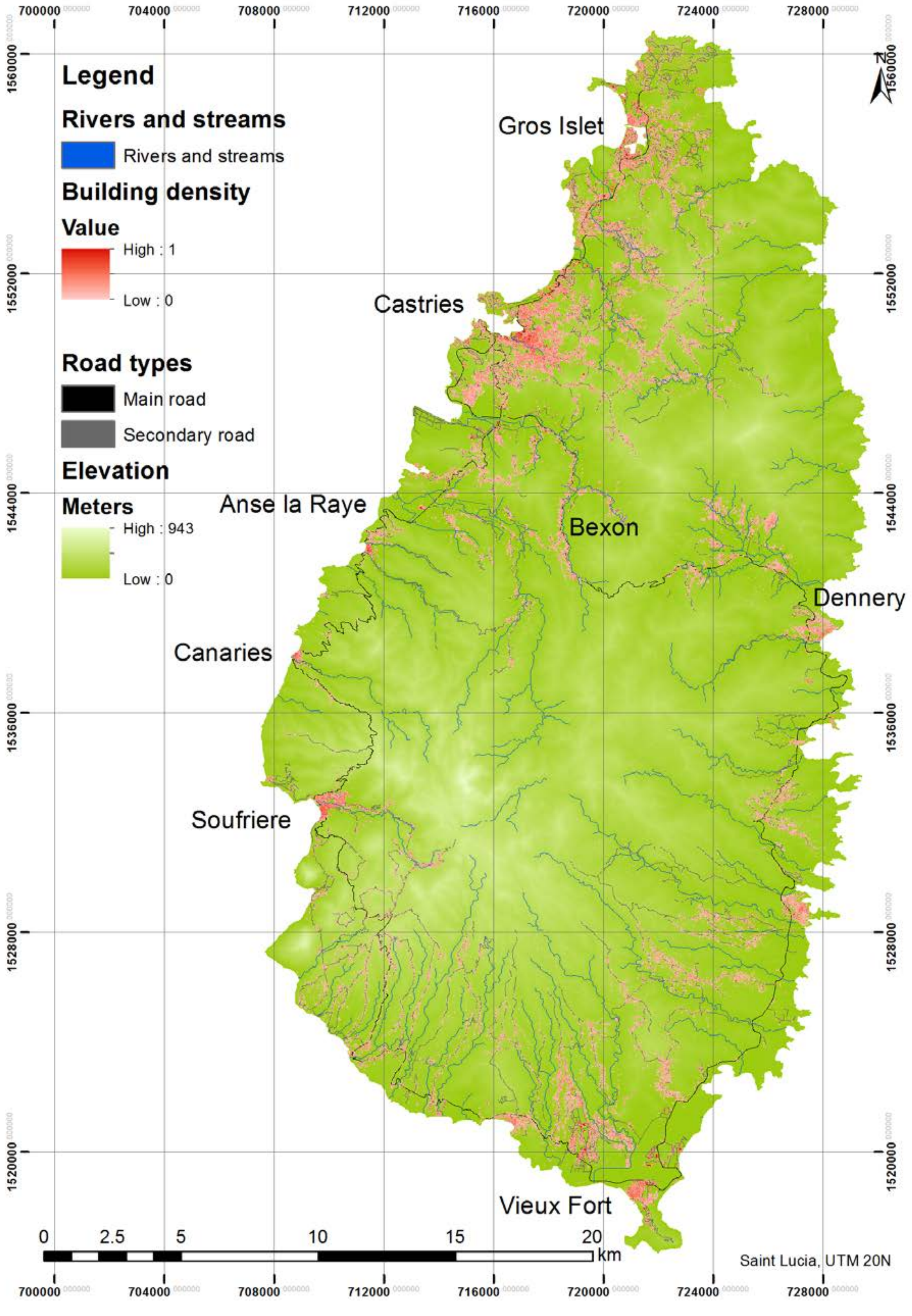
APPENDIX A

List of base data for openLISEM

Group	Name	Description	Source
Rainfall	Hydro-Estimator	Hourly rainfall estimates derived from satellites, by NOAA/NESDIS.	NOAA/NESDIS: http://www.star.nesdis.noaa.gov/smcd/emb/ff/digGlobalData.php
	Rain gauges	Daily rainfall measurements (1955-2005) and minute measurements (~2003 - 2014).	CHARIM project
DEM	Elevation model	20x20 meter raster derived from 2.5 meter contour lines.	CHARIM project
Soil units	Soil classes	Map with 23 soil classes	CHARIM project
Land use/cover	Vegetation cover	Land use/cover map with 14 classes.	CHARIM project
Infrastructure	Building footprints	Shape files of building footprints.	CHARIM project
	Road map	Road map with main roads, secondary roads and tertiary roads.	CHARIM project
	Channels/Bridges/culverts	Map with rivers channels and other channels, bridges and culverts.	CHARIM project

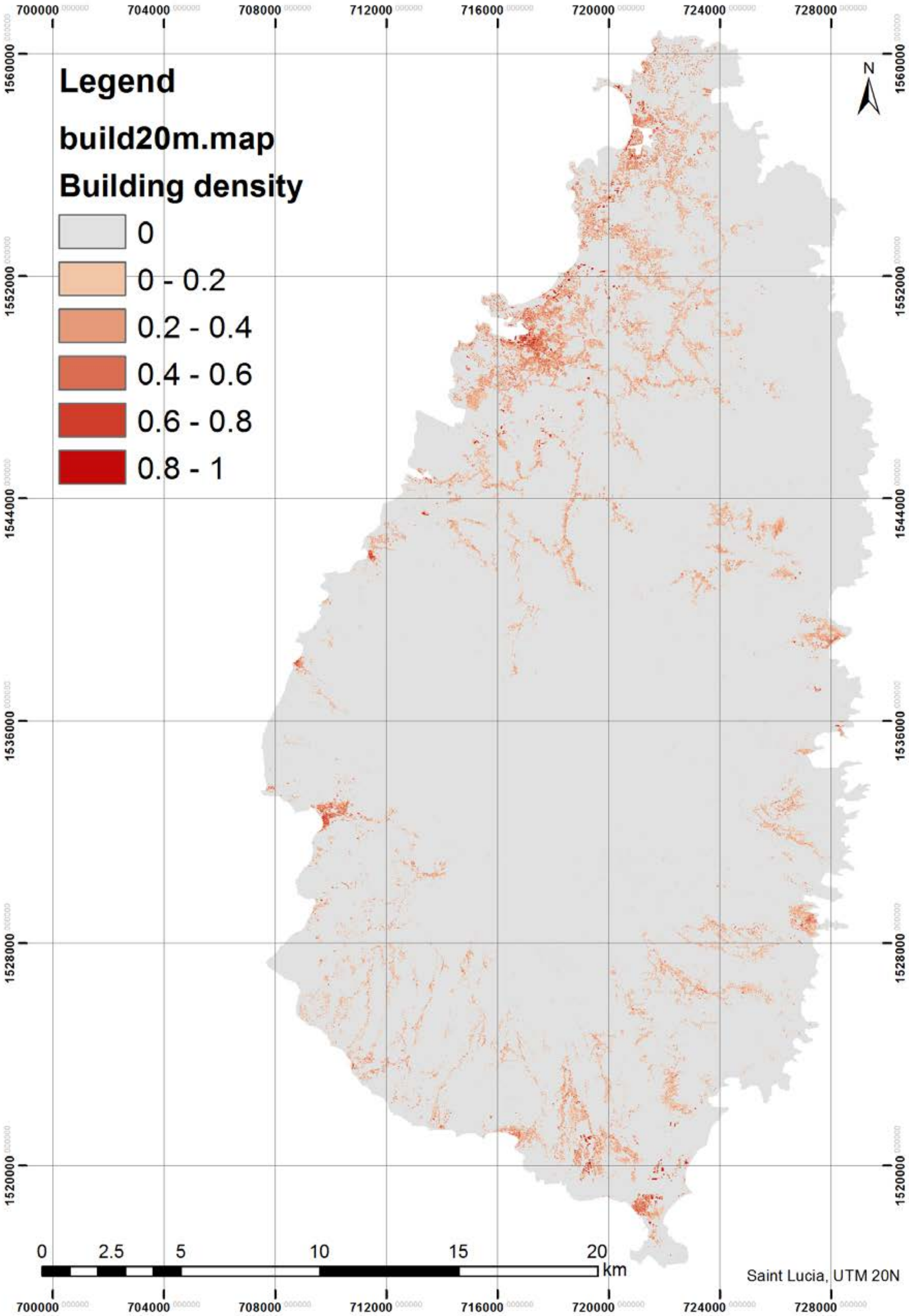
APPENDIX B

Map of Saint Lucia



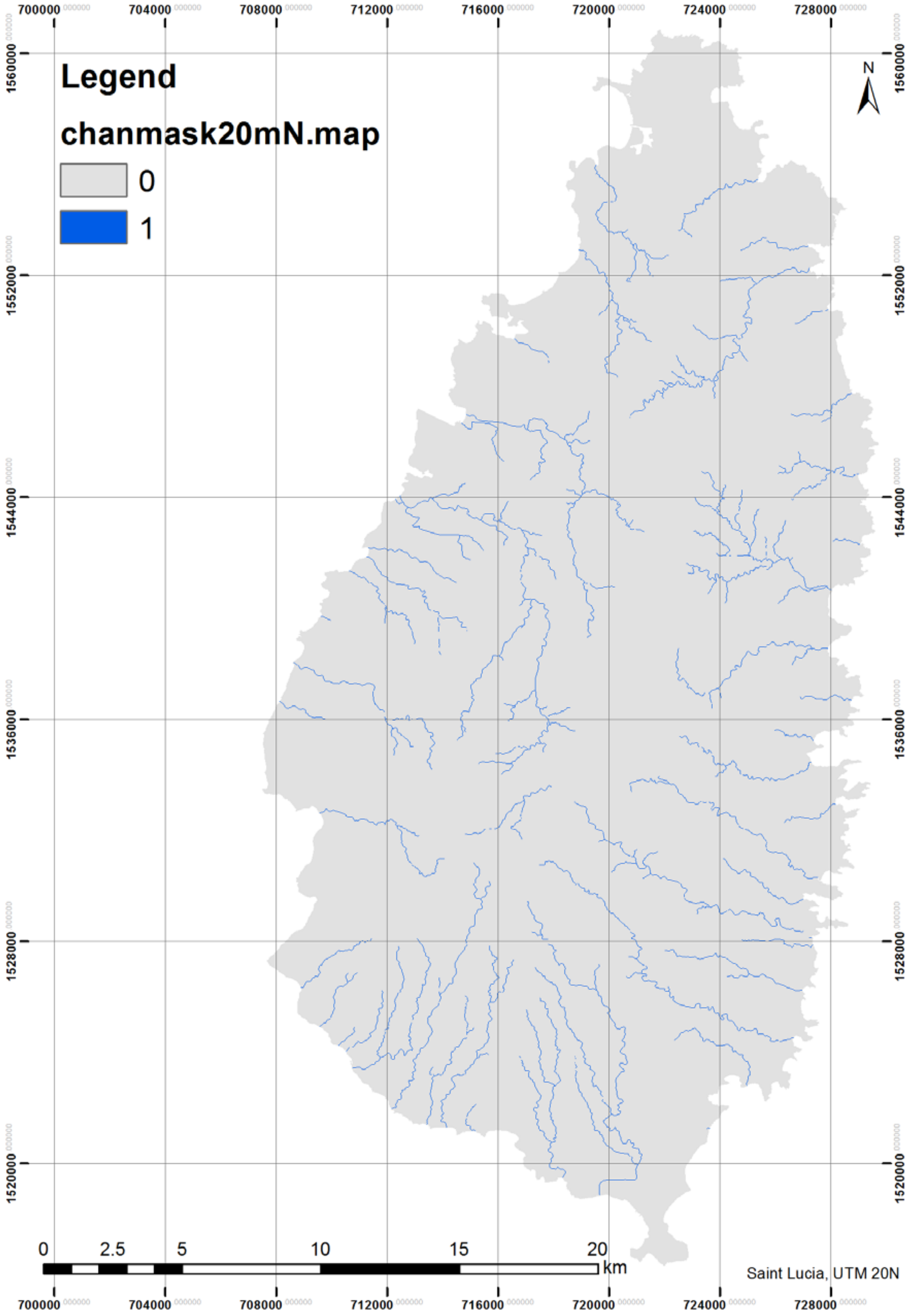
APPENDIX C

Building density map



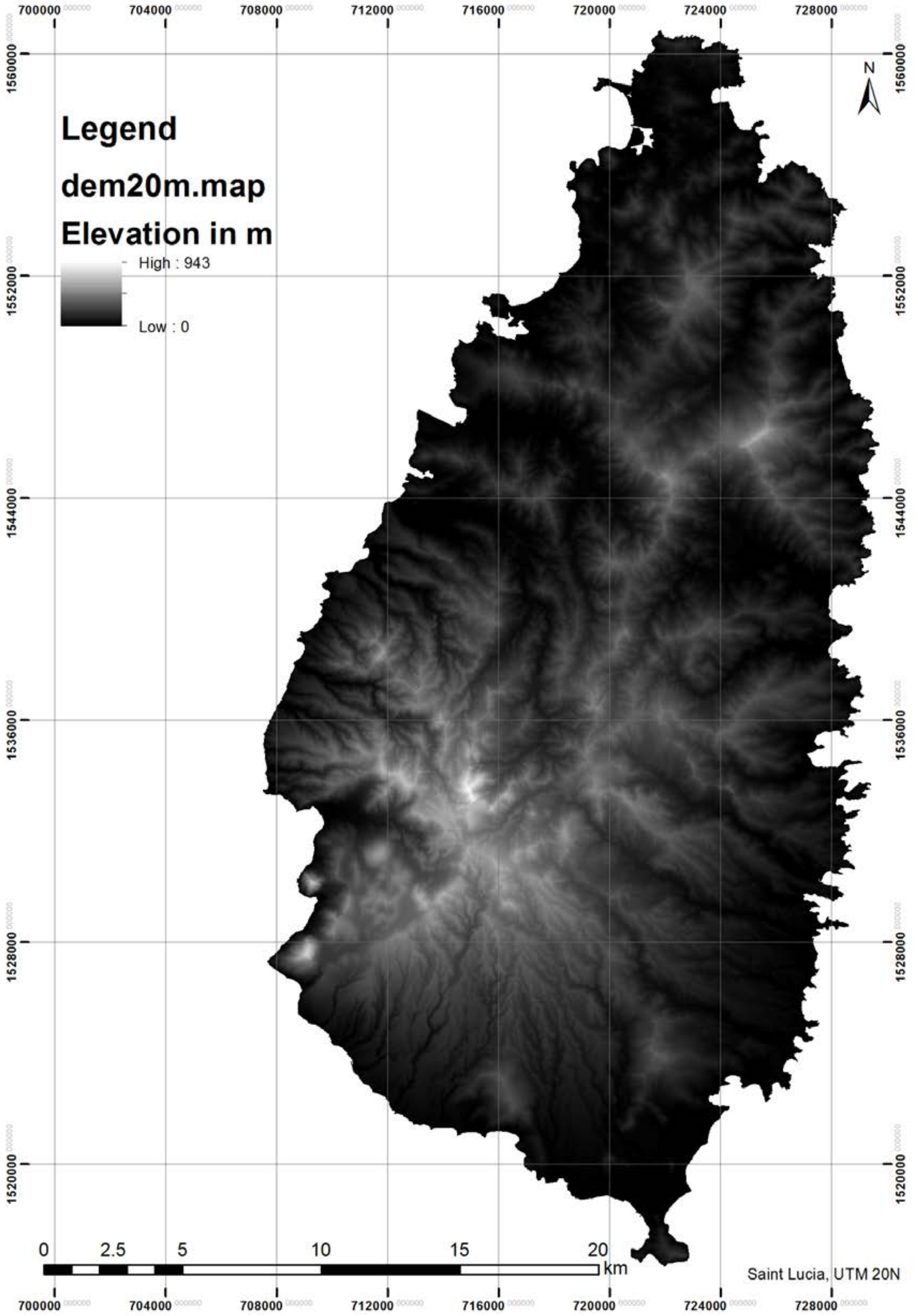
APPENDIX D

Channel/river map



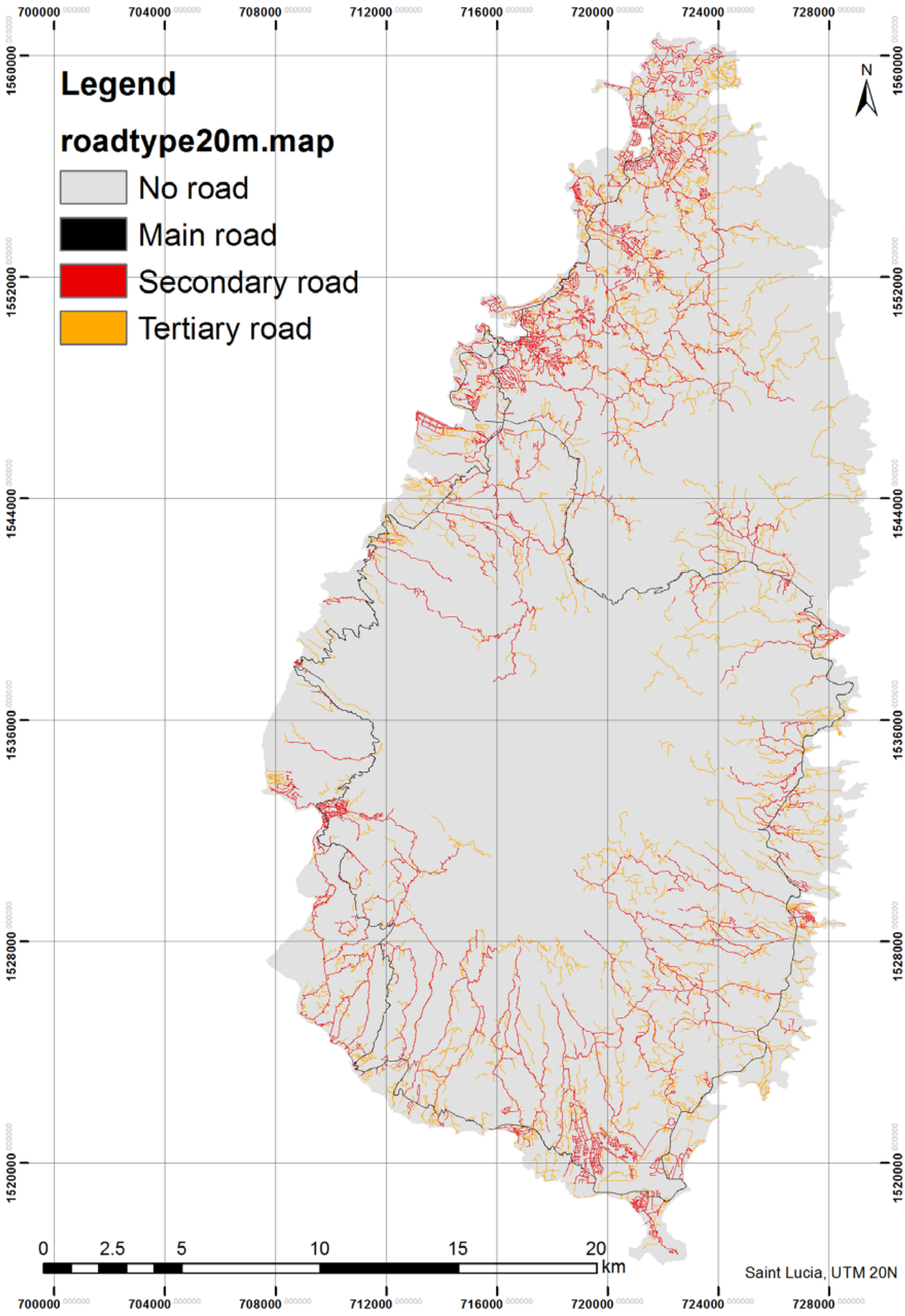
APPENDIX E

Elevation map



APPENDIX F

Road map



APPENDIX G

ArcGIS model builder for converting Hydro-Estimator data to TIFF.