# FLASH FLOOD BEHAVIOUR ON A SMALL CARIBBEAN ISLAND: A COMPARISON OF TWO WATERSHEDS ON GRENADA

RAHMAT ARIS PRATOMO
[March, 2015]

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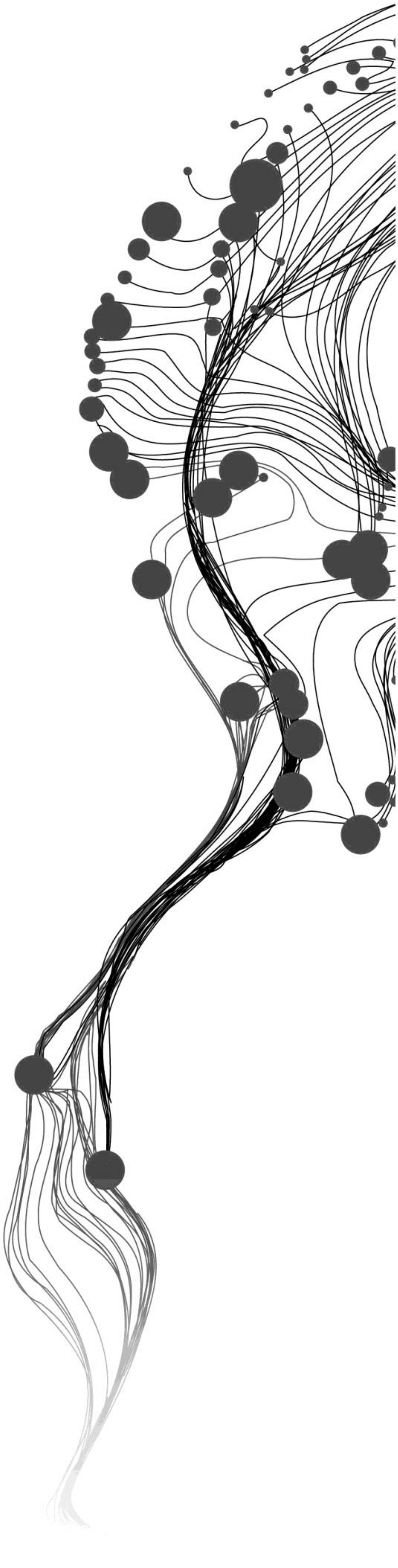

# FLASH FLOOD BEHAVIOUR ON A SMALL CARIBBEAN ISLAND: A COMPARISON OF TWO WATERSHEDS ON GRENADA

RAHMAT ARIS PRATOMO
Enschede, The Netherlands, [March, 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.
Specialization: Applied Earth Science-Natural Hazard and Disaster Risk Management

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# ABSTRACT

Flood assessment is very required and necessary conducting in the susceptibility flood area. However, many research have been conducted and they were only assess the flood events, it did not explain the flood characteristics. This research is developed to compare the response of flash flood behaviours in Gouyave watershed and St. John's watershed, Grenada, Caribbean Islands. Those two watersheds have different characteristics, specifically those land-use types. Approximately 49% St. John watershed is built-up area, whereas most of Gouyave watershed is still forested. St. George represents city or urban area in Grenada and Gouyave represents the village in Grenada that are susceptible to flooding. Some tools are combined to developing this research, such as ArcGIS 10.2, ILWIS 3.3, and ERDAS Imagine 2013 software for GIS operation. Then, PC raster and Open-LISEM software for flood modelling.
OpenLISEM software was used to analyze the flood characteristics in two watersheds, specifically for hydrology, and rainfall data which are combined with land-use types and soil types for developing flood model. This research started with collecting research data from fieldwork in Gouyave watershed and St. John's watershed during a month. Identifying land-use types were conducted by interpretation of satellite imagery (Pleiades). Then, soil physical measurements, that are consist of Ksat, initial soil moisture, porosity, random roughness, and manning's, were conducted during fieldwork in Construction Materials Laboratory of the Grenada Bureau of Standards. In the flood modelling, several data was used, such as DEM map, Ksat map, surface roughness map, manning's n map, and soil moisture map. In order to get the best accuracy value of flood modelling, it was conducted also sensitivity analysis with determining a certain values. The most sensitive parameters to flood model are Ksat and initial soil moisture. Before continuing the development of flood model, the model calibration and model validation was required to conduct in order to check the best model performance. Then, determining the rainfall intensity for different return period using Gumbel method. It was resulted five return perids, 2, 5, 10, 35, and 100 years return periods. The 2, 35, and 100 years return period was used as input data for flood modelling. The flood characteristics can be shown from the flood model in three different return periods. The flood characteristics that were analyzed such as peak discharge, total discharge, total infiltration, flood depth, flood duration, flood propagation time, flood volume, and flood area in different return period. Based on the assessment, there is not occur flood event in 2 years return period because the rainfall intensity in this period is classified into low categories. In the 35 years return period and 100 years return period, the flood characteristics in St. John's watershed, such as peak discharge, flood depth, flood volume, and flood area are higher than Gouyave watershed. It is concluded that St. John's watershed is more response to flood than Gouyave watershed. The classification of flood depth in Gouyave watershed and St. John's watershed also conducted in this research and the results is five classes of flood depth. In the end of this research, it assessed the exposed buildings and land-use types that are affected to flood. In two watersheds area, the built-up area, shrub, and grass land are the highest land-use that affected by flood.

Keywords: flood, LISEM, Carribean, sensitivity, flood characteristics

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*Rahmat Aris Pratomo*
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# LIST OF ABBREVIATIONS

DEM : Digital Elevation Model
ILWIS : Integrated Land and Water Information System
LAI : Leaf Area Index
LDD : Local Drain Direction
LISEM : Limburg Soil Erosion Model
RMSE : Root Mean Square Error

# 1. INTRODUCTION

## 1.1. Background

Flood is the most frequent natural hazards worldwide. More than fifty percent of the total population in the world is living in low lands near the rivers and coasts that are highly exposed to flooding (Mhonda, 2013). Generally, flood is the abnormal rise of the water level of a stream that may result in the overflow of the normal level of the stream with the subsequent inundation of areas that are not normally being submerged (Wigati, 2008). The flood impact does not only occur locally, but may also affect the whole area of river basin. The characteristics of flood depend on the geophysical and climatology conditions of an area (Rajibul Islam, 2012).

Flood can be categorized into two types, namely coastal flooding and river flooding, based on the location where it occur (Carby, 2011). Coastal flooding is a result of fluctuations in surge and wave setup, whereas river flooding is generated by excesses in river discharge, often due to intense rainfall or manipulation of river flow control structures (Carrasco, a.R., Ferreira, O., A., & Freire, P., 2012). A local river flooding that occur suddenly with great volume and short duration following less than six hours of heavy rainfall, often from severe thunderstorms or due to dam or levee failure is called a flash flood (APFM, 2007a).

There are other factors that trigger the occurrence of flash floods. These are topography, soil conditions, and coverage of terrain. The topography conditions, like high-lands, the steep cliffs, and narrow valleys can increase the possibility of flash flood occurrence. Furthermore, saturated soil and impermeable and shallow geological layers can increase the surface run-off (APFM, 2007b). Several natural hazards such as landslides and snow melting can also lead to flash flood.

Grenada is a part of Eastern Caribbean region. It is located between The Caribbean Sea and The North Atlantic Ocean (Stanton, E.A., Ackerman,F., West, K., & Rio, P., 2008). Annually the rainy season begins in June and ends until November. The average of annual rainfall in Grenada is 2350 mm/year in 2011 (Mecometer, 2014). Most of flood events are caused by local heavy rainfall, such as the latest event in 2011 that hit Grenada. Flood occurred in some locations in Grenada and one of the affected areas was in Gouyave watershed. Flood event in 2011 was influenced by hurricane Ophelia. The Grenada's local governments explained that several flood events in 2011 occurred in Grenada Because of these considerations, food event in 2011 are used as event base for flood modeling.

Some of the highest intensity rainfall are also delivered by tropical storms and hurricanes that can hit the population lives, its properties, and their livelihoods (Stanton, E.A., Ackerman,F., West, K., & Rio, P., 2008). Historically, in the beginning of the 20$^{th}$ century until 2004, Grenada had been hit by one unnamed storm in 1921, Hurricane Janet in 1955 and Hurricane Flora in 1963. After 50 years, in 2004 and 2005, Hurricane Ivan and Hurricane Emily (classified as category 3 and category 2) hit in Grenada (GFDRR, 2010). Ivan was the worst hurricane that has been struck the island since Hurricane Janet in 1955. At least 80 percent of the population was affected and more than 14,000 building damaged (Stewart, 2005). The latest hurricane in 2013 also caused flood in some flood-prone areas. However, the flood events in 2013 did not give great damages to Grenada's area, like flood events in 2011. Because Grenada is often hit by these hurricanes, Grenada area and surroundings is called "the hurricane belt".

Related with regional development, the impact of flash floods is affected to the development of Grenada's area as a tourism destination. The development of tourism activities and infrastructures will be obstructed, are caused by the Grenada's susceptibility to flooding. It means that flood assessment is required to conduct in the urban centers and the downstream areas, as susceptibility areas to flood. Then, Grenada's government can develop mitigation actions to reduce the flood impacts.

The climatic conditions and geomorphology characteristic in this region is dynamic. It makes Grenada prone to flood. Flash-floods that occurred in some locations usually have different characteristics than other areas. Besides the geomorphologic and climatologic factors, the watershed responses to flood becomes one of the flood characteristics to be analyzed, so the responses of watershed to flood becomes one of important assessment in this research. The understanding of overall flood characteristics in Grenada is important to support and develop the Grenada's mitigation actions to reduce the impacts of flash-floods.

## 1.2. Research Problem

Niles (2010) and GFDRR (2010) declared that there are some locations in Grenada that have high susceptibility to flooding. Susceptibility refers to locations or where the hazard events are probably occur which are determined from local terrain conditions (Santangelo, N., et al, 2011). The combination of the high amount of rainfall, steep slopes, and rolling hills with low porosity of soil contributes to high run-off rapidly causing floods downstream. The land use development means land use conversions which are changed the green area or natural land-use to built-up area affected to the increasing of impermeability of this land-use. The impermeability is also influenced to the rate of infiltration rates. It seems that the developed area or built-up area has low infiltration rates. It refers that the land use conversions change the soil impermeability and it decrease the rate of infiltration. So, the rate of soil infiltration also triggers the increasing flash-flood events in Grenada (Niles, 2010).

St. George is the biggest city and also the capital city of Grenada. Approximately 36% of the population in Grenada lives in St. George. Other villages in Grenada are Gouyave, Grenville, Victoria Sauteurs, and Hillsborough/Carriacou. St. George, Gouyave, and Grenville are areas where a part of population is at risk to flooding (CCA, 1991). CCA (1991) records that there are 6 divisions in Grenada that have high susceptibility of flood and only St. David has a low probability of flood.

This research is focused on the assessment and comparison of flood characteristics in two different watershed areas. Those two areas are chosen to represent different watershed characteristics. Gouyave represents rural area in Grenada and St. George represents urban area in Grenada. Approximately 5,33% of Gouyave watershed area is built-up areas. It is different with St. John watershed that has 23,28% built-up areas. Some upperpart areas of St. John's watershed have become developed areas, whereas most of the upperparts of Gouyave watershed are still forested. Both of them are susceptible to flooding (CCA, 1991). The increasing of flash flood events in Grenada and its impacts are caused by the high intensity of land-use conversions in Gouyave watershed and St. John's watershed. (Niles, 2010). The changes in land-use types increase the soil impermeability and decrease the rate of soil infiltration. Besides from the effects of land use conversions, these two watersheds have highly intensity in the monthly rainfall average. CEHI (2006) reported that the rainfall in Gouyave watershed during rainy season (Jun-Nov) is 250-350 mm, whereas the rainfall in St. John watershed at same period is 150-250 mm.

In Grenada, flood events often occur in two areas, St. George city in the St. John's watershed area and Gouyave town in the Gouyave watershed are. Flash-flood events in St. George occurred in the downstream of St. John River, while flash-flood events in Gouyave town also often occurred in the downstream parts of Charlotte River. The flash flood that occurred in Gouyave Watershed and St. John's Watershed can be characterized into two types based on its location. (1) The flash flood in upper part flow along the river to downstream with high velocity as influenced by the high river gradient. (2) In the lower part, the flood water overflow from the river and it spread to areas surrounding the river. It is influenced by the change in gradient from steep to flat in river. The Grenada locations which are pointed out the flood conditions and flood susceptibility area of Gouyave watershed and St. John's watershed, are shown in **Figure 1-1.a, b, c and d**.

(a) (b) (c) (d)

Figure 1-1 (a) Flood condition in St. John's watershed, (b) Flood condition in Gouyave watershed in 2011, (c) Identified potential areas of flood propagation in St. John's watershed (Cooper & Opadeyi, 2006), and (d) Identified potential areas of flood propagation in Gouyave watershed (Westen, 2014)

Until this period, some relevant studies and reports have been done for Grenada, including (1) Cooper & Opadeyi (2006), who explained the flood map in national and local scale (St. George). That research only explained the flood areas in the downstream of St. John River. (2) A report prepared by (CDERA, 2003) identified the susceptibility-areas of flood events and recommended mitigation actions in Grenada. The assessment of flash flood behaviors/characteristics is very limited. The previous studies of flood assessment in Grenada did not explain clearly about the flash-flood characteristics and these impacts in the flood susceptibility area of Grenada, such as the lower-parts of Gouyave watershed and St. John’s watershed.

Based on these considerations, it is required and important to conduct a research that fills this information gap. This new research will analyze and compare flood characteristics in Gouyave watershed and St. John’s watershed that will be generated from flood modelling. In order to analyze the problems based on the event of flash-floods in Gouyave watershed and St. John’s watershed, it is required to use open LISEM software. OpenLISEM software is a tool that can support this analysis and develop flood modelling.

## 1.3. Research Objectives and Questions

### 1.3.1. Research Objectives

The main objective of this research is to compare the response of flash flood behaviors in Gouyave watershed and St. John's watershed, Grenada, Caribbean Islands. In order to achieve the main objective of this research, the following sub-objectives will be addressed:

1. To characterize the physical parameters (land-use and soil properties) for flash flood generation in Gouyave watershed and St. John's watershed;
2. To determine the frequency and magnitude of rainfall based on recorded daily totals and create design events for a series of return periods.
3. To assess the sensitivity of parameters on the LISEM flood model, and choose a set of calibration parameters based on a best fit against stakeholder based observed water depth (2011);
4. To compare the flood characteristics for different returns in Gouyave watershed and St. John's watershed;
5. To assess the exposure buildings and land use types to flood based on different return periods in Gouyave watershed and St. John's watershed.

### 1.3.2. Research Questions

The research questions are formulated based on some sub-objectives presented above.

Specific objective 1:
1. What are the land use types and soil types of Gouyave watershed and St. John's watershed?
2. How can soil properties measured in the field best be related to land use or soil types?

Specific objective 2:
1. What are daily maximum value for given return periods
2. How do we generate a design events corresponding to these daily maxima?

Specific objective 3:
1. Which parameters have the most influence to flood modelling?
2. Do the flood models represent the 2011 flood event?

Specific objective 4:
1. What are the characteristics of flash-floods in different return periods?

Specific objective 5:
1. Which types of land use/land cover are exposed to flooding in the Gouyave watershed and St. John's watershed?
2. How many buildings are exposure to flooding in the Gouyave watershed and St. John's watershed?

## 1.4. Thesis Structures

This thesis consists of seven chapters:

**Chapter one** identifies the research background, research problem that should be answered in this study, research objectives and questions.

**Chapter two** consists of summary and synthesis of literature reviews that are used as theoretical background for strengthening the research components. This chapter is divided into five main topics. They are classification of floods, factor influencing floods, characteristics of flash flood, flood modelling, and LISEM for flood modelling.

**Chapter three** contains the methods of this research. It is explained the research procedures and implementation, description of research area, data sources and data collecting methods, and also types and tools of analysis in this research.

**Chapter four** explained the physical parameters which are influenced to flood modelling. Those parameters are land use, soil physical properties, and rainfall.

**Chapter five** shows the flood modelling in the event base (year 2011 of flood event). This chapter is divided into 4 parts: LISEM input data, sensitivity analysis, model calibration, and model validation. This chapter also compares the flash-floods characteristics in Gouyave watershed and St. John's watershed based on three return periods.

**Chapter six** explains the exposure building and land-use that area affected by flood based on three return periods. This chapter also informs the classification of flood depth in Gouyave watershed and St. John's watershed.

In the end, **chapter seven** is explained the research conclusions, recommendations, and limitations of this research.

# 2. LITERATURE REVIEW

## 2.1. Classification of Floods

Flood is a natural phenomenon which is defined as an overflow of water into lands that are used or are usable by human and are not normally covered by water (Mandych, 2009). The common characteristics of flood are the temporary nature of the inundation of lands by a river, stream, lake, or ocean. In addition, floods usually occur in short-term or seasonal events in the particular areas. Generally, floods are caused by two major factors, such as physical conditions and geographic conditions. The physical conditions mean change and interaction in the lithosphere, atmosphere, or hydrosphere. Then, the geographic causes refer to human activities and interventions or inappropriate planning and development. Moreover, the climatic factors, such as the extreme temperature changes and the extreme rainfall intensity, as impacts of climate change, are also influenced to flood events. In fact, the high intensity of rainfall becomes the most influence factor that causes flash-flood events.

Based on some respective causes, floods can be classified into 4 types (Dhar, O.N. & Nandargi, S, 2003). Those types are:

a. Seasonal floods, floods that usually occur in a particular season, like a rainy season. It is triggered by high intensity of rainfall in certain areas.

b. Flash floods, single flood events that occur suddenly in hilly or mountainous watersheds and hit into river channels. It has high velocity and can destroy infrastructures. It usually happens with rapid cresting with very short warning time.

c. Glacier melting. It is characterized by melting waters from glacier after the last of ice age and now, it is as an impact of global warming. The higher temperature in the earth surface makes the intensity of glacier melting higher. Sea level rise due to the increasing of sea water is not considered as hazards because it occurs in the long time period (van Westen, C.J., et al, 2011). Glacier melting is affected to the increasing of water volume in the ocean and flow into low-lying areas. However, the intensity of glacier melting enhances the volume of sea water is a normal situation.

d. Storm surges/tidal waves. It is defined as water that is pushed up into dry-land by onshore winds (Juan, Li and Chen Yong, 2014). It only occurs near the coast or estuaries and it is influenced by wind conditions. Besides that, the storm surges or tidal wave is also influenced by land use conversions and climate change effects. The increasing of population growth and human activities make a widespread conversion of natural landscape into settlements, urban centers, or tourist resort. The changes in coastal area from natural landscape to artificial landscape affect to the decreasing of coastal ability in reducing the rate of tidal waves. Moreover, the climate change effects which are composed by temperature anomalies and sea-level pressure gradients influence to wind patterns and storm ( Nicholls, Robert J. and Poh Poh Wong, 2007). The very high speed of wind, storm intensity, and storm frequency enhance the susceptibility of storm damage and coastal flooding.

## 2.2. Flash Floods and Factor Influencing Flash-Floods

Creutin, J.D. and M.Borga (2003) identifies that flash flood is a hydrological phenomenon which flows very fast and in which water can reach a peak level in less than 64 hours. Moreover, Saber, et al, (2010) highlighted that flash flood is a natural hazard which occur in arid and semi-arid locations with a very high velocity and occur in short duration, which is caused by high intensity of rainfall or dam failure and it impact to the infrastructure damages and loss of life. Thus, it can be concluded that flash flood is a dangerous natural hazard which can damage urban infrastructures and threaten human's lifes and socio-economic sectors.

Various factors, such as physical processes and non-physical processes influence flash flood events. The physical processes include changes in geological and morphological factors, hydrological factors, and also human influences (Mandych, 2009). Kelsch, M (2001) highlighted that flash floods are hazards that area caused by severe rainfall, intensive run-off development with mudflows, soil erosion and landslides. Common characteristics which are influenced to flash-floods are morphological factors, rainfall as climatologic factors, and land-use as human interventions.

### 2.2.1. Influences of physical factors to flash-floods

#### 2.2.1.1. Geomorphological conditions

Surface conditions affect flash flood events. The geomorphological conditions of the area which are mountainous and steep slopes are some trigger factors of flash floods (Diakakis, M, E. Andreadakis, and I. Fountoulis, 2011). The highlands usually have the river upstream. If the volume of water in the river increases and the terrain is steep, the water flows down with higher intensity. If the downstream river cannot accommodate the water from upstream, the flash floods can occur and water flows with high velocity to the downstream area. It is different with flat-slope area; run-off water would be flown in low or moderate velocity and water only inundate in those area for a long time. Whereas, in the steep-slope, run-off water usually flow down into the lower areas with high velocity and volume. The geographic situation in the area where the flood takes place affect to the scale of floods, depth of inundation, and its duration (Mandych, 2009). The characteristics of catchment area, including catchment shapes, drainage patterns and waterway steepness is also necessary to analyzed (X.Liu, Z. Zhang, and K. McDougall, 2011). Those parameters are necessary for identifying the hydrologic behaviors for each catchment area. The hydrologic behaviors illustrate the slope gradient of waterways and catchment area, and also, the land characteristics to catch run-off water.

#### 2.2.1.2. Soil characteristics

Beside the geomorphological conditions, soil characteristics also influenced to flash-flood events. The characteristics of the soil that affect flash-flood events are soil moisture, soil permeability, and soil porosity. Soil moisture is the quantity of water which is contained or stored in the upper-part of the soil. Soil moisture is defined as the amount of water stored in the soil. It makes soil pores will not absorb into the soil. It means the infiltration ability is decreased and the possibility of flash floods is larger. In addition, soil porosity is the proportion of empty spaces in the soil which can be occupied by water or air. The porous soil is drought, so it is hold and keeps water. The rate of soil infiltration is less because of the soil difficulties to hold and store water in the soil pores (Pedzisai, 2010).

Other soil parameter is influenced is soil permeability. Soil permeability is the soil parameter that indicates the soil capacity to transmit or pass water or other fluids. The most common indicator of this variable is soil textures, which gives an overview of the proportion of soil grain size (Masters, 2009). Generally, the small soil sizes, such as clay and silt. The soil surfaces of these soils are smooth, wide, and has smaller percentage of porous than sandy soil. These characters make silt and clay are very functioning in water retention. Thus, silt and clay are strong to hold water and store their organic materials. However, these soil types are difficult to pass/flow run-off water, so run-off water will be tend/pool and it does not infiltrate into the ground. It is different with sandy soil. Sandy soil with large soil particle sizes has higher infiltration rates. It has more porous textures and this character make sandy soil is easy to water and air movement into the soil. Thus, the rate of infiltration of sandy soil is faster and higher than clay and silt.

Beside soil textures, there is soil profile which is affected also to the soil infiltration. Soil profile describes the vertical organization of soil layers and the depth of soil column. For example, sandy soils have higher infiltration rates. However, when there is thin layer of clay material below the sand, the infiltration rates become small, so that the surface run-off becomes higher. The decreasing amount of water in surface areas is an effect from high infiltration ability of soil which is combined with deeper soil.

Human interventions, such as over-cultivation to the soil, soil compaction, and land clearing, also give impacts to soil (Masters, 2009). Those activities change soil structure and its cohesion, so that it potentially decreases their ability to absorb water. The granular soils which are entered into the soil can fill/store in soil pores. This condition makes the size of soil pores become smaller, so that it can obstruct the infiltration rates.

#### 2.2.1.3. Drainage basin

Besides the characteristics and properties of the soil, the drainage basin also affect to the flood events. There are several basin factors that influence the susceptibility to flooding, such as basin slope and surface roughness. Types and ranges of slope will be affected to the run-off time and amount of infiltration. The intensity of run-off water in high-slope areas is higher than run-off water in flat-slope. This is due to the higher magnitude of the gravitational force that pulls water into the soil surface (Creutin, J.D. and M.Borga, 2003). The higher intensity and magnitude of run-off water make the infiltration rate is decreased. The higher frequency of run-water in the stream discharge allows the less infiltration rates (van Westen, C.J., et al, 2011).

Furthermore, the physical conditions such as basin size and shape are also influenced. Runoff water from the upstream area of the larger basin size to the downstream area takes more time than water runoff in the smaller basins. In addition, the shape of the basin is also giving big impacts on the flow of runoff water and its duration. The wide basin shape or round will affect to the runoff water from some points, the run-off water will converge in one location at the same time.

### 2.2.2. Influences of rainfall to flash-floods

Like the basin characteristic, the rainfall is important to determine the characteristics of run-off. The rainfall factors that influence to the flood events are the rainfall intensity and its duration. Besides that, flash flood can be caused by slow-moving thunderstorms, heavy rains from hurricanes, and tropical storms (Macklin, Larry D, Paul J.Ehret, and Michael W. Neyer, 1999). The high intensity of rainfall effects to the soil saturation. Soil saturation is the comparison between volume run-off water and volume of soil pores. If the soil saturation is high, the rate of soil infiltration becomes decreased.

The decreasing of soil infiltration rates are affected to the increasing of volume and magnitude of surface run-off. Thus, the flash-floods are possible to occur. It seems that there is a strong relationship between rainfall intensity, soil saturation, and the overland flow (Rustanto, 2010). The climate parameters, specifically surface temperature and rainfall also influent the slope stability. If the high intensity of rainfall occurs in steep-slope locations, the flood susceptibility of these locations becomes higher. This condition occurs if the soil characteristics in this area are smooth and porous which is not being able to infiltrate the water. Moreover, the high velocity of run-off water will be eroded the soil, so it is not only occur flash-floods, but also it can trigger landslides.

The hurricanes and tropical storms also influence the flash-flood events. The hurricanes and tropical storms are caused by the highest differences of air pressures. The difference in air pressure causes the turbulences of winds which are accompanied by heavy rains. Both of parameters increase the influences of trigger factors which make the higher of potential damages from flash-floods. The strong energies and high speeds of hurricanes and/or tropical storms hit and damage many buildings and infrastructures which are traversed by flash-floods. In addition, the physical materials are also carried out by flash-floods, such as soil, mud, buildings, and other infrastructures. As a result, the potential loses are generated by flash-floods are increased the damages to the societies.

Return periods of rainfall is also considered in flash-flood events. Return period is "indicated the interval of period in years which hazards is likely to occur based on the historical records of rainfall" (van Westen, C.J., et al, 2011). The assessment of return period requires the analysis of the rainfall characteristics during certain times. Data required to conduct this assessment is historical measured rainfall data. The return period assessment aims to analyze the run-off characteristics in certain locations. Thus, the preventions and responses actions to flash-flood events can be prepared and planned properly according to the flash-flood characteristics.

### 2.2.3. Influences of land-use types to flash-floods

Other factors that influent the flash flood events come from land use changes, mainly due to the human development activities. Ezemoye, M.N. & Emeribe, C.N. (2011) pointed out that urbanization processes in urban areas and interventions in the river and coastal areas for agriculture, residential, industrial, and commercial activities may also trigger flash-flood events. The high intensity of human activities and the surface compaction in particular areas decrease the capacity of land infiltration, interception, and surface storage (Pedzisai, 2010). Areas which are dominated with built-up areas have a lower infiltration capacity than agriculture lands and forest. In the un-developed areas, there are vegetation roots which can help to absorb and keep the water into the soil. The vegetation can also slow down the water and thus, reduce the velocity and volume of surface run-off. It is different with develop or built-up areas. Generally, built-up areas are closed by many pavements. They do not have natural lands which can support to the water absorption, so run-off will flow directly with high velocity. Based on this condition, the developed or built-up area has lower infiltration ability than undeveloped areas.

The differences of land cover also give different effects to surface run-off and flash flood events. For example, the agriculture lands have less infiltration than forest. This is due to the vegetation's roots in the agriculture lands are not enough strong to absorb the water. Dunn in Pedzisai (2010) also declared that type and density of vegetation are important factors that are very influence to the soil infiltration rates. Furhermore, the vegetation roots are also important to decrease the run-off velocity. The vegetation roots store the run-off water strongly, specifically vegetation roots

Related with urban areas, run-off water in urban areas is flown in the drainage systems. However, the drainage cannot accommodate the run-off because low infiltration, interception, and less surface storage in build-up areas. These increases make the high possibility and impacts of flash floods. Moreover, the channel geometry also has a considerable influence on the possibility of flood events (Pedzisai, 2010). The shallow and narrows rivers are easily flooded.

Imamura, F. & TO, D.V (1997) declared that flash floods that occur in coastal areas have unique characteristics because they are frequently triggered by tidal surges or a dyke collapse. The combination between the high intensity of rainfall, the wind speed, and tidal surges make a great power of waves. It hit to the coastal areas and makes flash floods become more destructive.

## 2.3. Characterictics of Flash Floods

Flash floods are short-lived and destructive. It has a rapid stream rise with depths of water and can reach the banks of the creek very quickly. Bashir in Pedzisai (2010) highlighted that the specific peak discharge of flash floods is greater than 10 and can reach a value of 100 $m^3/s/km^2$. Alkema (2007) declared that flash flood occur suddenly and it is very extremely dangerous with high flow velocity and high impulsive, as result of maximum flow depth and maximum velocity. Flash-floods occurred due to the thunderstorm are moving slowly and or multiple thunderstorms which are occurred in some locations. Flash floods usually occur within six hours of the causing event (US National Oceanic and Atmospheric Administration, 2010) (US National Oceanic and Atmospheric Administration, 2010). However, the threshold of actual time in other locations may different and it is influenced with the location characteristics.

Flash-floods are based on the intensity and duration of rainfall, the catchment areas and shapes, drainage patterns, and waterway steepness. Flash-floods are very fast, have short durations, high speeds, and carry soil materials, mud, stone, wood, and other materials. In addition, flash floods have rapid water flow and extreme energy which are derived from built-up areas, agriculture lands, or overflow of river water due to increase drastically the volume of river water. The increasing of potential of sediment transport within water run-off is caused by the deforestation and wild-fires. These activities change the soil characteristics, specifically soil become hydrophobic and it cannot infiltrate run-of water (US National Oceanic and Atmospheric Administration, 2010). It is usually occurs after the high intensity of wild-fires in coniferous forest.

The flash flood can reach 3-6 m height and loaded with debris. Furthermore, flash flood also can trigger other hazards, like landslides and mudslides. High intensity of rainfall in the steep-slopes can decrease the soil stability and makes landslides or damaging buildings and properties (X.Liu, Z. Zhang, and K. McDougall, 2011). Flash floods usually happen in area with steep slopes and with impermeable surface or with saturated soils. CSIRO (2000) explains that the characteristics of flash flood can be classified into 5 categories based on their flow depth and velocity. It can be shown in **Table 1**.

Table 2-1 Flash-Flood Hazard Categories

| Hazard Category | Base Flood Events | Characteristics |
|---|---|---|
| Low | 100 year | Areas that are inundated in a 100 year flood, but the floodwaters are relatively shallow (typically less than 1 m deep) and are not flowing with velocity. |
| High - Wading Unsafe | 100 year | The depth and/or velocity are sufficiently high that wading is not possible, risk of drowning. |
| High - Depth | 100 year | Areas where the floodwaters are deep (>1 m) but area not flowing with high velocity. Damage only to building contents, large trucks able to evacuate. |
| High - Floodway | 100 year | Typically areas where there is deep water flowing with high velocity. Truck evacuation not possible, structural damage to light framed houses, high risk to life |
| Extreme | 100 year | Typically areas where the velocity is > 2 m/s. All buildings likely to be destroyed, high probability of death(CSIRO, 2000) |

*Source: CSIRO (2000)*

## 2.4. Flood Modelling

Flash flood is an unpredictable and sudden event that brings the great power with high destructive power and incredible speed (Bashir on Pedzisai, 2010). The flash floods impacts greatly affect humanity and are rated among the deadliest of all natural disasters. This is also caused by the difficulties to predict the flash floods events. Flood modelling contributes to the reduction of the flash-flood impacts and to reduce the uncertainty conditions in the flood-susceptibility areas.

Flood modelling is important things to estimate the run-off from rainfall in order to know the inundation areas of flood (Prachansri, 2007). Moreover, run-off modelling is needed for getting to know the characteristics of flash flood and forecast the flash flood threshold in some areas (Pedzisai, 2010). The results of flood modelling can support for preparing and conducting the effective actions to reduce the flash-flood impacts. Flash-flood prediction is an important consideration in the decision making of disaster management (Pedzisai, 2010). The best model is obtained, if there are similarities between model's performances with the reality of flash-flood events. Thus, the best model can represent the reality or the generated situations of flash-flood events in the past.

#### 2.4.1. Data preparation and assessment, according to the data requirements;

To get the best and most appropriate model, it is required some make considerations that are relevant to the modelling objectives, such as data availability, scale and time series data, technical knowledge, and also computing facilities. Thus, the data used to build model must be appropriated also with the aims of model. In the flash flood modelling, the intensity of rainfall is one of the important aspects to be analyzed. It is used to estimate the increasing of flood effects to some areas, specifically in order to get the real time forecasting.

Pedzisai (2010) also described that to build the appropriate run-off model, size and unit measurements of data are important. For example, pixel size is important for slope analyses. Besides that, time series of rainfall data are very important. Data preparations for conducting flood modelling based on five standard parameters (Setiawan, 2009), that are consist of (1) overland flow and channel flow; (2) soil surface, such as manning's n, random roughness, and other; (3) green and Ampt infiltration; (4) vegetation characteristics, like leaf area index, fraction canopy coverage; and (5) catchment characteristics, include slope gradient, catchment boundaries, and other variables. All of data that will be used as an input map for flood modelling should be rasterized in same resolution, so that the modelling process can be conducted well. Before applying in LISEM software, data preparations can be operated in PC Raster.

#### 2.4.2. Formulate and build flood modelling;

The Limburg Soil Erosion Model (LISEM) is a model that is used to conduct flood modelling. This software was constructed for quantifying the amount of run-off in the catchment areas in considering the changes of land use and the other factors affected the surface run-off (Prachansri, 2007). It is important to prepare the detail and high resolutions data to get the appropriate model using LISEM. Flood modelling using LISEM includes the following sub-modelling hydrological processes, rainfall, surface storage in micro-depression, infiltration, vertical movements of water in the soil, overland flow, and channel flow.

#### 2.4.3. Generating the result of flood modelling;

There are several indicators which are important to describe the characteristics of flash-floods. Flash-flood characteristics include peak discharge, total discharge, infiltration, and other flood parameters, such as flood volume, flood area, and flood volume (Maddox, R.A., Canova, F. & R., H.L., 1980). These parameters are calculated as results of flood modelling.

a. Peak discharge is the highest point on the hydrograph when the discharge level is located in the highest point.

b. Total discharge is the total of run-off of water flow in the rivers, channels, or certain locations when flash-flood occurred.

c. Infiltration is the process of absorb or transmit water into the soil which is influenced with soil characteristics, vegetation's roots, and land use types.

d. Maximum flood depth is defined as maximum depth of water which occurred during flood events during several times.

e. Flood area is the affected areas of flood events. The areas affected by flood can be predicted with considering flood vulnerability parameters.

f. Maximum flood volume is maximum of run-off water from which is caused by the high intensity of climatic factors or hydrological effects.

#### 2.4.4. Conduct calibration, validation, and sensitivity analysis;

There are some actions that should be done after running flood model, such as model calibration, model validation, and sensitivity analysis are required. They are important to guarantee that results are appropriate and we can trust the modelling results. Several steps should be conducted to get the best model performances, such as sensitivity analysis, model calibration, and model validation.

##### 2.4.4.1. Sensitivity analysis

Sensitivity analysis is used to determine changes in behavior/characteristics of the model as a result of adjustments/adaptation to one or more parameter values in the model (De Roo, A.P.J and Victor Jetten, 1999). Sensitivity analysis aims to determine the parameters that have the greatest influence on the model result. Some steps to conduct sensitivity analysis, such as:

- The sensitivity analysis performed with 3 times the calibration to identify the most sensitive parameter.
- The level of sensitivity of a parameter may depend on other parameters. Sensitivity analysis can be done by changing the combination of parameters.
- Sensitivity analysis is conducted by the simulations using symmetrically and uniformly model by adding specific value such as 10% adding and 10% subtracting (Prachansri, 2007). However, this value is not always used. It seems that the adding and subtracting values can be modified according to the research aims and characteristics of study area. Thus, the research should be estimated and predicted the appropriate value for developing sensitivity analysis.
- The result of sensitivity analysis is model parameter which is classified into the most sensitive parameters to flooding.

##### 2.4.4.2. Calibration

Calibration requires for minimizing the deviation between the results of the flood modeling (simulated data) and the observed or measured data of flood events. Conducting the model calibration aims to obtain the similarity between flood modelling results with to the measured values. If the measured data and simulated data are more similar, the model can be categorized into an accurate model. It means that the accuracy of flood model can be shown from the similarity result between measured data and simulated data. Calibration process is conducted by identify and assess the appropriate values for certain parameters (Hunter, Neil M, et al., 2005). The certain parameters involved in calibration process are selected from the result of sensitivity analysis.

##### 2.4.4.3. Validation

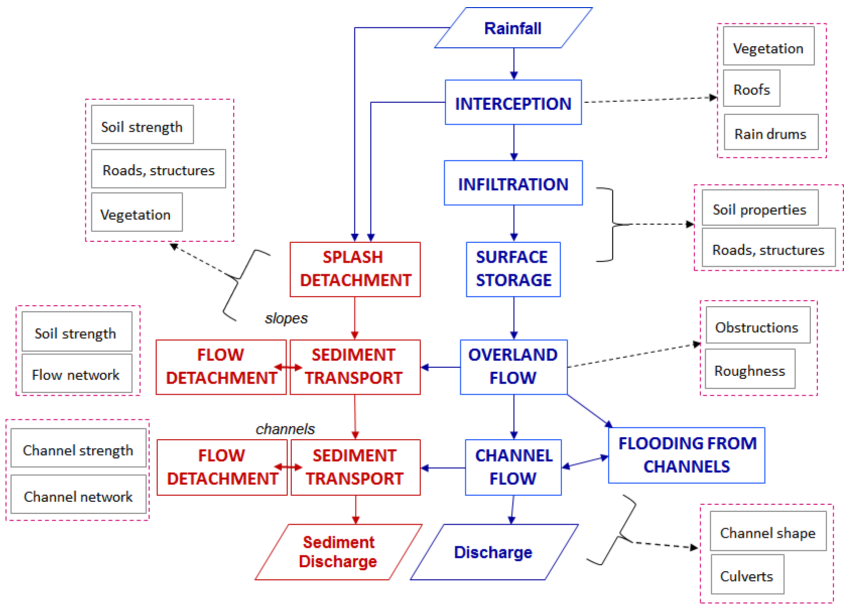
Validation process is conducted to analyze and validate the model. From the calibration processes, it can be known the assumptions and the relationships between the measured and simulated data. Model validation is conducted by assessing the flood model into other locations. From validation processes, researcher can reproduced the real behavior sufficiently and model can be applicable in other flood plains (Connel, Robert J, et al, 2001). The results of flood modelling should be reflected the essential features and behaviors of the flash-flood existing events (van Westen, C.J., et al, 2011). This process is conducted by assess and apply flood models in other locations that are susceptible by flash-floods. The method used to conduct this assessment using mathematical method, such model biasness and RMCE (Root Mean Square Error). These methods are explained clearly in the section 5.3.

## 2.5. LISEM for flood modelling

The Limburg Soil Erosion Model (LISEM) is modelling software based on physical hydrological and soil erosion model in the catchment area. According to Jetten (2015) openLISEM is "an event based natural hazard model, to simulate runoff, erosion and flash floods for a single rainfall event. It can be used for integrated catchment management on small to medium scales (equals 300 $km^2$ and less) and simulate processes in detail in space and time." It can design and simulate run-off and erosion that are affected from high intensity of rainfall or single storms.

As described by Baartman et al., (2012) the surface water balance includes processes such as interception of rainfall by vegetation (De Jong and Jetten, 2007) and buildings, infiltration using a 1 or 2 layer Green and Ampt infiltration method (Kutilek and Nielsen, 1994), the effect of surface storage in micro depressions (Kamphorst et al., 2000; Jetten and de Roo, 2001) and overland flow and channel flow with a kinematic wave (Vent e Chow et al., 1988). Shallow floods from the channel system are simulated with a finite volume solution of the Saint Venant equations as described by (Delestre et al., 2012).

The data requirements as an input data for Open LISEM is typically 10m to 20m spatial resolutions are used and timesteps less than 1 minute, while the total simulated time is typically between 1 hour and 1 day.To achieve the appropriate model, the input data for LISEM should be clear, detailed, and have high resolutions. OpenLISEM is usually used to hydrological and soil erosion model which have complicated processes. In order to develop model with OpenLISEM, it is important to prepare the detail characteristics of soil surface, such as channel information, road information, building information, soil structures, and soil physical information. Basic structure of OpenLISEM can be shown at **Figure2-1**.




*Source: LISEM basic theory, ITC, the Netherlands*
Figure 2-1 OpenLISEM Basic Structure

OpenLISEM software is can be used to planning and conservation purposes include hazard management. This model is enabling to generate the land-use change and its impacts to flood events, for example land-use change and its relationship with flood. With OpenLISEM, analysis of land-use effects is developed to analyze the effect of land use change in related variables, such as random roughness, manning's n, initial soil moisture content, saturated soil moisture content, saturated hydraulic conductivity, leaf area index, and vegetation height. All of those parameters are explain clearly in **section**

# 3. RESEARCH AREA AND METHODOLOGY

## 3.1 Research Area

### 3.1.1. Location

Grenada is one of the small island states in the Eastern part of the Caribbean region. It is located between latitudes 11° 59' and 12° 20' N and longitudes 61° 36' and 61° 48' W. The main island of Grenada has a surface area of312 km². Its topography is dominated by steep-slopes with mountains in the center of this island. In 2010, the total population in Grenada was estimated 110,000 people (GFDRR, 2010).

The main island of Grenada has 71 watersheds. The 12 largest watersheds are (Grenada's Land Use Division): Great river watershed; Beausejour watershed; St. Patrick's watershed; St. John's watershed; La Chaussee watershed; Victoria watershed; Tivoli watershed; Pearls watershed; Chemin watershed; Union watershed; Gouyave watershed; and Dougladston watershed. From several watersheds in Grenada, this research is only conducted in St. John's watershed that is included in St. George Parish and Gouyave watershed that is included in St. John Parish.

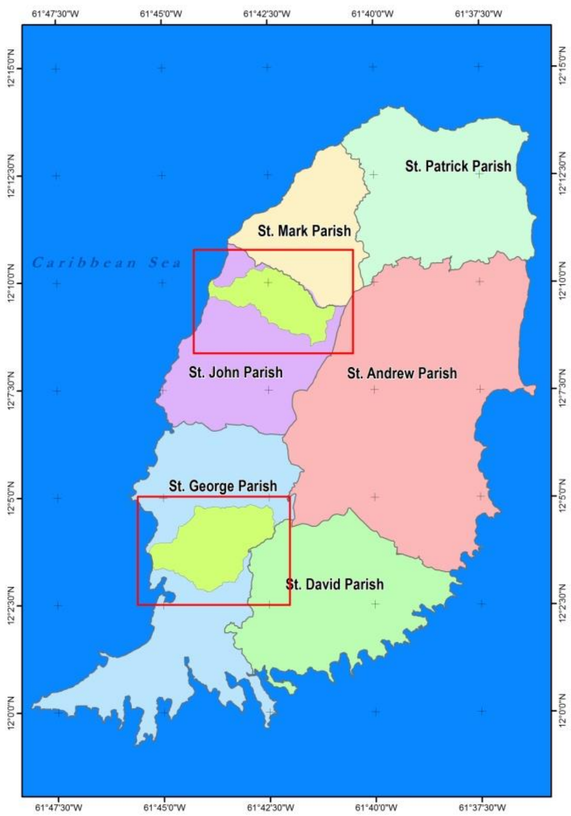
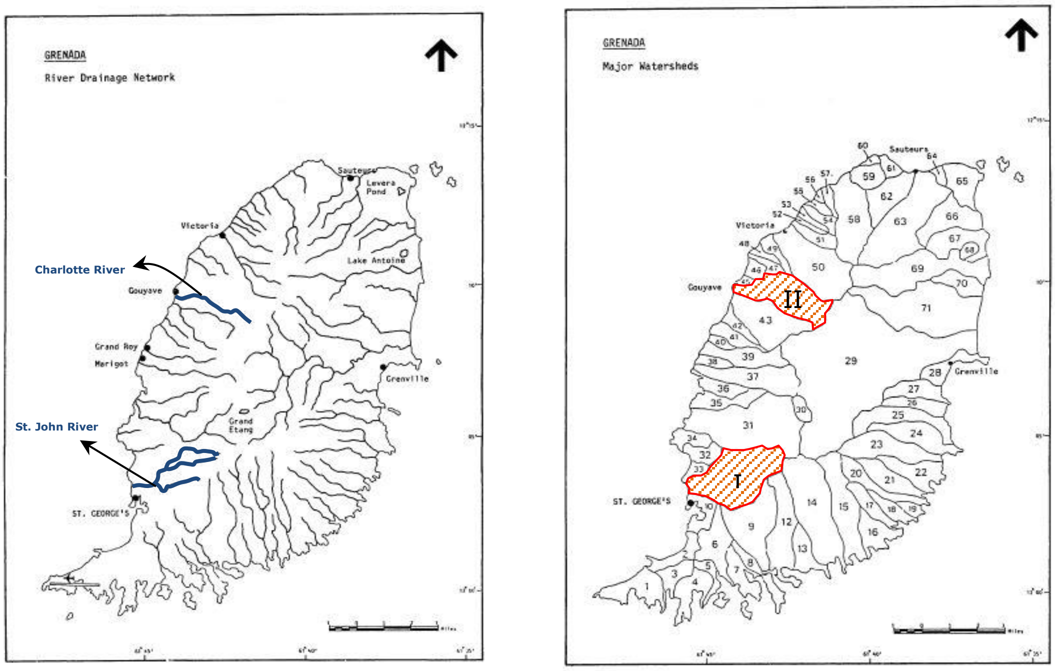


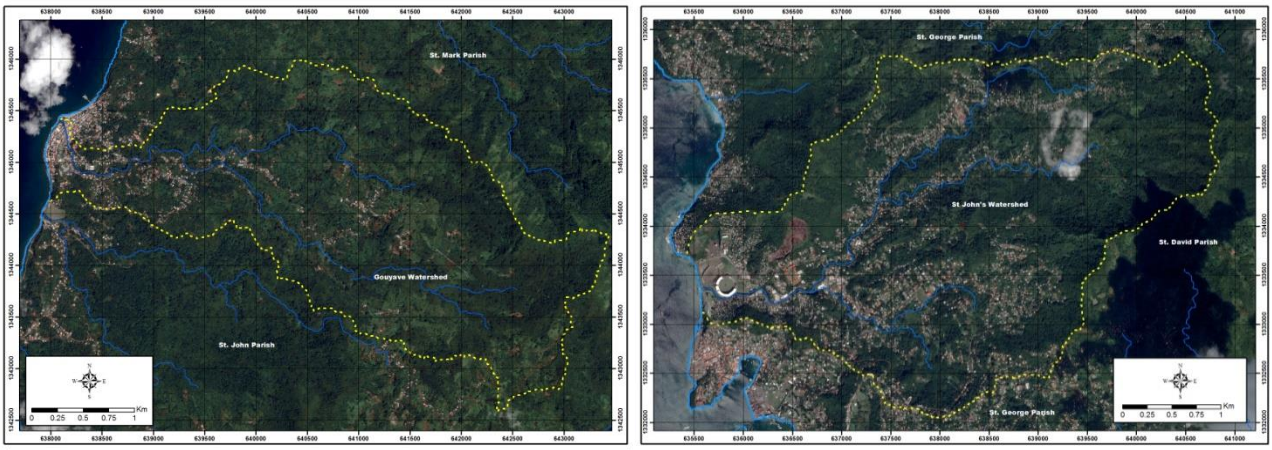

Figure 3-1 Orientation map of Gouyave watershed and St. John's watershed to 6 parish in Grenada

The Gouyave watershed is located in the north-west of Grenada and has a surface area of 8,39 km². The main river in this watershed is Charlotte River that divides Gouyave town into two areas in the downstream. The total area of St. John's watershed is 12,17 km² with St. John River as the main river. This watershed is located in the south-western part of Grenada. The lower parts of this area are dominated by the built-up areas of St. George, the capital city of Grenada. **Figure 3-2** shows the location of St. John's watershed and Gouyave watershed. Then, **Figure 3-3** shows the satellite imagery of St. John's watershed and Gouyave watershed.




(a) (b)

Figure 3-2 (a) St. John's River and Charlotte River and (b) St. John Watershed (I) and Gouyave Watershed (II)



(a) (b)

Figure 3-3 (a) Satellite Imagery of Gouyave Watershed and (b) Satellite Imagery of St. John's Watershed

### 3.1.2. Topography

Most of areas in Gouyave watershed are dominated with highlands, mountain peaks, and deep narrow valleys with elevation more than 200 m above sea level. The highest point in Gouyave watershed located in 690 meters above sea level The Gouyave highland-areas are dominated in the eastern parts and southern parts of this area. Moreover, Gouyave areas which have elevation in 50-100 m above sea level (low-land areas) are located near the coastal area. It is different with the St. John's watershed area. Most of

St. John's watershed areas are flat with elevation 50-150 m above sea level. However, the highest point in St. John's watershed located in 474 meters above sea level. The highland areas in St. John's watershed are only found in the eastern parts of this area, near the St. David Parish. The elevation map of St. John's watershed and Gouyave watershed can be shown in **Figure 3-4**.

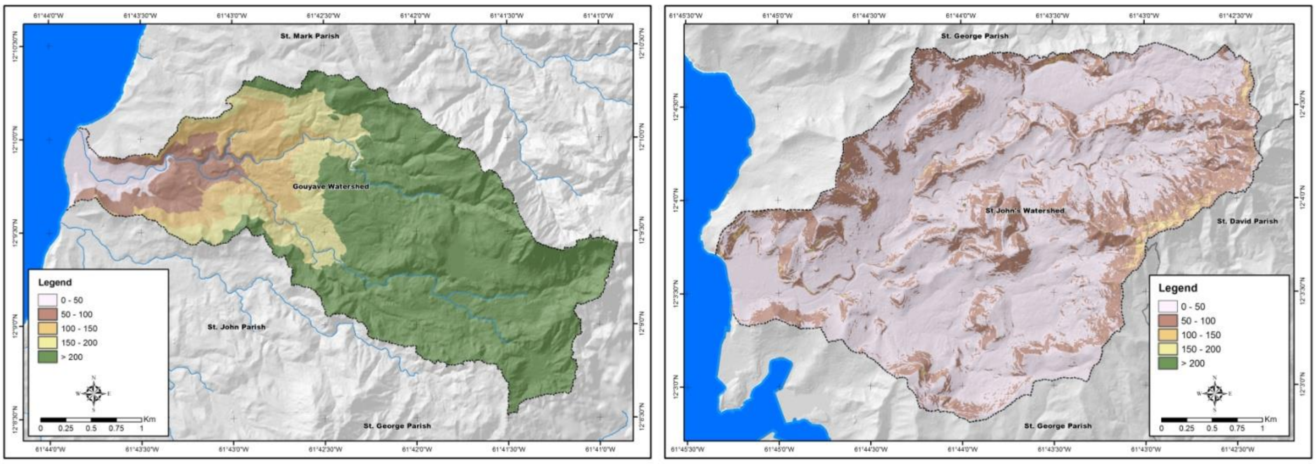



Figure 3-4 (a) Elevation Map of Gouyave Watershed and (b) Elevation Map of St. John's Watershed

The slope categories in Gouyave watershed and St. John's watershed are divided into 6 classes, such as:

- Class 1, flat or almost flat (0 - 2%)
- Class 2, gently sloping (2 - 8%)
- Class 3, sloping (8 - 13%)
- Class 4, moderately steep (13 - 25%)
- Class 5, steep (25 - 55%)
- Class 6, very steep (more than 55%)

The detail information for slope categories in each area is shown in **Table 3-1**.

Table 3-1 Slope Categories in St. John Watershed and Gouyave Watershed

| Gouyave Watershed | | | St. John's Watershed | | |
|---|---|---|---|---|---|
| Slope-Class | Area (km$^2$) | Percentage (%) | Slope-Class | Area (km$^2$) | Percentage (%) |
| 1 | 0.151 | 1.80 | 1 | 0.230 | 1.89 |
| 2 | 0.491 | 5.85 | 2 | 0.528 | 4.33 |
| 3 | 0.695 | 8.29 | 3 | 0.834 | 6.84 |
| 4 | 1.777 | 21.19 | 4 | 2.477 | 20.33 |
| 5 | 3.348 | 39.92 | 5 | 5.550 | 45.55 |
| 6 | 1.925 | 22.95 | 6 | 2.566 | 21.06 |

Generally, St. John's watershed and Gouyave watershed are dominated with steep area; consist of moderately steep, steep, until very steep. In St. John's watershed, slope-class 5 (steep, 25-55%) is enough dominated. The total area that is covered by slope-class 5 is 5.550 km$^2$ or 46% from total area of St. John's watershed. Furthermore, the slope-class category that is dominated in Gouyave watershed (39.92% from total area) is slope-category 5. It is covered 3.348 km$^2$ of Gouyave watershed area. The steep-slope in the majority of St. John's watershed area and Gouyave watershed area indicate that those locations are susceptible to flooding, because the steep-slope will increase the velocity and water volume of surface run-off.

### 3.1.3. Land-Use Characteristics

Land use classes in this research are adopted from land-use classes which are derived from the previous studies with homogenous land-use classes. The land-use types in Gouyave watershed are very dominated with green areas, such as forest, mixed-trees, and agriculture lands. Forest and mixed-trees covered in the most of Gouyave upper-part areas. There is only tropical forest-type in Gouyave watershed. The tropical climate is also influenced the agriculture activities in Gouyave which is produce paddy, nutmegs, bananas, cocoa, and other food crops. Other land-use types that are existed in Gouyave watershed are built-up area, grassland, shrub, and bare-land. The built-up areas only can be found in the lower-parts of Gouyave watershed, near coastal area.

There are 6 land-use types in St. John's watershed, such as bare, built-up area, forest, grassland, mixed-trees, and shrub. The built-up areas are located in the upper-parts and the lower-parts of St. John's watershed. Built-up area in St. John's watershed consist of housing, government's offices, hospitals, trade and commercial areas, and other human facilities. Moreover, there are many land conversions that change forest/other green areas into built-up areas in the some upper-parts of St. John's watershed due to human activities. However, forest and mixed-trees are still the land-use types that dominate St. John's watershed. Differently with Gouyave watershed, there are not agriculture lands in St. John's watershed area.

(a) (b)

Figure 3-5 (a) and (b) Built-up areas in Gouyave watershed and St. John's watershed

(a) (b)

Figure 3-6 (a) Forest and (b) Mixed-trees

(a) (b)

Figure 3-7 (a) Shrub and (b) Agriculture lands

### 3.1.4. Rainfall

There are 58 rainfall stations in Grenada, but only several rainfall stations that have been operated until now. However, those stations only recorded rainfall data with un-continuously for each year. The rainfall station that has continuous data is only Maurice Bishop International Airport (MBIA). This rainfall data is used to develop flood modelling in two watershed areas, Gouyave watershed and St. John's watershed.

The Maurice Bishop International Airport has time series of daily rainfall data started from 1986 until 2014. During 1986 until 2014, the average of annual rainfall is 1.109,6 mm. The highest annual rainfall occurred in 2010 with 1.513,3 mm and the lowest annual rainfall occurred in 1992 that only 338,6 mm. Furthermore, the highest of maximum daily rainfall is 177,5 in year 1990 and the lowest is 55 mm in year 2014.

Table 3-2 Maximum Daily Rainfall and Annual Rainfall (mm) during 1986-2014

| Years | Maximum daily rainfall (mm) | Annual Rainfall (mm) | Years | Maximum daily rainfall (mm) | Annual Rainfall (mm) |
|---|---|---|---|---|---|
| **1986** | 57 | 1130.6 | **2001** | 71.6 | 1060.4 |
| **1987** | 86.2 | 1094.5 | **2002** | 71.6 | 1208.2 |
| **1988** | 80.9 | 1402.4 | **2003** | 112.2 | 1312.2 |
| **1989** | 65.4 | 917.1 | **2004** | 133.7 | 1220.8 |
| **1990** | 177.5 | 693.9 | **2005** | 79.6 | 1090.7 |
| **1991** | 103.5 | 1328.4 | **2006** | 71.7 | 1021.5 |
| **1992** | 52.9 | 338.6 | **2007** | 86.6 | 1299.2 |
| **1993** | 63.8 | 744.9 | **2008** | 72.5 | 1341.4 |
| **1994** | 93 | 790.6 | **2009** | 53.2 | 1228.8 |
| **1995** | 72.1 | 1358.9 | **2010** | 80.7 | 1513.3 |
| **1996** | 60.1 | 1154.3 | **2011** | 172.9 | 927.1 |
| **1997** | 48.3 | 1050.5 | **2012** | 62 | 1063.3 |
| **1998** | 81.9 | 1249.2 | **2013** | 74.3 | 1079.4 |
| **1999** | 39.6 | 1016.9 | **2014** | 55 | 1231.7 |
| **2000** | 66.2 | 1310.2 | | | |

*Source: Primary Data from Maurice Bishop International Airport (MBIA), Grenada*

The number of annual rainfall data during 1986-2014 can be seen at **Figure 8** below.

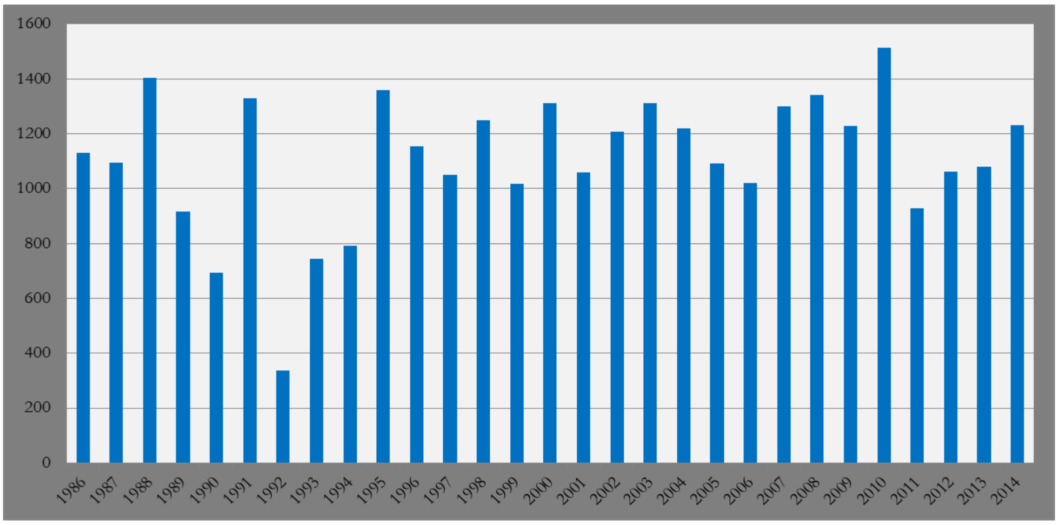



Figure 3-8 the Annual Rainfall in Grenada during 1986-2014

### 3.1.5. Soil Characteristics

Generally, soil characteristics in Grenada, specifically in St. John's watershed and Gouyave watershed is influenced by mountain and hill soils (Grenada's Environmental Profile). From **Table 4** can be found that the dominant soil types in Gouyave watershed are belmont clay loam (very steep & shallow phase) and capitol clay loam (very steep & shallow phase) which is make up 38,82% and 28.19% area of Gouyave watershed. Both of soil types are formed from mountainous areas with steep slopes and high rainfall. The characteristic of capitol clay loam is very fertile, so it is very potential to use as agriculture lands. However, this soil is moderately erodible (Grenada's Environmental Profile).

Then, the Belmont clay loam is usually found in the middle area of Gouyave watershed which has a high slope. The common characteristic of this soil type is moderately erodible (Grenada's Environmental Profile). Therefore, the best use of Belmont clay loam is for forest because it has capability to reduce the massive erosion if it is covered by natural vegetation. It is suitable with existing land-use type in Gouyave watershed area.

Table 3-3 Soil textures of Gouyave watershed

| Soil Texture Descriptions | Areas ($km^2$) | Percentage (%) |
|---|---|---|
| Belmont clay loam | 1.03 | 12.23 |
| Belmont clay loam (stony & bouldery phase) | 0.12 | 1.39 |
| Belmont clay loam (very steep & shallow phase) | 3.26 | 38.82 |
| Bonair bouldery sandy loam | 0.18 | 2.15 |
| Capitol clay loam | 0.07 | 0.89 |
| Capitol clay loam (very steep & shallow phase) | 2.37 | 28.19 |
| Concord clay loam | 0.07 | 0.78 |
| Palmiste clay loam | 0.46 | 5.54 |
| Plains clay loam | 0.03 | 0.38 |
| Plains sandy loam | 0.00 | 0.00 |
| Woburn clay loam | 0.68 | 8.12 |
| No information | 0.13 | 1.52 |
| **Total** | **8.39** | **100.00** |

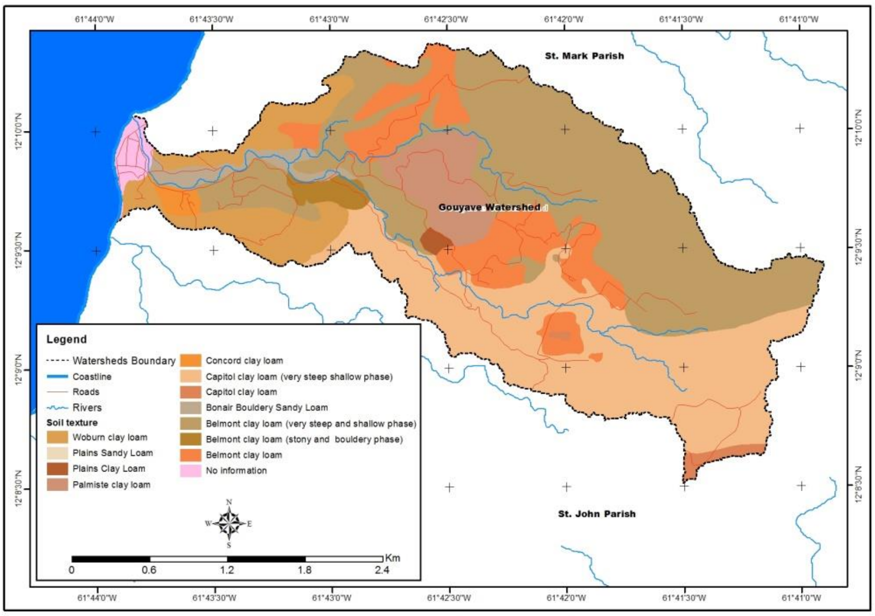



Figure 3-9 Soil characteristics of Gouyave watershed

Soil textures in St. John's watershed is dominated with *Woburn clay loam*. It is covered 31, 42% of St. John's watershed area. The characteristics of this soil-type are well drained, shallow, moderate fertility, and highly erodible. According to these characters, *Woburn clay loam* is rather suitable for food crops. Other soil texture which is covered in the most of upper-parts and lower-parts of St. John's watershed area is capitol clay loam. Generally, capitol clay loam is very fertile, so it is very potential to use as agriculture lands. However, there are not agriculture lands in St. John's watershed. The detail of soil textures in St. John's can be found at the following table.

Table 3-4 Soil textures of St. John's watershed

| Soil Texture Descriptions | Areas ($km^2$) | Percentage (%) |
|---|---|---|
| Belmont clay loam | 0.07 | 0.57 |
| Belmont clay loam (very steep & shallow phase) | 0.03 | 0.25 |
| Capitol clay loam | 3.06 | 25.12 |
| Capitol clay loam (very steep & shallow phase) | 0.07 | 0.60 |
| Concord clay loam | 2.29 | 18.82 |
| Hartman clay | 0.00 | 0.00 |
| Parnassus clay | 0.62 | 5.11 |
| Perseverence clay | 1.13 | 9.32 |
| Perseverence clay (stony/bouldery phase ) | 0.44 | 3.58 |
| Plains Clay Loam | 0.18 | 1.47 |
| Woburn clay loam | 3.82 | 31.42 |
| Woburn clay loam (stony/bouldery phase) | 0.04 | 0.35 |
| No information | 0.41 | 3.38 |
| **Total** | **12.17** | **100.00** |

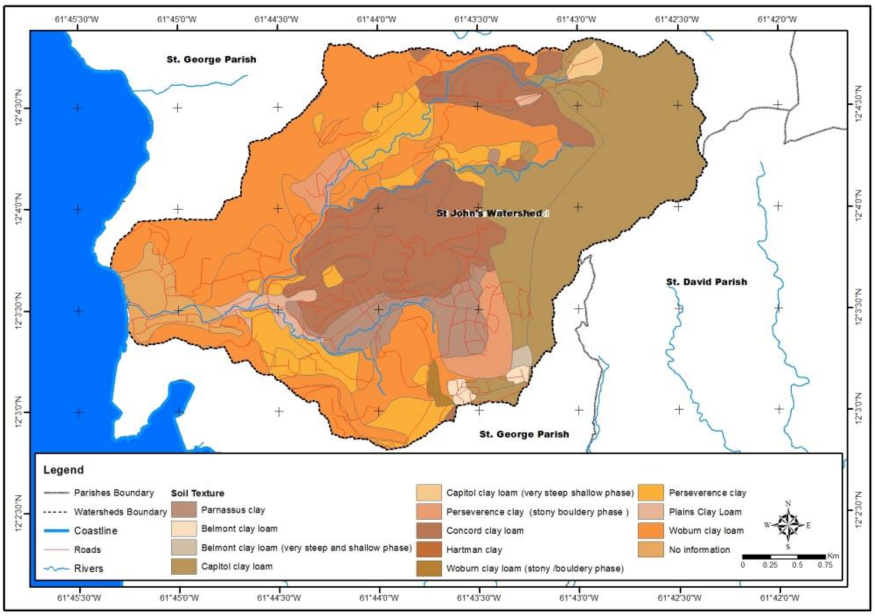



Figure 3-10 Soil characteristics of St. John's watershed

### 3.1.6. Geology Characteristics

The geology characteristics in St. John's watershed area and Gouyave watershed area are classified into 6 types. Based on **Table 3-5**, the dominant geology characteristic in Gouyave watershed is undifferentiated volcanic, mainly reworked (Pleistocene) which is covered 6,12 $km^2$ or 72,92% area of Gouyave watershed. The mount St. Catherine Volcanic is only covered the upper-parts area of Gouyave watershed. Then, the lower parts of Gouyave watershed is dominated with alluvial and superficial deposits.

Table 3-5 Geology Characteristics of Gouyave watershed

| Geology Description | Areas ($km^2$) | Percentage (%) |
|---|---|---|
| Alluvial and Superficial Deposits(Recent) | 0.15 | 1.74 |
| Lava Domes | 0.55 | 6.53 |
| Mount St. Catherine Volcanic (Pliocene-Pleistocene) | 0.78 | 9.33 |
| Town | 0.13 | 1.52 |
| Tufton Hall Formation (Late Eocene-Early Oligocene) | 0.67 | 7.95 |
| Undifferentiated Volcanic, mainly reworked(Pleistocene) | 6.12 | 72.92 |
| **Total** | **8.39** | **100.00** |

The undifferentiated volcanic is covered 87,25% area of St. John's watershed, specifically in the upper-parts and center parts of St. John's area (**Figure 3-12).** It is different with coastal area which is dominated with town (3, 38% area). It is interested in surrounding the river; this area is mostly covered by alluvial and superficial deposits. More information about geology characteristics can be shown at **Table 3-6.**

Table 3-6 Geology Characteristics of St. John's watershed

| Geology Description | Areas ($km^2$) | Percentage (%) |
|---|---|---|
| Alluvial and Superficial Deposits(Recent) | 0.23 | 1.90 |
| Lava Domes | 0.06 | 0.50 |
| Point Saline Beds | 0.21 | 1.73 |
| South East Mountain Volcanic (Miocene) | 0.64 | 5.23 |

| Geology Description | Areas ($km^2$) | Percentage (%) |
|---|---|---|
| Town | 0.41 | 3.38 |
| Undifferentiated Volcanic, mainly reworked (Pleistocene) | 10.62 | 87.25 |
| **Total** | **12.17** | **100.00** |

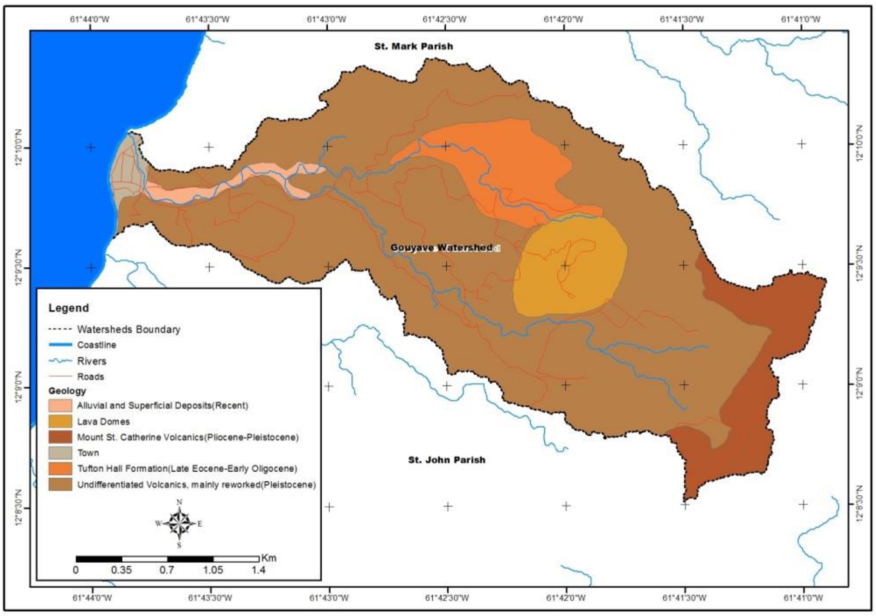



Figure 3-11 Geology characteristics of Gouyave watershed

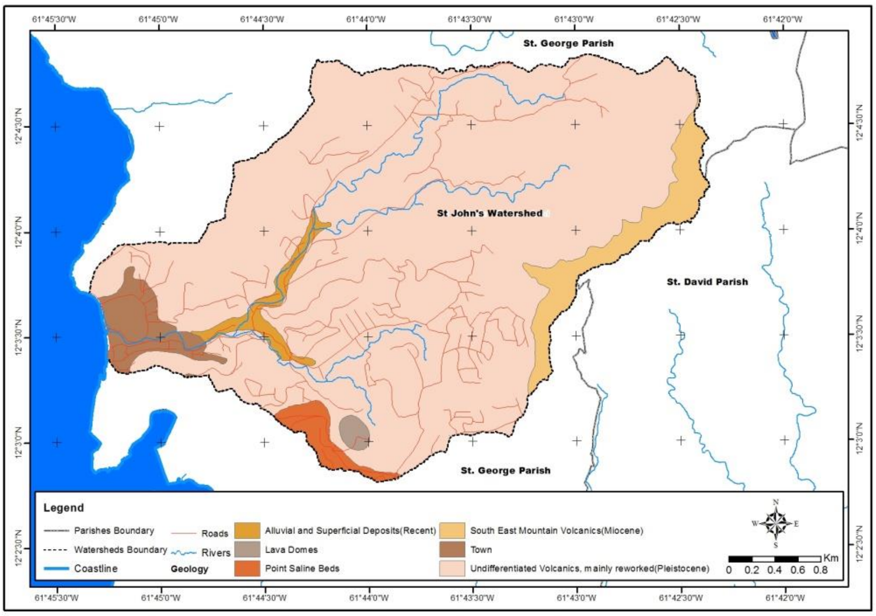



Figure 3-12 Geology characteristics of St. John's watershed

## 3.2 Research Framework

The research framework is developed to compare the flash flood behaviors at Gouyave Watershed and St. John's Watershed, Grenada. It also describes the input, process, and output of research. There are some stages that are conducted for achieving the research objectives. These phases are divided into 3 parts: pre-fieldwork, during fieldwork, and the post-fieldwork phase. The research framework can be seen at **Figure 3-13**.

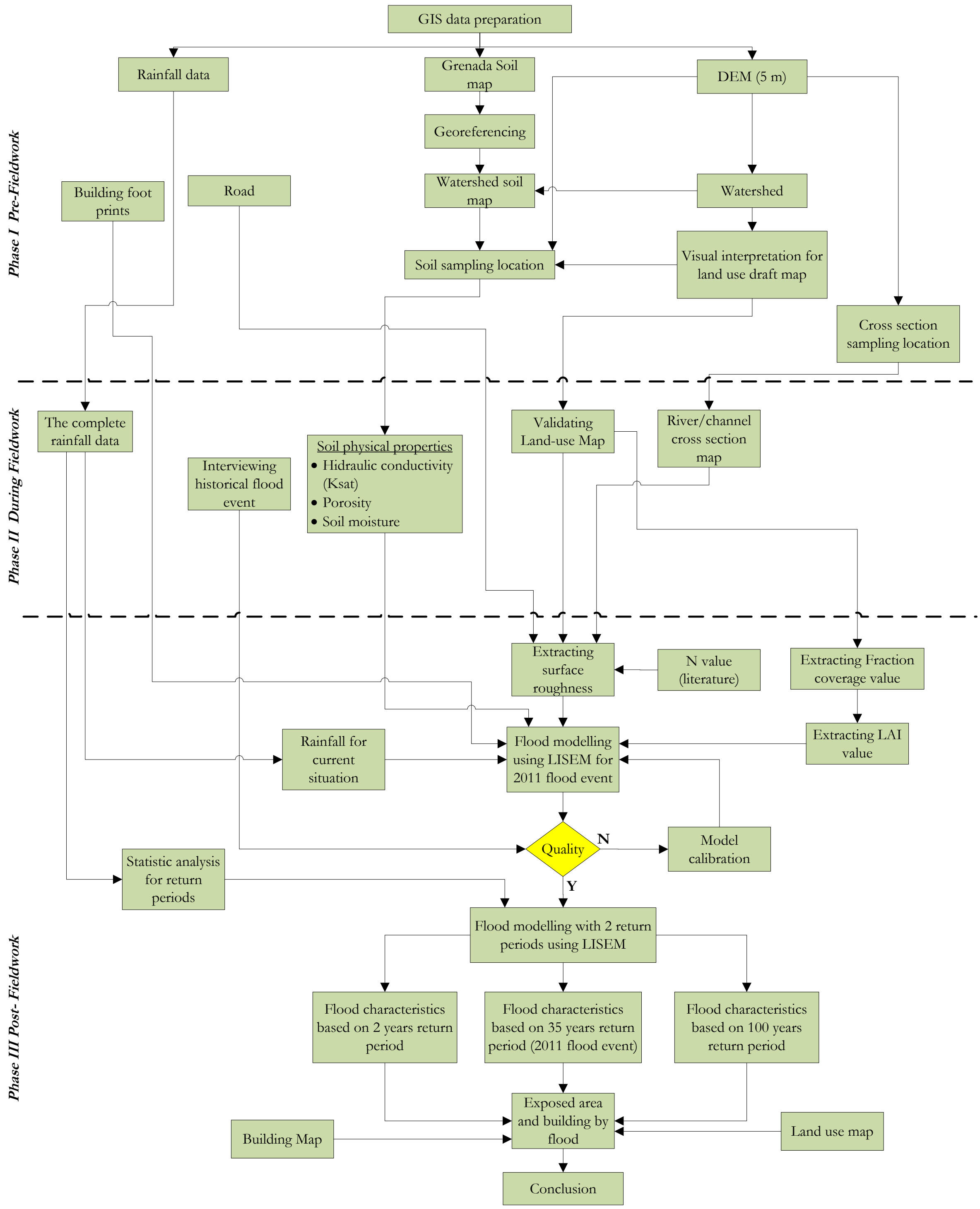



Figure 3-13 Research Framework

## 3.3 Data Collection

Data collection processes in this research is divided into 2 steps. They are pre-fieldwork and during fieldwork. In the first step (pre-fieldwork), researcher collected data and information from documents, data recordings, and or data calculations. The researcher also prepared some data that will be used during the fieldwork. The data that were prepared before conducting the field-work can be shown at **Table 3-7**.

Table 3-7 Data Collection before Fieldwork

| Nu | Data | Source/Method |
|---|---|---|
| 1 | Grenada's base map (coast line, administrative units, roads, and rivers) | Grenada's government |
| 2 | Digital elevation model (with 5 m and 10 m resolution) | Grenada's government |
| 3 | Rainfall data at Maribeau (2003 to 2004 hourly); Pearls 44 ba (2005-2006); La Sagesse Agricultureal station; Kubalal; Cardi; Botanic gardens (2003 -2012) | Grenada's government |
| 4 | Building footprints in St. John's and Gouyave watershed | Grenada's government |
| 5 | High resolution images (Pleiades images with 2 m and 50 cm resolution) | Grenada's government |
| 6 | Soil map, with soil texture information | (Niles, 2010) |
| 7 | Geomorphology map | (Niles, 2010) |

The data in **Table 3-7** was used as input to get the preliminary information before the fieldwork. Fieldwork was conducted during 20 days. In the fieldwork, researcher conducted the primary and secondary data collections. The primary data collection was conducted by interviews of the Grenada's citizens, governments, and non-government's institutions, and also by field observations. Moreover, researcher also took some soil samples and measured soil physical properties in Construction Materials Laboratory of the Grenada Bureau of Standards (**see section 3.4.2**). Then, the secondary data was obtained from the recorded data that have been prepared by certain institutions, such as the complete daily rainfall data from Maurice Bishop International Airport (MBIA).

After the data completed, researcher compiled and prepared those data for analyzing and creating flood modelling using OpenLISEM software. The details of this stage are generating the physical parameters, determining the rainfall intensity using statistical analysis, developing flood modelling, and also developing flood time propagation modelling. The detail data that used in this research can be shown in **Table 3-8**.

Table 3-8 Data Used in the Research from Fieldwork

| Nu | Data | Source/Method |
|---|---|---|
| 1 | Daily rainfall data | Grenada's rainfall station |
| 2 | Land use and land cover | Observation/Field survey |
| 3 | Soil physical properties:<br>• Saturated hydraulic conductivity (Ksat)<br>• Porosity | Observation/Field survey |
| 4 | River/channel cross section data (depth and width). | Observation/Field survey |
| 5 | Flood depth caused by heavy local rainfall in 2011 or caused by hurricane in 2013 | Interviewing the Grenada's government and the citizen around the St. John and Charlotte River |

## 3.4 Methods

### 3.4.1 Software

Software used in this research, such as:

a. Arc-GIS 10.2
b. ILWIS 3.3
c. ERDAS Imagine 2014
d. PC Raster
e. Open LISEM
f. Microsoft office (word, excel, and power-point)

### 3.4.2 Sampling Procedures

In order to simplify the data collection process, get cost effectiveness and get an accessibility to study area, it is required to determine some samples which can represent the characteristics of study area. The sampling method is used to develop the analysis of soil physical properties. *Stratified random sampling* was applied in collecting soil samples during the fieldwork. This sampling method was choosed due to the combination of land use/cover and DEM map. The numbers of samples were determined by the proportion areas for each land-use type.

The land use changes may affect the peak run-off behavior and affect the magnitude of flood (Prachansri, 2007). In addition, land use practices and developments have an important role in determining the land cover and influencing to the run-off generation process, that are associated with soil physical characteristics (Pedzisai, 2010). The land conversions or land-use changes from non-built-up area into built-up area can decrease the infiltration capacity and increase the run-off volume and magnitude. This effect can also influence the soil physical properties, such as Ksat and porosity. If soil infiltration capacity is decreased, the possibility of flood event is increased.

Eighty (80 units) of soil samples were taken using a stratified random sampling method for St. John's watershed and Gouyave watershed. They were stratified according to the total area for each land use **(Table 3-9)**, total sample for dominant land-use type (mix trees) is 51 samples. Whereas, the agriculture lands, bare, and grass land are only represented by 1 sample, suitable with the extent area. The 80 soil samples collected and analyzed during the fieldwork in Grenada. However, researcher added 17 samples during fieldwork. These additional samples are needed to increase the data accuracy and the result of soil analysis can be represented all of study area. Thus, total samples in this research are 97 samples. Soil sample locations for this research can be shown at **Figure 3-14 and Figure 3-15**.

Table 3-9 Number of soil samples number based on land-use types

| Land use/Land cover | Areas ($km^2$) | Gouyave watershed | | St John's watershed | |
|---|---|---|---|---|---|
| | | Sample plan | Additional sample | Sample plan | Additional sample |
| Agriculture | 0.18 | 1 | 3 | - | - |
| Bare Land | 0.19 | - | 1 | 1 | - |
| Forest | 4.47 | 10 | - | 10 | - |
| Grass Land | 0.24 | - | 2 | 1 | - |
| Mix Tree | 11 | 15 | 6 | 35 | 3 |
| Shrub | 1.16 | 1 | 1 | 2 | 5 |
| **Total** | | **27** | **13** | **49** | **8** |

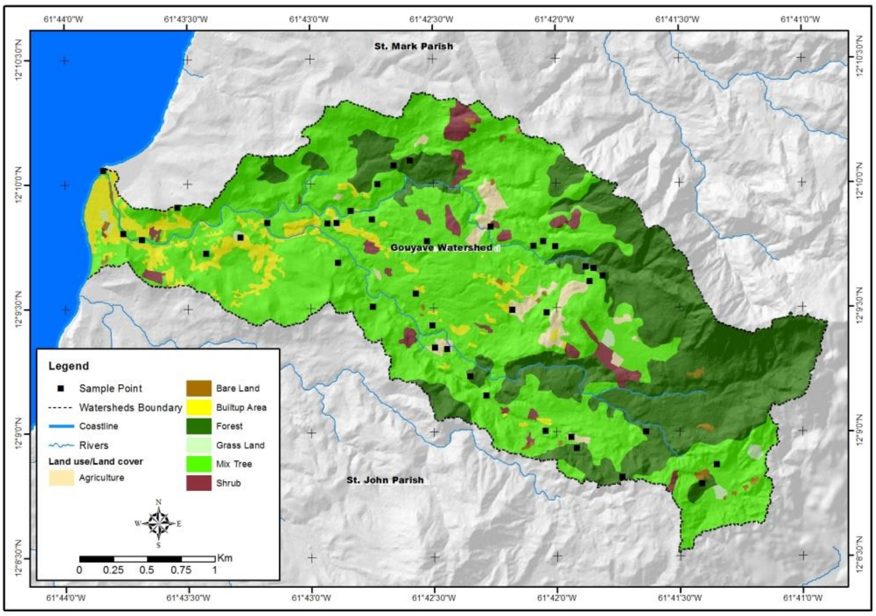



Figure 3-14 Soil sample locations in Gouyave watershed

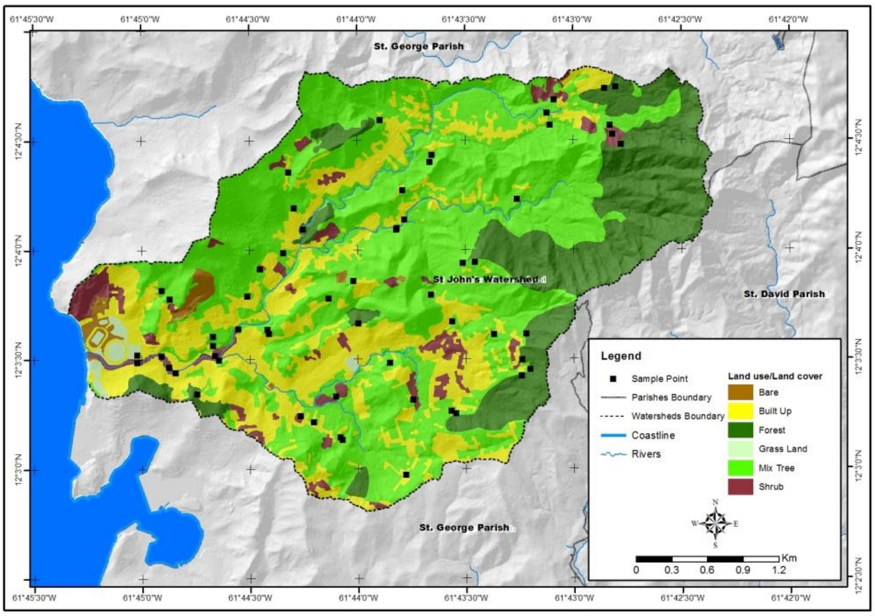



Figure 3-15 Soil sample locations in St. Johns watershed

### 3.4.3 Soil physical measurements

The soil measurements were conducted in laboratory during the fieldwork phase in Construction Materials Laboratory of the Grenada Bureau of Standards. These measurements conducted in order to get the saturated hydraulic conductivity (Ksat), saturated soil moisture, initial soil moisture, and porosity. The soil sampling process were conducted by several steps, such as (1) Measured soil physical properties by measuring the undisturbed soil with taking 100 $m^3$ of soil sample. (2) Inserted soil ring sample into soil sample, ensure that the soil still undisturbed. The soil ring that was used has 5 cm (diameter) and 5 cm (height). (3) Dig around the ring and removed the excess soil from bottom ring using a flat bladed knife. (4) In order to keep its soil moisture, it was necessary for covering soil ring with plastic bag. (5) Then, labeled the plastic bag with soil sample number. (6) Measured the undisturbed soil for saturated hydraulic conductivity (Ksat), saturated soil moisture content, initial soil moisture content, and porosity. The detail stages for soil physical measurements can be shown at **Figure 3-16.**

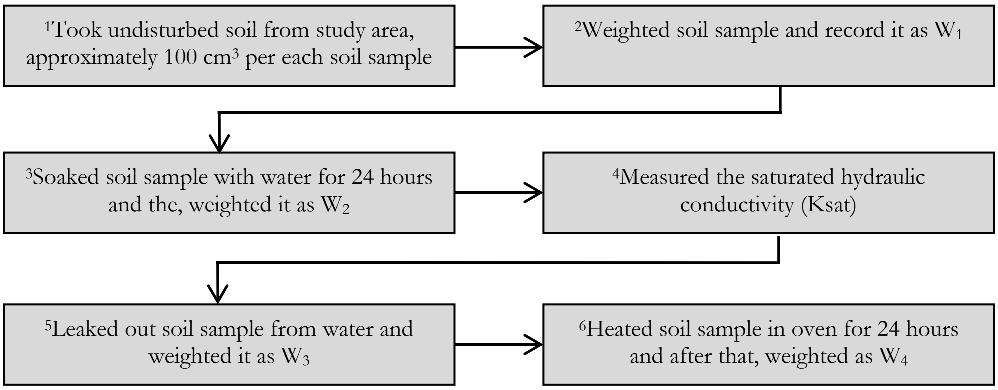



Figure 3-16 Detail stages for conducting soil physical measurements

The formula for calculating Ksat is:

$$\mathbf{Ksat} = \frac{Q}{A}\, x\, \left(\frac{L}{L+dh}\right) \quad \ldots\ldots \quad (1)$$

Note:
Q = the gradient of the volume (cm$^3$) during t minutes
A = surface area of the ring measurement (cm$^2$)
L = surface area of the ring measurement (cm)
dh = depth of the pounded water (cm)

The formula for calculating porosity is:

$$\mathbf{P} = \frac{W2-W4}{V}\ \mathrm{X}\ 100 \quad \ldots\ldots \quad (2)$$

Note:
P = porosity
$W_2$ = the saturate weight
$W_4$ = the dry weight after heat in oven
V = the ring volume (cm$^3$)

The formula for calculating initial soil moisture content is:

$$\emptyset_1 = \frac{W1-W4}{V}\ X\ 100 \quad \ldots\ldots \quad (3)$$

Note:
$\emptyset_1$ = initial soil moisture content (%)
$W_1$ = the base of soil weight
$W_4$ = the dry weight after heat in oven
V = the ring volume (cm$^3$)

The formula for calculating saturated soil moisture content is:

$$\emptyset_2 = \frac{W3-W4}{V}\ X\ 100 \quad \ldots\ldots \quad (4)$$

Note:
$\emptyset_2$ = initial soil moisture
$W_3$ = the dry weight
$W_4$ = the dry weight after heat in oven
V = the ring volume (cm$^3$)

Then, some equipment's that were used in the soil physical measurements can be seen at **Figure 3-17.**


(a) (b)

Figure 3-17 (a) Psedeu laboratory method used Ksat Measurement (Alkema, 2009) and field observation and (b) Heating soil samples in oven for 24 hours to measure the porosity values

### 3.4.4 Parameterization Method for LISEM

In order to get the best and appropriate result of flood modelling, LISEM requires specific input data. The input data for this modelling is determined based on several parameters in developing flood modelling. Those parameters are catchment characteristics parameter, vegetation parameter, green and Ampt infiltration parameters, soil surface parameter, and also overland flow and channel flow parameter (Setiawan, 2009). Those parameters are obtained from literatures values which are compared with soil and land characteristics in research area. The detail data requirements for developing flood modelling using LISEM are listed in **Table 3-10.**

Table 3-10 Input parameters for flood modelling with LISEM

| Parameters | Name | Method | Unit |
|---|---|---|---|
| ***Catchment characteristic*** | | | |
| Local drain direction | LDD.map | Derived from DEM | - |
| Catchment boundaries | AREA. map | Derived from DEM | - |
| Area covered by rain gauges | ID.map | Mapping | - |
| Slope gradient (sine of slope angle) | GRAD.map | Derived from DEM | - |
| Location of outlet and sub outlets | OUTLET.map | Derived from DEM | - |
| Rainfall data | ASCII | Derived from fieldwork | mm/hr |
| | | | |
| ***Vegetation*** | | | |
| Leaf area index | LAI.map | Derived from PER.map | - |
| Fraction of soil covered by vegetation | PER.map | Field observation | - |
| Vegetation height | CH.map | Field observation | m |
| | | | |
| ***Soil surface*** | | | |
| Manning's n scalar | N.map | Derived from literature | - |
| Random roughness | RR.map | Derived from literature | cm |
| Width of impermeable roads | ROADWIDT.map | mapping | m |
| | | | |
| ***Green and Ampt Layer I*** | | | |
| Saturated hydraulic conductivity | KSAT1.map | Measure from fieldwork | mm/hr |
| Saturated volumetric soil moisture content | THETAS1.map | Measure from fieldwork | - |

| Parameters | Name | Method | Unit |
|---|---|---|---|
| Initial volumetric soil moisture content | THETAI1.map | Measure from fieldwork | - |
| Soil water tension at the wetting front | PSI1.map | Derived from literature | cm |
| Soil depth | SOILDEP1.map | Field observation | mm |
| | | | |
| ***Green and Ampt Layer II*** | | | |
| Saturated hydraulic conductivity | KSAT2.map | Derived from saxton equations | mm/hr |
| Saturated volumetric soil moisture content | THETAS2.map | Measure from fieldwork | - |
| Initial volumetric soil moisture content | THETAI2.map | Derived from saxton equations | - |
| Soil water tension at the wetting front | PSI2.map | Derived from literature | cm |
| Soil depth | SOILDEP2.map | Field observation | mm |
| | | | |
| ***Channels*** | | | |
| Local drain direction of channel network | LDDCHAN.map | Derived from Idd.map | - |
| Channel gradient | CHANGRAD.map | Derived from grad.map | - |
| Manning's for the channel | CHANMAN.map | Derived from literature | - |
| Width of channel scalar | CHANWIDT.map | Derived from Idd.map | m |
| Channel cross section shape | CHANSIDE.map | Field observation | - |

*Source: Modification from Jetten (2002) and Setiawan (2009)*

#### 3.3.4.1 Catchment Characteristics parameter

To determine the catchment characteristics are required some parameters, such as catchment boundaries, local drain direction, outlet and sub-outlet location, slope gradient, and rain gauge location. The rainfall data was obtained from the Maurice Bishop International Airport (MBIA) in Grenada. However, the slope gradient data and land drain direction map are obtained from the DEM map which is resulted from interpolating topographic map and contour map.

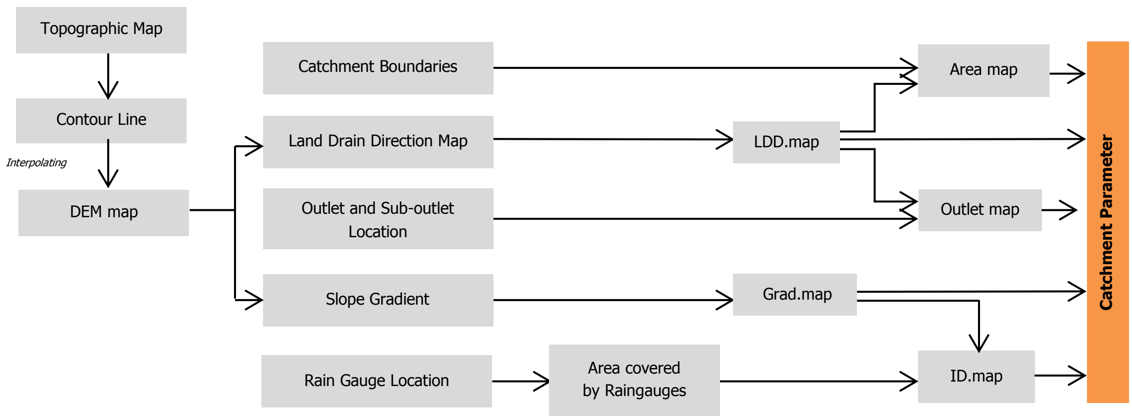



Figure 3-18 Flowchart to obtain catchment characteristics parameters

#### 3.3.4.2 Vegetation parameter

The vegetation parameters required for the flood modelling are leaf area index (LAI. map), percentage of soil covered by vegetation (PER map, in fraction unit), and vegetation height (CH map, in m2/m2). In LISEM, the percentage of soil covered by vegetation is used to calculate the water interception. In order to get all of those parameters, it is needed the field verification of land use for updating the land-use map. From land-use map and field observation, it can be estimated the percentages of vegetation fraction and vegetation height. The values of vegetation fraction percentage and vegetation values can be informed in Table 12. Then, the leaf area index is estimated for calculating the water storage on the leaves. The leaf area index can be found using NDVI (Normalized Difference Vegetation Index) assessment. NDVI is an analysis which is conducted to determine the conditions of land cover, specifically in types and detail characteristic of vegetation (Xiao, Jingfeng and Aaron Moody, 2005). The input data for NVDI analysis is derived from imagery satellite, then those data is interpreted using image interpretation keys. However, in this research, it was difficult to get the imagery satellite in research area to know the vegetation covers because the research area was covered by huge clouds. Thus, LAI factors were determined using comparison study from literature (Pedzisai, 2010 and Prachansri, 2007). Based on percentage of land coverage the LAI values can be shown at **Table 3-12**.

Table 3-11 Values of Vegetation Fraction Percentage and Vegetation Height

| Land-use Types | Canopy cover percentage (-) | Vegetation Height (m) |
|---|---|---|
| Bare land | 0.2 | 0.05 |
| Built-up area | 0.1 | 3 |
| Forest | 0.8 | 13 |
| Grass land | 0.85 | 0.5 |
| Mix-Tree | 0.7 | 10 |
| Shrub | 0.4 | 1.2 |
| Agriculture/Mix-crop | 0.35 | 4 |

*Source: field-observation*

Table 3-12 Values of Leaf Area Index

| Land-use Types | Leaf Area Index ($m^2/m^2$) |
|---|---|
| Bare land | 0.56 |
| Built-up area | 0.263 |
| Forest | 4.02 |
| Grass land | 4.74 |
| Mix-Tree | 3.01 |
| Shrub | 1.28 |
| Agriculture/Mix-crop | 1.08 |

*Source: adopted from Pedzisai (2010) and Prachansri (2007)*

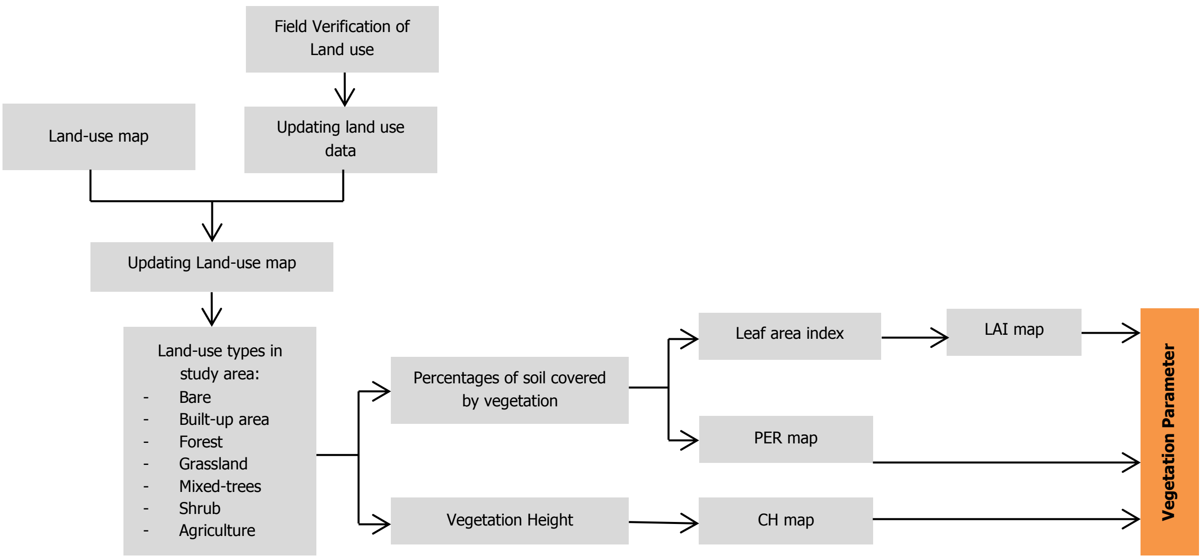



Figure 3-19 Flowchart to obtain vegetation parameters

#### 3.3.4.3 Green and Ampt infiltration parameter

For running the green and Ampt infiltration, the several parameters are required such as hydraulic conductivity (Ksat1 map, Ksat2 map), initial soil moisture content (ThetaI1 map, ThetaI2 map), and saturated soil moisture content (ThetaS1 map, ThetaS2 map). Layer 1 is derived fieldwork and layer 2 is derived from literature. The soil water tension value is obtained based on the literature of wetting front.

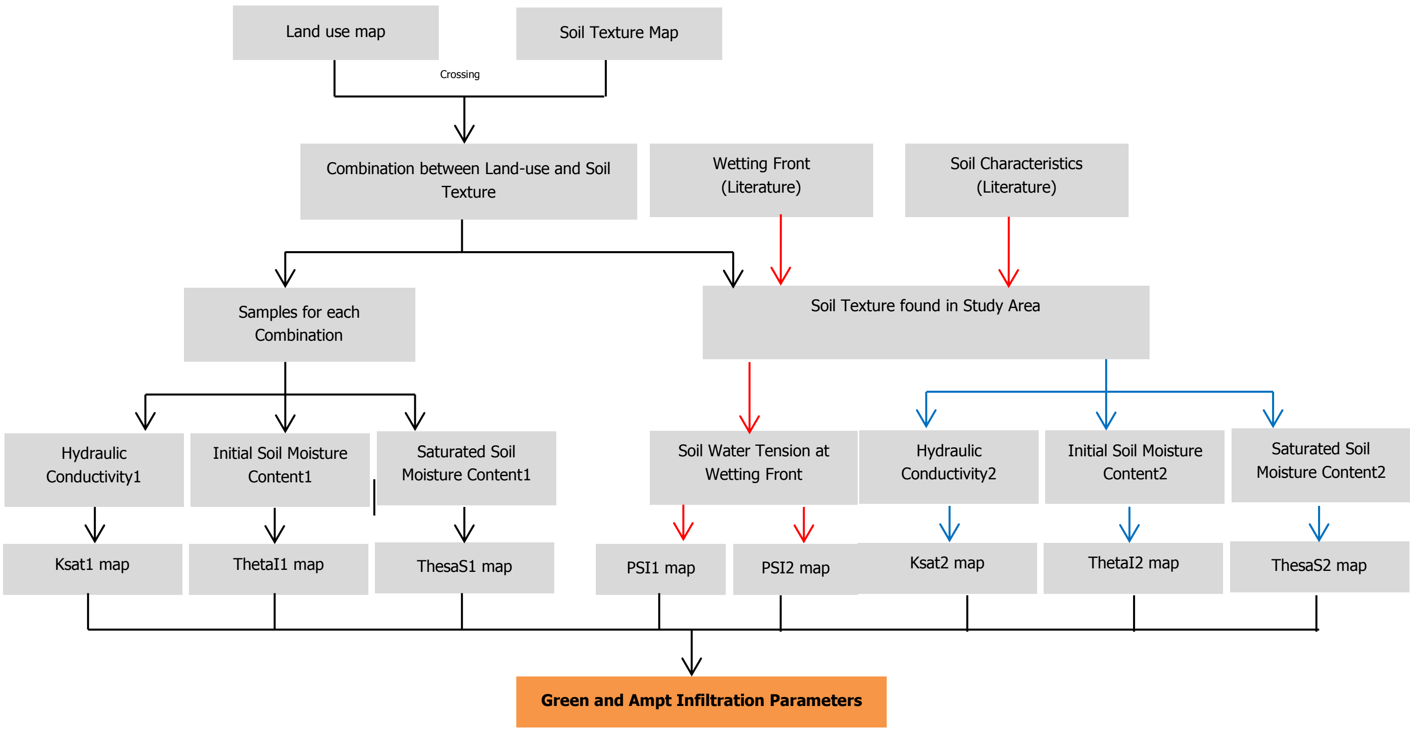



Figure 3-20 Flowchart to obtain green and Ampt infiltration parameters

#### 3.3.4.4 Soil surface parameter

The basic data for determining the soil surface parameter is land-use map. The parameters used to determine and obtain the soil surface parameters are manning's coefficient (N map), width of impermeable road (ROADWIDT map), and random roughness of soil surface (RR map). The random roughness is important to calculate soil surface water storage and overland flow. The manning's coefficients and the random roughness adopted from the combination of Chow (1959), Setiawan (2009), Pedzisai (2010), Prachansri (2007), Solomon (2005) and it is determined for each land-use types in research area. Those values can be seen at **Table 3-13 and Table 3-14.**

Table 3-13 Manning's Coefficient Values

| Land use types | Manning's Coefficient Values (cm) |
|---|---|
| Bare land | 0.023 |
| Built-up area | 0.03 |
| Forest | 0.1 |
| Grass land | 0.023 |
| Mix-Tree | 0.1 |
| Shrub | 0.04 |
| Agriculture/Mix-crop | 0.08 |

*Source: adopted from Chow (1959), Setiawan (2009), Pedzisai (2010), Prachansri (2007), Solomon (2005)*

Table 3-14 Random Roughness Values

| Land use types | Random Roughness of Soil Surface (cm) |
|---|---|
| Bare land | 0.05 |
| Built-up area | 0.05 |
| Forest | 0.5 |
| Grass land | 0.2 |
| Mix-Tree | 0.5 |
| Shrub | 0.2 |
| Agriculture/Mix-crop | 0.2 |

*Source: adopted from Chow (1959), Setiawan (2009), Pedzisai (2010), Prachansri (2007), Solomon (2005)*

However, the road width is important to assume the infiltration. Roads is constructed by hard/heavy materials that make the soil surface impermeable for water, it means that no infiltration. Thus, the road width is calculated by conducting the road measurements and mapping in the field.

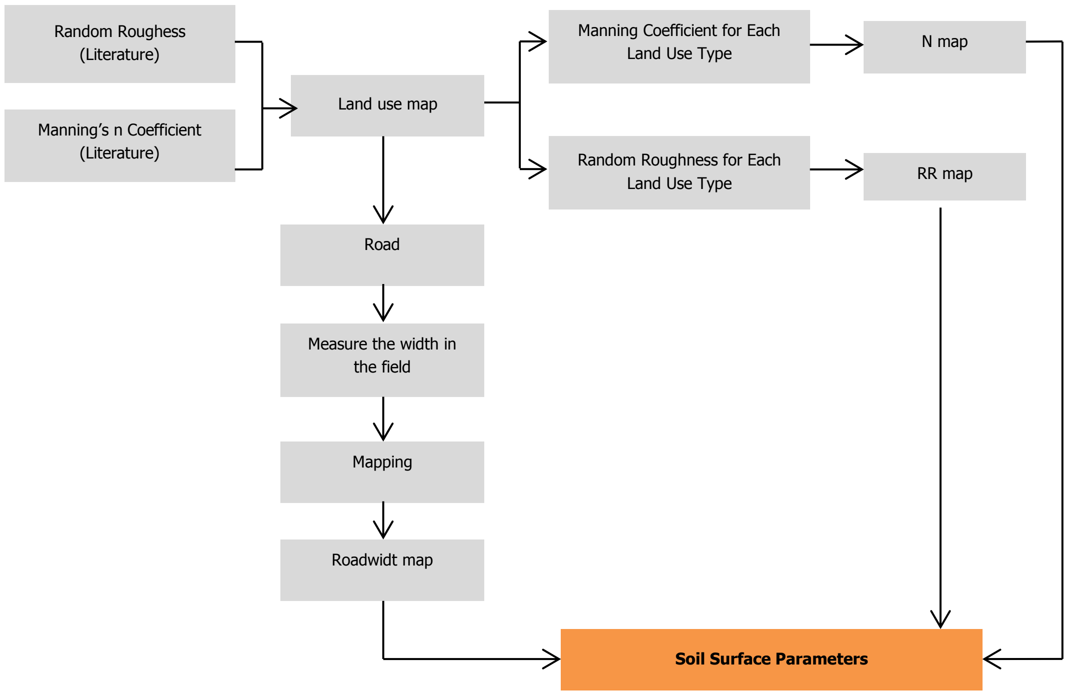



Figure 3-21 Flowchart to obtain soil surface parameters

#### 3.3.4.5 Overland flow and channel flow parameter

The parameters used to determine the overland and channel flow are width of channel, channel cross-section shape, manning's coefficient for channel, local drain drainage of channel network, and channel gradient. The input data required for obtain those parameters and use it in modelling using LISEM, such as:

- The channel mask map was created from local drain drainage map (LDD map) using PC raster operation. From this map, it can be produced the width of channel (Chanwidt map) and the channel cross-section shape (Chanside map).
- The values of manning's coefficient is usually use in the hydrological model for calculating the overland flow and channel flow velocity. The N map (mannning's and value for the channel) that is retrieved from literature is used to produce the manning's for the channel (Chanman map).

- DEM map is used to produced LDDChan map (LDD of channel network) and Changrad map (Channel gradient)

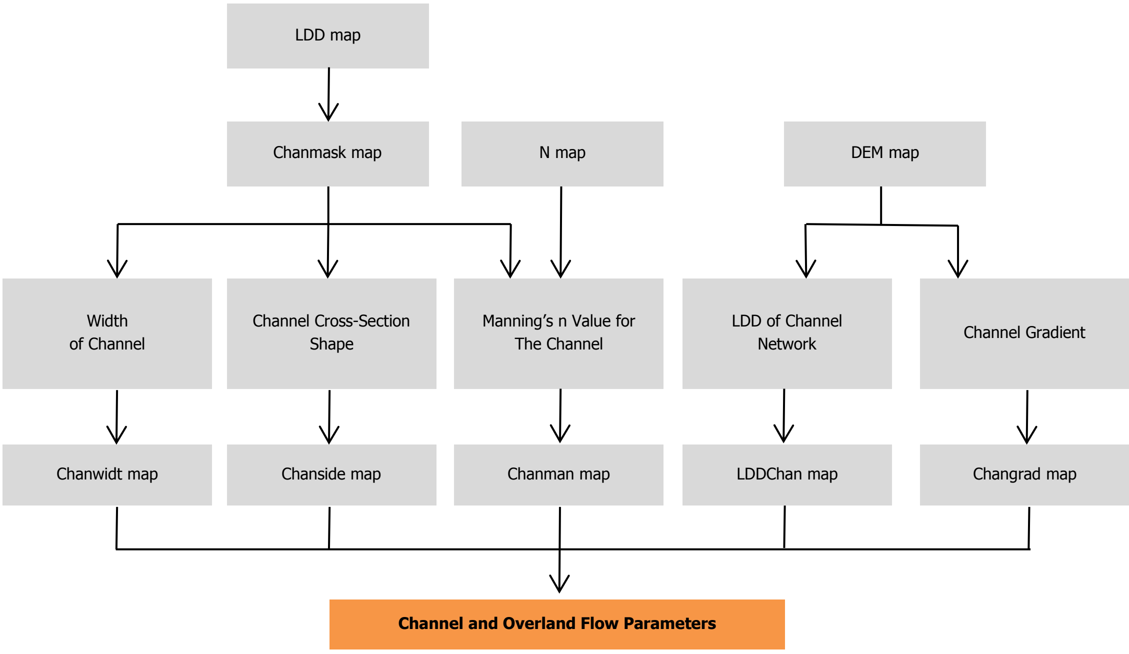



Figure 3-22 Flowchart to obtain overland flow and channel flow

# 4. PHYSICAL PARAMETERS FOR FLASH-FLOOD MODELLING

## 4.1 Land-use types in the research area

Land use of Gouyave watershed and St. John's watershed are known from the visual interpretation of satellite imagery (Pleiades). Most of area in St. John's watershed and Gouyave watershed are covered with natural vegetation areas, such as forest, grassland, and mix-tress. However, there are not agriculture lands in St. John's watershed. Therefore, total area of natural vegetation area in St. John's watershed (8.46 km$^2$) is larger than the green total area in Gouyave watershed (7.26 km$^2$).

**Table 16** shows that both the Gouyave and St. John's watershed are dominated by mixed-trees. In Gouyave watershed, they covered 4, 78 km$^2$ or 56.96% of the total area and in St. John is 6.22 km$^2$ or more than 50% of the watershed area. Moreover, the built-up areas in two watersheds are very different. The built-up areas in St. John's watershed are enough dominate (23.28%), while in the Gouyave watershed; it is only 5.53% from total area. It is indicated that the St. John's watershed represent urban area and Gouyave watershed represent rural area. The detail characteristics of land use in St. John's watershed show in **Table 17.**

Table 4-1 Land-use in Gouyave Watershed

| Land cover/land use | Extent (km$^2$) | Percentage (%) |
|---|---|---|
| Agriculture | 0.19 | 2.26 |
| Bare land | 0.05 | 0.54 |
| Built-up area | 0.46 | 5.53 |
| Forest | 2.44 | 29.01 |
| Grass land | 0.04 | 0.49 |
| Mixed-trees | 4.78 | 56.96 |
| Shrub | 0.44 | 5.22 |
| **Total Area** | **8.39** | **100.00** |

Table 4-2 Land-use in St. John's Watershed

| Land cover/land use | Extent (km$^2$) | Percentage (%) |
|---|---|---|
| Bare land | 0.15 | 1.19 |
| Built-up area | 2.83 | 23.28 |
| Forest | 2.04 | 16.77 |
| Grass land | 0.20 | 1.66 |
| Mixed-trees | 6.22 | 51.12 |
| Shrub | 0.73 | 5.98 |
| **Total Area** | **12.18** | **100.00** |

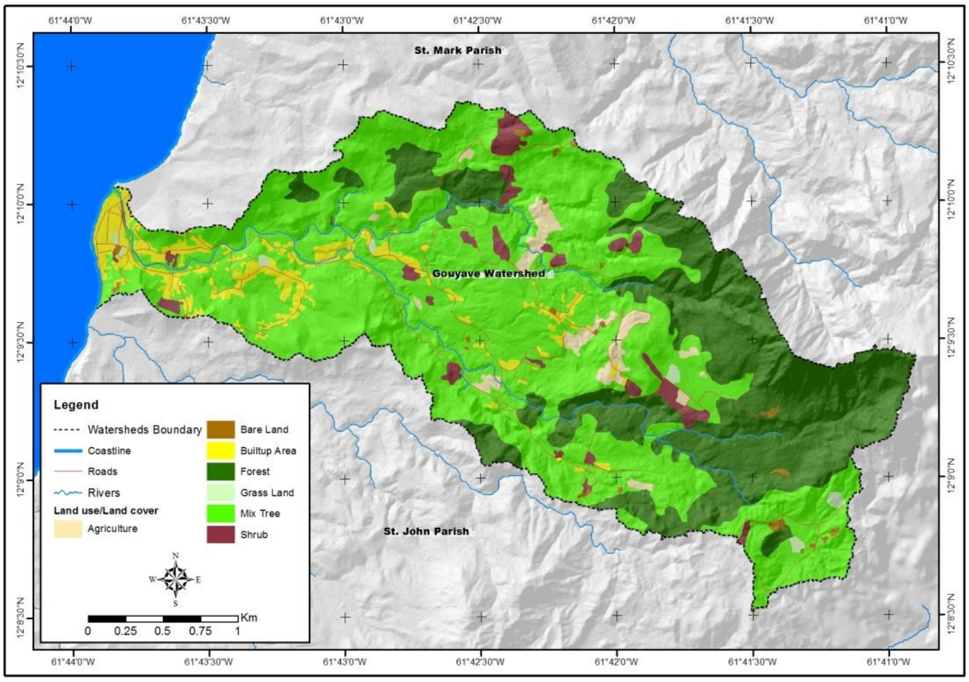



Figure 4-1 Land-use map of Gouyave watershed

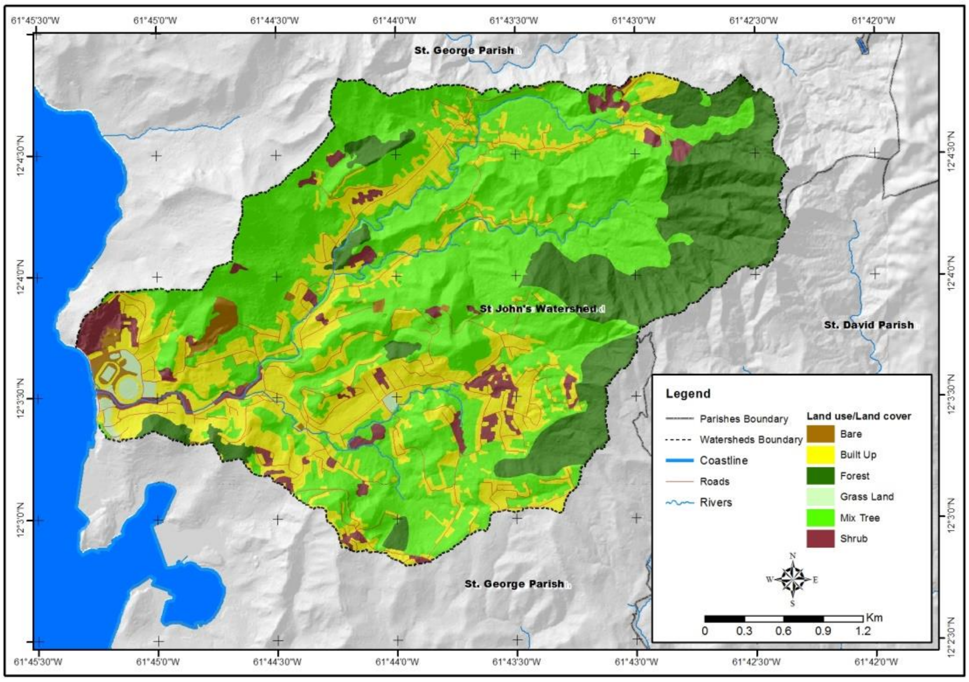



Figure 4-2 Land-use map of St. John's watershed

In order to get the best and appropriate interpretation from satellite imagery, it is required for assessing the accuracy of the classification result. The reference (ground-truth) data were taken during the fieldwork. All of references points are taken on each land-use type. Total samples that used for land-use accuracy assessment for St. John's watershed were 80 samples, whereas there were 55 samples for Gouyave watershed. The value of overall accuracy in Gouyave watershed is 80% and the value of overall accuracy in St. John's is 86, 25%. The complete results of overall accuracy analysis can be shown at **Table 4-3 and Table 4-4.**

Table 4-3 Overall Accuracy of Land-use in Gouyave watershed

| Preliminary Classification | Ground Checked Classification/Reference Data | | | | | | | Row Total |
|---|---|---|---|---|---|---|---|---|
| | Agriculture | Bare Land | Built Up | Forest | Grass Land | Mix Tree | Shrub | |
| Agriculture | **1** | 1 | 0 | 0 | 0 | 0 | 0 | 2 |
| Bare Land | 2 | **2** | 0 | 0 | 0 | 0 | 0 | 4 |
| Built Up | 0 | 0 | **4** | 0 | 0 | 0 | 0 | 4 |
| Forest | 0 | 0 | 0 | **7** | 0 | 0 | 0 | 7 |
| Grass Land | 0 | 0 | 0 | **0** | **3** | 0 | 0 | 3 |
| Mix Tree | 3 | 0 | 0 | 3 | **0** | **25** | 1 | 32 |
| Shrub | 1 | 0 | 0 | 0 | 0 | 0 | **2** | 3 |
| **Column Total** | **7** | **3** | **4** | **10** | **3** | **25** | **3** | **55** |

Overall accuracy = ((1+2+4+7+2+25+2)/54) x100% = 80.00%

Table 4-4 Overall Accuracy of Land-use in St. John's watershed

| Preliminary Classification | Ground Checked Classification/Reference Data | | | | | | Row Total |
|---|---|---|---|---|---|---|---|
| | Bare | Built Up | Forest | Grass Land | Mix Tree | Shrub | |
| Bare | **4** | 1 | 0 | 0 | 0 | 0 | 5 |
| Built Up | 0 | **6** | 0 | 0 | 0 | 0 | 6 |
| Forest | 0 | 0 | **10** | 0 | 1 | 0 | 11 |
| Grass Land | 0 | 0 | 0 | **4** | 0 | 0 | 4 |
| Mix Tree | 0 | 2 | 0 | 1 | **38** | 6 | 47 |
| Shrub | 0 | 0 | 0 | 0 | 0 | **7** | 7 |
| **Column Total** | **4** | **9** | **10** | **5** | **39** | **13** | **80** |

Overall accuracy = ((4+6+10+4+38+7)/80) x100% = 86.25%

## 4.2 Soil physical properties

Soil characteristics, consist of saturated hydraulic conductivity and porosity, is the key role in determining the flood modelling. These characteristics affect to the rate/level of run-off water which is infiltrate into the soil. The infiltration rates are influenced by the characteristics of land use and soil types. It is implied that the differences of land use and soil types have a relation one to another and it will be determined also the infiltration rate and volume of run-off.

### 4.2.1 Analysis of soil properties in relation to land use types

The analysis of soil properties consist of two parameters, saturated hydraulic conductivity (Ksat) and porosity. The saturated hydraulic conductivity (Ksat) is the rates of water to infiltrate in the soil. Ksat value is influenced with the distribution and space of soil pore (Prachansri, 2007). Generally, a natural landscape or land use, such as forest and mixed-trees, has high value of Ksat. It is due to land with natural vegetation is not cultivated or intervened by human activities. The arrangements of heavy machinery ploughing and tillage change the soil pores, make the soil compact, and it decrease the hydraulic conductivity (Prachansri, 2007). If the Ksat value is decreased, the infiltration is decreased too. The vegetation roots in forest usually hard and strong, so it can help to increase the Ksat (hydraulic conductivity) and support the water infiltration into the soil. It means that the infiltration rates will be high and stable. That condition is different with developed area/built-up area. Ksat values usually less because of soil compaction and other activities. It means the less infiltration rates. Soil infiltration affects surface run-off. The water volume that can be absorbed in the soil decrease the volume of surface run-off.

Soil porosity is different with Ksat. Soil porosity is void spaces between soil particles in a unit volume of material (Nimmo, 2004). The soil particles are determined in soil particle shape and its arrangements. Nimmo (2004) also explains that the diversity of soil particle shapes, sizes, and their arrangement make the porosity value decrease. If soil porosity is less, the soil infiltration capacity would be high. Means and standard deviation values of Ksat that area determined by land use or land cover types, can be informed at this following table.

Table 4-5 Means and Standard Deviation of Ksat and Porosity for Difference Land Use Types

| **Land use** | **n** | **Ksat (mm/hr)** | | **Porosity($cm^3/cm^3$)** | |
|---|---|---|---|---|---|
| | | **Mean** | **Sd** | **Mean** | **Sd** |
| Agriculture | 4 | 205.36 | 341.78 | 0.62 | 0.03 |
| Bare Land | 2 | 27.86 | 21.21 | 0.53 | 0.06 |
| Forest | 20 | 158.43 | 116.23 | 0.64 | 0.08 |
| Grass Land | 3 | 55.00 | 54.60 | 0.61 | 0.03 |
| Mix Tree | 59 | 150.05 | 154.38 | 0.56 | 0.06 |
| Shrub | 9 | 112.42 | 175.30 | 0.53 | 0.03 |

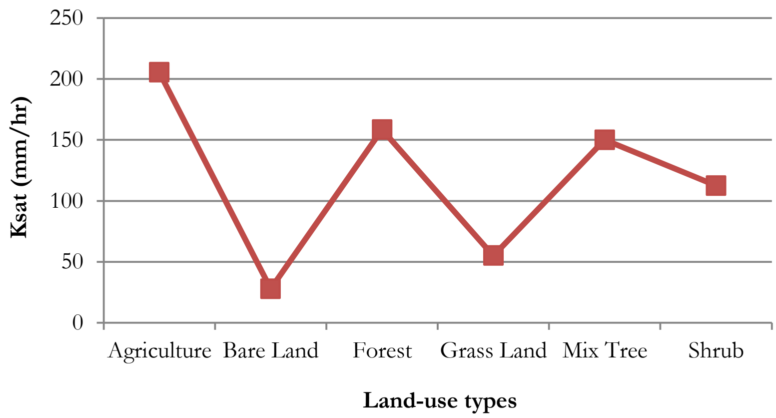
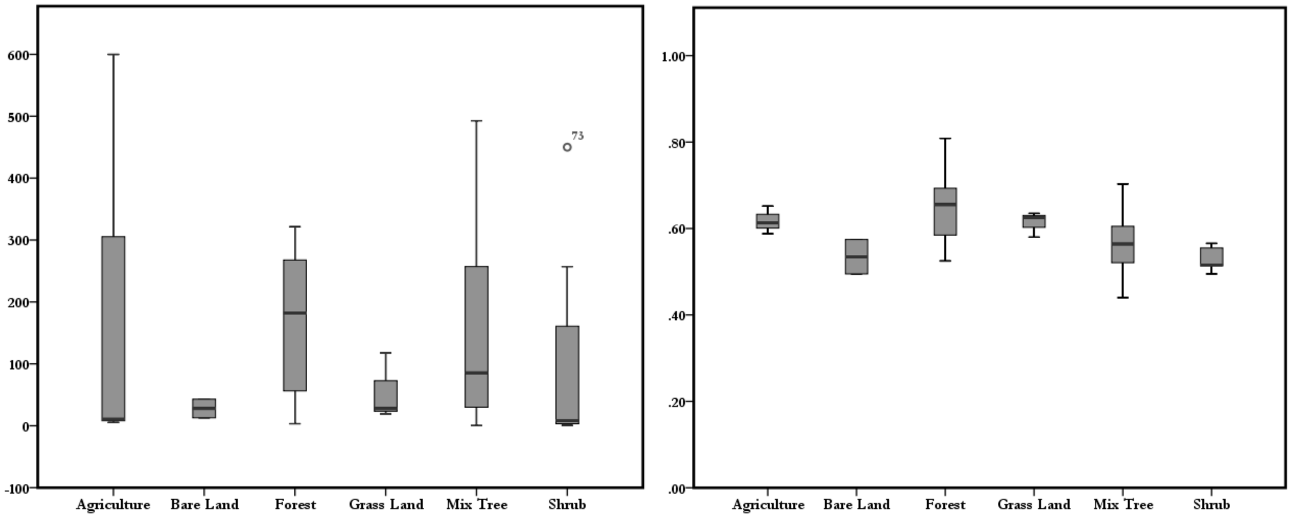



Figure 4-3 Means of Ksat values in different land use types

**Table 4-5** shows means and standard deviation of Ksat mean values based on each land use type. Ksat and porosity values in different on land-use types are varied that can be shown from their means and its distribution. Generally, the uncultivated lands, such as forest, mix-tree, and shrub have high value of Ksat means and the cultivated lands, such as bare land and grass land have low value of Ksat mean. The Ksat values of uncultivated areas are more than 100 mm/hour) and the cultivated areas are less than 100 mm/hour.

**Figure 4-3 shows** all of Ksat mean values. It shows that the differences between Ksat mean values among land-use types in this research area are very high and dramatically. The highest Ksat mean is agriculture lands, and the lowest is bare land. However, the Ksat mean value of agriculture area is very different and highest than other. Ksat mean value of agriculture lands is 205.36 mm/hour. This value is the average value of four measured Ksat values in agriculture areas, so there is outlier data, so that the Ksat mean values of agriculture lands have low value and high value. The distribution data of Ksat agriculture lands can be seen at **Figure 4-4a.** The highest Ksat mean value of agriculture land (205.36 mm/hour) can be explained by the many organic materials in top-soil of agriculture lands, such as vegetation roots and leaves that are stored in the soil.

In addition, most of standard deviation (Sd) values of each land use types are near the values of Ksat mean. It means that the most of data in each land use types are distributed normally, except agriculture lands, shrub, and grass land (see **Figure 4-4a).** However, the standard deviation (SD) of agriculture lands is highest than other (341.78 mm/hour). It indicates that the data distribution is far from the average values of Ksat. Thus, it is required to conduct data calibration of Ksat value because the uncertainty of the Ksat means value. Besides agriculture land, the distribution data of shrub and grass land are not distributed normally, but the standard deviation values are not different with Ksat mean values.




(a) (b)

Figure 4-4 Ksat boxplot (a) and porosity boxplot (b) based on land-use types

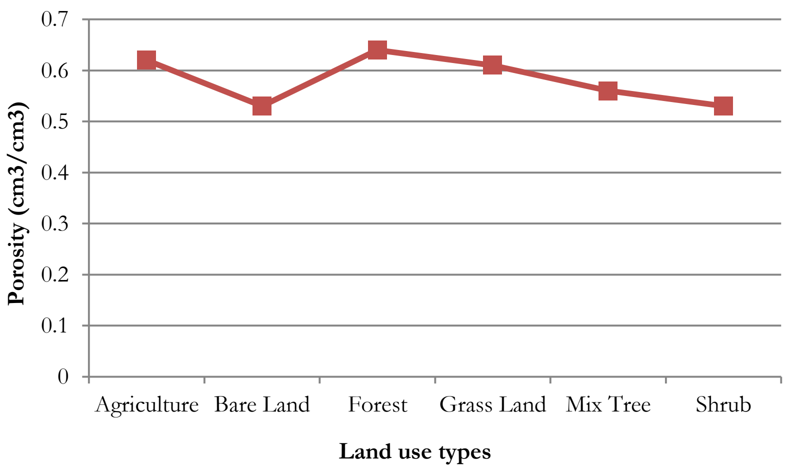



Figure 4-5 Means of porosity values in different land use types

Related with porosity, generally, mean porosity values per each land use types are almost same and it is not very different for each other's (see **Table 4-5**). Mean of porosity for each land use types are 0.53 until 0.64 Forest has the highest value of mean and standard deviation of porosity. Mean of porosity value of forest is 0.64 and their standard deviation is 0.08. Generally, the average values of porosity for each land use types are almost equal; with the difference values are between 3-11 cm³/cm³ (see **Figure 4-5**).

The distribution data of porosity values per each land use types show in **From Figure 4-4.b**. Almost of porosity data per each land uses are distributed normally. The highest mean value of forest porosity (0.64) is due to there are diversities in soil structure shapes and its arrangements. From mean of porosity values can be shown that agricultures lands, forest, and grass land have the lower infiltration rates than bare land, mix-tress, and shrub.

### 4.2.2 Analysis of soil properties in relation to soil types

Analysis of soil properties (Ksat and porosity) also conducted based on soil types. It is important to identify the relationship between soil type characteristics to Ksat and porosity. Generally, Ksat amd porosity values in different soil types are enough varied. **Figure 4-6** shows the porosity values for each soil textures and it can be shown the difference values between all of soil types. The highest mean of porosity is Belmont clay loam (stony and boulder phase) with 428.57 mm/hour, but it is only represented by 1 soil samples (see **Table 4-5**). The highest mean value of Belmont is caused by there are many organic materials, such as vegetation roots and leaves that are stored in the soil.

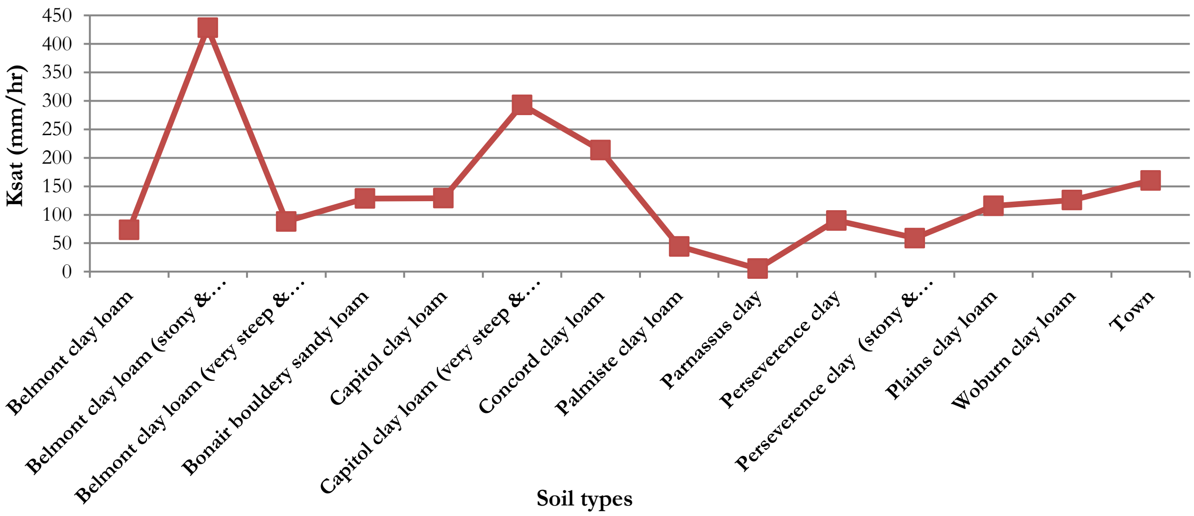



Figure 4-6 Means of Ksat values in different soil textures

Table 4-6 Mean and Standard Deviation of Ksat and Porosity for Difference Soil Types

| Soil Textures | n | Ksat (mm/hr) | | Porosity (cm³/cm³) | |
|---|---|---|---|---|---|
| | | Mean | Sd | Mean | Sd |
| Belmont clay loam | 6 | 73.66 | 56.76 | 0.55 | 0.05 |
| Belmont clay loam (stony & bouldery phase) | 1 | 428.57 | 0 | 0.54 | 0.00 |
| Belmont clay loam (very steep & shallow phase) | 12 | 88.34 | 86.27 | 0.60 | 0.06 |
| Bonair bouldery sandy loam | 2 | 128.57 | 151.52 | 0.49 | 0.04 |
| Capitol clay loam | 13 | 129.06 | 123.53 | 0.64 | 0.05 |
| Capitol clay loam (very steep & shallow phase) | 13 | 293.04 | 200.53 | 0.67 | 0.07 |
| Concord clay loam | 12 | 213.62 | 173.48 | 0.56 | 0.05 |
| Palmiste clay loam | 2 | 44.46 | 9.85 | 0.52 | 0.00 |
| Parnassus clay | 1 | 5.36 | 0 | 0.56 | 0.00 |

| Soil Textures | n | Ksat (mm/hr) | | Porosity (cm³/cm³) | |
|---|---|---|---|---|---|
| | | Mean | Sd | Mean | Sd |
| Perseverence clay | 4 | 90.00 | 96.24 | 0.50 | 0.03 |
| Perseverence clay (stony & bouldery phase ) | 4 | 59.00 | 54.25 | 0.60 | 0.02 |
| Plains clay loam | 4 | 115.71 | 129.07 | 0.52 | 0.02 |
| Woburn clay loam | 19 | 125.79 | 166.23 | 0.56 | 0.06 |
| No information | 4 | 160.18 | 198.3 | 0.55 | 0.06 |

In addition, **clay-loam textures** in research area, consist of Belmont clay loam, Belmont clay loam (very steep & shallow phase), capitol clay loam, capital clay loam (very steep & shallow phase), concord clay loam, plains clay loam, and Woburn clay loam). They have more than 100 mm/hour of Ksat mean. Then, Ksat mean values of the **clay textures** (perseverance clay and perseverance clay (stony & boulder phase) are less than 100 mm/hour, but it is only parnassus clay that has the lowest mean of Ksat (5.36 mm/hour).

Almost of Ksat standard deviations are lower than their mean values **(Table 4-6)**. Data distribution of Ksat can be shown at **Figure 4-7a.** Almost of data distribution of Ksat value is distributed normally, except some soil textures which only ha 1-2 soil samples and the data are not represented the each soil texture. They are belmont clay loam (stonny and boulder phase), palmiste clay loam, and parnassus clay.

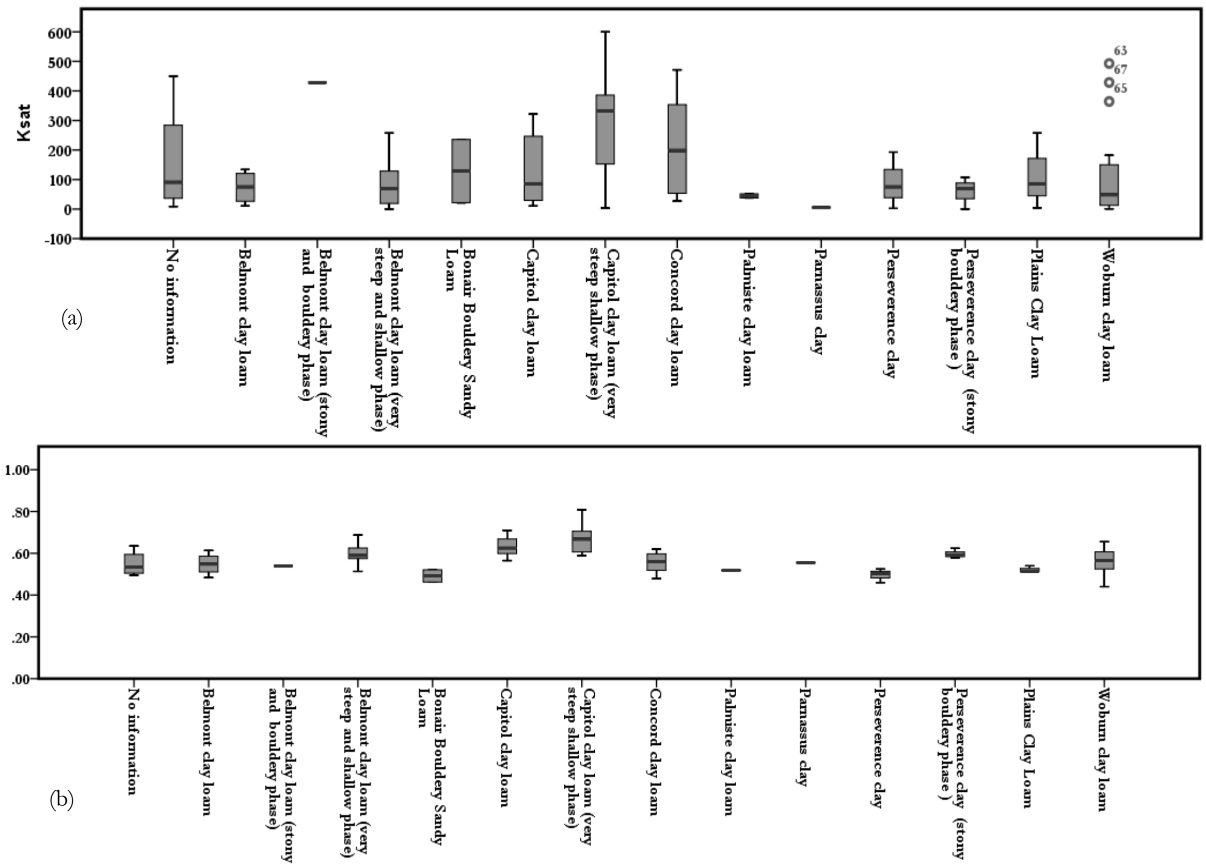



Figure 4-7 Ksat boxplot (a) and porosity boxplot (b) based on soil types

Besides Ksat, **Table 4-6** also shows the porosity values of soil textures. Generally, from the results of porosity mean values, all of clay-loam soil textures have higher values than clay and sandy soil. The mean porosity values of clay-loam are between 0.49 until 0.67 The lowest of porosity mean value is sandy soil (Bonair boulder sandy loam) because it has un-fragmented soil fractures and formed from sandy textures and the porosity of sandy soil is the lowest than other (Grenada's Environmental Profile). Then, mean of porosity value for each soil textures are not high differences. It can be shown from **Figure 4-8.** Related with distribution data of porosity, most of porosity values data per each soil textures are distributed normally (see **Figure 4-7b**).

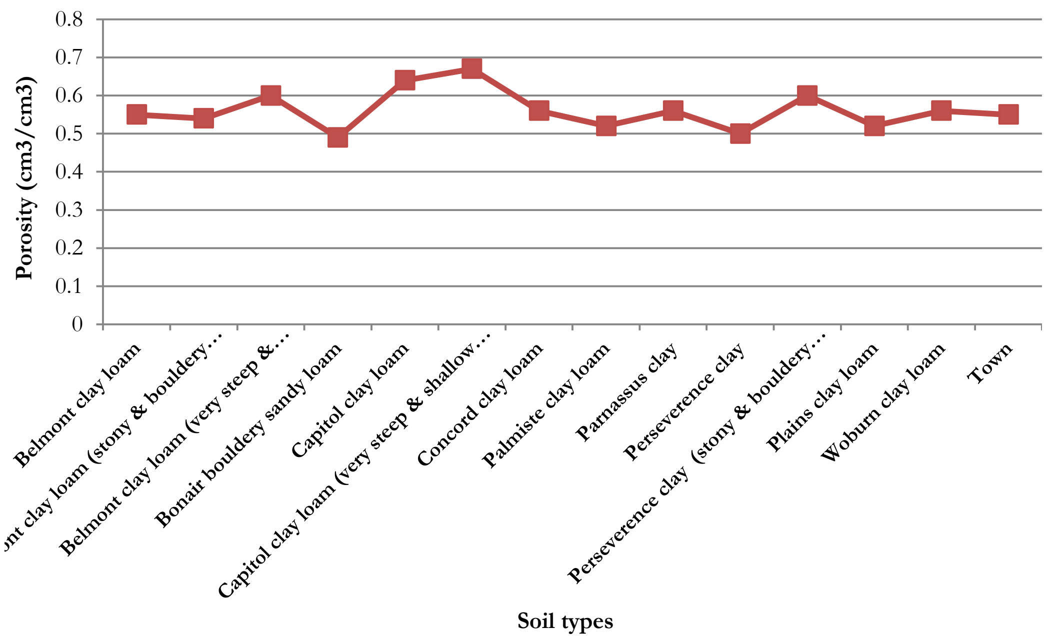



Figure 4-8 Means of porosity values in different soil types

Based on the field observation and statistical analysis, it can be concluded that Ksat and porosity values based on land-use types are more variance and suitable for flood model than Ksat and porosity values based on soil types. It can be shown from their data distributions and their mean values. In order to obtain the accuracy and representative values of Ksat and porosity in flood model and to reduce the uncertainty values, it is required to ignore the outlier values from Ksat and porosity values.

## 4.3 Rainfall

The extreme rainfall is the most influencing factor to flood events. In flood modelling, it is required to assess and predict the extreme rainfall and its influences to the run-off and flood events. The assessment of extreme rainfall in research area was used by predict and return period of rainfall based on rainfall history data. In this research, the Gumbel method was used to describe the occurrence probability of extreme rainfalls and identify the distribution of extreme values. The result of Gumbel distribution in this research can be shown at **Figure 4-9**.

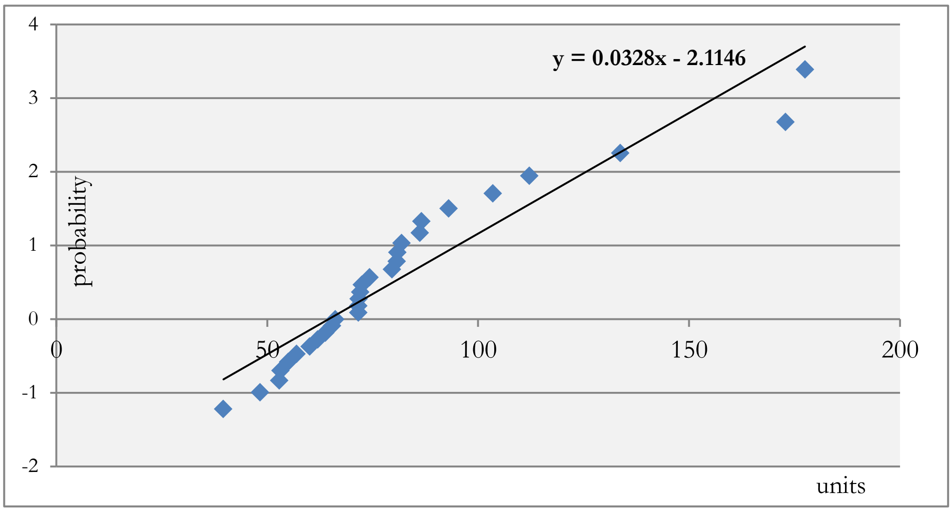



Figure 4-9 Gumbel Distribution

Table 4-7 Return Periods and Maximum Daily Rainfall

| Return Period | Right prob | Left prob | y= -ln(-ln(left prob) | Max daily rainfall |
|---|---|---|---|---|
| 2 | 0.50 | 0.50 | 0.37 | 75.64 |
| 5 | 0.20 | 0.80 | 1.50 | 110.20 |
| 10 | 0.10 | 0.90 | 2.25 | 133.08 |
| 35 | 0.03 | 0.97 | 3.54 | 172.42 |
| 100 | 0.01 | 0.99 | 4.60 | 204.72 |

Based on **Table 22,** can be concluded that:

In order to analyze the flood behaviors in two watershed areas, Gouyave watershed and St. John's watershed, it was used 3 return periods based on the probability of storm events and extreme events. Those 3 years return period which are used are 2 years return period, 35 years return period, and 100 years return period. The 5 years return periods and 10 return periods are only used to identify how is the sensitivity of watersheds to response flood events.

- 2 years return periods represent maximum daily rainfall in 2013. The maximum daily rainfall in 2013 (75.64) includes in low-categories of rainfall. In this year, flood events occurred in some locations of Grenada, but it did not give the great damage impacts.
- 35 years return period represent maximum daily rainfall in 2011. Maximum daily rainfall in 2011 is used as a current situation. In 2011, occurred some damage floods in Gouyave watershed area and St. John's watershed area. Based on these reasons, rainfall intensity in 2011 use as the basic data for conducting data calibration and data validation in this research.
- 100 years return periods represent the most extreme conditions to identify and assess the potential flood areas which are caused by the most extreme rainfall condition.

Because of the limitation of information about rain intensity for flood modelling, this assessment was used the 24-hour rain synthetic rainfall distributions intensity method as was developed by Natural Resources Conservation Service/Soil conservation service (NRCS/SCS), United States of America. They developed four synthetic rainfall distributions known as type I, IA, II, and III based on the storm and geographic regions that resulted in variety of rainfall intensity. Type IA is the least intense and type II the most intense short duration rainfall which represent various regions of the United States, while Types I and IA represent the Pacific maritime climate with wet winters and dry summers. Type II represents the rest of the country, and Type III represents Gulf of Mexico and Atlantic coastal areas where tropical storms bring large 24-hour rainfall amounts. Based on the climate characteristics, type III the most appropriate distribution in Grenada. The rainfall intensity with different return periods can be shown at **Figure 4-10**.

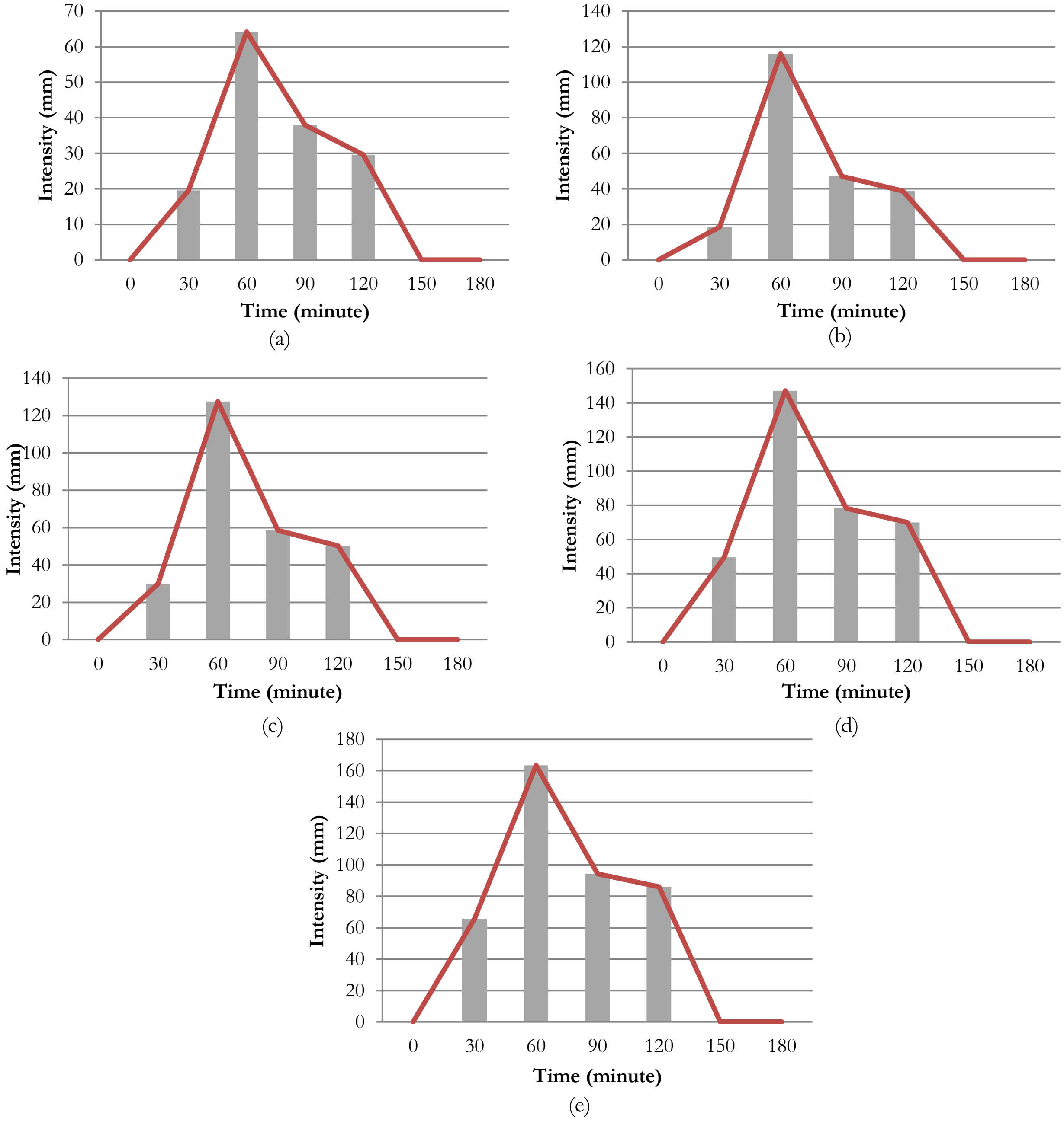



Figure 4-10 The rainfall intensity in (a) 2 years return period; (b) 5 years return period; (c) 10 years return period; (d) 35 years return period; and (e) 100 years return period

# 5. FLOOD MODELLING

## 5.1. LISEM Input Data

In this research, there were several basic maps which are derived as input map, such as the Digital Elevation Model (DEM), soil map, and land use map. The Digital Elevation Model (DEM) was created based on the interpolating contour line from topographic map. It was derived using ILWIS 3.3 and its resolution is 5 meters. This map was rasterized to 20 meters resolution before analyzing. In addition, soil map, it was provided by Grenada's governments and it was combined with the results of soil physical measurements in fieldwork. Beside DEM, the flood modelling in this research used Ksat maps, initial moisture maps (Thethai1.map), surface roughness maps (n.map), and random roughness maps (rr.map). These maps are generated from land-use map.

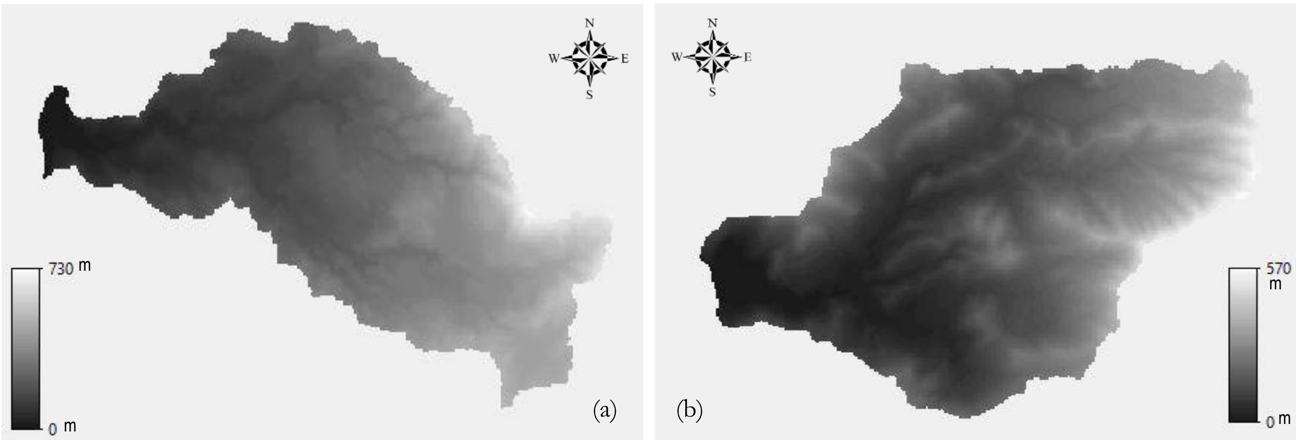



Figure 5-1 (a) DEM map Gouyave watershed and (b) DEM map of St. John's watershed

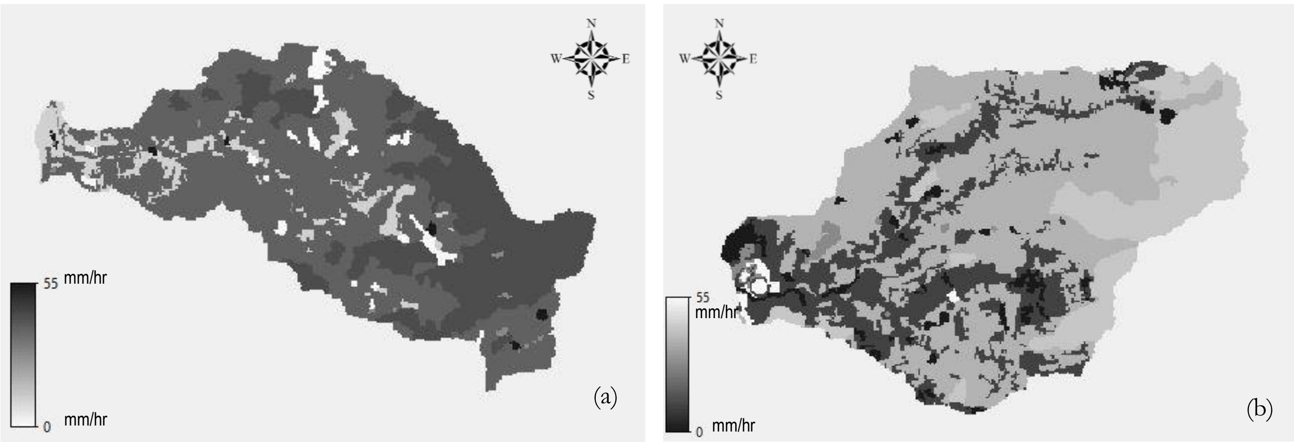



Figure 5-2 (a) Ksat map Gouyave watershed and (b) Ksat map of St. John's watershed

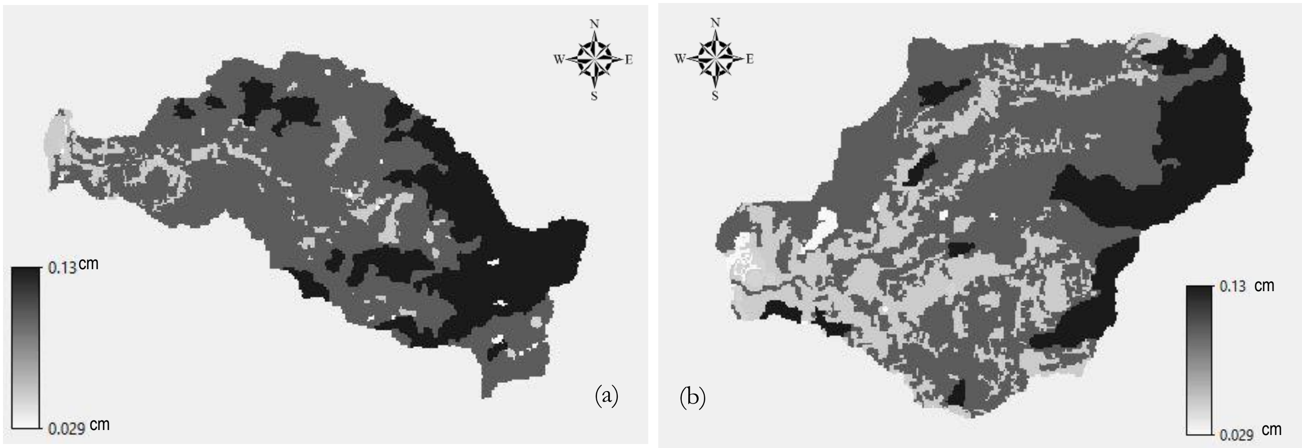



Figure 5-3 (a) N.map Gouyave watershed and (b) N.map of St. John's watershed

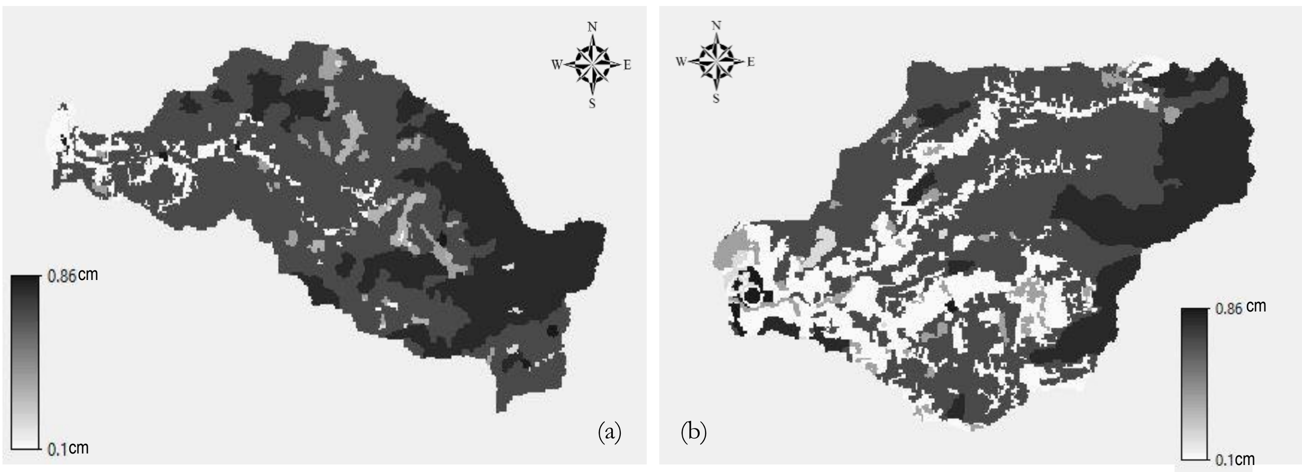



Figure 5-4 (a) PER.map Gouyave watershed and (b) PER.map of St. John's watershed

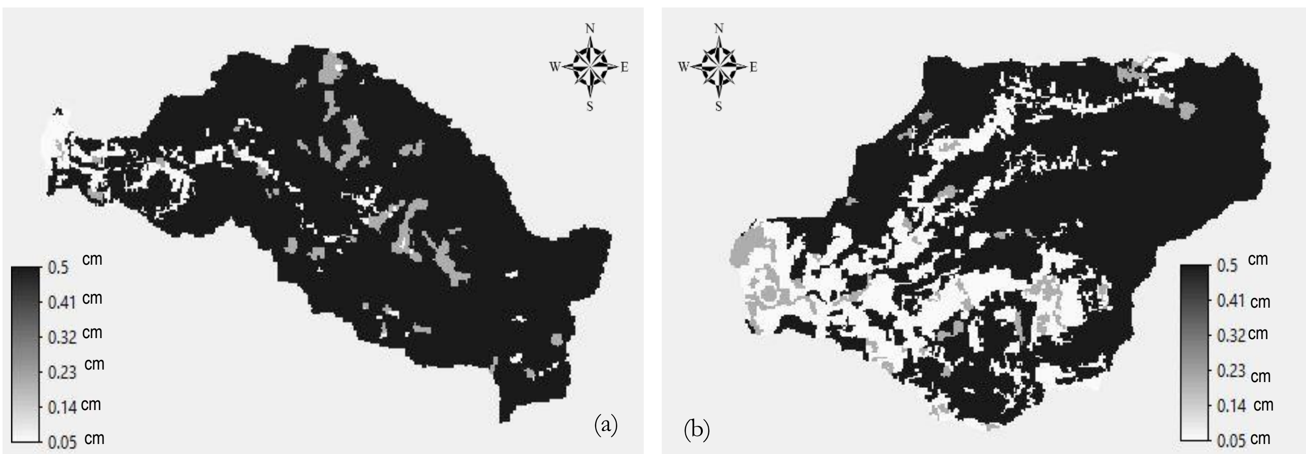



Figure 5-5 (a) RR.map Gouyave watershed and (b) RR.map of St. John's watershed

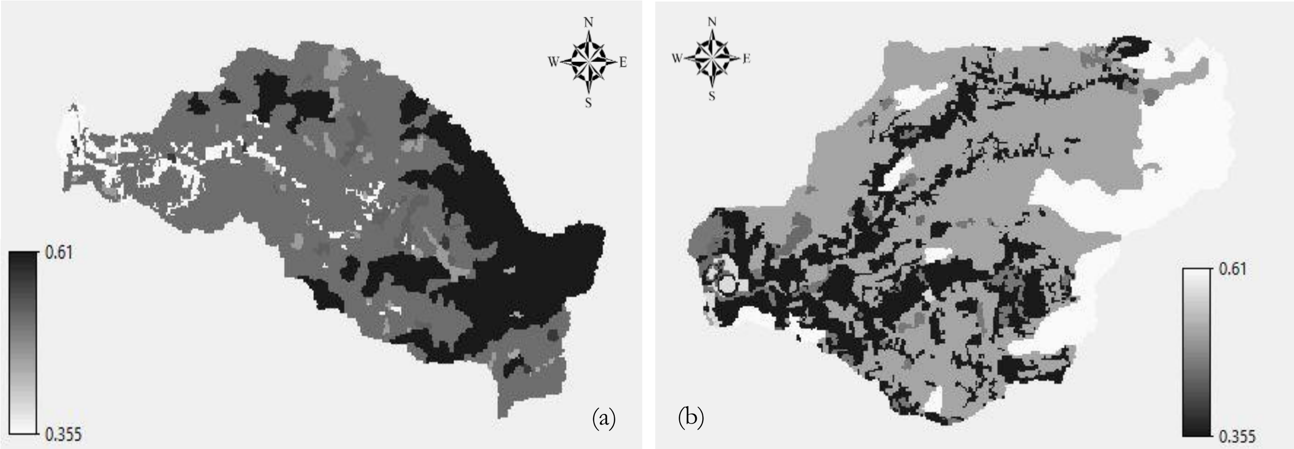



Figure 5-6 (a) Thetai1.map Gouyave watershed and (b) Thethai1.map of St. John's watershed

This research conducted flood modelling in two watershed areas. In this modelling, it is only used the input data from Gouyave watershed. Furthermore, the parameters which were used for developing flood modelling in Gouyave watershed were adapted to develop the flood modelling of St. John's watershed. It is used for validating data. This modelling also conducted in two layers was caused by Ksat factors. The first layer was obtained from field observation, whereas the second layer was obtained from literature. It was due to the green and Ampt infiltrations which are derived from field observation have high values. The top-soil contains many organic materials, so the green and Ampt infiltration values from field observation was high. Whereas, the sub-soil values was derived from literature based on each soil types.

## 5.2. Sensitivity Analysis

The sensitivity analysis was used to find-out the parameter that would have the most influence on the modelling output results. Then, it can be known the uncertainty of the calibrated parameters (De Roo, A.P.J and Victor Jetten, 1999). The sensitivity of each parameter might be depending on the other parameters level (Jetten, in Pedzisai, 2010). The several parameters were calibrated, including:

- The saturated hydraulic conductivity (Ksat);
- Initial soil moisture;
- Surface roughness;
- Random roughness;
- Fraction coverage.

A process to identify the parameter sensitivity is changing and combining the used parameters to flood modelling. These simulations were conducted once by symmetrically and uniformly subtracting 25% from and adding 25% to the parameter values. This value could be represented the significant value of variance per each parameter. Then, change and combination result from those parameters were evaluated with considering the run-off (flood) characteristics, such as peak discharge, total discharge, infiltration, flood maximum, and flood area. The sensitivity assessment for those parameters can be shown at **Table 5-1.**

Table 5-1 Results of Sensitivity Analysis
(peak discharge, total discharge, flood max, and flood area) in percentage (%)

| Parameters | Sensitivity Analysis | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Peak discharge (%) | | | Total discharge (%) | | | Infiltration (%) | | | Flood Max (%) | | | Flood area (%) | | |
| | Add 25% | Sub 25% | Var | Add 25% | Sub 25% | Var | Add 25% | Sub 25% | Var | Add 25% | Sub 25% | Var | Add 25% | Sub 25% | Var |
| Ksat | -20.87 | 14.97 | 35.84 | -22.44 | 25.14 | 47.57 | 12.60 | -14.78 | 27.38 | -76.82 | 11.36 | 88.18 | -43.27 | 31.25 | 74.52 |
| Initial moisture | 7.60 | -22.80 | 30.40 | 8.54 | -20.00 | 28.54 | -4.94 | 11.48 | 16.42 | 4.55 | - 21.82 | 26.36 | 12.50 | 46.63 | 59.13 |
| Surface roughness (n) | -6.71 | 4.07 | 10.79 | -0.49 | 0.41 | 0.90 | 0.45 | -0.50 | 0.96 | -2.27 | 0.00 | 2.27 | -6.25 | 4.33 | 10.58 |
| Random roughness | 0.20 | -0.09 | 0.29 | 0.14 | -0.17 | 0.32 | -0.08 | 0.09 | 0.18 | 0.00 | 0.00 | 0.00 | 0.48 | 0.00 | 0.48 |
| Fraction coverage | -0.09 | 1.56 | 1.65 | -0.20 | 0.49 | 0.69 | -0.07 | 0.19 | 0.25 | 0.00 | 0.00 | 0.00 | -0.48 | 2.40 | 2.88 |

The detail of sensitivity analysis graphic and its description can also be shown as follows:

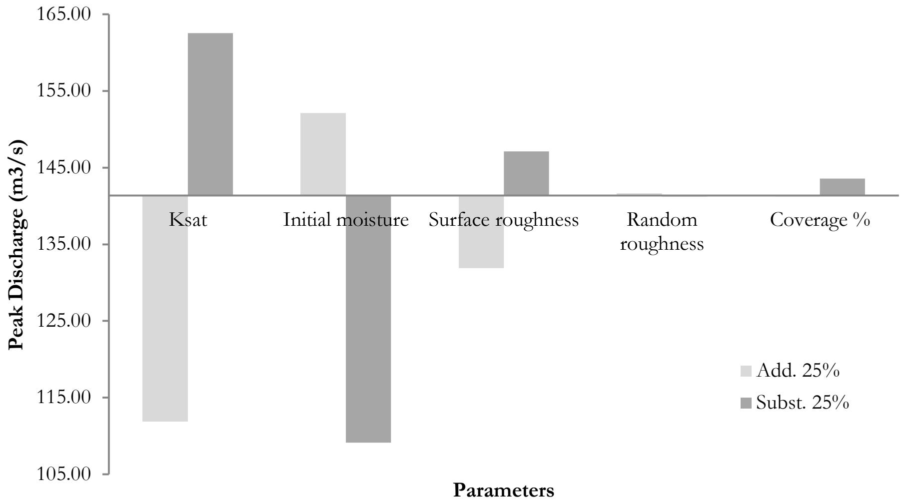
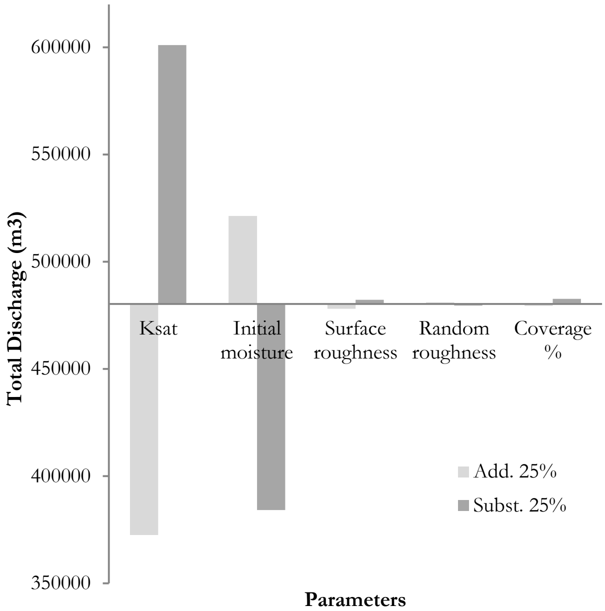


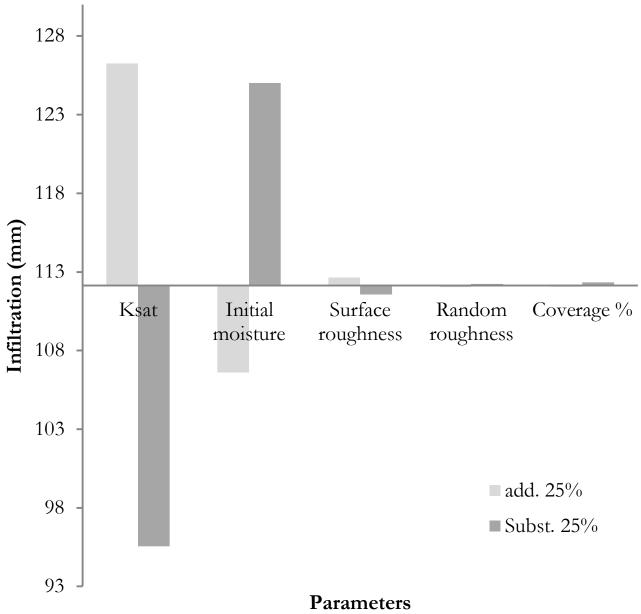

Figure 5-7 The sensitivity level of parameters to peak discharge

Between addition and subtraction of 25% parameter value, Ksat shows high sensitivity towards **peak discharge** with variance about 35.84%, followed by initial moisture with variance 30.40% and surface roughness with variance about 10.79% as shown in **Figure 5-7**. Changes of random roughness and fraction coverage value only give a little effect and seems insensitive to peak discharge with variance near zero. Random roughness and fraction coverage are less sensitive with variance about 0.29% and 1.65%.

**Figure 5-8** shows the most sensitive parameters to both (a) **total discharge** and (b) **total infiltration** characteristics are Ksat and initial moisture**.** Ksat is the most sensitive parameter which influence total discharge and infiltration value with variance about 47.57% and 27.38%. The second sensitive parameter is initial moisture with variance about 28.54% for total discharge and 16.42% for infiltration. In conclusion, Ksat and initial moisture are the parameters which directly influence to total discharge and infiltration. Consideration about finding the right value of Ksat and initial moisture is needed to optimize flood modelling in order to make the most accurate model. Infiltration show straight relation with Ksat value, infiltration increase as Ksat value raise and decrease the possibility of flood, while the other sensitive initial moisture show inverse relation towards infiltration, as shown in the table, the increase of initial moisture value about 25% resulted in -4.94% infiltrations which increase possibility of flood.




(a)




(b)

Figure 5-8 The sensitivity level of parameters to total discharge (a) and total infiltration (b)

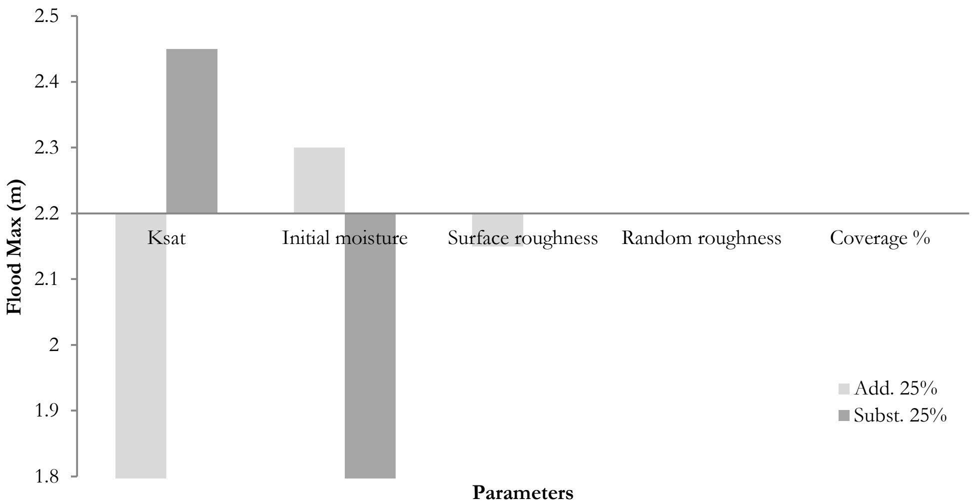



Figure 5-9 The sensitivity level of parameters to flood depth max

**Figure 5-9** shows that Ksat, initial moisture and surface roughness parameters are sensitive in the influence of **flood depth maximum,** with variance of each parameter about 88.18%, 26.36%, and 2.27%. With the same percentage change among those parameters, Ksat value changes significantly showing that Ksat is the most sensitive parameters. The change of Ksat value show inverse relation with flood depth max, the higher value of Ksat decreased possibility of flood.

Among those parameters, the largest **flood area** may occur from the change of Ksat for it higher sensitivity variance about 74.52% than Ksat with variance 59.13% and surface roughness 10.58%. However, the other parameters such as random roughness and fraction coverage have not significant changes to flood area.

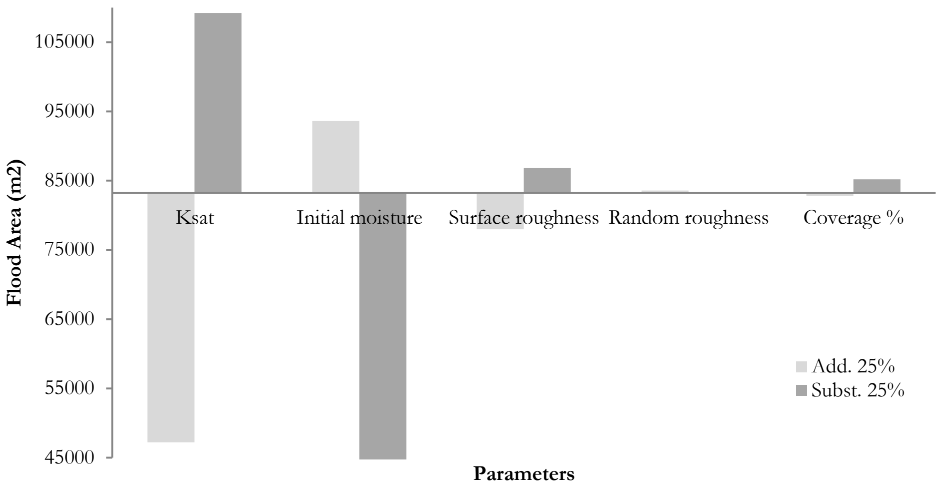



Figure 5-10 The sensitivity level of parameters to flood area

Based on this sensitivity analysis, flood characteristics are very influenced by the saturated hydraulic conductivity (Ksat), initial moisture, and surface roughness. These parameters should be examined as accurately as possible to get the most appropriate flood model predictions. Ksat and initial moisture that give high impact to flood probability is in line with some former assessments and experiments about flood modeling (Prachansri, 2007; De Roo, A.P.J. and Jetten, 1999, and De Roo, et al, 1996).

The model seems to be insensitive with random roughness parameter and fraction coverage, proven that by the change about 25% addition and reduction of those parameters resulted in nearly same value, close to zero. The addition and subtraction 25% value only give small influence for peak discharge; total discharge, infiltration, and flood max and flood area as shown in **Table 5-1.**

## 5.3. Model Calibration and Validation

Hessel (2002) highlighted that the calibration process is required to obtain the acceptable of predictive results and increase the research quality. Moreover, models are not only formed based on physical aspects. In this research, flood model calibration was conducted by minimizing the deviation between the results of the flood modelling and the observed flood data, flood depth and flood extent. The flood depth data was obtained from interviews during fieldwork, but flood extent data cannot be collected. Furthermore, the flood calibration was done based on flood depth. Flood depth data was taken from flash-flood events in 2011. The 2011 used as current situation and it is used to assess the accuracy of flood depth predictions. During fieldwork, researcher only collected 5 flood depth points. These points were selected based on the result of interview about flood depth maximum in flood event at 2011. Then, researcher conducted manual measurements using measurement-tape. This was conducted due to the difficulties to obtain information about flood depth levels in two watersheds. Almost of citizen in those two watershed areas explained that there are several times of flood events in 2011, but the information about the exactly time and flood depth when flood occurred, could not explain by those citizen.  Thus, the five points and it locations can be seen at **Table 5-3.**

Table 5-2 Flood depth points and locations in Gouyave watershed and St. John's watershed

| Nu | Location | Latitude | Longitude | Flood Depth Measurement (m) |
|---|---|---|---|---|
| 1 | Gouyave Watershed | 12° 10' 2.862" N | 61° 43' 49.561" W | 1.2 |
| 2 | | 12° 9' 58.956" N | 61° 43' 48.492" W | 0.5 |
| 3 | | 12° 9' 58.126" N | 61° 43' 48.265" W | 0.3 |
| 1 | St. John's Watershed | 12° 3' 27.340" N | 61° 45' 7.055" W | 0.7 |
| 2 | | 12° 3' 21.170" N | 61° 44' 19.498" W | 0.4 |

In this research, first calibration process was conducted in flood model of Gouyave watershed. It is conducted first because Gouyave watershed has 3 point measurements, while St. John's watershed only has 2 point measurements. In addition, the diversity of land-use types in Gouyave watershed is considered also. Land-use types in Gouyave watershed are more diverse than St. John's watershed. The three most sensitive parameters (which are mentioned in **section 5.2**) were used as calibration parameters. Six sets of parameter-value combinations were used for each simulation are given below.

Table 5-3 Result of Model Calibration

| Land-use Types | Initial | | | Trial 1 | | | Trial 2 | | | Trial 3 | | | Trial 4 | | | Trial 5 (Mix) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | K | P | M | K | P | M | K | P | M | K | P | M | K | P | M | K | P | M |
| Agriculture | 10.714 | 0.585 | 0.05 | 8.034 | 0.585 | 0.05 | 8.034 | 0.585 | 0.05 | 8.034 | 0.585 | 0.05 | 8.034 | 0.585 | 0.05 | 10.714 | 0.585 | 0.08 |
| Bare land | 27.86 | 0.495 | 0.03 | 27.86 | 0.495 | 0.03 | 27.86 | 0.495 | 0.03 | 27.86 | 0.495 | 0.03 | 27.86 | 0.495 | 0.03 | 12.86 | 0.495 | 0.023 |
| Built-up Area | 10 | 0.4 | 0.05 | 10 | 0.4 | 0.05 | 10 | 0.4 | 0.05 | 10 | 0.4 | 0.05 | 10 | 0.4 | 0.05 | 10 | 0.4 | 0.03 |
| Forest | 42.857 | 0.677 | 0.13 | 158 | 0.677 | 0.13 | 47.14 | 0.677 | 0.13 | 158 | 0.578 | 0.13 | 47.14 | 0.578 | 0.13 | 69.643 | 0.578 | 0.1 |
| Grass land | 55 | 0.635 | 0.046 | 23.57 | 0.635 | 0.046 | 23.57 | 0.635 | 0.046 | 23.57 | 0.58 | 0.046 | 23.57 | 0.58 | 0.046 | 19.29 | 0.58 | 0.023 |
| Mix tree | 37.5 | 0.567 | 0.1 | 57 | 0.567 | 0.1 | 35.89 | 0.567 | 0.1 | 57 | 0.554 | 0.1 | 35.89 | 0.554 | 0.1 | 42.857 | 0.554 | 0.1 |
| Shrub | 0.536 | 0.513 | 0.1 | 15.96 | 0.513 | 0.1 | 15.96 | 0.513 | 0.1 | 15.96 | 0.51 | 0.1 | 15.96 | 0.51 | 0.1 | 15.96 | 0.51 | 0.04 |

K : Ksat
P : Porosity
M : Mannings

The initial simulation was the model simulation which is similar with model in sensitivity analysis. Trial 1 and trial 2 were conducted by changing the Ksat value. Ksat value in Trial 1 used the average of Ksat values and considered Ksat with high values. Trial 2 conducted by removing the highest Ksat value. Moreover, in trial 3 and trial 4, researcher combined the Ksat value in trial 1 and trial 2 with other porosity value. In the end, trial 5, it was conducted by combining those three parameters.

The results of model calibrations were evaluated by comparing between results model and observed data. Then, the model evaluation also conducted using the objective functions, including **model bias** and **Root Mean Square Error** (RMSE). Bias is calculated from the differences of mean values between paired observed and simulated values. The best overall model performance is shown when bias values closer to zero. Brief overviews of these statistical measures are provided below.

Bias is calculated with:

$$\frac{\sum_{i=1}^{n}(y_i - x_i)}{n} \quad \text{..........} \quad \textbf{(5.1)}$$

Where:
n : total number of observations
$x_1$ : the observed value
$y_1$ : the model-simulated value

Root Mean Square Error (RMSE) is a square root of average values of the squared prediction errors. RMSE is conducted to measure the discrepancy between model resulted values and observed values on an individual basis. Then, it can assess the performance of overall model. Because of quadratic terms, the larger discrepancies give the greater weight. It seems that the smaller value indicates the better model performance.

Root Mean Square Error (RMSE) is calculated with:

$$\sqrt{\frac{\sum_{i=1}^{n} (y_i - x_i)^2}{n-1}} \quad \text{.......} \quad (5.2)$$

Where:
n : total number of observations
$x_1$ : the observed value
$y_1$ : the model-simulated value

The result of model calibration from Gouyave watershed using Bias and RMSE can be shown at **Table 5-4.**

Table 5-4 Result of Model Calibration using Bias and RMSE

| Nu | Latitude | Longitude | Flood depth (m) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Point measurement | Initial | Trial 1 | Trial 2 | Trial 3 | Trial 4 | Trial 5 |
| 1 | 12° 10' 2.862" N | 61° 43' 49.561" W | 1.2 | 1.200 | 0.440 | 1.180 | 0.440 | 0.000 | 0.900 |
| 2 | 12° 9' 58.956" N | 61° 43' 48.492" W | 0.5 | 1.080 | 0.000 | 1.010 | 0.000 | 0.000 | 0.460 |
| 3 | 12° 9' 58.126" N | 61° 43' 48.265" W | 0.3 | 1.030 | 0.000 | 0.940 | 0.000 | 0.000 | 0.270 |
| **Bias (Unit = meter)** | | | | **0.437** | **0.520** | **0.390** | **0.520** | **0.667** | **0.123** |
| **RMSE (unit = meter)** | | | | **0.776** | **0.934** | **0.682** | **0.934** | **1.317** | **0.303** |

**Table 5-4** shows the **Trial 5** the best simulation for Gouyave watershed. The result of model calibration using Bias and RMSE of trial 5 are 0.123 and 0.303. The Bias value and RMSE value are the lowest than others and they close to zero. However, trial 4 is the worst combination for this model because the Bias value and RMSE value away from zero. Based on these calibrations, the configuration of trial 5 is used as model validation in St. John's watershed. This validation does not change data which was used in trial 5. The result of model validation in St. John's watershed follows at **Table 5-5.**

Table 5-5 Result of Model Validation using BIAS and RMSE

| Nu | Latitude | Longitude | Flood depth (m) | |
|---|---|---|---|---|
| | | | Point measurement | Simulated point |
| 1 | 12° 3' 27.340" N | 61° 45' 7.055" W | 0.7 | 0.800 |

| Nu | Latitude | Longitude | Flood depth (m) | |
|---|---|---|---|---|
| | | | Point measurement | Simulated point |
| 2 | 12° 3' 21.170" N | 61° 44' 19.498" W | 0.4 | 0.160 |
| Bias (Unit = meter) | | | | 0.170 |
| RMSE (unit = meter) | | | | 0.260 |

From **Table 5-5** can be seen that Bias value (0.170) and RMSE value (0.26). It could be concluded that this model has the best performance.

## 5.4. Comparison of flood characteristics based on the difference return periods

In this section, the flood characteristics are developed using difference return periods. Rainfall data which are used as calculated using Gumbel method. It was explained in Table 22 in **section 4.3**. The flood model comparison was conducted to analyze the flood characteristics in two watersheds area, Gouyave watershed and St. John's watershed. The comparison result of flood characteristics in two watershed areas can be shown at **Table 5-6**.

Table 5-6 Comparison of flood characteristics in Gouyave watershed and St. John's watershed for 3 different return periods

| Flood characteristics | 2 years return period | | 35 years return period | | 100 years return period | |
|---|---|---|---|---|---|---|
| | Gouyave | St. John's | Gouyave | St. John's | Gouyave | St. John's |
| Peak discharge ($m^3/s$) | 3.890 | 26.400 | 110.990 | 119.769 | 150.590 | 134.820 |
| Total discharge ($m^3$) | 20791.630 | 86591.380 | 387064.160 | 458750.140 | 579248.980 | 636098.370 |
| Average discharge (m3) | 2478.144 | 7109.309 | 46133.988 | 37664.215 | 69040.403 | 52224.825 |
| Q/P (%) | 3.260 | 9.420 | 27.210 | 31.100 | 35.600 | 41.110 |
| Total infiltration (mm) | 72.470 | 67.920 | 124.460 | 109.770 | 131.100 | 114.680 |
| Max flood depth (m) | 0.000 | 0.000 | 1.740 | 3.350 | 2.250 | 3.400 |
| Average flood depth (m) | 0.000 | 0.000 | 0.170 | 0.680 | 0.400 | 0.705 |
| Max flood duration (min) | 0.000 | 0.000 | 345.000 | 96.000 | 350.000 | 106.000 |
| Average flood duration (min) | 0.000 | 0.000 | 66.350 | 28.140 | 54.840 | 41.800 |
| Max flood propagation (min) | 0.000 | 0.000 | 86.000 | 64.000 | 112.000 | 72.000 |
| Average flood propagation (min) | 0.000 | 0.000 | 63.760 | 53.870 | 62.418 | 51.732 |
| Flood volume (m3) | 0.000 | 0.000 | 12805.560 | 109846.424 | 42803.230 | 142377.003 |
| Flood area (m2) | 0.000 | 0.000 | 41600.000 | 146000.000 | 94400.000 | 186000.000 |

From **Table 5-6** show that peak discharge in St. John's watershed is extremely high, specifically in 2 years return period, than peak discharge in 35 years and 100 years return period. This is probably caused by the capacity of channel in 2 years return period can hold all of run-off, so there is no flood event occur in St. John's (see **Figure 5-10**). From this hydrograph, peak discharge in St. John's watershed is higher than in Gouyave watershed. The difference of peak discharge in those watersheds is very high. In the Gouyave watershed, peak discharge is lower, but the duration of run-off is longer with lower run-off volume (Q/P). However, peak discharge in St. John's watershed is very high, but the duration of run-off water is faster and run-off volume is higher (Q/P) than in Gouyave watershed. This condition is due to the rainfall intensity in 2 years return period is categorized in low class, so it does not enough influence and affects to flood events

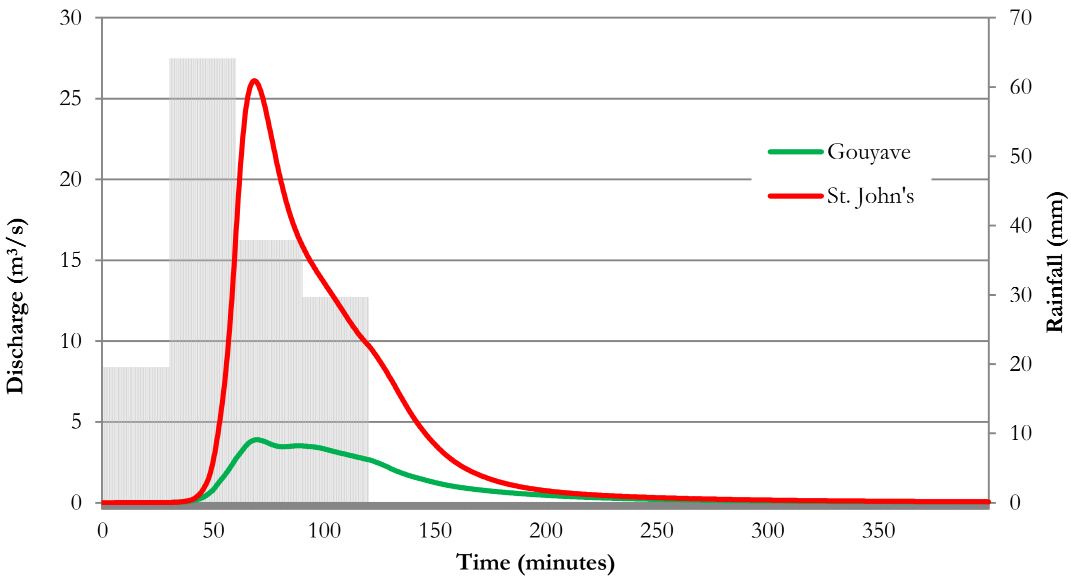



Figure 5-10 Simulated discharge of Gouyave watershed and St. John's watershed in 2 years return period

**Figure 5-11** shows the hydrograph of Gouyave watershed and St. John's watershed in 35 years return period. This hydrograph show flood events can be occurred in St. John's watershed and Gouyave watershed. Peak time of Gouyave watershed (64 minutes) is faster than St. John's watershed (70 minutes). It means that the response in St. John's watershed is slightly faster, as it just needs 64 minutes to reach peak discharge (119.769 $m^3/s$). The difference in reaching peak discharge in those two areas is also caused by the differences of total area that are affected to flooding.

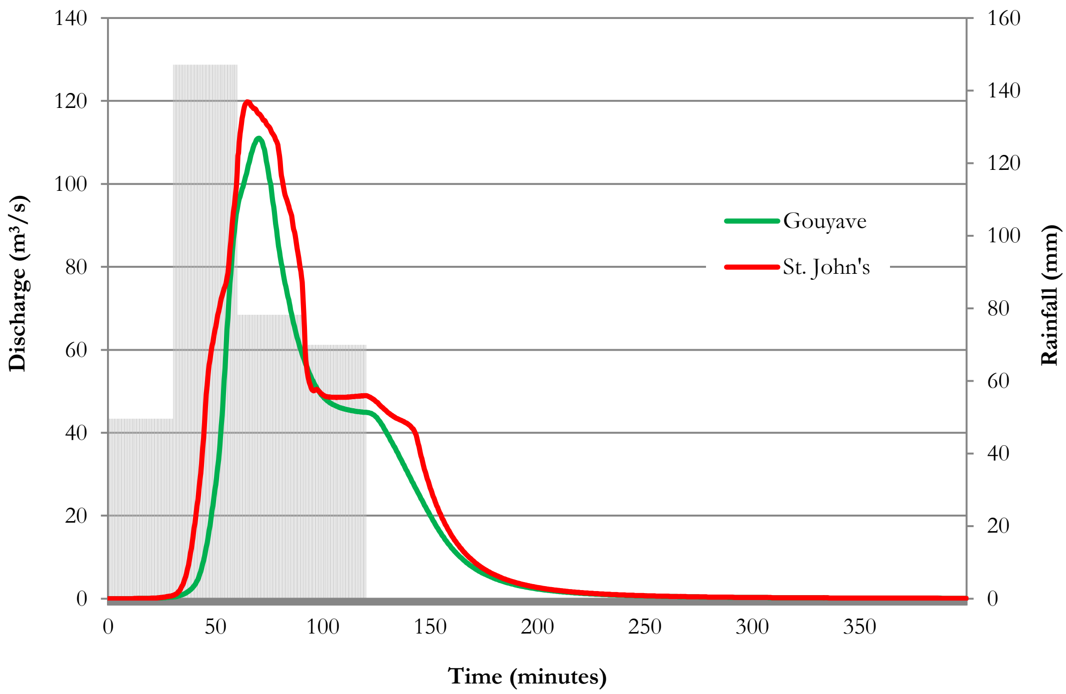



Figure 5-11 Simulated discharge of Gouyave watershed and St. John's watershed in 35 years return period

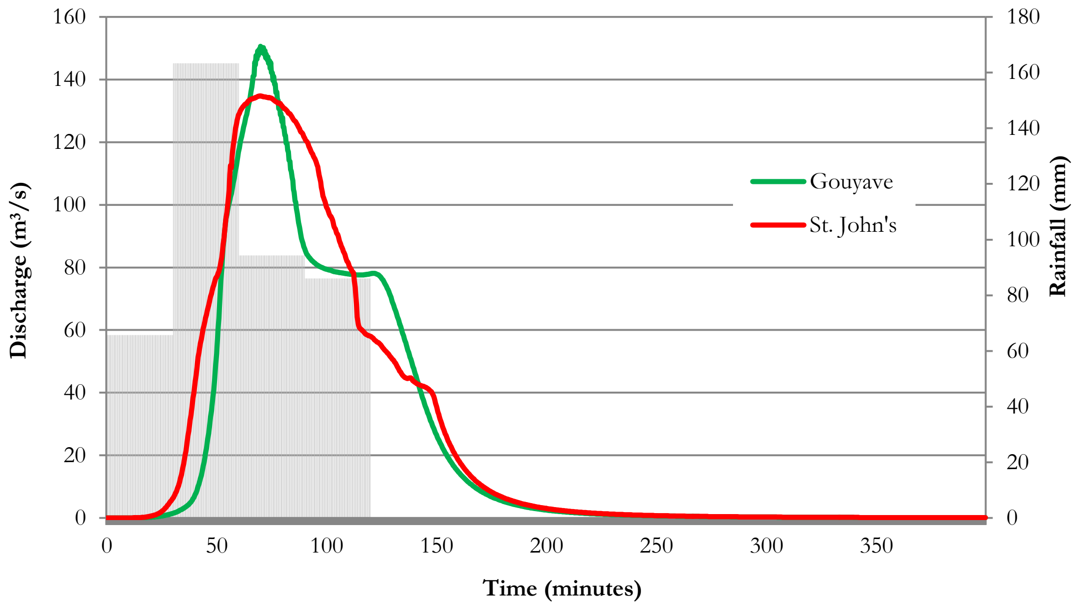



Figure 5-12 Simulated discharge of Gouyave watershed and St. John's watershed in 100 years return period

The hydrograph in **Figure5-12** shows the prediction of discharge and flood pattern in Gouyave watershed and St. John's watershed. These hydrographs show that the Gouyave watershed and St. John's watershed are predicted to occur flood events. Flood will be occurred in 120 minutes in Gouyave watershed. The maximum flood depth in Gouyave watershed is 2.25 meter with flood propagation time is 112 minutes. Whereas, maximum flood depth in St. John's watershed is 3.40 meter with flood propagation time is 72 minutes, it is less than flood propagation time in Gouyave watershed.

Related with total discharge, total discharge in St. John's watershed for 3 different return period (2,35, and 100 years) is higher than total discharge in Gouyave watershed, specifically total discharge in 2 years return period. It is caused by the St. John's watershed have larger area than Gouyave watershed. It means that St. John's has more catchment areas and it have bigger potential run-off than Gouyave watershed.

Moreover, the maximum flood depth in St. John's watershed in 35 years return period (3.350 m) and 100 return period (3.40 m) are higher than maximum flood depth in Gouyave watershed 1.74 m and 2.25 m). Flood depth map can be shown at **Figure 5-13 until Figure 5-16.** The maximum flood duration in St. John's watershed in those two return periods are lower than Gouyave watershed, but the maximum flood propagation in St. John's watershed for 2 different period is faster than Gouyave watershed. It is caused by (1) the basin shape in St. John's watershed in the upperparts is more round than basin shape in Gouyave watershed. It makes water from multiple locations in the upstream of St. John's watershed flow run-off water and it is more likely to arrive at the same time in downstream areas. It makes the flood depth in St. John watershed is higher and the propagation time in St John's watershed is faster than Gouyave watershed. Because the flood propagation time in St. John's is faster, the durations of flood that is inundated this areas is not for a long time (2) most of area in St. John's watershed is dominated with steep-slope. It makes run-off velocity is faster than run-off water in flat-steep. It makes the run-off water arrive faster in downstream areas. Thus, from this explanation, it can be concluded that St. John's watershed which has highest total discharge and peak discharge, it also has higher maximum flood depth, shorter duration of flood, and faster propagation time.

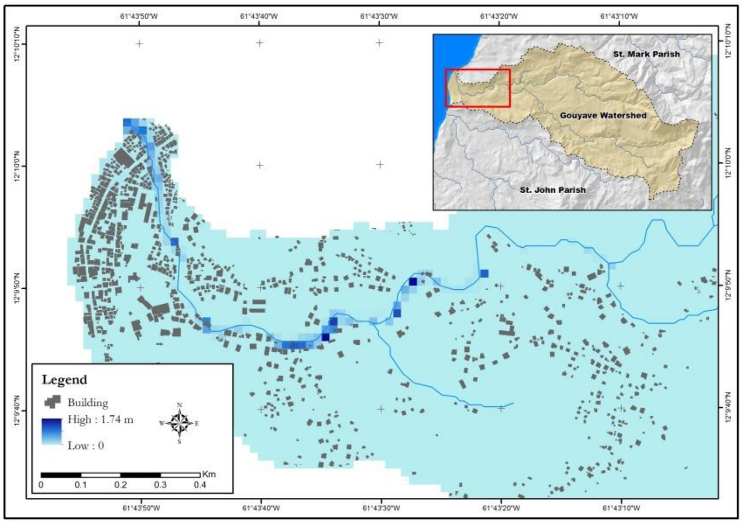



Figure 5-13 Flood depth in Gouyave watershed at 35 years return period

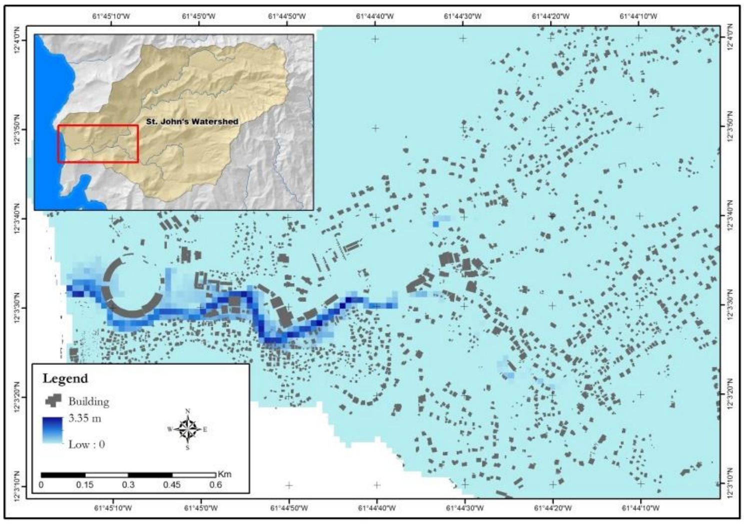



Figure 5-14 Flood depth in St. John's watershed at 35 years of return period

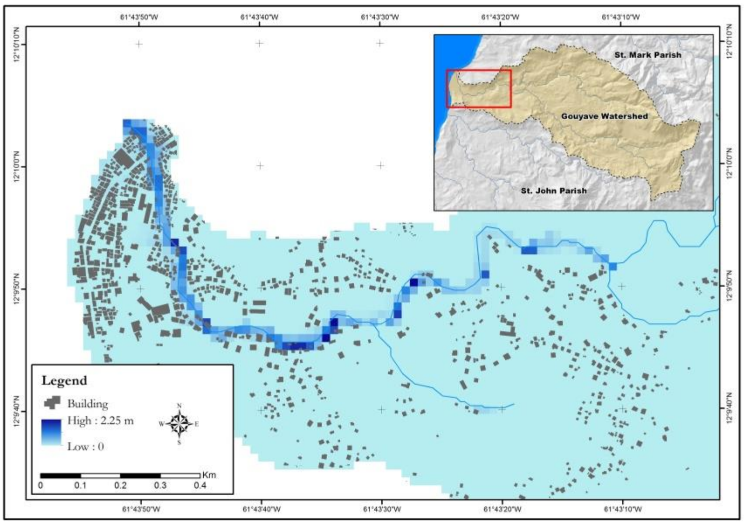



Figure 5-15 Flood depth in Gouyave watershed at 100 years return period

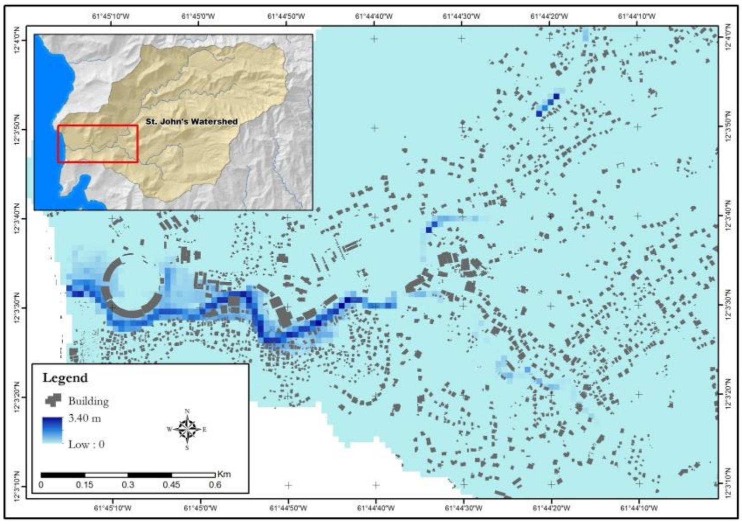



Figure 5-16 Flood depth in St. John's watershed at 100 years return period

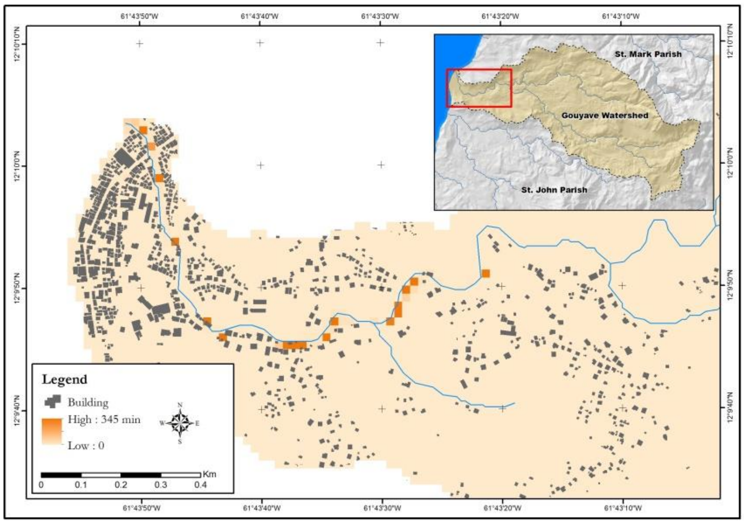



Figure 5-17 Flood time Gouyave watershed at 35 years of return period*

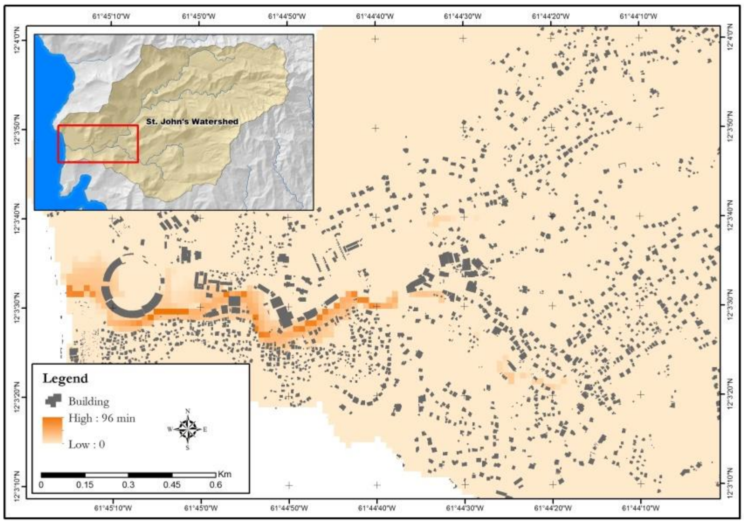



Figure 5-18 Flood time in St. John's watershed at 35 years return period*

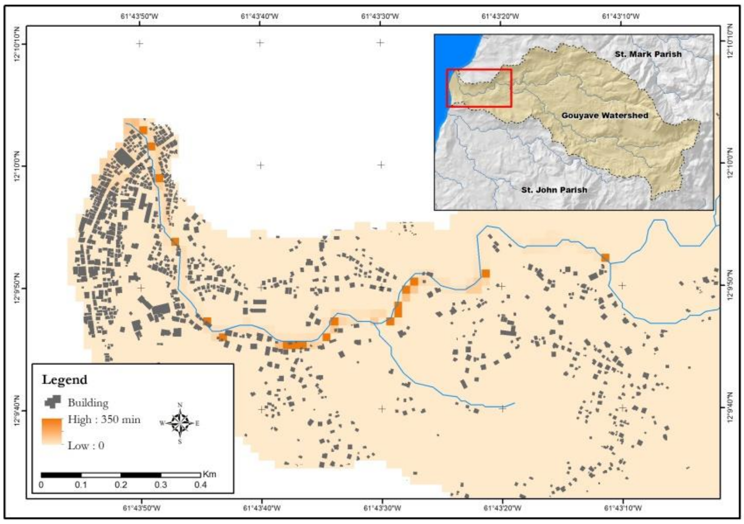



Figure 5-19 Flood time Gouyave watershed at 100 years of return period*

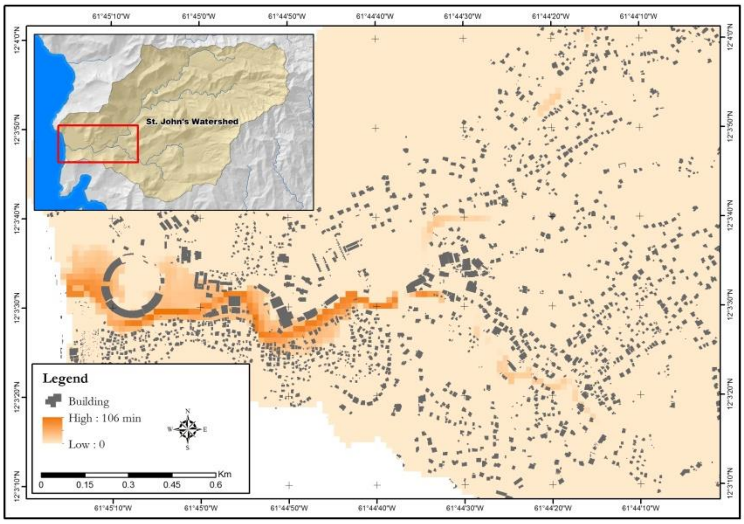



Figure 5-20 Flood time in St. John's watershed at 100 years return period*

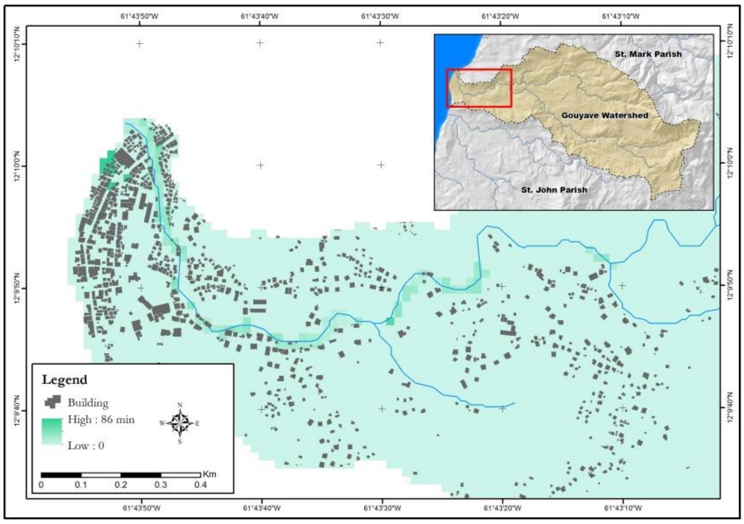



Figure 5-21 Flood propagation time in Gouyave watershed at 35 years of return period*

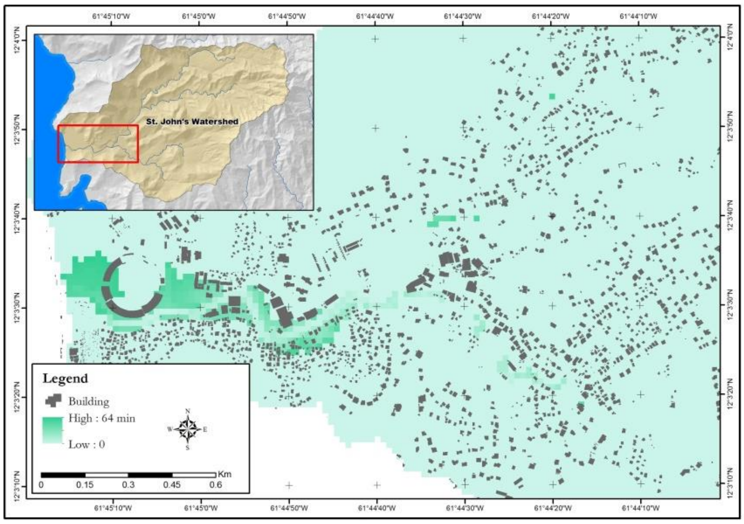



Figure 5-22 Flood propagation time in St. John's watershed at 35 years return period*

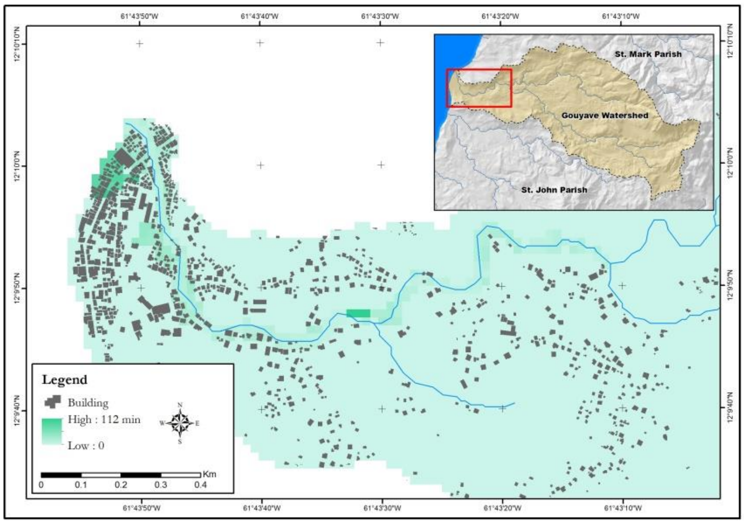



Figure 5-23 Flood propagation time in Gouyave watershed at 100 years of return period*

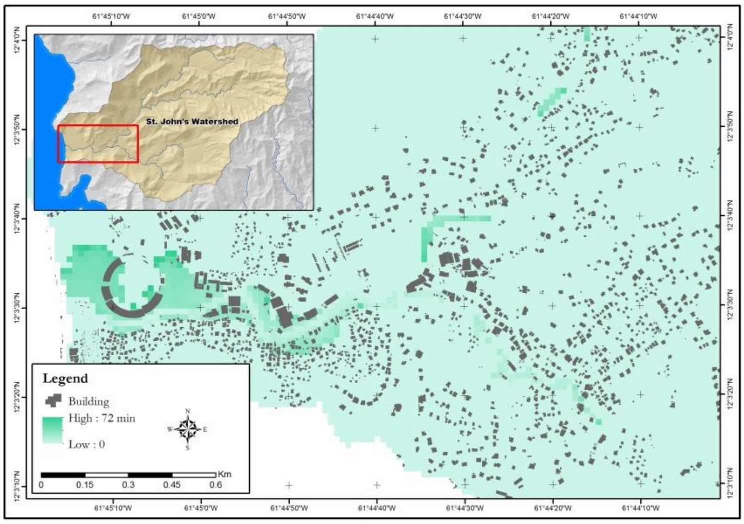



Figure 5-24 Flood propagation time in St. John's watershed at 100 years return period*

* Notes: the areas that show on the flood durations and flood propagation time are different with the areas show in flood depth because the model is error.

## 5.5. Analysis of watershed responses to flood in different return period

It is necessary to analyze how sensitive both watersheds to response flooding. In the previous analysis, it does not explain the sensitivity level of watershed for different return period. In 2 years return period, there is no watershed response to flood because flood is not occured. Furthermore, flood occur in Gouyave watershed and St. John's watershed in 35 years return period, but it can be concluded in which return period, both of watershed areas are hit by flooding. There were 5 scenarios of return periods selected, such as 2, 5, 10, 35, and 100 years return period.

Table 5-7 Classification of flood, flood extents and flood volume in 35 years return period

| Characteristics | Gouyave watershed | | | | | St. John's watershed | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 2 years | 5 years | 10 years | 35 years | 100 years | 2 years | 5 years | 10 years | 35 years | 100 years |
| Peak discharge (m3/s) | 3.89 | 39.14 | 65.55 | 110.99 | 150.59 | 26.40 | 78.95 | 102.80 | 119.77 | 134.82 |
| Total discharge (m3) | 20791.63 | 105173.52 | 188707.33 | 387064.16 | 579248.98 | 86591.38 | 256625.48 | 323887.87 | 458750.14 | 636098.37 |
| Flood depth max (m) | 0.00 | 0.00 | 0.21 | 1.74 | 2.25 | 0.00 | 2.75 | 2.95 | 3.35 | 3.40 |
| Flood volume (m3) | 0.00 | 0.00 | 82.93 | 12805.56 | 42803.23 | 0.00 | 43128.17 | 69357.11 | 109846.42 | 142377.00 |
| Flood area (m2) | 0.00 | 0.00 | 400.00 | 41600.00 | 94400.00 | 0.00 | 62000.00 | 98000.00 | 146000.00 | 186000.00 |

**Table 5-7** show that St. John's watershed has higher of sensitivity level to flood than in Gouyave watershed. In 5 years return periods, both of watershed areas are safe from flood events. The Gouyave channels can store total run-off in these areas, 20791.63 $m^3$ for Gouyave watershed and 86591.38 $m^3$ for St. John's watershed. Gouyave watershed response flood in 10 years return period with maximum flood depth 0.21 m, while St. John's watershed has response flood in 2.75 m of flood depth in the same return period (5 years return period). The differences in the rates of flood response in two watersheds area are caused by the different characteristics of St. John's watershed and Gouyave watershed. St. John's watershed is more urbanized than Gouyave watershed. Besides that, St. John's watershed is dominated with clay soil types. It is also influenced to the decreasing of infiltration rate which can be increased the run-off.

# 6. FLOOD SCENARIOS

Flood scenario is developed based on the differences of return period. The model simulations were carried out for three case scenarios with 2 years return period, 35 years return period, and 100 year return period. The results of flood scenarios were analyzed to know the difference exposure buildings and land-use types in Gouyave watershed and St. John's watershed based on flood depth. In this research, flood depths are classified according to the assumption of flood height based on the human body measurements. This classification is divided flood depth into 5 criteria,

- Areas with flood depth 0.0 m until 0.2 m;
- Areas with flood depth 0.2 m until 0.5 m;
- Areas with flood depth 0.5 m until 1.0 m;
- Areas with flood depth 1.0 m until 1.5 m;
- Areas with flood depth > 1.5 m.

## 6.1. The building exposed by flooding

### 6.1.1. 2 years return period

There is no flood event for this return period. Determination of return period was assumed by the rainfall data. The 2 years return period flood was choosen to check whether there would be a flood event for this return period. The result of modelling shows that there is no flood in the St. John's and Gouyave watershed. It is matched with the observation during the fieldwork.

### 6.1.2. 35 years return period

Related with exposure building caused by flooding, the numbers of building which were affected to flood in St. John's watershed is 216 units. The highest number of building that can be affected to flood is occurred in 0.2 m until 0.5 m of flood depth. In the Gouyave watershed that flood affected number of houses or building totals up to 61 units. The comparison between buildings loses in St. John's watershed and Gouyave watershed per each flood depth level are shown in **Figure 6-2**.

Table 6-1 The exposure buildings by flood in 35 years return period

| Class | Flood depth (m) | Building (unit) | |
|---|---|---|---|
| | | Gouyave watershed | St. John's watershed |
| Very low | 0.0 - 0.2 | 42 | 65 |
| Low | 0.2 - 0.5 | 10 | 78 |
| Moderate | 0.5 - 1.0 | 7 | 55 |
| High | 1.0 - 1.5 | 1 | 8 |
| Very high | > 1.5 | 1 | 10 |

The comparison of buildings numbers that are exposure by flood in St. John's watershed and Gouyave watershed for 35 years return period can be shown at **Figure 6-1**. In the two watersheds area, the highest exposure buildings by flood occur when the flood depth reach 0.2 m until 0.5 m. If the flood depth is only until 1.5 m, the affected building is become lowest. The building locations that exposed by flood can be seen at **Figure 6-2** and **Figure 6-3.**

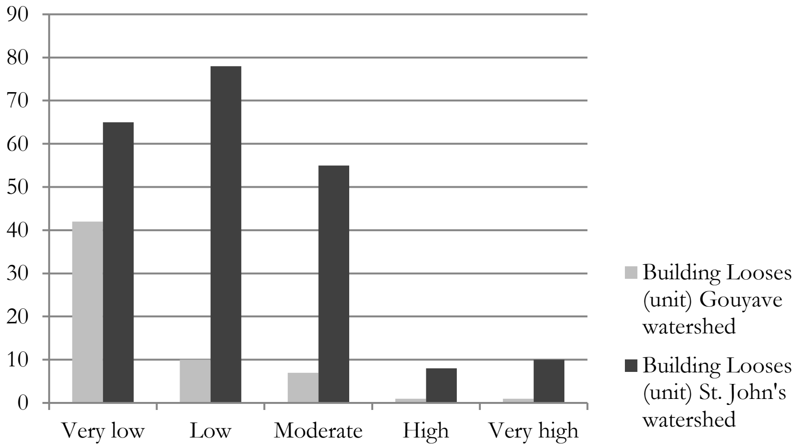



Figure 6-1 The exposure buildings of Gouyave watershed and St. John's watershed per each flood depth level in 35 years return period

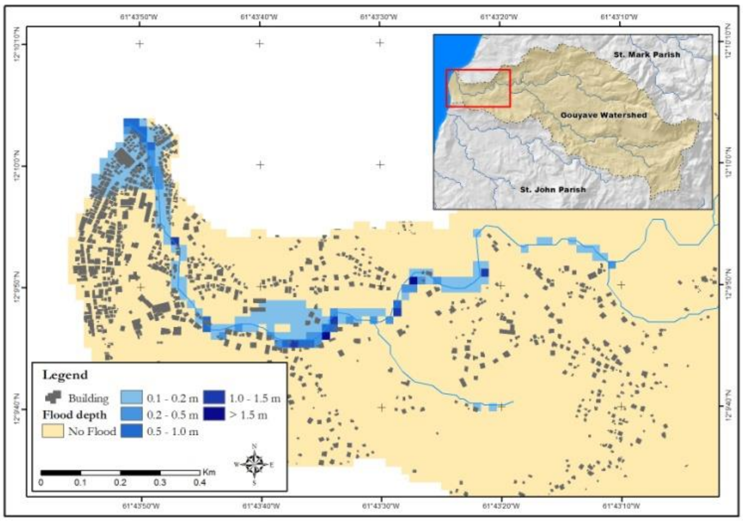



Figure 6-2  Flood depth in Gouyave watershed in 35 years return period

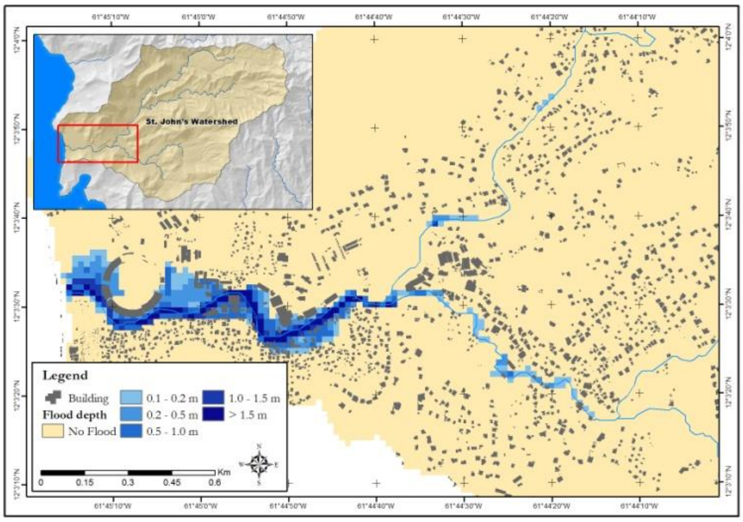



Figure 6-3 Flood depth in St. John's watershed in 35 years return period

### 6.1.3. 100 years return period

The 100 years return period is the extreme daily rainfall that used in flood modelling at both watershed. Total comparison in exposed buildings affected by flooding in two watersheds seems that the numbers of exposed building in St. John's watershed is higher than Gouyave watershed. The comparison between buildings losses in St. John's watershed and Gouyave watershed per each flood depth are shown in **Figure 6-4.**

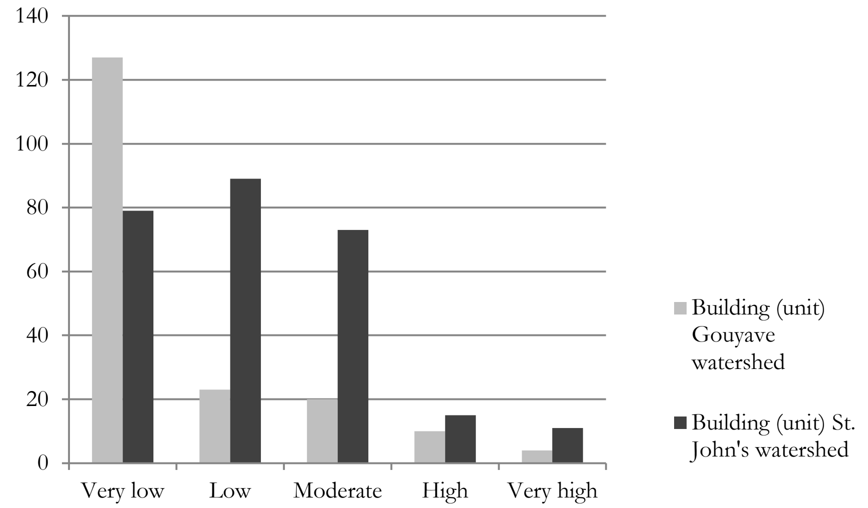



Figure 6-4 The exposure buildings of Gouyave watershed and St. John's watershed per each flood depth level in 100 years return period

Related with exposed building by flooding, the numbers of building which can be affected to flooding in St. John's watershed is 267 units. The highest number of building that can be affected by flood in low flood level is 89 units with the flood depth 0.2-0.5 meter. In the very-high flood level, the exposed building by flooding is only 11 units. In addition, the total number of Gouyave's buildings that are potential inundated by flood is 184 units. The highest numbers of building that are exposed by flood is 127 units.

Table 6-2 The exposure buildings by flood in 100 years return period

| Class | Flood depth (m) | Building (unit) | |
|---|---|---|---|
| | | Gouyave watershed | St. John's watershed |
| Very low | 0.0 - 0.2 | 127 | 79 |
| Low | 0.2 - 0.5 | 23 | 89 |
| Moderate | 0.5 - 1.0 | 20 | 73 |
| High | 1.0 - 1.5 | 10 | 15 |
| Very high | > 1.5 | 4 | 11 |

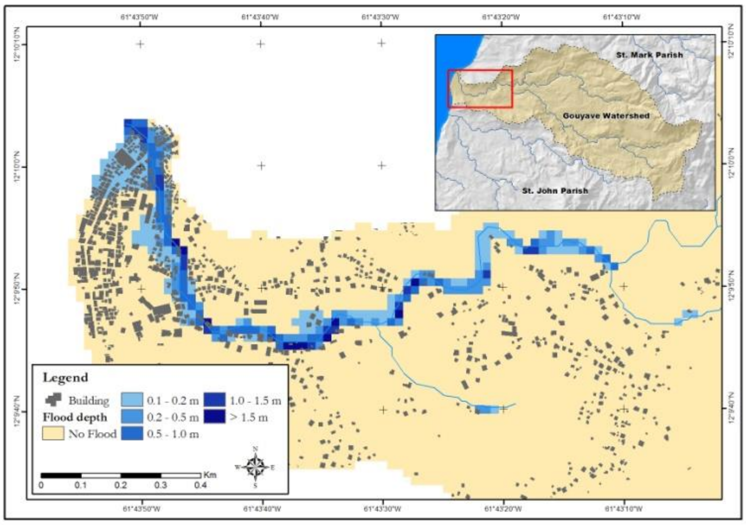



Figure 6-5 Flood depth in Gouyave watershed in 100 years return period

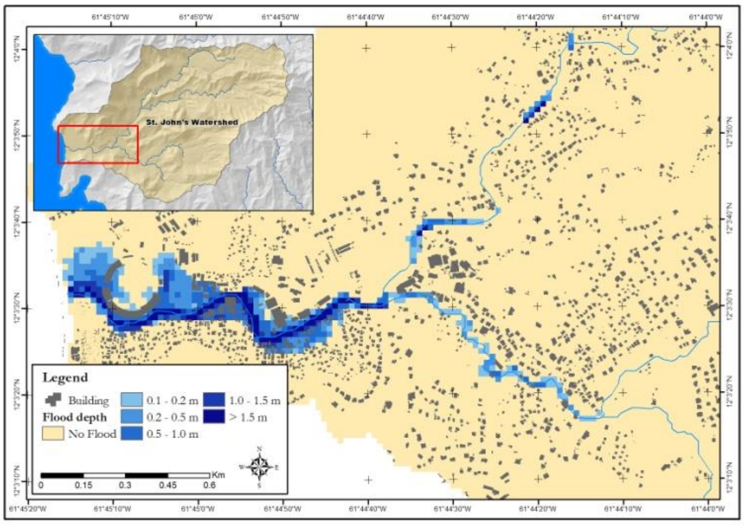



Figure 6-6 Flood depth in St. John's watershed in 100 years return period

## 6.2. The land-use exposed by flooding

### 6.2.1. 2 years return period

There is no flood event for this return period. Determination of return period was assumed by the rainfall data. The result of modelling shows that there is no flood in the St. John's and Gouyave watershed. It is matched with the observation during the fieldwork.

### 6.2.2. 35 years return period

Based on **Table 6-**8, the built-up area is the largest area that are exposed by flooding in Gouyave watershed. The total built-up area that affected by flooding is 30377.27 m$^2$. These areas are concentrated in the lower-parts of Gouyave watershed which are dominated with housing and infrastructures (see **Figure 6-2**). Moreover, bare land is the lowest affected area of flooding. Total areas that are affected by flooding is only 447.89 m$^2$ or 0.72% from total area of affected land-use by flooding.

Table 6-3 The exposure land-use by flood in Gouyave watershed (35 years return period)

| Land use | Extent (m²) | | | | | |
|---|---|---|---|---|---|---|
| | 0.1 - 0.2 m | 0.2 - 0.5 m | 0.5 - 1.0 m | 1.0 - 1.5 m | > 1.5 m | Total |
| Bare Land | 337.68 | 110.22 | - | - | - | 447.89 |
| Built-up Area | 26970.36 | 2321.37 | 961.87 | 33.85 | 89.81 | 30377.27 |
| Mix Tree | 18824.33 | 3382.27 | 2191.22 | 1271.88 | 617.20 | 26286.88 |
| Shrub | 4374.66 | - | - | - | - | 4374.66 |

Similar with Gouyave watershed, built-up areas is the highest land-use types that are exposed by flooding in St. John's watershed. Total 68534.44 m² or 50,16% of the total area affected by flooding. It is caused by the infiltration rates of soil in built-up area is low. There is not enough natural vegetation surrounding the built-up areas. 22,61% of shrub also potentially exposed by flooding in 35 years of return period. Overall, the total areas that are affected to flooding in St. John's watershed is higher than Gouyave watershed.

Table 6-4 The exposure land-use by flood in St. John's watershed (35 years return period)

| Land use | Extent (m²) | | | | | |
|---|---|---|---|---|---|---|
| | 0.1 - 0.2 m | 0.2 - 0.5 m | 0.5 - 1.0 m | 1.0 - 1.5 m | > 1.5 m | Total |
| Bare Land | 2472.91 | 3488.64 | 653.89 | 4.83 | - | 6620.28 |
| Built-up area | 17882.58 | 22899.74 | 18879.45 | 5004.91 | 3867.76 | 68534.44 |
| Grass Land | 7344.20 | 8467.46 | 3181.52 | 1985.25 | 397.75 | 21376.19 |
| Mix Tree | 5398.06 | 1765.30 | 1799.61 | 202.48 | 18.27 | 9183.72 |
| Shrub | 1097.27 | 4789.68 | 8324.43 | 4985.48 | 11695.89 | 30892.75 |

### 6.2.3. 100 years return period

If flood occurs in 0.1 meter until > 1.5 meter in depth, most of area in Gouyave watershed is influenced (**Table 6-5**). The built-up area is the most influenced land-use by flooding. Total area of built-up area that affected by flooding is 40543.62 m². The built-up area are inundated by flood is 50.29% from total area that are exposed by flooding in Gouyave watershed. In addition, a total mixed-tree area which is inundated by flooding is 38747.57 m2. If the built-up area and un-built-up area is compared, total area of developed (built-up) area is higher with proportion 50.29% and 49.70%. Detail information about the exposed building in Gouyave watershed can be seen at **Table 6-6.**

Table 6-5 The exposure land-use by flood in Gouyave watershed (100 years return period)

| Land use/Land cover | Extent (m²) | | | | | |
|---|---|---|---|---|---|---|
| | 0.1 - 0.2 m | 0.2 - 0.5 m | 0.5 - 1.0 m | 1.0 - 1.5 m | > 1.5 m | Total |
| Bare Land | 98.96 | 7.28 | 352.24 | 66.51 | - | 524.99 |
| Built-up Area | 27637.84 | 6075.60 | 5364.61 | 1214.46 | 251.11 | 40543.62 |
| Grass Land | 328.09 | - | - | - | - | 328.09 |
| Mix Tree | 14576.35 | 11353.64 | 7162.13 | 3062.77 | 2592.67 | 38747.57 |
| Shrub | 449.74 | 12.40 | 11.76 | - | - | 473.90 |

Similar with Gouyave watershed, the most influence land-use by flooding is built-up area. Generally, built-up areas have low infiltration rates due to there are not enough catchment area that can be supported to infiltrate the water. The total extent of built-up area that is affected is 83,291.48 m². It is much dominated land-use as affected by flooding. Besides the built-up area, shrub and grass land also high affected to flood. It is different with forest; total area of forest inundated by flood is only 0.33 m² because forest contains much natural vegetation which has high infiltration rates (see **section 4.2.1**).

Table 6-6 The exposure land-use by flood in St. John's watershed (100 years return period)

| Land use/Land cover | Extent (m²) | | | | | |
|---|---|---|---|---|---|---|
| | **0.1 - 0.2 m** | **0.2 - 0.5 m** | **0.5 - 1.0 m** | **1.0 - 1.5 m** | **> 1.5 m** | **Total** |
| Bare Land | 2419.63 | 5150.19 | 1319.66 | 132.80 | - | 9022.29 |
| Builtup area | 22706.20 | 22663.65 | 25395.41 | 8026.86 | 4499.36 | 83291.48 |
| Forest | - | 0.33 | - | - | - | 0.33 |
| Grass Land | 9737.92 | 13280.78 | 4196.19 | 3589.26 | 418.10 | 31222.24 |
| Mix Tree | 5884.42 | 5106.73 | 3269.71 | 660.52 | 1143.81 | 16065.19 |
| Shrub | 1939.11 | 4250.69 | 7499.19 | 5852.84 | 13682.70 | 33224.54 |

Comparison between the exposed land-use types in Gouyave watershed and St. John's watershed can be shown at this following figure. **Figure 6-8** shows that the most influence land-use in those watersheds in is built-up areas, specifically when flood occurred in 0.1 to 1 meter. It can show from the height of built-up areas in this graphic. The lowest total area of land-use that is exposed by flooding is forest and bare land.

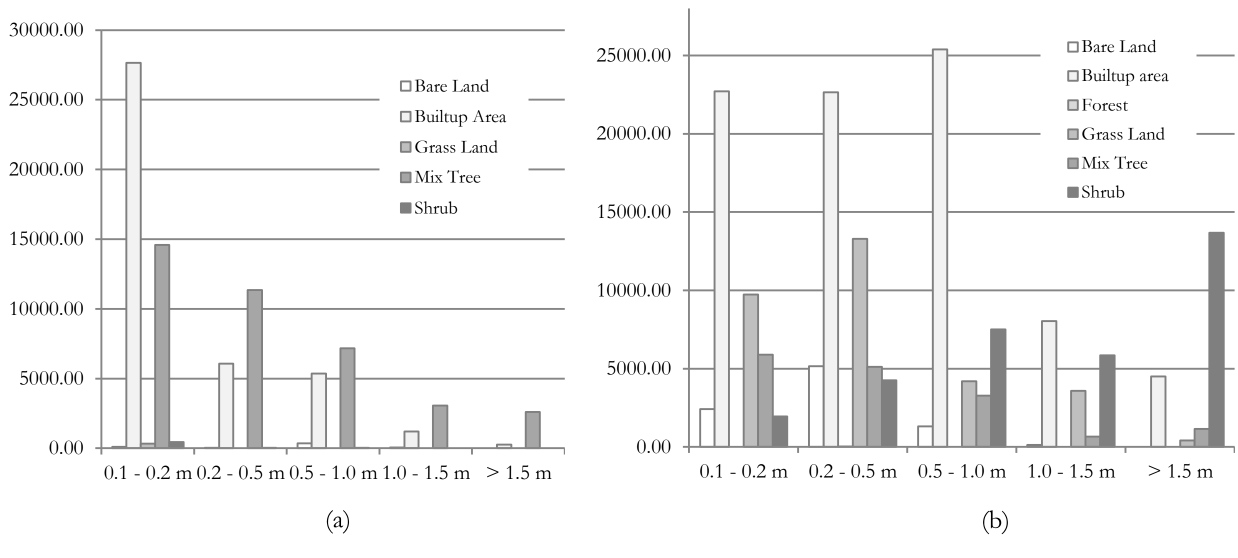



Figure 6-7 The comparison of exposure buildings in Gouyave watershed (a) and St. John's watershed (b)

# 7. CONCLUSIONS AND RECOMMENDATIONS

## 7.1. Conclusions

The main objective of this research is to compare the response of flash flood behaviours in Gouyave watershed and St. John's watershed, Grenada. This main objective was sub-divided into some objectives; identification of the physical characteristics (land-use and soil) for flash-floods modelling in Gouyave watershed and St. John's watershed, determination of the frequency and magnitude of rainfall based on recorded daily totals and design series of return periods, assessment of sensitivity parameters on the LISEM and flood model, comparison the flood characteristics for different return periods, and assessment of exposure buildings and land-use based on different return periods. Based on the findings of this research, it is possible to conclude the following:

- Land use characteristics in Gouyave watershed and St. John's watershed are dominated by land-use type "mixed-tree". More than 50% of Gouyave watershed area and St. John's watershed area are covered by this land-use type. The built-up area in Gouyave watershed is 5.53% which makes the Gouyave watershed typical rural area. The built-up area in the St. John's watershed is 23.28% and gives it a much more urbanized character.
- Each land-use types have a different characteristic related with the soil physical properties, especially Ksat and porosity. The natural land-use classes, such as forest and mixed-trees and cultivated land, like agriculture lands have high values of Ksat, but a low value of porosity. It seems that they have higher infiltration ability than other land-use types. Ksat and porosity have a reverse relation. The result and its consequence of these conditions are shown in the results of Ksat and porosity analysis based on land-use types.
- Related with Ksat and porosity, the Ksat and porosity values based on land-use types are more suitable and more variance than Ksat and porosity based on soil types. It is due to their distributions and their mean values are more variance. It can ignore the outlier values for getting the best accuracy and appropriate values for modelling.
- Several maps are used as base data for the flood modelling. These are the DEM map, Ksat maps, initial moisture maps, surface roughness maps, and random roughness maps. To get the most sensitive parameter, a sensitivity analysis was conducted. The most sensitive parameters in flood modelling are saturated hydraulic conductivity (Ksat) and initial soil moisture content.
- Model calibration and validation was analyzed using Bias method and RMSE method. From the result of the model calibration and validation, it can be concluded that the flood modelling results have a good accuracy. Besides that, this model can represents the overall of existing conditions of flood events in research areas.
- There are five return periods that were assessed as basic data of rainfall. They are 2, 5, 10, 35, and 100 years return periods. Based on the assessment, the rainfall data in 2011 used as basic reference data or it seems the event base of flood because it can represent the base situation of flood events in two watershed areas.
- The characteristics of Gouyave watershed and St. John's watershed are influenced by several flood characters, such as peak discharge and total discharge, total infiltration, flood depth, flood

duration, flood propagation, flood volume, and flood area. Based on the analysis, St. John's watershed is more sensitive to flood. It is shown from some flood characters in St. John's watershed is higher than flood characters in Gouyave watershed, like peak discharge, flood depth, flood propagation time, flood volume, and flood area. Besides that, based on different return periods, St. John's watershed has good response to flood than Gouyave watershed. The flood event occurs in St. John's watershed at 5 years return period, while flood occur in Gouyave watershed at 10 years return period.

- The exposure analysis to flood event was conducted to assess the exposure buildings and land-use types that are affected by flood. The built-up areas, shrub, and grass land are potentially affected by flood in 35 years return periods and 100 years return periods in two watersheds areas. Related with buildings numbers, numbers of buildings in St. John's watershed that are exposure by flood are higher than numbers of buildings in Gouyave watershed, specifically when flood depth reaches 0.2 meter until 0.5 meter.

## 7.2. Limitations of research

- Researcher did not obtain the detail rainfall data. Thus, this research only used the rainfall intensity from Natural Resources Conservation Service/Soil conservation service (NRCS/SCS), United States of America.
- Digital Elevation Model (DEM) which was used in this research has resolution 5 meters, but in the downstream areas of research area (Gouyave watershed and St. John's watershed), DEM a little bit coarse.
- The Leaf Area Index (LAI) values were generated from literature. It was not accessible using the data from fieldwork that are generated by NDVI because of technical reason to collecting the LAI data. Whereas, the LAI value generated using NDVI are better.
- This research did not conduct discharge measurements during fieldwork to calibrate, so the calibration model only used flood depth points measurement with limited numbers.

## 7.3. Recommendations

Based on the conclusions and limitations of research, this research recommends the following:

- Grenada's government is necessary for measuring the detail rainfall data per 30 minutes in order to conduct the best result of flood modelling.
- It is required to develop the similar researches which are emphasized in the assessment of economic loses, specifically in the St. John's watershed where the majority of flood-prone areas are locations of public facilities, office buildings, stadium, and housing areas, which are have high economic values.

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# APPENDICES

**Appendix 1**
Point reference for land use accuracy assessment in Gouyave watershed

| Coordinate | | | | Land use/land cover |
|---|---|---|---|---|
| UTM X | UTM Y | Latitude | Longitude | |
| 641557.785 | 1343442.401 | 12° 8' 58.817" N | 61° 41' 56.415" W | Agriculture |
| 640639.523 | 1344096.140 | 12° 9' 20.237" N | 61° 42' 26.688" W | Agriculture |
| 640548.940 | 1344104.798 | 12° 9' 20.533" N | 61° 42' 29.683" W | Agriculture |
| 641119.857 | 1344386.172 | 12° 9' 29.603" N | 61° 42' 10.752" W | Agriculture |
| 641428.000 | 1344340.000 | 12° 9' 28.052" N | 61° 42' 0.566" W | Agriculture |
| 640459.779 | 1345645.964 | 12° 10' 10.708" N | 61° 42' 32.391" W | Agriculture |
| 640124.440 | 1344640.186 | 12° 9' 38.024" N | 61° 42' 43.642" W | Agriculture |
| 641034.000 | 1345640.000 | 12° 10' 10.425" N | 61° 42' 13.395" W | Bare Land |
| 642553.194 | 1343182.425 | 12° 8' 50.201" N | 61° 41' 23.528" W | Bare Land |
| 638118.107 | 1344761.872 | 12° 9' 42.292" N | 61° 43' 49.996" W | Bare Land |
| 638095.672 | 1345410.075 | 12° 10' 3.393" N | 61° 43' 50.638" W | Built Up |
| 638744.000 | 1344777.000 | 12° 9' 42.689" N | 61° 43' 29.288" W | Built Up |
| 638612.000 | 1344679.000 | 12° 9' 39.519" N | 61° 43' 33.670" W | Built Up |
| 638880.827 | 1344738.498 | 12° 9' 41.415" N | 61° 43' 24.768" W | Built Up |
| 642518.693 | 1343099.848 | 12° 8' 47.518" N | 61° 41' 24.682" W | Forest |
| 641929.033 | 1343147.942 | 12° 8' 49.176" N | 61° 41' 44.180" W | Forest |
| 641598.941 | 1343358.621 | 12° 8' 56.084" N | 61° 41' 55.066" W | Forest |
| 642105.037 | 1343483.901 | 12° 9' 0.083" N | 61° 41' 38.305" W | Forest |
| 640810.088 | 1343892.404 | 12° 9' 13.580" N | 61° 42' 21.078" W | Forest |
| 641782.033 | 1344640.654 | 12° 9' 37.782" N | 61° 41' 48.807" W | Forest |
| 641716.990 | 1344695.266 | 12° 9' 39.570" N | 61° 41' 50.950" W | Forest |
| 641656.090 | 1344706.394 | 12° 9' 39.942" N | 61° 41' 52.962" W | Forest |
| 640241.501 | 1345454.005 | 12° 10' 4.494" N | 61° 42' 39.642" W | Forest |
| 640361.733 | 1345491.113 | 12° 10' 5.683" N | 61° 42' 35.659" W | Forest |
| 639112.576 | 1344918.212 | 12° 9' 47.229" N | 61° 43' 17.073" W | Grass Land |
| 639819.262 | 1345028.0483 | 12° 9' 50.695" N | 61° 42' 53.677" W | Grass Land |
| 641830.406 | 1344151.411 | 12° 9' 21.851" N | 61° 41' 47.284" W | Grass Land |
| 642628.027 | 1343238.811 | 12° 8' 52.024" N | 61° 41' 21.043" W | Mix Tree |
| 641366.871 | 1343487.611 | 12° 9' 0.319" N | 61° 42' 2.723" W | Mix Tree |
| 640929.309 | 1343746.840 | 12° 9' 8.824" N | 61° 42' 17.157" W | Mix Tree |
| 640529.239 | 1344269.934 | 12° 9' 25.911" N | 61° 42' 30.309" W | Mix Tree |
| 641373.703 | 1344366.276 | 12° 9' 28.916" N | 61° 42' 2.358" W | Mix Tree |
| 640090.638 | 1344409.321 | 12° 9' 30.515" N | 61° 42' 44.797" W | Mix Tree |
| 640407.602 | 1344504.951 | 12° 9' 33.579" N | 61° 42' 34.296" W | Mix Tree |
| 641685.998 | 1344599.438 | 12° 9' 36.456" N | 61° 41' 51.990" W | Mix Tree |
| 640289.577 | 1344701.385 | 12° 9' 39.991" N | 61° 42' 38.170" W | Mix Tree |
| 639830.932 | 1344733.404 | 12° 9' 41.103" N | 61° 42' 53.337" W | Mix Tree |
| 638858.172 | 1344798.859 | 12° 9' 43.383" N | 61° 43' 25.508" W | Mix Tree |

| Coordinate | | | | Land use/land cover |
|---|---|---|---|---|
| UTM X | UTM Y | Latitude | Longitude | |
| 641485.460 | 1344822.359 | 12° 9' 43.743" N | 61° 41' 58.589" W | Mix Tree |
| 639965.312 | 1344846.015 | 12° 9' 44.748" N | 61° 42' 48.874" W | Mix Tree |
| 641436.150 | 1344856.232 | 12° 9' 44.853" N | 61° 42' 0.215" W | Mix Tree |
| 641277.651 | 1344859.626 | 12° 9' 44.988" N | 61° 42' 5.458" W | Mix Tree |
| 640487.559 | 1344892.622 | 12° 9' 46.184" N | 61° 42' 31.590" W | Mix Tree |
| 638383.092 | 1344900.787 | 12° 9' 46.773" N | 61° 43' 41.209" W | Mix Tree |
| 638244.858 | 1344946.651 | 12° 9' 48.287" N | 61° 43' 45.775" W | Mix Tree |
| 639754.244 | 1345024.039 | 12° 9' 50.575" N | 61° 42' 55.829" W | Mix Tree |
| 639308.573 | 1345028.053 | 12° 9' 50.774" N | 61° 43' 10.572" W | Mix Tree |
| 640083.402 | 1345052.672 | 12° 9' 51.456" N | 61° 42' 44.935" W | Mix Tree |
| 639924.848 | 1345118.304 | 12° 9' 53.617" N | 61° 42' 50.170" W | Mix Tree |
| 638645.573 | 1345139.242 | 12° 9' 54.494" N | 61° 43' 32.488" W | Mix Tree |
| 640122.101 | 1345313.889 | 12° 9' 59.952" N | 61° 42' 43.614" W | Mix Tree |
| 641094.787 | 1345181.283 | 12° 9' 55.485" N | 61° 42' 11.456" W | Mix Tree |
| 640960.590 | 1345002.069 | 12° 9' 49.673" N | 61° 42' 15.924" W | Shrub |
| 641982.844 | 1343890.135 | 12° 9' 13.324" N | 61° 41' 42.283" W | Shrub |
| 641799.554 | 1344043.221 | 12° 9' 18.335" N | 61° 41' 48.322" W | Shrub |

**Appendix 2**

Point reference for land use accuracy assessment in St. John watershed

| Coordinate | | | | Land use/land cover |
|---|---|---|---|---|
| UTM X | UTM Y | Latitude | Longitude | |
| 637043.748 | 1334081.450 | 12° 3' 54.828" N | 61° 44' 27.168" W | Bare Land |
| 636603.864 | 1333911.025 | 12° 3' 49.347" N | 61° 44' 41.741" W | Bare Land |
| 637744.728 | 1334000.687 | 12° 3' 52.094" N | 61° 44' 3.999" W | Bare Land |
| 638234.206 | 1333991.575 | 12° 3' 51.724" N | 61° 43' 47.813" W | Bare Land |
| 636332.525 | 1333209.941 | 12° 3' 26.568" N | 61° 44' 50.820" W | Built Up |
| 638645.000 | 1333460.000 | 12° 3' 34.360" N | 61° 43' 34.310" W | Built Up |
| 636296.000 | 1333573.000 | 12° 3' 38.390" N | 61° 44' 51.973" W | Built Up |
| 637178.000 | 1334007.000 | 12° 3' 52.385" N | 61° 44' 22.740" W | Built Up |
| 637493.000 | 1334761.000 | 12° 4' 16.879" N | 61° 44' 12.208" W | Built Up |
| 635634.000 | 1333625.000 | 12° 3' 40.181" N | 61° 45' 13.857" W | Built Up |
| 637507.797 | 1332325.173 | 12° 2' 57.595" N | 61° 44' 12.089" W | Built Up |
| 636944.484 | 1332910.005 | 12° 3' 16.714" N | 61° 44' 30.628" W | Built Up |
| 637449.777 | 1333251.638 | 12° 3' 27.758" N | 61° 44' 13.867" W | Built Up |
| 636518.673 | 1333028.717 | 12° 3' 20.642" N | 61° 44' 44.692" W | Forest |
| 639243.775 | 1333193.165 | 12° 3' 25.585" N | 61° 43' 14.550" W | Forest |
| 639314.199 | 1333246.473 | 12° 3' 27.309" N | 61° 43' 12.213" W | Forest |
| 639248.927 | 1333330.599 | 12° 3' 30.057" N | 61° 43' 14.358" W | Forest |
| 639281.733 | 1333546.730 | 12° 3' 37.087" N | 61° 43' 13.240" W | Forest |
| 637869.002 | 1333628.083 | 12° 3' 39.948" N | 61° 43' 59.946" W | Forest |
| 637404.864 | 1334417.657 | 12° 4' 5.717" N | 61° 44' 15.175" W | Forest |
| 640071.209 | 1335139.671 | 12° 4' 28.813" N | 61° 42' 46.885" W | Forest |
| 639932.480 | 1335608.705 | 12° 4' 44.100" N | 61° 42' 51.400" W | Forest |
| 640022.999 | 1335623.817 | 12° 4' 44.578" N | 61° 42' 48.405" W | Forest |
| 636014.159 | 1333356.884 | 12° 3' 31.398" N | 61° 45' 1.326" W | Grass Land |
| 638604.000 | 1335388.000 | 12° 4' 37.119" N | 61° 43' 35.369" W | Grass Land |
| 637818.998 | 1333272.990 | 12° 3' 28.398" N | 61° 44' 1.654" W | Grass Land |
| 635853.370 | 1333551.724 | 12° 3' 37.764" N | 61° 45' 6.614" W | Grass Land |
| 635670.889 | 1333379.695 | 12° 3' 32.191" N | 61° 45' 12.674" W | Grass Land |
| 638273.970 | 1332353.934 | 12° 2' 58.416" N | 61° 43' 46.749" W | Mix Tree |
| 637739.456 | 1332645.251 | 12° 3' 7.978" N | 61° 44' 4.380" W | Mix Tree |
| 637723.388 | 1332667.169 | 12° 3' 8.694" N | 61° 44' 4.908" W | Mix Tree |
| 637496.909 | 1332794.059 | 12° 3' 12.858" N | 61° 44' 12.378" W | Mix Tree |
| 638691.256 | 1332869.302 | 12° 3' 15.127" N | 61° 43' 32.871" W | Mix Tree |
| 638654.544 | 1332890.294 | 12° 3' 15.816" N | 61° 43' 34.082" W | Mix Tree |
| 638137.062 | 1333297.136 | 12° 3' 29.136" N | 61° 43' 51.132" W | Mix Tree |
| 636701.198 | 1333314.490 | 12° 3' 29.916" N | 61° 44' 38.612" W | Mix Tree |
| 636649.060 | 1333437.718 | 12° 3' 33.935" N | 61° 44' 40.318" W | Mix Tree |
| 636646.655 | 1333516.331 | 12° 3' 36.494" N | 61° 44' 40.386" W | Mix Tree |
| 637120.262 | 1333539.743 | 12° 3' 37.185" N | 61° 44' 24.720" W | Mix Tree |
| 639010.644 | 1333539.917 | 12° 3' 36.906" N | 61° 43' 22.206" W | Mix Tree |

| Coordinate | | | | Land use/land cover |
|---|---|---|---|---|
| UTM X | UTM Y | Latitude | Longitude | |
| 637108.318 | 1333576.372 | 12° 3' 38.379" N | 61° 44' 25.109" W | Mix Tree |
| 636862.119 | 1333578.450 | 12° 3' 38.483" N | 61° 44' 33.251" W | Mix Tree |
| 638657.376 | 1333647.737 | 12° 3' 40.469" N | 61° 43' 33.872" W | Mix Tree |
| 636283.257 | 1333827.464 | 12° 3' 46.675" N | 61° 44' 52.356" W | Mix Tree |
| 637618.533 | 1333835.934 | 12° 3' 46.751" N | 61° 44' 8.197" W | Mix Tree |
| 636935.890 | 1333855.320 | 12° 3' 47.484" N | 61° 44' 30.769" W | Mix Tree |
| 638478.398 | 1333872.652 | 12° 3' 47.816" N | 61° 43' 39.756" W | Mix Tree |
| 636216.469 | 1333899.476 | 12° 3' 49.028" N | 61° 44' 54.554" W | Mix Tree |
| 637827.618 | 1333985.148 | 12° 3' 51.576" N | 61° 44' 1.260" W | Mix Tree |
| 638749.038 | 1334137.226 | 12° 3' 56.387" N | 61° 43' 30.765" W | Mix Tree |
| 638847.434 | 1334148.181 | 12° 3' 56.728" N | 61° 43' 27.510" W | Mix Tree |
| 637238.666 | 1334218.815 | 12° 3' 59.270" N | 61° 44' 20.701" W | Mix Tree |
| 638187.941 | 1334416.703 | 12° 4' 5.568" N | 61° 43' 49.278" W | Mix Tree |
| 638191.807 | 1334432.040 | 12° 4' 6.067" N | 61° 43' 49.148" W | Mix Tree |
| 638254.761 | 1334503.064 | 12° 4' 8.369" N | 61° 43' 47.055" W | Mix Tree |
| 637328.774 | 1334594.459 | 12° 4' 11.483" N | 61° 44' 17.664" W | Mix Tree |
| 639202.187 | 1334678.949 | 12° 4' 13.950" N | 61° 43' 15.696" W | Mix Tree |
| 638240.645 | 1334749.687 | 12° 4' 16.398" N | 61° 43' 47.484" W | Mix Tree |
| 637278.260 | 1334898.798 | 12° 4' 21.396" N | 61° 44' 19.288" W | Mix Tree |
| 638466.329 | 1334987.063 | 12° 4' 24.090" N | 61° 43' 39.984" W | Mix Tree |
| 638484.334 | 1335043.998 | 12° 4' 25.940" N | 61° 43' 39.380" W | Mix Tree |
| 639477.047 | 1335300.735 | 12° 4' 34.146" N | 61° 43' 6.510" W | Mix Tree |
| 639977.776 | 1335302.530 | 12° 4' 34.128" N | 61° 42' 49.950" W | Mix Tree |
| 638048.506 | 1335338.511 | 12° 4' 35.592" N | 61° 43' 53.748" W | Mix Tree |
| 639452.939 | 1335400.887 | 12° 4' 37.409" N | 61° 43' 7.292" W | Mix Tree |
| 639513.059 | 1335514.190 | 12° 4' 41.088" N | 61° 43' 5.286" W | Mix Tree |
| 638374.000 | 1334105.000 | 12° 3' 55.395" N | 61° 43' 43.173" W | Mix Tree |
| 637384.720 | 1332846.394 | 12° 3' 14.578" N | 61° 44' 16.080" W | Shrub |
| 638333.407 | 1332985.492 | 12° 3' 18.963" N | 61° 43' 44.687" W | Shrub |
| 637683.183 | 1333008.976 | 12° 3' 19.825" N | 61° 44' 6.185" W | Shrub |
| 636277.511 | 1333257.988 | 12° 3' 28.140" N | 61° 44' 52.632" W | Shrub |
| 636013.712 | 1333295.680 | 12° 3' 29.406" N | 61° 45' 1.350" W | Shrub |
| 636214.869 | 1333347.845 | 12° 3' 31.074" N | 61° 44' 54.690" W | Shrub |
| 636665.250 | 1333353.128 | 12° 3' 31.179" N | 61° 44' 39.795" W | Shrub |
| 639998.826 | 1335224.283 | 12° 4' 31.578" N | 61° 42' 49.266" W | Shrub |
| 639870.000 | 1335210.000 | 12° 4' 31.133" N | 61° 42' 53.529" W | Shrub |
| 639476.000 | 1335176.000 | 12° 4' 30.086" N | 61° 43' 6.564" W | Shrub |
| 637641.847 | 1334398.663 | 12° 4' 5.063" N | 61° 44' 7.340" W | Shrub |
| 638145.748 | 1333963.531 | 12° 3' 50.825" N | 61° 43' 50.743" W | Shrub |
| 637179.132 | 1334960.529 | 12° 4' 23.420" N | 61° 44' 22.557" W | Shrub |

**Appendix 3**

Soil physical properties measurement from soil sample collected during fieldwork

| Location | Coordinate | | | | Hydraulic Conductivity (mm/hr) | Porosity (%) |
|---|---|---|---|---|---|---|
| | UTM X | UTM Y | Latitude | Longitude | | |
| Gouyave | 639112.576 | 1344918.212 | 12° 9' 47.229" N | 61° 43' 17.073" W | 19.29 | 58.01 |
| | 639819.262 | 1345028.048 | 12° 9' 50.695" N | 61° 42' 53.677" W | 27.86 | 62.51 |
| | 641716.991 | 1344695.266 | 12° 9' 39.570" N | 61° 41' 50.950" W | 192.86 | 67.64 |
| | 638645.573 | 1345139.242 | 12° 9' 54.494" N | 61° 43' 32.488" W | 1.07 | 63.71 |
| | 641119.857 | 1344386.172 | 12° 9' 29.603" N | 61° 42' 10.752" W | 10.71 | 61.36 |
| | 641345.760 | 1344892.210 | 12° 9' 46.038" N | 61° 42' 3.199" W | 12.86 | 57.46 |
| | 641277.651 | 1344859.626 | 12° 9' 44.988" N | 61° 42' 5.458" W | 107.14 | 58.27 |
| | 640529.239 | 1344269.934 | 12° 9' 25.911" N | 61° 42' 30.309" W | 107.14 | 53.80 |
| | 640487.559 | 1344892.622 | 12° 9' 46.184" N | 61° 42' 31.590" W | 37.50 | 51.81 |
| | 642628.027 | 1343238.811 | 12° 8' 52.024" N | 61° 41' 21.043" W | 385.71 | 68.37 |
| | 641929.033 | 1343147.942 | 12° 8' 49.176" N | 61° 41' 44.180" W | 300.00 | 80.87 |
| | 641598.941 | 1343358.621 | 12° 8' 56.084" N | 61° 41' 55.066" W | 3.21 | 69.88 |
| | 639308.573 | 1345028.053 | 12° 9' 50.774" N | 61° 43' 10.572" W | 235.71 | 52.09 |
| | 640083.402 | 1345052.672 | 12° 9' 51.456" N | 61° 42' 44.935" W | 51.43 | 51.85 |
| | 639830.932 | 1344733.404 | 12° 9' 41.103" N | 61° 42' 53.337" W | 428.57 | 54.01 |
| | 641557.785 | 1343442.401 | 12° 8' 58.817" N | 61° 41' 56.415" W | 5.36 | 65.19 |
| | 641656.091 | 1344706.394 | 12° 9' 39.942" N | 61° 41' 52.962" W | 257.14 | 68.74 |
| | 638383.092 | 1344900.787 | 12° 9' 46.773" N | 61° 43' 41.209" W | 21.43 | 46.20 |
| | 638858.172 | 1344798.859 | 12° 9' 43.383" N | 61° 43' 25.508" W | 107.14 | 52.93 |
| | 642518.693 | 1343099.848 | 12° 8' 47.518" N | 61° 41' 24.682" W | 321.43 | 71.26 |
| | 640929.309 | 1343746.840 | 12° 9' 8.824" N | 61° 42' 17.157" W | 342.86 | 60.90 |
| | 640548.940 | 1344104.798 | 12° 9' 20.533" N | 61° 42' 29.683" W | 600.00 | 58.80 |
| | 641366.871 | 1343487.611 | 12° 9' 0.319" N | 61° 42' 2.723" W | 385.71 | 60.33 |
| | 640361.733 | 1345491.113 | 12° 10' 5.683" N | 61° 42' 35.659" W | 42.86 | 55.88 |
| | 639754.244 | 1345024.039 | 12° 9' 50.575" N | 61° 42' 55.829" W | 128.57 | 60.37 |
| | 639924.849 | 1345118.304 | 12° 9' 53.617" N | 61° 42' 50.170" W | 133.93 | 48.36 |
| | 641436.150 | 1344856.232 | 12° 9' 44.853" N | 61° 42' 0.215" W | 30.00 | 59.62 |
| | 640960.590 | 1345002.069 | 12° 9' 49.673" N | 61° 42' 15.924" W | 0.54 | 51.32 |
| St. John | 636646.655 | 1333516.332 | 12° 3' 36.494" N | 61° 44' 40.386" W | 492.86 | 65.50 |
| | 636701.198 | 1333314.490 | 12° 3' 29.916" N | 61° 44' 38.612" W | 4.29 | 54.00 |
| | 636277.512 | 1333257.988 | 12° 3' 28.140" N | 61° 44' 52.632" W | 8.57 | 51.50 |
| | 636014.159 | 1333356.884 | 12° 3' 31.398" N | 61° 45' 1.326" W | 117.86 | 63.50 |
| | 636649.060 | 1333437.718 | 12° 3' 33.935" N | 61° 44' 40.318" W | 85.71 | 51.00 |
| | 636518.673 | 1333028.717 | 12° 3' 20.642" N | 61° 44' 44.692" W | 182.14 | 52.50 |
| | 637108.318 | 1333576.373 | 12° 3' 38.379" N | 61° 44' 25.109" W | 75.00 | 46.00 |
| | 639248.928 | 1333330.599 | 12° 3' 30.057" N | 61° 43' 14.358" W | 278.57 | 56.50 |
| | 639314.199 | 1333246.473 | 12° 3' 27.309" N | 61° 43' 12.213" W | 21.43 | 58.00 |
| | 639243.775 | 1333193.165 | 12° 3' 25.585" N | 61° 43' 14.550" W | 85.71 | 71.00 |
| | 639281.733 | 1333546.730 | 12° 3' 37.087" N | 61° 43' 13.240" W | 300.00 | 62.50 |

| Location | Coordinate | | | | Hydraulic Conductivity (mm/hr) | Porosity (%) |
|---|---|---|---|---|---|---|
| | UTM X | UTM Y | Latitude | Longitude | | |
| | 637043.748 | 1334081.450 | 12° 3' 54.828" N | 61° 44' 27.168" W | 42.86 | 49.50 |
| | 636862.119 | 1333578.450 | 12° 3' 38.483" N | 61° 44' 33.251" W | 15.00 | 44.00 |
| | 636283.257 | 1333827.464 | 12° 3' 46.675" N | 61° 44' 52.356" W | 364.29 | 55.65 |
| | 637683.183 | 1333008.976 | 12° 3' 19.825" N | 61° 44' 6.185" W | 5.36 | 55.52 |
| | 636935.890 | 1333855.320 | 12° 3' 47.484" N | 61° 44' 30.769" W | 48.21 | 63.02 |
| | 638466.329 | 1334987.063 | 12° 4' 24.090" N | 61° 43' 39.984" W | 428.57 | 60.38 |
| | 639977.776 | 1335302.530 | 12° 4' 34.128" N | 61° 42' 49.950" W | 321.43 | 67.81 |
| | 640022.999 | 1335623.817 | 12° 4' 44.578" N | 61° 42' 48.405" W | 214.29 | 65.86 |
| | 636665.250 | 1333353.128 | 12° 3' 31.179" N | 61° 44' 39.795" W | 257.14 | 51.50 |
| | 639932.480 | 1335608.705 | 12° 4' 44.100" N | 61° 42' 51.400" W | 21.43 | 65.53 |
| | 640071.210 | 1335139.671 | 12° 4' 28.813" N | 61° 42' 46.885" W | 85.71 | 60.15 |
| | 639452.939 | 1335400.887 | 12° 4' 37.409" N | 61° 43' 7.292" W | 10.71 | 61.65 |
| | 638484.334 | 1335043.998 | 12° 4' 25.940" N | 61° 43' 39.380" W | 85.71 | 56.42 |
| | 637328.774 | 1334594.459 | 12° 4' 11.483" N | 61° 44' 17.664" W | 107.14 | 57.89 |
| | 638240.645 | 1334749.687 | 12° 4' 16.398" N | 61° 43' 47.484" W | 2.14 | 52.44 |
| | 636216.469 | 1333899.476 | 12° 3' 49.028" N | 61° 44' 54.554" W | 117.86 | 57.66 |
| | 637278.260 | 1334898.798 | 12° 4' 21.396" N | 61° 44' 19.288" W | 19.29 | 61.00 |
| | 637404.864 | 1334417.657 | 12° 4' 5.717" N | 61° 44' 15.175" W | 69.64 | 58.96 |
| | 638191.807 | 1334432.040 | 12° 4' 6.067" N | 61° 43' 49.148" W | 64.29 | 62.00 |
| | 639202.187 | 1334678.949 | 12° 4' 13.950" N | 61° 43' 15.696" W | 37.50 | 59.62 |
| | 637739.456 | 1332645.251 | 12° 3' 7.978" N | 61° 44' 4.380" W | 75.00 | 48.82 |
| | 637496.909 | 1332794.059 | 12° 3' 12.858" N | 61° 44' 12.378" W | 2.14 | 52.47 |
| | 638478.398 | 1333872.652 | 12° 3' 47.816" N | 61° 43' 39.756" W | 26.79 | 57.67 |
| | 637618.533 | 1333835.934 | 12° 3' 46.751" N | 61° 44' 8.197" W | 471.43 | 50.21 |
| | 638187.941 | 1334416.703 | 12° 4' 5.568" N | 61° 43' 49.278" W | 42.86 | 60.50 |
| | 637120.262 | 1333539.743 | 12° 3' 37.185" N | 61° 44' 24.720" W | 278.57 | 53.51 |
| | 637723.388 | 1332667.169 | 12° 3' 8.694" N | 61° 44' 4.908" W | 10.71 | 55.72 |
| | 637827.618 | 1333985.148 | 12° 3' 51.576" N | 61° 44' 1.260" W | 257.14 | 47.87 |
| | 639010.644 | 1333539.917 | 12° 3' 36.906" N | 61° 43' 22.206" W | 42.86 | 70.32 |
| | 638749.038 | 1334137.226 | 12° 3' 56.387" N | 61° 43' 30.765" W | 139.29 | 54.47 |
| | 638273.971 | 1332353.934 | 12° 2' 58.416" N | 61° 43' 46.749" W | 192.86 | 50.33 |
| | 638333.407 | 1332985.492 | 12° 3' 18.963" N | 61° 43' 44.687" W | 1.07 | 56.56 |
| | 638654.544 | 1332890.294 | 12° 3' 15.816" N | 61° 43' 34.082" W | 0.21 | 62.39 |
| | 638254.761 | 1334503.064 | 12° 4' 8.369" N | 61° 43' 47.055" W | 428.57 | 59.00 |
| | 636013.712 | 1333295.680 | 12° 3' 29.406" N | 61° 45' 1.350" W | 450.00 | 49.50 |
| | 636214.869 | 1333347.845 | 12° 3' 31.074" N | 61° 44' 54.690" W | 64.29 | 55.50 |

**Appendix 4**

PCRaster script for generating of a LISEM input database (Jetten, 2015)

```
binding
##################
### input maps ###
##################

mask = mask_gou.map;

DEM = dem20_gou.map;
# digital elevation model, area must be <= mask

unitmapbase = landuse_gou.map;
# land use types
soiltype = soil_gou.map;
# Land use type for layer 1
soiltexture = soiltext_gou.map;
# soil texture classes for layer 2

soildepth = soildepth_gou.map;

barriers = barriers_gou.map;
# in m, anything that obstructs flooding: northern bypass, roads, NOT houses
# added to the DEM

road = road_gou.map;
# type 1 = highway, 2 = 2.5 car width is larger, 3 is 1.5 car width

rivers = newmask.map;#chanmask_gou.map;
# river mask
mainout = mainout_gou.map;
# forced outlet rivers to the sea, because of imperfect dem

#levees = chanlevee50m.map;
# height (m) small levees on both sides of the channel, subpixel

culverts = culverts_gou.map;
# location with main culverts

outpointuser = outpoint_gou.map;
# points for user output hydrographs

house_cover0 = house_gou.map;
# housing density fraction (0-1)

hard_surf0 = hardsurf_gou.map;
# hard surfaces (0-1) such as airport, parking lots etc

stones = stone_gou.map;
# no info for grenada

######################################
### hydrological data input tables ###
######################################

soiltbl2 = Infiltration2_gou.txt; # soil texture class hydro properties
soiltbl = Infiltration_gouT5.txt; # land use class hydro properties
lutbl = landuse_manning_gouT5.txt; # land use surface properties
```

```
##############################################
### output LISEM database, default names ###
##############################################

# basic topography related maps
DEMm = dem.map; # adjusted dem
barriersc = barriers.map;
Ldd = ldd.map; # Local Drain Direction surface runoff
grad = grad.map; # slope, sine!
id = id.map; # pluviograph influence zones
outlet = outlet.map; # location outlets and checkpoints
landuse = landunit.map; # land units combined soil and vegetation
outpoint=outpoint.map; # points where hydrograph output is generated

# impermeable roads, tarmac, concrete
roadwidth = roadwidth.map; # rad width (m)

# vegetation maps
coverc= per.map; # cover fraction (-)
lai= lai.map; # leaf area index (m2/m2) for interception storage
cropheight= ch.map; # plant height in m, for erosion, not used
grasswid = grasswid.map; # width of grass strips for infiltration

# Green and AMpt infiltration maps
ksat1 = ksat1.map; # sat hydraulic conductivity (mm/h)
pore1 = thetas1.map; # porosity (-)
thetai1 = thetai1.map; # initial moisture content (-)
psi1 = psi1.map; # suction unsat zone (cm)
soildep1 = soildep1.map; # soil depth (mm), assumed constant
# second layer G&A
ksat2 = ksat2.map; # sat hydraulic conductivity (mm/h)
pore2 = thetas2.map; # porosity (-)
thetai2 = thetai2.map; # initial moisture content (-)
psi2 = psi2.map; # suction unsat zone (cm)
soildep2 = soildep2.map; # soil depth (mm), assumed constant
ksatcomp = ksatcomp.map; # ksat of compacted areas (mm/h)

# surface maps
rr = rr.map; # surface roughness (cm)
mann = n.map; # mannings n ()
stone = stonefrc.map; # stone fraction on surface (-)
crust = crustfrc.map; # crusted soil (-), not present
comp = compfrc.map; # compacted soil (-), murrum roads
hard = hardsurf.map; # impermeable surfaces (0 or 1)
# erosion maps , not used
cohsoil = coh.map; # cohesion (kPa)
cohplant = cohadd.map; # added root cohesion (kPa)
D50 = d50.map; # median of texture (mu)
aggrstab = aggrstab.map; # aggregate stability number (-)
chancoh = chancoh.map; # channel cohesion (kPa)

# channel maps
lddchan = lddchan.map; # channel 1D network
chanwidth = chanwidt.map; # channel width (m)
changrad = changrad.map; # channel gradient, sine
chanman = chanman.map; # channel manning (-)
chanside = chanside.map; # angle channel side walls, 0 = rectangular

# channel flooding maps: channels that have a depth > 0 can flood
```

```
# channels with a depth 0 will never flood but are infinitely deep!
chandepth_ = chandepth_.map; # channel depth (m)
chandepth = chandepth.map; # channel depth (m)
chanmaxq = chanmaxq.map; # maximum discharge (m3/s) in culvert locations in channel
chanlevees = chanlevee.map; # main levees along channels
chanksat = chanksat.map; # ksat in case channel infiltrates, for dry channels
floodzone = floodzone.map; # flooding limited to areas with value 1

# houses
housecov = housecover.map; # house cover fraction
roofstore = roofstore.map; # roof interception (mm) \
raindrumsize = scalar(0); # raindrum size (m3)
drumstore = drumstore.map; # locations of rainwater harvesting in drums (0/1)
baresoil = baresoil.map; # not used in lisem, for reference
initial

# limited all maps to mask extent
unitmap = scalar(unitmapbase)*mask;
soils = scalar(soiltype)*mask;
soils2 = scalar(soiltexture)*mask;
DEM *= mask;
chanm = if(cover(rivers,0) > 0,1,0)*mask;

######################
### LAND COVER MAP ###
######################

report landuse = unitmap;

########################
### BASE RELIEF MAPS ###
########################
report barriersc = barriers;

#report barriersc = if(scenario eq 0, 0, barriersc);
# no barrier when channel = culvert

report DEMm = DEM * 1;
DEMm = DEM + barriersc;
# large barriers, for instance dike near airport

report Ldd = lddcreate (DEMm-chanm*10-mainout*10, $1, $1, $1, $1);
# report ldd_gou.map = lddn.map;
# runoff flow network based on dem, main outlet, channels and barriers
report outlet = pit(Ldd);

report grad = max(sin(atan(slope((DEMm)))), 0.005)*mask;
#### not used in lisem, auxilary maps
report ups_gou.map=accuflux(Ldd,1);
report ws.map=catchment(Ldd, pit(Ldd));
asp = scalar( aspect(DEMm));
shade = cos(15)*sin(grad)*cos(asp+45) + sin(15)*cos(grad);
report shade.map = (shade-mapminimum(shade))/(mapmaximum(shade)-mapminimum(shade));
#### not used in lisem

###########################################
### MAPS WITH RAINFALL INFLUENCE ZONE ###
###########################################
report id = nominal(mask);
# rainfall zone. homogeneous map for hazards
```

```
########################
### VEGETATION MAPS ###
########################
report coverc = lookupscalar(lutbl, 3, nominal(unitmap)) * mask;
# fraction plant soil cover

# LAI of plants inside gridcell (m2/m2)
coverc = min(coverc, 0.95);
# lai = ln(1-coverc)/-0.4;
report lai = lookupscalar(lutbl, 5, nominal(unitmap)) * mask;

##################
### HOUSE MAPS ###
##################

report housecov=house_cover0*mask;
# copy directly input
report roofstore = if(housecov gt 0,1,0)*mask;
# interception storage 1 mm
report drumstore.map=if(housecov gt 0,raindrumsize,0)*mask;
# possible water rain drum at home in m3

############################################################
### INFILTRATION MAPS for option two layer GREEN & AMPT ###
############################################################

ksat2 = lookupscalar(soiltbl2, 1, soils2) * mask;
pore2 = lookupscalar(soiltbl2, 2, soils2) * mask;
# basic values from saxton equations

report psi2 = 30; #lookupscalar(soiltbl, 3, soils) * mask;
report psi1 = 1.5*psi2;

soildep2 = soildepth *mask;
soildep1 = min(soildepth/2, 150);
report soildep2 = if (soils eq 23, 10, soildep2);
report soildep1 = if (soils eq 23, 5, soildep1);

report stone = mask*max(0,stones-1)/100*2;
# stone fraction influences hydrology, based on class 1 to 7

# natural = unitmap eq 7 or unitmap eq 9 or unitmap eq 10
# or unitmap eq 12 or unitmap eq 13 or unitmap eq 14;
# land cover types that have a natural soil

report ksat1 = lookupscalar(soiltbl, 1, soils) * mask ;
report pore1 = lookupscalar(soiltbl, 2, soils) * mask;
# basic values from observation/fieldwork

# report ksat1 = if(natural,max(200, 2*ksat2),ksat2);
# report pore1 = if(natural,0.56,pore2);
# top soil is very open under natural systems

report ksat2 *= (1-stone);
report pore2 *= (1-stone);
# subsoil is less permeable with stones, less porosity
report thetai2 = 0.8*pore2;
report thetai1 = 0.9*pore1;
# initial moisture as 80 - 90% of porosity
```

```
##########################
### SOIL SURFACE MAPS ###
##########################
report rr = max(lookupscalar(lutbl, 2, nominal(unitmap)) * mask, 0.01);
# micro relief, random roughness (=std dev in cm)
report mann = lookupscalar(lutbl, 1, nominal(unitmap)) * mask;
# in the lisem code Manning's n is increased with house effect

report crust = mask*0;
# crust fraction assumed zero
report comp = 0*mask;#if (road eq 1 or road eq 5, 0.2, 0)*mask;
#fraction compacted, e.g. dirt roads
report ksatcomp = 0.1*mask; # 0.1 mm/h over width of dirt road
report hard = hard_surf0;
#hard surface, here airports and large impenetrable areas

report roadwidth = if (road eq 1, 8, if(road eq 2, 6, if(road eq 3, 4, 0)))*mask;
# width tarred roads in m
#####################
### CHANNEL MAPS ###
#####################

chanmask = if(rivers ne 0,1)*mask;
# create missing value outside channel
report lddchan = lddcreate((DEMm-mainout*100)*chanmask,1e20,1e20,1e20,1e20);
# create a channel network
report outpoint = cover(scalar(pit(lddchan)),mask*0);

changrad = max(0.01,sin(atan(slope(chanmask*DEMm))));
report changrad = windowaverage(changrad, 5*celllength())*chanmask;
# channel slope, copy surface but smooth to avoid abrupt changes

report chanman = chanmask*0.065;
# fairly rough and rocky channel beds
report chanside = chanmask*scalar(0);
# rectangular channel

# chanwidth = max(3.0, min(15.0, accuflux(lddchan, 1)/20));
report chanwidth = if (rivers eq 1, 12, if(rivers eq 2, 10, if(rivers eq 3, 8, if(rivers eq 4, 12, if(rivers eq 5, 4, if(rivers eq
6, 15, 0))))))*mask;
culvert_fraction_width = 0.8;
# report chanwidth = if(culverts gt 0, chanwidth*culvert_fraction_width, chanwidth);
# channel width is 15m at outlet and beccoming less away form the coast to 3 m
chandepth_ = soildepth/2000*chanmask + min(1.0, max(0.4, accuflux(lddchan, 1)/100));
# channel depth approx 2.8m at outlet to < 1 m at start bbranch

report chandepth = if(newmask.map eq 1, chandepth_ -0.5, if(newmask.map eq 2, chandepth_ -0.2, if(newmask.map
eq 3, chandepth_ -0.3, if(newmask.map eq 6, chandepth_ -0.6,chandepth_))));
# channel depth approx 2.8m at outlet to < 1 m at start bbranch

report chanmaxq = 0*mask;
report chanksat = 0*mask;
# assume rocky channel or some baseflow so no extra infiltration
report chanlevees = 0*mask;
# no known levees

floodzone = scalar(spread(rivers ne 0, 0, DEMm) le 7000) ;
report floodzone = mask; #windowmaximum(floodzone, 3*celllength());
# max floodzones based on a geomorphological factor
```

```
####################
### EROSION MAPS ###
####################
# some default values
report D50 = 20 * mask; # fine material
report cohsoil = 8 * mask; # strong clay aggregates
report cohplant = coverc * 4 * mask; # additional plant root strength
report aggrstab = 12 * mask; # aggregate stability
report chancoh = 20 * chanmask; # strong channels?
report cropheight = lookupscalar(lutbl, 4, nominal(unitmap)) * mask; #plant height in m
```