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Implementation of hydrological and hydraulic models to forecast river flood risks and proposition of management measures. Case study of Nyabugogo River basin in Rwanda

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DECLARATION

I**, Gisele ICYIMPAYE**, hereby declare that this thesis represents my personnel work and released to the best of my knowledge. I also declare that all information, material and results from other works presented here, have been fully cited and referenced in accordance with the academic rules and ethics.

Signed  15th September 2018

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CERTIFICATION

This thesis has been submitted with my approval as the supervisor

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ABSTRACT

Nyabugogo River within Nyabugogo catchment in Rwanda is being flooded at every year resulting in human losses and economic losses. For sustainable flood management; flood risk assessment is a useful component as it demonstrates the expected water depth, floodplain area and the expected damage for each event. Therefore, the aim of this study was to forecast Nyabugogo river flood risk and propose mitigation measures which can reduce flood impacts by using HEC-HMS integrated with HEC-GEOHMS and HEC-RAS integrated with HEC-GEORAS. The study focused on assessing the causes and impacts of the flood; assessing the existing flood management measures and describing the geospatial characteristics of the catchment then generating inundation maps and water depth for each event modeled. Floods in Nyabugogo river are mainly due to high topography, soil texture mainly composed of clay; rainfall, informal settlement; urbanization and inappropriate agriculture practices. The results of hydrologic modelling showed the peak discharges of 515.7; 680.2; 761.5 and 875.5 m^3/sec for 10,30,50 and 100 return period year respectively and The results of hydraulic modelling demonstrated that flood inundation area increased slightly from the lower event to the high event modelled with 423.35; 426.11; 428.08 and 430.60 ha for 10,30,50 and 100 return period year respectively and also water depth increased slightly as the return period increase where the high water depth was 3.24 m obtained for 100 year return period. For all the event modelled, the more vulnerable land use obtained within the inundations maps were annual cropland, open grassland, open shurbland, settlement, sparse forest and wetland; with 54.804, 53.672, 53.238, 54.804, 139.359, 50.106 ha of inundation area for 100 year return period for each land use respectively. Therefore, some proposed mitigation measures include construction of storage reservoir at the upstream location of the reach; relocation of infrastructures within the flood plain area; buffer zoning around Nyabugogo river, the use of rain water tank for each house and raising public awareness on flood risks. Thus, this study can provide a basic support for decision making and also can help in the planning and management of land use and future probable flood event within the catchment.

Keywords: **Flood risk, Modelling, HEC-RAS, HEC-HMS, Nyabugogo River Basin.**

RESUME

La rivière Nyabugogo dans le bassin versant de Nyabugogo au Rwanda est inondée chaque année, entraînant des pertes humaines et des pertes économiques. Pour une gestion durable des inondations ; l'évaluation du risque d'inondation est un élément utile car elle démontre la profondeur de l'eau, la zone d'inondation prévue et les dommages attendus pour chaque événement. Par conséquent, le but de cette étude est d'étudier les paramètres influençant les évènements d'inondation de la rivière Nyabugogo, de cartographier les zones inondables et de proposer des mesures d'atténuation qui peuvent réduire les impacts des inondations en utilisant HEC-HMS intégré avec HEC-GEOHMS et HEC-RAS HMS intégré avec HECGEORAS. L'étude s'est concentrée sur l'évaluation des causes et des impacts de l'inondation ; évaluer les mesures de gestion des inondations existantes et décrire les caractéristiques géo spatiales du bassin hydrographique, puis générer des cartes d'inondation et la profondeur de l'eau pour chaque événement modélisé. Les inondations dans la rivière Nyabugogo sont principalement dues à la topographie, la texture du sol étant principalement composée d'argile ; précipitation, habitation informel ; l'urbanisation et les pratiques agricoles inappropriées. Les résultats de la modélisation hydrologique ont montré que les débits de pointe pour les différentes périodes de retour 5 10, 30, 50 et 100 ans sont respectivement 515,7 ; 680,2 ; 761,5 et 875,5 m^3 / sec. Les résultats de la modélisation hydraulique ont démontré que la zone d'inondation a légèrement augmenté de l'événement inférieur à l'événement élevé modélisé avec 423,35 ; 426.11; 428,08 et 430,60 ha respectivement pour les périodes de retour considérées. Aussi la profondeur de l'eau a augmenté légèrement en tenant compte de la période de retour avec la plus grande profondeur de 3,24 m pour 100 ans. Pour l'ensemble des événements modélisés, les occupations du sol les plus vénérables dans les cartes des inondations obtenues sont : terres cultivées, prairies, zones plantées, zone urbaine, forêts et zones humides avec respectivement 54,804, 53,672, 53,238, 54,804, 139,359 et 50,106 ha de surfaces inondées pour une période de retour de 100 ans et pour chaque type d'occupation. Par conséquent, certaines mesures d'atténuation proposées comprennent la construction d'un réservoir de stockage à l'emplacement en amont de la rivière ; la réallocation des infrastructures dans les zones inondables ; créer un zonage autour de la rivière Nyabugogo en se basant sur les cartes établies, l'implantation d'un réservoir d'eau de pluie pour chaque maison et la sensibilisation du public aux risques d'inondation. Ainsi, Cette étude constitue un support de base pour l'aide la décision. C'est aussi une base pour la planification et la gestion de l'occupation du sol et des évènements probables d'inondation dans le bassin versant.

Mots clés : **Risque d'inondation, modélisation, HEC-RAS, HEC-HMS, Rivière Nyabugogo.**

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LIST OF ABBREVIATIONS

HEC-HMS: Hydrologic Engineering Center- Hydrologic Modelling System.

GIS: Geographical Information System.

HEC-GEOHMS: Hydrologic Engineering Center- geographical Hydrologic Modelling System.

HEC-RAS: Hydrologic Engineering Center- River Analysis System.

HEC-GEORAS: Hydrologic Engineering Center- Geographical River Analysis System.

PAUWES: Pan African University Institute of Water and Energy Sciences including climate change.

RWFA: Rwanda Water and Forestry Authority.

MIDIMAR: Ministry of Disaster and Refugee Affairs of Rwanda

WASAC: Water and Sanitation Cooperation.

NISR: National Institute of Statistics of Rwanda

UNISDR: United Nations International Strategy for Disaster Risk Reduction

NIDM: Indian, National Institute of Disaster Management.

CN: Curve Number

DEM: Digital Elevation Model

TIN: Triangular Irregular Network.

SCS: Soil Conservation Service.

SHG: Hydrological Soil Group

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1 GENERAL INTRODUCTION

1.1 Background

Floods are among the most harmful of natural hazards which are likely to be more frequent, dominant and serious in the future because of climate change and urbanization coupled with increase of population in flood prone area and other diverse factors such as rainfall characteristics, catchment characteristics, river characteristics, snow melt and different human activities which lead to flood (Machtar,2010). Flood is a weather related disaster in the type of hydrological which occurs when the river water inundates or overflow the land which is generally dry and it affects individual life and property then causes economic, social impacts and harm the natural environment in different Countries of world (Queensland Government, 2011). Generally, the losses of flood are categorized into direct and indirect losses where direct losses are physicals damage of roads, buildings, cars and death of people, and indirect losses are water quality deterioration, interruption of transport, lowering of economic status of a region. (Queensland Government, 2011)

Globally, from the year 1995 to 2015, 3062 floods disasters were recorded and accounted for 47% of all weather related disasters which include geophysical hazards like earthquakes and volcanoes, meteorological hazards like storm and climatological hazards like drought **(**UNISDR,2015). During the same period, floods affected 2.3 billion people which represented 56% of all people affected by weather - related disasters where 157,000 people died due to floods accompanied with the economic loss of USD 662 billion **(**UNISDR,2015).

Rwanda also as many other Countries is experiencing floods in its different regions at least each year due to its geographical features of hilly slopes and climatic profile with annual average precipitation of 1200 mm without forgetting the overexploitation of natural environment such deforestation, inappropriate farming practices and housing systems(MIDIMAR,2012). Flood and landslides are significant disasters that frequently affecting Rwanda and most affected people do not have mechanisms to manage natural hazards. Hence, the most vulnerable area to flood and landslides mapped by MIDIMAR which is the Ministry of Disaster and Refugee Affairs were shown by Fig1.1.so that the management measures should be taken based on those vulnerable areas.

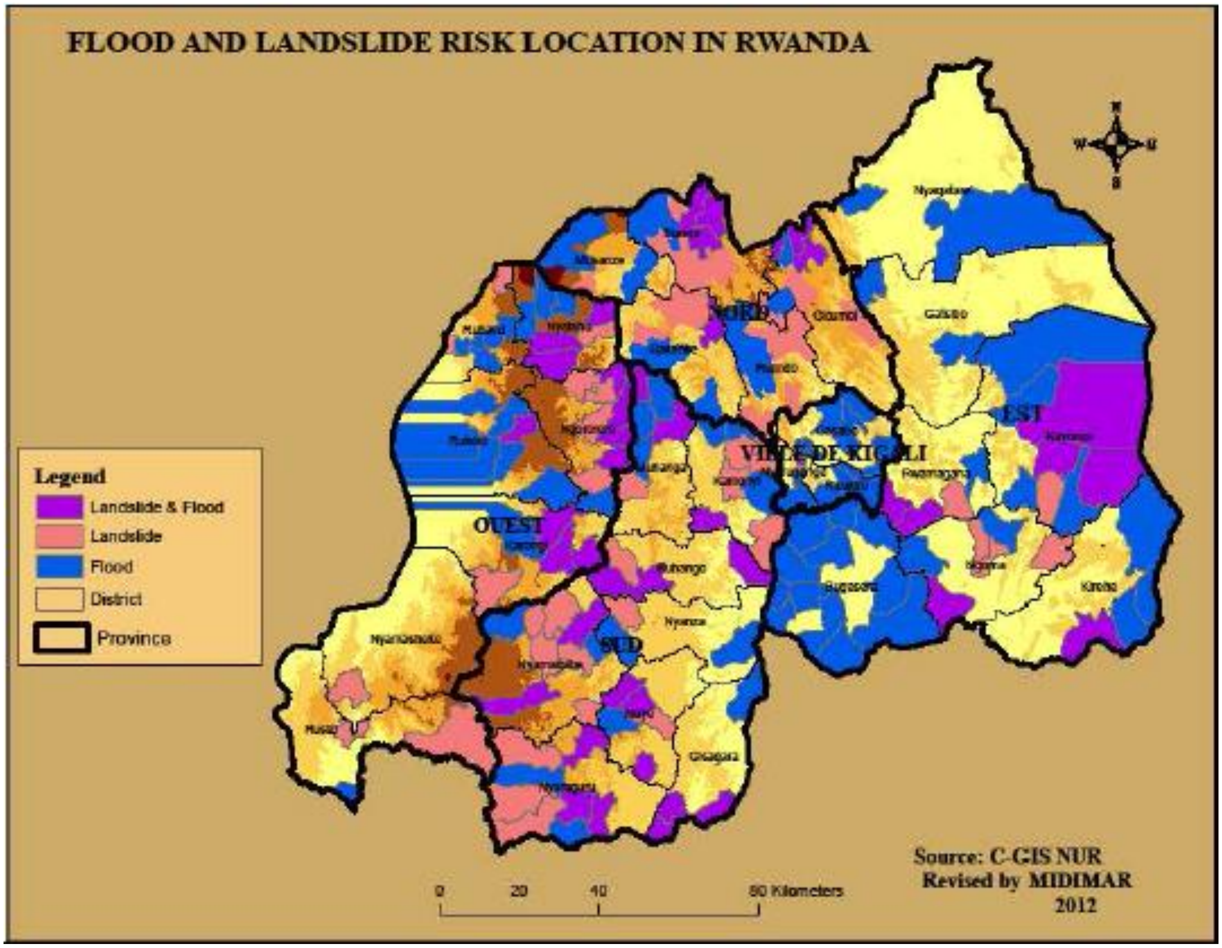


Figure 1.1: Vulnerable area to floods and landslides in Rwanda *(*MIDIMAR,2012).

Historically flood events have been observed in Rwanda since 1960 and their occurrence starting to increase significantly since 2000 with impacts on people, environment and human activity (Habonimana et al, 2015). Following are the most recently floods that happened in Rwanda where in the year 2011, North–western party of the Country experienced flood after heavy rain and at least 10 people died, 354 houses were destroyed and 3000 hectares of farmland were damaged (MIDIMAR, 2012). In the year 2012, some districts of North-western party of Country got flooded and as results five deaths were recorded and wide damage to houses and other property of the indigenous population where 2232 households with 11,160 people had been affected, 348 houses were totally destroyed, 446 were partly damaged and that flood had damaged water supplies networks plus almost 1000 hectares of potatoes, maize, bananas and tea were inundated (DREF, 2012**).**

In the year 2015**,** On 3 April 2015, Rubavu and Nyamasheke district located in the Western Province of Rwanda experienced heavy rainfall which resulted in flooding and landslides. 3 425 people (685 households) had been affected; 206 hectares of crops had been inundated, and household items washed away **(**IFRCRCS,2015). In the year 2016, on 07- 08 May, 49 people died due to floods caused by heavy rainfall where Gakenke district in North province, Muhanga district in South, Rubavu and Ngororero district in Western Province were the worst affected district ; Within the same period, the quality of water resources had been affected as former Energy Water and sanitation (EWASA) Ltd transformed into Water and Sanitation Cooperation (WASAC) temporally postponed water treatment at Nzonve treatment plants due to increase of turbidity(Floodlist,2016).

Kigali city which is the capital of the Country in which Nyabugogo River passes through experienced also floods events. Heavy rainfall, Urbanization which promotes the presence of impervious layer in different places coupled with increase of population and inadequate drainage cause flash flood in different areas of Kigali city leading to flooding in the downstream area (Habonimana et al., 2015). According to NISR of 2012, Rwanda has annual urban growth rate of 4.1% population where Kigali alone housed about half of the urban population in 2012 and it has more than one million populations which is equal to 10.8% of Country's population (NISR **,**2012**);** This show how Kigali is being urbanized especially on the hill slopes therefore the development of flush flood and increase of runoff water which is contributing to flooding in Nyabugogo River. Generally, floods on Nyabugogo River cause effects which are classified as primary effects in which there is physical damage of any type of infrastructure such as bridges, cars, buildings, sewerage systems, roadways and canals and loss of people, secondary effects which affect water supplies, crops, food supplies, trees, vegetation, transport and cause disease then tertiary and long term effects which affect economic status of a region or a place (Munyaneza et al.,2013).

Studies have been done to mitigate floods and Rwanda through its Ministries such as Ministry of Disaster and Refugee Affairs , Ministry of water and environment and other Government institution are doing better to avoid and mitigate flooding problems like where there was a mapping of vulnerable area to flood and landslides to know exactly in which area the management actions should focus to mitigate and adapter to both floods and landslides , relocation of people within high risk zones of flooding and landslides. However, floods event continues to cause losses not only in Nyabugogo catchment but also in other catchment of the Country therefore there is a need of forecasting flood risks using models so that decisions could be taken based on the results of those models to make people aware of the events and came up with mitigation measures to secure different useful aspects necessary in achieving sustainable development goals.

1.2 Problem Statement

Flood event has many effects on economic, social and environment aspects which are useful to achieve the sustainable development goals and it is taken to be the best common and extremely destructive of all hazards also predicted to become more frequent, dominant and serious in the coming year generally in the growing towns (Nduta et al.,2015).

High demographic pressure of Kigali city and its urbanization as Kigali account half of Rwandan urban population which is 4.1% in 2012 (Habonimana et al., 2015) coupled with effects of climate change which is changing rainfall patterns as rainfall trends analysis showed that rain seasons are tending to become shorter with higher intensity, like in 2006 where the annual precipitation was higher than the average precipitation over previous 30 years (REMA, 2009) including the geography of the region composed of hill slopes and inappropriate agriculture practices within the surrounding area of Kigali contribute to flash flood and end up by causing flooding in Nyabugogo river especially at its downstream location situated in Kigali city resulting into the loss of people and their properties, pollution water quality of river as it drained away different sediments from different areas of Kigali city and interruption transport mode since there is National roads intersecting different roads which go to different locations within the Country like (Kigali-Gatuna, Kigali-Gitarama, Kigali –Musanze).Normally Nyabugogo river is facing flood event at least each year and causing social losses and the economic losses as according to NEW TIMES paper, 178 million francs Rwanda which is equal to 209412 USD are lost annually by Nyabugogo business due to the effects of flooding(New times –Rwanda, 2016). As the results of impacts of the flood more people could be exposed to health challenges and inability to meet their social security needs like health insurance.

1.3 Objective

1.3.1 Main objective

The main objective of this study is to forecast flood risks on Nyabugogo River and to propose different management measure which can reduce flood effects.

1.3.2 Specific objectives

1. To investigate the causes and impacts of flood in the catchment.
2. To identify the existing flood management measures.
3. To Describe the geospatial data characteristics of the catchment that are relevant to flood generation.
4. To generate inundation maps and water depths for different return period.

1.4 Justification of the Study

It has been recognized that Nyabugogo River is getting flooded at least each year and this cause economical loss of about 178 million francs Rwanda which is equal to 209412 USD as reported by New times in 2016. In addition to this, it causes human deaths. Assessing Flood risks through the mapping of flood prone area with their stage can be a way of providing information to Policy and Decision makers to which extend flood will damage the area and be a basic for choosing and implementing flood management measures to reduce economic losses as whereas deaths of people. Also the assessment of flood risk to Nyabugogo River can contribute to a more consistent framework of flood risk control to others river within the Country.

1.5 Research Question

1. What are the geospatial datasets relevant to generate flood?
2. What are hydrological datasets which are relevant to generate flood?
3. What are the model needed to simulate hydrological data and river flow?
4. What are the causes, effects of the previous flood events in the catchment?
5. What are available or existing the mitigation measures of flood in the catchment?

1.6 Scope and Limitations

Flood risk assessment includes two components which are the probability of occurrence and the consequences it will bring after taking place. This study particularly focused on the probability of occurrence where flood frequencies were created then used to estimate flood prone area and the flood levels with the application of hydrological and hydraulic models including GIS Software to visualize the vulnerable land use and propose some management measures. The study did not focus on the economic assessment of flood damage which come up with the expected loss for each particular flood stage level.

2 LITERATURE REVIEW

This chapter discussed about the literature review on floods especially their types, causes and effects; models used to assess flood risk and approaches which can be applied and the important ace of flood risk assessment.

2.1 About Flood

Flood is defined as an overflowing of the ordinary boundaries of a river or other water body or the accumulation of water over a land not normally submerged (IPCC, 2014)**.** Flood has been a challenge in the last years even till todays it continues to be a big challenge as it affects people, environment and economy status of a region. According to the UNISDR (The United Nations International Strategy for Disaster Risk Reduction) report of 2015, in the last 20 years ago from 1995 -2015, 3062 floods disasters were recorded affecting of 2.3 billion people and causing loss of 15700 people and loss of USD 662billion. Flood results from hazards which include Natural hazards and Man- made hazards. Natural hazards consist of severe storm, heavy rainfall, sudden melting of snow or ice; this once happen increase the height of water level and cause overflow but not always natural hazard lead to flooding; Man- made hazards consist of failure of hydraulic structures such weir, sluice; breach of dam or dike; a storm surge barrier not closing and absence of vegetation; those cause flooding under severe weather condition like severe storm**.** (http://eschooltoday.com/natural-disasters/floods/what-causes-floods.html). Apart from understanding flood, it's good to understand flood risk where Scientists, Engineers and Floodplain managers had described flood risk as the possibility or the chance of flooding to occur and its potential consequences or damage which includes social, economic and environment consequences within an area where risks are assessed (California 's flood future, 2013).

Flood risk depends on:

- Hazard which represent the cause of the harm, its probability, extent, and depth.
- Performance which means how better the flood management system react to the hazards as the system may be inadequate or adequate.
- Exposure which indicate who and what might be damaged by hazard
- Vulnerability which represent the weakness of property and people to be damage like how flood affects people and property
- Consequence represent losses resulting from hazard (California 's flood future, 2013).

When you want to analyze or forecast flood risk they are different questions you have to ask yourself as a flood analyst so that you come up with good and accurate sustainable mitigation measures. They include what can go wrong in the case of flooding? How probable is that will happen? If it does happen, what may be the consequences? What can be done to reduce or eliminate the risk of flooding**? (**Bizimana et al.,2010). Hence**,** Flood forecasting is a technology which use a combination of measured daily rainfall or forecasted rainfall, measured streamflow or forecasted streamflow data with the river basin characteristics to estimate flow rates and water levels with the purpose of knowing how the river condition will be in one or several days so that the information can be provided or transferred to the decision makers as well as to the people to get prepared and respond to flood (Ghosh, 2013).

2.2 Causes and Effects of Floods

2.2.1 Causes of floods

Floods can result from a combination of hydrological extremes which are natural phenomena, such as extreme precipitation and flows but they can also happen as an outcome of human activities

a) Natural phenomena

The most important factor which contributes to flood is rainfall (its intensity, duration). Extreme rainfall may happen over a prolonged period of time and make the soil to be saturated which ends up by increasing water table as it reaches the ground surface therefore the increase of runoff. Intense rainfall may occur over a short period of time and cause flood especially when the ground surface is hard after a long period without rainfall .in such case, infiltration capacity is low to capture the rainfall therefore more water flow to the river. Todays, rainfall patterns are being influenced by climate change as the rainfall is being increasing in high latitudes and decreasing in most sub-tropical regions. (IPCC, 2007). Besides rainfall, the hydrological behavior of watershed has an impact on the possibility of flooding based on its rapid or delaying hydrological response governed by watershed characteristics like topography, land use and land cover, geology, geomorphology and soil (Romshoo et al., 2015). when it is raining the topography of basin is assumed to be the first factor to control hydrological response of the basin as it the major cause of debris flows and Landslides; the other characteristics also having significant role in affecting hydrological response of the watershed are permeability and water holding capacity (Romshoo et al., 2015).

b) Human activities

Mostly in different Countries, people move from rural areas to urban areas or within cities where they settle in the areas vulnerable to floods. Urbanization coupled with population growth increase flood risks as in urban areas, the land is covered by roads, buildings, drainage networks which change the permeable land into the impermeable land with less infiltration capacity to store rainwater and snowmelt, this impermeable land accelerate runoff, increase peak flow in the drainage channels and ends up by causing flood downstream (Mukherjee, 2016).

Major effects of urbanization have been identified and they include **a)** big amount of rainfall converted into surface runoff **b)** acceleration of rainfall –runoff response of the catchment for a specific rainfall event resulting into steeper raising limb of flow hydrograph with reduced lag time and time to peak **c)** increase of magnitude of peak flow **d)** degradation of water quality in rivers and streams due influent discharge. (Deepak at el., 2015)**.**

On the other hand**,** deforestation contributes to flooding. A terrain with no forest has a greater risk of soil erosion because rainfall is not intercepted. Forest cover may reduce flood particularly in small catchment (<10 km^2), but usually has little influence in large catchments (>10 km^2) or during severe meteorological events. Forests protect against flooding for small scale rainfall events that are not responsible for severe flooding in downstream areas while during an extreme rainfall events like those resulting in massive flooding which follow the prolonged period of rainfall, forests cannot reduce flood as the soil becomes saturated and water is no longer infiltrated into the soil (Hammond at el., 2015).

2.2.2 Impacts of flooding

Floods impacts are explained based on their classification and also types, therefore this section explains floods classification impacts and floods types.

2.2.2.1 Classification of flood impacts

To understand flood impacts, it's better to know their classification where they are classified firstly according to tangible and intangible impacts. Tangible impacts are those ones which can be easily quantified in terms of money, they include loss of profits in the case of business interruption and damage of property like houses, roads, water supply networks, Ridge, power plants, the raise cost of treating water due to water quality contamination. Intangible impacts are those which are not easily quantified in monetary terms, they include loss of life, impacts on mental of well-being and impacts on environments like contamination of water quality, spreading of waterborne disease (Hammond at el., 2015).

Secondary, according to directs and indirect impacts .The direct impacts which take place at the time of flood and stand to the loss of human life; loss of properties ; destruction of crops and livestock; destruction of infrastructure such roads, bridges, and power plant , interruption of transport , business interruption which lead to loss of profit ; indirect impacts happen later after flooding and stand to deterioration of health conditions owing to waterborne diseases, deterioration of water quality downstream which raise the cost of treatment problems of emotional and fear of sleeping when it is raining.(Queensland Government, 2011).

However, flood effect can be both tangible and direct; tangible and indirect; intangible and direct or intangible indirect as shown in the table 2**.**1.

Table 2.1: Flood classification impacts (Gautam at el., 2003).

Impacts	**Tangible**	**Intangible**
Direct	Damage of property like houses, roads, water supply networks, Ridge, power plants.	loss of life, impacts on mental of well-being, loss of esthetic quality of environment
Indirect	loss of profits in the case of business interruption, loss of agricultural production ,spread of waterborne disease	Fear of sleeping when it is raining, increased hazards vulnerability of the survivors

2.2.2.2 Types of floods impacts

Flood have economic, social and environment impacts as shown in Table 2.2 which vary depending on location, duration, depth, and speed as well as the vulnerability and value of the affected natural and constructed environments **(**Queensland Government, 2011).

Table 2.2: Types of floods impacts (Gautam at el., 2003).

Economic impacts	**Social impacts**	**Environmental impacts**
Loss of infrastructures such as roads, water supply networks and sewer system	loss of life	Destruction of flora
Government facility losses	Human injury like physical, emotional and psychological	Destruction of fauna
Residential losses like property, furniture	Health hazards like pollution of water, spreading of water-borne diseases, and deficiency of food supply.	Damage to habitat, food chains, species diversity and stability.
Public facilities losses such as market, school, hospital.	Displacement of people.	Damage to recreational resources
Employments losses, sales losses, income losses.	Traumatism both emotional and psychological due to loss of relatives, friends and property.	Damage to archeological and historical resources
Loss of recreational facilities and resources	Loss of recreational opportunities	pollution of surface and groundwater sources
Displacement of farms and business	Loss of cohesion in the community	Landslide
Increase in operational costs of replacement ,repair, and rehabilitation of infrastructure and public facilities	Insecurity to jobs and income interruptions	

2.3 Types of flood

According to NIDM, 2013 (Indian, National Institute of Disaster Management), flood is classified based on duration, where there is flash flood, slow onset flood and rapid onset flood.

a) **Flash flood** which is the most dangerous of flood produced by short, intense, heavy rainfall. It occurs in a short time of period like few minutes and can stay for a maximum of a few hours. It causes damage to people and properties as people do not have time to evacuate and it take place in steep slopes area which have streams moving though narrow canyons; it happens also in urban area where drainage systems are not adequate to cope but it can also happen in rural area where the nature of terrain and slope of the streams could influence very rapid development of flood. (NIDM, 2013).

b) **Slow onset flood** normally happens over a period of time and may be caused by on overflowing water from a dam, this type of flood takes its time to happen and once happen it stays on for a long period of time at least a week and it can also stay for even a month therefore it causes more damage to properties as people themselves have time to leave (NIDM, 2013).

c) **Rapid onset flood** happens more quickly than slow onset it takes for a shorter time period normally a day or two and it may remain for a week, this kind of flood cause loss of lives and damage to properties as people do not have time to prepare for evacuation since the flow of water is faster and dangerous (NIDM, 2013).

According to Intermap technology, 2014, Floods are classified based on the location of occurrence where there are coastal, urban, river flood.

a) **Coastal flood** occurs in places that are connected to the coastal of sea, ocean or large open water body. It due to extreme tidal conditions caused by severe climate or weather such as storm surge, high tide and tsunamis which are waves produced by earthquakes at the sea (Intermap technology, 2014)**.**

b) **Urban flooding** also called surface flooding are due to heavy rainfall in area where surface ground is much more paved as water cannot infiltrate into the ground; it is also associated with limited capacity of drainage system to drain storm water so rainfall create a flood event which is independent of an overflowing of water body (Intermap technology, 2014)**.**

c) **River flooding** take place when excessive rain falls in river basin with tributaries which drain large areas having many independent river basins and cause the flow to exceed river capacity .it may last a few hours or many days based on the intensity, amount and distribution of the rainfall event. (Intermap technology, 2014)**.**

d) It has been also shown that River flood may also resulted from urban flood upstream as result of land use change, urbanization, break of engineering works like dams, levees leading to sudden flooding downstream (Bizimana at el.,2010)

2.4 Flood forecasting Modelling Approaches

Models have been defined as the simple representation of the realities of world (Fura, 2013). They are applied to mimic and deliver well understanding of the different processes or phenomena's such as rainfall –runoff process and expansion of cities. Being simple representation, Models have the capacity to simulate and predict the future of the different event such as flood, drought and increase of population based on the historical available dataset**;** However, the manner of representation is governed by theories and methods behind (Fura, 2013). There is a need of quantifying flood risk based on the estimation of flood magnitude for the selected return period in which two types of rainfall-runoff model approaches have been classified. The first type uses historical time series data of rainfall to simulate runoff; the resulting simulated runoff time series are compared with the measured/ observed runoff time series; then the difference value between the observed runoff time series data and the simulated runoff can be taken as the existence of errors (Plate, 2009). By determining their variance, you know the level of the uncertainty and their mean value helps to know the measure of model bias correction and support to adjust the parameter to correct the errors (Plate, 2009).

The second type of rainfall-runoff model approaches relies on event as it is not applied on the whole time series data. Its purpose is to predict extreme value of runoff such as peaks volumes**.** (Plate, 2009). In case of flood risk management purposes; This type of rainfall –runoff approaches apply hypothetical rainfall fields which are the T- years area averaged precipitation fields that are greater or less uniformly distributed over the catchment therefore, the act of taking this assumption of T-years area averaged precipitation result in T-year flood errors (Plate, 2009). The point of intersection within those two approaches applied to the rainfall-runoff model is that the physical transformation of rainfall into runoff has to be described.

2.4.1 Hydraulic Modelling Approaches

To continue the quantification of risk, hydraulic models are used to determine the characteristics of streamflow produced by rainfall runoff model such depth and velocities. They are different types of hydraulic models which are physical or numerical having one dimensional (1D), two dimensional 2D, and three dimensional 3D approaches but with the same principles of conservation of mass, energy and momentum (Patterson, 2013). Generally, one dimensional (1D) has a fixed path to which the flow is passing and at each node the velocity is taken as average where for two dimensional (2D), the velocity is determined in two directions in which the flow passes across a horizontal network either regular or irregular but the depth is averaged then for three dimensional (3D), the velocity changes in three dimensions and the flow of water flow in any direction (Patterson, 2013). One dimension (1D) model is able to simulate flood in relations of discharge and water level using Saint Venant equation as long as there is a single desired direction where the flow changes slowly in the river cross section (Gharbi et al., (2016)

Saint Venant equation for 1D

$$\frac{\delta S}{\delta T}+\frac{\delta Q}{\delta X}=0, \qquad \frac{\delta U}{\delta t}+U\frac{\delta U}{\delta X}+g\frac{\delta h}{\delta x}=g(I-J) \qquad \textbf{(2-1)}$$

with I :slope ,J : energy slope obtained from $J=U^2/K^2{}_S R^{4/3}{}_h$ With R_h :hyrdraulic radius, ks: strickler coefficient.

Two dimensional 2D Model has ability to predict flood using 2D shallow water equation which include one equation of continuity and two equations of conservation of momentum (Beffa, 2008). Both 1D and 2D model has advantages and disadvantages therefore, different researchers had used models such as SOBEK (Fred, 2015); DIVAST (Lin at el.,2005); SWI20 and HEC-RAS [(Abdulaziz,2017); Pistocchi, at el.,2002).] based on their aim either of simulating floodplain under steady flow or unsteady flow. The integration of 1D and 2D increase the capabilities of simulating the floodplain through the unsteady condition.

2.5 Hydrological and hydraulic Models

Hydrological and hydraulic models are among the component of flood risk management which is a cycle of process starting from occurrence of an extreme flood leading to the restoration and construction step of risk assessment followed by project planning and application and at the ends the action and preparedness for the next extreme flooding event to prevent flooding (Plate, 2009). Hence, Hydrological and hydraulic models are used both in planning and operation. Fig 2.1 shows how planning and management of flood is done.

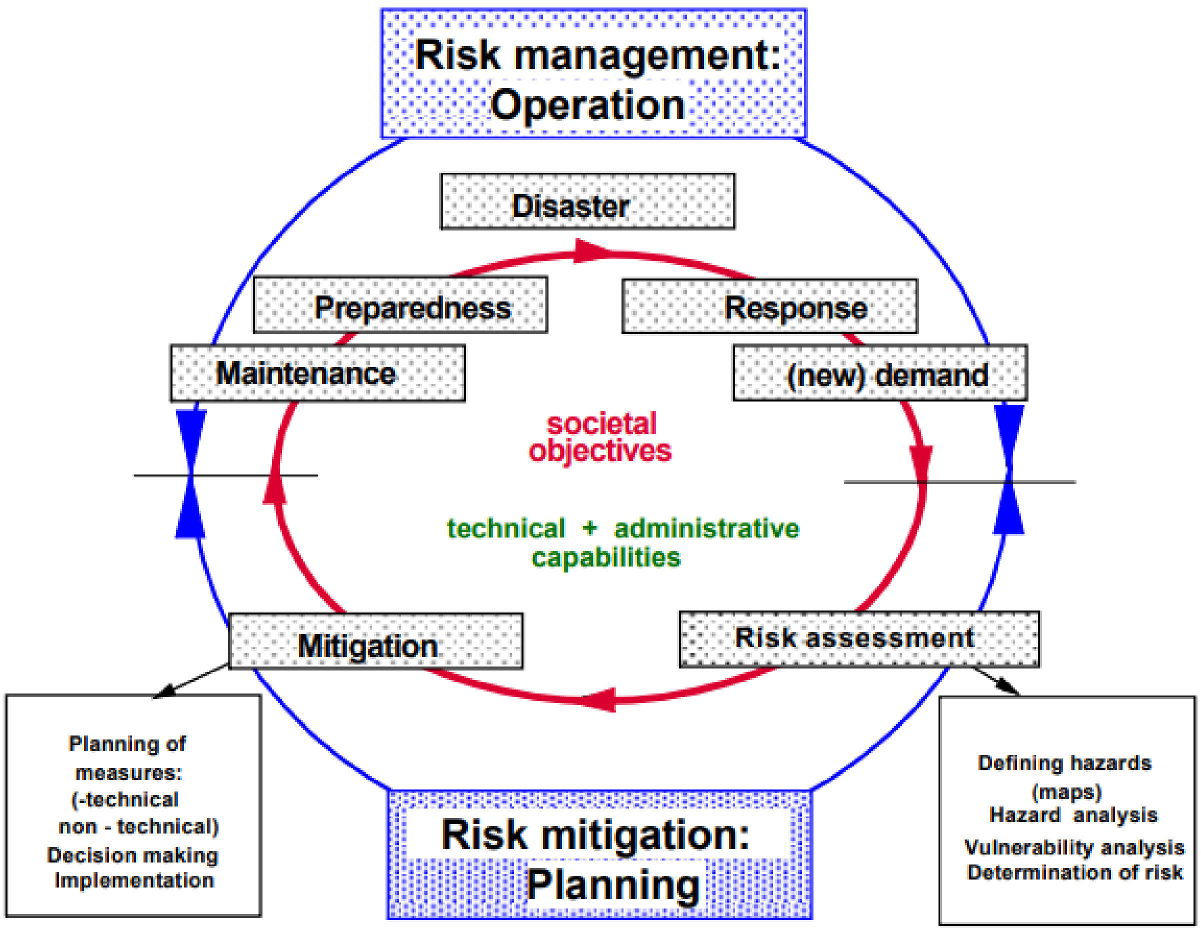


Figure 2.1: Risk management cycle (Plate, 2009).

2.5.1 Rainfall-runoff (HEC-HMS)

HEC-HMS is a hydrological model software developed by the US Army of Engineers- Hydrological Engineering Center (HEC). HEC-HMS is a physical based and conceptual semi-distributed model which is designed to simulate watershed complete hydrologic processes like rainfall-runoff processes (Scharffenberg, 2016**)**. HEC –HMS has four important components which are basin model; meteorological model; control specifications and time series data manager.

Basin model characterizes the physical description of the catchment including information on the mathematical approaches or equations that will be used in simulating the hydrology of the watershed and the values for all the variables in those equations since the variables in those equations are parameters when you change them; directly the output is changed. Sub-basin, junction, reach, source, sink, reservoir, diversion and outlet are the basin elements where each of them need some parameters to describe the behavior of hydrologic system.

Meteorological model requires meteorological information to drive the hydrological simulation in HEC –HMS and it stores information of rainfall falling in the catchment along with evapotranspiration (Scharffenberg, 2016**)**.

Control specification model essentially communicates how long the simulation will last and the time step to continue the simulation. It is used to indicate the starting time and date, ending time and date then Time series data manager help the user to introduce the recorded rainfall data to the model and produce the hyetograph and it must be linked to the meteorological model. After running the HEC-HMS model the hydrograph is produced and it can be used directly or in conjunction with other software for studies of water availability, urban drainage, flow forecasting, future urbanization impact, reservoir spillway design, flood damage reduction, floodplain regulation, and systems operation (Scharffenberg, 2016**)**.

HEC-HMS model input and output

The main Hec-Hms input comprise of: catchment stream network and size; infiltration loss method; transform method; base flow method; Meteorological data and Time of simulation. The main output consists of: hydrographs and flow volume.

2.5.2 Hydraulic model (HEC-RAS)

HEC-RAS is a hydraulic model of river analysis system developed by US Army of Engineers of Hydrologic Center .it allows the performance river analysis components which are: one dimensional steady flow; one or two dimensional unsteady flow calculations for a full network either natural or artificial; sediment transport; mobile bed computations and water temperature and quality modelling (Gary,2016).

HEC-RAS has a modelling component to achieve each of those river analysis component like for steady flow calculation which is done to produce surface water profiles at steady condition with either subcritical or supercritical and or mixed flow regime of water surface profile based on the solution of one dimensional energy equation in the case of gradually varied water surface profile where Friction (Manning's equation) and contraction/expansion are used to evaluate energy losses. Steady flow analysis can be done based also on the momentum equation when the water surface is rapidly varying like for hydraulic jump, low flow hydraulic produced at the bridges and the stream junctions (Gary,2016).

Apart from steady simulation, HEC-RAS is able to simulate one –dimensional, two-dimensional or combination of one and two dimensional unsteady flow condition over a full network of open channel (Gary,2016). Unsteady flow computation also considers effects of various abstractions such as bridges, culverts, weirs, spillways, and others structures storage areas; in addition to that this unsteady flow computation has ability to model hydraulic connections between storage areas, two dimensional flow areas and between stream reaches within the floodplain (Gary,2016).

The main objective of HEC-RAS is to find the water surface elevations within the area of interest under steady or unsteady flow condition and to achieve this it require some basic input data which are grouped into geometric data, steady flow data, unsteady flow data, sediment data and water quality data among those data categories only geometry data (distance between river cross section; elevation, length, Manning value for land use within floodplain) are needed for any kind of analysis within HEC-RAS others are needed when the user want to perform a specific kind of analysis like steady flow data are required when there is a need of performing steady flow water surface elevations(Gary,2016). HEC-RAS main output comprise water surface elevation, rating curves, hydraulic parameters like Energy grade line, flow area, flow velocity, stream flow visualization showing extent of flooding (Gary,2016).

2.5.3 Geographical information systems

Geographical information system (GIS) is a computer based tool for capturing, storing, manipulating, mapping and analyzing spatial referenced data. When it comes to hazard assessment such as floods, landslides, since 1960s, GIS has been applied to assess and map those hazards especially in most western Countries where application of GIS in mapping and assessment has existed as a significant field. (Chingombe at el., 2014). Different GIS –based model has been used to assess flood by different Researches where there are MIKE URBAN (Mukherjee, 2016)., SOBEK (Manyifika, 2015), HEC-RAS (Chandresh at el.,2016), HEC-HMS **(**Yongping at el.,2011). Hence, this study has been interested on two GIS- based model which are HEC-RAS and HEC-HMS models specifically to their geospatial hydrologic modelling extensions of GIS software named Hydrologic Engineering Center Geospatial Hydrologic Modelling Extension (HEC-GEOMS) and Hydrologic Engineering Center's River Analysis System (HEC-GEORAS). HEC-GEOHMS is a geospatial tool for Engineers and hydrologist which help to process spatial information, watershed characteristics, delineate sub-basin and streams in other to get hydrographical network and to compute physical characteristics and hydrological parameters of watershed and create required schematic watershed input to hydrological model, hence To prepare this schematic watershed input to hydrologic model Digital elevation model, stream network, CN grid from the combination of soil and land use data are required (Fleming at el.,2009).

HEC-GEORAS is a combination of ARG GIS tool specially designed to produce geospatial data need to be used in HEC-RAS .Through RAS geometry tools, HEC-GEORAS, helps the users in the creation of geometric data file of the river from the existing digital terrain model(DEM) which contains stream network, bank lines, flow paths ,cross sections locations and other hydraulic characteristics of the river system; this geometric data file is imported to HEC-RAS model for hydraulic calculation and after hydraulic calculation ,the user imports the HEC-RAS results to HEC-GEORAS for spatial analysis where HEC-GEORAS can produce and display results of inundated area ,water depth and velocities (Ackerman at el.,2009).

2.6 Flood forecasting and its significance

Flood forecasting is a technology which use a combination of measured rainfall or forecasted rainfall, measured streamflow or forecasted streamflow data with the river basin characteristics to estimate flow rates and water levels with the purpose of knowing how the river condition will be in one or several days and what will be affected within that river condition in order to propose flood mitigation measures and disseminate the information to the decision makers as well as to people to get prepared and respond to flood **(**Ghosh, 2013). Actually there are two main approaches of forecasting flood, the first one consist of mathematical modelling approach which is based on modelling the physical dynamics between the main interacting components of the hydrological system so rainfall –runoff model can be used to convert rainfall and flow data into hydrograph predictions by taking into account the spatial variation of storage capacity then hydraulic channel flow routing model is used to determine the flows **(**Nduta at el.,2015). The second approach consists of modelling the statistical relationship among hydrologic input and output without clearly considering the physical process relationship which occur between them **(**Nduta at el.,2015).

Forecasting flood like other hydrological phenomenon are of great importance in almost all Countries in the world for their economic development as where as to their rural and urban population in the flood prone areas. It has big value for the suitable use of river energy, local transport, irrigation, water supply and flood control and its management **(**Ghosh, 2013). Timely forecasting accompanied with warning help to minimize the damage by taking precautions measures such as evacuation of people and property to the safe places, it is also important for the efficient operation of existing reservoirs as the initial storage of reservoir can be drown to the lowest possible level to provide enough storage before the arrival of flooding water to pass flood and plays as storage at the end **(**Ghosh, 2013). Forecasting Flood provide information to the different institutions like those ones in charge of water, transport and communication and local authorities for the preparation and response. So it is a necessary part of flood management planning and development strategy which require high level of cooperation between water management agencies, local or municipal authorities, transport and communication operations and emergency agency. Knowing that there is no preventive or defense measures which is completely effective to prevent flood, the reality of economic limits to the provision of defenses, together with the possibility that the capacity of defense systems may be exceeded or that they may fail, require other measures in place. Like engineering measures such as flood gates or demountable barriers, reservoirs, dams and non-engineering measures such as domestic protection (sandbagging) and flood forecasting, prediction and warning which end up by local evacuation (to flood shelters) **(**WMO-No 1072, 2011).

3 MATERILAL AND METHODS

This section has three parties where the first one describes briefly the characteristics of the study area which include catchment location, population and poverty status, the climate, topography, soil and land use of the catchment. The second party explains different methods applied during the study then the last section explained data collection and its processing.

3.1 Description of the study area

The following description of the study area involves the localization of the catchment within the Country and its physical characteristics basically topography, soil and land use which are the basic data set to run hydrological and hydraulic model.

3.1.1 Overview of the catchment

Nyabugogo catchment is located in Rwanda which has two hydrographic basins (Nile basin and Congo basin covering 67% and 33% of Rwanda's territory respectively (MINIRENA, 2011). Nyabugogo basin where Nyabugogo river passes through is situated in Nile basin as the main sub -catchment of Nyabarongo downstream catchment. it contains Nyabugogo river which is a tributary of lower Nyabarongo river. Nyabugogo catchment is the most densely catchment of the Country, it covers both rural and urban areas including Kigali city which is the capital of Rwanda and it is between 1352 m to 2288m above sea level and extended between latitude: 01^{0}51'46.06''-01^{0}46'11.22'' degrees South and Longitude:30^{0}05'57.02''-30^{0}04'07.41'' degrees East. The drainage area is about 1661.359 km2 representing 6.31% of the total surface area of the Country (Water for Growth Rwanda, 2017). Fig 3.1 shows the location of Nyabugogo catchment within the Country.

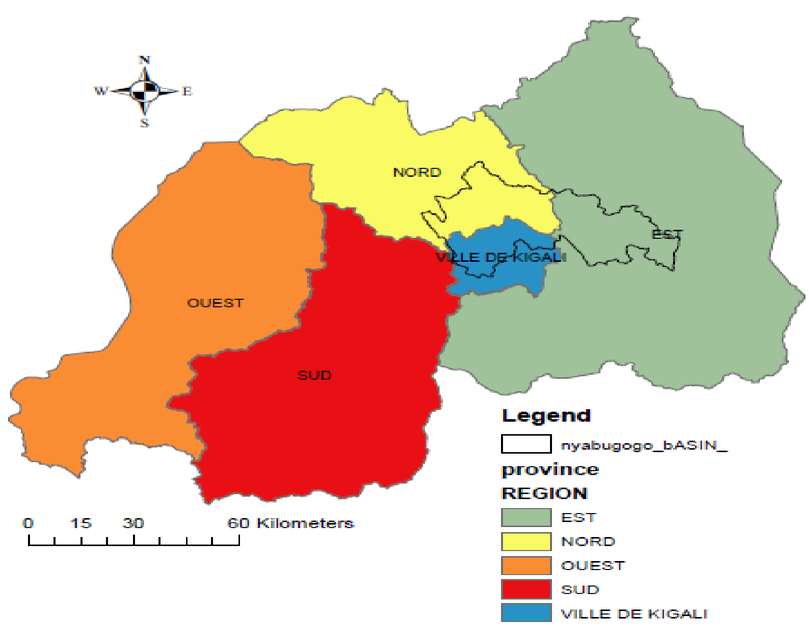


Figure 3.1: Location of Nyabugogo catchment in Rwanda

3.1.2 Administrative division of Nyabugogo catchment

According to Fig 3.2 Nyabugogo catchment overlaps 8 districts which are, Rulindo, Rwamagana, Gatsibo, Gicumbi, Kayonza, Kicukiro, Nyarugenge, Gasabo where these last three ones are urban districts of Kigali city. Table 3.1 shows the overlaps area of the catchment on the districts.

Figure 3.2: District within Nyabugogo catchment (Water for Growth Rwanda, 2017**)**

Table 3.1:Overlaps of Nyabugogo catchment within districts (Water for Growth Rwanda, 2017**)**

Catchment name	Districts name	District area km2	Overlap area of the catchment on district	% of catchment area on districts
Nyabugogo with 1661.359 km2	Rulindo,	566.96	294.12	17.70
	Rwamagana,	681.96	190.29	11.5
	Gatsibo,	1582.32	304.50	18.33
	Gicumbi, ,	829.52	339.64	20.45
	Kayonza,	1934.96	174.57	10.50
	Kicukiro,	166.71	19.88	1.2
	Nyarugenge	133.98	44.20	2.66
	Gasabo	429.21	304.50	18.33

3.1.3 Socio -economic background

a) Population and poverty

Rwanda is among of the sub- Saharan African Countries with high population density which account of 416.64person/km^2 and according to the population and housing census conducted in 2012, it showed that a number of 1355222 people were living in Nyabugogo catchment with 46.1% in urban area and 53.1% in rural areas where 49% were male; 51% were female and 48% of the total population were below 20 years

(NISR),2012**).** Fig 3.3 demonstrates how the population densities are distributed in Nyabugogo catchment where Kigali city has an extremely high population density especially in the sector of Gitega, Kimisagara and Nyakabanda of Nyarugenge District.

Poverty rates inside the catchment area are high with 8%- 49 % of the population categorized poor due to high population growth and decline in soil fertility in a largely agricultural based economy and it tend to be high in areas with very high population density of the catchment and also in the areas where agricultural is the principle economic activity **(**Water for Growth Rwanda, 2017)**.**

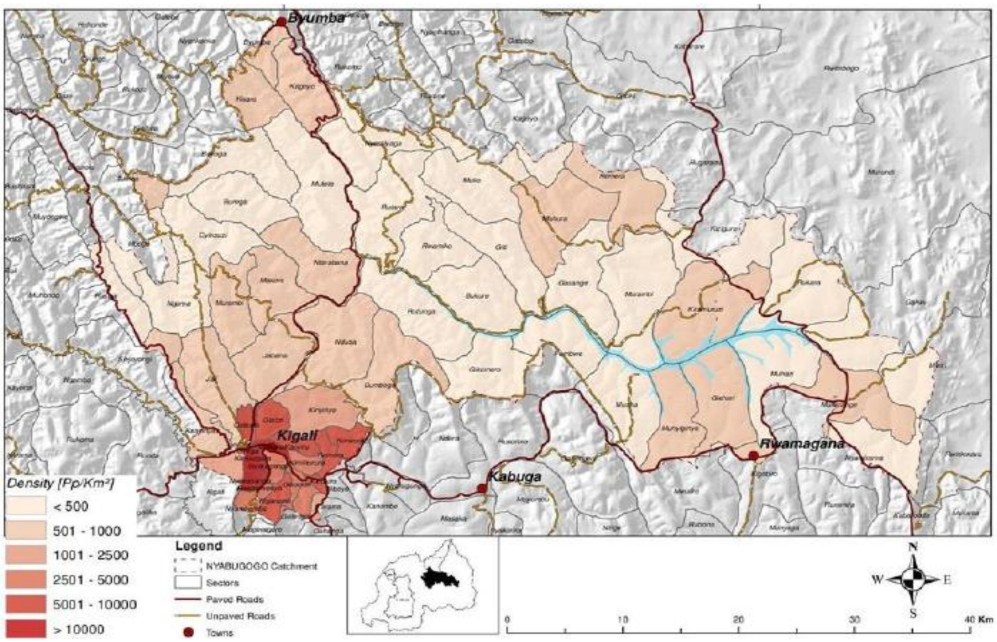


Figure 3.3: Population densities in Nyabugogo catchment (Water for Growth Rwanda, 2017)**.**

a) Economic activity

The main economic activity in the catchment is the agriculture which covers 897 km^2 about 54% of the catchment area (Rukundo at el., 2016). Others activities which contribute to the economy of the catchments include fishing, forestry, services like utility, financial services, trade, mining and quarrying operations in Gatsibo and Kayonza manufacturing activities in Kigali like textiles, paint, brick making all of this contribute to the economy.

3.1.4 Climate characteristics of the catchment

The climate of Nyabugogo catchment is similar to that one of the country. Rwanda is a hilly and mountainous Country with 900 -4507 m of altitude, it experiences tropical temperate climate because of its high altitude and the average annual temperature varies between 16^0C to 20^OC. (European Commission, Republic of Rwanda, 2006).

The country has two rainy seasons and two dry seasons per year where the period of heavy rain start form March till May and period of moderate rains start from mid -September to October then longest dry season is between June to mid -September and short dry season starts rom December to February .Rainfall is abundant with the average annual of 1200mm but it varies from region to region as we have 700 mm to 1400 mm in the eastern plateau and lowlands of the west, 1200 mm to 1400 mm in the central plateau where Nyabugogo catchment is specifically located and 2000 mm in the high altitude region.(MINIRENA,2011).

3.1.5 Topography

Topography of the catchment is the main factor which influences the spatial and temporal variability of hydrological process the catchment and it can be represented by Digital elevation model (DEM), Triangular irregular network (TIN) and contour line. DEM help to delineate the catchment and obtain different characteristics of the catchment such as hydrographical network, slope of the catchment (Mendas,2010). Digital elevation model was collected from Rwanda Water and Forestry Authority (RWFA) with 10m resolution. Nyabugogo catchment has Topography which vary between 1352 m and 2288 m above mean see level as shown by Fig 3.4

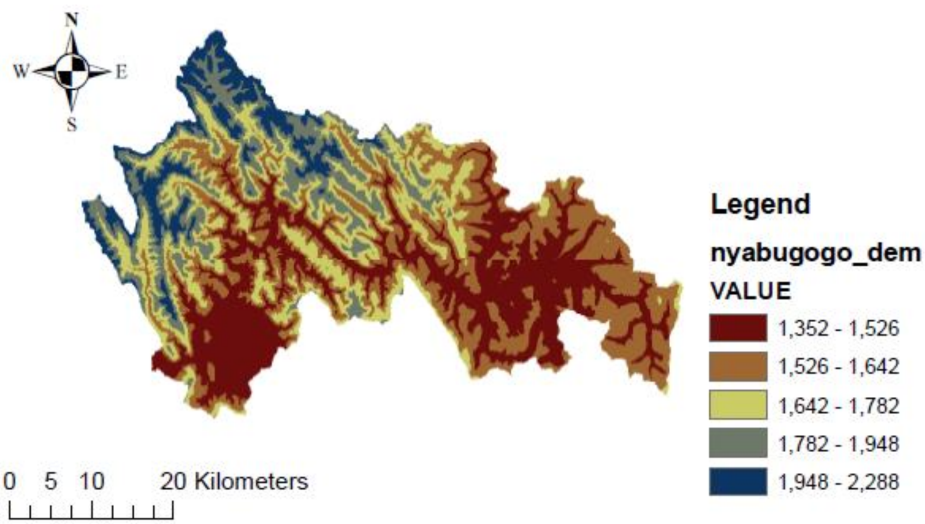


Figure 3.4: Topography of the catchment

3.1.6 Soil of the catchment

Soil data has been provided by Rwanda Water and Forest Authority (RWFA). The dominant soil types found almost in all party of the catchment as shown by Fig 3.5 are nitisols, lixisols, acrisols, alisols. the other soil types which are also dominant is mineral soil conditioned by flat topography especially in western party, combisols and ferralsols are also found in the catchment. Apart from soil types the texture as important factor influencing the runoff generation has been shown where Nyabugogo soil texture is dominated by clay which is also mixed with other texture like sand, silt and loam as shown by Fig 3.6

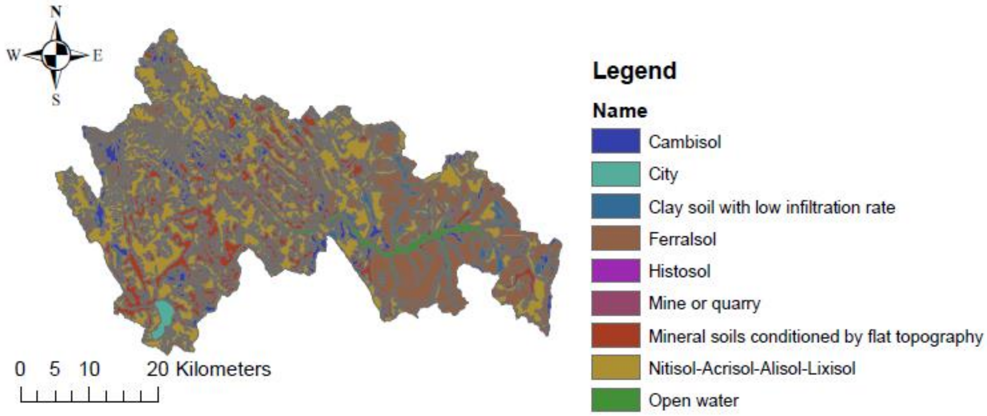


Figure 3.5: Soil types of Nyabugogo catchment

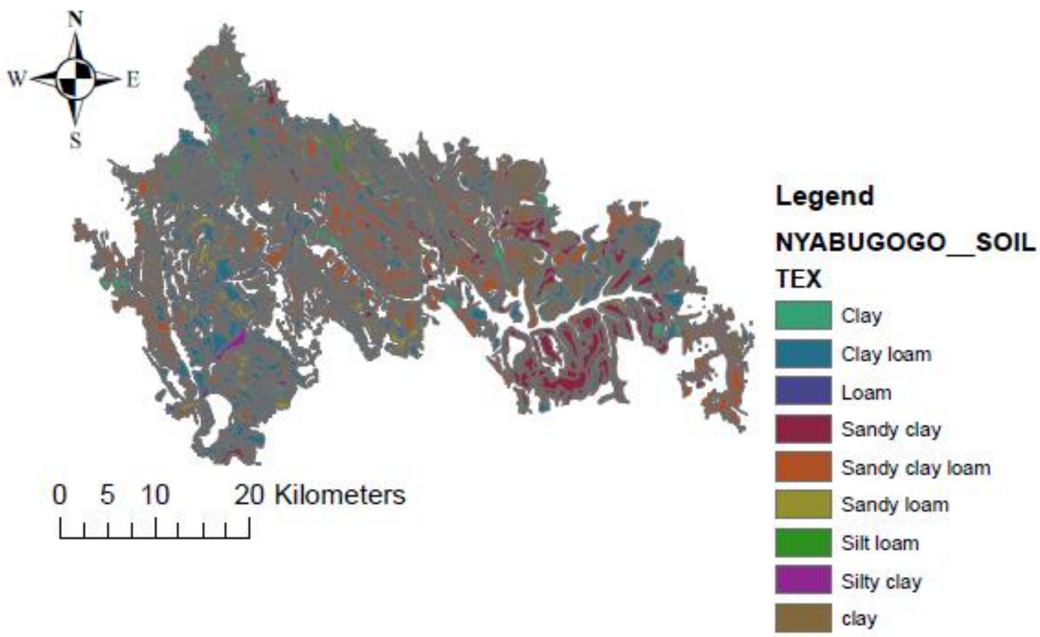


Figure 3.6: Soil texture of Nyabugogo catchment.

3.1.7 Land cover of the catchment

Land use is one of the driver of hydrology of a watershed. Nyabugogo land use were provided by Rwanda Water and Forest Authority(RWFA). The land use is dominated by annual crop land as shown by Fig 3.7

and the most densely housing area of the catchment is covered by the settlement land use and is located in Kigali city.

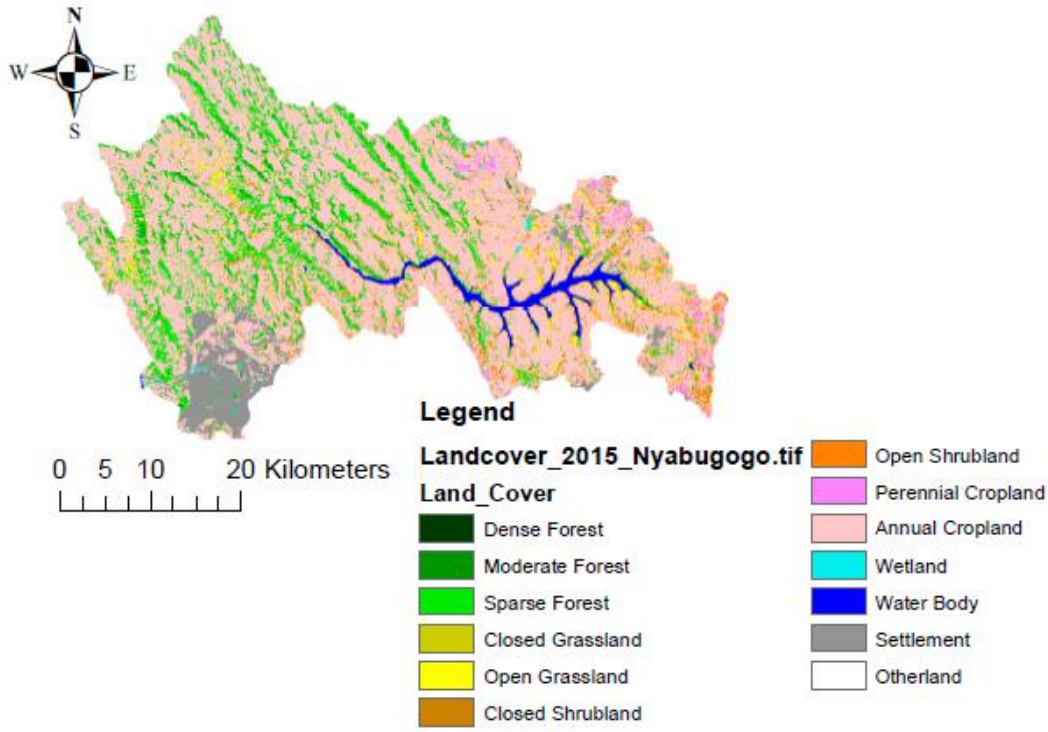


Figure 3.7: Land cover of Nyabugogo catchment

3.2 Methodology

This section explains the methodology applied during this study to perform rainfall -runoff and hydraulic modelling and to discover the causes, effects of flooding within the catchment including the existing measures to prevent and / or reduce flooding in the catchment.

3.2.1 Extreme frequency rainfall events

The management of flood damage and also the design of water infrastructure need a sufficient information of extreme rainfall events of high return periods. Normally the return periods needed in those projects exceed the available period of recorded events data and could not be detached from them **(**Van-Thanh, at el., 2016); Therefore, there is a need of estimating extreme rainfall based on statistical frequency analysis of annual maximum recorded rainfall data since The frequency analysis of extreme rainfall events is necessary to estimate the large events and their chance of occurrence **(**Salaheddine at el.,2010)**.** For accurate hydrologic analysis of flooding there are different probability distributions method used to estimate extreme rainfall such Beta –P; Generalized extreme value(GEV), Beta-k, Generalized Logistic (GLO), Generalized Pareto(GPA), Gumbel, Log-Pearson Type III, Pearson Type III and Generalized Normal(GNO)

(Salaheddine at el.,2010). Among all of the mentioned probability distribution methods, only Gumbel' extreme value distribution method has been applied in this study to execute flood probability analysis in order to find the relationship within chance of occurrence of individual rainfall event and its return period then determine flood magnitude corresponding to a given return period.

Following are the formulas and procedures used to execute flood probability distribution and flood magnitude using Gumbel's extreme value distribution method.

- Sort the maximum daily rainfall of each year.
    - (P_{max})
- Determine the mean and standard variation of the sorted maximum rainfall data
    - $P\ mean = \frac{1}{n}\sum_{1}^{n} Pmax$ **(3-1)**
    - $S=\sqrt{\frac{1}{n-1}\sum_{1}^{n}(Pi - Pave)^2}$ **(3-2)**
- Determine the reduced variate Y
    - $Y=1.282\,\frac{Pi-Pave}{S} + 0.577$ **(3-3)**
- Calculate the probability P
    - $P= 1 - e^{-e\,\wedge -Y}$ **(3-4)**
- Determine the return period T
    - $T=1/P$ **(3-5)**
- Determine frequency rainfall P_T (mm)corresponding to each return period T(years)
    - $P_T= P_{ave} + K_T S$ **(3-6)**
    - $K_T=\frac{-\sqrt{6}}{\pi}(0.5772 + \ln(\ln(\frac{T}{T-1})))$ **(3-7)**

    K_T Knows as Gumbel frequency factor.

3.2.2 Rainfall -Runoff Modelling methods

There are a number of hydrological models used to simulate rainfall into runoff taking into consideration all the processes of how rainfall is transformed into runoff. In this project it was preferably to use HEC-HMS 4.2.01 model which contains different models used depending on the purpose of the study. Those models are: Clark unit hydrography, kinematic wave, mod Clark, SCS unit hydrography, Snyder unit hydrography, exponential recession model, and user specified unit hydrography (Scharffenberg, 2016). HEC- HMS model works in Conjunction with HEC-GEOHMS which is a GIS extension used to prepare the Basin input model needed for HEC-HMS to simulate rainfall into runoff based on Basin Geomorphological characteristics.

3.2.2.1 Runoff volume calculation

To obtain runoff from rainfall in HEC-HMS Model as all rainfall don't become runoff due to infiltration, the Soil Conservation Service (SCS) Curve Number model was applied. It was introduced for the first time by the SCS US Department of Agriculture to produce direct runoff from rainfall event (Soulis, (2012). It considers many factor affecting runoff generation and integrate them into CN parameter. Those factors are cumulative precipitation, soil cover and land use of the catchment or area of interest (Feldman, 2000).

The SCS Curve number formula to obtain runoff from a given rainfall is

$$\mathbf{Q}=\frac{(\mathbf{P}-\mathbf{Ia})2}{(\mathbf{P}-\mathbf{Ia})+\mathbf{S}} \quad \textbf{(3-8)}$$

where Q: Runoff at time t,

P: depth rainfall at time t,

S: potential maximum retention after runoff begins

I_a: initial abstraction before runoff start to flow and it consist of all water retained by surface depression, anticipated by vegetation, evaporation and infiltration.

$$I_a = 0.2S \quad \textbf{(3-9)}$$

By combining (Eq.8) and (Eq 9); the direct runoff become:

$$\mathbf{Q}=\frac{(\mathbf{P}-\mathbf{0.2S})2}{\mathbf{P}+\mathbf{0.8S}} \quad \textbf{(3-10)}$$

the factor S is connected to soil and cover conduction where in in foot pout system

$$S= \frac{1000-10CN}{CN} \quad \textbf{(3-11)}$$

and in System international

$$S=\frac{25400-254CN}{CN} \quad \textbf{(3-12)}$$

with CN curve number varying from 30 for impermeable area to 100 for water.

CN for a watershed with different land use and land cover is computed by the following formula

$$CN_{composite} =\frac{\sum AiCNi}{\sum Ai} \quad \textbf{(3-13)}$$

With:

i: watershed index subdivision for uniform land use and soil types,

CNi: curve number for subdivision,

Ai: subdivision area.

In order to determine Curve number for each sub-basin, the curve number Grid have been prepared following those steps:

Step1: Preparation of land use data using Arc-GIS. The collected land use was before classified into 14 land use types, then it was reclassified to reduce their number through the use of spatial analysis tools in

Arc toolbox by clicking on Spatial Analyst Tools->Reclass->reclassify. Then after reclassification, it was converted into polygon through Conversion Tools in Arc toolbox by clicking on conversion tools->from raster-> raster to polygon.

Step2: Preparation of Soil data by assigning the soil hydrological groups based on the soil texture then define percentage area corresponding to each soil hydrological group. All of this was accomplished in Arc-GIS

Step 3: Union of prepared soil and prepared land use through Analysis tools in Arc-toolbox.

Step 4: Creation of CN_look up to relate reclassified land use types with soil hydrological by assigning Curve Number.

Step 5: Preparing HYDRO DEM (fill) of the catchment.

Step6: Generation of Curve Number grid using utility function of HEC-GEOHMS.

3.2.2.2 Direct runoff calculation

To compute direct runoff of excess rainfall within a watershed; the SCS unit hydrography model has been applied. the direct runoff consists of transforming excess precipitation into point runoff (Feldman,2000). According to the Hydrological Modelling System Technical Reference Manual of HEC-HMS it explains that the Unit Hydrograph is dimensionless with single peaked UH actually which is peak discharge.

The relationship between UH peak and time of UH peak is:

$$Up= C\frac{A}{Tp} \qquad \textbf{(3-14)}$$

with:

A: watershed area

C: conversion constant which is equal to 2.08 (SI) and 484 (foot pound system).

The relation between time to peak and duration unit excess precipitation is given by:

$$T_p=\frac{\Delta t}{2}+\text{t lag} \qquad \textbf{(3-15)}$$

with **Δt** excess precipitation duration and **t_{lag}** as basin lag time which is the time to which the river reaches its highest level or the time difference between the peak of rain event and the peak discharge. When the basin lag time is identified the program resolve equation 3-15 to find time to peak then solve equation 3-14 to find peak discharge.

3.2.2.3 Base flow computation

To model the base flow, the exponential recession method has been used in this research**.** The base flow is taken as the amount water which could occur in the stream deprived of direct runoff resulting from rainfall. it can be also defined as contribution of groundwater to the stream (Feldman,2000).

The base flow at time t is obtained by the following equation:

$Q_t=Q_0K^t$ **(3-16)**

With

Qt: base flow at any time t;

Q_0: initial base flow at time t equal to zero

K: exponential decay constant.

The value of $\mathbf{Q_O}$ is taken at the point where the hydrograph streamflow starts to rise and it can be specified as flow rate (m_3/ sec or cfs) or as flow unit area ($m^3/s/km^2$ or cfs /sq. mi) where **K** is defined as the ratio of the base flow at time $\mathbf{t_0}$ to the base flow one day earlier.

The user-specified threshold flow need to be defined as the recession model is applied both at the starting time of simulating the storm event and later in the event when the subsurface flow are reaching the streams. Therefore, the threshold can be specified as the ratio to the peak flow or as flow rate and it assumed that at the threshold value, the base flow is taken as initial base flow recession (Feldman,2000). Hence, the needed parameters to this model are: initial base flow recession, exponential decay constant and threshold discharge or threshold ratio to peak.

3.2.2.4 Channel flow computation

HEC-HMS has different model for computing channel flow model taken as also routing model based on fundamental equations of open channel which are momentum equation and continuity equation by taking into consideration the upstream hydrograph as the boundary condition to obtain the downstream hydrograph (Feldman,2000).

Among all the existing routing model inside the HEC-HMS model, the Muskingum model has been applied for this study to compute the downstream hydrograph.

Muskingum model is based on the simple finite difference approximation of continuity equation: $\frac{\mathrm{It-1+It}}{2} - \frac{\mathrm{Qt-1+Qt}}{2} = \frac{\mathrm{St-St-1}}{\Delta \mathrm{t}}$. **(3-17)**

Fig 3.8 shows the different storage volume in the reach where the volume storage is equal to the sum of prism storage and wedge storage. Prism storage is the volume of water within water surface profile at steady flow and wedge storage is the extra volume under the profile of flood wave, it is taken as negative when there is no flood and positive when there is flood (Feldman,2000).

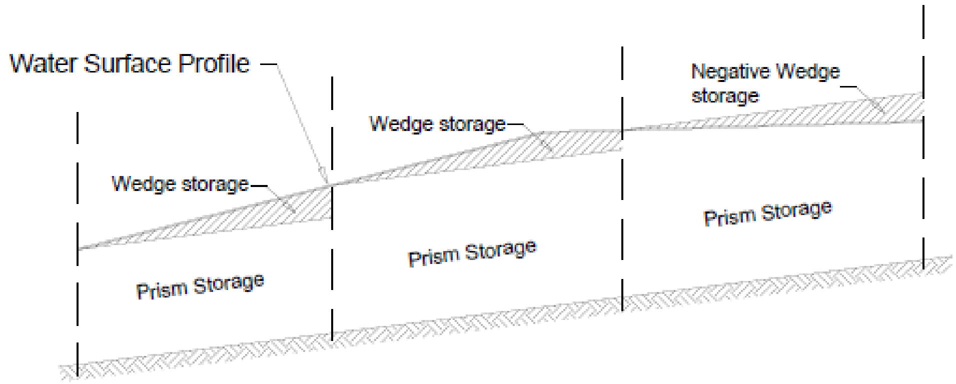


Figure 3.8: Physical representation of prism and wedge storage within a reach (Feldman,2000).

Muskingum model describe the prism storage and wedge storage as follow: the prism storage is taken as the outflow rate (Q) multiplied by its travel time (K) through the reach and the wedge storage is taken as the weighted difference between the inflow and outflow through the reach multiplied by travel time (K). (Feldman,2000); Therefore, the volume storage in the reach is:

$S_t = K\,Q_t + KX(I_t - Q_t)$ **(3-18)**

With

K: the travel time of flood wave in hour

X: dimensionless weight varying between 0-0.5.

Hence by assigning the value of K and X in the program, the ordinates of outflow hydrograph are computed based on the given ordinates inflow hydrograph.

3.2.2.5 Calibration of HEC-HMS model

Calibration is a process of adjusting the model parameter in order to produce the best fit between the observed and simulated results and to obtain the reality within the range of accuracy defined by the performance criteria (Manyifika, 2015). There exist performance criteria which can be applied during calibration such as Nash Sutcliffe coefficient; peak weighted RMS error; Percent peak; RMS Error, Sum of absolute residuals. In this research Nash Sutcliffe coefficient has been applied to assess the effectiveness of HEC-HMS model and is expressed mathematically as

$$\mathbf{NS}=1-\frac{\sum_{n-1}^{N}(\mathbf{Qobs}-\mathbf{Qsim})2}{\sum_{n-1}^{N}(\mathbf{Qobs}-\mathbf{Qmean})2} \qquad \textbf{(3-19)}$$

and it varies between $-\infty$ and 1,with large value indicating better fit (Krause at el.,2005).

The data used to calibrate were historical rainfall data and the streamflow data of the April Month, 2016, those data were chosen since it the month where the Country use to have too much rain. The hydrograph produced by the streamflow data and the one simulated were compared. After the hydrograph comparison, the automatic calibration has been done based on the performance criteria.

3.2.3 Hydraulic modelling methods

To perform the hydraulic modelling of Nyabugogo river, HEC_RAS software Combined with GIS extension named HEC_GEORAS have been used in this study. The River flow analysis applied to this study was 1D dimensional steady flow computations with subcritical flow regime.

Following are the steps adopted to come up with flood inundating maps and they are well explained in the next section of data processing for hydraulic modelling.

Step1: Preparation of geometric data with the use RAS geometry of the HEC-GEORAS software

Step2: Exporting RAS data from HEC-GEORAS and importing them into HEC_RAS model

Step3: Introducing of Peak discharges simulated by hydrological modeling done by HEC-HMS model.

Step4: Running steady flow analysis with subcritical flow regime in HEC-RAS model to determine water surface elevations.

Step5: Exporting HEC-RAS results and importing them into HEC_GEORAS

Step6: Generating flood inundation maps with the use of RAS mapping of HEC_GEORAS.

3.2.3.1 Governing equations in HEC-RAS

HEC- RAS has different governing equations explained below of determining water surface elevations and velocity at each cross section with 1D dimensional steady flow water surfaces profiles.

a. Water Surface Profiles

Steady flow analysis is used to determine the water surface profiles for a full network or for a single river reach with the ability of modelling subcritical, supercritical and mixed flow regime (Gary,2016). Those water surface profiles are calculated from one section to the next section by solving the energy equation with the energy loss due to friction loss and form loss caused by contraction and/or expansion. The governing energy equation is expressed by Fig3.9

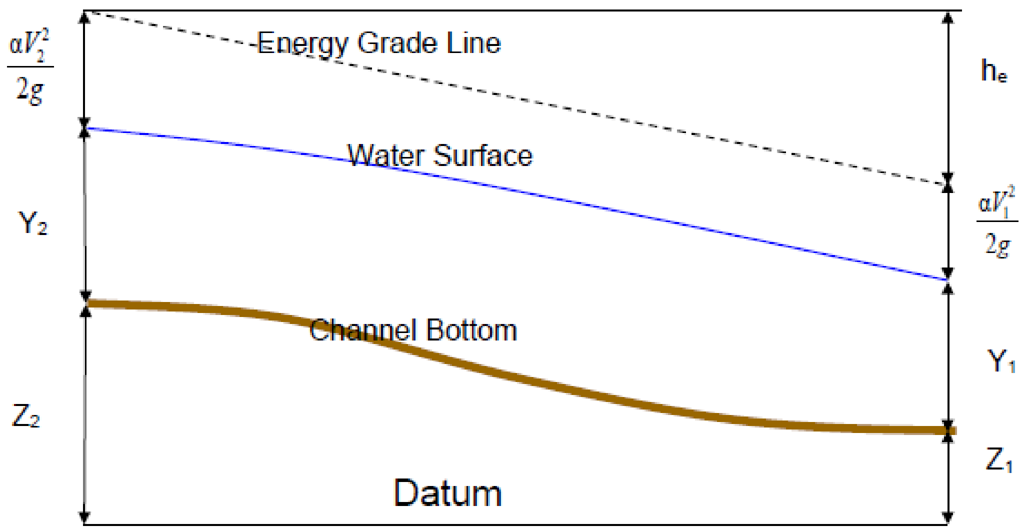


Figure 3.9: Component of energy equation (Gary.W. B. (2016).

Bernoulli equation and continuity equation are the most important equations to find out energy equation represented by the above Fig III.9.

Bernoulli equation $E= Z+Y+\frac{V^2}{2g}$ **(3-20).**

Where E: Total energy head; Z: bottom elevation with respect to the datum; Y: water depth

V: velocity perpendicular to the cross section and g: gravity acceleration

Continuity equation Q=AV **(3-21)**

Where

Q: the discharge; A: cross section of the flow and V: velocity

By considering the Bernoulli equation, the balance of energy between two sides can be written as

$\mathbf{Z_2+Y_2+\alpha_2 V_2^2/2g = Z_1+Y_1+\alpha_1 V_1^2/2g+hl.}$ **(3-22)**

With

Z_2 and Z_1: elevation of the main channel inverts

Y_2 and Y_1: depth of water at cross section

V_2 andV_1: average velocity

g: gravitational acceleration

hl: energy head loss

α_2 and α_2: velocity weighting coefficient or energy correction coefficient

b. Determination of conveyance

To obtain the total conveyance for a cross section, the flow has to be subdivided into units for which the velocity is uniformly distributed. HEC_RAS takes the input cross section n -value as shown by Fig 3.10

like the basis for subdivision to divide the flow in the overbank areas then the conveyance is determined within each subdivision using the manning's equation expressed as follow:

$$K=\frac{1.486AR^{\wedge}(\frac{2}{3})}{n} \quad \textbf{(3-23)}$$

with

K: conveyance for subdivision

n: manning 's roughness coefficient for subdivision

A: flow area for subdivision

R: hydraulic radius for subdivision

After the conveyance overbanks is obtained, HEC-RAS sum up them to determine a conveyance for the left and right overbank then the total conveyance for the cross section is obtained by adding the conveyance for left and right overbank to the one of the main channel which is calculated as single conveyance element.

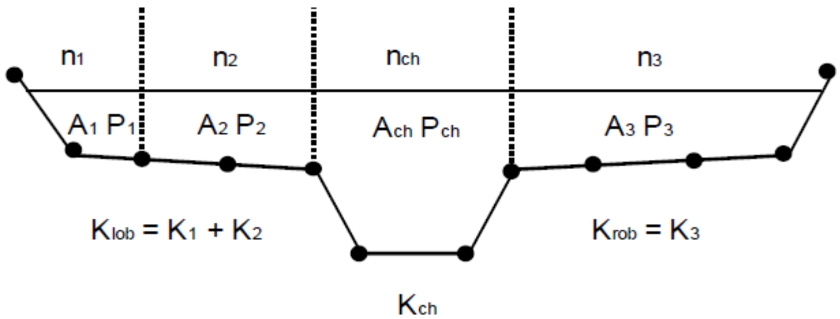


Figure 3.10: Subdivision method [37]

c. **Energy correction coefficient** α

HEC- RAS use the conveyance K to determine velocity weighting coefficient or energy correction coefficient α seen in the energy equation (3-22) and is expressed as:

$$\alpha = \frac{At^2[\frac{K^3lob}{A^2lob}+\frac{K^3ch}{A^2ch}+\frac{K^3rob}{A^2\,rob}]}{K^3\,t} \quad \textbf{(3-24).}$$

with

At: total flow area of cross section

A_{lob}, A_{ch}, A_{rob}: flow area of left overbank, channel and right over bank.

K_{lob}, K_{ch}, $K_{rob:}$ Conveyance of left overbank, channel and right overbank respectively

K_t: total conveyance of cross section

d. **Head Loss**

The head loss is computed as the sum of friction loss and minor loss (contraction/expansion loss) and is expressed by the following equation:

$$hl = L\,Smean_f + C\left(\alpha_2 \frac{V_2^2}{2g} - \alpha_1 \frac{V_1^2}{2g}\right) \quad (3\text{-}25)$$

minor loss due to contraction /expansion

friction loss

with

S_{meanf}: representative friction slope between two sections and expressed by:

$$Smean_f : \left[\frac{Q1+Q2}{K1+K2}\right]^2 \quad (3\text{-}26)$$

C: expansion or contraction loss coefficient equal to 0.1 for contraction and 0.3 for expansion; the contraction is thought when the downstream velocity is greater than upstream velocity where the expansion is assumed when the downstream velocity is smaller than upstream velocity.

L: discharge weighted reach length from cross section one to cross section two obtained by the following equation:

$$L = \frac{LlobQmeanlob + LchQmeanch + LrobQmeanrob}{Qmeanlob + Qmeanch + Qmeanrob} \quad (3\text{-}27)$$

With:

L_{lob}, L_{ch}, L_{rob}: cross section length identified for the flow in the left overbank, channel and right overbank respectively

$Q_{meanlob}$, Q_{meanch}, $Q_{meanrob}$: arithmetic average of the flow between section for the left overbank, main channel and right overbank.

3.3 Data Collection and Processing

This chapter explains the collected data used to analyze flood risks in Nyabugogo river. To analyze flood risk; there is a need of collecting different set of data to perform the analysis where time series data of meteorological and hydrological are needed including soil data, land use/cover and DEM.

3.3.1 Processing of Rainfall data

Rainfall data collected from Rwanda Water and Forest Authority were daily rainfall data from 1988 to 2017 taken at Gitega station situated at -1.95 latitude and 30.06 longitude with 1516 of elevation. First of all, a visual interpretation was done to check if there is no missing data. The visual result showed that there was no missing rainfall data. By the application of Gumbel's extreme value probability distribution, the frequency analysis of recorded rainfall data was elaborated to produce the probability distribution shown by Fig 3.11 and frequency rainfall corresponding to 5, 10, 30, 25, 50 and 100 return period year shown by table 3.2.

The maximum annual rainfall of the corrected rainfall data and the results of each step to get the probability distribution were shown on Appendix1.

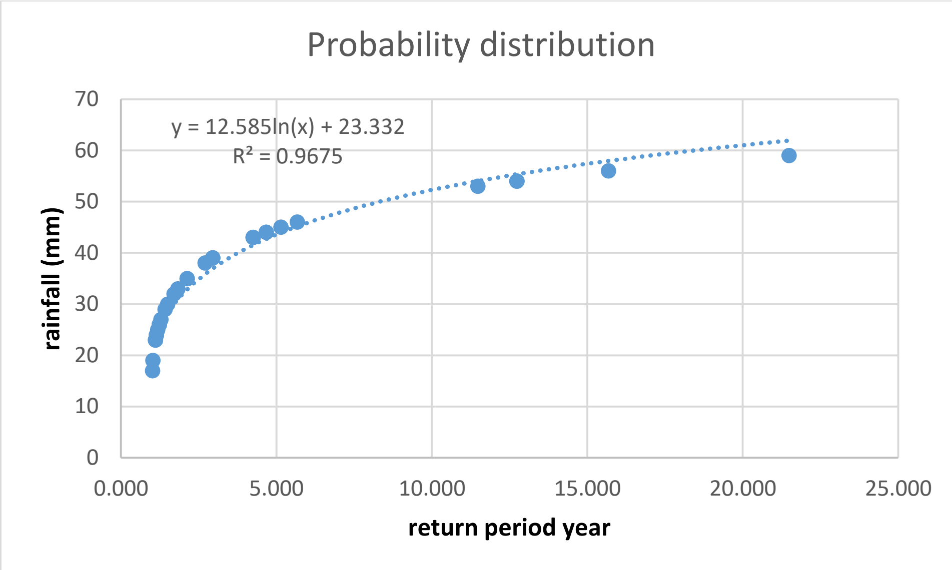


Figure 3.11: Rainfall Frequency Analysis Gumbel's Extreme Value probability Distribution.

Table 3.2: Frequency Precipitation corresponding to each return period year.

Return period T (year)	Gumbel frequency factor within each return period K_T	frequency precipitation $P_{T(mm)}$
2	-0.164	32.055
5	0.720	43.586
10	1.305	52.310
30	2.190	66.136
50	2.594	72.564
100	3.138	81.288

It is known that historical precipitation data are important for calibration and verification of model parameter basically for a real time forecasting and for the evaluation the proposed design or regulation performance (Feldman ,2000). Therefore, from the historical rainfall data collected, the rainfall of April 2016 shown at Appendix2was selected and used in calibration because it is the month of rainy season where the Country has rain almost each day.

3.3.2 Processing of River Flow Data

Discharge data were obtained from Rwanda Water and Forestry Authority (RWFA). the collected data were daily rainfall from 1988 to 2016 gauged at Nemba station situated at -1.94765 latitude and 30.02192 longitude. Basically those data were needed in calibration process to compare its hydrograph with the simulated hydrography at the outlet of the catchment and adjust the model parameter.

First of all, a visual interpretation of Nyabugogo discharge was done. It has been found that the discharge contains numerous missing data almost 10 years were missed which are 1992,1993,1994,2001,2002,2003,2014,2015. The main reasons of having those missing data was the Genocide for the year of 1992- 1994 and lack of financial capacity for the rest of years. After the visual interpretation, I decided to use the river flow data of the month of April 2016 shown at Appendix2 as they don't have any missing data and it's the month where the country has rain almost every day and it's the nearest year with all the daily discharge data.

3.3.3 Processing of Spatial data for hydrological modelling

In order to perform hydrological modelling, first of all CN grid was created by processing collected spatial data of the watershed, which are soil, land use and DEM where Arc –GIS 10.3 through its different tools was used to prepare land use and soil data and DEM needed to produce CN grid of the catchment through utility tool of HEC-GEOMS.

Secondary Arc hydro tools was used for terrain processing in order to generate different layers which are fill sink; flow direction grid; flow accumulation grid; stream definition grid; stream segmentation grid; catchment grid delineation, slope grid; drainage line polygon; catchment polygon and adjoint catchment polygon.

Third those resulting layers were used for further HEC-GEOHMS processing which are starting HMS Project, generate catchment characteristics like river length, river slope, basin slope, longest flow path basin centroid, basin centroid elevation and also integrate the CN grid to generate HMS parameter and HEC-HMS Basin model. Finally, the importation of basin model to HEC-HMS model for hydrological simulation.

3.3.3.1 Preparation of Soil data of the Catchment

Nyabugogo soil was clipped from the whole Rwanda soil data collected from Rwanda Water and Forestry Authority(RWFA). The soil hydrological group was assigned based on the available soil texture following the description showed by Table 3.3. Nyabugogo soil hydrological group are composed of A, B, C and D as shown by Fig 3.12

Table 3.3: Hydrological soil group (United state Department of Agriculture. ,1986).

HSG	Soil texture	Description
A	Sand, sandy loam or loam sandy	Low runoff potential, high infiltration rate when thoroughly wet.
B	Sand clay loam	Moderate infiltration and moderate low runoff potential.
C	Silt, silty loam ,loam	slow infiltration rate but also moderate high runoff potential when thoroughly wet .
D	Clay, Clay Loam , Silty Clay Loam, silty clay , Sand Clay.	High runoff potential and very slow infiltration as water is restricted to flow into the soil.

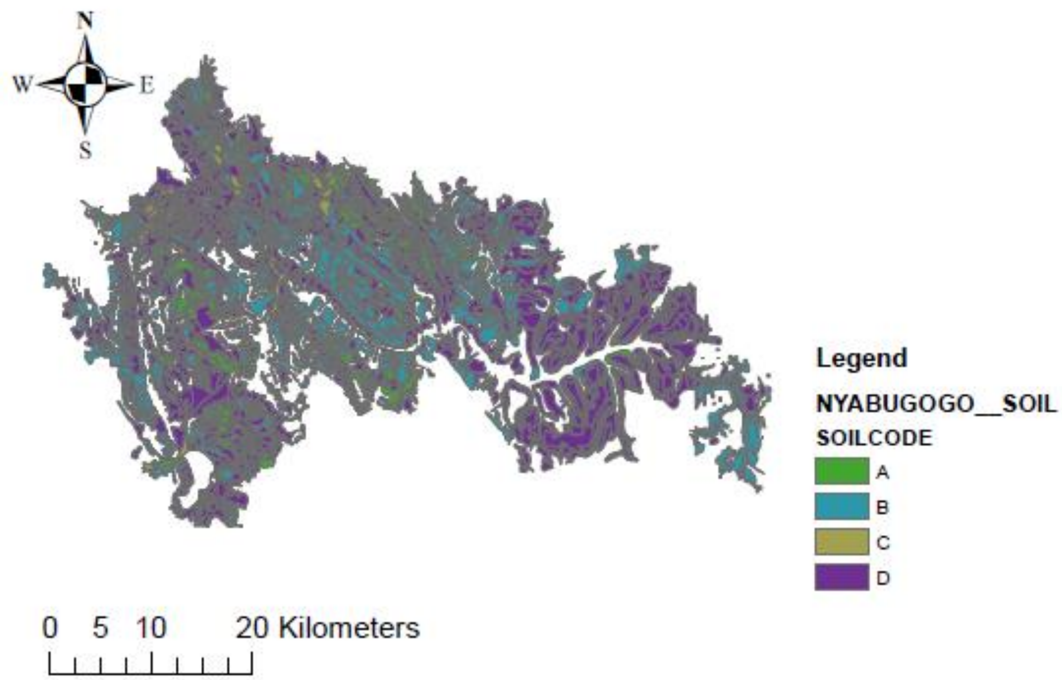


Figure 3.12: Nyabugogo Soil Hydrological Group

3.3.3.2 Preparation of land use of the catchment

Land use was collected from Rwanda Water and Forestry Authority (RWFA) with the different land use grid value as shown by Fig 3.13 each value represents land use types as shown by table III.4. The processing was done through reclassification by using spatial analyst tools found in Arc Toolbox following these steps: Spatial Analysist tools -> Reclass ->Reclassify to combine different land use resulting into Fig 3.14

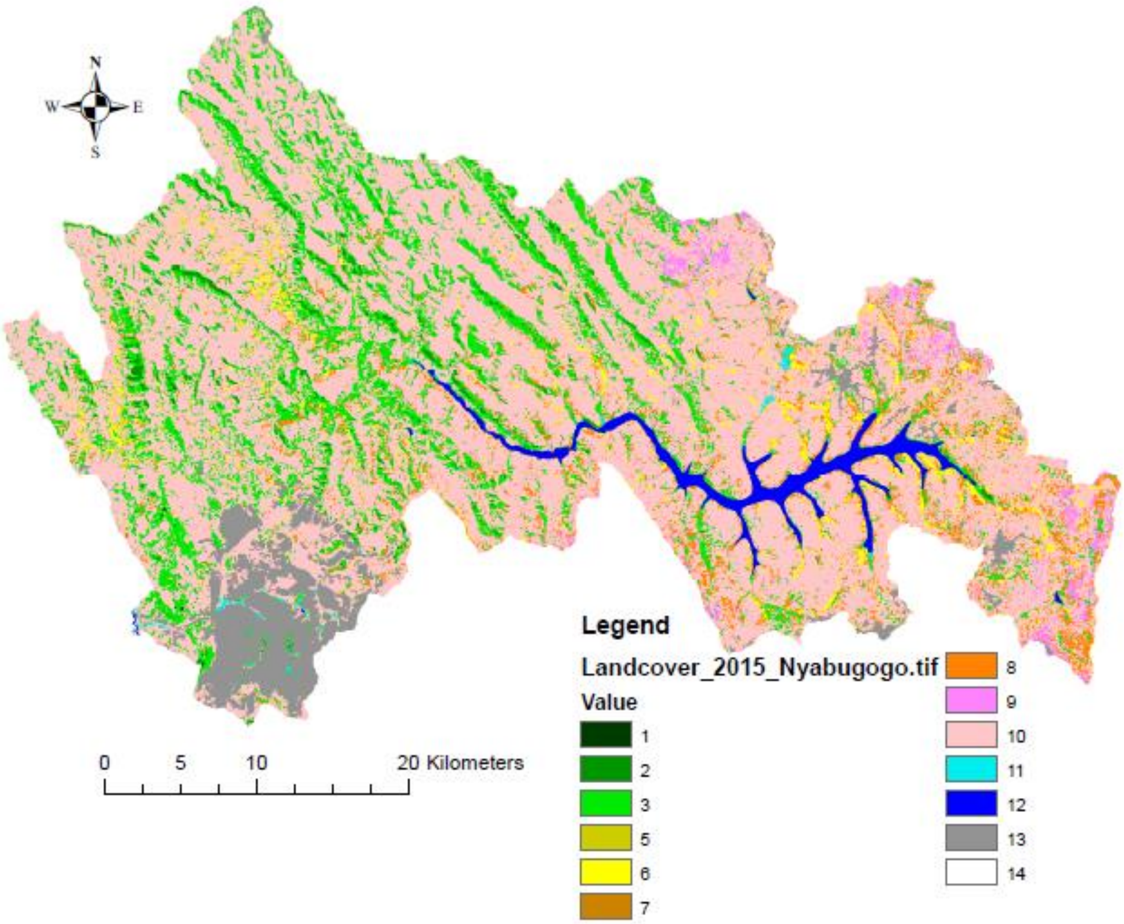


Figure 3.13: Land use grid value

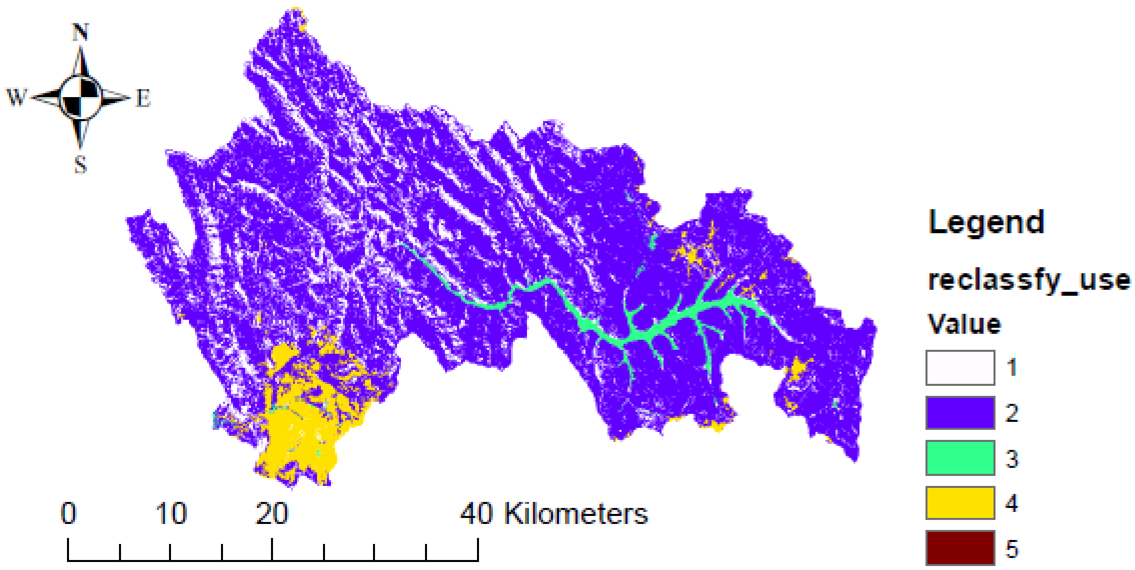


Figure 3.14: Reclassify land use

Table 3.4: Reclassified land use/cover

Original classification land use		Reclassified land use	
Value	Description	New value	Description
1	Dense forest	1	Forest
2	Moderate forest		
3	Sparse forest		
5	Closed grassland	2	Agricultural
6	Open grassland		
7	Closed Shurbland		
8	Open shurbland		
9	Perennial cropland		
10	Annual cropland		
11	Wetland	3	water
12	Water body		
13	Settlement	4	Settlement
14	Other land	5	Other land

After reclassifying land use, the next step to process Land use data was to convert the reclassified land use grid into a polygon feature class. This conversion was done using conversion tool found in Arc Toolbox following this steps: conversion tool- from raster-raster to polygon. where the input was the reclassified land use and the output was land use polygon saved as shape file.

3.3.3.3 Merging land use and soil data

Union of prepared soil and prepared land use through Analysis tools was done in Arc toolbox by clicking on Analyst Tools->Overlay->union. It was seen that the attributes from both land use and soil were combined into one attribute table. In the same attribute table of the union soil-land use, the filed land use was created and populated by grid code field.

3.3.3.4 Creation of CN-LOOKUP table

After the merging of soil and land use data, a table called CN-LOOKUP shown by table 3.5; was created based on the CN value corresponding to the land use and SHG based on the Urban hydrology for small watershed TR of 1986.

Table 3.5: CN look up table

lookup_table

OBJECTID *	LUVALUE	DESCRIPTION	A	B	C	D
1	1	FOREST	30	58	71	78
2	2	AGRICULTURAL	67	77	83	87
3	3	WATER	100	100	100	100
4	4	SETTLEMENT	77	85	90	92
5	5	OTHER	30	53	71	78

3.3.3.5 Preparation of DEM (fill grid)

The above Fig 3.4 in the in catchment characteristics demonstrate the DEM of watershed varying between 1352- 2288m. Actually watershed DEM was extracted from the DEM of the whole Country using spatial analyst tool of Arc toolbox following those step: arc tool box- spatial analyst tool-extraction –extraction by mask. To obtain fil grid, fill function of Arc –hydro tool was used.

3.3.3.6 Generation of CN grid

HEC-GEOHMS through its tool called Utility uses the merged soil-land use layer; the created CN-LOOKUP table and HDRO DEM(Fill) as input to generate CN grid. Fig 3.15 demonstrates the generated CN grid of Nyabugogo catchment varying between 30-100. Normally CN is a coefficient which reduces the total precipitation to runoff potential after losses such evaporation, infiltration, absorption, surface storage and transpiration consequently the high curve number the high runoff volume will be.

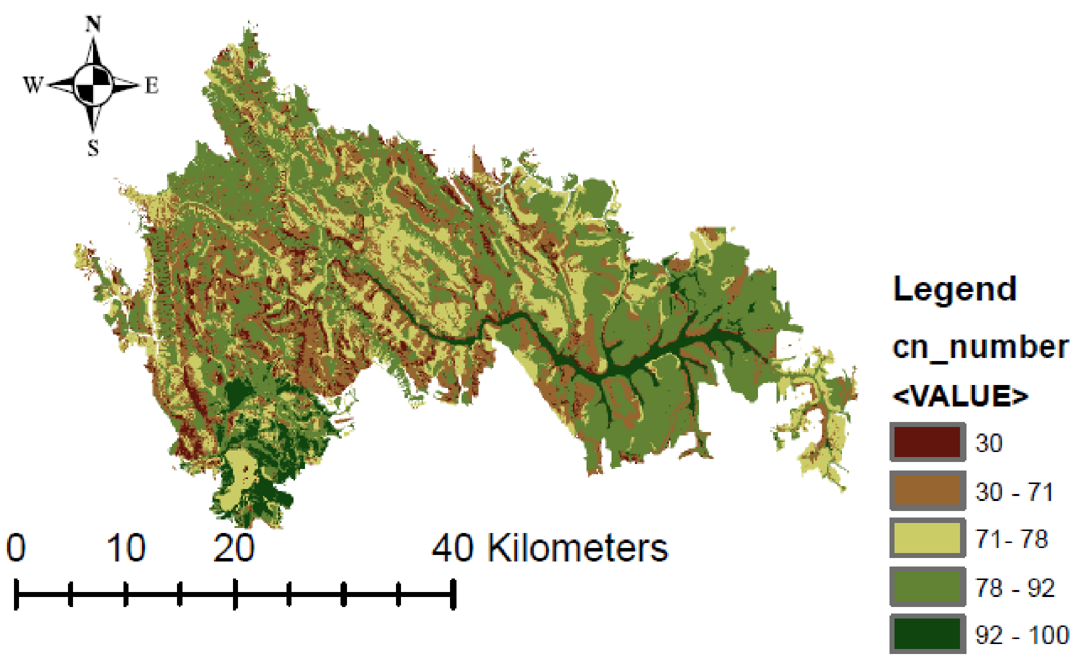


Figure 3.15: Curve Number of Nyabugogo catchment.

3.3.3.7 Terrain processing in Arc-hydro tools

Arc- hydro tools have been used to delineate watershed and get some different layers needed for further processing to perform hydrological modelling some of the produced layers are shown by Fig 3.16. Following are function of arc-hydro tools used: fill; flow direction flow accumulation; stream definition; stream segmentation; catchment grid delineation; catchment polygon processing; drainage line processing, adjoint catchment processing and slope of the watershed.

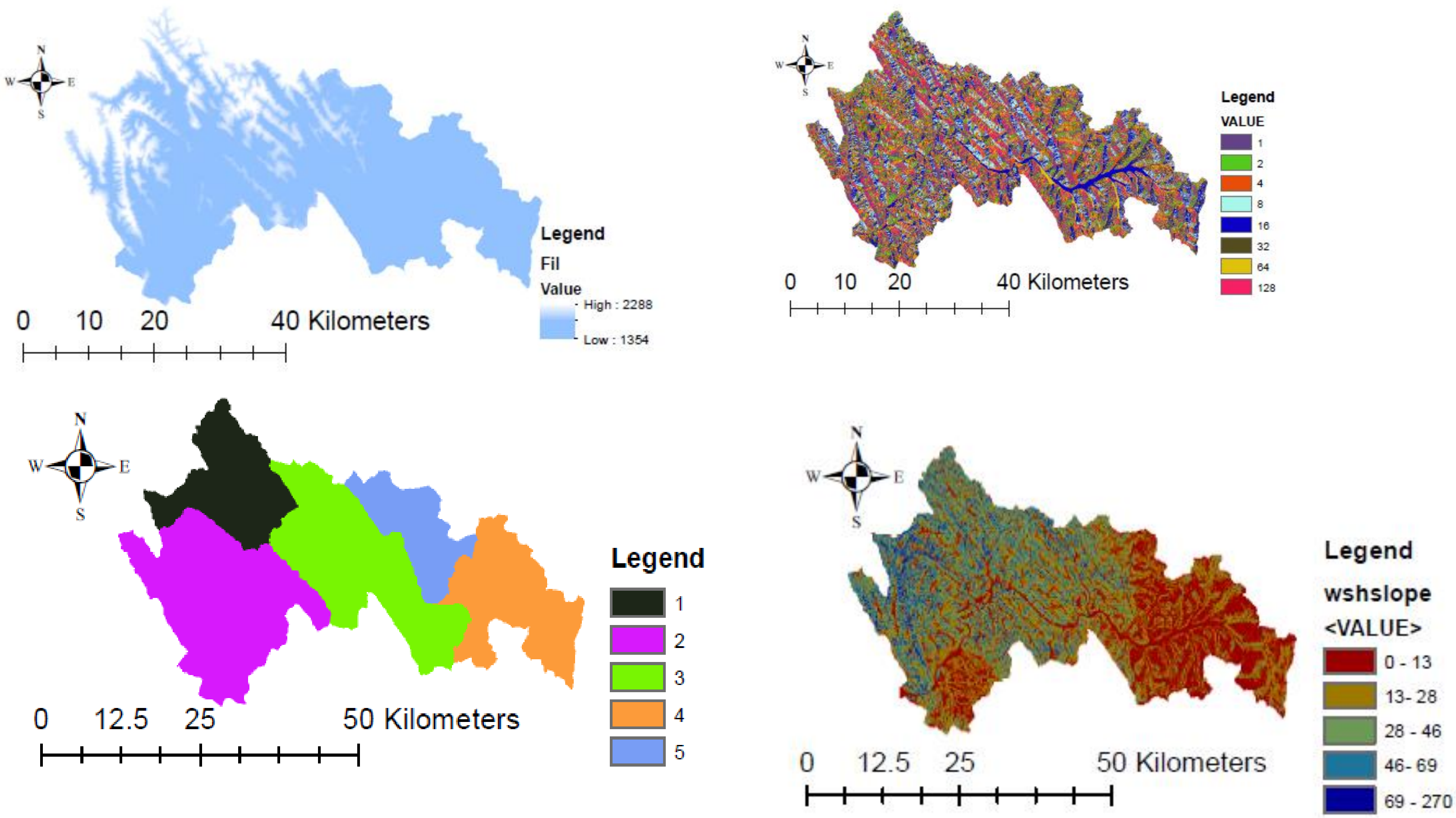


Figure 3.16: Some Results (fill, flow direction, cat, slope) from Arc-Hydro Tools

3.3.3.8 Further processing in HEC-GEOHMS tool and basin model development

The resulting layer obtained from Arc-hydro tools which are flow direction grid; flow accumulation grid; stream definition grid; stream segmentation grid; catchment grid delineation, slope grid; drainage line polygon; catchment polygon and adjoint catchment polygon were used to continue processing in HEC-GEOHMS.

- ❖ First of all, Project setup tools has been used for data management, start new project and generate a project.

  Basically for Data management function, the resulting layer from Arc-hydro tool have been settled; for Start new project function the two new feature classes which are project area and project point have been created including the definition of watershed outlet using Add project point tool depending on the location you want the outlet then for Generate project function to produce a project for the study area.

- ❖ Secondary; Basin processing tool has been used to perform merge basin function which is a process of merging two or more adjacent basins into one in case there is numerous sub-basins.
- ❖ Third action was Extraction of basin characteristics performed by different tools of Characteristics tool of HEC-GEOHMS.

  Different tools used were River length to compute the length of river segments and stores them in filled called River Len; River slope to determine the slope of the river segments and stores them in filed named slp; Basin slope to determine the average slope for each sub-basins; longest flow path to create the layer demonstrating the longest flow path within the sub-basins; Basin centroid which creates the centroid point feature class to stock centroid of each sub-basin; Basin centroid elevation to compute the elevation of each created basin centroid according to the underlying DEM then Centroidal longest flow path which creates a new feature class showing flow path for each centroid along longest path. Fig 3.17 shows the created river, sub-basin, centroid of Nyabugogo catchment.

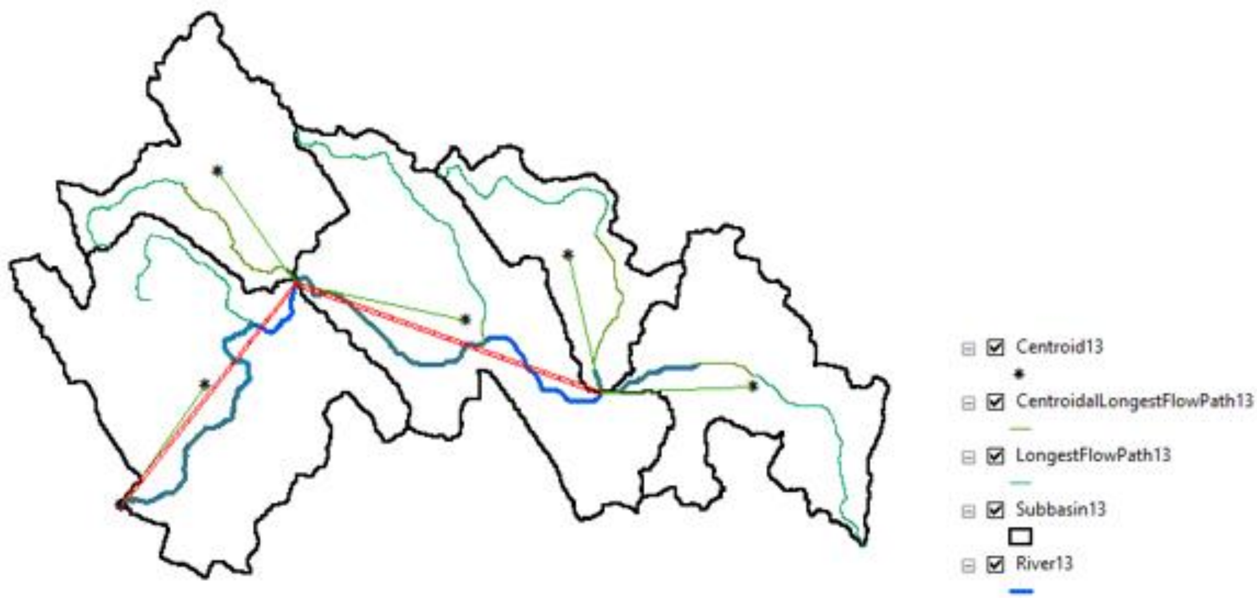


Figure 3.17: Some of the extracted basin characteristics

- After the extraction of basin characteristics, the next action was to assign the HMS input or parameters where the Parameter function of HEC-GEOHMS provides different tools to determine and assign watershed and stream parameters such as SCS curve number, time of concentration, channel routing coefficients.

  Under the parameter tools, the first thing done, was Select HMS process where the methods that HEC-HMS model should use to transform rainfall to runoff have been selected and of course this may be changed inside the HEC-HMS model. Therefore, SCS for loss method to get excess rainfall from total rainfall; SCS for transform method to convert excess rainfall into direct runoff and Muskingum for channel routing method have been selected.

  Second, River auto name tool has been used to assign name to different river segments and Basin auto name tool to assign names for each sub-basin.

  Since SCS method was selected for loss and transform methods, each sub-basin must have its SCS curve number and basin lag time, to perform this; CN grid already generated was added to the map then still under Parameter tool, the Sub basin parameter from raster function has been used to extract average CN for each sub-basin from the CN grid and this made the creation of filed named Basin CN for each sub- basin then CN lag function has been selected to compute basin lag (which is the weighted time of concentration) in hours for each sub-basin and the field named basin lag was populated for each sub-basin.

Table 3.6: Some of sub-basin and river parameters

Table

Subbasin13

BasinSlope	LossMet	TransMet	BaseMet	PctImp	InitAbst	BasinCN	Rain2Y	LagMethod	Tc	BasinLag	Area_HMS
37.801865	SCS	SCS	<Null>	<Null>	<Null>	76.366386	<Null>	CNLag	<Null>	2.44562	256.3145
30.606941	SCS	SCS	<Null>	<Null>	<Null>	73.832156	<Null>	CNLag	<Null>	4.117269	493.5493
25.782276	SCS	SCS	<Null>	<Null>	<Null>	75.381071	<Null>	CNLag	<Null>	4.398979	431.6782
11.38017	SCS	SCS	<Null>	<Null>	<Null>	82.4116	<Null>	CNLag	<Null>	3.936923	295.9641
18.625006	SCS	SCS	<Null>	<Null>	<Null>	79.529908	<Null>	CNLag	<Null>	3.692914	172.6475

1 (0 out of 5 Selected)

Table

River13

HydroID	NextDownID	DrainID	Slp	ElevUP	ElevDS	RivLen
1	5	6	0.0014	1440	1438	1414.177849
2	4	10	0	1446	1446	2534.249276
3	4	9	0.0001	1447	1446	9163.610024
4	5	8	0.0002	1446	1438	36823.262607
5	-1	7	0.0023	1438	1356	35000.070683

1 (0 out of 5 Selected)

River13

Table Of Contents Table

- Creation of HEC-HMS file by HMS tool of HEC-GEOHMS.

  Under HMS tool, the First Tool named Map to HMS units has been used to convert units where the user can select the unit type for HMS unit conversion.SI has been selected for this case. Second, check data tool has been selected to check the quality of all input detests. Next, HMS schematic tool has been selected to produce GIS representation of hydrologic system using a schematic network with basin elements like nodes, links, junctions or edges including their connectivity and then the legend was added by picking Toggle HMS legend – HMS legend function. Fig 3.18 Shows the schematic view of HEC-HMS Basin model obtained and composed of five sub-basins; two reaches and one sink.

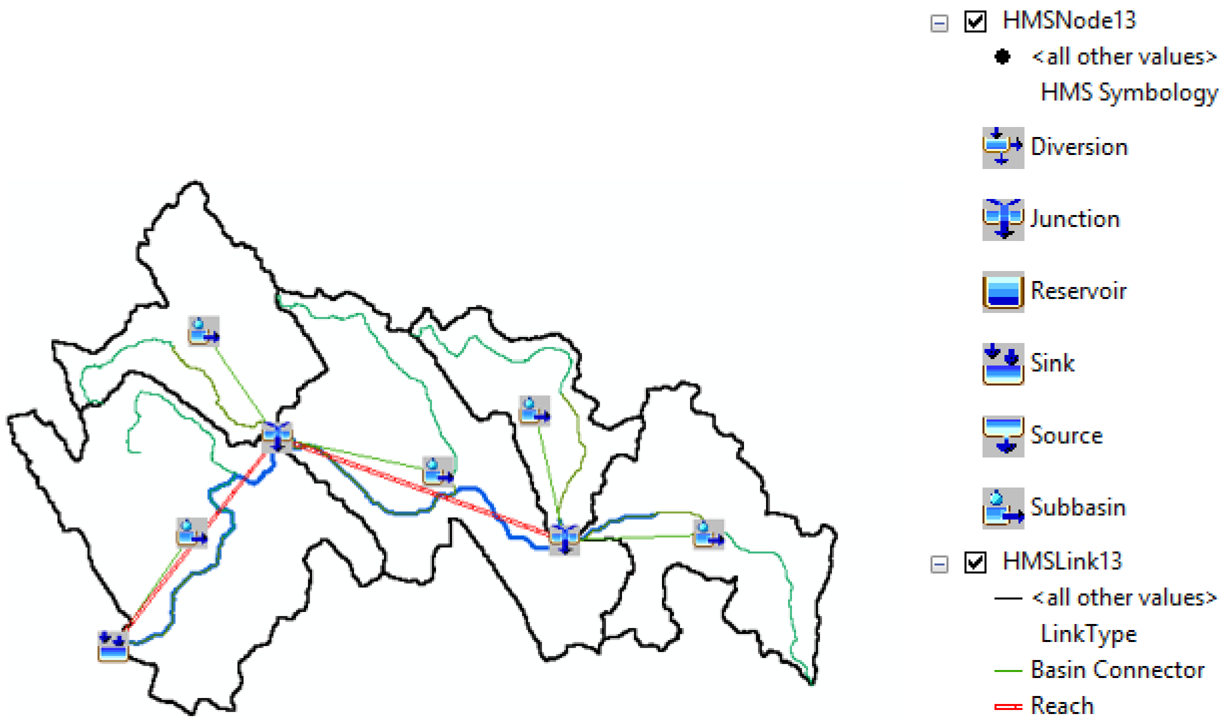


Figure 3.18: Schematic view of HEC-HMS Basin model

- ❖ After obtaining the schematic view of HMS model, the next tools used in HMS tool included: Adding coordinates tool has used to attach geographic coordinates to HMS link and HMS node features classes to not loose geospatial information when exporting the schematic to other models.; prepare data for model export to organize sub-basin and river features for export.; Background shape file tool to capture the geographic information (x, y) of sub -basin boundaries and stream alignments in a text file that can be viewed and displayed in HEC-HMS.; Basin model tools to export information on hydrologic elements like nodes and links , their connectivity and other related geographical information to a text file with basin extension .
- ❖ The last function used which is under HMS tool of HEC-GEOHMS is named create HMS project tool to copy all the created files of the project to a specific directory and create a. hms file with information on other files to be imported to HEC-HMS MODEL.

3.3.3.9 Hydrological Modelling in HEC-HMS Model

After obtaining the basin model input for HEC-HM with its basic input parameter in HEC-GEOHMS, it was opened in HEC-HMS model as shown by Fig 3.19 where the basin model has 5 sub-basins, 2 reaches, 2 junctions and one outlet

.

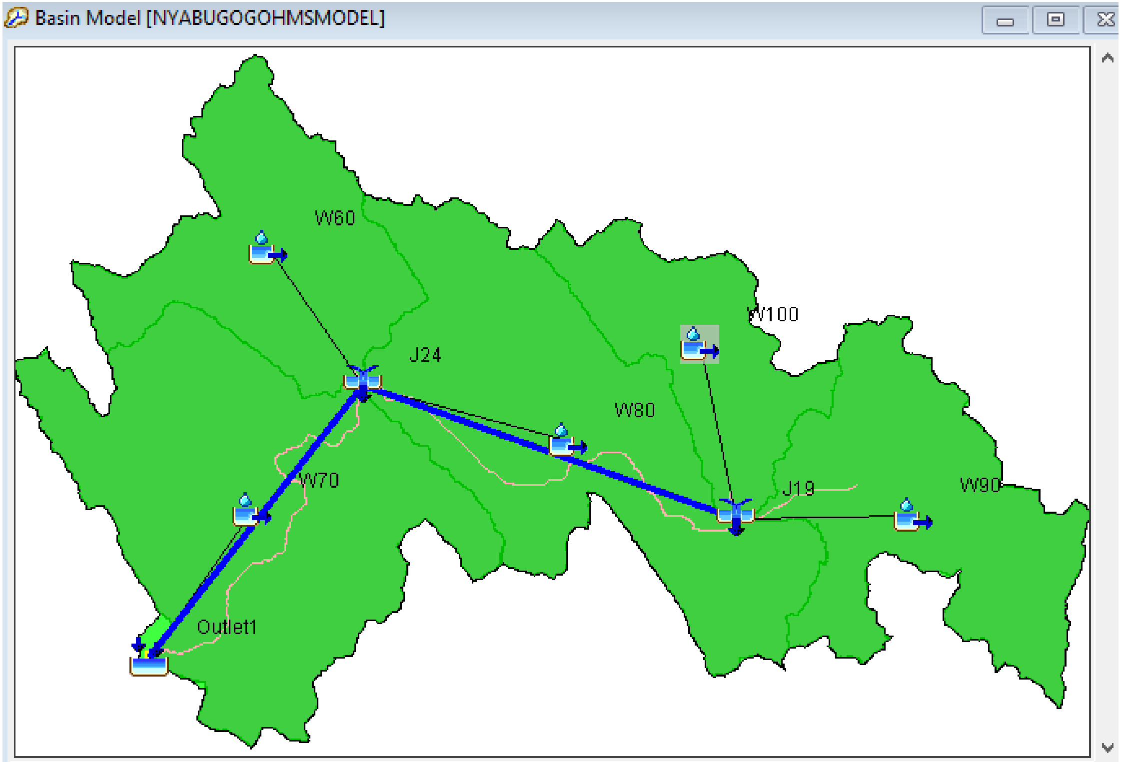


Figure 3.19: Nyabugogo HEC-HMS Basin Model

Once the basin model has been presented in the HEC-HMS model, meteorological model file has been created. Since the model need to be calibrated before the use of frequency rainfall; the time series data of rainfall and discharge for the period of 1 April 2016 - 30 April 2016 were used to calibrate the model. Hence, Meteorological model was created by meteorological model manager in the components tab of HEC-HMS, then specified hydrograph method was chosen for precipitation. To introduce time series data of rainfall and discharge, both precipitation gage and discharge gage were created by using time series data manager in the components tab and precipitation gage was linked to all sub-basin where discharge gage was linked to the outlet.

Control specification model file starting from 01April2016 till 30 April 2016 with 1-day interval was created by control specification manager in the components tab this tells the HEC-HMS model how long the simulation will take and time step to continue simulation then Simulation run was performed.

The resulting hydrographs (simulated and observed) were compared then optimization feature used to calibrate the model based on Nash –Sutcliffe efficiency as the objective function and parameter like SCS curve number –curve number scale factor and Muskingum k factor was done.

After calibration, frequency rainfall data were introduced in the model where 10, 30,50,100 return period year meteorological models were created again the same as I created the first one above, the precipitation method adopted was SCS Storm. Control specification file starting from 06June 2018 to 9June 2018 with

12 hours' time was created the same way as I created the first one above then simulation run was done for each return period.

3.3.4 Processing of Spatial Data for hydraulic modelling

This section explains how the data has been processed to produce inundation maps. It consists of three parts; the first party was pre-processing of data in HEC-GEORAS., the second part was running hydraulic analysis in HEC-RAS and the third part was post- processing of HEC-RAS results in HEC-GEORAS. The dataset required were Terrain model in grid or TIN Format and the land use of the area.

3.3.4.1 Preprocessing of spatial data in HEC-GEORAS

First of all, the DEM in grid format used in the part of hydrological modeling was converted into Triangular Irregular Network (TIN) shown by Fig 3.20, the conversion was done through Arc toolbox- 3D analyst tools- conversion tools- from raster –raster to TIN.

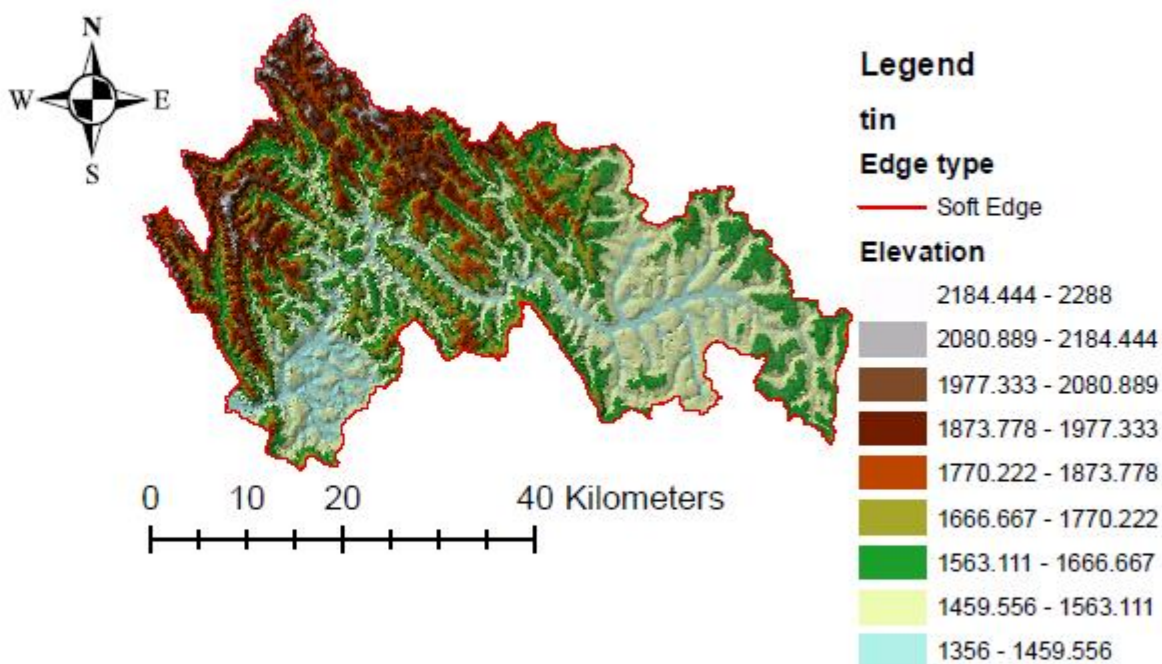


Figure 3.20: Nyabugogo Catchment TIN

To start the digitization of geometry file, the tool layer setup under RAS Geometry has been used to set layer for HEC-RAS preprocessing therefore TIN data were used to construct geometry file needed as the main input to HEC-RAS model. With the use of RAS geometry tools, empty GIS layers for stream centerline, banks lines, flow paths and XS cut lines have been created.

Following points explain how the empty layers have been digitized:

- Stream centerline necessary to assign river station for cross section and to create the river reach network for HEC-RAS was digitized from upstream to downstream following lower elevation by using the sketch tool in editor mode. After digitizing, river name and reach and other attributes was assigned using ID tool and Stream centerline attributes tool respectively.
- Banks lines which are used to differentiate the main canal from the overbank floodplain areas and also to assign cross sections properties were the next to be digitized similarly using the sketch tool in editor mode starting from one on the left of the main channel to the right side of the channel in the downstream direction
- Flow paths necessary to find the downstream reach lengths among cross sections following the main channel and over bank areas also to determine HEC_RAS attributes data such bank stations (defined as the locations which separate main river from floodplain), downstream reach (taken as the distance between cross sections) and the Manning number. were digitized starting from left to right in the downstream direction. After digitization, the designation (left, channel and right) of each flow path was assigned using Select flow path and assign line type attributes tool.
- Cross sections XS cut lines used to extract elevation data from the terrain in order to form the ground profile across the channel flow and also the intersection of cross section with other RAS layers like stream centerline were digitized using Construct XS cut lines tool then edit some of them to make sure no cross section cross each other. Actually they are digitized from the left overbank to right overbank in downstream direction, crossing each of the three flow path lines (_left, channel, right) and two bank station once time and also they must be perpendicular to the direction of the flow without crossing each other.
- HEC-GEORAS provide the option of extracting roughness coefficient value from the available land use since the roughness coefficient characterize the resistance to flood flows in channel and floodplains therefore extraction of manning value from the land use was by Manning 's value extract tool in RAS geometry,

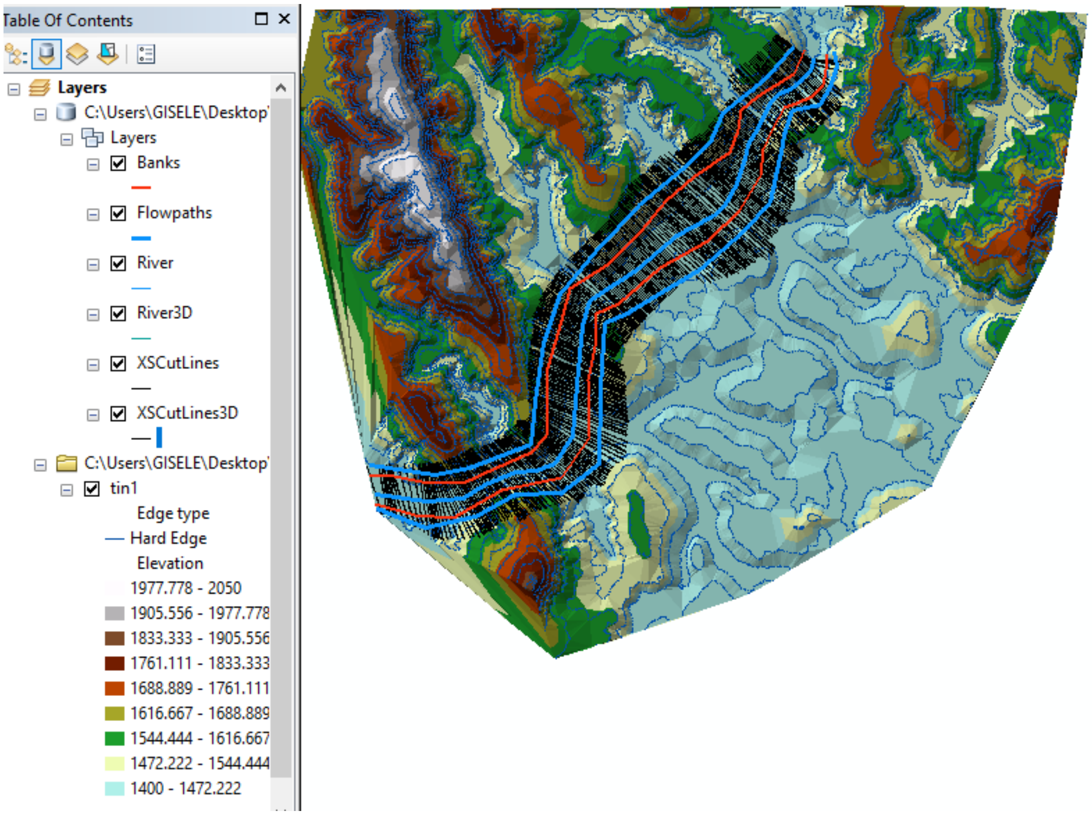


Figure 3.21: Geometry cross section of Nyabugogo river

After digitizing all necessary geometric data, layer setup tool under RAS geometry was used to check the layers to be exported, then after checking Export GIS Data tool in RAS geometry was used to export RAS geometry file to be used in HEC-RAS.

3.3.4.2 Hydraulic modelling in HEC –RAS model

b.1 Geometric file

The main purpose of hydraulic modeling was to convert the flow data obtained from hydrological modelling done by HEC-HMS into water surface elevations along the stream reach. The geometry file has been imported to HEC-RAS with its characteristics which are cross sections coordinates composed of stations, elevation and manning; downstream reach lengths and main channel banks composed of left bank and right bank.

By clicking on Edit geometry data on HEC- RAS Window, a window of geometric data appeared and on that window I clicked on file, import geometry data and then on GIS format to view the geometry cross section of the reach study area.

Fig 3.22 shows the geometry of Nyabugogo river in HEC-RAS and Fig 3.23 demonstrates the view of HEC-RAS window and the imported geometric

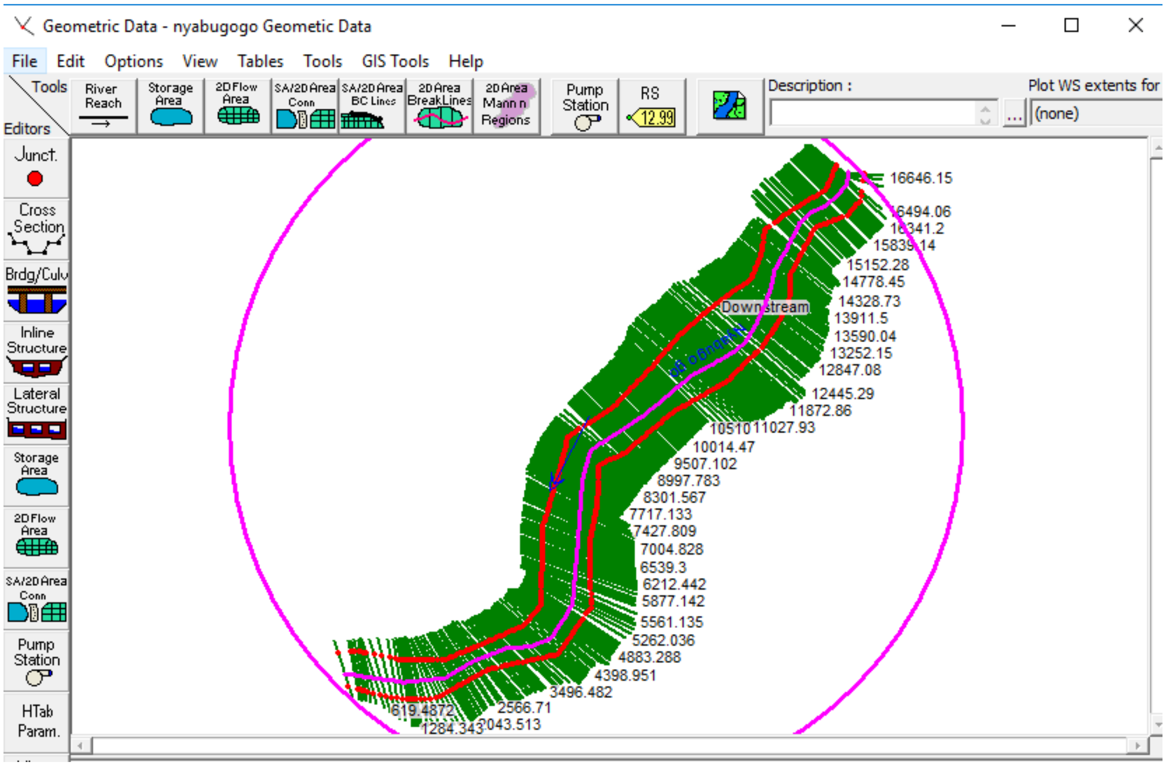


Figure 3.22: Schematic view of geometric file of Nyabugogo river.

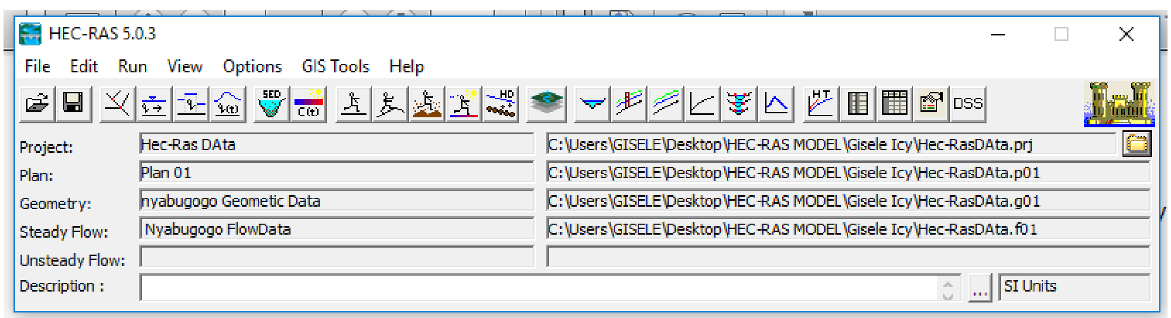


Figure 3.23: HEC-RAS view window

After the geometry data were imported to the model, the next step was quality check on data where for example the cross section with more than 20 manning value had to be edited using graphical cross section editor available on tools of geometric data window. This helped to change the distribution of manning on the banks.

b.2 Flow data

HEC-RAS model has the ability of running steady flow and unsteady flow condition. Steady flow analysis is selected for flood plain management and flood insurance studies to assess the effects of flood encroachment. (Gary,2016).) to perform steady flow analysis, three necessary information which are peak discharge, boundary condition and flow regime were applied.

The peak discharge of 10,30,50 and 100 years return period introduced to the model were obtained from hydrological modelling using HEC-HMS and they are shown by Fig 3.24

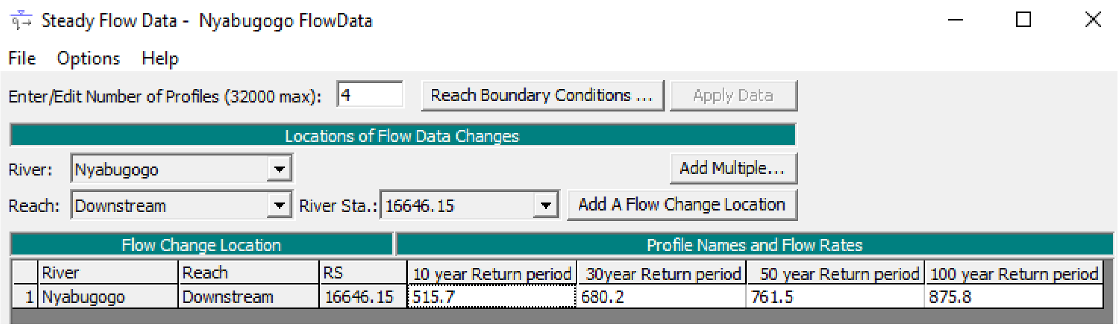


Figure 3.24: Flow data in HEC-RAS model

The flow regime selected was subcritical flow. the subcritical flow is said when the Froude number is less than one at this condition the flow is characterized by low velocity and large depths, no formation of jump can happen on this regime. Since the flow regime was subcritical, the boundary condition was needed at the downstream reach to perform upstream computation. there are four boundary condition within HEC-RAS where the user choose one of them, the downstream boundary condition chosen was normal depth with channel bed slope of 0. 0839.This channel bed slope was calculated on the digitized river (stream centerline in 3D) following those steps Customize->3D analyst->profile graph.

Also discharge information was another boundary condition which was required to each cross section to perform water surface elevation at each cross section and it was applied to the upstream as long as the flow regime was subcritical.

The next step was to run the model with subcritical flow regime and see the results then export them for further analysis (Post processing) in HEC-GEORAS. The exportation of HEC-RAS Results was done by clicking on File menu of HEC-RAS main window, then on Export GIS data; here at table appeared then I marked what profile and other information I want to export then press export data.

3.3.4.3 Post processing in HEC-GEORAS

This part consists of post – processing procedures of the computing water surface elevation to delineate floodplain for different event modelled which was performed by different tools under RAS mapping tool. Following steps have been used:

- ❖ First of all, to import HEC-RAS results, import RAS SDF file tool available on HEC-GEORAS main window was used to convert the exported HEC-RAS sdf file into XML file supported by GEORAS.
- ❖ Layer setup under RAS mapping has been used to set layer for HEC-GEORAS post processing where the user specifies the name of the new analysis; RAS GIS export XML file, single terrain TIN; the output directory (where the results of water surface and flood delineation grid will be

saved), output geodatabase (to save vector data generated in post processing), data set name and, rasterization cell size necessary used to convert TIN datasets (Terrain TIN and Water surface TINs) into grid raster format which allow grid cell computations. Rasterization cell size used here was 1m.

- ❖ Import RAS data tool was used to create preliminary data sets essentially to post processing. At this step HEC-GEORAS read the export file and create preliminary feature classes such as XS cut lines, bounding polygon, River 2D and Bank points.
- ❖ Inundation mapping / water surface generation tool was used to create water surface TIN corresponding to each profile (10,30,50 and 100 year return period). Fig 3.25 shows an example of created the water surface TIN for 100year return period

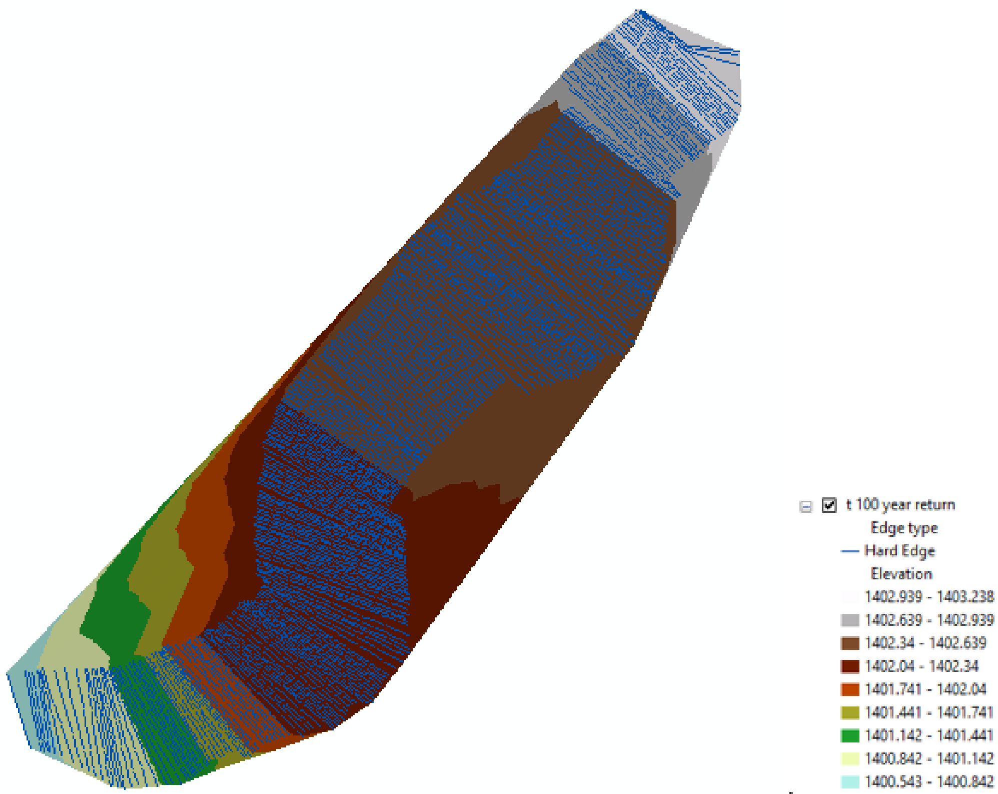


Figure 3.25: Water surface TIN for 100 year return period.

- ❖ Finally, Inundation mapping/ floodplain delineation using raster tool was used to generate Floodplain polygon and water depth corresponding to each water surface profile TIN created previously

The processing of data helped to obtain the result for both hydrological and hydraulic modelling which are displayed and explained in the next chapter IV.

4 RESULTS AND DISCUSSIONS

This chap explains different factors influencing flooding on Nyabugogo river, effects of flooding and the existing management measures in the catchment. It explains the result produced from HEC-HMS, HEC-RAS model and HEC-GEORAS.

4.1 Cause and impacts of flood on Nyabugogo river

4.1.1 Causes of flooding in Nyabugogo river

The observed factors influencing flood in Nyabugogo river were meteorological factor, catchment characteristics, urbanization and informal settlement

a. Meteorological factor

One the meteorological factor contributing to flood is rainfall. It has been found that the average annual rainfall is between 1200-1400 mm and the high rainfall intensity is observed in long period of rain starting from March till May**.** Figure 4.1 shows the monthly rainfall form the year 2012 to 2017. Where rainfall is unevenly distributed in a year with the high rainfall observed during the months of March till May and September till October which are the period of long rainy season and short rainy season respectively and those period are related to the period where the flood used to take place in Nyabugogo river like the one of the of 23rd March 2013.

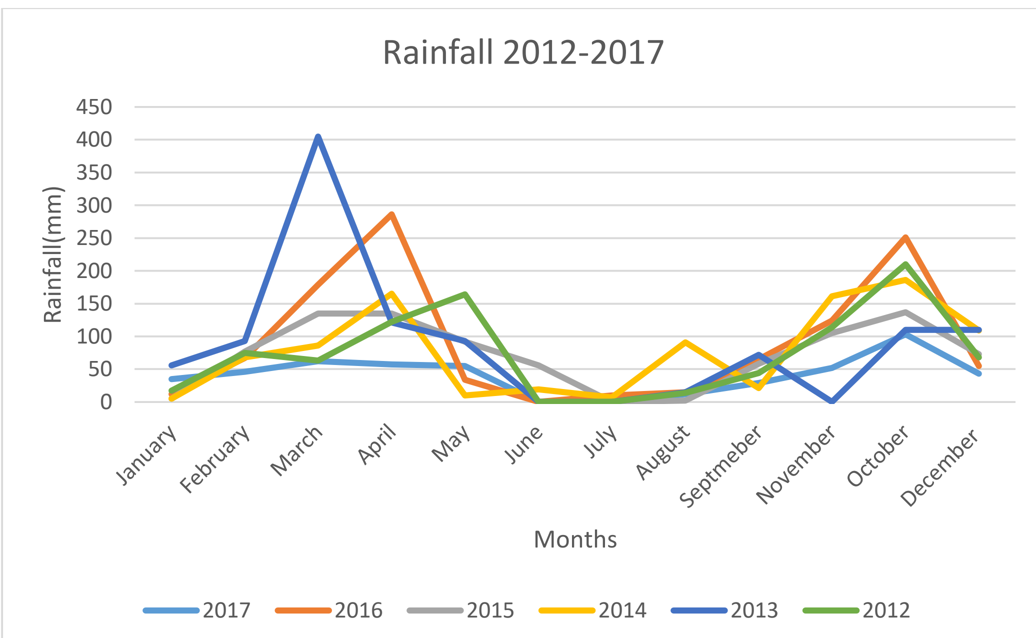


Figure 4.1: Monthly rainfall 2012-2017

b. Catchment characteristics

Watershed characteristics influencing flood in Nyabugogo river are topography, land use, soil texture. First, it has been shown on Fig 3.4 stated above that Nyabugogo catchment has Topography which vary between 1352 m to 2288 m above mean see level; on this topography, Nyabugogo river is located at lower elevation between 1352 -1526 m plus the fact that Nyabugogo river is located at the downstream of the catchment make all runoff from the hillside to flow toward it.

Secondary, Soil characteristics is also another factor influencing runoff generation hence flooding, as Fig 3.6 shown above in chap 3 demonstrate it, Texture of Nyabugogo soil is composed of clay, clay loam, sand clay, silt clay which have high runoff potential and very slow infiltration, it is also composed of silt loam and loam which have slow infiltration rate but also moderate high runoff potential when thoroughly wet.

Lastly; Land use and land cover degradation is also another factor which is influencing flood in Nyabugogo catchment apart from topography and soil; from the land use map demonstrated by Fig 3.7 in chapter 3, particularly at the downstream of Nyabugogo catchment, there is a build-up area of Kigali city with high density housing; the fact that this area of high density is located in Kigali city produce the huge amount of runoff as it is an urbanized area then the produced runoff flow toward the Nyabugogo river. Also Land degradation in Nyabugogo catchment influenced by over-grazing and collection of fuelwood leading to deforestation especially in the upland of the watershed (Water for Growth Rwanda, 2017) reduce the infiltration capacity of the soil and contribute to huge runoff generation.

c. Urbanization

The urbanization is among the factor which influence the huge amount of runoff hence flooding, due to the increase of impervious surface as those impervious surfaces are composed of roads, houses reduce infiltration capacity of the soil (Mukherjee, 2016) Since Nyabugogo river passes through Kigali city which is classed among the fastest growing cities of Africa with annual growth rate of 4.0% of population (NISR,2012)**,** this factor shows how Nyabugogo river is being flooded due to urbanization. Fig 4.2 shows how the build-up area (urbanization) has increased from 1987 to 2014, where there is a considerable increase of build- up area.

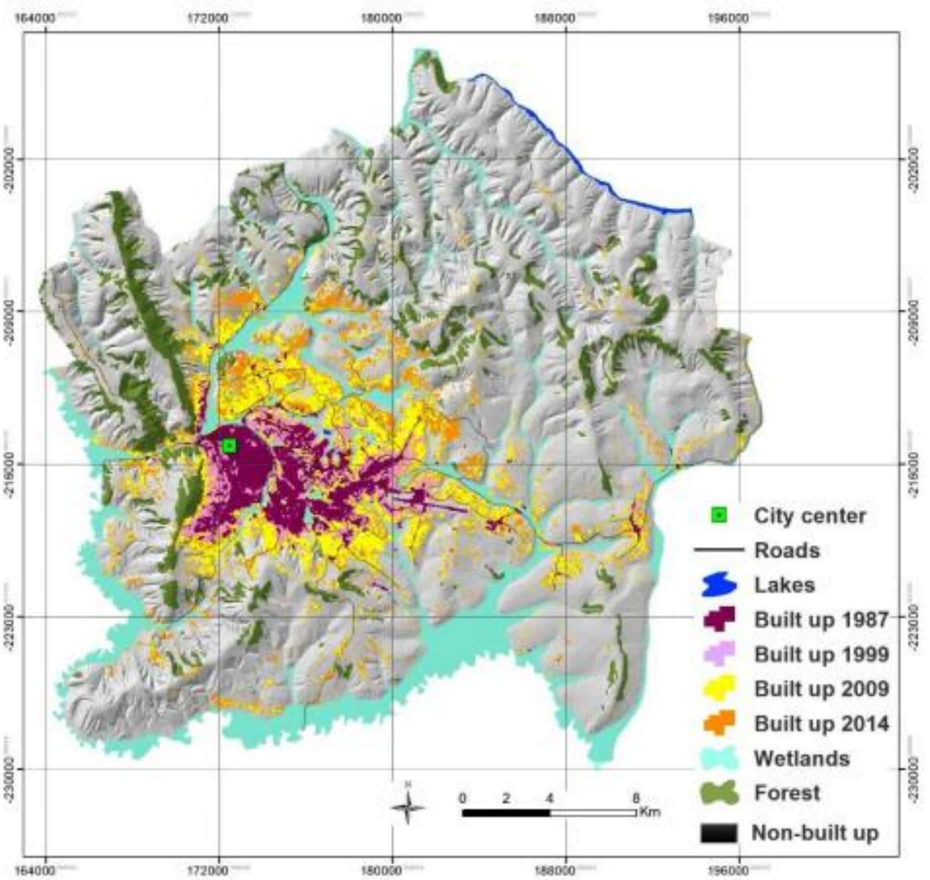


Figure 4.2: Built-up area in Kigali city from 1987till 2014 [55]

d. Informal settlement

Informal settlement is also another factor influencing flooding and landslides in Nyabugogo river especially in Kigali city since they are located on the steeper slope without storm water management technology. In 2015, the Ministry of infrastructure declared that 79% of population lives in informal settlements in Kigali city (MINENFRA, 2015).

4.1.2 Impacts of flooding of Nyabugogo river

The impacts of flooding of Nyabugogo river have been categorized in into primary; secondary tertiary impacts. The observed primary impacts were loss of people, loss of properties; the secondary impacts were transport interruption, water quality deterioration and the tertiary impacts were disturbance of economic status. Some of the cases are: In April 2006, a flood event damaged 40 houses and caused two deaths; Again Kiruhura market and RWANTEXICO factory both were located in Nyabugogo river basin before their relocation got flooded as Nyabugogo River overflowed into the shops of market and in different houses of factories reaching 1.5 m of height as shown by Fig 4.3. (Bizimana, 2010).

Figure 4.3: Flood water level observed in April 2006 (Bizimana, 2010).

In February 2013, flood affected Nyabugogo River and caused loss of four peoples who were in the car drained away by water, and it affected different socio-economic activities such as business shops and it interrupted transport modes as shown by Fig 4.4 (Munyaneza,2013); Therefore, according to new times, about 178 million francs Rwanda which is equal to 209412 USD are lost annually by Nyabugogo business due to the effects of flooding ((REMA,2009)**.**

Figure 4.4: A man carrying a lady across the flood area and the car damaged by flooding water (Munyaneza,2013)

4.2 Existing management measures of flood in Nyabugogo catchment

Currently the Rwanda Water and Forestry Authority through its Department of Integrated Water Resources Management has elaborated the program called Nyabugogo catchment plan 2017-2023, this program is intended to develop the catchment in order to meet water demand in terms of quantity and quality needed for socio economic activities and minimize water related disasters. It is in this line that different activities within the aim of land scape rehabilitation, land conservation and disaster risk management are being implemented.

Table 4.1: Existing flood management measures in Nyabugogo catchment (Water for Growth Rwanda. (2017).

Target	Measures	Location
Land rehabilitation and land conservation	Afforestation and landscape restoration	Gicumbi, Rulindo, Gatsibo, Rwamagana and Kayonza
	water ponds to collect water from road drainage and settlement sites	Rulindo
	Regular removal of sand and solid waste in water channel specifically in Nyabugogo channel	Nyarugenge and Kicukiro
	Buffer zone protection alongside lakes and rivers	Rwamagana, Kayonza ,Rulindo and Gicumbi
Control of the hazard risk to public infrastructure , communities and property	Construction of appropriate structure works to increase flow capacity of Nyabugogo river	Nyarugenge, Kicukiro, Gasabo
	Construction of multipurpose dam on Muhazi (flood control, irrigation and domestic water supply) which is still a project waiting to be implemented.	Gicumbi and Gasabo
	Rainwater harvesting for households and public institutions	All districts within the catchment
	Reallocation of household living in high risk zones of landslides and flooding	Rulindo , Kigali city and Gicumbi.

Some of those stated measures have been started being implemented like afforestation where 884.3 ha of Gicumbi district has benefited forest plantation; 1800 ha near the right side of the lake Muhazi dyke located at upstream of the catchment have been developed by agro forestry, construction of progressive bench and narrow cut terraces, re-afforestation, river and reservoir buffer zone protection and gully rehabilitation.

Rainwater harvesting technology is also being applied in Kigali city with 4% of household using rain water tank ,27% of households using ditches including and 2.9% households using piped away (Water for Growth Rwanda,2017)**,** it is Cleary shown that rain water tank technology is still at lower level which must be increased as it the one which is reliable compared to other used technology.

Currently there are on –going projects like the construction of multipurpose dam in Nyabugogo catchment, specifically in its upstream which is intended to be used for irrigation, power generation and also flood control. The act of Reallocating household living in high risk zones of landslides and flooding is being applied in Nyabugogo catchment as where as in the other catchments of the Country. Regularly removal of sand and solid waste in the channel normally done through the monthly community activity called Umuganda which used to happen at the last surtaday of each month.

4.3 HEC-HMS model simulation results and discussion

This section explains the results obtained from hydrological modelling where it involves results of calibration and results of simulated discharge corresponding to 10,30,50 and 100 year return period.

4.3.1 HEC-HMS calibration results

Calibration of model is a process of setting model parameters so that the simulated results match with the observed results and it is done after making comparison between the simulated and observed runoff results. Therefore, the use of historical rainfall data and streamflow data of 1st April 2016 -30th April 2016 has produced the following hydrograph shown by Fig 4.5 at the outlet of the watershed with the peaks discharge represented by Fig 4.6.

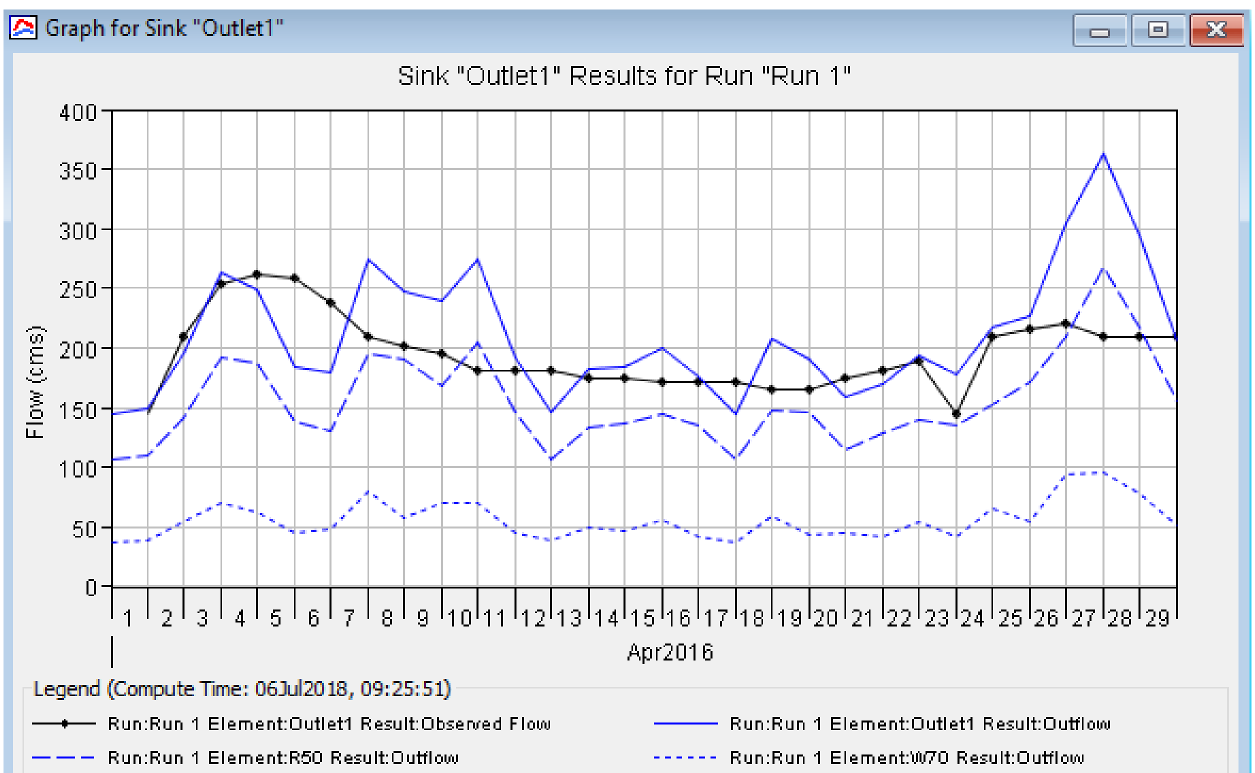


Figure 4.5: Observed and Simulated hydrograph at the outlet

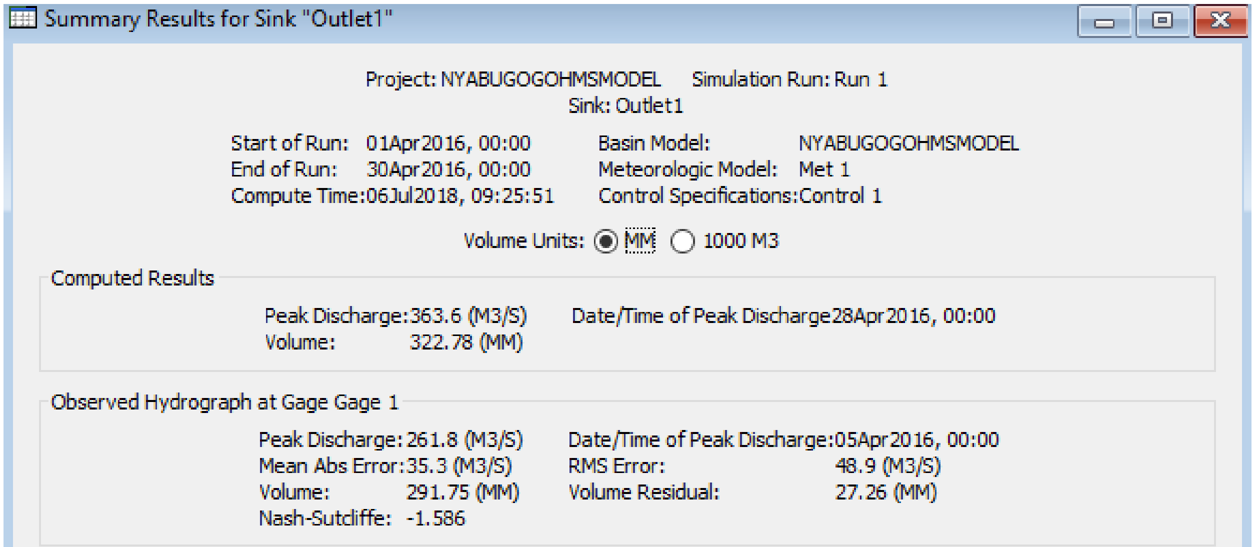


Figure 4.6: HMS simulation summary at the outlet.

From Fig 4.6 the difference between computed and observed peak discharge is 101.8 m^3/sec and Nash Sutcliffe coefficient value is equal to -1.586. Actually Nash Sutcliffe coefficient value is in the range of $[-\infty, 1]$ with greater value representing better fit between simulated and observed data **(**Krause at el., 2005). The difference between computed and observed peak discharge was high and also even if the Nash Sutcliffe coefficient value was within the range, it was still lower. Therefore; to minimize the difference between simulated and observed discharge and increase the value of Nash Sutcliffe coefficient; Calibration was done by using optimization feature of HEC-HMS model which allows multiple parameter calibration at the same time. SCS curve number –curve number scale factor and Muskingum parameters were selected for calibration. Fig 4.7; Fig 4.8 and Fig 4.9 shows the results of optimization process.

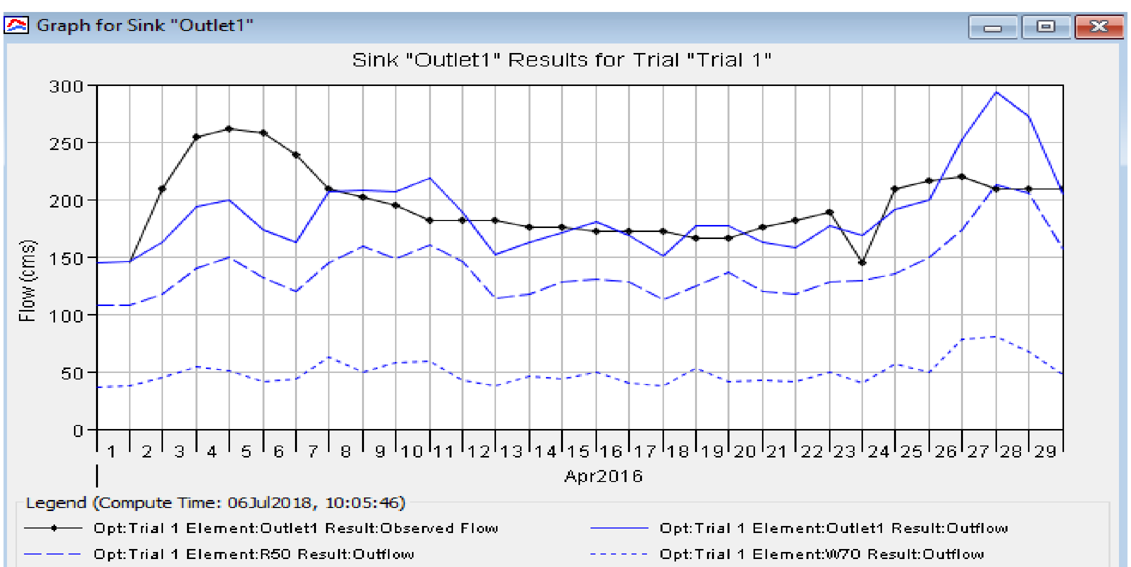
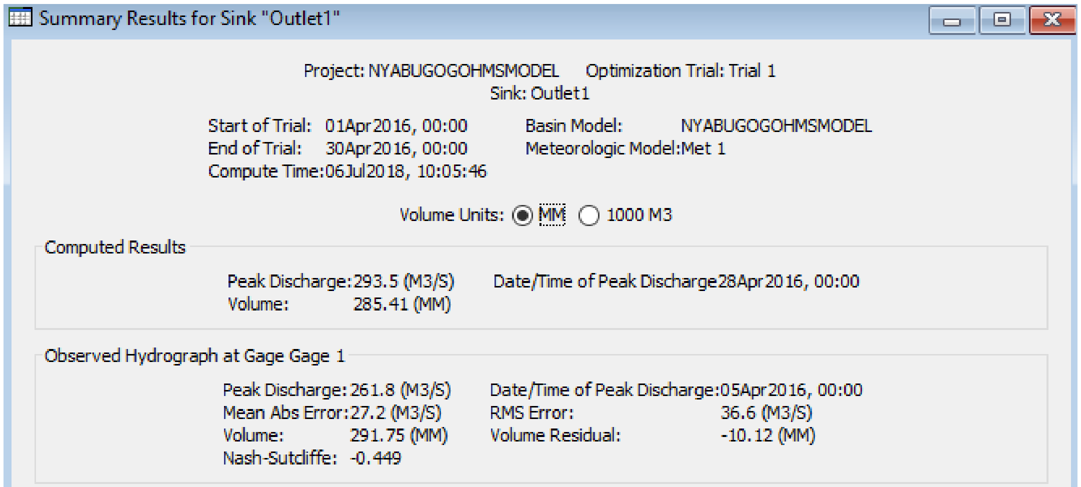


Figure 4.7: Observed and Simulated hydrograph of calibration process



Summary Results for Sink "Outlet1"

Project: NYABUGOGOHMSMODEL Optimization Trial: Trial 1
Sink: Outlet1

Start of Trial: 01Apr2016, 00:00 Basin Model: NYABUGOGOHMSMODEL
End of Trial: 30Apr2016, 00:00 Meteorologic Model: Met 1
Compute Time: 06Jul2018, 10:05:46

Volume Units: MM 1000 M3

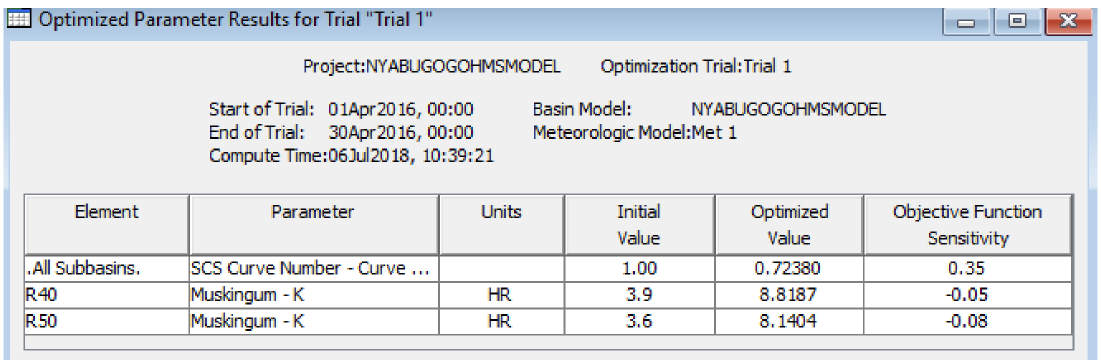
Computed Results

Peak Discharge: 293.5 (M3/S) Date/Time of Peak Discharge 28Apr2016, 00:00
Volume: 285.41 (MM)

Observed Hydrograph at Gage Gage 1

Peak Discharge: 261.8 (M3/S) Date/Time of Peak Discharge: 05Apr2016, 00:00
Mean Abs Error: 27.2 (M3/S) RMS Error: 36.6 (M3/S)
Volume: 291.75 (MM) Volume Residual: -10.12 (MM)
Nash-Sutcliffe: -0.449

Figure 4.8: HMS optimization summary at the outlet



Optimized Parameter Results for Trial "Trial 1"

Project: NYABUGOGOHMSMODEL Optimization Trial: Trial 1

Start of Trial: 01Apr2016, 00:00 Basin Model: NYABUGOGOHMSMODEL
End of Trial: 30Apr2016, 00:00 Meteorologic Model: Met 1
Compute Time: 06Jul2018, 10:39:21

Element	Parameter	Units	Initial Value	Optimized Value	Objective Function Sensitivity
.All Subbasins.	SCS Curve Number - Curve ...		1.00	0.72380	0.35
R40	Muskingum - K	HR	3.9	8.8187	-0.05
R50	Muskingum - K	HR	3.6	8.1404	-0.08

Figure 4.9: HMS optimized parameters

From Fig 4; 8, 31.7 m^3/ sec and -0.449 were computed as the difference between the simulated and the observed peak discharge and as Nash Sutcliffe coefficient respectively consequently there was a reduction of the difference between the simulated and observed discharge and increase of Nash Sutcliffe coefficient compared to the results obtained before calibration process. On the other side the date and time to peak for both simulated and observed peak discharge were different, there reason behind is the errors in discharge measurement since there was no automatic record of gauging discharge, hired people were used to make record of discharge and sometimes those people don't make record directly after the rain.

4.3.2 HEC-HMS results from frequency precipitation depth

After calibration, the frequency precipitation depths based on the specific return period were introduced in the model to simulate hydrograph and peak discharge. The introduced frequency precipitation depth was the one of 10,30, 50 and 100 year return period. Their results are shown by Fig 4.10; Fig 4.11; Fig 4.12, Fig 4.13, Fig 4.14, Fig 4.15, Fig 4.16 and Fig 4.17.

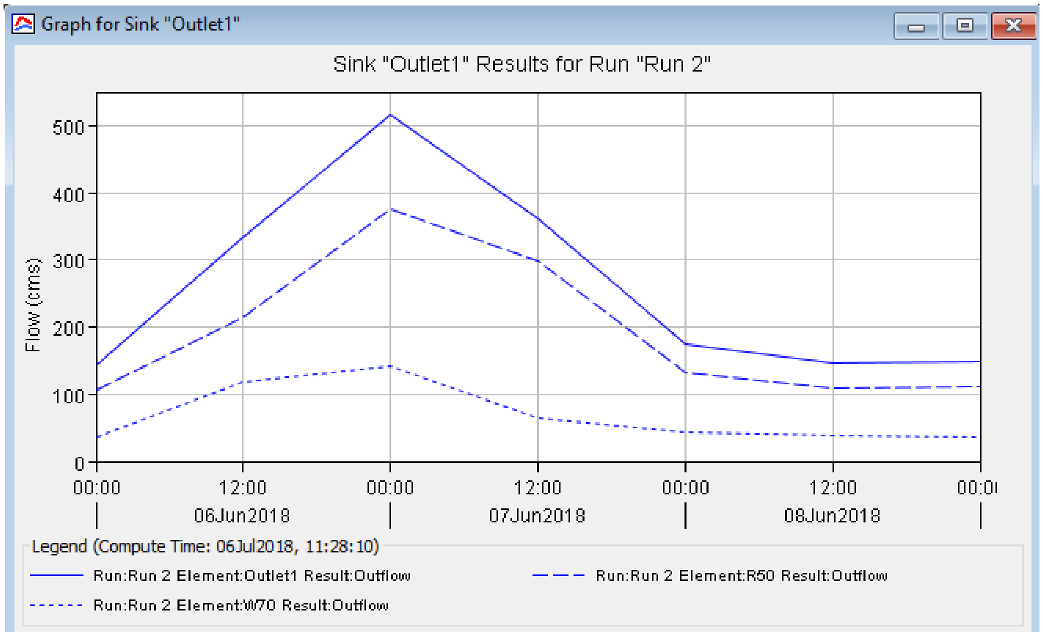


Figure 4.10: 10 year return period hydrograph at the outlet

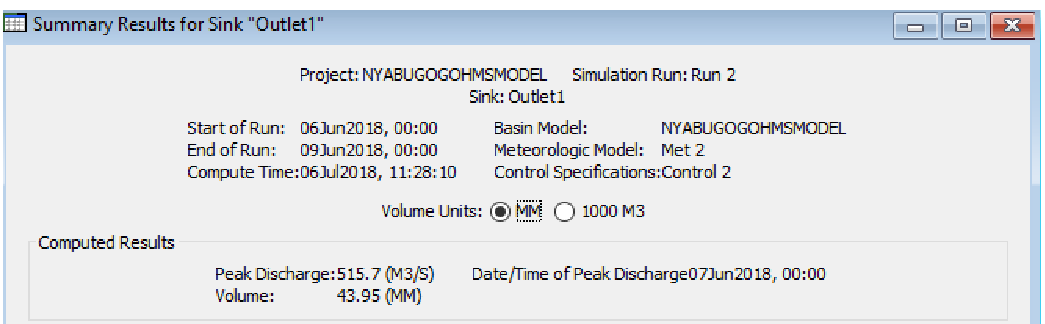


Figure 4.11: 10 years return period peak

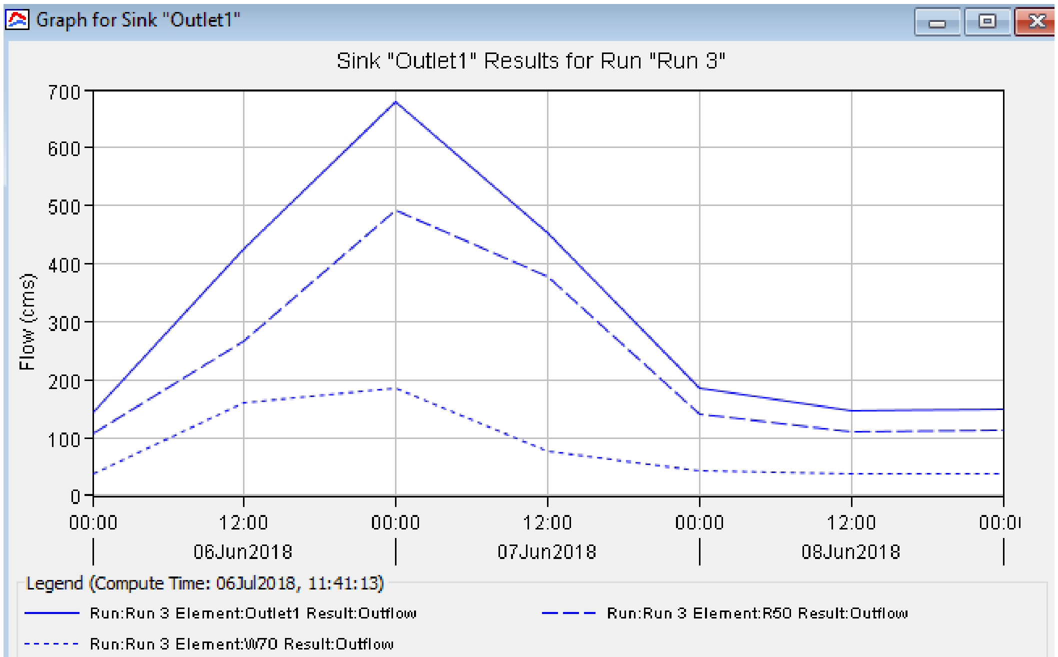


Figure 4.12: 30 year return period hydrograph at the outlet

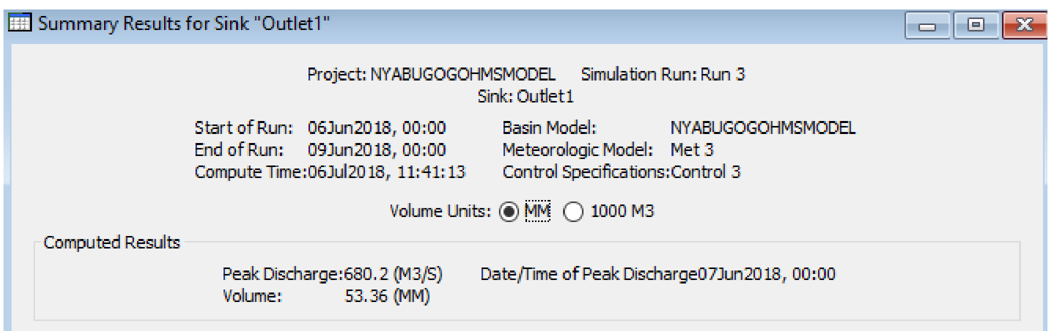


Figure 4.13: 30 years return period peak

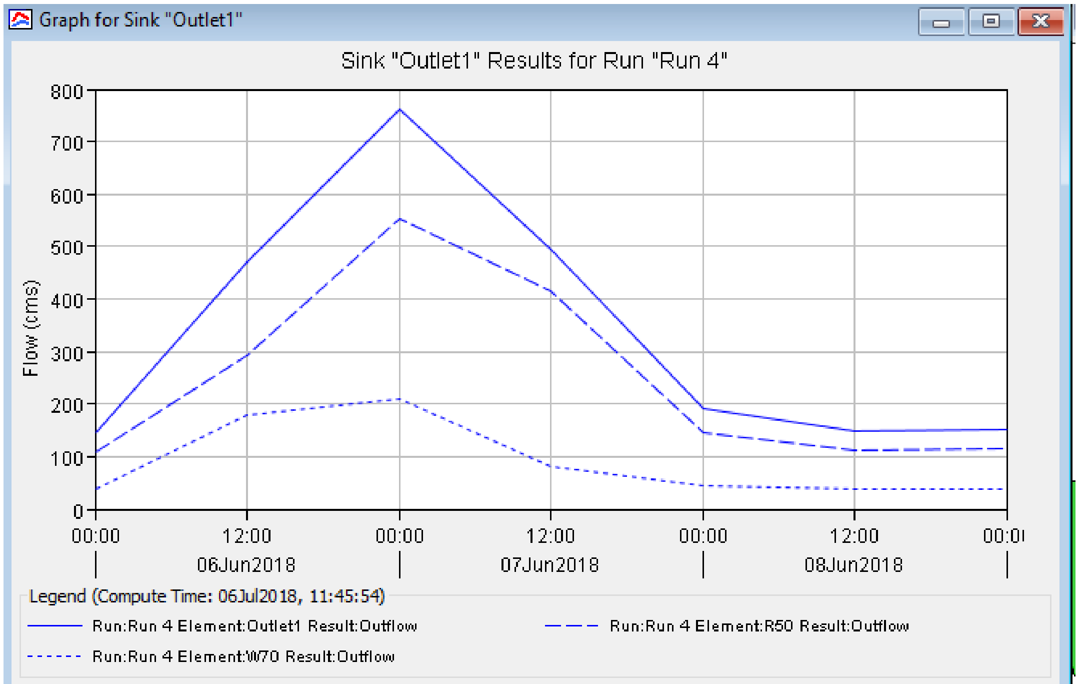


Figure 4.14:50 year return period hydrograph at the outlet

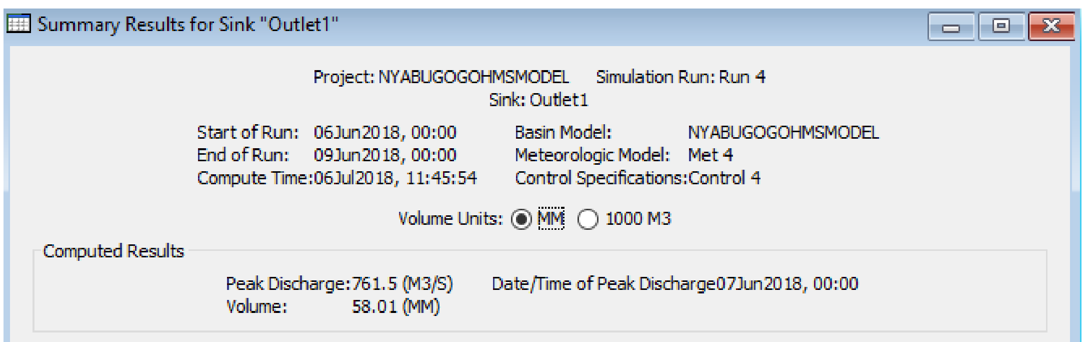


Figure 4.15: 50 years return period peak

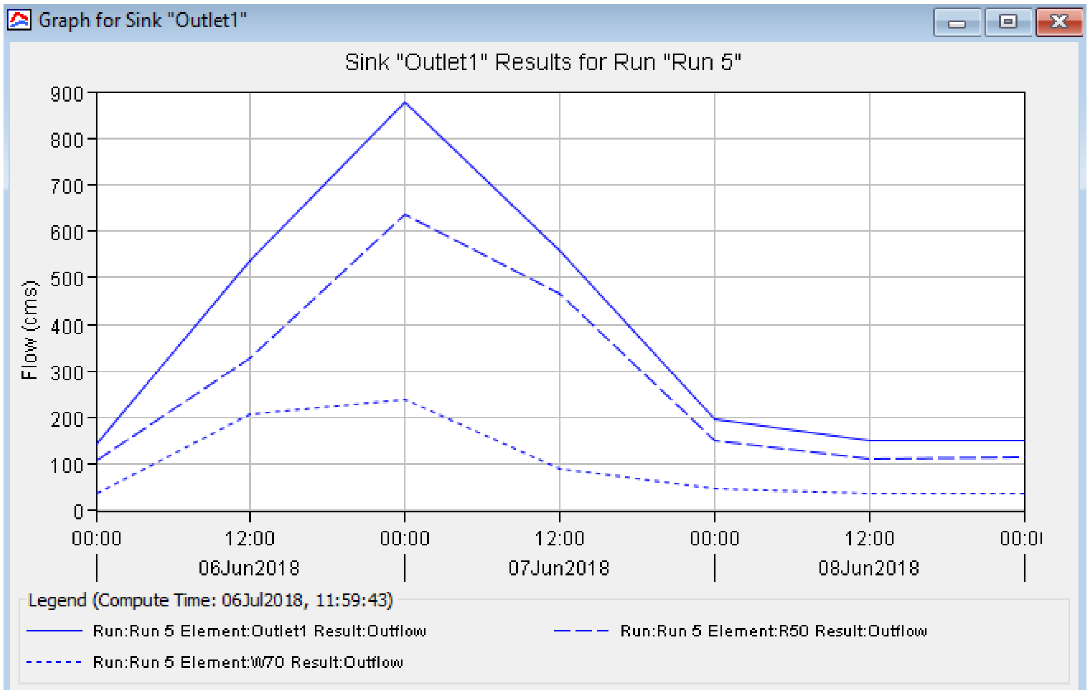


Figure 4.16:100 year return period hydrograph at the outlet

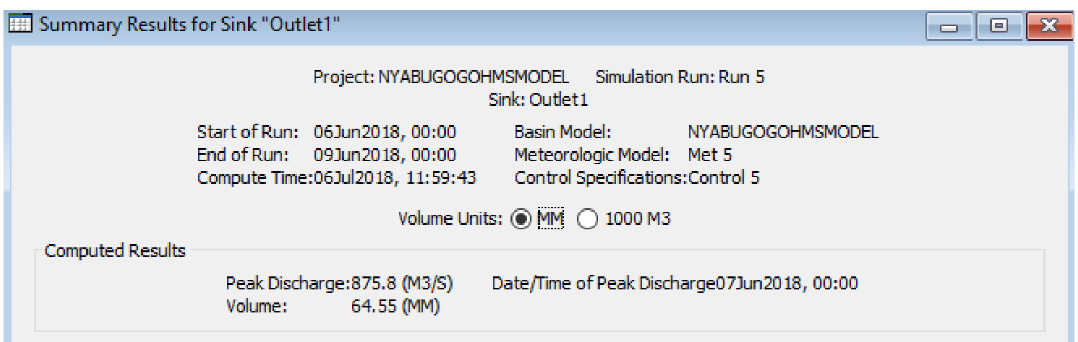


Figure 4.17: 100 years return period peak

From the above obtained simulated hydrographs for different return period, the peak discharged increased from the low return period to the high return period but the date/ time to peak were similar. Table 4.2 summarize the peak discharged for each event modelled.

Table 4.2: HEC-HMS simulated peak discharge corresponding to frequency precipitation.

Return period year	**Peak discharge (m3/sec)**
10	515.7
30	680.2
50	761.5
100	875.8

4.4 HEC-RAS model simulation and discussion results

This section describes some of the results obtained from hydraulic modelling. It involves the profiles plot and cross sections output parameters (hydraulic parameters) for 10, 30, 50 and 100 return period years respectively.

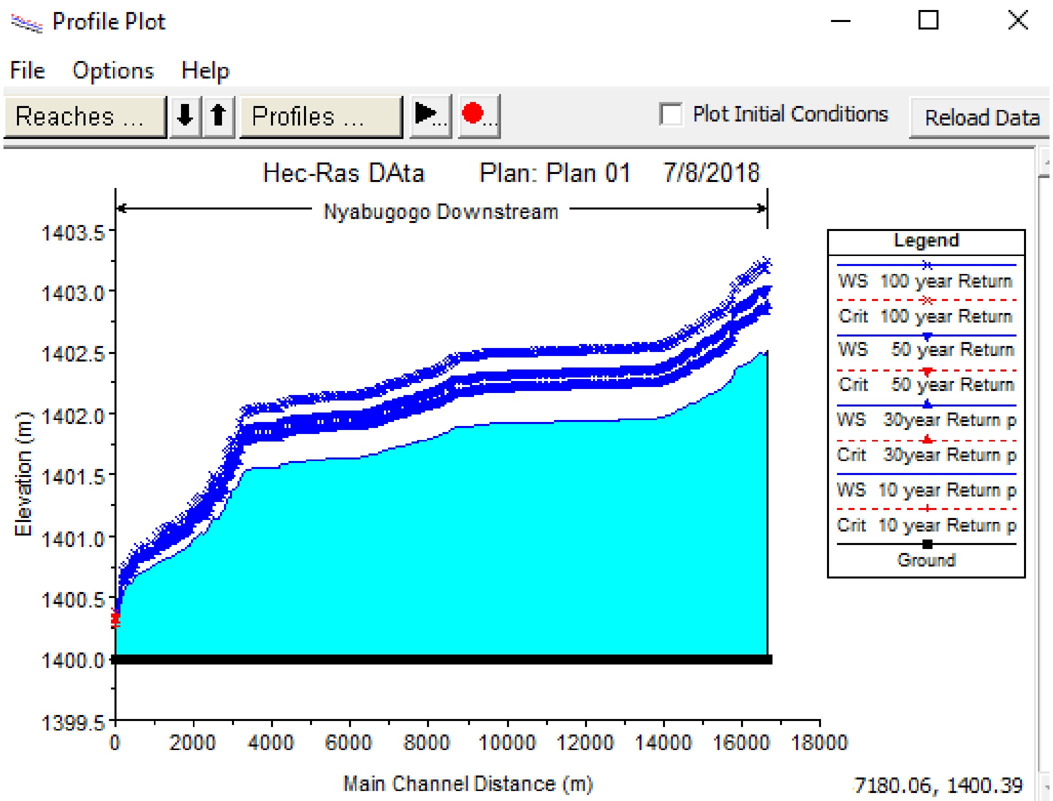
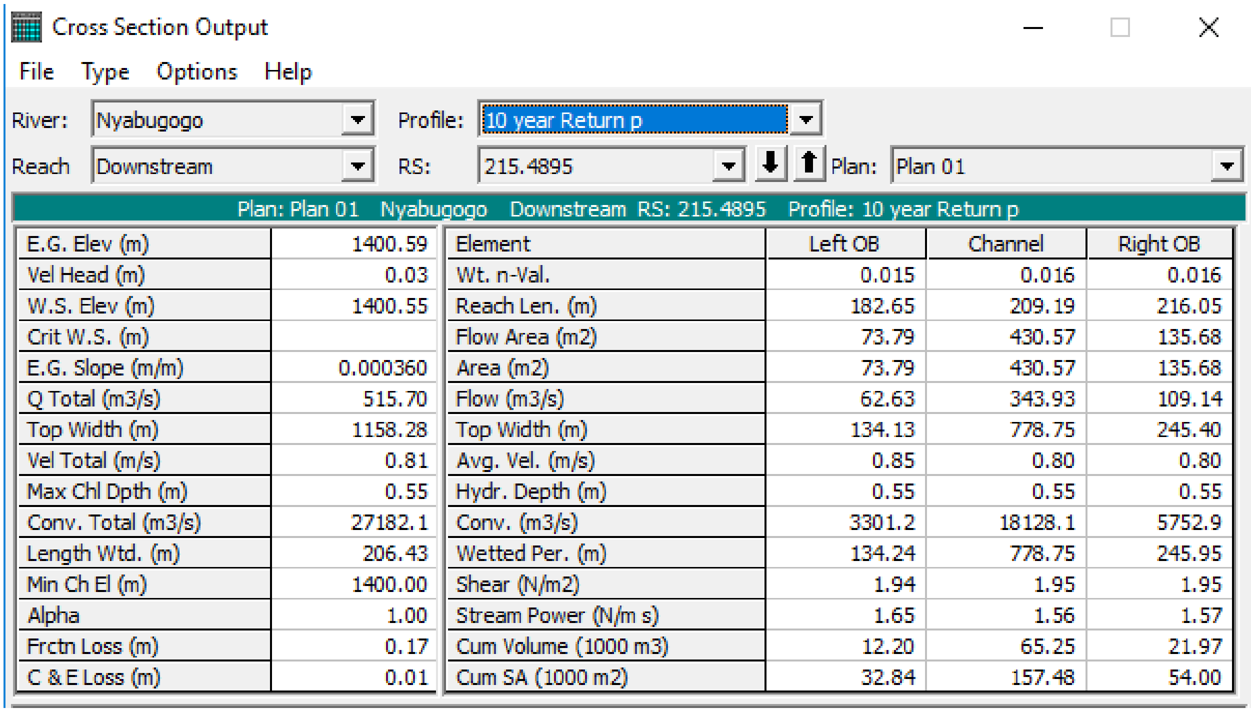


Figure 4.18: Profile plot for Nyabugogo river

Actually the profile plot represents water surface elevation line and critical depth line. Consequently, from Fig 4.18 above; the blue lines represent the water surface elevation corresponding to each return period. Water surface elevation increase slightly from upstream to downstream and from lower return period to the high return period year, Critical depth also increase slightly as the return period year increase where 10, 30,50 and 100 years return period had critical line at 1400.27 m,1400.31m, 1400.33m, and 1400.39 m respectively.

Apart from profile plot, HEC-RAS displayed hydraulic parameters for any station of the cross section of the reach with respect to each event modelled. Fig 4.19, Fig 4.20; Fig 4.21; Fig 4.22 show the hydraulic parameters for 10,30,50 and 100 year return period specifically for 215.4895 station.



Cross Section Output

File Type Options Help

River: Nyabugogo Profile: 10 year Return p

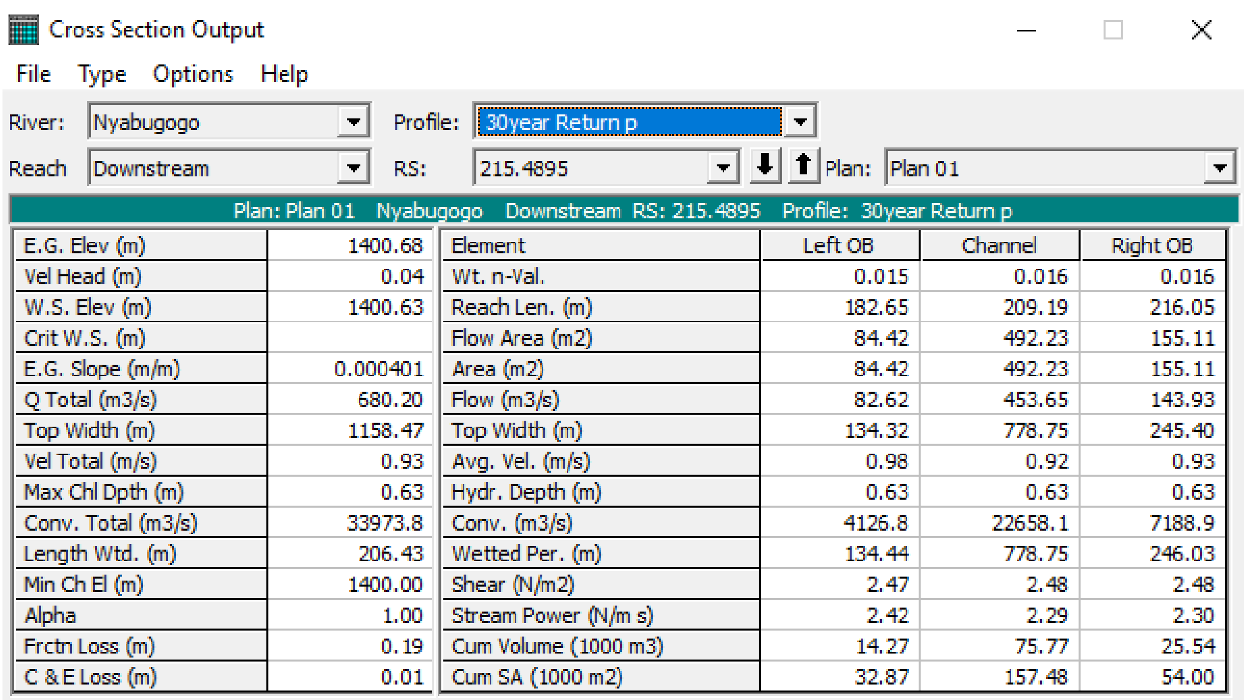
Reach Downstream RS: 215.4895 Plan: Plan 01

Plan: Plan 01 Nyabugogo Downstream RS: 215.4895 Profile: 10 year Return p

E.G. Elev (m)	1400.59
Vel Head (m)	0.03
W.S. Elev (m)	1400.55
Crit W.S. (m)	
E.G. Slope (m/m)	0.000360
Q Total (m3/s)	515.70
Top Width (m)	1158.28
Vel Total (m/s)	0.81
Max Chl Dpth (m)	0.55
Conv. Total (m3/s)	27182.1
Length Wtd. (m)	206.43
Min Ch El (m)	1400.00
Alpha	1.00
Frctn Loss (m)	0.17
C & E Loss (m)	0.01

Element	Left OB	Channel	Right OB
Wt. n-Val.	0.015	0.016	0.016
Reach Len. (m)	182.65	209.19	216.05
Flow Area (m2)	73.79	430.57	135.68
Area (m2)	73.79	430.57	135.68
Flow (m3/s)	62.63	343.93	109.14
Top Width (m)	134.13	778.75	245.40
Avg. Vel. (m/s)	0.85	0.80	0.80
Hydr. Depth (m)	0.55	0.55	0.55
Conv. (m3/s)	3301.2	18128.1	5752.9
Wetted Per. (m)	134.24	778.75	245.95
Shear (N/m2)	1.94	1.95	1.95
Stream Power (N/m s)	1.65	1.56	1.57
Cum Volume (1000 m3)	12.20	65.25	21.97
Cum SA (1000 m2)	32.84	157.48	54.00

Figure 4.19: Hydraulic parameter for 10 year return period.



Cross Section Output

File Type Options Help

River: Nyabugogo Profile: 30year Return p

Reach Downstream RS: 215.4895 Plan: Plan 01

Plan: Plan 01 Nyabugogo Downstream RS: 215.4895 Profile: 30year Return p

E.G. Elev (m)	1400.68
Vel Head (m)	0.04
W.S. Elev (m)	1400.63
Crit W.S. (m)	
E.G. Slope (m/m)	0.000401
Q Total (m3/s)	680.20
Top Width (m)	1158.47
Vel Total (m/s)	0.93
Max Chl Dpth (m)	0.63
Conv. Total (m3/s)	33973.8
Length Wtd. (m)	206.43
Min Ch El (m)	1400.00
Alpha	1.00
Frctn Loss (m)	0.19
C & E Loss (m)	0.01

Element	Left OB	Channel	Right OB
Wt. n-Val.	0.015	0.016	0.016
Reach Len. (m)	182.65	209.19	216.05
Flow Area (m2)	84.42	492.23	155.11
Area (m2)	84.42	492.23	155.11
Flow (m3/s)	82.62	453.65	143.93
Top Width (m)	134.32	778.75	245.40
Avg. Vel. (m/s)	0.98	0.92	0.93
Hydr. Depth (m)	0.63	0.63	0.63
Conv. (m3/s)	4126.8	22658.1	7188.9
Wetted Per. (m)	134.44	778.75	246.03
Shear (N/m2)	2.47	2.48	2.48
Stream Power (N/m s)	2.42	2.29	2.30
Cum Volume (1000 m3)	14.27	75.77	25.54
Cum SA (1000 m2)	32.87	157.48	54.00

Figure 4.20: Hydraulic parameter for 30 year return period.

Cross Section Output

File Type Options Help

River: Nyabugogo Profile: 50 year Return

Reach Downstream RS: 215.4895 Plan: Plan 01

Plan: Plan 01 Nyabugogo Downstream RS: 215.4895 Profile: 50 year Return

		Element	Left OB	Channel	Right OB
E.G. Elev (m)	1400.72	Wt. n-Val.	0.015	0.016	0.016
Vel Head (m)	0.05	Reach Len. (m)	182.65	209.19	216.05
W.S. Elev (m)	1400.67	Flow Area (m2)	89.36	520.85	164.13
Crit W.S. (m)		Area (m2)	89.36	520.85	164.13
E.G. Slope (m/m)	0.000416	Flow (m3/s)	92.51	507.87	161.12
Q Total (m3/s)	761.50	Top Width (m)	134.40	778.75	245.40
Top Width (m)	1158.55	Avg. Vel. (m/s)	1.04	0.98	0.98
Vel Total (m/s)	0.98	Hydr. Depth (m)	0.66	0.67	0.67
Max Chl Dpth (m)	0.67	Conv. (m3/s)	4534.9	24896.7	7898.4
Conv. Total (m3/s)	37330.0	Wetted Per. (m)	134.54	778.75	246.07
Length Wtd. (m)	206.43	Shear (N/m2)	2.71	2.73	2.72
Min Ch El (m)	1400.00	Stream Power (N/m s)	2.81	2.66	2.67
Alpha	1.00	Cum Volume (1000 m3)	15.23	80.62	27.18
Frctn Loss (m)	0.19	Cum SA (1000 m2)	32.89	157.48	54.00
C & E Loss (m)	0.01				

Figure 4.21: Hydraulic parameter for 50 year return period.

Cross Section Output

File Type Options Help

River: Nyabugogo Profile: 100 year Return

Reach Downstream RS: 215.4895 Plan: Plan 01

Plan: Plan 01 Nyabugogo Downstream RS: 215.4895 Profile: 100 year Return

		Element	Left OB	Channel	Right OB
E.G. Elev (m)	1400.78	Wt. n-Val.	0.015	0.016	0.016
Vel Head (m)	0.06	Reach Len. (m)	182.65	209.19	216.05
W.S. Elev (m)	1400.72	Flow Area (m2)	96.00	559.33	176.26
Crit W.S. (m)		Area (m2)	96.00	559.33	176.26
E.G. Slope (m/m)	0.000434	Flow (m3/s)	106.41	584.11	185.28
Q Total (m3/s)	875.80	Top Width (m)	134.52	778.75	245.40
Top Width (m)	1158.67	Avg. Vel. (m/s)	1.11	1.04	1.05
Vel Total (m/s)	1.05	Hydr. Depth (m)	0.71	0.72	0.72
Max Chl Dpth (m)	0.72	Conv. (m3/s)	5107.4	28037.1	8893.4
Conv. Total (m3/s)	42037.9	Wetted Per. (m)	134.67	778.75	246.12
Length Wtd. (m)	206.43	Shear (N/m2)	3.03	3.06	3.05
Min Ch El (m)	1400.00	Stream Power (N/m s)	3.36	3.19	3.20
Alpha	1.00	Cum Volume (1000 m3)	16.49	87.06	29.37
Frctn Loss (m)	0.19	Cum SA (1000 m2)	32.91	157.48	54.00
C & E Loss (m)	0.01				

Figure 4.22: Hydraulic parameter for 100 year return period.

According to the above figures (Fig 4.19, Fig 4.20; Fig 4.21 and Fig 4.22); the value of hydraulic parameters like Energy grade line elevation, velocity head, water surface elevation and total velocity increase slightly as the return period year increase.

4.5 Floodplain delineation results and discussion

This section represents the overall final results obtained from the process of flood risk forecasting on the reach study area including their analysis.

4.5.1 Floodplain inundation area and flood depth maps

Basically two maps for each event modelled were generated, those two maps include one map showing floodplain area or inundation coverage which indicates the extents of flooding and one map showing depths of inundation like how deeper it would be for different return period event. Therefore, following figures (Fig 4.23; Fig 4.24), (Fig 4.25, Fig 4.26); (Fig 4.27, Fig 4.28) and (Fig 4.29, Fig 4.30) Show the inundation area and water depth for 10,30,50 and 100 year return period respectively.

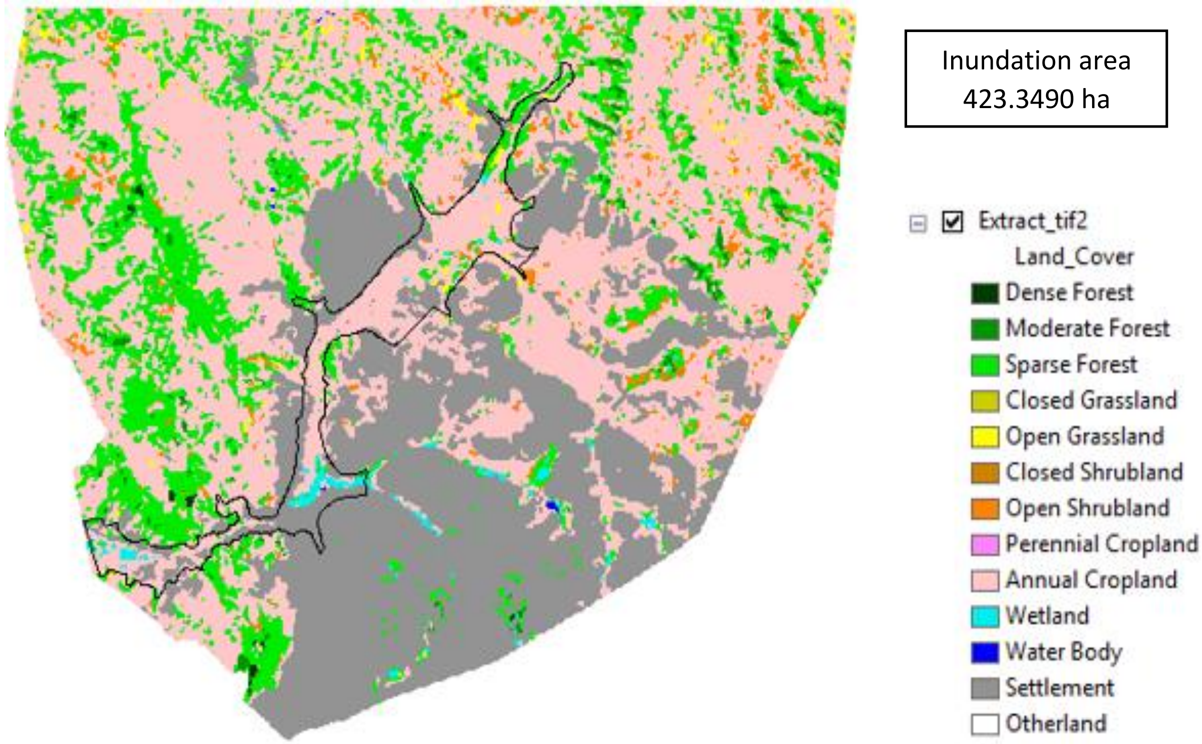


Figure 4.23: Floodplain inundation map for 10 year return period

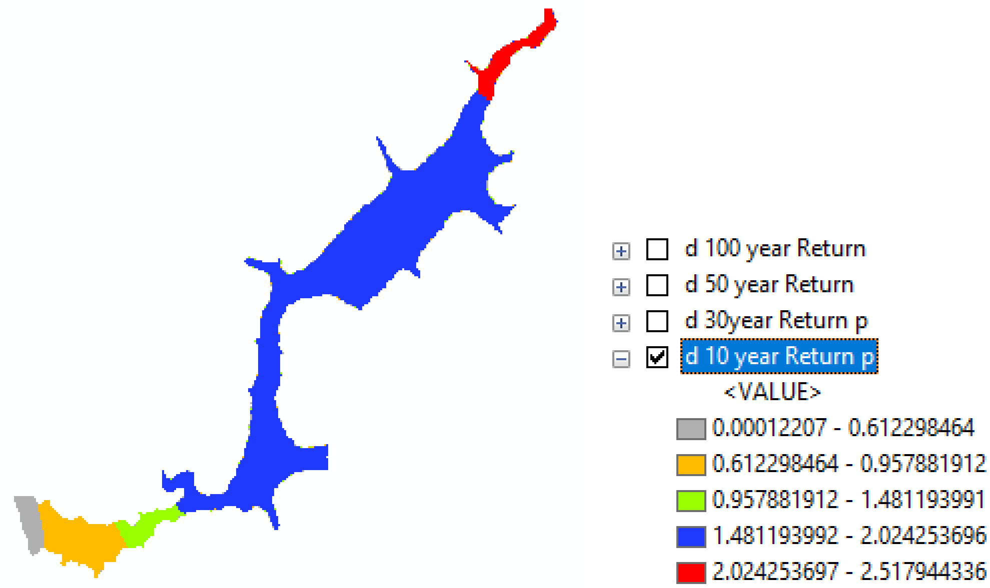


Figure 4.24: Flood depth map for 10 year return period

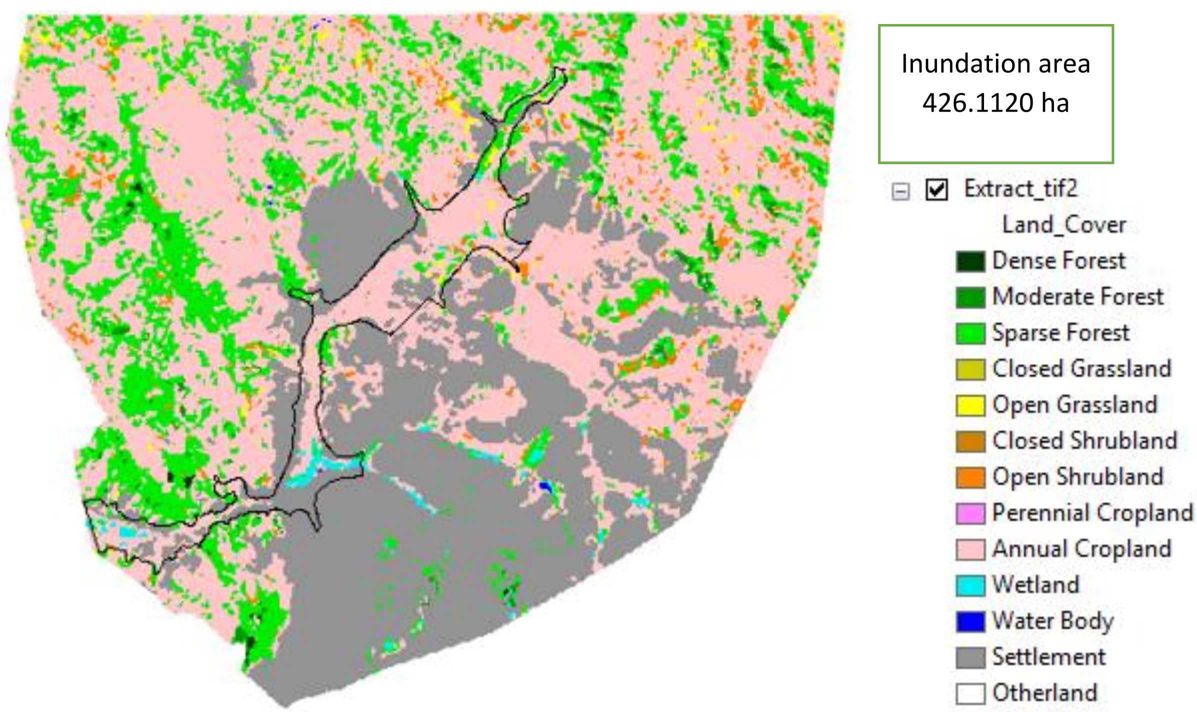


Figure 4.25: Floodplain inundation map for 30 year return period

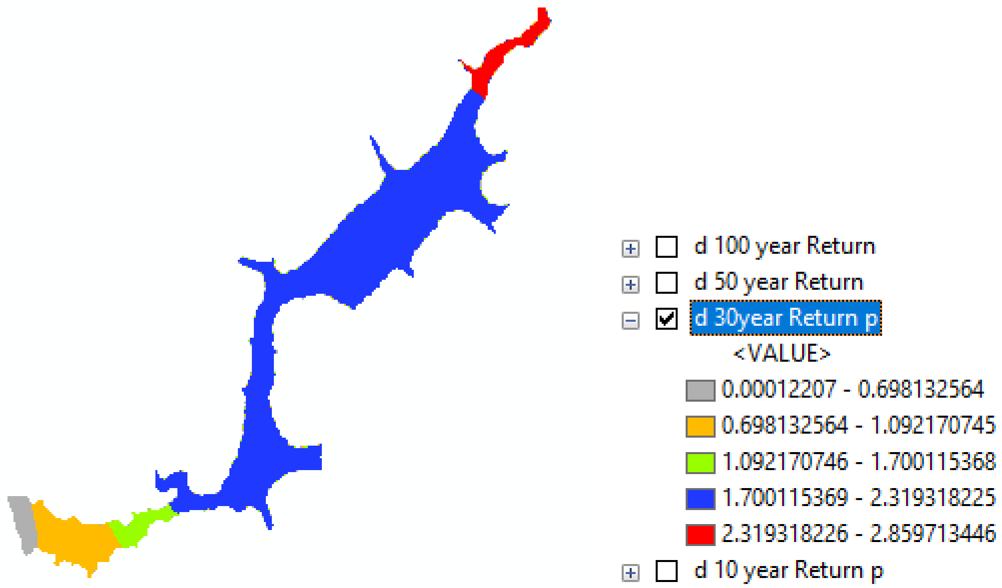


Figure 4.26: Flood depth map for 30 year return period

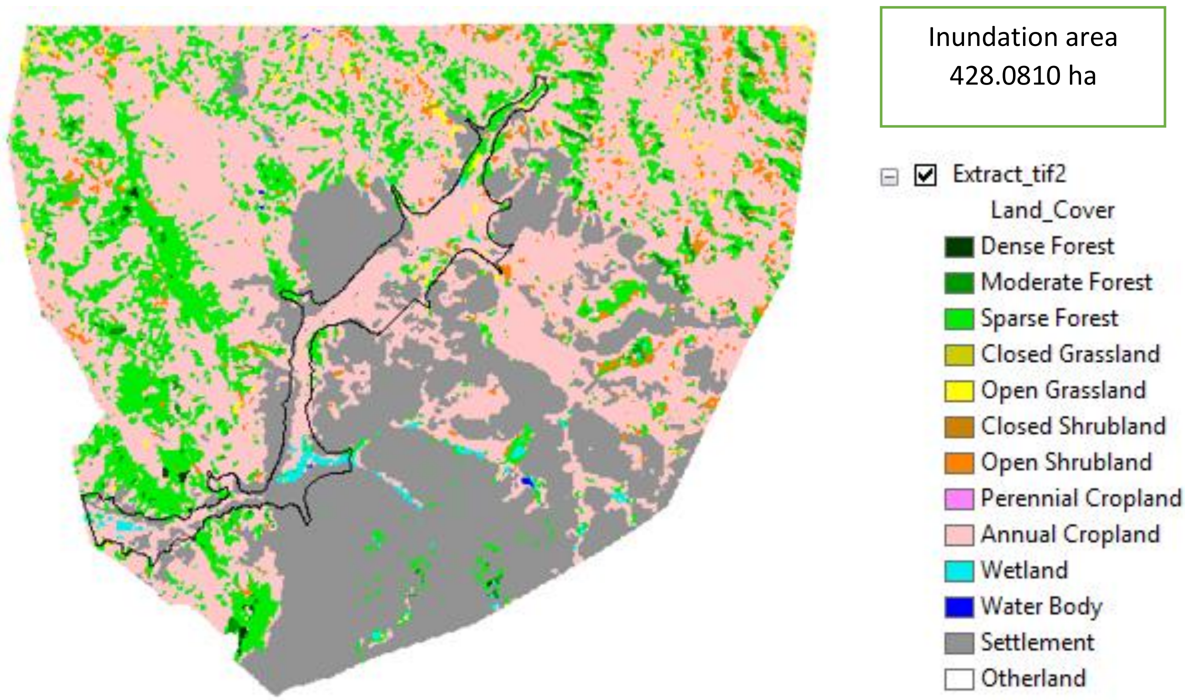


Figure 4.27: Floodplain inundation map for 50 year return period

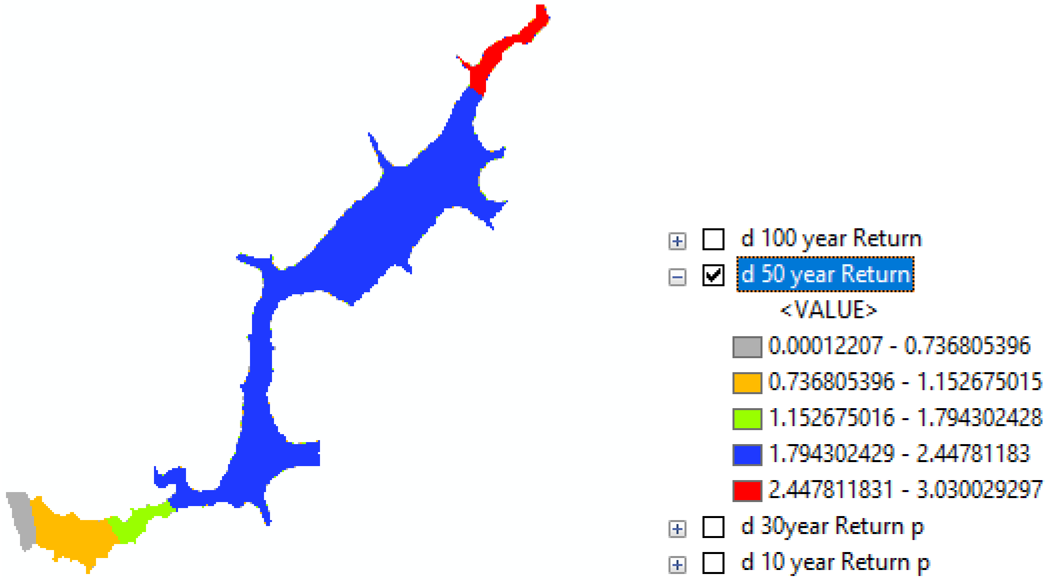


Figure 4.28: Flood depth map for 50 year return period

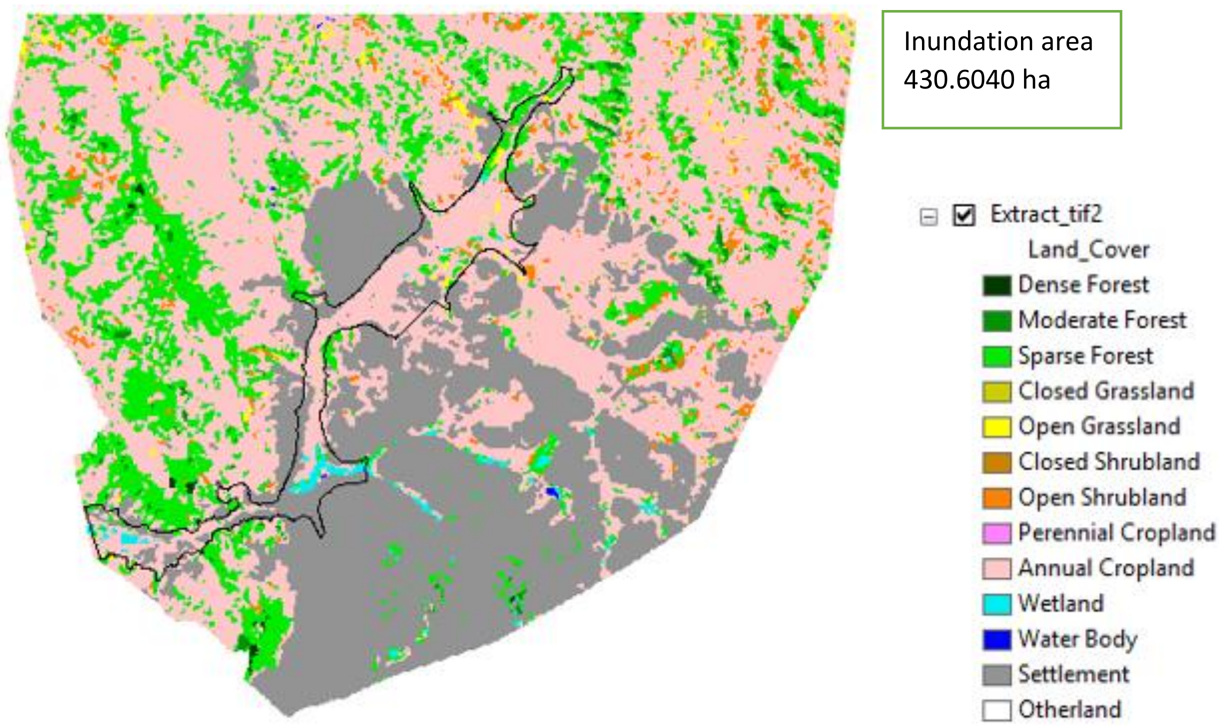


Figure 4.29: Floodplain inundation map for 100 year return period

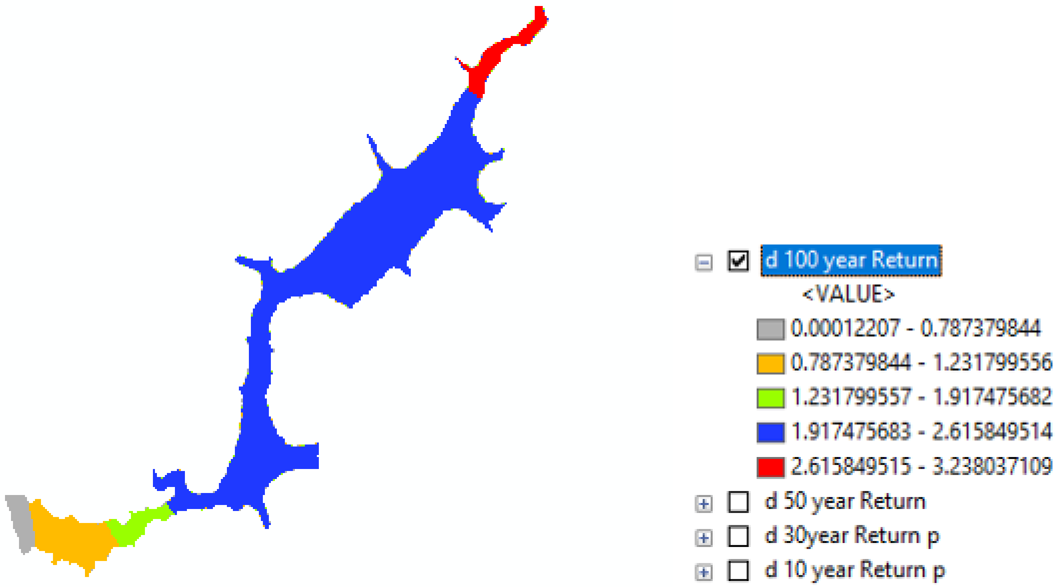


Figure 4.30: Flood depth map for 100 year return period

4.5.2 Floodplain delineation area and flood depth analysis

The section of results discussion encountered discussion on floodplain inundation area and on flood depth.

- **Floodplain inundation area analysis**

The computed flood inundation areas for each return period event were represented by the above figures of Floodplain inundation maps. They can be summarized by table 4.3 for each return period year.

Table 4.3: Inundation area corresponding to each event modelled.

Return period year	Inundation area (ha)
10	423.3490
30	426.1120
50	428.0810
100	430.6040

The relationship between the area of inundation and the return period year is shown Fig 4.31 below having the equation:

Y= 3.1461ln(X)+415.85Eq.27

with Y: representing inundation area and X: representing return period year and regression coefficient of R^2 of 0.9882

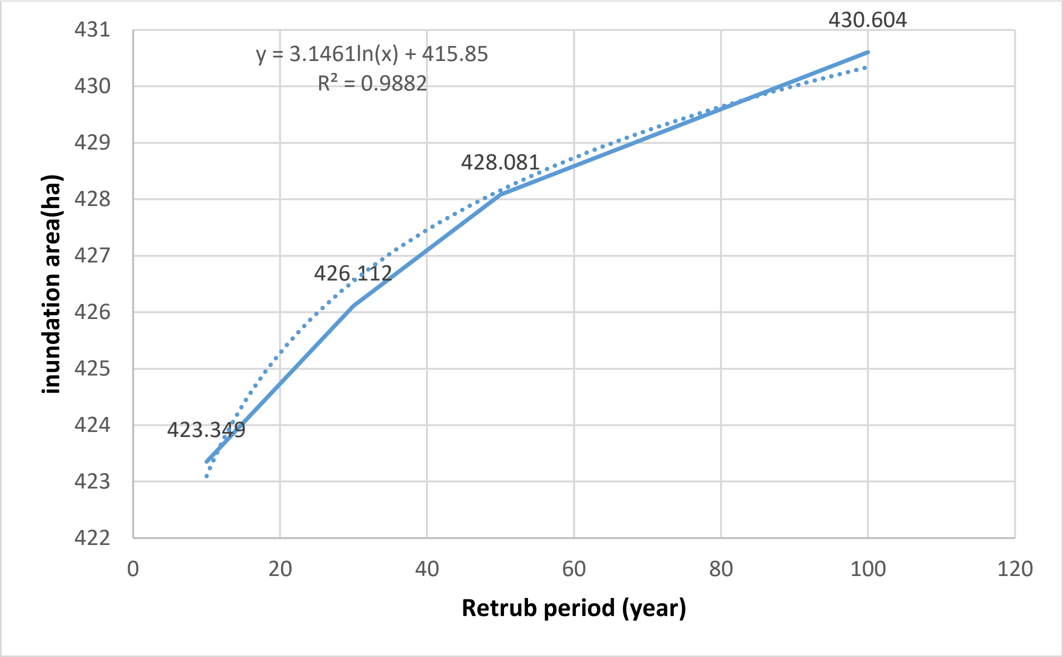


Figure 4.31: Return period verus inundation arae relationship

HEC-RAS performed steady flow analysis with the following discharges 515.7; 680.2; 761.5 and 875.8 m^3/sec which inundated 423.3490; 426.1120; 428.0810 and 430.6040 ha area respectively. Looking on the area of inundation with respect to discharges, there was a slight increase in inundation area as show by Fig 4.32.

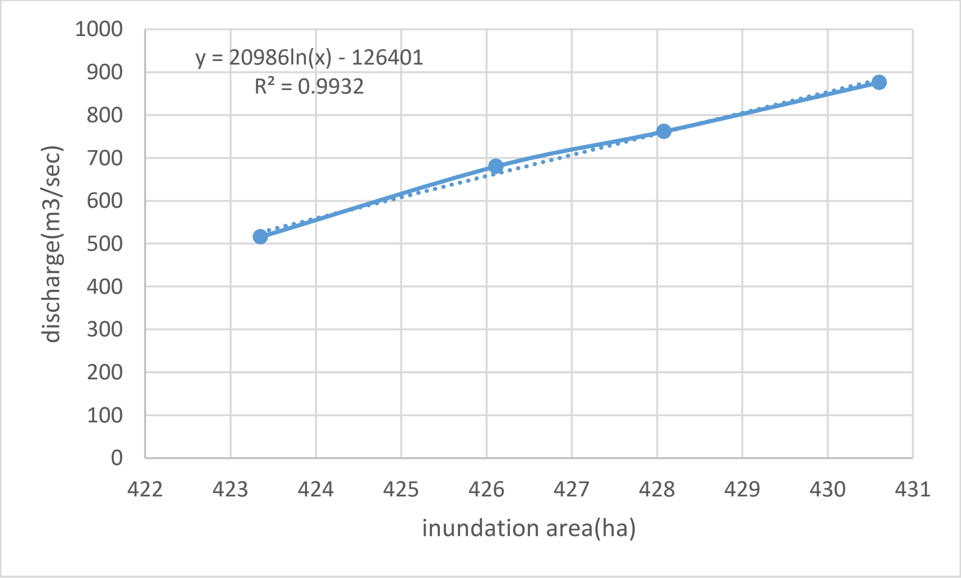


Figure 4.32: Inundation area verus discharge

Based on the flood inundation maps, relation between **i**nundation arae and retun peirod year and relationship between dicharges and inundations area shown Figures 4.31 and 4.32 above following results were observed:

- The area of inundation increase slightly as the rerun period year increase and also discharge increase
- Flood inundation area for 30 years return period increased by 0.652 % (2.763ha) of 10 years return period inundation area
- Flood inundation area for 50 years return period increased by 1.117% (4.732ha) of 10 years return period inundation area
- Flood inundation area for 100 years return period increased by 1.713% (7.255ha) of 10 years return period inundation area.

The intersection of the land use map with the flood inundation area polygon was done to obtained the vulnerable land use for each flood event modelled. The resulting vulnerable maps are shown by the following figures

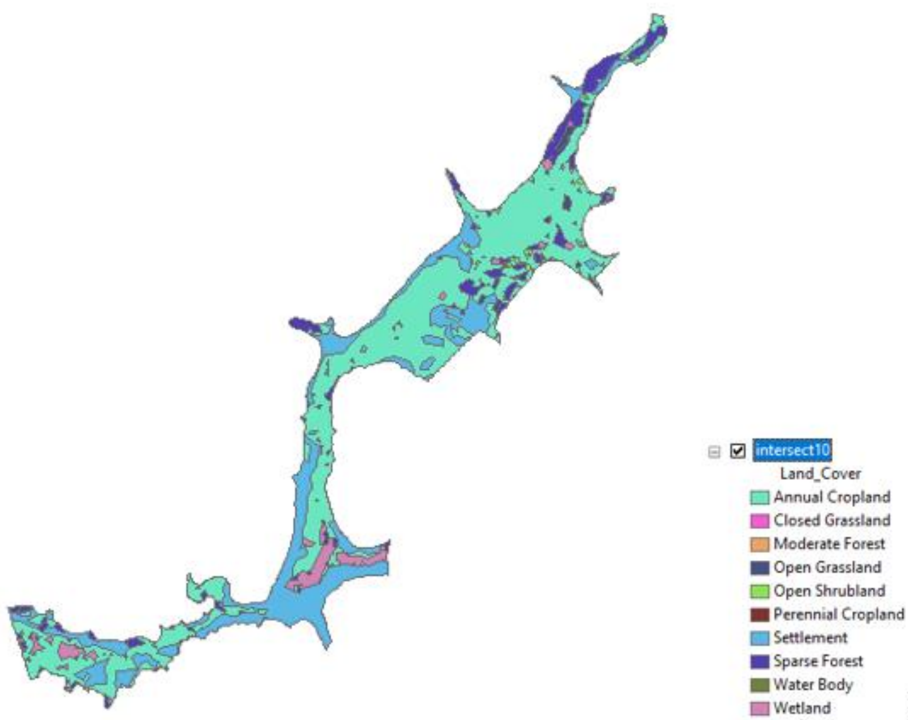


Figure 4.33: Venerable map for 10-year flood

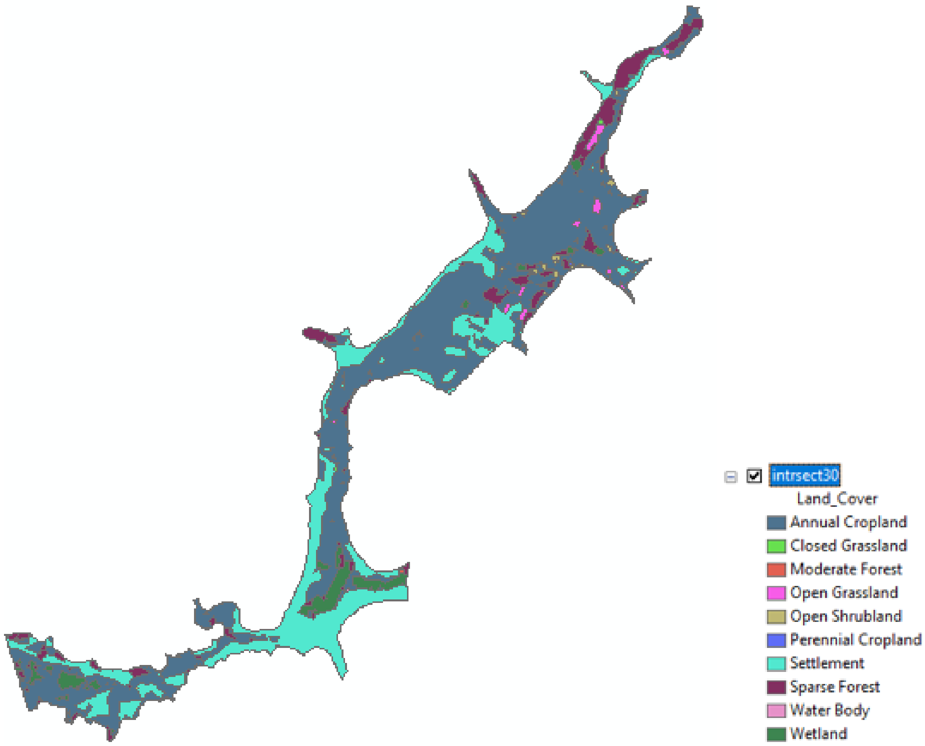


Figure 4.34: Venerable map for 30-year flood

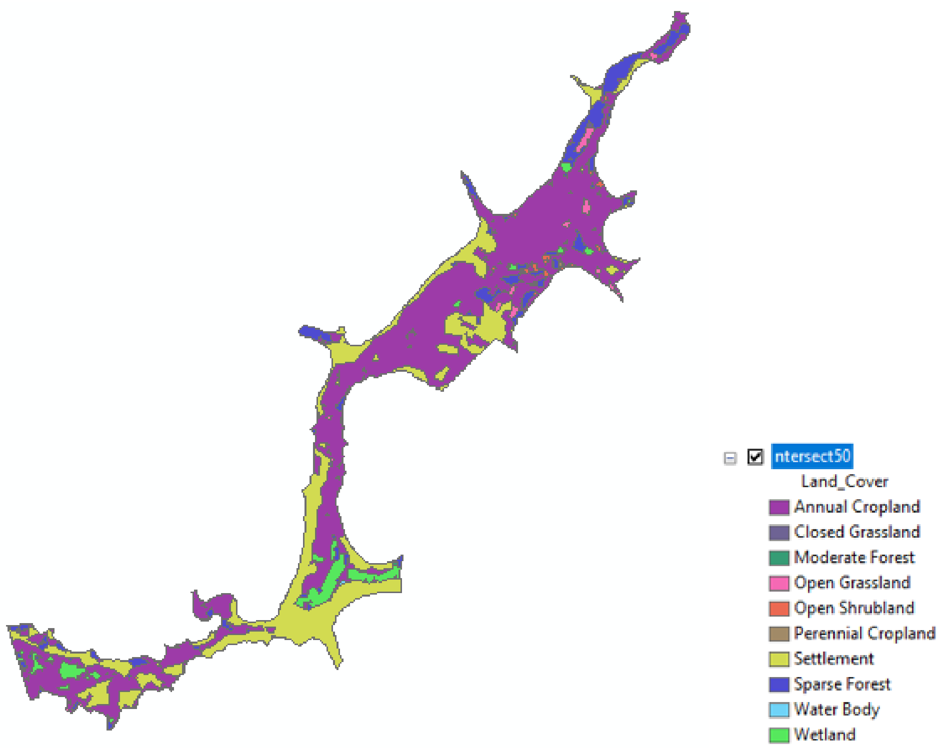


Figure 4.35: Venerable map for 50-year flood

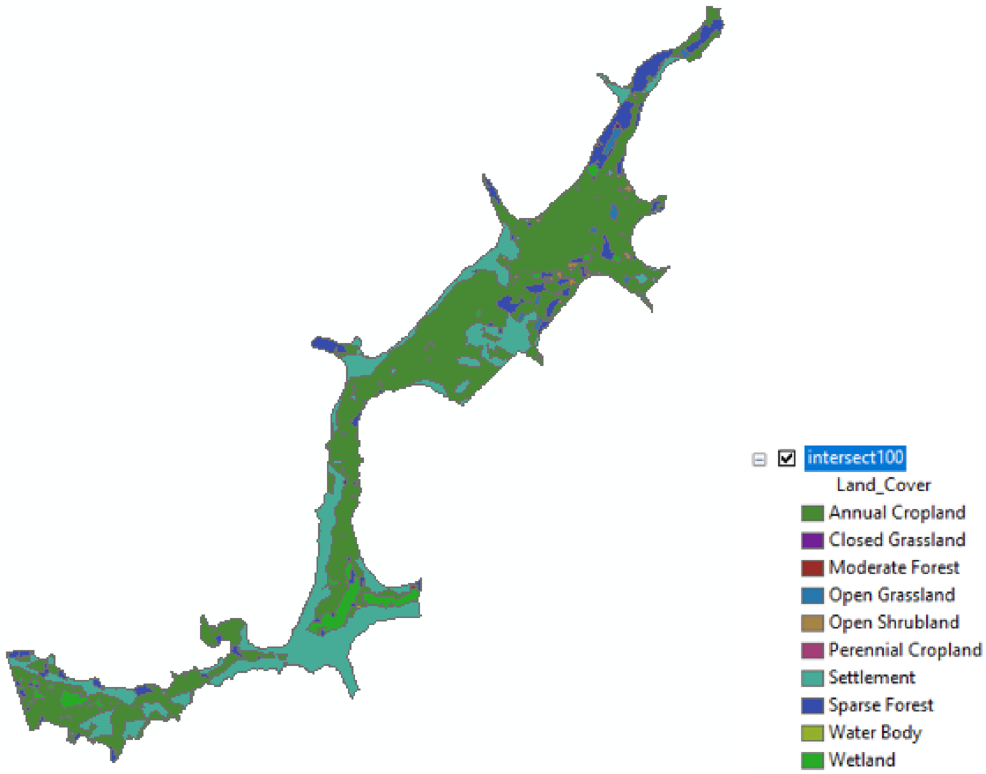


Figure 4.36: Venerable map for 100-year flood

The intersection of inundation area polygon with the land use shown by the above figures of venerable map; indicated that the venerable land use/ cover consists of annual cropland, closed grassland, moderate forest, open grassland, open shurbland, settlement, sparse forest, water body and wetland. Each of those land use occupies a certain percentage area of inundation as represented by the following table 4.4.

Table 4.4: Inundation area with respect to the land use vulnerability

Land use type	**Total vulnerable area**(ha)							
	10 years		**30 years**		**50 years**		**100years**	
	Area(ha)	%	Area(ha)	%	Area(ha)	%	Area(ha)	%
Annual cropland	55.22	13.04	54.232	12.7272	54.483	12.7272	54.804	12.7272
Closed grassland	9.203	2.17	9.296	2.1818	9.339	2.1818	9.394	2.1818
Moderate forest	4.602	1.0869	4.648	1.0909	4.669	1.0909	4.697	1.0909
Open grassland	50.618	11.956	51.133	12	51.369	12	51.672	12
Open shurbland	52.152	12.318	52.682	12.36	52.369	12.7272	53.238	12.363
Perennial cropland	7.669	1.811	7.747	1.818	7.783	1.1818	7.829	1.8181
Settlement	53.686	12.681	54.232	12.7272	54.483	32.363	54.804	12.7272
Sparse forest	136.515	32.246	137.905	32.363	138.542	32.363	139.359	32.363
Water body	4.602	1.086	4.648	1.0909	4.669	1.0909	4.697	1.0909
Wetland	49.084	11.594	49.583	11.636	49.813	11.636	50.106	11.636
TOTAL	423.349	100	426.112	100	428.081	100	430.604	100

From table 4.4, it is shown that the most venerable land uses for all the event modelled consist of annual cropland, open grassland, open shurbland, settlement, sparse forest and wetland; There is a slightly increase in inundation area corresponding to the venerable land use based on the event modelled.

By considering the high event modelled of 100 years, the inundation area is 54.804, 53.672, 53.238, 54.804, 139.359, 50.106 ha corresponding to the annual cropland, open grassland, open shurbland, settlement, sparse forest and wetland respectively which represent the most venerable land use as shown by following Figure 4.37.

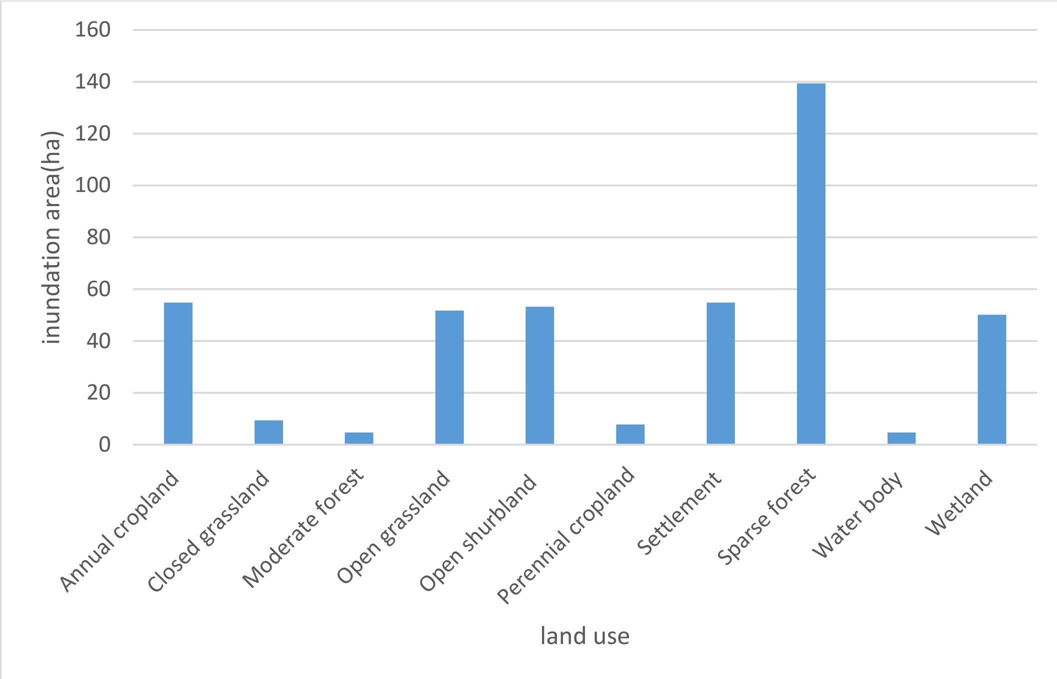


Figure 4.37: Inundation area for each venerable land use for 100 year return period

4.5.3 Flood depth results analysis

Flood depth showed by the figures above by (Fig. 4.24, Fig. 4.26; Fig. 4.28 and Fig. 4.30) were divided into 5 classes ranging from the lower depth to the high depth where each class represents a range of flood depths or water surface elevation for each event modelled.

Following table (4.5, 4.6, 4.7 and 4.8) demonstrate the area covered by the significant water depth for

Table 4.5: Inundation area coverage for 10 years return period significant water depth.

Water depth (m)	Area of inundation coverage (ha)	Percentage of coverage (%)
0.612298464- 0.957881912	141.9100	33.522
0.957881912-1.481193991	56.6200	13.374
1.481193992-2.024253696	106.6490	25.191
2.024253697-2.517944336	65.7500	15.531
total	**370.929**	87.618

Table 4.6: Inundation area coverage for 30 years return period significant water depth

Water depth (m)	Area coverage (ha)	Percentage of coverage (%)
0.698132564 -1.092170745	142.8300	33.519
1.092170746-1.700115368	57.7600	13.555
1.700115369-2.319318225	106.8620	25.079
2.319318226-2.859713446	64.2100	15.069
Total	**371.662**	88.222

Table 4.7: Inundation area coverage for 50 years return period significant water depth

Water depth(m)	Area coverage (ha)	Percentage of coverage(%)
0.736805396-1.152675015	143.1100	33.431
1.152675015-1.794302428	57.9400	13.534
1.794302428-2.44781183	106.8510	24.961
2.44781183-3.030029297	65.0400	15.193
Total	**372.941**	87.119

Table 4.8: Inundation area coverage for 100 years return period water depth

Water depth(m)	Area coverage (ha)	Percentage of coverage(%)
0.787379844-1.231799556	144.0000	33.442
1.231799557-1.917475682	58.5300	13.592
1.917475683-2.615849514	106.8440	24.813
2.615849515-3.238037109	65.8700	15.297
total	**375.244**	87.144

From the above tables (4.5, 4.6, 4.7 and 4.8) showing the proportions of the total area covered by each class of flood depth for any given flow magnitude or return period event modeled following analysis were observed:

- The total area coverage increase as the return period increase or flow magnitude increase.
- The water depth range increase as the return period increase or flow magnitude increase.
- The big area covered for 10years comprise33.522% of the total area and its depth range between (0.612298464- 0.957881912) m
- The big area covered for 30years comprise 33.519% of the total area and its depth range between (0.698132564 -1.092170745) m

- ❖ The big area covered for 50years comprise 33.431% of the total area and its depth range between (0.736805396-1.152675015) m
- ❖ The big area covered for 100years comprise 33.442% of the total area and its depth range between (0.787379844-1.231799556) m
- ❖ The lower water depth for all return period event modelled was 0.0012207 m but this value of water could be considered since it is insignificant value, therefore from the important water depth, the lower water depth was 0.698132564 m.
- ❖ The high water depth of 3.238037109 was observed for 100 year return period.

Apart from demonstrating inundation area, water depth and the venerable land use, flood risk modelling shows where the flood water breach out the river bank therefore from the cross- section plot results in HEC-RAS, the river station where the flood (water surface) is out the banks (right and left banks) can be visualized. By considering the high event modelled of 100 years return period; river stations and cross section with the flood (water surface) breaching out the banks were shown in Appendix3.

4.6 Flood mitigation measures

Flood mitigation refers to the measures adopted to reduce potential impacts of flood on people, environment and economy of the region**.** Basically flood mitigation measures are grouped into engineering such as construction of reservoir, dyke and diversion of water to side channels, levees along floodways and non-engineering such relocation and zoning flood prone areas.

In the case of Nyabugogo river, where annual cropland, open grassland, open shrub land, settlement, sparse forest and wetland where the most observed land use to be affected, following mitigation were proposed:

- ❖ Flood proofing measures

These measures can be applied to the building within the flood delineation area in two ways which are elevating of building so that flood waters go under it or constructing a wall to avoid flood water from reaching a building.

- ❖ Construction of storage reservoir at the upstream location of the reach.

Since there are agricultures activities within the flood delineation area, the storage reservoir can be used both for flood protection and irrigation purpose.

- ❖ Relocation of infrastructures within the flood delineation area.
- ❖ Buffer zoning around Nyabugogo river
- ❖ Rainwater Harvesting Strategies

Rain water harvesting techniques especially rain water tank for each house within the catchment can reduce the amount runoff and also serve a source of water supply.

- ❖ Raising public awareness on flood risks

Flood risks assessment as a vital component of flood management which elaborate hazards maps and provide information to the city planners, policy decision makers and also to other risks managers within different Government institutions; this information should not be limited to them it has to be disseminated to the local people especially the ones who are expected to be affected in order to raise their awareness in a sense of being responsible to manage flood.

5 CONCLUSION AND RECOMMENDATIONS

This section summarize the results obtained from the used of HEC-HMS and HEC-RAS model and the recommendation which should be used for future flood risk forecasting on Nyabugogo river to gain more accurate floodplain area maps.

5.1 Conclusion

The use of HEC-HMS and HEC-RAS models contributed in the forecasting of Nyabugogo river flood risks by identifying the flood plain area, the expected water depth and showing the vulnerability in terms of land use types affected for different return period. Flooding in Nyabugogo river were found to be caused by high rainfall intensity, topography varying between 1352- 2888 m, soil texture mainly composed of clay mixed with other texture, urbanization, informal settlement and inappropriate agriculture practices. Frequency analysis of daily annual maximum rainfall data has been performed to obtain frequency rainfall depth for different return period considered then HEC-HMS model was used to transform frequency rainfall depth into runoff to obtain peak discharges. HEC-RAS combined with HEC-GEORAS was used to obtain the flood delineation area and water depth corresponding to each event. The analysis of obtained from floodplain area and water depth showed that there is a slight increase in floodplain area from the lower event to high event modelled due to the high topography of the area; the high water depth obtained of 3.2 m was on 100 years return period and the more vulnerable land use types affected mostly for all the event consisted of annual cropland, open grassland, open shrub land, settlement, sparse forest and wetland. Although the increase in floodplain area were small, there is a need of protecting the affected area therefore different flood mitigation measures have been proposed however their cost benefit analysis need to be considered before implementation.

5.2 Recommendations

Following recommendations have been proposed:

- ❖ Updated data such as land use/ cover; and accurate flow data should be available to produce the exact results reflecting the current situation in area.
- ❖ As the hydrology within the river basin and its hydraulic change continuously, it is necessary to update Floodplain maps in order to disseminate the current information.
- ❖ Further research should conduct the economic assessment of the expected damage.
- ❖ Cost benefit analysis of any flood mitigation measures should be evaluated before its implementation.
- ❖ Different flood management measures should be applied in the whole Nile river basin to protect its water resources in terms of quality.

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APPENDIXES

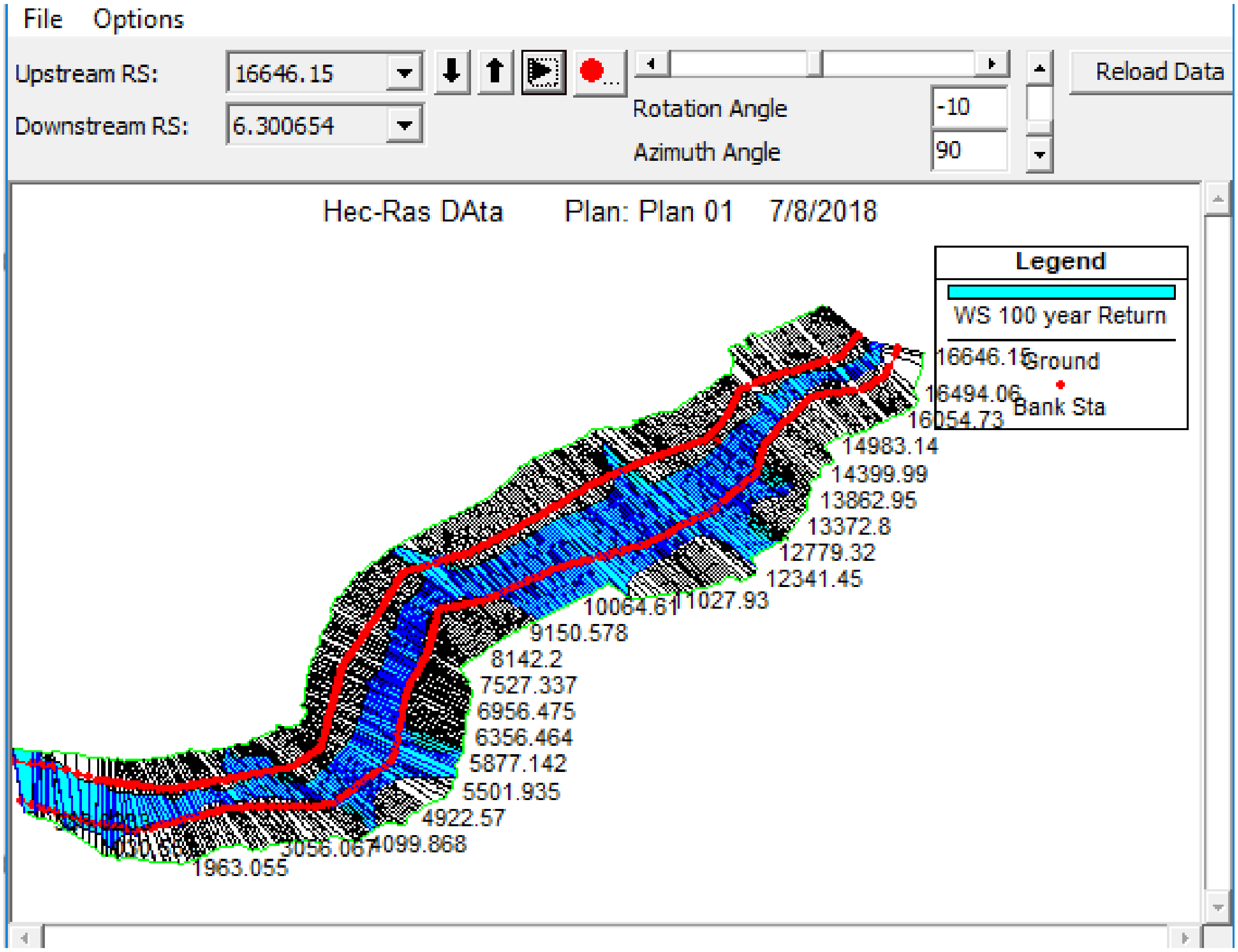
Appendix 1: Gumbel extreme value probability distribution results.

YEAR	P_{max}	(Pi-Pave)	(Pi-Pave)2	P-Pave/S	Reduced variate Y	Probability(P)	T
1988	53	16.83333	283.361	1.4185	2.395467	0.087101077	11.48091
1989	43	6.833333	46.694	0.5758	1.31519	0.235416039	4.247799
1990	45	8.833333	78.028	0.7443	1.531245	0.194479187	5.141938
1991	39	2.833333	8.028	0.2388	0.883079	0.338673706	2.952695
1992	54	17.83333	318.028	1.5027	2.503495	0.078542511	12.73196
1993	46	9.833333	96.694	0.8286	1.639273	0.176441882	5.667589
1994	44	7.833333	61.361	0.6601	1.423217	0.214109334	4.670511
1995	38	1.833333	3.361	0.1545	0.775051	0.369145703	2.708957
1996	29	-7.16667	51.361	-0.6039	-0.1972	0.70417469	1.420102
1997	19	-17.1667	294.694	-1.4465	-1.27748	0.972334637	1.028453
1998	35	-1.16667	1.361	-0.0983	0.450968	0.471129384	2.122559
1999	30	-6.16667	38.028	-0.5196	-0.08917	0.664880357	1.50403
2000	26	-10.1667	103.361	-0.8567	-0.52128	0.814404454	1.227891
2001	27	-9.16667	84.028	-0.7724	-0.41325	0.779471734	1.28292
2002	25	-11.1667	124.694	-0.9410	-0.62931	0.846846571	1.180851
2003	26	-10.1667	103.361	-0.8567	-0.52128	0.814404454	1.227891
2004	35	-1.16667	1.361	-0.0983	0.450968	0.471129384	2.122559
2005	17	-19.1667	367.361	-1.6151	-1.49353	0.988354015	1.011783
2006	24	-12.1667	148.028	-1.0252	-0.73734	0.876357699	1.141087
2007	24	-12.1667	148.028	-1.0252	-0.73734	0.876357699	1.141087
2008	32	-4.16667	17.361	-0.3511	0.126884	0.585563487	1.707757
2009	23	-13.1667	173.361	-1.1095	-0.84537	0.902590184	1.107923
2010	56	19.83333	393.361	1.6713	2.71955	0.063779629	15.67899
2011	39	2.833333	8.028	0.2388	0.883079	0.338673706	2.952695
2012	44	7.833333	61.361	0.6601	1.423217	0.214109334	4.670511
2013	59	22.83333	521.361	1.9241	3.043633	0.046543427	21.48531
2014	43	6.833333	46.694	0.5758	1.31519	0.235416039	4.247799
2015	54	17.83333	318.028	1.5027	2.503495	0.078542511	12.73196
2016	33	-3.16667	10.028	-0.2668	0.234912	0.54644571	1.830008
2017	23	-13.1667	173.361	-1.1095	-0.84537	0.902590184	1.107923
P total	1085						
Paverage	36.16667						
(Pi-Pave)^2 total	4084.167						
standard deviation	11.86732						

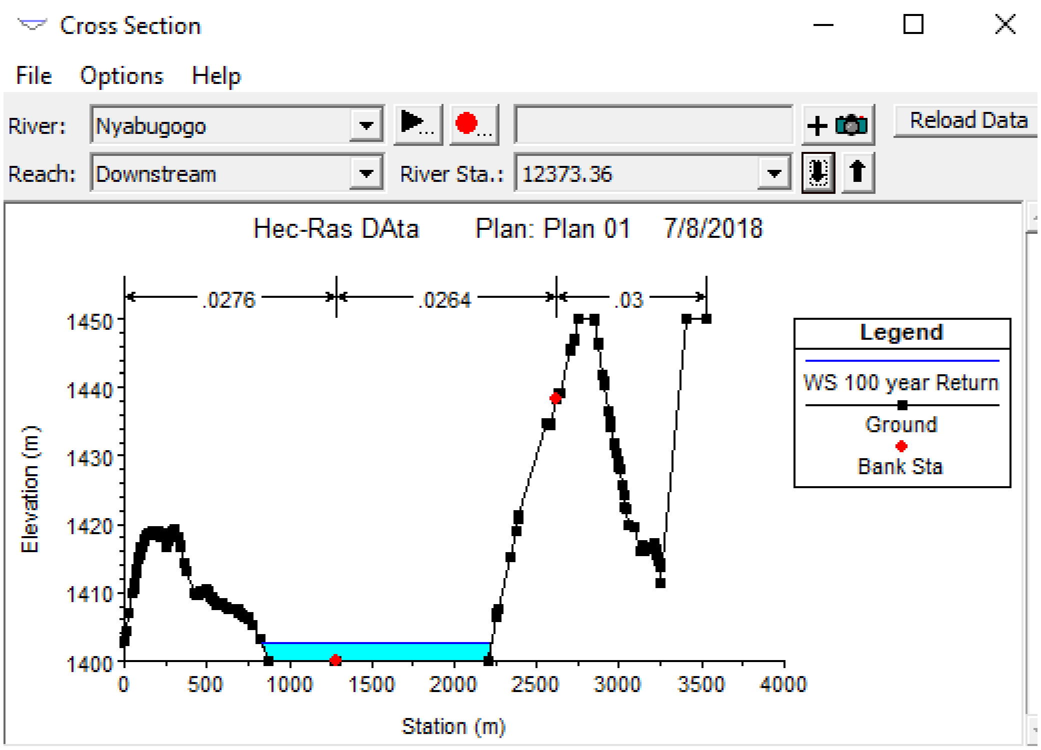
Appendix 2: HEC-HMS calibration data

date	discharge m3/sec	rainfall(mm)
4/1/2016	144.144	3
4/2/2016	144.144	6
4/3/2016	209.174	16
4/4/2016	253.954	16
4/5/2016	261.837	7
4/6/2016	257.88	1
4/7/2016	238.547	4
4/8/2016	209.174	15
4/9/2016	202.131	3
4/10/2016	195.207	10
4/11/2016	181.721	8
4/12/2016	181.721	0
4/13/2016	181.721	0
4/14/2016	175.158	4
4/15/2016	175.158	2
4/16/2016	171.921	5
4/17/2016	171.921	0
4/18/2016	171.921	0
4/19/2016	165.538	7
4/20/2016	165.538	0
4/21/2016	175.158	2
4/22/2016	181.721	1
4/23/2016	188.404	5
4/24/2016	144.144	0
4/25/2016	209.174	8
4/26/2016	216.337	3
4/27/2016	219.964	15
4/28/2016	209.174	12
4/29/2016	209.174	7
4/30/2016	209.174	1

Appendix 3: Location where water surface breach out the bank on the study reach.



100 years return period water surface within the banks

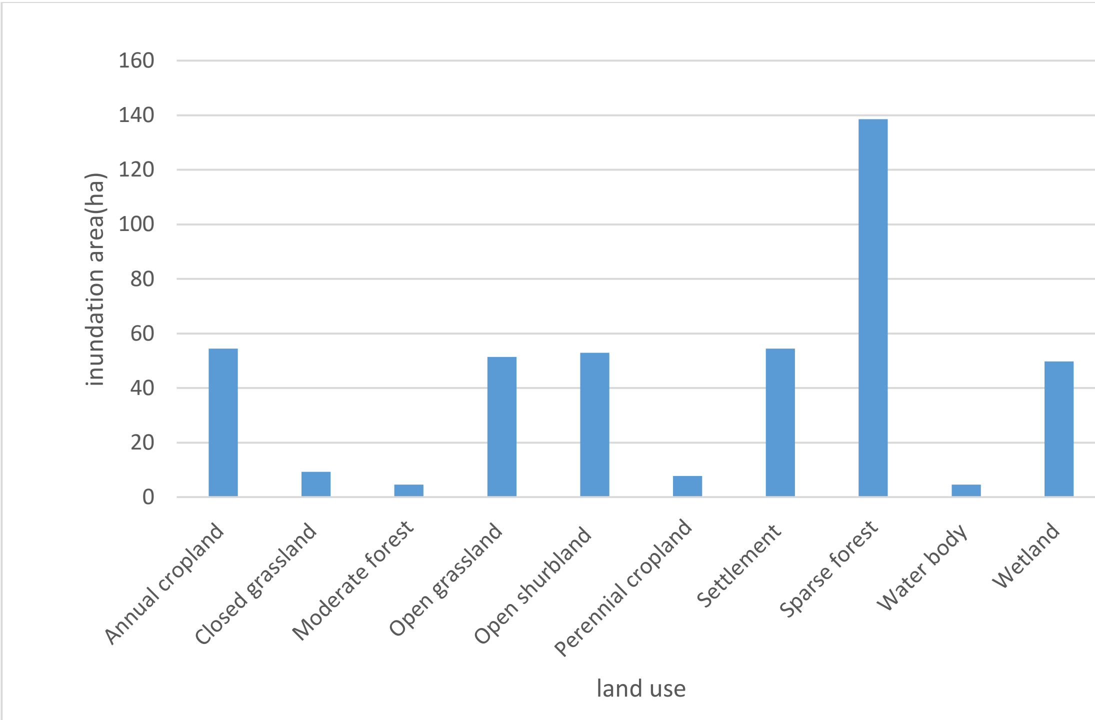


Water surface breaching out the banks at station 12203.18

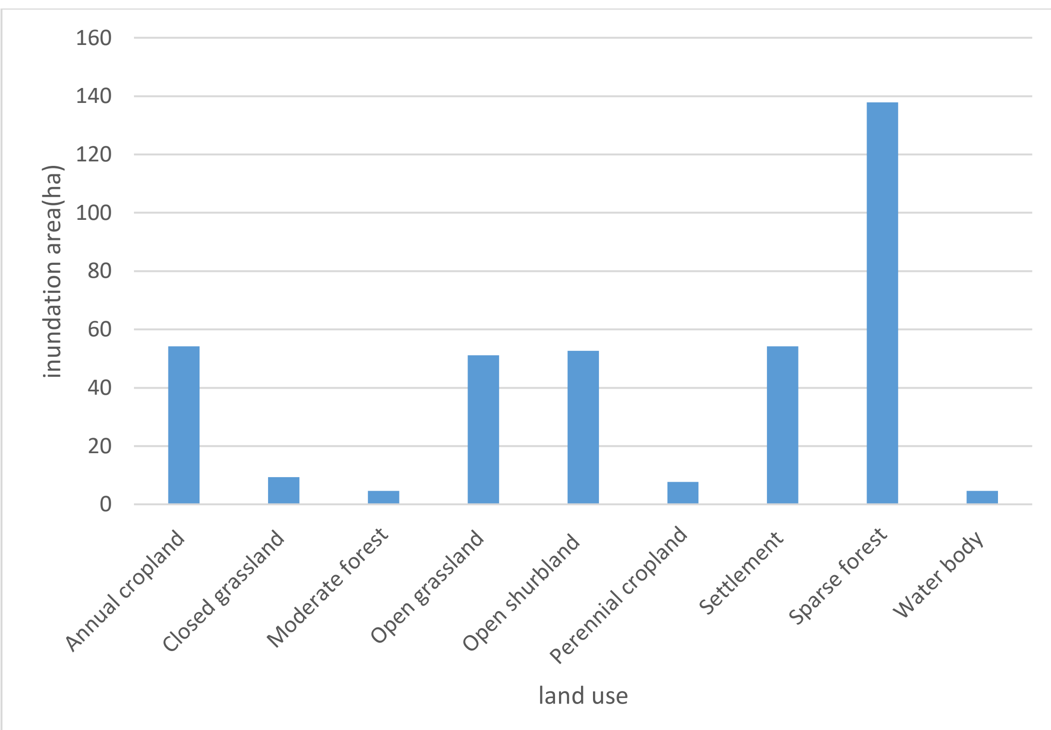
Station where water surface breaches out the river bank

Cross section at the Left overbank (LOB)		
From station	To station	Length (m)
13806.17	9303.374	4640.82
6118.817	4310.55	2158.03
2257.391	2043.513	200.06
1653.797	388.0233	1438.25
272.4249	6.300654	241.71
Cross section at the Right overbank (ROB)		
From station	To station	Length(m)
12298.49	11987.52	302.01
9048.715	8610.659	545.97
4150.433	3221.409	727.12
762.679	6.300654	697.71

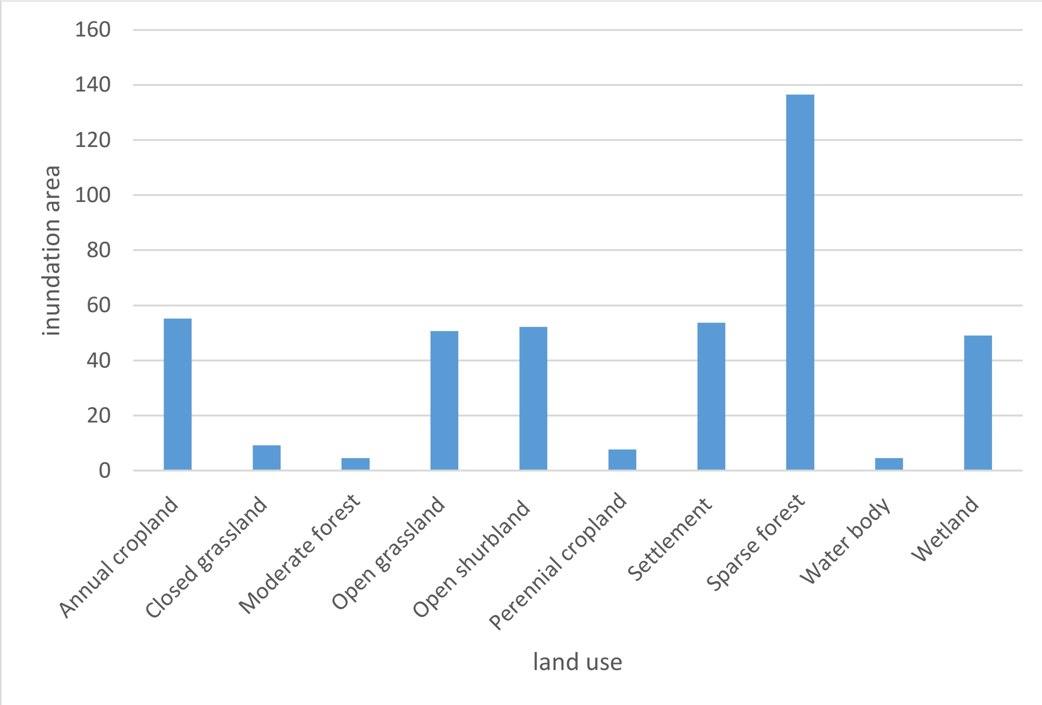
Appendix 4: Inundation area for each venerable land use for 50, 30, 10 return period year.



Inundation area for each venerable land use for 50 year return period.



Inundation area for each venerable land use for 30 year return period.



Inundation area for each venerable land use for 10 year return period.

Appendix 5: Research Grant Financial Statement Report

The research grant offered to me was 2986 USD. Based On Law N° 55/2007 of 30/11/2007 Governing The Central Bank of Rwanda, assigns to the BNR (National Bank of Rwanda), the responsibility of formulating monetary policy, the Rwandan francs(Frw) is the monetary unit of the Republic of Rwanda. In addition, following the rules and condition in Algeria, governing the use of foreign currency, one party of the research grant was exchanged to DZD and the other one was exchanged to Frw.

On 28th February 2018, 1 USD =106 DZD, (Societe General Algeria, 2018), therefore 896.471 USD which is equal to 95026 dinars were used to buy flight ticket,

On 14 March 2018, 1 USD = 859.695FRW (BNR, 2018), hence 2052.494 USD were exchanged to Rwandan francs.

Expenditures table

Item	**Cost**	**Cost in dollars**
Flight ticket	95026 DZD	896.471
Local Transport in Rwanda	336570 Frw	391.499
Software training	517800 Frw	602.306
Internet	215750 Frw	250.961
Data used in the project	694400 Frw	807.728
TOTAL		**2948.965**

The following receipts demonstrated below are for the item in the table above with total amount of 2948.965 USD. The remaining 37.035 USD were used both in taxi transport and printing of thesis report, where On 13th march and 1st June 2018, I used taxi Jaune from Tlemcen to Algiers and from Algiers to Tlemcen where I paid the total amount of 3000 dinars, for this no receipt were given to me since the taxi man don’t provide receipt to their customers. Again for printing and binding, there is no receipt which was provided, this were done in Tlemcen near faculty of Medicine; it took 2000 dinars.

Electronic Ticket Receipt

Traveler : **ICYIMPAYE Gisele**

Amadeus Booking ref : QLRE67
Issue date : 07 MARCH 2018
Airline booking ref : QR /QLRE67
Issuing airline : QATAR AIRWAYS
Ticket number : 157-2498438716

Agency : POMARIA TRAVEL
3 PLACE KAIROUAN
TLEMCEN
ALGERIE

Telephone : +213 43 265353
Email : contact@pomariatravel.com
IATA : 03211574
Agent : 0000

Itinerary

From	To	Flight	Class	Date	Departure	Arrival	Resa (1)	NVB (2)	NVA (3)	Last check-in	Baggage (4)	Seat
Tuesday 13 March 2018												
ALGIERS	**DOHA**	QR1380	W	13MAR	15:15	23:59	OK01	13MAR	13MAR		45K	
Terminal I	Terminal					Fare Basis			WJHOP5ZE			
Operated by		QATAR AIRWAYS				Marketed by			QATAR AIRWAYS			
Equipment		Airbus A330-300							Duration		06:44 (Non Stop)	
Wednesday 14 March 2018												
DOHA	**KIGALI**	QR1387	W	14MAR	07:55	15:10	OK01	14MAR	14MAR		45K	
Terminal	Terminal					Fare Basis			WJHOP5ZE			
Operated by		QATAR AIRWAYS				Marketed by			QATAR AIRWAYS			
Equipment		Airbus A330-200							Duration		08:15(1 Stop)	
Thursday 31 May 2018												
KIGALI	**DOHA**	QR1387	W	31MAY	14:10	23:40	OK01	31MAY	31MAY		45K	
Terminal	Terminal					Fare Basis			WJHOP5ZE			
Operated by		QATAR AIRWAYS				Marketed by			QATAR AIRWAYS			
Equipment									Duration		08:30(1 Stop)	
Friday 01 June 2018												
DOHA	**ALGIERS**	QR1379	W	01JUN	07:30	13:00	OK01	01JUN	01JUN		45K	
Terminal	Terminal I					Fare Basis			WJHOP5ZE			
Operated by		QATAR AIRWAYS				Marketed by			QATAR AIRWAYS			
Equipment		Airbus A330-300							Duration		07:30 (Non Stop)	

(1) Ok = confirmed (2)NVB= Not valid before (3)NVA= Not valid after(4) Each passenger can check in a specific amount of baggage at no extra cost as indicated above in the column baggage.

Receipt

AGENCE DE VOYAGES S.A.R.L POMARIA TRAVEL
03, Place Kairouan TLEMCEN
Tél: 043. 27. 79. 64
Fax : 043. 26. 40. 71

BILLET NON REMBOURSABLE

Name	:	ICYIMPAYE Gisele		
Ticket Number	:	157 2498438716		
Form of payment	:	CASH		
Fare Calculation	:	ALG QR X/DOH QR KGL253.57QR X/DOH QR ALG253.57NUC5		
Air Fare	:	DZD 58700		
Tax	:	DZD 1300XE	DZD 20DZ	DZD 1500DZ
		DZD 2214G4	DZD 116PZ	DZD 4605RW
		DZD 1152C8	DZD 1011XT	
Airline Surcharges	:	DZD 23 024YQ	DZD 1 384YR	
Total Amount	:	DZD 95026		
Issuing Airline and date	:	QATAR AIRWAYS 07 March 2018		
Restriction(s)/Endorsements	:	/C1-4 NON END/NONREF CHANGE FEE APPLIES VALID ON Q		

The fare that applies on the date of purchase is only valid for the entire itinerary and the specific travel dates mentioned on the ticket.

SMART TAXI LTD
Tel: +250 78258624, E-mail: info@smartaxi.com, Kigali- Rwanda

DATE : 26 march 2018

INVOICE No: 134

Client Name: ICYIMPAYE GISELE

No	DESCRIPTION	U.P	TOTAL
1 Day	Nyamasheke District To Kigali	129.450	129.450
		TOTAL	129,450

Driver Name: Bugingo James

Signature:

SMART TAXI LTD Tel: +250 78 258 624 E-mail: info@smartaxi.com KIGALI - RWANDA

SMART TAXI LTD

Tel. +250 78258624; E-mail: info@smartaxi.com, Kigali- Rwanda

DATE : 15 March 2018

INVOICE No: 131

Client Name: ICYIMPAYE GISELE

No	DESCRIPTION	U.P	TOTAL
1Day	Kigali to Nyamasheke District	129,450	129,450
		TOTAL	129,450

Driver Name: Bugingo James

Signature: [signature]

SMART TAXI LTD KIGALI - RWANDA Tel: +250782258624 E-mail: info@smartaxi.com

SMART TAXI LTD

Tel: +250 78258624, E-mail: info@smartaxi.com, Kigali- Rwanda

DATE : 29 March 2018

INVOICE No: 136

Client Name: ICYIMPAYE GISELE

No	DESCRIPTION	U.P	TOTAL
3 Days	Nyakabanda Sector to Nyabugogo river Catchment.	25,890	77,670
		TOTAL	77,670

Driver Name: Bugingo James

Signature:

SMART TAXI LTD
Tel: 078258624
E-mail: info@smartaxi.com
KIGALI - RWANDA

BSD TECH LTD.

TIN No:106448413 , Mobile No:0784884300 / 0725789586 ,
Email:bsdtechltd@gmail.com , Account No:000400693227212 Bank of Kigali,
No: 10100661330016-1 UNGUKA BANK

INVOICE

No :

DATE : 16/05/2018

M/S ICYIMPAYE GISELE

S/N	DESCRIPTION	QTY	PRICE Frw	AMOUNT Frw
1	SOFTWARE TRAINING	15Days	34,520	517,800
	FOR:			
	ARC-GIS, HEC-HMS, HEC-RAS			
	15 Days Training			
	TOTAL			
	VAT			
	Grand Total			517,800

- No warranty on Batteries, Consumables & Adaptors
- Warranty not applicable for voltage variations, lightening, natural calamities.
- Goodsonce sold will not betaken back or exchanged
- Warranty is as per warranty center terms BSD TECH LTD is not responsible for warranty center delay's

For BSD TECH LTD.

Authorized Signatory

BSD TECH LTD
TIN:106448413
Tel:0784884300
0725789586
E-mail:bsdtechltd@gmail.com

MTN FRANCHISEE/PHONECOM Ltd
Tel : (+250) 788322270 / 0788322203
P.O.Box 6157 KIGALI
TIN: 101919508

Date : 2018-05-03

INVOICE No 1896 / 2018

COMPANY : ICYIMPAYE GISELE
DISCOUNT : 0 %
DUE DATE : 2018-03-16

No	DESCRIPTION	QTY	U.P	TOTAL
1	AT1000	215.00	1,000.0000	215,000
2	VTU	750.00	1.0000	750
			VALUE	215,750
			TOTAL	215,750

Total amount in words : two hundred and fifteen thousand, seven hundred and fifty Rwandan Francs only.

Done at KIGALI, 2018-05-03

MTN
PAID
FRANCHISE
PHONECOM Ltd

REPUBLIC OF RWANDA

Rwanda Water and Forestry Authority (RWFA)
P.O.BOX: 7445 KIGALI

Efficiency Management of Water and Forestry Resources Is Our Aim

Invoice number: **2018/RFWA/0081**

ICYIMPAYE Gisele/ PAUWES has to pay **694400** RFW for data collection.

Data type	Unit cost in RFW	Total cost in RFW
DEM(10m resolution)	140000	140 000
Discharge daily from 1988 till 2017	120000	120 000
Catchment Boundaries Shape- file for the country	80400	80400
Rainfall (daily from 1988 till 2017)	84000	84000
Soil Data (shape file of the Country)	120000	120000
Land Cover/ Use shape file of the Country	150000	150000
	TOTAL	**694400**

PAID

Done at Kigali on 10May 2018

Director General
Rwanda Water and Forestry Authority

Plaza, KN 3rd Road, P.O.Box 7445 Kigali, Rwanda, E-mail: info@rwfa.rw, Twitter: @info.rwfa