THESIS ID:

DEPARTMENT OF CIVIL ENGINEERING
SCHOOL OF ENGINEERING (Huye Campus)
COLLEGE OF SCIENCE AND TECHNOLOGY
P.O. Box 117 BUTARE, Rwanda

" DESIGN OF APPROPRIATE HYDRAULIC STRUCTURES FOR SUSTAINABLE FLOOD CONTROL IN THE NYABUGOGO CATCHMENT, WITH FOCUS ON THE MPAZI SUB CATCHMENT "

A THESIS

Submitted by
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Under the guidance of
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Submitted in partial fulfilment of the requirements for the award of

MASTER OF SCIENCE DEGREE IN
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COLLEGE OF SCIENCE AND TECHNOLOGY
P.O. Box 117 Butare, Rwanda

Huye, October, 2014

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CERTIFICATE

This is to certify that the Thesis Work entitled*"* **Design of Appropriate Hydraulic Structures for Sustainable Flood Control in the Nyabugogo Catchment, with focus on the Mpazi Sub Catchment***"* is a record of the original bonifide work done by Eng. Gérard HAKIZIMANA (Reg. No: 10208239) in partial fulfilment of the requirement for the award of Master of Science Degree in Water Resources and Environmental Management of College of Science and Technology during the academic year 2013-2014.

Supervisor:
Dr. Eng. Omar MUNYANEZA

Submitted for the final defense of the thesis held at College of Science and Technology on **October,15th, 2014**

DECLARATION

I hereby declare that the thesis entitled**" Design of Appropriate Hydraulic Structures for Sustainable Flood Control in the Nyabugogo Catchment, with focus on the Mpazi Sub Catchment"** submitted for the Degree of Master of Science is my original work and the thesis has not formed the basis for the award of any Degree, Diploma, Associateship, Fellowship of similar other titles. It has not been submitted to any other University or Institution for the award of any Degree or Diploma.

Huye – Rwanda ………………………..

Date: October, 2014 Eng. Gérard HAKIZIMANA

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BONAFIDE CERTIFICATE

Certified that this thesis titled*”* **Design of Appropriate Hydraulic Structures for Sustainable Flood Control in the Nyabugogo Catchment, with focus on the Mpazi Sub Catchment** “is the bonafide work of **Eng. Gérard HAKIZIMANA (Reg.No:10208239)** who carried out the research under my supervision. Certified further that to the best of my knowledge the work reported herein does not form part of any other thesis or dissertation on the basis of which a degree or award was conferred on an earlier occasion for this or any other candidate.

Signature of the Supervisor……………………….
Supervisor: Dr. Eng. Omar MUNYANEZA
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DEDICATION

To the Almighty God, the provider of everything,

To my dear father and mother,

To my brothers and sisters,

To the members of the MKS Global Services Ltd,

To all who helped me for the completion of this work,

I dedicate this Msc research thesis.

ACKNOWLEDGEMENTS

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Special thanks also to my fellow Msc colleagues from WREM; it was a valuable experience to work with enthusiastic and dedicated students like you.

Thanks to all those who have contributed directly or indirectly to the realization of this project.

May God bless you so much!

ABSTRACT

A flood is a great flowing or overflowing of water onto land that is not usually submerged. A flood happens when too much rain falls and cannot be absorbed by the soil. Most of countries in Africa are regularly affected by severe and often multi-year disasters including landslides and floods. Rwanda is among countries which face floods disasters because of its topography.

The Nyabugogo area due to low altitude and its nature of convergence zone of drainage systems of Kigali city has been repeatedly subjected to floods. The Mpazi sub-catchment ($8.37 km^2$) is the major contributor to the flooding in the Nyabugogo area, due to degraded steep slopes in the water heads of Kigali Mountain, dense unplanned settlements in Kimisagara, Nyakabanda, Cyahafi and Muhima areas, clogged culverts and bridges and that impede the flow of water in the Mpazi channel, and then cause the flooding.

The aim of this study was to design appropriate hydraulic structures for sustainable flood control in the Nyabugogo catchment with focus on the Mpazi Sub catchment.

Daily rainfall data from January 2003 to June 2014 have been collected from two meteorological stations; the KANOMBE airport station and the Nyabugogo wetland station. The peak rainfall height determined by using the extreme value theorem has fallen on 23rd February, 2010. The peak runoff water discharge has been calculated by using the rational method and its prediction in 30 years has been calculated by using the linear model ($Q = 118.9\ m^3/s$). The discharge capacity of the existing hydraulic structures has been calculated; by using the Manning equation for the open channel and the rectangular culverts design formula for the culverts. The existing hydraulic structures are not able of carrying the predicted peak or design discharge. For a long term sustainable flood control solution for the Mpazi sub catchment as well as in the Nyabugogo catchment, new hydraulic structures have been proposed.

The proposed new design, once applied will contribute to the flood control observed in this sub catchment.

***Keywords**: Sustainable flood control, Nyabugogo catchment, Mpazi sub-catchment, hydraulic structures*

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LIST OF SYMBOLS AND ABBREVIATIONS

MININFRA: Ministry of infrastructures

MINIRENA: Minister of Natural Resources

RDF : Rwanda Defence Force

RNRA: Rwanda Natural Resources Authority

MIDIMAR: Ministry of Disaster Management

EU: European Union

US: United States

ARF: Area Reduction Factor

UK= United Kingdom

CHAP 1. GENERAL INTRODUCTION

1.1. BACKGROUND

A flood is an overflowing of water onto normally dry land. The Nyabugogo catchment, especially the Mpazi Sub catchment which was the target in this research has suffered from the flooding problem for several times. This is mainly due to its altitude which is low compared to other surrounding areas and its nature of convergence zone of drainage systems of Kigali city that has been repeatedly subjected to floods.

The Nyabugogo is a perennial river with some development around it with regards to abstractions and diversions for agriculture and supply purposes. The large temporal variation in precipitation within the region leads to great inter-annual variations in the Nyabugogo flows. Both flood and drought periods are experienced.

Nyabugogo River flooding, usually causes some effects which can be classified as follows: (1) Primary effects: Physical damage which can damage any type of structure including bridges, cars, buildings, Sewerage systems, roadways and canals ; (2) Secondary effects: Water supplies, diseases, crops and flood supplies, tress, vegetation and transport; (3) Tertiary and long-term effects: Economic (Munyaneza O., 2013).

The flooding along the Nyabugogo therefore has several traits and the principal cause is the flash flood from the minute Mpazi sub catchment. This basin is highly urbanized and has an extreme low retention capacity which causes that any high intensity and slightly prolonged rainfall event generates an extreme flood wave response in the channel system that breaks out at multiple places along the channel depending on its dimension, slopes and deposits of boulders, debris and stones, thus generating substantial damage to life and properties.

These events are driven by rainfall and may occur throughout the wet seasons from October up to May.

The stone masonry channel of Mpazi is extensively damaged and dwellings too close along the channel are at risk of sudden collapse and washing away during any rainstorm. (SHER Ingénieurs Conseil; 2013)

During the flooding periods, the destroyed materials and eroded soil flow with the water and are deposited downstream, this resulting with time in the clogging of the outlet of the drainage channel.

As the channel is clogged, the flow of water is interrupted and results in flooding the area around. One major cause is Mpazi channel which receives upstream rain water.

The Mpazi drainage channel is a trapezoidal channel made in stone masonry, collecting rain water from Gitega, Kimisagara, Muhima and Nyabugogo areas, and is characterized by many flash floods during rainy seasons and drains rain-water into Nyabugogo River. It drains an urban area of around 8 km^2 to the Nyabugogo River. It is characterized by flash floods, which can cause considerable damage to valuable infrastructure, and is a threat to human beings. (MANYIFIKA M.; 2013)

Recently (in 2013) flood have been affecting Nyabugogo wetland and causes loss of properties, loss of 4 human lives through a car which was drawn by the water and animal life and disruption of socio-economic activities, disruption of the business in the area and other issues related to transport facilitation that at times become stand still due to flooding in the wetland during the rainy season. (Munyaneza O. et al, 2013).

This research has focused on the Mpazi sub catchment downstream where is located the Nyabugogo business area because is where critical points vulnerable to the flooding and destroyed structures by the flowing water have been localized.

Therefore, the aim of this research is to contribute to the mitigation of flood in the Nyabugogo by proposing an appropriate design of hydraulic structures which, if implemented, can reduce the magnitude of the effect of flood in the area.

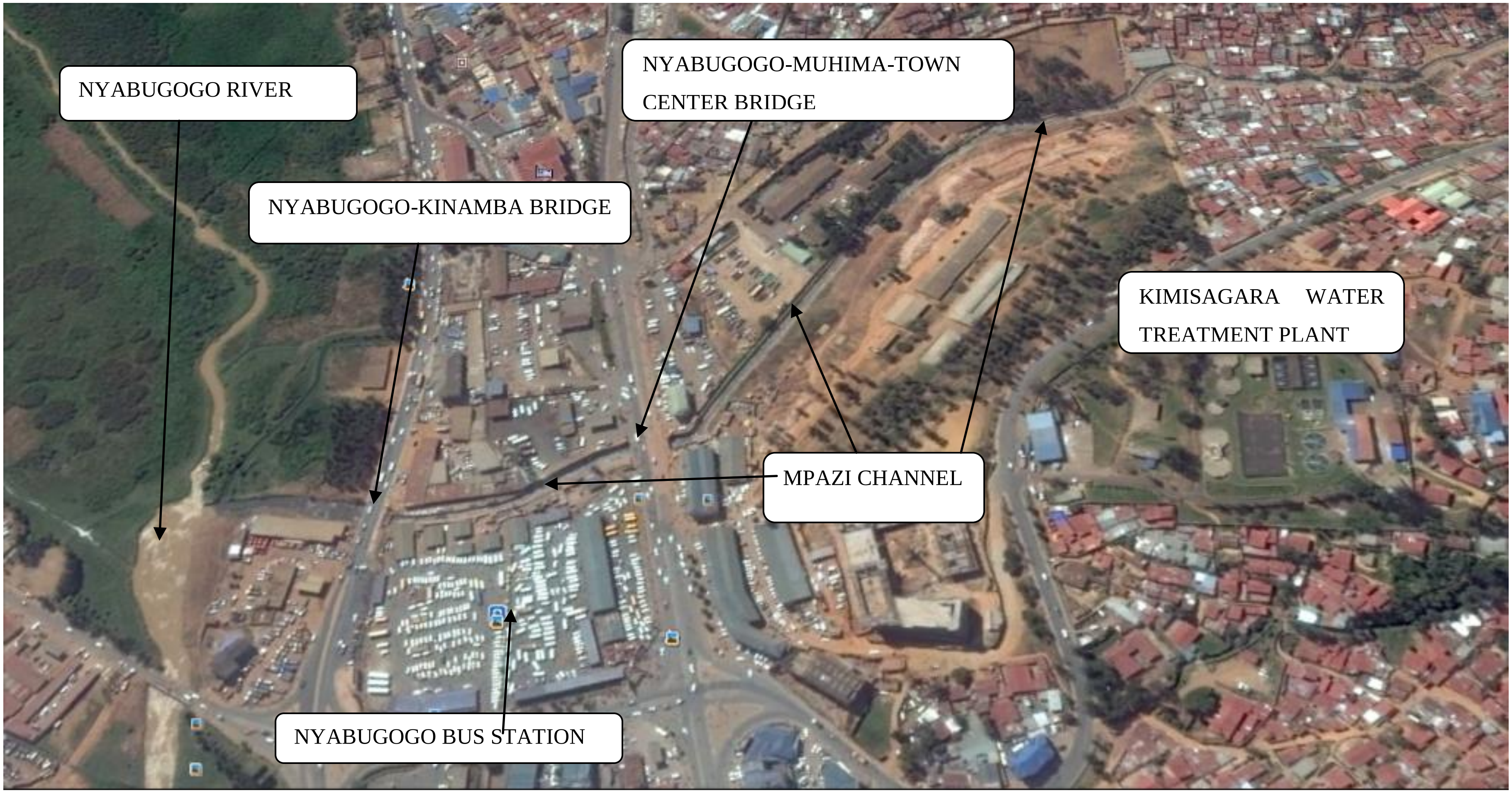

Figure 1: Mpazi sub catchment downstream

1.2. PROBLEM STATEMENT

In Rwanda, different areas are prone to floods and landslides and this is due to various aspects such as geo-aspects, land-use type and others.

The Mpazi sub-catchment was identified as the major contributor to flooding in Nyabugogo area, due to degraded steep slopes in the water heads of Mount Kigali, dense unplanned settlements in Kimisagara, Nyakabanda, Cyahafi and Muhima areas, clogged culverts and bridges that impede the flow of water due to solid waste dumped in the Mpazi channel.

The Mpazi drainage channel drains rainwater as fast as possible. In its design no attention was paid to the effect of very rapid urbanization in that part of the town. Its slope varies between 3 to 4 % on average, leading to uncontrollable discharges in the lower part near the Nyabugogo bus station as the channel provide no energy reduction measures of the runoff.

The water pressure is too high during heavy rains with a steep upstream slope causing a wash away of the channel walls in the corners. (MANYIFIKA M.; 2013)

To reduce these floods many interventions, coordinated by Minirena through Rwanda Natural Resources Authority, have been implemented and include dredging the roads culverts, roads rehabilitation and rehabilitation of Mpazi channel. (Ndayisaba, 2014)

Even if these measures have been taken, the flooding is still the main challenge for the Nyabugogo business zone.

Photo 1: Floods hinder activities in the Nyabugogo area (RNRA, 2013)

The investigations carried out within the framework of the special program of the National Water Resources Master Plan for Rwanda in the period between October 2012 and February 2013 have revealed the causes of flooding that were not clear before. Although the Nyabugogo River contributes to the flooding problem at the Muhima market, it is now evident that this river is not the main cause of the flooding.

On the contrary, it is the diminutive Mpazi sub-catchment, heavily urbanized and with steep slopes that is causing the recurrent and very dangerous flash floods that enter and flood the bus station.

The main ingredients of the flash floods are:

- the upper part of the Mpazi sub-catchment is mostly steep and rocky ground with sparse vegetation; the retention capacity in this part of the catchment is very low
- the remainder of the Mpazi sub catchment is high density housing area in which up to 90% of the surface area consists of tin roof and the remainder is compacted barren earth or rock; the retention capacity in this part of the catchment is lower still
- the Mpazi sub catchment is very small and steep which leads to very short lead time between the onset of high intensity rainfall and the arrival of a flash flood
- the stone masonry channel is damaged at several locations; this mobilises large boulders to be carried down the channel and deposit at lower slopes where it reduces channel capacity. . (SHER Ingénieurs Conseil; 2013)

The principal purpose of this research is the design of appropriate hydraulic structures for sustainable flood control in the Nyabugogo catchment-Mpazi sub catchment.

1.3. RESEARCH OBJECTIVE

1.3.1. Main Objective

The main objective is the design of appropriate hydraulic structures for sustainable flood control in the Nyabugogo catchment, with focus on the Mpazi Sub catchment.

1.3.2. Specific objectives

In line with the research hypothesis, the following research objectives have been outlined:

- To quantify the current peak runoff water discharge for the Mpazi sub catchment and its prediction in 30years,
- To calculate the discharge which can be carried by the existing hydraulic structures,
- To design the appropriate hydraulic structures which are able of carrying the predicted peak runoff water discharge for a sustainable flood control solution.

1.4. SCOPE OF THE RESEARCH

According to the main objective of this research which is the design of appropriate hydraulic structures for sustainable flood control in the Nyabugogo catchment especially in the Mpazi sub catchment. The design of those hydraulic structures has been limited in the Mpazi drainage channel.

1.5. METHODOLOGY

The full implementation of the study has been carried out in the selected site which is the Nyabugogo catchment- Mpazi sub catchment. The following techniques have been used:

- The Collection of daily rainfall data from the KANOMBE airport meteorological station (January 2003 to December 2013) and daily rainfall data from the meteorological station installed in the Nyabugogo swamp during the research period (January to June 2014),
- Calculation of the current peak runoff water discharge for the Mpazi sub catchment and its prediction in 30 years by using the rational method,
- Determination of the discharge which can be carried by the existing hydraulic structures by using the Manning equation for the open channel and the rectangular culverts design formula for the culverts,
- Design of appropriate hydraulic structures able of carrying the predicted peak runoff water discharge.

1.6. THESIS STRUCTURE

This research has been structured as shown below:

Chapter 1: General introduction

Chapter 2: Literature review

Chapter 3: Methodology

Chapter 4: Data analysis

Chapter 5: Conclusion and recommendations

CHAP 2. LITERATURE REVIEW

2.1. CATCHMENT

A catchment is defined as the land area that contributes runoff to a given hydro edge.

Other terms that are used to describe a catchment are drainage basin, drainage area, river basin and water basin. Drainage basins drain into other drainage basins in a hierarchical pattern, with smaller sub-drainage basins combining into larger drainage basins.

In closed drainage basins, the water converges to a single point inside the basin, known as a sink, which may be a permanent lake, dry lake, or a point where surface water is lost in underground. The drainage basin includes both the streams and rivers that convey the water as well as the land surfaces from which water drains into those channels, and is separated from adjacent basins by a drainage divide.

The drainage basin acts as a funnel by collecting all the water within the area covered by the basin and channeling it to a single point. Each drainage basin is separated topographically from adjacent basins by a perimeter, the drainage divide or watershed making up a succession of higher geographical features (such as a ridge, hill or mountains) forming a barrier.

Drainage basins are similar but not identical to hydrologic units, which are drainage areas delineated so as to nest into a multi-level hierarchical drainage system. Hydrologic units are designed to allow multiple inlets, outlets, or sinks. In a strict sense, all drainage basins are hydrologic units but not all hydrologic units are drainage basins. (Patricia S. H.; 2010)

2.2. FLOOD

A flood is an overflow of water that submerges land which is usually dry. The European Union (EU) floods directive defines a flood as a conveying by water of land not normally covered by water.

A flood occurs when the peak flow coming into a reservoir is larger than the capacity of reservoir.

Flood severity is characterized by water level, flood duration and velocity, while probability refers to flood frequency.

The relationship between flood exposure and vulnerability of exposed elements is directly proportional: as exposure increases, vulnerability increases.

2.2.1. Flood in Rwanda

Most of countries in Africa are regularly affected by severe and often multi-year disasters including landslides and floods. However, all areas within Africa are not equally vulnerable to these disasters. Rwanda, because of its geographical feature and climatic profile is one of the sub-Sahara African countries prone to disasters and especially localized landslides and floods. Rwanda experiences disaster cases resulting from natural hazard including flooding, landslides, strong winds, heavy rains and storms. The causes of vulnerabilities to disasters include geographic characteristics such as steep slopes and others.

Rwanda is vulnerable to a range of disasters and emergency situations. Floods and landslide are key disasters that frequently affect localized areas of the country and most of the affected people do not have efficient mechanisms to cope with natural hazards. In addition, the hilly topography and high annual precipitation rates with overexploitation of the natural environment such as deforestation, inappropriate farming and poor housing techniques accelerate the disaster risks and hence result into losses of lives and damages to property from the community exposed to these disaster risks. (Bizimana, 2010)

Therefore, in Rwanda, most vulnerable areas prone to landslides and floods are located in the North-Western part namely Nyabihu, Rubavu, and Musanze, Burera, Gakenke and many others. This situation calls upon the Ministry of Disaster Management and Refugee to conduct a scientific field study to identify the areas mostly prone to floods and landslides all over the country and this will contribute a lot in the process of sustainable management of disaster risks.

As Kigali City urbanized, people began occupying the Nyabugogo River's flood plains, raising the issue of flood exposure. (Bizimana, 2010)

Due to the steepness of relief and intense rainfall, the swampy valleys constitute hazardous locations for settlements and a drainage challenge, especially along Nyabugogo River. (Bizimana, 2010)

Nyabugogo wetland, located in the City of Kigali, is one of the major flood prone areas in the country, where almost every year flood events are recorded. (Munyaneza, 2013)

Recent Flood History in Rwanda

Due to the steepness of its terrain, intense rainfall, and population pressure on land, many areas of Rwanda have been flooded in the last twenty years. In May 1988, a flood occurred in former Ruhengeri Province (Bizimana, 2010)

During September and December 2001 floods damaged infrastructure and crops in west Rwanda (MININFRA/Rwanda 2004b) and another flood occurred that November in Kijote settlement (formerly Gisenyi Province)

Recently, on 28 April 2002, the main road connecting traffic between Rwanda's two major cities (Kigali and Butare, now Huye) was cut off at Nyabarongo Bridge and became temporarily impassible. This situation created traffic congestion.

More recently, a flood in April 2006 destroyed 40 houses and resulted in two deaths (New Times, 10 April 2006). The Kiruhura market in the Nyabugogo River plain is located in a narrow valley between two steep mountainous areas and the river overflowed into the shops reaching 1.5 m in height, 132 small shops had to be temporarily relocated upstream. (Bizimana, 2010)

November 2006, 25 people died in Rulindo district when the Base River burst its banks and swamped a village. Similarly in Rubavu District (Western Province) during a flood in September 2007, houses were flooded and people died (New Times1).

In May 2006, the Kigali City council decided to relocate the market to a new site free of flood hazard risks. Similarly, the RWANTEXICO factory was flooded to 1.5 m and ceased functioning, See the figure bellow.

Photo 2: Flood level observed at Rwatexco

Source: Photo taken by Jean Pierre Bizimana, September 2006

In 2011, floods also destroyed around 354 houses in the Western Province and damaged about 3,000 hectares of farmland, forcing farmers to seek refuge on higher ground (MIDIMAR Report, 2011).

On 07th May 2011, around 14 people lost lives due to a heavy landslide that stroke the steep slope in Gakoro cell, Rugera Sector of Nyabihu District in the Western Province (MIDIMAR report, May 2011).

In November 2011, Torrential rains caused flooding and landslides which affected community and livelihoods in two Sectors of Burera District including Kinyababa and Burera and huge losses were basically composed of human lives and enormous agricultural farms collapsed.

For all these emergencies, MIDIMAR and partners responded with relief items to assist victims and the cost of interventions in these events were estimated to eleven Million Rwanda francs (MIDIMAR Report, 2011).

Within a period of ten months (Dec/2010-Sept 2011), disasters produced a complex web of impacts, which spans various sectors of the economy. During this same period, Rwanda registered 43 losses of lives and 73 people were injured. Besides, 1854 houses were destroyed, 2, 989, 9 Ha of crops were damaged and one hundred (100) school classrooms were seriously destroyed.

As a result, the cost of the intervention activities in terms of disaster response and recovery to assist the victims was more than 515,520,000 Rwandan francs (MIDIMAR reports, May - September 2011).

Above mentioned reasons is the justification to conduct a scientific study so as to identify all areas mostly affected by floods and landslides in Rwanda.

The cases described above show that repeated flooding is becoming a serious problem and challenge for urban and regional planners in the City. The flood challenge requires that new strategies and mitigation measures be implemented in areas identified as being at risk of floods. (Bizimana, 2010)

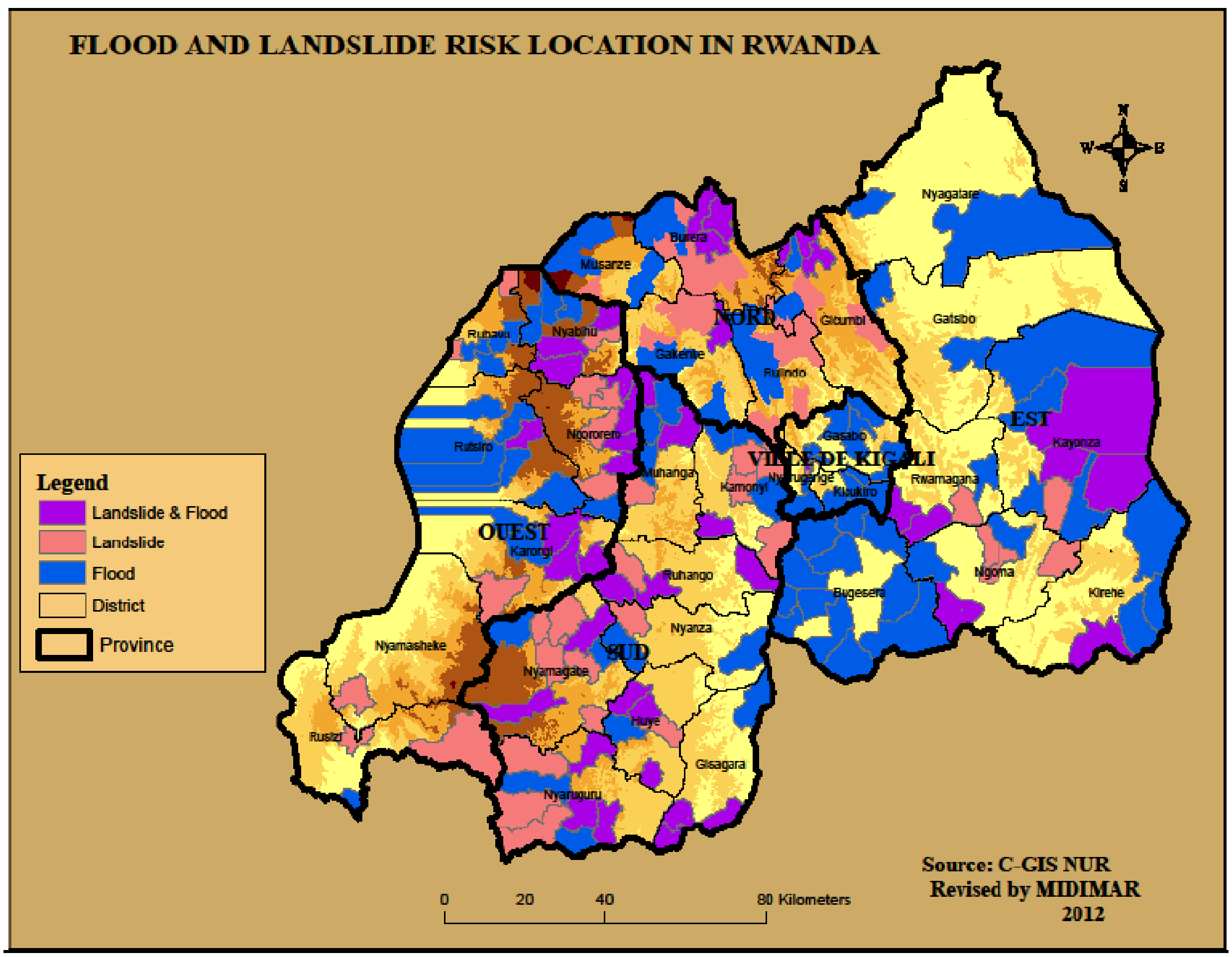

Figure 2: Flood and landslide risk location in Rwanda

Urban Growth and Rainfall Exposure in Kigali City

Kigali is the only official city in Rwanda. It is located in the central part of the country (Figure3). The growth of Kigali City during the colonial period (from 1909 to 1962) was very slow and limited to the Nyarugenge hill .Soon after independence, when all administrative functions were relocated to Kigali, the city extended beyond Nyarugenge hill to neighboring hills such as Nyamirambo, Gikondo, Kimihurura and Kacyiru (MININFRA 2006).

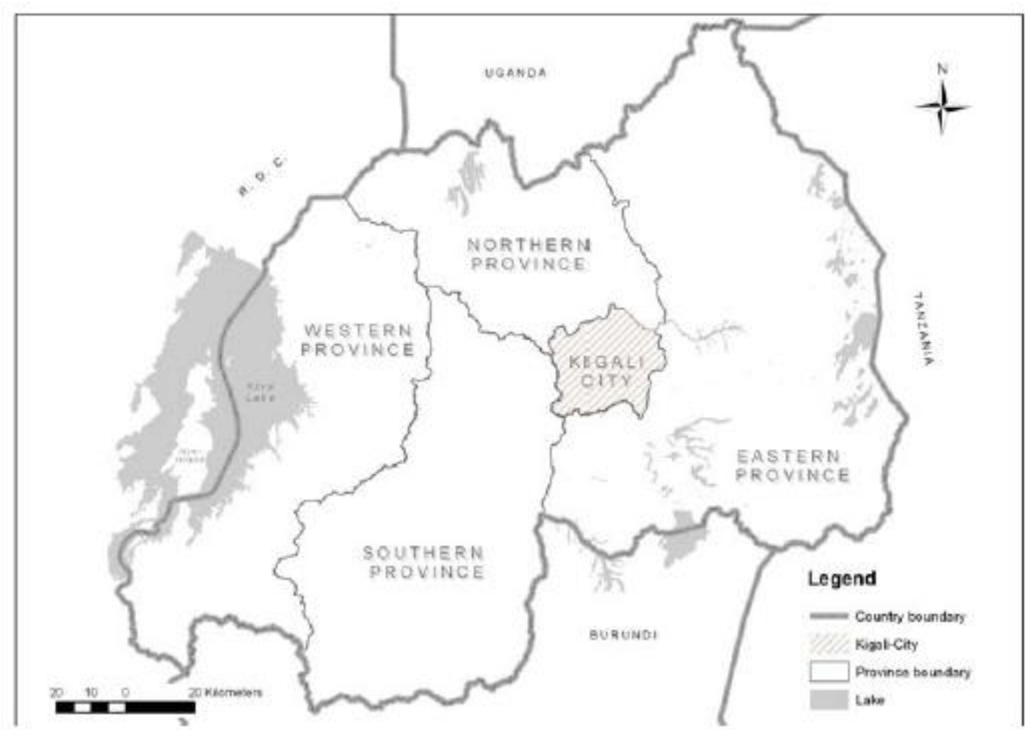

Figure 3: Location of Kigali city in Rwanda

Source: MINITRACO/CGIS-NUR, 2001 and NISR, 2006

The Nyabugogo River is between the steep hills of Gisozi, Mont Jari and Kanyinya, Mont Kigali and Nyarugenge. Due to the steepness of relief and intense rainfall, the swampy valleys constitute hazardous locations for settlements and a drainage challenge, especially along Nyabugogo River.

As Kigali City urbanized, people began occupying the Nyabugogo River’s flood plains, raising the issue of flood exposure.

The combination of intense rainfall, wetland areas, and steep slopes make the areas around Kigali City highly susceptible to risk of flooding. (Bizimana, 2010)

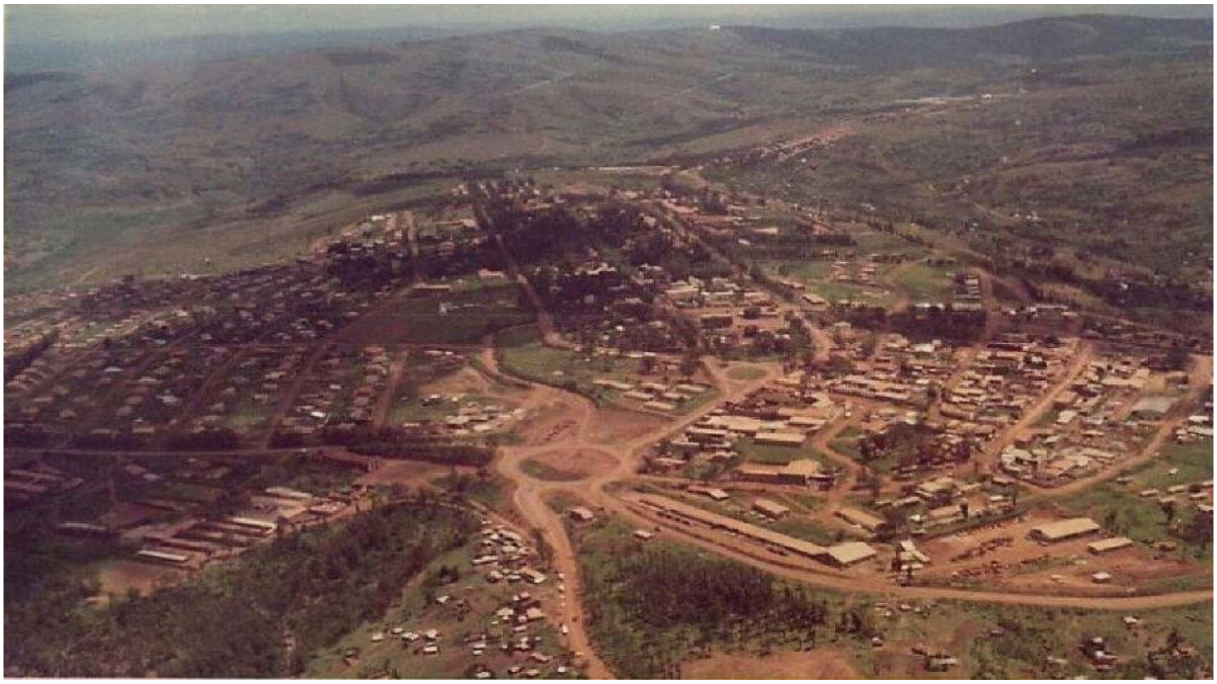

Photo 3: Kigali city in 1962

Source: Kigali city master plan

Photo 4: Kigali city in 2014

Source: Google earth

2.2.2. Types of floods

a) River Floods: Rivers floods happen when rivers and streams cannot carry away all the extra water that falls as rain. The water rises in the rivers and streams and overflows onto normally dry land. Floods destroy farmland, wash away people's houses and drown people and animals. Towns and cities are flooded too. (MIDIMAR, 2012)

b) Flash floods: A flash flood is a quick flood caused by a sudden cloudburst or thunder storm. Huge amounts of water fall in a short time and in cities and towns the drains overflow and roads become flooded. Flash floods also happen in mountainous areas, where steep slopes cause the water to travel at high speeds. The rushing water erodes the soil, washing it away down the slopes. Flash floods often occur rapidly and with little warning. (MIDIMAR, 2012)

These floods generally develop over a period of days, when there is too much rainwater to fit in the rivers and water spreads over the land next to it (the 'floodplain'). However, they can happen very quickly when lots of heavy rain falls over a short period of time. These 'flash floods' occur with little or no warning and cause the biggest loss of human life than any other type of flooding. (http://www.environment-agency.gov.uk/flood)

c) Coastal flooding: Can be caused by strong winds blowing waves onto the land. Hurricanes and major storms produce most coastal floods. Very high tides and tsunamis also flood the coasts. In many countries, large groups of people live along the coasts and for these people coastal flooding can be very serious. Thousands of people have been drowned in coastal flooding in many parts of the world. (MIDIMAR, 2012)

Coastal areas are also at risk from sea flooding, when storms and big waves bring seawater onto the land. The worst cases of flooding may occur if there is a combination of storms, 'spring tides' and low atmospheric pressure. (http://www.environment-agency.gov.uk/flood)

2.2.3. Causes of floods

Floods are caused by many factors: heavy precipitation, severe winds over water, unusual high tides, tsunamis, or failure of dams, levels, retention ponds, or other structures that contained the water.

During times of rain or snow, some of the water is retained in ponds or soil, some is absorbed by grass and vegetation, some evaporates, and the rest travels over the land as surface runoff.

Floods occur when ponds, lakes, riverbeds, soil, and vegetation cannot absorb all the water. Water then runs off the land in quantities that cannot be carried within stream channels or retained in natural ponds, lakes, and man-made reservoirs. (European flood alert system; 2009) River flooding is often caused by heavy rain, sometimes increased by melting snow. A flood that rises rapidly, with little or no advance warning, is called a flash flood. Flash floods usually result from intense rainfall over a relatively small area, or if the area was already saturated from previous precipitation. (European flood alert system; 2009)

Causes of flooding in Rwanda

The various causes of flooding in all of thirty (30) Districts of the country lies predominantly on climate change which result into heavy rain with storms and impact on river and flash flooding through overflowing of various streams passing through different districts .

The analysis from the Table below, reveals that Districts are affected by river flooding as well as flash flooding and threatening river from the top to the bottom are as follows. (Bizimana, 2010)

Table 1: Flash flooding and River flooding in Rwanda

N0	Districts	Flooding type	Triggering factor	Intensity
1.	Rulindo	Flash	Heavy rain and steep slopes	High
2.	Nyabihu	Both	Heavy rain which overlap various streams in the area	High
3.	Nyamagabe	Both	Heavy rain which overlap various streams in the area	High
4.	Ngororero	Both	Heavy rain which overlap various streams in the area including Nyabarongo river	High
5.	Rubavu	Both	Heavy rain which overlap various streams in the area including Sebeya river	High

Table 2: River flooding in Rwanda 2010-2011

N0	Districts	Number of affected sectors	Threatening river	Triggering factor
1.	Bugesera	12	Nyabarongo river	Heavy rain and low drainage system
2.	Rutsiro	8	Nyabarongo river and its affluent	Heavy rain
3.	Gasabo	7	Nyabugogo river	Heavy rain and low drainage system
4.	Musanze	7	Base, Mukungwa rivers	Heavy rain and low drainage system
4.	Muhanga	5	Nyabarongo river	Heavy rain
5.	Kamonyi	5	Nyabarongo river	Heavy rain
6.	Gisagara	5	Akanyaru river	Heavy rain and low drainage system
7.	Nyamagabe	5	Mwogo, Sebeya and Mbirurume rivers (Nyabarongo tributaries)	Heavy rain and low drainage system
8.	Nyaruguru	4	Mwogo, Sebeya and Mbirurume rivers (Nyabarongo tributaries)	Heavy rain and low drainage system
9.	Kicukiro (Masaka swamp area)	4	Nyabarongo river	Heavy rain and low drainage system
10.	Kirehe	4	Akagera river	Heavy rain and low drainage system

Source: MIDIMAR, 2012

2.2.4. Effects of floods

Flooding has many impacts. It damages property and endangers the lives of humans and other species. Rapid water runoff causes soil erosion and concomitant sediment deposition elsewhere (such as further downstream or down a coast).

Structural damage can occur in bridge abutments, bank lines, sewer lines, and other structures within floodways. (European flood alert system; 2009)

Floodwater can seriously disrupt public and personal transport by cutting off roads and railway lines, as well as communication links when telephone lines are damaged. Floods disrupt normal drainage systems in cities, and sewage spills are common, which represents a serious health hazard, along with standing water and wet materials in the home. Bacteria, mould and viruses, cause disease, trigger allergic reactions, and continue to damage materials long after a flood. (http://www.environment-agency.gov.uk/flood)

Severe floods not only ruin homes / businesses and destroy personal property, but the water left behind cause's further damage to property and contents. The environment and wildlife is also at risk when damage when damage to businesses causes the accidental release of toxic materials like paints, pesticides, gasoline etc. (http://www.environment-agency.gov.uk/flood)

2.2.5. Flood control and disaster management

Flood control refers to all methods used to reduce or prevent the detrimental effects of flood waters .Some of the common techniques used for flood control are installation of rocks, rock rip-raps, sandbags, maintaining normal slopes with vegetation or application of soil cements on steeper slopes and construction or expansion of drainage channels. (European flood alert system; 2009)

AIMS OF DISASTER MANAGEMENT

Reduce (Avoid, if possible) the potential losses from hazards.

Assure prompt and appropriate assistance to victims when necessary.

Achieve rapid and durable recovery.

Table 3: Floods and water Hazards

Elements at Risk	Main Mitigation Strategies.
Everything in the flood plain.	Land use control
Earthen or soluble structures	Engineering of structures
Buried services and utilities	Elevation of structures
Food stores	Flood control structures
Crops and livestock	Reforestation projects (watershed management)

Source: (http://www.environment-agency.gov.uk/flood)

2.2.6. Flood control structures and techniques

Flood Fighting is an effort made to prevent or mitigate the effects of flood waters.

Flood events are a part of nature. They have existed and will continue to exist. As far as feasible, human interference into the processes of nature should be reversed, compensated and, in the future, prevented.

Flood control structures are designed to protect coastal and river-bank areas, including urban and agricultural communities, homes, and other economically valuable areas, and the people located within them. These structures are used to divert flows of water, by re-directing rivers, slowing natural changes in embankments and coastlines, or preventing inundation of vulnerable coastlines or floodplains. Dikes, spurs, levees, and seawalls often act as the first line of defense against overflowing rivers, floods, storm surges, and—in the longer term—rising seas.

By keeping water out, flood control structures lessen harm to physical infrastructure and help to ensure continuation of communities' economic and social activity. But flood control structures do not completely eliminate risk. Flooding may occur if the design water levels are exceeded.

If poorly designed, constructed, operated or maintained, these structures can increase risk by providing a false sense of security and encouraging settlements or economic activity in hazard-prone areas. (USAID; 2011)

Structures used to control floods; include dams, levees, channels and others.

Dredging of river channels, clearing of debris along riverbanks, and stabilization of riverbanks also moderate the effects of flood.

Plastic sheeting is laid out flat on the slope; sandbags are placed around the perimeter with additional bags placed randomly for weight. If the slope is steep, wooden stakes can be driven into the ground just above the area to be protected. (USAID; 2011)

a) Dam: A dam is a barrier that impounds water or underground streams. Dams generally serve the primary purpose of retaining water. A dam can also be used to collect water or for storage of water which can be evenly distributed between locations.

 

Photo 5: Dams

Source: The British dam society; 2011

b) Levee: It is an embankment designed to prevent the flooding of a river or a wall made of land or other materials that is built next to a river to stop the river from overflowing (Cambridge Advanced learner's Dictionary, third edition).

Levee and Embankment Threats

The main causes of levee failure or flood related problems due to high water are:

- Seepage through or under the levee heavy enough to cause a "boil".
- Erosion of the levee or embankment due to swift moving water or wave action.
- Overtopping resulting from water surface elevations higher than the levee or embankment. (Rick Burnett, 2012)

c) Dredging: Is the removal of sediments and debris from the bottom of lakes, rivers, harbors, and other water bodies. Dredging often is focused on maintaining or increasing the depth of navigation channels, anchorages, or berthing areas to ensure the safe passage of boats and ships.

Photo 6: Dredging of the Nyabugogo River

(Source: Ministry of Defence, 2012)

e) Open Channel

An open channel is a passage for water or other liquids to flow along, or part of a river or other area of water which is deep and wide enough to provide a route for ships to travel along. (Cambridge Advanced learner's Dictionary, 3rd edition, 2008).

2.2.7. Channel discharge capacity

The hydraulic capacity of a drainage channel is dependent on the size, shape, slope and roughness of the channel section. For a given channel, the hydraulic capacity becomes greater as the grade or depth of flow increases. The channel capacity decreases as the channel surface becomes rougher. A rough channel can sometimes be an advantage on steep slopes where it is desirable to keep flow velocities from becoming excessively high.

A good open channel design minimizes the effect on existing water surface profiles. Open channel designs, which lower the water surface elevation, can result in excessive flow velocities and cause erosion problems.

Additional hydraulic considerations include those of channel and flood water characteristics such as: movable beds, heavy bed loads and bulking during flood discharges.

2.2.7.1. Manning's Equation

Robert Manning (1816-1897) was an Irish accountant who spent more time studying engineering than accounting. In 1890 he developed the Manning formula which is still in common use today. The formula takes two basic forms as follows:

In metric units.

$V=\frac{1}{n}*R^{2/3}*S^{1/2}$ **Equation 2.1**

$Q=A*V=\frac{1}{n}*A*R^{2/3}*S^{1/2}$ **Equation 2.2**

Where Q= Quantity of flow in cubic meters per second.

V = Mean velocity, in meters per second

n = Manning coefficient of roughness

S = Channel slope, in meters per meter

R = Hydraulic Radius, in meters

R = A/WP

Where A = Cross sectional flow area, in square meters

WP = Wetted perimeter, in meters

Commonly accepted values for Manning's roughness coefficient, n, based on materials and workmanship required in the Standard Specifications. (Tennessee hydraulics memoranda; 2004)

2.2.8. Culverts

The function of the Culvert is to convey or transport storm runoff (or other discharge) from one side of the roadway to the other - either culvert or bridge.

Culvert maintenance requirements include efforts to assure clear and open conduits, protection against corrosion and abrasion, repair and protection against local and general scour, and structural distress repair. (South African National Road Agency; 2013)

2.2.8.1. Design of rectangular culverts

Rectangular culverts are culverts which have the rectangular shape. The rectangular culverts design formula is described below.

D= Height (inside) (m)

B= Width (Inside) (m)

H_1= Upstream energy Level, relative to the invert level (m).

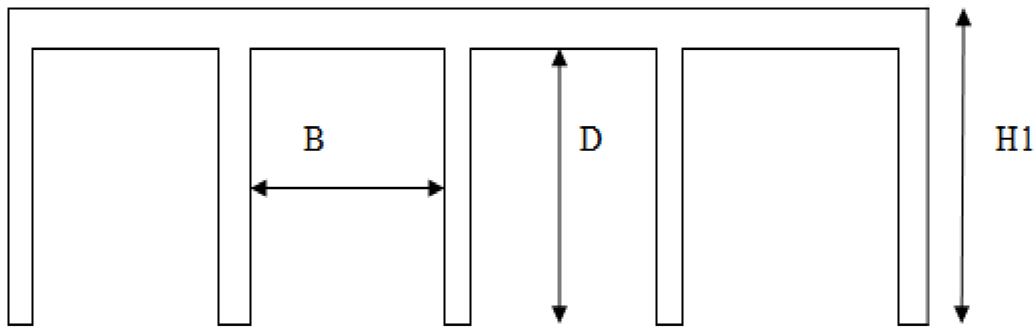

Figure 2.1 Culverts' elements

For $0 < H1/D \leq 1.2$

$$Q = \frac{2}{3} C_B B H_1 \sqrt{\frac{2}{3} g H_1}$$ Equation 2.3

Where: C_B=1.0 for rounded inlets (r>0.1B)

C_B =0.9 for square inlets

For H1/D>1.2

$$Q = C_h B D \sqrt{2g(H_1 - C_h D)}$$ Equation 2.4

Where: C_h=0.8 for rounded inlets

C_h=0.6 for square inlets (South African National Road Agency; 2013)

3.6. ESTIMATION OF THE RUNOFF DISCHARGE

The rational method is appropriate for estimating peak discharges for small drainage areas of up to about 200 acres (80 hectares) with no significant flood storage. The method provides the designer with a peak discharge value.

3.6.1. Estimation by using the Rational Method

The rational method estimates the peak rate of runoff at a specific location in a watershed as a function of the drainage area, runoff coefficient, and mean rainfall intensity for duration equal to the time of concentration.

The rational formula is:

$$Q = \frac{CIA}{Z}$$

Equation 3.1

Where:

Q = maximum rate of runoff (m^3/sec.)

C = runoff coefficient

I = average rainfall intensity (mm/hr.)

A = drainage area (in ha)

Z = conversion factor, 1 for English and 360 for metric.

Notice: It has been found by experiments that as the catchment area increases (>2 km2) the rational formula becomes less accurate (Langousis, 2005). De Laat and Savenije (2002) recommended its application in small catchments (smaller than 15 km^2). In such a case the point area should be multiplied by ARF (Area Reduction Factor) as shown in Fig. 7. The application of ARF to larger catchments was supported by Chow *et al.* (1988) and its accuracy was tested successfully by Butler and Davies (2004). Butler and Davies (2004) said “Point rainfall is not necessarily representative of rainfall over a larger area because average rainfall intensity decreases with increasing area. In order to deal with this problem, and avoid overestimating flows from larger catchments, areal reduction factors (ARF) have been demonstrated by Chow *et al.* (1988). The expression is valid depending on climate and/or storm duration. (Munyaneza; 2014)

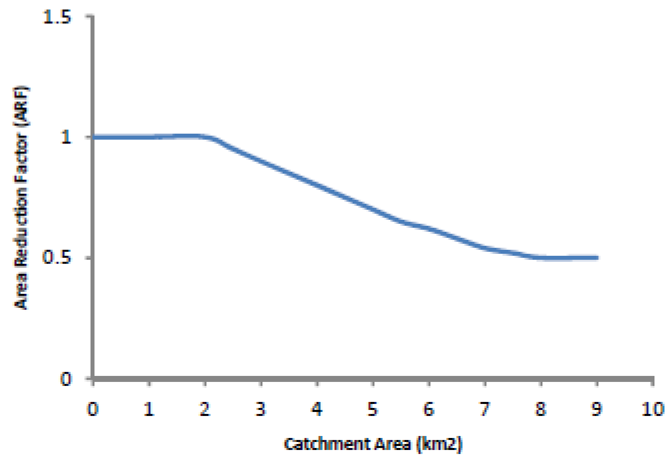

Figure 4: Area reduction factor curve for larger catchments (adapted from Langousis, 2005)

c) Runoff Coefficient (C)

i) What is it?

The runoff coefficient (C) is a dimensionless coefficient relating the amount of runoff to the amount of precipitation received. It is a larger value for areas with low infiltration and high runoff (pavement, steep gradient), and lower for permeable, well vegetated areas (forest, flat land).

ii) Why is it important?

It is important for flood control channel construction and for possible flood zone hazard delineation. A high runoff coefficient (C) value may indicate flash flooding areas during storms as water moves fast overland on its way to a river channel or a valley floor. (CIV246; 2009)

iii) How is it measured?

The general runoff coefficient is obtained as weighted average of partial runoff coefficients (C_i)

$$C=\frac{\sum_{i=1}^{n} Ai*Ci}{\sum_{i=1}^{n} Ai}$$

Equation 3.4

It is also calculated by determining the soil type, gradient, permeability and land use.

The values are taken from the table below. The larger values correspond to higher runoff and lower infiltration. (CIV246; 2009)

Table 4: Runoff coefficient in relation with land use

Source: (CIV246; 2009)

Land Use	C	Land Use	C
Business: Downtown areas Neighborhood areas	 0.70 - 0.95 0.50 - 0.70	***Lawns:*** Sandy soil, flat, 2% Sandy soil, avg., 2-7% Sandy soil, steep, 7% Heavy soil, flat, 2% Heavy soil, avg., 2-7% Heavy soil, steep, 7%	 0.05 - 0.10 0.10 - 0.15 0.15 - 0.20 0.13 - 0.17 0.18 - 0.22 0.25 - 0.35
Residential: Single-family areas Multi units, detached Munti units, attached Suburban	 0.30 - 0.50 0.40 - 0.60 0.60 - 0.75 0.25 - 0.40	***Agricultural land:*** *Bare packed soil* *Smooth *Rough *Cultivated rows* *Heavy soil, no crop *Heavy soil, with crop *Sandy soil, no crop *Sandy soil, with crop *Pasture* *Heavy soil *Sandy soil Woodlands	 0.30 - 0.60 0.20 - 0.50 0.30 - 0.60 0.20 - 0.50 0.20 - 0.40 0.10 - 0.25 0.15 - 0.45 0.05 - 0.25 0.05 - 0.25
Industrial: Light areas Heavy areas	 0.50 - 0.80 0.60 - 0.90	*Streets:* Asphaltic Concrete Brick	 0.70 - 0.95 0.80 - 0.95 0.70 - 0.85
Parks, cemeteries	0.10 - 0.25	Unimproved areas	0.10 - 0.30
Playgrounds	0.20 - 0.35	Drives and walks	0.75 - 0.85
Railroad yard areas	0.20 - 0.40	Roofs	0.75 - 0.95

Note: The designer must use judgment to select the appropriate "C" value within the range. Generally, larger areas with permeable soils, flat slopes and dense vegetation should have the lowest "C" values. Smaller areas with dense soils, moderate to steep slopes, and sparse vegetation should assigned the highest "C" values. (CIV246; 2009)

iv) Land use prediction

The land use prediction has a great influence on the runoff coefficient and then on the runoff discharge.

$L_{i+n}=L_i\ (1+n\frac{a}{100})$ **Equation 3.5**

Where: Li = Built area at year i

L_{i+n} = Forecasted built area after n years

n = Design period (years)

a = Annual urbanization growth rate (%)

a) Rainfall Intensity

With the drainage area A, the designer will determine appropriate values of I and C for use in Equation 3-1 is given by:

$$I = \frac{P_d}{t_c}$$

Equation 3.6

Where:

P_d =is the maximum daily precipitation (mm).

For this research, we have taken daily data from January 2003 to June 2014.

T_c = drainage area time of concentration (hr.)

Note: For design purposes we use the highest rainfall intensity at the project site.

b) Time of concentration (T_c)

Time of concentration (**T_c**) is the time required for runoff to travel from the hydraulically most distant point in the watershed to the outlet. Time of concentration is generally applied only to surface runoff and may be computed using many different methods. Time of concentration will vary depending upon slope and character of the watershed and the flow path.

The Kirpich/Ramser formula is mostly used to calculate the time of concentration (Dawod et al., 2011 and Munyaneza et al, 2012).

$T_c=0.0195L^{0.77}S^{-0.385}$ **Equation 3.7**

Where: $\mathbf{T_c}$ = Time of concentration [min], L = Length of main stream [m]: This is got from ArcGIS tools, S = Average slope of main stream [m/m].

Table 5: Manning's Roughness Coefficients For Artificial Channels - n Table

(Source: HEC-15, 1988)

		Depth Ranges		
Lining Category	**Lining Type**	**0-0.5 ft**	**0.5-2.0 ft**	**>2.0 ft**
Rigid	Concrete	0.015	0.013	0.013
	Grouted Riprap	0.040	0.030	0.028
	Stone Masonry	0.042	0.032	0.030
	Soil Cement	0.025	0.022	0.020
	Asphalt	0.018	0.016	0.016
Unlined	Bare Soil	0.023	0.020	0.020
	Rock Cut	0.045	0.035	0.025
Temporary*	Woven Paper Net	0.016	0.015	0.015
	Jute Net	0.028	0.022	0.019
	Fiberglass Roving	0.028	0.022	0.019
	Straw With Net	0.065	0.033	0.025
	Curled Wood Mat	0.066	0.035	0.028
	Synthetic Mat	0.036	0.025	0.021
Gravel Riprap	1-inch D_{50}	0.044	0.033	0.030
	2-inch D_{50}	0.066	0.041	0.034
Rock Riprap	6-inch D_{50}	0.104	0.069	0.035
	12-inch D_{50}	---	0.078	0.040

Note: Values listed are representative values for the respective depth ranges. Manning's roughness coefficients, n, vary with the flow depth.

CHAPTER 3: METHODOLOGY

3.1. CATCHMENT DESCRIPTION

The Nyabugogo Catchment is located in the central eastern part of Rwanda. The catchment drains a total area of about 1,647 km^2 dispatched in 8 districts: Rulindo, Gicumbi, Gatsibo, Kayonza, Rwamagana, Gasabo, Nyarugenge and Kicukiro.

The climate of the catchment is mostly of temperate and equatorial type with average temperature ranging between 16°C and 23°C, depending on the altitude of the area. The annual rainfall in Rwanda varies from about 800 mm to 1,600 mm. There are normally four seasons in Rwanda. The first is a long dry season that spans from June to September, followed by a short rainy season spanning from October to December. This season receives 30% to 40% of the annual rainfall with the highest rains falling in November. The third is a short dry season starting in December and ending in January. The fourth is a rainy season spanning from February to end of May. This season receives around 60% of annual rainfall.

The Nyabugogo River traverses the City of Kigali and has many tributaries such as the Mwange River, Rusine River and Marenge River on its upstream portion. It is later fed by other rivers from the urbanised part of Kigali such as the Rwanzekuma River, the Ruganwa River, the Mpazi River and the Yanze River. (Nhapi et al., 2011)

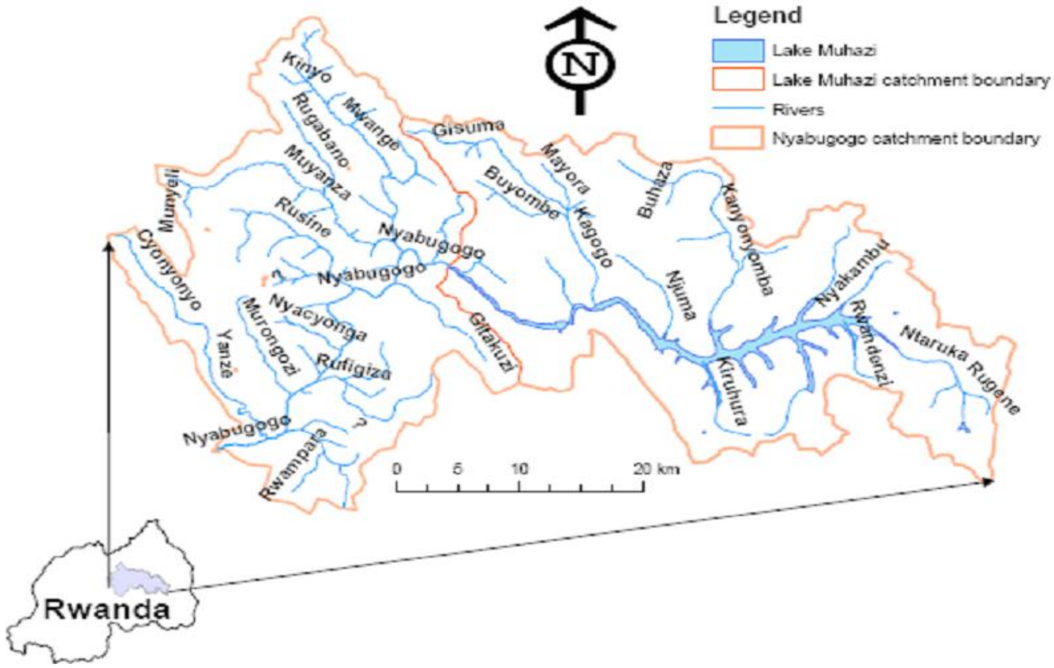

Figure 5: The Nyabugogo catchment including its location in Rwanda

(Source: Nhapi et al., 2011)

3.2. MPAZI CHANNEL

Mpazi is a trapezoidal channel made in stone masonry collecting rain water from Gitega, Kimisagara, Muhima and Nyabugogo areas, and is characterized by many flash floods during rainy seasons.

In general, Mpazi drainage channel drains rainwater as fast as possible. In its design no attention was paid to the effect of very rapid urbanized in that part of the town. Its slope varies between 3 to 4 % on average, leading to uncontrollable discharges in the lower part near the Nyabugogo bus stand as the channel provide no energy reduction measures of the runoff. One could therefore say that it was not well designed and its construction is of a doubtful quality.

The channel was constructed on a soft soil which cannot support the weight of the stones used it can be seen in some points. The water pressure is too high during heavy rains with a steep upstream slope causing a wash away of the channel walls especially at the corners. The channel has a lot of corners which needs to be widened to reduce the water pressure at those points. (RNRA, 2013)

3.3. SUB CATCHMENT DESCRIPTION

The Nyabugogo catchment cover many sub-catchments located in different districts of Kigali city, Northern Province and Eastern province.

The research was focused on the Mpazi sub-catchment which is entirely located in the Nyarugenge district.

This sub catchment is geographically located between longitudes 1^{o} 56’00’’S and 1^{0}59’00’’S, and between latitudes 30^{o}02’00’’E and 30^{o}04’00’’E, as it is shown by the figure bellow:

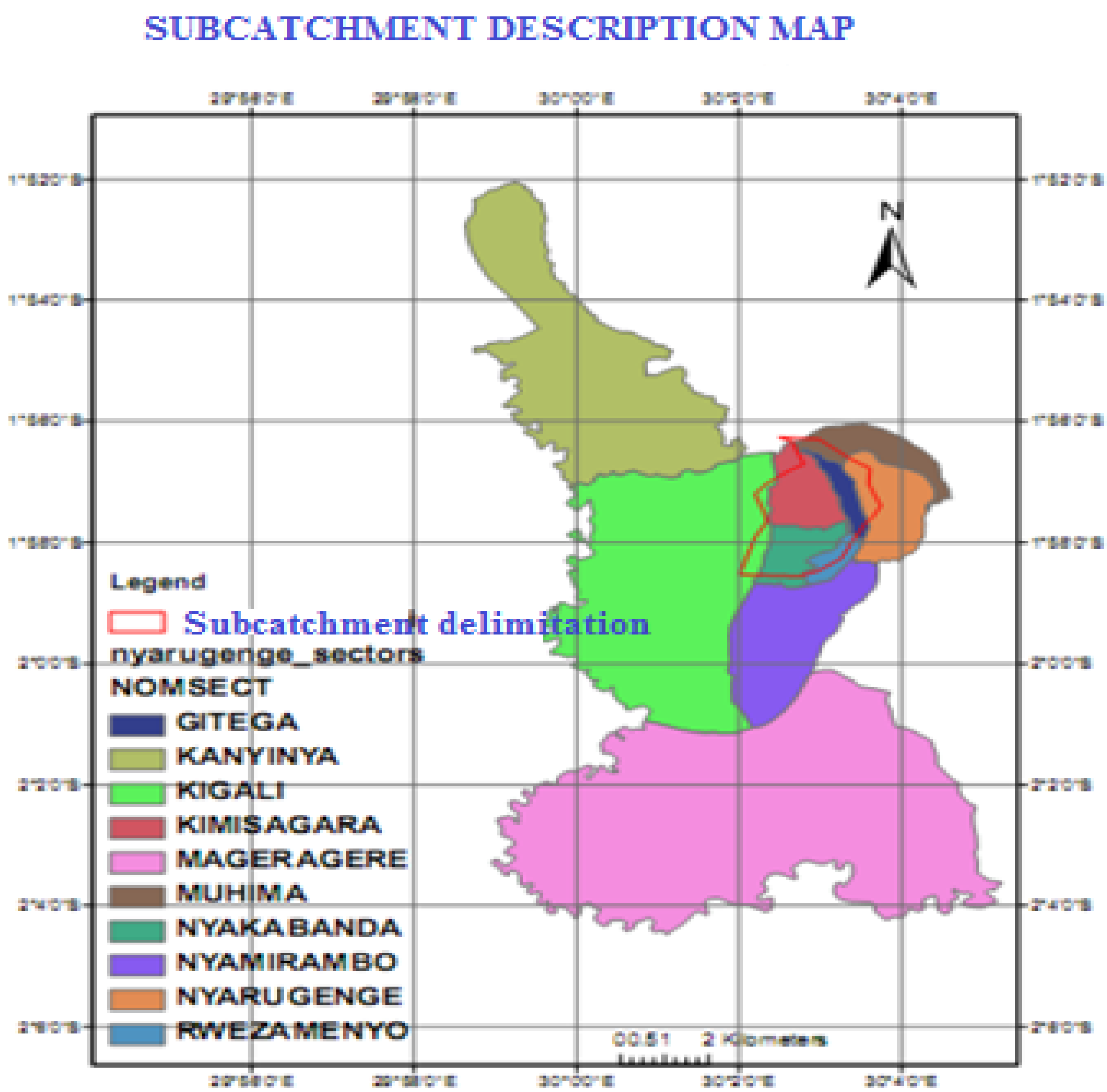

Figure 6: Mpazi sub catchment description map

3.4. SUB CATCHMENT DELINEATION

The delineation of the catchment has been done using ArcGis software and the covered area is 8.37 km^2.

By using this software, the following steps have been followed for the catchment delineation:

1. Open ArcMap and create a contour map of Rwanda
2. Spatial analyst tools > hydrology > Fill > OK
3. Create Flow direction
4. Create Flow accumulation
5. Create Watershed (catchment) outlet ("pour") points
6. Convert the pour (outlet) point features to a raster.
7. Raster to vector (Convert the watershed grid to a polygon shapefile)
8. Add area field in the attribute table of created shapefile and calculate geometric automatically.

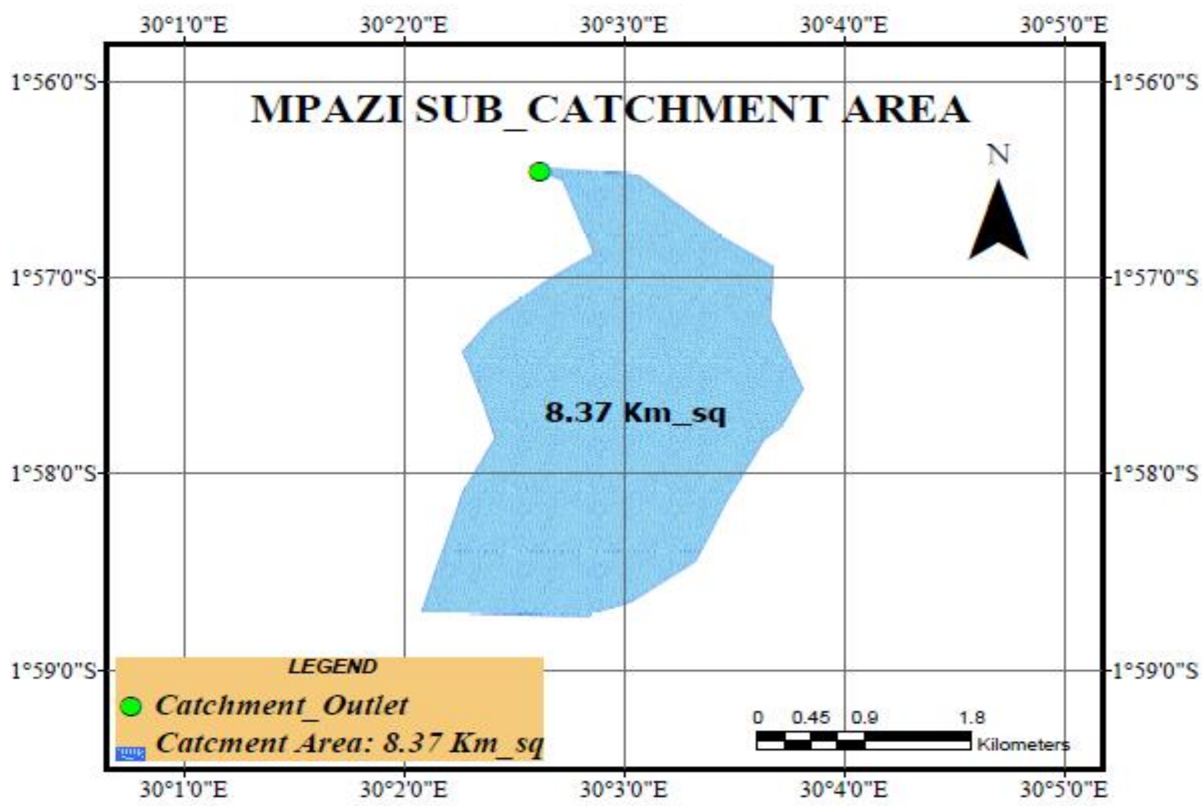

Figure 7: Mpazi delineation map

3.5. THE MPAZI SUB CATCHMENT CHARACTERISTICS

3.5.1 Topography

The Mpazi sub catchment is located in a mountain area which is dominated by a high sloped area.

This sub catchment is mainly dominated by a steep slope area. The figure bellow shows its topography by contour lines. These contour lines show very well how the water flow is by gravity.

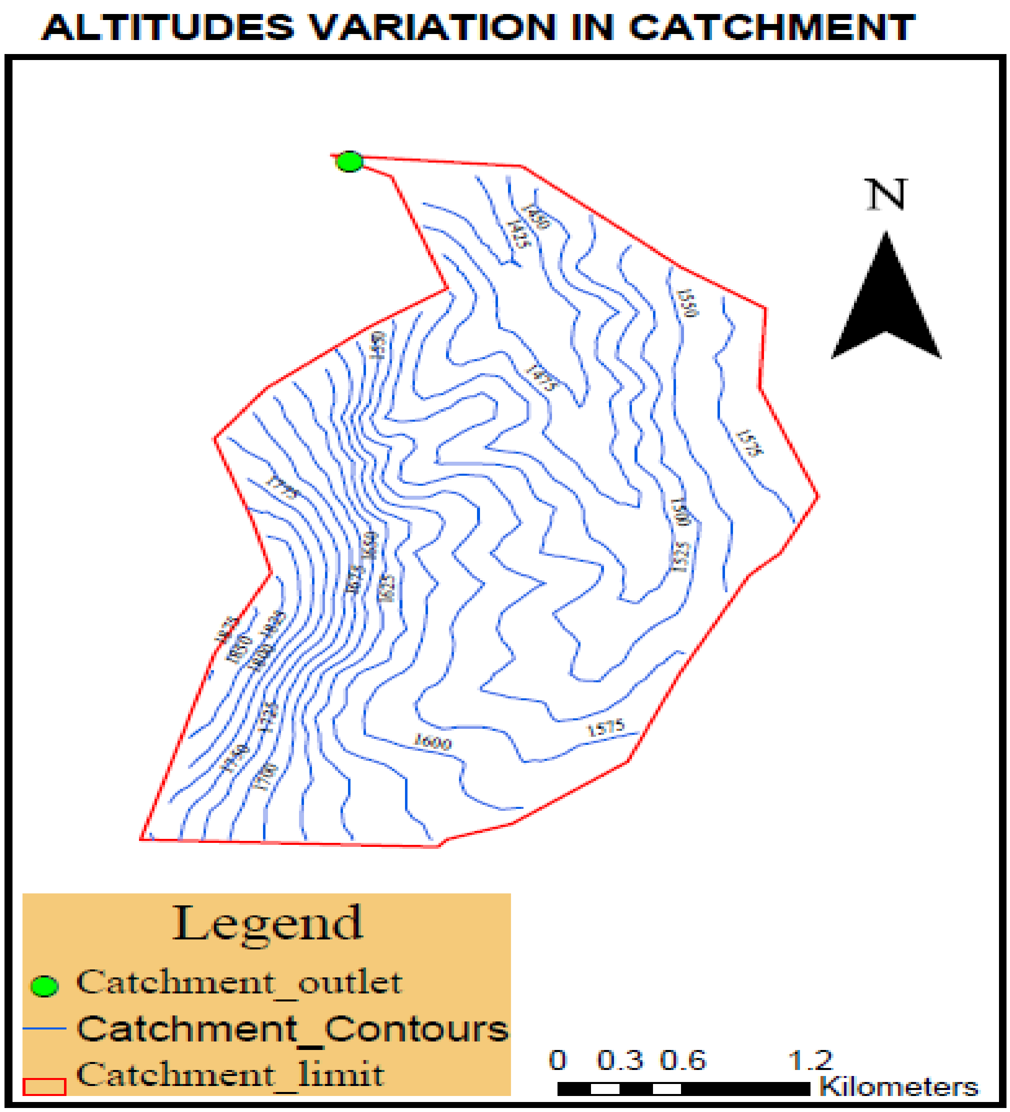

Figure 8: Mpazi topography

3.5.2 Land use

The catchment is mainly occupied by a build up area and the other part is for the green space.

The analysis has shown that the buildup area occupy 6.49 Km^2 (77.54%) while the green area is 1.88 Km^2 (22.46 %.).

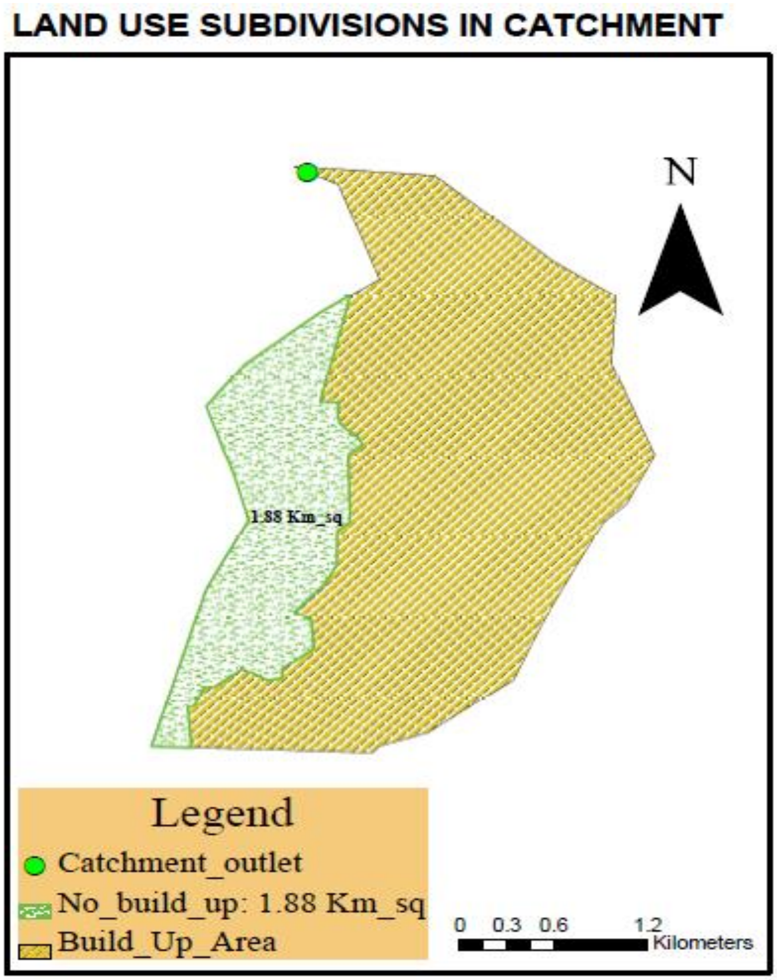

Figure 9: Land use subdivision

a) Length of main stream (L)

The length of the main channel in the catchment is calculated through ArcMap, is the distance between the outlet point and the very far point .For this case, the length is found to be equal to **5.98 km** as it is represented by the figure 10.

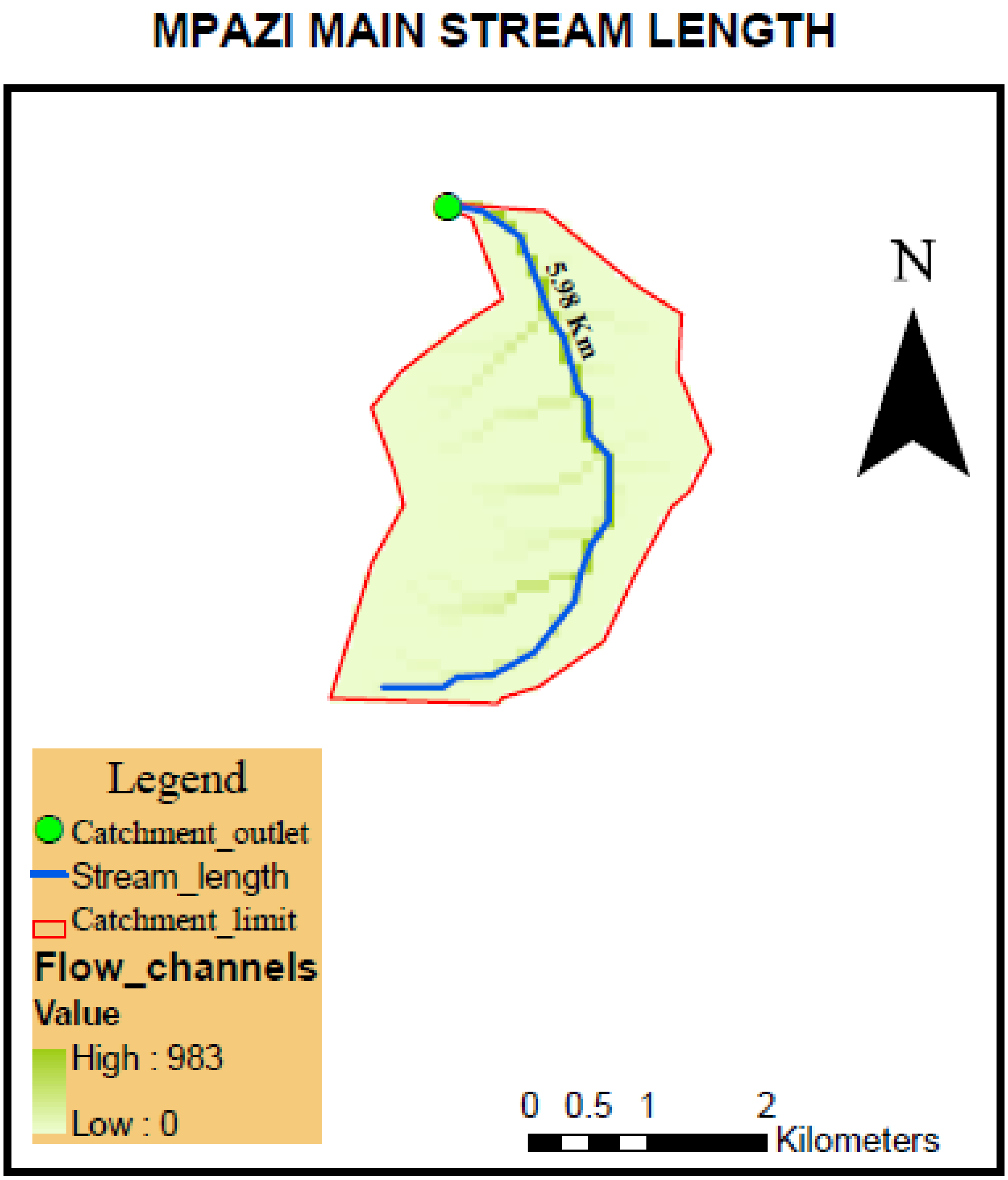

Figure 10: Mpazi main stream length

CHAPTER 4: DATA ANALYSIS

4.1. CALCULATION OF THE PEAK RUNOFF DISCHARGE

In the assessment of drainage system performance, the research has considered the flooding worst case in the considered period. This research has covered a period of eleven years and six months; starting from January 2003 to June 2014. The collected data have shown that severe rain occurred on 23rd February, 2010 where the observed precipitation was 89.2 mm.

4.1.1. Time of concentration

The Time of concentration (**T_c**) which is the time required for runoff to travel from the hydraulically most distant point in the watershed to the outlet is given by the equation 3.4

The length of main river channel is L = 5980 m

Slope along the main channel (S) is $S = \frac{\Delta H}{L}$ **Equation 4.1**

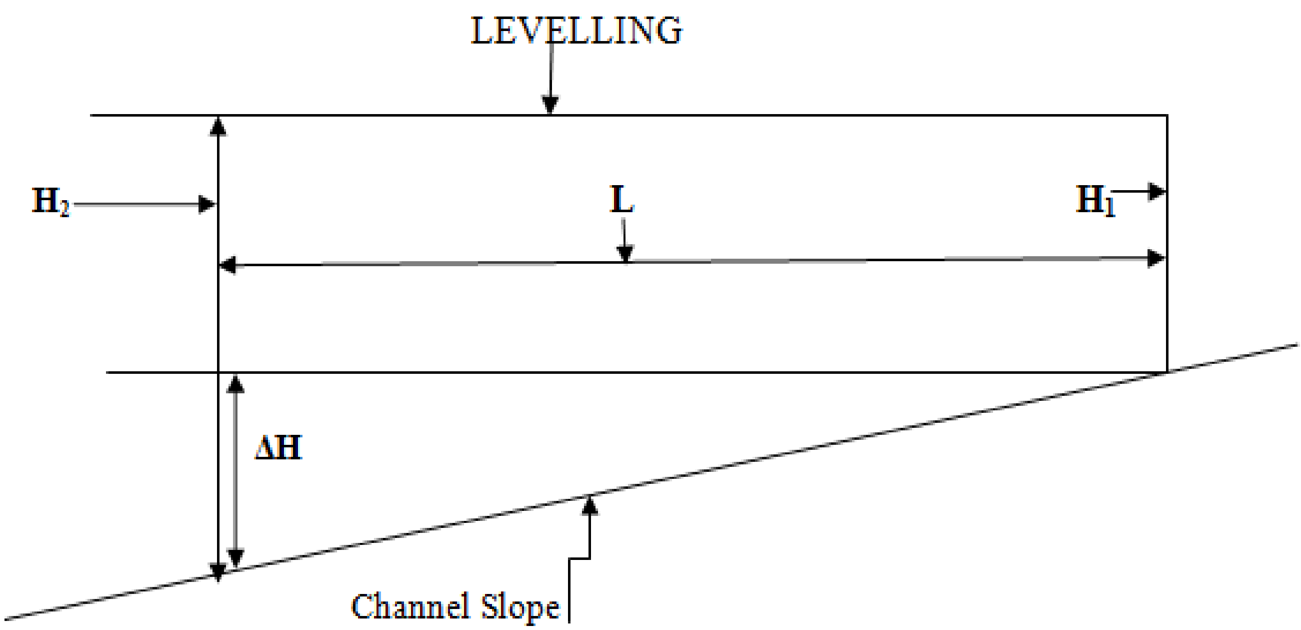

Figure 11: Scheme of the channel

Table 6: Bed slope of the existing channel

Measured Points	Difference in height (ΔH in cm)	Horizontal Length (L in cm)	Slope (%)
A-B	11	300	3.67
C-D	14	500	2.8
E-F	22	800	2.75
G-H	43	1500	2.87
I-J	74	2000	3.7
K-L	95	3000	3.17
	Average slope (%)		3.16

From this table, we find that the average slope is **0.0316**

The time of concentration is $\mathbf{T_c}=0.0195L^{0.77}(S)^{-0.385}$

$T_c=0.0195(5980)^{0.77}(0.0316)^{-0.385}=59.7\text{min}$

$T_c=59.7\text{min}$

The time of concentration for the Mpazi sub catchment has been found to be **59.7min.**

It means that the time required for runoff to travel from the hydraulically most distant point in the watershed to the outlet is equal to **59.7min.**

4.2. RUNOFF DISCHARGE

The runoff discharge is calculated by using the Equation 3.1

$$Q=\frac{CAI}{Z}$$

4.2.1 Area of the catchment

From the ArcGis, the Area of the Mpazi sub-catchment was found to be 8.37 km^2= 837ha. As its area exceeds $2km^2$, it is recommended to apply an area reduction factor. From the figure 3.4, the ARF was found to be 0.6. Then the reduced area is **837 ha*0.6=502.2ha.**

4.2.2 Runoff coefficient

The whole studied area is subdivided into two categories according to its land use. There is a green space and a buildup area. The runoff coefficient (C_i) is selected from the table 2.

Table 7: Runoff coefficient-Land use relationship

Sub-catchment	Soil type and/or Land use	Area ,Ai, in [ha]	Runoff coefficient (C_i)
Green area	Heavy soil with crops	188	0.5
Buildup area	Multi units attached	649	0.75

The runoff coefficient for this kind of land use has to be calculated by using the following formula:

$C=\frac{\sum_{k=1}^{n} Ai*Ci}{\sum_{i=1}^{n} Ai}=\frac{(188)*0.5+(649)*0.75}{837}=0.694$ **Equation 4.2**

4.2.3. Rainfall intensity

The rainfall intensity has to be calculated by using the average rainfall intensity method.

$I=\frac{P}{tc}$ **Equation 4.3**

$I=\frac{89.2}{59.7}$; **I=1.495 mm/min**

I=89.7 mm/hr ⇒ this is the highest intensity

Usually the design takes into consideration the highest intensity observed in the studied area and in the taken period. That highest intensity is extracted from the highest rainfall precipitation.

The runoff rate $Q=\frac{CIA}{360}$

The runoff water discharge for the Mpazi sub catchment has been calculated by replacing each parameter by its value as it has been shown by the equation 3.1.

$Q=\frac{0.694*89.7*502.2}{360}$

$Q= 86.8\ m^3/s$

This is the highest runoff water discharge which has been observed in the Mpazi in the taken period of study**.**

4.3. LAND USE PREDICTION

The land use is a major factor in the determination of the runoff coefficient of a given area, and this is a key element in the calculation of the runoff discharge. And the runoff discharge was the main pillar in this research.

The Mpazi is an urban area which is composed by two parts in terms of land exploitation. Those two parts are the part which is built on and the part which is occupied by the green space.

In this 2014, the Mpazi sub catchment has an area of 837ha and its land is exploited as it is shown below:

Build up area=649 ha (77.54%)

Green area=188ha (22.46 %.)

The design period of 30 years for sustainable flood control and has been calculated by using the linear prediction formula.

Built area: $L_i+_n=L_i\ (1+n\frac{a}{100})$

Where: Li = 649 ha

n = 30years

i=2014

i+n=2044

$L_i=L_{2014}$

$L_{i+n} = L_{2044}$

a = 9%

For the Kigali city, the annual urbanization growth rate is 9% (MININFRA, 2008)

$L_{2044}= 649\ (1+ 30\frac{9}{100})$ =**2401ha**

From this calculation, it is seen that the built area in 30years from now is greater than the catchment area. It means that the whole catchment will be built on and the remaining part of the population will go to build on other catchments. Even if other measures of reducing the rate of urbanization can be taken by the government, this will not have any impact on the design because the design has taken into consideration the worst situation.

The whole catchment will in general be composed by roofs, Concrete and asphalt which all have a runoff coefficient equal to 0.95 (from the table 1). Then the runoff coefficient has been calculated as:

$$C=\frac{\sum_{k=1}^{n} Ai*Ci}{\sum_{i=1}^{n} Ai}=\frac{(0)*0.5+(837)*0.95}{837}=\mathbf{0.95}$$

The change of the runoff coefficient has to have a great influence on the runoff water discharge for the sub catchment. The sub catchment runoff water discharge in 30 years from now had been calculated by replacing the new runoff coefficient by its value.

$$Q=\frac{0.95*89.7*502.2}{360}=\mathbf{118.9\ m^3/s}$$

The predicted runoff water discharge for the Mpazi sub catchment is **118.9 m^3/s.**

4.4. THE DISCHARGE CAPACITY OF THE EXISTING HYDRAULIC STRUCTURES

The existing hydraulic structures in the Mpazi drainage channel which have been considered in this research are the main open channel and two culverts located: the first is under the bridge on the road which connect the Nyabugogo bus station to the Muhima area and the Kigali town and the second is under the bridge on the road which connect the Nyabugogo bus station to the Kinamba area as it is shown by the following photos.

Photo 7: Existing hydraulic structures

4.4.1. Existing channel discharge capacity

The existing channel has a trapezoidal section and it is constructed in stone masonry. Its discharge capacity has been calculated by using the Manning's equation. Its section is shown by the sketch below:

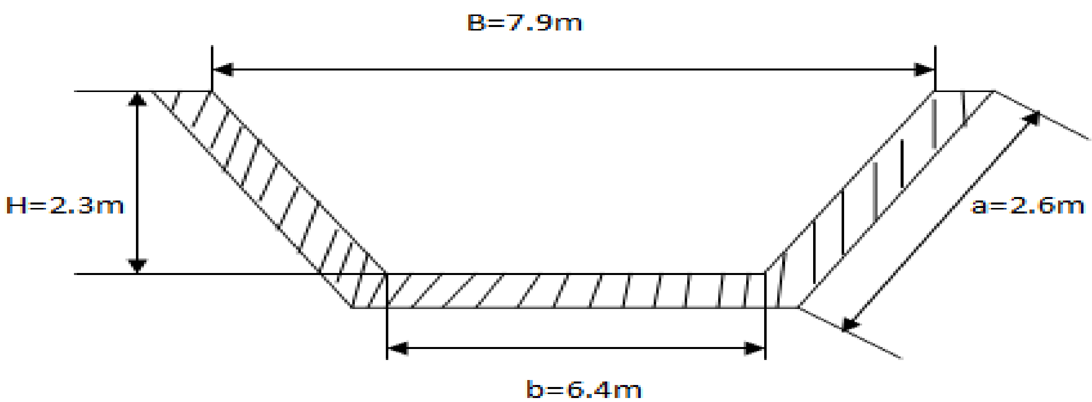

Figure 12: Section of the existing main channel

The determination of the discharge Capacity of an open channel using the Manning equation has taken into consideration of the calculation of the following parameters:

The Area: $A= (7.9+6.4)*2.3/2=16.445m^2$

The Wetted perimeter: $WP =2*2.6+6.4=11.6m$

The Hydraulic radius $R= A/WP=1.42m$

Then the discharge capacity of the open channel has to be calculated by using the following formula:

$Q=A*V=\frac{1}{n}*A*R^{2/3}*S^{1/2}$

The Mpazi main channel slope is S=0.0316 as it has been shown in Table 4.

The Manning's coefficient n is equal to 0.030 because the channel is constructed in stone masonry. Then the Hydraulic discharge capacity of the existing open channel is:

$Q=\frac{1}{0.03}*(16.445)*(1.42)^{2/3}*(0.0316)^{1/2}=$**$123.1m^3/s$**

The hydraulic discharge capacity of the existing channel at its time of construction was **123.1 m^3/s.**

The on field situation: The so called on field situation is the situation of high sedimentation which has been observed during the research period. The open channel is exposed to various uses like solid waste dumped in, the sedimentation of considerable quantities of stones and soil particles from the channel surrounding areas especially during heavy rains and this contribute to the reduction of the channel discharge capacity because it reduces the channel height. During heavy rains, the height of the channel is in average reduced of 20cm 0r 0.20m.

The calculation of the discharge Capacity of the open channel has to take into consideration the current situation where the channel height becomes 2.1m.

The Area: A= (7.9+6.4)*2.1/2=15.015 m^2

The Wetted perimeter: WP = $(2*2.6+6.4) - ((0.4)-(0.2))^{1/2}$=11.15 m

Then the discharge capacity of the open channel has been again calculated by using the formula:

$Q=A*V=\frac{1}{n}*A*R^{2/3}*S^{1/2}$

$Q=\frac{1}{0.03}*(15.015)*(1.34)^{2/3}*(0.0316)^{1/2}=$**$108.26\ m^3/s$**

The Hydraulic discharge capacity of the existing open channel during heavy rains with high sedimentation is **108.26 m^3/s.**

4.4.2. Existing Culverts discharge capacity

The discharge of the culverts will be calculated by using the rectangular culverts design formula:

$$Q = C_h BD\sqrt{2g(H_1 - C_h D)}$$

With: C_h=0.6 for square inlets

Where: D= The inside Height (in m)

B= The inside width (in m)

H_1= The upstream energy Level, relative to the invert level (m).

4.4.2.1. The culvert under the bridge on the Road Nyabugogo-Muhima -Town Center

The culvert under the bridge on the Road Nyabugogo-Muhima -Town Center is the culvert which is near the region called Amashyirahamwe. The research data collection had been done when the channel was rehabilitated. The rehabilitation consisted in increasing its width by doubling its horizontal dimension which is its width; from two openings to four openings. The research has taken into consideration the rehabilitated or the current dimensions. The following photos show the so called culvert.

Photo 8: Existing culverts under the bridge on the Road Nyabugogo-Muhima-Town Center

The so called culvert is with a rectangular shape and has four openings with the inside height D = 3m; the inside width B = 2m and the upstream energy level, relative to the invert level H1= 3.8 m each.

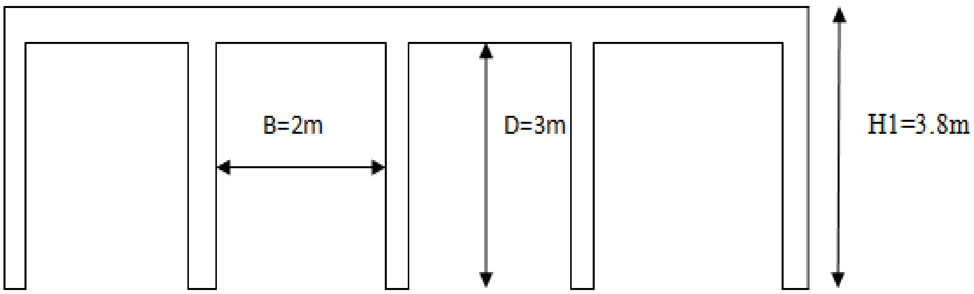

Figure 13: Existing culvert under the bridge on the Road Nyabugogo-Muhima-Town center

The discharge capacity of this culvert has been calculated by taking into consideration, its shape, its parameters and the relation H1/D.

Dimensions: B=8m and D=3m; H1=3.8m

H1/D=3.8m/3m=**1.26**

H1/D>1.2,

For this case**,** the formula which has to be used is**:**

$$Q = C_h BD\sqrt{2g(H_1 - C_h D)}$$; Ch=0.6; g=9.81m/s^2

Q=0.6*8*3$*\sqrt{2*9.81*(3.8-0.6*3)}$ =**90.2m^3/s**

The discharge capacity for the existing culvert on the Road Nyabugogo-Muhima-Town Center is **90.2m^3/s** on the design period.

The on field situation: The so called on field situation is the observed situation during the period of high sedimentation like for the open channel. This has been observed during the research period. During this period, the height of the culvert opening was reduced of 20cm 0r 0.20m in average.

The calculation of the discharge Capacity of the culvert has taken into consideration the current situation which is followed by the change of the culvert vertical parameters and then, the reduction of its discharge capacity.

The discharge capacity of this culvert has been calculated by also taking into consideration, its shape, its parameters and the relation H1/D.

Dimensions: B=8m and D=2.8 m; H1=3.6 m

H1/D=3.6m/2.8m=**1.28**

H1/D>1.2,

For this case**,** the following formula has to be used is**:**

$$Q = C_h BD\sqrt{2g(H_1 - C_h D)}$$; Ch=0.6; g=9.81m/s^2

Q=0.6*8*2.8$*\sqrt{2*9.81*(3.6-0.6*2.8)}$ = **82.5 m^3/s.**

The discharge capacity for the existing culvert on the Road Nyabugogo-Muhima-Town Center during the period of high sedimentation is **82.5 m^3/s.**

4.4.2.2 The culvert under the bridge on the Road Nyabugogo-Kinamba

Photo 9: Existing culvert under the bridge on the Road Nyabugogo-Kinamba

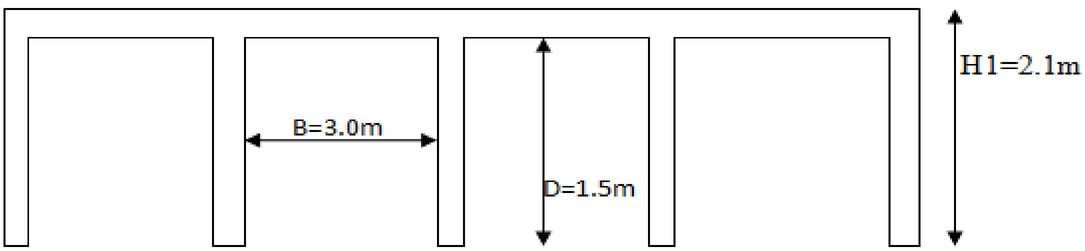

Figure 14: Existing culvert under the bridge on the Road Nyabugogo-Kinamba

This culvert is the culvert which is near the outlet of the Mpazi sub catchment. It has four openings with the inside width B= 3m; the inside height D=1.5m and the upstream energy level, relative to the invert level (H_1= 2.1 m) for each.

The discharge capacity of this culvert has been calculated by taking into consideration, its shape, its parameters and the relation H1/D.

Dimensions: B=12m and D=1.5m and H1=2.1m

H1/D=2.1 m/1.5m=**1.4**

H1/D>1.2; for this case**,** the formula which has to be used:

$$Q = C_h B D \sqrt{2g(H_1 - C_h D)}$$; Ch=0.6; g=9.81m/s^2

Q=0.6*12*1.5$* \sqrt{2*9.81*(2.1-0.6*1.5)}$ =**52.4m^3/s**

The discharge capacity for the existing culverts on the Road Nyabugogo-Kinamba is **$Q=52.4m^3/s$.**

The on field situation: The so called on field situation is the observed situation during the period of high sedimentation. This is the situation which has been observed during the research period.

During this period, the height of the culvert opening is in general reduced of 40cm 0r 0.40m in average.

The calculation of the discharge Capacity of the culvert has taken into consideration the current situation which is followed by the change of the culvert vertical parameters.

The discharge capacity of this culvert has also been calculated by taking into consideration, its shape, its parameters and the relation H1/D.

Dimensions: B=12m and D=1.1m; H1=1.7 m

H1/D=1.7 m/1.1m=**1.5**

H1/D>1.2

For this case**,** the following formula has to be used:

$Q = C_h BD\sqrt{2g(H_1 - C_h D)}$; Ch=0.6; $g=9.81m/s^2$

$Q=0.6*12*1.1*\sqrt{2*9.81*(1.7-0.6*1.1)}$ =**$35.8\ m^3/s$**

The discharge capacity for the existing culverts on the Road Nyabugogo-Kinamba is **$35.8\ m^3/s$.**

From the calculations done above; the existing open channel has the capacity of carrying a discharge of **$108.26\ m^3/s$;** the existing culvert under the bridge on the Road Nyabugogo-Muhima-Town Center has the capacity of carrying a discharge of **$82.5\ m^3/s$** and the existing culvert under the bridge on the Road Nyabugogo-Kinamba has the capacity of carrying a discharge of **$35.8\ m^3/s$.** The predicted or the design discharge in 30years is expected to be **$118.9\ m^3/s$.** The existing hydraulic structures have not in general the capacity of carrying the current and the predicted Mpazi runoff water discharge. This situation has conducted to the design of new hydraulic structures for a sustainable flood control solution.

4.5. DESIGN OF NEW HYDRAULIC STRUCTURES

The design of the new hydraulic structures has been done by considering the predicted peak runoff water discharge for the whole Mpazi sub catchment. The predicted runoff water discharge is **118.9 m^3/s.**

4.5.1. Design of the new channel

4.5.1.1. Section of the new channel

In designing the new channel, it was better to maintain the slope of the existing channel for not lowering its outlet compared to the Nyabugogo River. The new design had focused on the widening of the channel; then the height had also been maintained.

The designed height was equal to 2.3m but the sedimentation occupies the channel height up to 0.2m or 20 cm. Then the useful height is in general equal to 2.1 m in average. The new design has taken into consideration that H=2.1m.

The new channel has to be trapezoidal in section also. Assume that:

- Side slope be 2:1
- Height is H=2.1m.
- Bed slope S=3.16% and
- The Manning's coefficient n is equal to 0.030 because the channel is constructed in stone masonry
- a: slope distance (m)

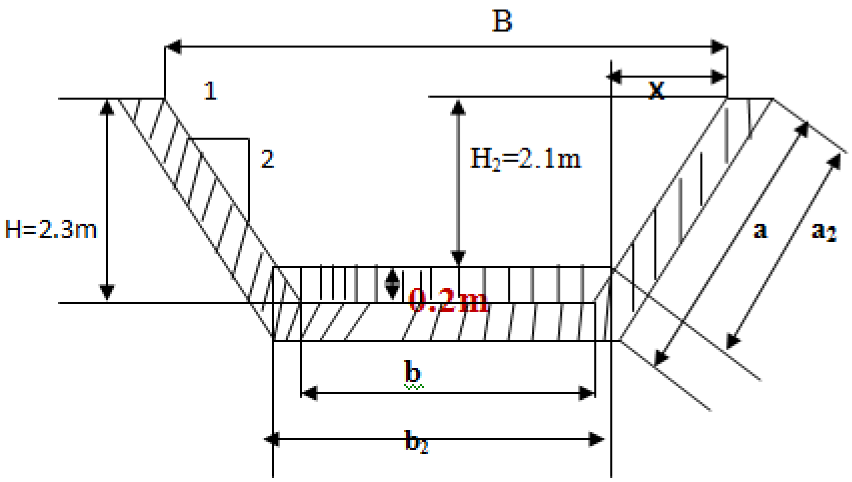

Figure 15: Sketch of the new channel section

For the design

The discharge $Q=A*V=\frac{1}{n}*A*R^{2/3}*S^{1/2}$

The Area

$A= (B+b)*H_2/2;$

Or $B=b_2+2x$

Then $A= (b_2+2x+ b_2)* H_2/2$

$\Rightarrow A= (b_2+2x)* H_2/2$

Or $x= H/2 \Rightarrow H_2=2x$

$A= (2b_2+H_2)*H_2/2$

$\Rightarrow A= (2b_2H_2+ H_2^2)/2$

Wetted perimeter (WP)

$WP= b_2+2a$

$a=\sqrt{x^2 + H2^2}$

Or $x=H_2/2$

$a=\sqrt{(\frac{H2}{2})^2 + H2^2}$

$a=H_2\sqrt{(1/4) + 1}$

$a_2=1.12H_2$

$a_2=2.35m$

Then $WP=b_2+2.24H_2$

The hydraulic radius R= A/WP=

$R= ((2b_2H_2 + H_2^2)/2)/ (b_2+2.24H_2)$

The hydraulic discharge of the channel is:

$118.9 = \frac{1}{0.03} ((2b_2H_2+ H_2^2)/2)*(((2b_2H_2 + H_2^2)/2)/ (b_2+2.24H_2))^{2/3} * (0.0316)^{1/2}$

The useful height for the channel **H_2=2.1m;**

From this equation, **b_2= 8.9m** and then

$B=b_2+H=11m$; then **B= 11m**

$a_2=1.12H$; then **a_2= 2.35m**

For the construction: The height of the channel to be constructed is the current height which is **H=2.3m.**

The bottom width of the channel to be constructed is calculated as it follows:

$b=b_2-(0.2m*2)*2$, then b=8.9m-0.8m

b=8.1m

And **a**=$a_2+\sqrt{(0.4)^2 + (0.2)^2}$

a=2.8m

The proposed new channel is a trapezoidal channel with a bottom width of 8.1m; a top width of 11m and a height of 2.3m. (b = 8.1m, B=11 m and h=2.3m)

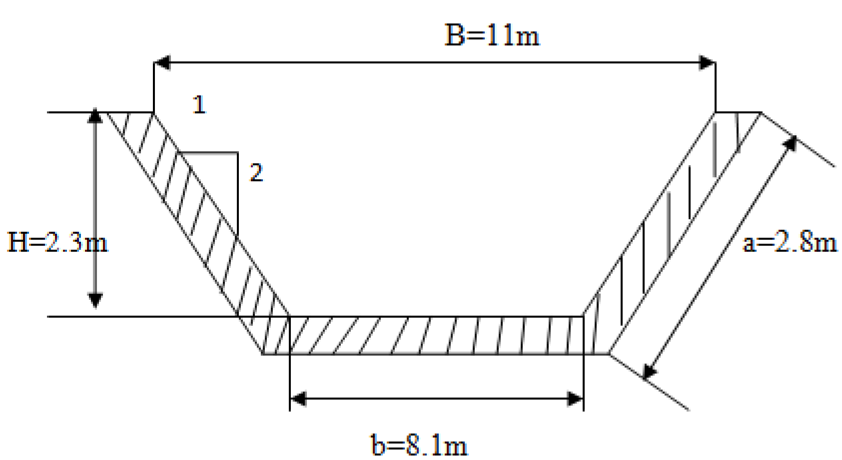

Figure 16: Designed new channel dimensions

4.5.2. Design of the new Culvert

In the design of the new culvert, the vertical parameters of the existing culvert have been maintained and the design has focused on the widening by increasing the number of the culvert's openings for not changing the position of the existing road.

4.5.2.1. The culvert under the bridge on the Road Nyabugogo-Muhima-Town Center

For the design of this culvert, the existing vertical parameters H1 and D have been taken into consideration and then the horizontal parameter which is the width B has been calculated**.** And the design focused on the useful height.

Dimensions: D=2.8m and H1=3.6m

H1/D=3.6m/2.8m=**1.28**

H1/D>1.2, then the following formula has to be used**:**

$Q = C_h BD\sqrt{2g(H_1 - C_h D)}$; Ch=0.6; g=9.81m/s^2

$118.9 = 0.6 * B * 2.8 * \sqrt{2 * 9.81 * (3.6 - 0.6 * 2.8)}$

$B = \frac{118.9}{0.6 * 2.8 * \sqrt{2 * 9.81 * (3.6 - 0.6 * 2.8)}}$

B=10.8m

The design of this culvert has taken into consideration the widening of the existing culvert. The widening had taken reference on the existing openings which have 2m width**.** For openings of 2m width: b=10.8m/2m=5.4 openings ≅ 6 openings.

The culvert under the bridge on the Road Nyabugogo-Muhima-Town Center has to be with six openings with the inside width (B= 2 m), the inside height (D= 3m) and the upstream energy level, relative to the invert level (H_1= 3.8 m) for each.

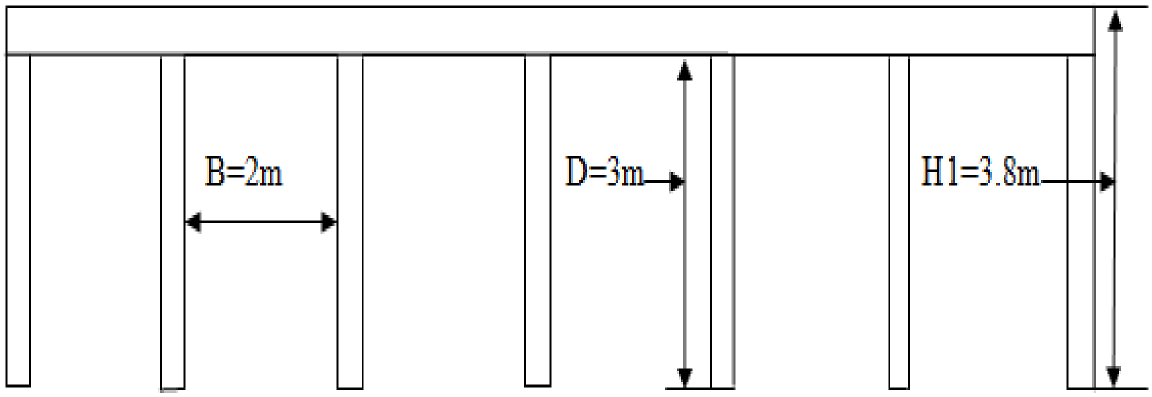

Figure 17: Designed culvert under the bridge on the Road Nyabugogo-Muhima-Town Center

4.5.2.2. The culverts under the bridge on the Road Nyabugogo-Kinamba

For the design of this culvert, also the existing vertical parameters H1 and D have been taken into consideration and the horizontal parameter which is the width B has been calculated**.** And also the design focused on the useful height.

Vertical dimensions: D=1.1m and H1=1.7m

H1/D=1.7 m/1.1 m=**1.5**

H1/D>1.2, then the following formula has been used:

$Q = C_h BD\sqrt{2g(H_1 - C_h D)}$; Ch=0.6; g=9.81m/s^2

$118.9 = 0.6*B*1.1* \sqrt{2 * 9.81 * (1.7 - 0.6 * 1.1)}$

$B = \frac{118.9}{0.6*1.1*\sqrt{2*9.81*(1.7-0.6*1.1)}}$

B=39.8m

The design of this culvert has taken into consideration the widening of the existing culvert. The widening had taken reference on the existing openings which have 3m width.

For openings of 3m width: b=39.8m /3m=13.3 openings ≅ 14 openings.

The culvert under the bridge on the Road Nyabugogo - Kinamba has to be with fourteen openings with the inside width (B= 3 m), the inside height (D= 1.5m) and the upstream energy level, relative to the invert level (H_1= 2.1 m) for each.

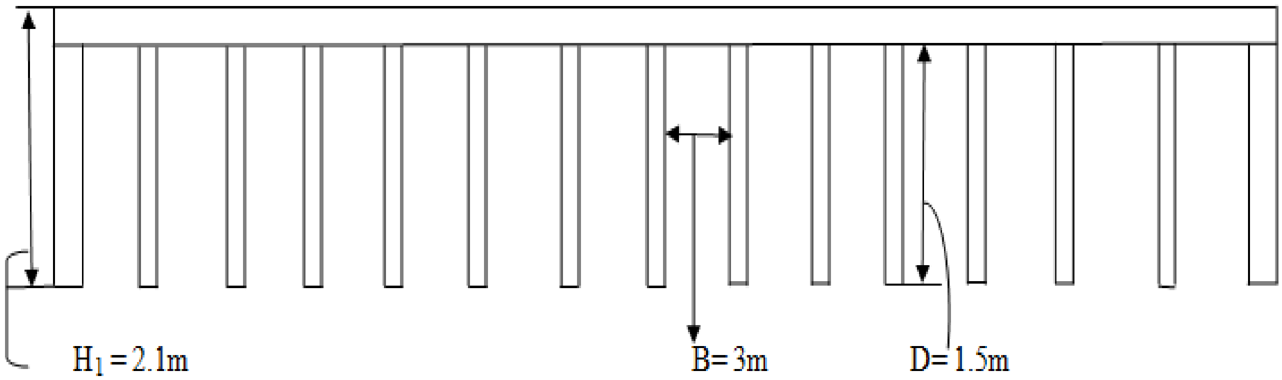

Figure 18: Designed culverts under the bridge on the Road Nyabugogo-Kinamba

Chap 5. CONCLUSION AND RECOMMENDATIONS

5.1. CONCLUSION

The aim of this research was to design the appropriate hydraulic structures for sustainable flood control in the Nyabugogo catchment. The research was focusing on the Mpazi sub catchment. The Mpazi is a mountainous sub catchment with area of around 8.37 km^2. Daily rainfall data from January 2003 to June 2014 have been collected from two meteorological stations; the KANOMBE airport station and the Nyabugogo wetland station. The peak rainfall height determined by using the extreme value theorem has fallen on 23rd February, 2010. The existing open channel has the capacity of carrying a discharge of **108.26 m^3/s;** the existing culverts under the bridge on the Road Nyabugogo-Muhima-Town Center has the capacity of carrying a discharge of **82.5 m^3/s** and the existing culverts under the bridge on the Road Nyabugogo-Kinamba has the capacity of carrying a discharge of **35.8 m^3/s.** The predicted or the design discharge in 30years is expected to be **118.9 m^3/s.** The existing hydraulic structures have not the capacity of carrying the current and the predicted Mpazi runoff water discharge.

For a sustainable flood control solution, new hydraulic structures have been proposed because the existing structures are unable of carrying the nowadays and the predicted discharge.

When these proposed hydraulic structures will be constructed, it will be a long term sustainable flood control solution for the Nyabugogo catchment as well as the Mpazi sub catchment.

5.2. RECOMMENDATIONS

From the research results, the following recommendations have been proposed:

- Reconstructing the new hydraulic structures because the existing structures are unable of carrying the predicted peak discharge
- To establish a flood risk management plan on the basis of the flood hazard maps and flood risk maps,
- The reinforcement of the rain water harvesting system for reducing the runoff,
- The Kigali city authorities have to encourage the vertical exploitation of the land by constructing storied buildings,
- The RNRA and REMA have to establish a detailed plan for increasing the infiltration by doing like the afforestation and other techniques,
- Regular and systematic removal of sediments for fighting against the clogging,
- Evacuation of the residents along the Mpazi channel for avoiding flood related risks,
- The part of the open channel after the Nyabugogo- Kinamba Bridge has to be dredged several times for removing all the deposed sediments transported by the water along the whole channel. When the maintenance will remain like it is today, the flooding will remain a big problem for the Nyabugogo area because of the return of the water which will not have where to pass during heavy rains due to the huge deposit of sediments taken by the water along the channel.

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