# EVALUATING DRAINAGE SYSTEMS PERFORMANCE AND INFILTRATION ENHANCEMENT TECHNIQUES AS FLOOD MITIGATION MEASURES IN NYABUGOGO CATCHMENT, RWANDA

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# Declaration

This Thesis is my original work and has not been presented for a degree in any other University.

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# Dedication

To my family for their unrelenting support and encouragement all through the course of my education

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# List of Abbreviations and Acronyms

| | |
|---|---|
| BMPs | Best Management Practices |
| CN | Curve Number |
| d | Index of Agreement |
| DEM | Digital Elevation Model |
| EPA | Environmental Protection Agency (United States of America) |
| Eq. | Equation |
| GI | Green Infrastructure |
| GIS | Geographic Information System |
| HEC-1 | Hydrologic Engineering Center’s computer program |
| HEC-HMS | Hydrologic Engineering Center’s Hydraulic Modeling System |
| IBT | Infiltration-based Techniques |
| LID | Low Impact Development |
| MIDMAR | Ministry of Disaster Management and Refugee Affairs |
| MININFRA | Ministry of Infrastructure |
| NSE | Nash–Sutcliffe efficiency |
| RLMUA | Rwanda Land Management and Use Authority |
| RMA | Rwanda Meteorology Agency |
| RTDA | Rwanda Transport Development Agency |
| RWFA | Rwanda Water and Forestry Authority |
| SNWA | Singapore National Water Agency |
| SUDS | Sustainable Urban Drainage Systems |
| SWMM | Storm Water Management Model |

| | |
|---|---|
| TR-20 | Technical Release 20 |
| TR-55 | Technical Release 55 |
| UNDESA | United Nations, Department of Economic and Social Affairs |
| USDA | United States Department of Agriculture |
| WFGR | Water for Growth Rwanda |
| WUSUD | Water Sensitive Urban Design |

# Abstract

Rapid urbanization contributes to the increase of impervious area which in return increases stormwater runoff peak and volumes. Nyabugogo catchment in Rwanda has been repeatedly subjected to a growing number of flooding events. The general objective of this research was to evaluate drainage systems performance and the impact of infiltration-based techniques in mitigating floods in Nyabugogo catchment. The United States Environmental Protection Agency's Storm Water Management Model (EPA SWMM 5.1) and the Geographic Information Systems (ArcGIS) tool were used to model and analyse stormwater characteristics. Data from three meteorological stations and three hydrological stations were used to calibrate and validate EPA SWMM. The model performance was judged satisfactory for flow simulation in Nyabugogo catchment with the values of $r^2$ greater than 0.6, NSE greater than 0.5 and d greater than 0.7. The indices of reliability, resiliency, vulnerability and sustainability were used to evaluate the performance of urban drainage systems of Nyabugogo catchment. The performance of the system decreased in reliability and resiliency, and increased in vulnerability as the design rainfall return period increased. Simulation results revealed the effectiveness of four infiltration-based techniques (IBTs); namely bio-retention ponds, infiltration trenches, vegetated swales and permeable pavement, on reducing floods in Nyabugogo catchment and the combination of four IBTs demonstrated a reduction of runoff quantity by 26.1 % using the index of unit-area peak discharge. The four IBTs are recommended to contribute in solving the flooding problems in Nyabugogo catchment.

# Chapter 1

# Introduction

## 1.1 Background to the Study

Urbanization contributes to the development level of a country (Annez et al., 2008). However, rapid urbanization leads to intense land-use change and the increase of impervious surface (Guan et al., 2015). The increased runoff volumes and peak flows associated with faster response time result in urban flood risks (Zhou, 2014). Changing the land-use from rural to an urban settlement has caused greater amounts of overland flow due to the increased cover of impervious areas (Swan, 2010). A study conducted on Hyderabad city in India concluded that urbanization leads to increases of the flood peaks from 1.8 to 8 times and flood volumes by up to 6 times (Rangari, 2016). Climate change represents an essential factor influencing urban water systems in terms of changes in water runoff and urban flooding (Zhou, 2014). For example, design intensities in Denmark are likely to increase by 10 to 50% within the next 100 years (Arnbjerg-Nielsen et al., 2013). The combination of rapid urbanization and climate change leads to the increase risks of flooding events in cities and suburbs (Moore et al., 2016).

Currently, many cities rely on conventional stormwater drainage systems of pipe and channel network designed to remove urban runoff as fast as possible (Mguni et al., 2016). These reduce the response time and therefore increase the peak runoff volume. The conventional stormwater drainage system of pipes and channel networks is no longer adequate to deal with larger and more intense stormwater events as they promote large runoff volumes and urban pollution (Schreier, 2014).

Historically, the rapid removal of surface runoff by discharge into lakes and rivers has been given the most attention in urban stormwater management, as solution to negative impacts of floods and pollution (Schreier, 2014). In addition, most of urban drainage systems are designed based on historical data which might no longer be valid due to dramatic changes of the urban land-use and climate change effects (Schreier, 2014). Urban hydrological models are used to understand and evaluate urban water quantity and quality responses to potential land-use changes and climate change. Models are calibrated and validated in order to produce accurate scenarios of runoff generation and pollutant loading with urban stormwater (Guan et al., 2015).

The urban population growth has been increasing and will keep that trend in future; dramatically changes the land-use and will result in an increased overland runoff that contributes to more flooding and pollution (United Nations Department of Economic and Social Affairs, 2014). There is a need to focus on alternative stormwater management techniques such as infiltration of rainfall on site, and detention of runoff during large storm events rather than removing stormwater runoff as fast as possible (Schreier, 2014).

To address the increasing flooding risks, new innovative approaches that are more effective than the traditional measures were identified (Joksimovic et al., 2014). The techniques include bio-retention ponds, infiltration trenches, vegetated swales and permeable pavements. The urban watersheds differ in geology, surface conditions, climate and land-use and brings a need to determine the optimal location and the most appropriate combinations of innovative approaches that work for a given area (Perez-Pedini et al., 2015). Since the flooding risk is increasing, research on the impacts of infiltration-based techniques on stormwater management to mitigate floods is therefore important.

## 1.2 Problem Statement

Large volume of stormwater resulting from rapid urbanization and climate change has been causing floods in numerous cities worldwide (Schreier, 2014). Nyabugogo catchment in Rwanda, has been repeatedly subjected to floods and their impacts have increased due to its low altitude and its nature of convergence zone of drainage systems of Kigali city (Rukundo et al., 2016). The conventional stormwater drainage systems have failed to deal with intense rainfall events and a drastically changed land-use in many cities including Kigali (Munyaneza et al., 2013). Nyabugogo River itself and drainage systems within catchment have lost the former carrying capacity to accommodate all excess water within its active domain due to drainage congestion, over siltation, riverbank erosion and poor maintenance planning (Water for Growth Rwanda, 2017).

In addition, the existing drainage systems have also resulted in huge pollution that is observed during rainy season (Rukundo, 2015). As a result, water supply system in the area is affected negatively; properties are damaged, disruption to business and traffic, discomfort to community, loss of human lives, loss of biodiversity, destruction of environment and deterioration of health conditions owing to water bone diseases (Rukundo, 2015). Therefore, there is a need to mitigate the negative impact of floods.

## 1.3 Objectives

### 1.3.1 General Objective

The general objective of this research was to evaluate drainage systems performance and the impact of infiltration enhancement techniques as flood mitigation measures in Nyabugogo catchment, Rwanda.

### 1.3.2 Specific Objectives

The specific objectives of this research were to:

1. Characterize the stormwater runoff of Nyabugogo catchment using EPA SWMM model,
2. Evaluate the performance of existing drainage systems in the Nyabugogo catchment using EPA SWMM,
3. Investigate the effectiveness of four infiltration-based techniques to mitigate floods in Nyabugogo catchment using EPA SWMM.

## 1.4 Research Questions

The objective of this research addresses the following questions related to Nyabugogo catchment floods problems:

1. What are the characteristics of stormwater runoff in the Nyabugogo Catchment?
2. How do the existing drainage systems in the Nyabugogo catchment perform during the intense rainfall events?
3. How effective are infiltration-based techniques in mitigating flooding in the Nyabugogo catchment?

## 1.5 Justification

Urbanization is growing rapidly in Rwanda (Ministry of Infrastructure, 2015). However, rapid urbanization has several negative impacts towards stormwater management including floods; for example in Nyabugogo catchment cause damage to properties, disruption to business and traffic, discomfort to community and in some cases loss of human lives and livestock (Ministry of Disaster Management and Refugee Affairs, 2016).

Runoff characteristics are related to multiple factors such as land-use, drainage systems, topography; and soil characteristics of the area. The study of catchments is complex, due to the uncertainty of future conditions and the lack of quality datasets (Rossman et al., 2016a). These challenges limit the understanding about past, current and future hydrological behaviours of urban catchments. However, hydrological models are used to understand and evaluate hydraulic and hydrological processes of catchments (Guan et al., 2015). EPA SWMM is a dynamic rainfall-runoff simulation model which has a good performance for the simulation of the quantity and quality of runoff from primarily urban areas (Xu et al., 2016).

It is necessary to characterize the stormwater runoff of the Nyabugogo catchment, to understand the performance of existing drainage systems and to investigate the effectiveness of techniques to enhance infiltration of stormwater in urban areas in order to contribute to floods mitigation. Therefore, the outcome of this study will serve as a source of additional information that may be of significant use to policy makers and planners during the designing and implementation of floods mitigation strategies in Nyabugogo catchment, Rwanda.

## 1.6 Scope of Study

The research first focused on sensitivity analysis, calibrating and validating EPA SWMM model to characterize the stormwater runoff in the Nyabugogo catchment. Meteorological, topographical, land-use, soil and river flow data were collected and used to calibrate and validate EPA SWMM. Stormwater runoff of Nyabugogo catchment was then characterized in terms of water depth. Secondly, the evaluation of the performance of existing drainage systems in the Nyabugogo catchment was conducted. Finally, the used EPA SWMM to investigate the effectiveness of infiltration-based techniques to mitigate floods. These are bio-retention ponds, infiltration trenches, vegetated swales and permeable pavements.

## 1.7 Organization of the report

This project contains five chapters; Chapter One presents the background of the study, statement of the problem, research objectives, research questions, justification, and the scope of the study. Chapter Two gives the literature review on the mentioned topic. Chapter Three gives the materials and methods; Chapter Four presents results and discussions while Chapter Five gives conclusions and recommendations.

# Chapter 2

# Literature Review

## 2.1 Overview of Urban Stormwater Modelling

Computer models of urban stormwater quantity and quality have been extremely useful in establishing whether various management strategies produce water quantity and quality that conform to the legislation and the control of water so that it does not cause excessive damage to property or loss of life and inconvenience to the public (Zoppou, 2001). Most of urban hydrologic models have two major components; namely, runoff generation and runoff routing. The runoff generation component is responsible for partitioning rainfall into surface runoff and losses, while the runoff routing component routes the surface runoff from the catchment to the outlet (César, 2011). Runoff from an urban drainage catchment consists of runoff from impervious areas, which flows into the storm drainage systems (Kourtis, Bellos, et al., 2017).

There is an increased use of computer based models to analyse complex drainage systems and to manage stormwater. These models generally consider the major hydrological and hydraulic processes of urban stormwater dynamics such as interception, infiltration, depression storage, overland flow, channel flow and pipe flow. The models can be used for both storm event modelling and continuous simulation to effectively manage stormwater (Sidek et al., 2016).

A description of some hydrological and hydraulic models and their capabilities is given in Table 2-1. They are grouped as urban models that are designed to simulate urban stormwater quantity and quality and non-urban models that are capable of being adapted for use in urban stormwater problems (Zoppou, 2001).

Table 2-1: Hydrological and hydraulic models

| **Model** | **Source** | **Main aspects** |
|---|---|---|
| Hydrologic Engineering Center's computer program (HEC-1) | Feldman (1995) | Lumped parameter, single storm event model which is able to simulate the runoff response of a watershed to precipitation. |
| Hydrologic Engineering Center's Hydraulic Modeling System (HEC-HMS) | Scharffenberg et al. (2010)<br>Halwatura et al. (2013) | HEC-HMS is used to analyse urban flooding, flood frequency, reservoir spillway capacity and stream restoration. |
| Technical Release 20 (TR-20) | USDA (2015) | Lumped parameter and single storm event model applied at a watershed scale. |
| Technical Release 55 (TR-55) | USDA (2009). | TR-55 presents simplified procedures for estimating runoff and peak discharges in small watersheds. |
| MIKE FLOOD | Vanderkimpen et al. (2009). | Capable of simulating flooding events for rivers and urban drainage systems. |
| MIKE URBAN | Kourtis, Bellos, et al. (2017). | Flexible system for modeling and design of water distribution networks and collection systems for wastewater and stormwater. |
| Hydrological Simulation Program–Fortran (HSPF) | Duda et al. (2012)<br>Parajuli et al. (2013) | Continuous simulation watershed model for runoff quantity and quality related with combined point and nonpoint sources |
| Hydro Planner | Mirza et al. (2013) | Provides the description of stormwater systems interact with natural water systems in terms of quantity and quality contribution. |
| EPA SWMM | Rossman et al. (2016) | Dynamic rainfall-runoff simulation model used for single event or long-term simulation of runoff quantity and quality from primarily urban areas. |

The runoff component of EPA SWMM operates on a collection of sub-catchment areas that receive precipitation and generate runoff and pollutant loads. The routing portion of EPA SWMM transports this runoff through a system of pipes, channels, storage devices, pumps, and regulators. EPA SWMM tracks the quantity and quality of runoff generated within each sub-catchment, and the flow rate, flow depth, and quality of water in each pipe and channel during a simulation period comprised of multiple time steps (Rossman et al., 2016a).

EPA SWMM conceptualizes a sub-catchment as a rectangular surface that has a uniform slope S and a width W that drains to a single outlet channel. Overland flow is generated by modeling the sub-catchment as a nonlinear reservoir as shown in Figure 2-1. The sub-catchment experiences inflow from precipitation and losses from evaporation and infiltration. The net excess ponds on the top of the sub-catchment surface to a depth (d). Ponded water above the depression storage depth ($d_s$) can become runoff outflow (q). Depression storage accounts for initial rainfall abstractions such as surface ponding, interception by flat roofs and vegetation, and surface wetting.

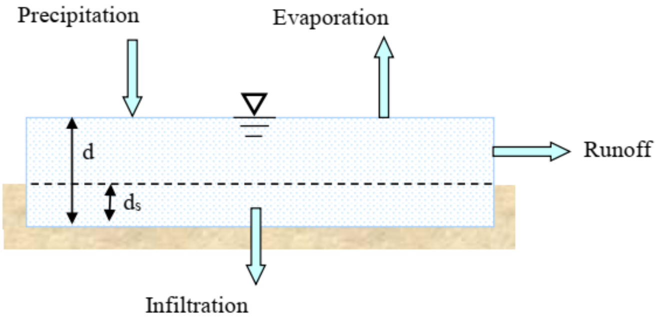

Figure 2-1: Nonlinear reservoir model of a sub-catchment in EPA SWMM

From conservation of mass, the net change in depth (d) per unit of time *t* is simply the difference between inflow and outflow rates over the sub-catchment, as in Eq. 2-1:

$$\frac{\partial d}{\partial t} = i - e - f - q \qquad \textbf{Eq. 2-1}$$

Where:

i = rate of rainfall (mm/s)

e = surface evaporation rate (mm/s)

f = infiltration rate (mm/s)

q = runoff rate (mm/s).

Assuming that flow across the sub-catchment's surface behaves as if it were uniform flow within a rectangular channel of width (W), height (d–ds), and slope (S), the Manning equation can be used to express the runoff's volumetric flow rate (Q) as in Eq. 2-2:

$$Q = \frac{1}{n} * S^{1/2} * R_x^{2/3} * A_x \qquad \textbf{Eq. 2-2}$$

Here n is a surface roughness coefficient, S the apparent or average slope of the sub-catchment, $A_x$ the area across the sub-catchment width through which the runoff flows, and $R_x$ is the hydraulic radius associated with this area. Referring to Figure 2-1, Ax is a rectangular area with width W and height d-ds. Because W will always be much larger than d it follows that $A_x = W(d - d_s)$ and $R_x = d - d_s$. Substituting these expressions into Eq. 2-2 gives Eq. 2-3:

$$Q = \frac{1}{n} * W * S^{1/2} * (d - d_s)^{5/3} \qquad \textbf{Eq. 2-3}$$

To obtain a runoff flow rate per unit of surface area, q, Eq. 2-3 is divided by the surface area of the sub-catchment A and gives Eq. 2-4:

$$q = \frac{W * S^{1/2}}{A * n} * (d - d_s)^{5/3} \qquad \textbf{Eq. 2-4}$$

Substituting this equation into the original mass balance relation Eq. 2-1 results in Eq. 2-5:

$$\frac{\partial d}{\partial t} = i - e - f - \alpha(d - d_s)^{5/3} \qquad \textbf{Eq. 2-5}$$

Where α is defined as Eq. 2-6:

$$\alpha = \frac{W * S^{1/2}}{A * n} \qquad \textbf{Eq. 2-6}$$

Eq. 2-5 is an ordinary nonlinear differential equation. For known values of i, e, f, ds and α can be solved numerically over each time step for ponded depth d. Once d is known, values of the runoff rate q can be found from Eq. 2-4. Note that Eq. 2-5 only applies when d is greater than $d_s$. When d <= $d_s$, runoff q is zero and the mass balance on d becomes simply Eq. 2-7:

$$\frac{\partial d}{\partial t} = i - e - f \qquad \textbf{Eq. 2-7}$$

A research conducted in Dahongmen catchment, Beijing, used the SWMM model to simulate the rainfall-runoff process. SWMM model had good performance for the simulation of rainfall-runoff process before and after urbanization. Nash–Sutcliffe efficiency (NSE) was greater than 0.6, and the relative error of flood peak discharge was smaller than 15 % both during calibration and validation periods (Xu et al., 2016).

A study carried out in a highly urbanized area of North-eastern China, concluded that EPA SWMM model was successfully used to model the quantity and quality of runoff. The NSE, relative error, and coefficient of determination ($r^2$) were used to evaluate model performance. Data from rainfall events were used to calibrate and validate the model. EPA SWMM model was chosen because it is the most widely used rainfall-runoff models for simulating hydrological processes and water quality in urban areas (Li et al., 2016).

EPA SWMM was used to simulate hydrological responses of five headwater streams to increases in precipitation and urban land cover based on projections to the year

2040. Simulations for different distributions of land cover change demonstrated that the location of impervious surfaces additions has a greater effect on the timing of delivery than on total amount of discharge. EPA SWMM was applied because of its ability to simulate the hydraulic dynamics of artificial drainage systems that are prevalent in urban areas (Wu et al., 2013).

Mathematical estimate of the error between the simulated and observed hydrologic variables was used to evaluate hydrologic model behaviour and performance. Coefficient of determination ($r^2$), NSE, and index of agreement (*d*) were used to evaluate model performance. The range of $r^2$ lies between 0 and 1 which describes how much of the observed dispersion is explained by the prediction. The range of NSE lies between 1.0 and $-\infty$. The range of *d* is similar to that of $r^2$ and lies between 0 and 1 (Krause et al., 2005). EPA SWMM was chosen because of its capacity of modelling single and continuous rainfall events, it is the most widely used for stormwater management modelling and it has nine built-in infiltration-based techniques which are used to mitigate floods.

## 2.2 Parameter sensitivity analysis for hydrologic simulation models

Sensitivity analysis aims to identify the key parameters that affect model performance and plays important roles in model parameterization, calibration, optimization, and uncertainty quantification (Song et al., 2015). In hydrological modeling, sensitivity analysis is defined as the investigation of the response function that links the variation in the model outputs to changes in the input parameters, which allows the determination of the relative contributions of different uncertainty sources to the variation in outputs using qualitative or quantitative approaches under a given set of assumptions and objectives (Song et al., 2015).

It is important to ensure that the model description and parameterization remain as simple as possible to allow adequate calibration, but it must also be distributed to capture the spatial variability in the key model parameters. For efficient parameter identification, sensitivity analysis is useful in providing the qualitative and quantitative indices needed to identify important and non-important parameters (Castaings et al., 2009).

A research conducted on parameter sensitivity analysis for hydrologic simulation models observed one parameter and two parameters sensitivity analysis and found that the one parameter sensitivity analysis is effective for ranking the parameters in order of importance in the model and to find the ranges of parameter values where they are most active. The sensitivity analysis considering each parameter alone is more effective than considering more parameters at the same time (Song et al., 2015).

## 2.3 Calibration and validation of hydrological models

Modeling of catchment hydrology is a valuable approach for understanding, reproducing, and predicting the behaviour of hydrological systems (Jia et al., 2015). Operational water management demands practical models that are capable of reliably predicting hydrologic behaviour and variability at watershed scales for engineering design and development (Zoppou, 2001). The model needs to be calibrated for a watershed. For model calibration, model results should be in acceptable range compared to recorded data, and the estimates of parameter values should be consistent with watershed characteristics (Rosa et al., 2015).

The calibration process requires a procedure to evaluate its success and the criterion of success has to be subjected to judgement adequacy. Statistical indicators are used to measure the goodness of fit because their functions are more likely to produce comparison between measured and modelled values (Rosa et al., 2015). Statistical indicators that are examined in deciding if a given calibration is acceptable include correlation coefficient, relative error (RE), normalized objective function (NOF), coefficient of determination ($r^2$), Nash-Sutcliffe efficiency (NSE), and index of agreement (d). Some of these indicators are selected to guide to an acceptable calibration (Maharjan et al., 2015). The coefficient of determination $r^2$ is defined as the squared value of the coefficient of correlation (Krause et al., 2005). The NSE is defined as one minus the sum of the absolute squared differences between the predicted and observed values normalized by the variance of the observed values during the period under investigation (Wu et al., 2013). The index of agreement represents the ratio of the mean square error and the potential error (Krause et al., 2005).

The calibration is completed by validation where the outcomes are evaluated if they provide adequate information related to the need for the model. The model validation aims to determine if the estimates achieved by the calibration are acceptable. For validation, the model is run with data of a time period other than that used for calibration and the results are evaluated using the same statistical indicators (Palanisamy et al., 2015).

## 2.4 Overview of Drainage systems Performance

The main purpose of storm drainage systems is to collect stormwater and convey it to receiving water bodies ensuring minimal damages. In recent times emphasis has been shifted from disposal of stormwater to total management of stormwater, considering stormwater as a resource (Dayarantne, 2000). The components of drainage systems can be categorized by function as those which collect stormwater runoff, convey and discharge it to an adequate receiving body without causing adverse on or off-site environmental impacts. In addition, major storm drainage systems provide a flood water relief function (Brown et al., 2013).

The drainage system part which collects stormwater runoff is composed of ditches, gutters, and drainage inlets. Ditches are used to intercept runoff and carry it to an adequate storm drain. Gutters are used to intercept pavement runoff and carry it along to an adequate storm drain inlet. Drainage inlets are the receptors for surface water collected in ditches and gutters, and serve as the mechanism whereby surface water enters storm drains (Brown et al., 2013).

Detention and retention facilities are used to receive stormwater runoff and to control the quantity of discharged runoff. A reduction in runoff quantity can be achieved by the storage of runoff in detention or retention basins, swales and other storage facilities (Brown et al., 2013). Retention basins are located in-stream or off-stream along urban waterways and are used to improve the quality of stormwater by natural removal of pollutants. Detention basins hold runoff for short time periods to reduce peak flow rates and later release into natural or artificial watercourses. The major receiving water bodies that are considered in urban drainage include rivers, lakes, bays, and sea and ground water storages (Wang, 2015).

A coupled urban drainage and flooding model (SWMM-Brezo) was used to simulate storm-sewer surcharge and surface inundation so as to establish the increase in the flood hazard resulting from the changes in land-use. The study attempted to integrate the impacts of climate change and urban growth on the future change of the urban flooding system. The results showed that the combined influence of climate change and urban growth on the urban flooding situation is significant (Baker et al., 2004). A study conducted on Can Tho city in Vietnam on the impacts of urbanization and climate change on future urban flooding assessed the performance of drainage systems and concluded that they are not suitable and adequate to mitigate floods. The areas with significant flood hazard were identified. The study recommended the consideration of changes for future urban development and rehabilitation of existing ones (Huong et al., 2013). The performance of drainage systems is evaluated using indices of reliability, resiliency, vulnerability and sustainability (Binesh et al., 2016). Reliability of a system is typically considered to be its probability of successful operation. To measure reliability, the chosen level of service measure and corresponding acceptable limit must be specified (Butler et al., 2017). The system reliability is reflected by how often the system fails (Behzadian et al., 2014).

Resiliency is defined as the degree to which the system minimises level of service failure magnitude and duration over its design life when subject to exceptional conditions (Butler et al., 2017). Essentially, it is a measure of how the system performs when subject to unexpected threats that exceed design conditions and the system is unable to meet the required level of service (Behzadian et al., 2014). Resiliency describes how quickly a system is likely to recover or bounce back from failure once failure has occurred. If failures are prolonged events and system recovery is slow, this may have serious implications for system design one would like to design systems which can recover and return to a satisfactory state rapidly (Francis et al., 2014). Vulnerability refers to the likely magnitude of a failure, if one occurs. Vulnerability represents the severity of the failure and can be expressed as the maximum difference between allowed and calculated value of a certain variable (Binesh et al., 2016). The whole system's total performance which is known as sustainability index of the system (Binesh et al., 2016).

## 2.5 Design storm for runoff management

Hydrologic systems are sometimes affected by the rainfall pattern and amount, such as extreme precipitation events which are one of the primary natural causes of flooding. The ability to anticipate extremes of rainfall would aid in many engineering purposes, such as flood control and storm water management (Alam et al., 2018). A design storm is a precipitation pattern defined for use in the design of a hydrologic system. Usually the design storm serves as the system input, and the resulting rates of flow through the system are calculated using rainfall-runoff and flow routing procedures (Basumatary et al., 2016). An idea on return period of rainfall intensity which can be expected within a defined period is obtained by many methods including rainfall intensity-duration-frequency (Wagesho et al., 2016).

Design storms can be based upon historical precipitation data at a site or can be constructed using the general characteristics of precipitation in the surrounding region. The application of design storms ranges from the use of point precipitation values in the rational method for determining peak flow rates in storm sewers and highway culverts, to the use of storm hyetographs as inputs for rainfall-runoff analysis of urban detention basins or for spillway design in large reservoir projects (Basumatary et al., 2016).

Design storm for a catchment can be derived on the basis of the intensity-duration-frequency (IDF) relationships. These relationships are either from IDF-curves plots, or from derived IDF formula (AlHassoun, 2011). For any project and for a given return period and specified rainfall duration, the required design storm intensity can be used for design of infrastructures and management strategies (Basumatary et al., 2016). AlHassoun developed empirical formulae to estimate rainfall intensity in Riyadh region based on IDF curves. These curves were generated from a 32-year recorded rainfall data for Riyadh region. The results of analysis of rainfall data in Riyadh region could be used for engineering design and floods mitigation strategies (AlHassoun, 2011).

## 2.6 Methods to enhance drainage systems performance and infiltration of stormwater

Historically, stormwater has been treated as threat, paved over our urban areas and simply flushed surface water down pipes into an overloaded sewerage system. But as recent repeated flooding events have shown, the traditional drainage systems of some urban areas no longer cope with the volumes and flow rate generated during intense rainfall (Graham et al., 2012).

To discharge stormwater as fast as possible is no longer a good option to manage it and doing things differently is now an essential requirement for managing surface water, especially when considering a changing climate and rapid urbanization (Schreier, 2014). Green techniques are the possible solution to challenging increase of flooding events and many green methods are used to effectively manage stormwater and mitigate floods. Green techniques include sustainable urban drainage systems (SUDS) which shares the same principles as best management practices (BMP), low impact development (LID), green infrastructure (GI), and water sensitive urban design (Peng et al., 2017).

There are two types of green techniques that are used to reduce the threat of stormwater runoff pollution from construction and development in urbanizing areas. The non-structural techniques to effectively manage urban stormwater runoff include public education, planning and management for impervious areas reduction, storm drain maintenance, spill prevention and clean-up, illegal dumping controls and stormwater reuse (Global Watch Mission, 2006). The structural techniques for urban stormwater management include bio-retention ponds, stormwater wetlands, vegetated swales, infiltration trenches, infiltration basin, pervious pavement and sand filters (Global Watch Mission, 2006). The most popular techniques applied nowadays include filter and infiltration trenches, permeable surfaces, water storage, swales, water harvesting, detention basins, wetlands and ponds (Zhou, 2014).

Low impact development techniques are approaches to manage stormwater with a primary focus on decreasing the percentage of runoff within the watershed thus promoting infiltration and decreasing surface runoff. The aim of LID approach is to preserve and recreate the natural, pre-development characteristics of a site as closely as possible, even after development, and reduce the impacts to an acceptable level by managing rainwater at its source instead of discharging it into conventional drainage systems (Fleischmann, 2014).

There are number of different LID technologies; namely, bio-retention ponds, green roofs, rain barrels and permeable pavements. Bio-retention ponds are depressional areas built to collect and treat stormwater runoff (Plate 2-1). Water held in depressional areas can infiltrate into the soil and recharge groundwater while evapotranspiration can decrease the amount of water entering the stormwater system (Ahiablame et al., 2012). Green roofs consist of thick soil with plants and trees on top of buildings, which absorb and hold precipitation that traditionally runs straight off of roof. Water is stored in the soil, and it is released back into the atmosphere through evapotranspiration by plants (Dietz, 2007).

Plate 2-1: Bio-retention ponds (Water by Design, 2014)

Rain barrels collect and hold precipitation running off roofs. The infiltration happens slowly and water can be used for gardening, greenhouse watering, or other purposes. Cisterns can reduce up to 100% of rooftop runoff, but become less effective for large storms because of capacity limitations (Ahiablame et al., 2012).

Permeable pavements have a surface with void spaces in order to allow infiltration of stormwater into the underlying soil (Brattebo et al., 2003). They have the potential to substantially reduce runoff volume compared to conventional asphalt and concrete, including systems installed over clayey subgrade soils (Zimmerman et al., 2010). Permeable pavements are designed to decrease peak runoff rates, reduce runoff quantity, and delay peak flows by promoting surface infiltration rates (Plate 2-1). The efficiency of permeable pavements for decreasing runoff depends on the type of pavement installed, the region of the world they operate in, rainfall in the study year, extent of surface usage, presence of an under-drain, and other factors. The effectiveness of permeable pavements also varies among storm conditions (Dietz, 2007).

Plate 2-2: (a) Permeable concrete pavement, (b) Permeable brick pavement, (c) Permeable grid pavement (Agouridis et al., 2011)

Vegetated swales are open channels designed to convey, treat and reduce stormwater runoff and usually consume about 5 to 15 percent of their contributing drainage area. They have long been used for stormwater conveyance, particularly for roadway drainage. Longitudinal slopes between 0.5 and 6% are allowable. This prevents ponding while providing residence time and preventing erosion (Storey et al., 2009).

Vegetative swales are infiltration-based stormwater management techniques commonly applied alongside streets and highways to manage the runoff quantity and quality from roads (Plate 2-2). It is an open drain vegetated with grass or other plants and could facilitate the removal of pollutants in surface runoff mainly by sedimentation and filtration and the runoff volume by infiltration.

Plate 2-3: Vegetated swales (Singapore National Water Agency, 2018)

During rainfall events, vegetative swales collect overland flow from adjacent roads surface. Its rough surface could slow down the velocity of overland flow while conveying it to another location so that pollutants in particle phases would easily settle down and runoff could infiltrate to the soil (Martin-mikle et al., 2015).

Riparian buffers are corridors of vegetation along rivers, streams, and tidal wetlands which help to protect water quality by providing a transition between upland development and adjoining surface water. Vegetated riparian buffers filter urban stormwater runoff from impervious areas before it reaches the water body (Storey et al., 2009).

Infiltration trenches are narrow ditches filled with gravel that intercept runoff from upslope impervious areas. They provide storage volume and additional time for captured runoff to infiltrate into the native soil below (Plate 2-4).

Plate 2-4: Infiltration trench (Rossman, 2016)

A research conducted on green stormwater infrastructure with low impact development focusing on bio-retention, green roofs, grass swales, and permeable pavements showed great potential for mitigating the effects of urbanization and land development on hydrology and water scarcity of an area. They were most effective for preserving the natural hydrologic function of a site, improving water quality, and retaining pollutants (Shafique et al., 2017).

SWMM was used to investigate hydrological change caused by urban development, several LID techniques including infiltration-based techniques and retention-based techniques were used while evaluating their impacts in reducing higher peak flows, as well as a larger total runoff volume. Stormwater management techniques showed a possibility to restore the pre-development total runoff volume and the key elements of natural flows for some small events through combined regulations (Guan et al., 2015). To evaluate the impact of infiltration-based techniques, the indicators of Richards-Baker Index, Runoff ratio and Unit-area peak discharge are used. Richards-Baker Index (R-B Index) measures oscillations in flow relative to total flow, and as such, appears to provide a useful characterization of the way watersheds process hydrologic inputs into their streamflow outputs. R-B Index has much less annual variability, as reflected in its coefficient of variation, and reveals many more trends in discharge data (Baker et al., 2004).

Runoff ratio is the runoff for each watershed divided by the precipitation for that watershed. It is the proportion of rainfall that does not infiltrate and is not taken up by evapotranspiration, and thus ends up as runoff. Some of the water which infiltrates emerges as base-flow or through springs and seeps and becomes part of runoff (Wu et al., 2013). Runoff ratio is controlled to some extent by natural factors. Soils containing large fractions of clay or silt absorb less water than sandy soils and thus produce higher runoff ratios. Topography has a strong control over runoff ratio. Watersheds with steep slopes tend to shed more water and infiltrate less due to rapid runoff. These areas will have high runoff ratios. Relatively flat areas underlain by coarse sandy soils generally have the lowest runoff ratios as most of the precipitation soaks into the ground. Unit-area peak discharge is the amount of peak discharge divided by watershed area, and indicates the greatest amount of discharge generated by a unit area in a single precipitation event. A greater value of peak discharge indicates greater potential for flooding (Wu et al., 2013).

## 2.7 Research gap

A research conducted in Nyabugogo catchment used the Statistical Downscaling Model (SDSM) to explore the future change in precipitation in the Nyabugogo catchment and found that there is an increase of monthly rainfall during the rainy season where floods occur in Kigali. Assessment of the climate and land use change projections and their impacts on flooding with HEC-HMS model showed that the land use change will affect the hydrologic processes of the watershed by increasing the amount of surface runoff, which will lead to severe flooding in Kigali (Rukundo et al., 2016).

The applicability of tracer methods were tested to identify the dominant runoff generation processes in the Nyabugogo swamp and confirmed the important contribution of subsurface runoff to the stream flow. The results of study demonstrated some important ground water recharge from river water. Finally, further researches to estimate the volume of water for floods mitigation purpose in the Nyabugogo flooding area were recommended (Munyaneza et al., 2015).

OpenLISEM was used to assess flood hazard contributed by two main streams of channels taking water to Nyabugogo River; namely: Mpazi and Rwezangoro. The study found that runoff water in drainage systems has very high velocity with very high peak discharges and have been associated with damages of roads, culvert, and bridge. The study focused only on the contribution of two main streams of channels on flash floods, however there are also river floods generated by Nyabugogo River. Further study that can cover the whole Nyabugogo catchment to assess the effects of flood in the Kigali City was recommended (Habonimana et al., 2012). The use of Self-Close Flood Barrier (SCFD) was proposed to contribute to the mitigation of flood at three high flood zones in the Nyabugogo wetland; the study recommended to conduct further modelling studies runoff management in the neighbourhood to support these structure as the urbanization increases and climate changes drastically (Munyaneza et al., 2013).

Based on the results found by different researches, it can be concluded that, the problem of increasing flooding risks is mainly caused by rapid urbanization and climate change. Traditional drainage systems of pipes and channels no longer deal with larger and more intense stormwater events. The new innovative approaches, which are more effective than the traditional measures to mitigate floods, were identified. The optimal location and the most appropriate combinations of innovative approaches that work for a given area need to be assessed in order to provide a sustainable solution to flooding events.

## 2.8 Conceptual framework

The independent variables in this study were meteorological, land-use, topographical, soil, river flow, and drainage network data. The moderating variables are four infiltration-based techniques to mitigate floods while the dependent variables are stormwater runoff characteristics, drainage system performance and impact of four infiltration-based techniques to mitigate floods. The conceptual framework of the study is shown in Figure 2-2.

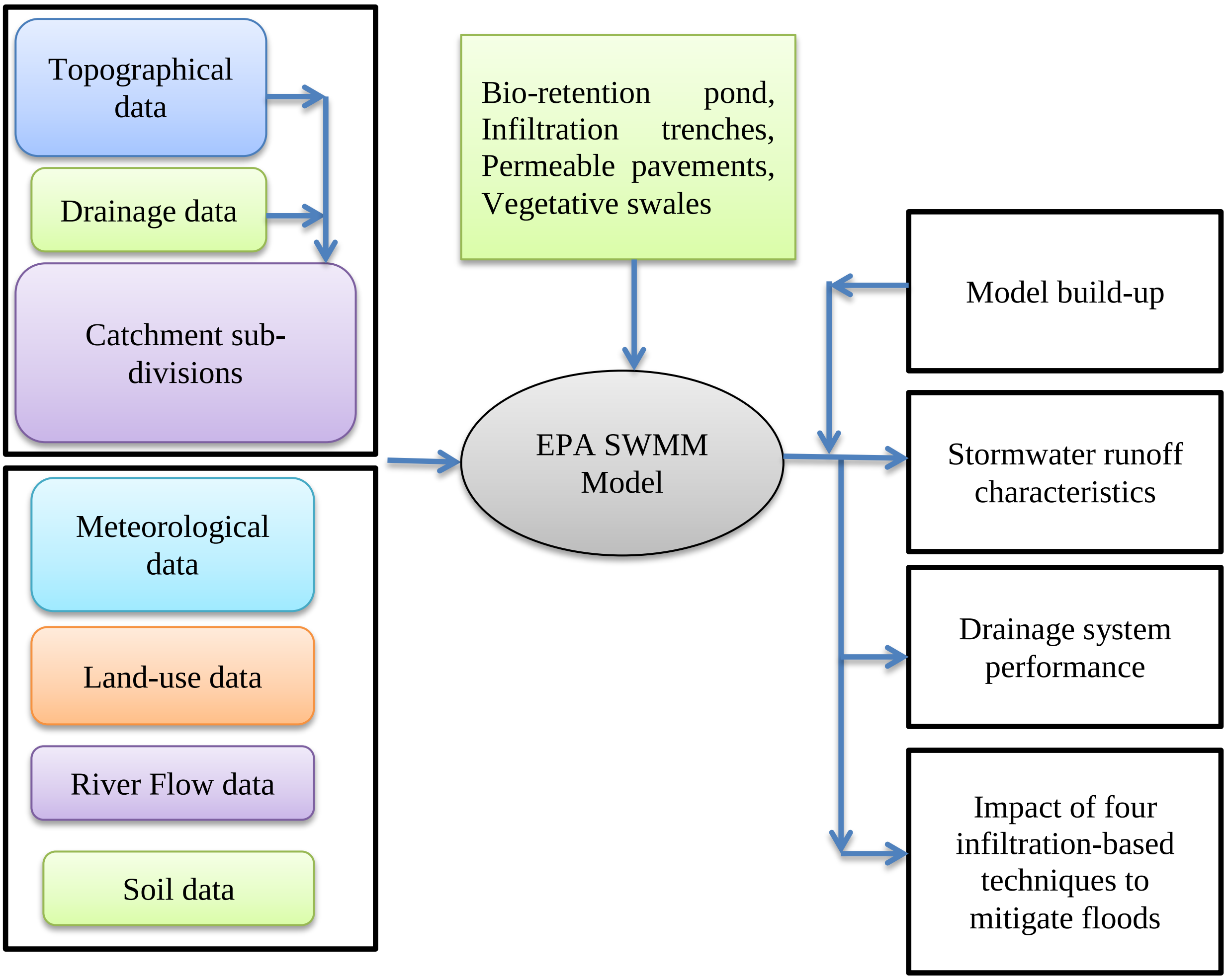

Figure 2-2: Conceptual framework

# Chapter 3

# Materials and methods

## 3.1 Study area description

Nyabugogo catchment covers the central, eastern and northern part of Rwanda (Figure 3-1). It covers a major portion of the City of Kigali (Figure 3-2) and few other districts (Manyifika, 2015). The main activity in the catchment is agriculture, which occupies about 897 $km^2$ (about 54%) of the catchment (Rukundo et al., 2016). Kigali city land was before covered by forest but now forests cover only an area of 10.6%. Urban development and farming activities including commercial daily and subsistence farming systems, have left only small, scattered patches of forest and other areas of natural vegetation. Urban land use include residential, commercial, and industrial, social and government infrastructure (Habonimana et al., 2012).

The climate of the catchment is mostly of temperate and equatorial type with average temperature ranging between 16 and 23°C, depending on the altitude of the area. The annual rainfall varies from about 800 to 1,600 mm (Rukundo et al., 2016; Water for Growth Rwanda, 2017). 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 (Munyaneza, 2014).

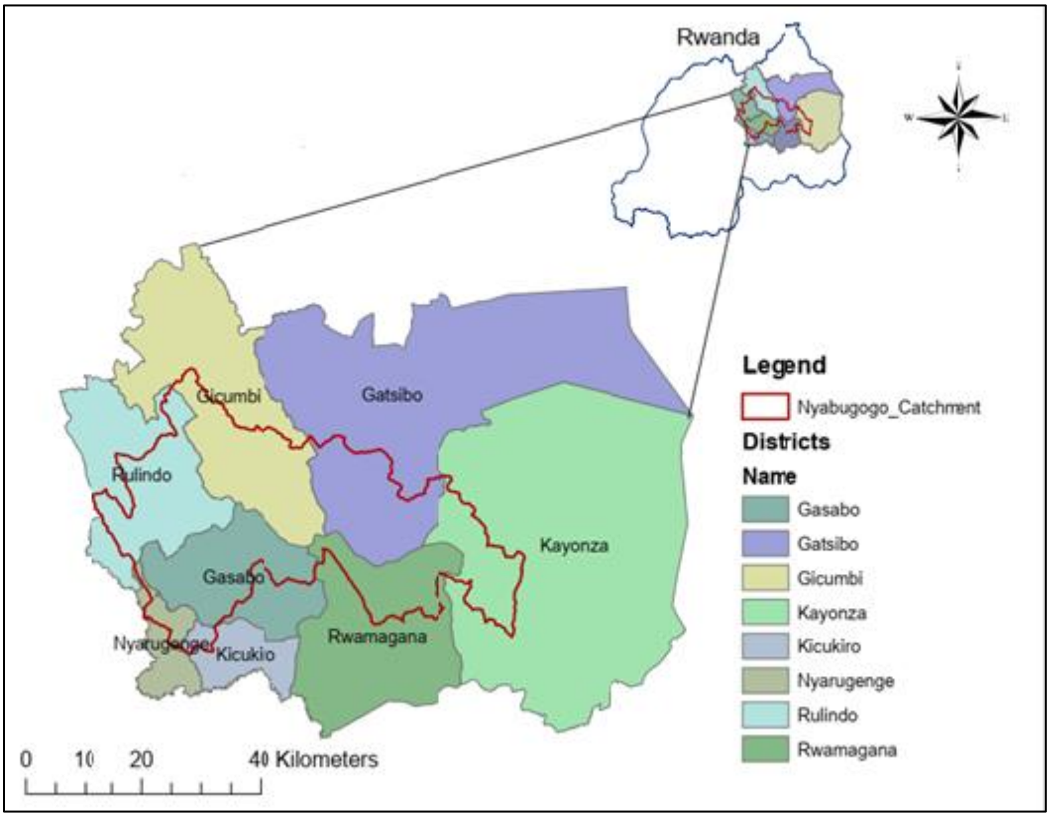

Figure 3-1: Nyabugogo Catchment location in Rwanda

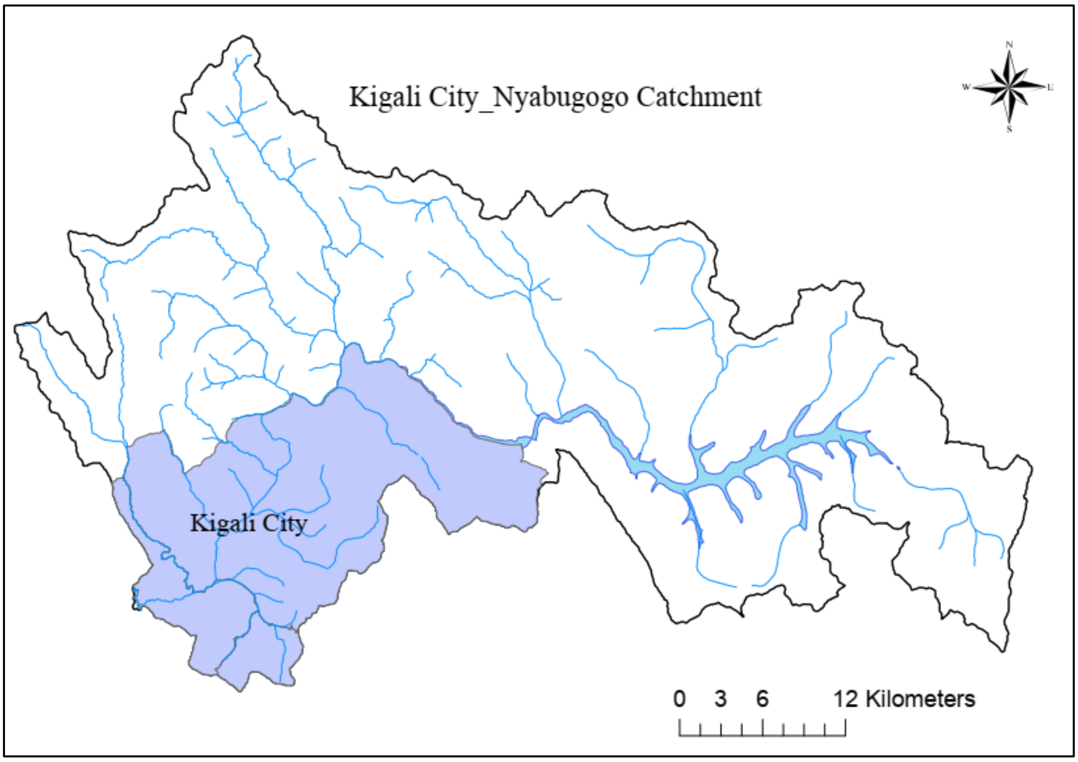

Figure 3-2: Kigali City part of Nyabugogo catchment

Kigali City is built on a rolling landscape of hills, ridges and valleys. The surrounding region ranges in altitude from 787 m to over 4000 m, but Kigali has a lower mid-altitudinal range of 1300 m in the wetlands, to the peak of Mount Kigali at 1850 m. The slopes of the city´s hills vary in steepness from inclines of up to 45% or 50%, to those in Valley wetland areas with slopes of less than 2% (Rukundo, 2015).

## 3.2 Stormwater runoff characteristics of Nyabugogo catchment

### 3.2.1 Research design for stormwater runoff characteristics

EPA SWMM model was used to simulate the stormwater runoff characteristics of Nyabugogo catchment. Meteorological data: (precipitation, temperature, evaporation, and wind speed, topographical data, land-use data and soil data (Appendix 1 to Appendix 11) and river flow data were used in this endeavour. EPA SWMM Model for Nyabugogo catchment was calibrated using meteorological data and river flow data. The calibration and validation were evaluated using coefficient of determination ($r^2$), Nash-Sutcliffe efficiency (NSE), and index of agreement (d) as efficiency criteria.

### 3.2.2 Data collection procedures for stormwater runoff characteristics

The initial task for modelling stormwater quantity of a catchment is to prepare the required data. The required data which were collected are described in Table 3-1.

### 3.2.3 Catchment delineation and sub-division

Catchment boundaries were delineated based on digital elevation model (DEM) using the ArcGIS tool. The DEM dataset was used to determine the catchment characteristics and to divide it into sub-catchments. The DEM of the catchment was extracted from the DEM which was provided by Rwanda Land Management and Use Authority for the calculation of local drainage direction, slope gradient of the drainage system, and the identification of the main outlet. The catchment was subdivided into eight sub-catchments where each sub-catchment was assigned to an outlet node in the drainage network.

Table 3-1: Required dataset for rainfall-runoff modelling

| Dataset type | Source | Description | Remarks |
|---|---|---|---|
| Meteorological data (Precipitation, temperature, evaporation, wind speed) | Rwanda Meteorology Agency | Daily data (1997-2017) | Kigali Airport, Gitega and Byumba meteorological stations |
| Topographical data | Rwanda Land Management and Use Authority (RLMUA) | Digital Elevation Map (DEM) | DEM of 30 m resolution |
| Land-use data | City of Kigali and RLMUA | Kigali master plan<br>Land-use maps | Kigali master plan provides a roadmap for the development of the City up to 2030. |
| Soil data | RLMUA | Soil classes | Shapefiles format |
| Stream flow data | Rwanda Water and Forestry Authority (RWFA) | Daily data (1997-2017) | Nemba, Muhazi and Yanze Stations |
| Drainage network | City of Kigali and RWFA | Kigali Master Plan<br>Drainage network maps | Shapefiles format |

### 3.2.4 EPA SWMM model parameterization

Model parameters were obtained by considering the physical catchment data which are: total catchment area, percentage of impervious area, catchment width, average slope, surface depression storage and surface roughness. Most of this information was derived from topographic map and drainage network dataset.

Curve numbers were assigned for each drainage area within the catchment. Curve numbers are indicators of the runoff potential of a watershed during a rainfall event.

The main significant variables for defining a curve number are the hydrologic soil group and cover type. In order to determine the pervious soil curve number, the hydrologic soil group for each drainage area was determined from the existing soil maps (Appendix 9).

The calibration and validation processes started by the determination of the most sensitive parameters for the catchment. Sensitivity analysis was used to identify key parameters and the parameter precision required for calibration. Model calibration was performed by carefully selecting values for model input parameters by comparing model predictions for a given set of assumed conditions with observed data for the same conditions. The verification of model efficiency and performance was done using the efficiency criteria; namely, coefficient of determination ($r^2$), Nash-Sutcliffe efficiency (NSE), and index of agreement (d).

The coefficient of determination $r^2$ is defined as the squared value of the coefficient of correlation (Krause et al., 2005). It is calculated as Eq. 3-1:

$$r^2 = \left[\frac{\sum_{i=1}^{n}(O_i-\bar{O})(P_i-\bar{P})}{\sqrt{\sum_{i=1}^{n}(O_i-\bar{O})^2}\sqrt{\sum_{i=1}^{n}(P_i-\bar{P})^2}}\right]^2 \qquad \textbf{Eq. 3-1}$$

With O: Observed values, $\bar{O}$: mean observed values, and P: Predicted (Modelled) values

The range of $r^2$ lies between 0 and 1 which describes how much of the observed dispersion is explained by the prediction. A value of zero means no correlation at all whereas a value of 1 means that the dispersion of the prediction is equal to that of the observation (Wu et al., 2013).

The NSE is defined as one minus the sum of the absolute squared differences between the predicted and observed values normalized by the variance of the observed values during the period under investigation (Wu et al., 2013). It is calculated as Eq. 3-2:

$$E = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2}$$ **Eq. 3-2**

With O: Observed values, Ō: mean observed values and P: Predicted (Modelled) values

The range of E lies between 1 and −∞. An efficiency of lower than zero indicates that the mean value of the observed time series would have been a better predictor than the model (Hewes et al., 2013).

The index of agreement represents the ratio of the mean square error and the potential error and is calculated as Eq. 3-3:

$$d = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(|P_i - \bar{O}| + O_i - \bar{O})^2}$$ **Eq. 3-3**

The range of d is similar to that of $r^2$ and lies between 0 and 1. A value of zero means no correlation at all whereas a value of 1 means that the dispersion of the prediction is equal to that of the observation (Krause et al., 2005).

Calibrated and validated EPA SWMM model was used to simulate the runoff characteristics of Nyabugogo catchment.

## 3.3 The performance of existing drainage systems in the Nyabugogo catchment

### 3.3.1 Research design for existing drainage systems performance evaluation

EPA SWMM model was used to simulate the stormwater runoff from existing buildout land-use patterns within the catchment to evaluate the performance of existing stormwater drainage systems. Land-use data and design storms were used to formulate scenarios of rainfall events while evaluating the performance of existing drainage systems in Nyabugogo catchment. Field survey was also carried out to complement the results simulated on performance existing drainage systems. GPS was used to locate the systems on the map.

### 3.3.2 Data collection procedures for existing drainage systems performance evaluation

The required data which were collected were described in Table 3-1.

### 3.3.3 Data processing and analysis for evaluation of existing drainage systems performance

The results obtained from simulations were subjected to testing using indices of reliability, resiliency, vulnerability and sustainability to evaluate the performance of urban drainage systems of Nyabugogo catchment.

Reliability is representative of the likelihood of system being in a satisfactory state and can be expressed as the ratio of the number of satisfactory states to the total number of system activities (Binesh et al., 2016). Reliability can be defined as total number of time intervals in which system can convey the runoff flow without surcharging, to the total simulated time steps in case urban drainage system. It is calculated as Eq. 3-4:

$$Reliability = \frac{1}{T}\sum_{t=1}^{T} Z_t$$ **Eq. 3-4**

With

$$Z_t = 1 \qquad \forall X_t \in S$$

$$Z_t = 0 \qquad \forall X_t \in F$$

Where:

$Z_t$ is the state of the drainage system in the time interval t, $X_t$ is the value of investigatory parameter in the time interval t, S is the satisfactory state, F is the failure state, and T is the duration of operating period. Failure states in this study were considered to be time intervals during which flow exceeded the channel capacity in the whole system.

Resiliency measures how quickly the system recovers after a failure occurs and can be defined as the inverse of the maximum duration of failure time that urban drainage system can experience over a specified planning horizon (Binesh et al., 2016). It is calculated as Eq. 3-5:

$$Resiliency = \frac{1}{MaxT_f}$$ **Eq. 3-5**

Where $T_f$ is the length of time (i.e. a number of consecutive time steps) during which flooding occurs. Flooding refers to any volume of water more than conduit capacity at any time step.

Vulnerability represents the severity of the failure and can be expressed as the maximum difference between allowed and calculated value of a certain variable. It is calculated as in Eq. 3-6:

$$Vulnerability = \begin{Bmatrix} O & if\ D_t \leq D_f \\ Max[D_t - D_f] & else \end{Bmatrix} \quad \textbf{Eq. 3-6}$$

Where $D_t$ is the notation of reference level of runoff depth which the system can convey without being surcharged (equals to channel depth), and $D_f$ is the calculated value of runoff depth.

The whole system's total performance which is known as sustainability index of the system, can be calculated as Eq. 3-7 (Binesh et al., 2016):

$$Sustainability = \frac{Reliability \times Resiliency}{Vulnerability} \quad \textbf{Eq. 3-7}$$

## 3.4 The effectiveness of infiltration-based techniques to mitigate floods in Nyabugogo catchment

### 3.4.1 Research design for evaluating the effectiveness of infiltration-based techniques

Bio-retention ponds, infiltration trenches, permeable pavement and vegetated swales are among eight different generic types of infiltration-based techniques to capture surface runoff and provide some combination of detention, infiltration, and evapotranspiration; EPA SWMM Model can explicitly model them (Rossman, 2015). EPA SWMM model was used to simulate impacts of bio-retention ponds, infiltration trenches, permeable pavement and vegetated swales on the water quantity using a baseline scenario with no method implementation as the control. Each scenario was designed to handle runoff from a specified percentage of impervious area. Scenarios were designed based on the return period, rainfall and the four infiltration-based techniques (Appendix 12 to Appendix 15) to quantify hydrological responses to independent and combined effects based on data of impervious surfaces of Nyabugogo catchment.

### 3.4.2 Data collection procedures for evaluating the effectiveness of infiltration-based techniques

The required data which were collected were described in Table 3-1. The parameters associated with bio-retention ponds, infiltration trenches, permeable pavement and vegetated swales were also used to evaluate the effectiveness of IBTs to mitigate floods in Nyabugogo catchment. The parameter associated with the mentioned techniques are described in EPA SWMM user’s Manual (Rossman, 2015).

### 3.4.3 Data processing and analysis for evaluating infiltration-based techniques

To quantify hydrological responses, three indices were calculated for current condition and scenario simulations: namely, unit-area peak discharge, Richards-Baker Index, and runoff ratio.

Unit-area peak discharge is the amount of peak discharge divided by watershed area, and indicates the greatest amount of discharge generated by a unit area in a single precipitation event. A greater value of peak discharge indicates greater potential for flooding (Wu et al., 2013).

The Richards-Baker index measures oscillations in discharge relative to total discharge also referred to as flashiness and as such, appears to provide a useful characterization of the way watersheds process hydrologic inputs into their stream flow outputs (Baker et al., 2004). A higher value of the Richards-Baker index indicates a greater difference between high and low flows, which may be linked to changes in channel morphology, water quality and habitat structure of stream ecosystems (Wu et al., 2013); It is calculated as Eq. 3-8:

$$R - B\ Index = \frac{\sum_{i=1}^{n} |q_i - q_{i-1}|}{\sum_{i=1}^{n} q_i} \qquad \textbf{Eq. 3-8}$$

Where n is the total number of discharge records, and $q_i$ is the $i^{th}$ measured discharge of a stream, and $q_{i-1}$ is the $i-1^{th}$ measured discharge of a stream.

The runoff ratio is the total discharge depth divided by total precipitation depth, which indicates the proportion of precipitation that is discharged in surface channels. A higher value of runoff ratio indicates an increase of surface runoff and may result in decreases in groundwater level because of less infiltration (Wu et al., 2013).

### 3.4.4 Infiltration-based techniques scenarios

To evaluate the effects of bio-retention ponds, permeable pavements, infiltration trenches, and vegetative swales on flooding in the Nyabugogo catchment, several scenarios were simulated using EPA SWMM model. Four infiltration-based techniques were used for scenarios formulation for further analysis. Permeable pavements work by allowing streets, parking lots, sidewalks, and other impervious covers to retain their natural infiltration capacity while maintaining the structural and functional features of the materials they replace. Permeable pavements contain small voids that allow water to drain through the pavement to an aggregate reservoir and then infiltrate into the soil. The depth of the gravel storage layer is an important design parameter. Bio-retention typically consists of a shallow, vegetated basin that collects and absorbs runoff from impervious areas.

The parameters for four infiltration based techniques were adopted from the range provided in SWMM User's manual (Rossman et al., 2016a). Example for Permeable pavement system with a storage depth of 60 cm, a permeable pavement system with a storage depth of 120 cm, and a bio-retention ponds with a soil media depth of 90 cm. Once the maximum extent of infiltration trenches, and vegetative swales, permeable pavement and bio-retention ponds was known, the scenarios were developed spanning 0, 25, 50, 75 and 100% of the maximum extent of modelling (Table 3-2).

Table 3-2: Simulation scenarios used to evaluate the effectiveness of IBTs for floods mitigation

| Scenarios | Extent of Infiltration-based technique |
|---|---|
| Permeable pavements | |
| Scenario 1 | No infiltration-based techniques are used |
| Scenario 2 | Permeable pavements used to an extent of 25% of impervious areas in sub-catchments S5, S6 and S8. |
| Scenario 3 | Permeable pavements used to an extent of 50% of impervious areas in sub-catchments S5, S6 and S8. |
| Scenario 4 | Permeable pavements used to an extent of 75% of impervious areas in sub-catchments S5, S6 and S8. |
| Scenario 5 | Permeable pavements used to an extent of 100% of impervious areas in sub-catchments S5, S6 and S8. |
| Vegetative swales | |
| Scenario 2 | Vegetative swales used to an extent of 25% of impervious areas in sub-catchments S1, S2, S3, S5, S6 and S8. |
| Scenario 3 | Vegetative swales used to an extent of 50% of impervious areas in sub-catchments S1, S2, S3, S5, S6 and S8. |
| Scenario 4 | Vegetative swales used to an extent of 75% of impervious areas in sub-catchments S1, S2, S3, S5, S6 and S8. |
| Scenario 5 | Vegetative swales used to an extent of 100% of impervious areas in sub-catchments S1, S2, S3, S5, S6 and S8. |
| Infiltration trenches | |
| Scenario 2 | Infiltration trenches used to an extent of 25% of impervious areas in sub-catchments S4 and S7. |
| Scenario 3 | Infiltration trenches used to an extent of 50% of impervious areas in sub-catchments S4 and S7. |
| Scenario 4 | Infiltration trenches used to an extent of 75% of impervious areas in sub-catchments S4 and S7. |
| Scenario 5 | Infiltration trenches used to an extent of 100% of impervious areas in sub-catchments S4 and S7. |
| | |

| | |
|---|---|
| Scenario 2 | Bio-retention ponds used to an extent of 25% of impervious areas in sub-catchments S4 and S7. |
| Scenario 3 | Bio-retention ponds used to an extent of 50% of impervious areas in sub-catchments S4 and S7. |
| Scenario 4 | Bio-retention ponds used to an extent of 75% of impervious areas in sub-catchments S4 and S7. |
| Scenario 5 | Bio-retention ponds used to an extent of 100% of impervious areas in sub-catchments S4 and S7. |
| Combination | |
| Infiltration trenches used to an extent of 50% of impervious areas in sub-catchments S4 and S7. Vegetative swales used to an extent of 50% of impervious areas in sub-catchments S1, S2, S3, S5, S6 and S8. Permeable pavements used to an extent of 50% of impervious areas in sub-catchments S5, S6 and S8. Bio-retention ponds used to an extent of 50% of impervious areas in sub-catchments S4 and S7. | |

A variety of infiltration-based techniques can achieve runoff reduction. In this research, scenarios of bio-retention ponds, permeable pavements, infiltration trenches, and vegetative swales working together and independently to reduce surface runoff in Nyabugogo catchment were evaluated.

#### 3.4.4.1 Design storm scenarios for rainfall-runoff modelling

The EPA SWMM model calibrated and validated for Nyabugogo catchment runoff modelling was used to simulate rainfall events. As the main objective of this study was to evaluate the impact of infiltration-based techniques to mitigate floods in Nyabugogo catchment, different rainfall intensities with return periods of 2, 5, 10, 20, 50, and 100 years were generated and modelled under two scenarios: before implementation of the of infiltration-based techniques and after implementation of infiltration-based techniques.

# Chapter 4

# Results and Discussions

## 4.1 Stormwater runoff characteristics of Nyabugogo catchment

### 4.1.1 Catchment delineation and model parameterization

The catchment was subdivided into eight sub-catchments and the characteristics required by the model were derived from different datasets. Each sub-catchment was assigned to an outlet node in the drainage network (Figure 4.1) and was used in EPA SWMM for simulations. The parameters required for EPA SWMM rainfall-runoff modeling were obtained by considering the physical catchment characteristics, rainfall and infiltration data. Most of this information was derived from topographic map and drainage network dataset.

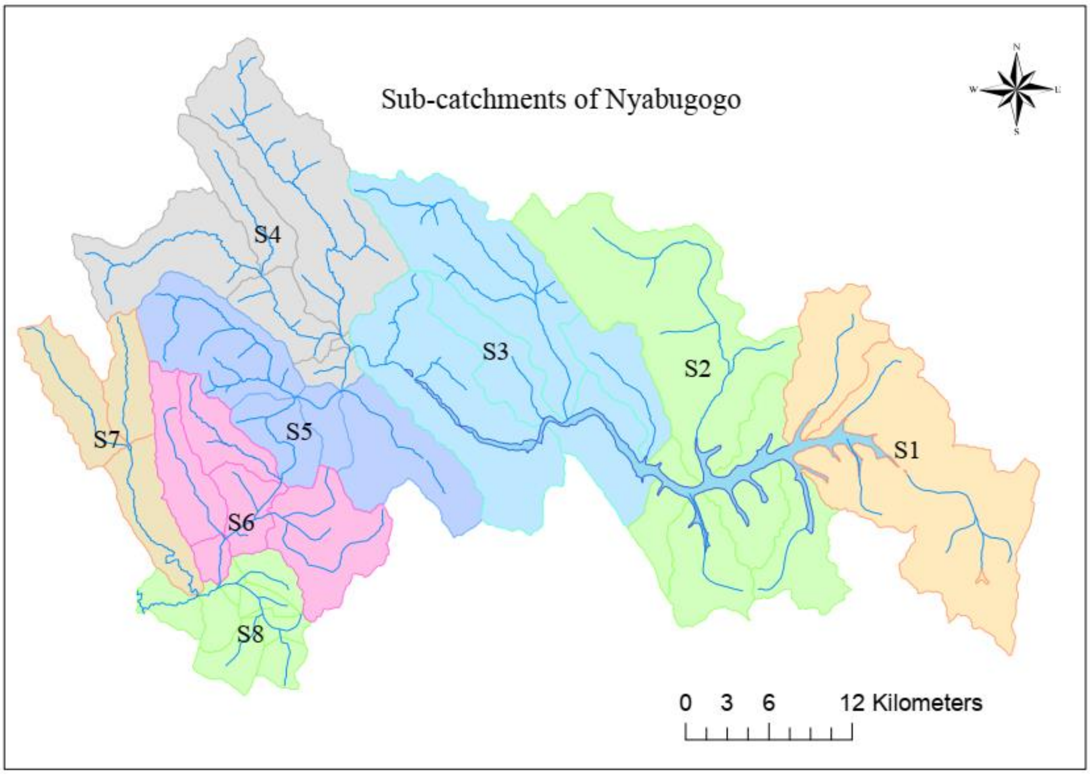

Figure 4-1: Sub-catchments of Nyabugogo

The physical characteristics of Nyabugogo catchment used for modeling are described in Table 4-1.

Table 4-1: Physical Characteristics of Nyabugogo catchment

| Sub catchments | Area (ha) | Impervious area (%) | Channel slope (%) | Channel Width (m) | Runoff Curve Number |
|---|---|---|---|---|---|
| S1 | 22,692 | 3.8 | 0.25 | 301.2 | 88.9 |
| S2 | 31,135 | 2.7 | 0.32 | 352.9 | 88.9 |
| S3 | 33,230 | 1.9 | 0.73 | 364.5 | 88.9 |
| S4 | 26,665 | 2.1 | 1.04 | 326.5 | 86.7 |
| S5 | 17,061 | 3.5 | 1.25 | 261.2 | 85.6 |
| S6 | 14,689 | 72 | 1.22 | 242.4 | 88.5 |
| S7 | 9,670 | 2.3 | 1.04 | 196.6 | 86.4 |
| S8 | 7,702 | 78.4 | 1.35 | 175.5 | 86.6 |

### 4.1.2 Sensitivity Analysis

For Nyabugogo Catchment, the sensitive input parameters used were flow width coefficient, Manning’s roughness coefficient for impervious area, Manning’s roughness coefficient for pervious area, Depth of depression storage on impervious area, Depth of depression storage on pervious area, Manning’s roughness coefficient for conduit and Time for a fully saturated soil to completely dry. The input parameters for catchment properties were adopted from the range provided in Table 4.2 of EPA SWMM User’s manual.

Width-K had an influence on runoff flow depth of $S_r = 0.7$, Conduit Roughness had an influence with $S_r$ of 0.57 for flow depth. Destore-Imperv and Destore-Perv had a low influence on flow depth. N-Imperv and Destore-Imperv had negative coefficients, which indicated that the output values increase with a decrease in these input parameters.

Table 4-2: Modelling Parameters

| Parameter | Description | Value range | Value |
|---|---|---|---|
| Width-K | flow width coefficient | 0.2–5 | 2 |
| N-Imperv | Manning’s roughness coefficient for impervious area | 0.011–0.015 | 0.015 |
| N-Perv | Manning’s roughness coefficient for pervious area | 0.05–0.8 | 0.08 |
| Destore-Imperv | Depth of depression storage on impervious area | 0–3 | 3 |
| Destore-Perv | Depth of depression storage on pervious area | 3–10 | 6 |
| Conduit Roughness | Manning’s roughness coefficient for conduit | 0.011–0.024 | 0.011 |
| Drying Time | Time for a fully saturated soil to completely dry | 1–7 | 5 |

A research conducted on modelling runoff quantity and quality in tropical urban catchments using stormwater management model found that the percentage impervious and flow width coefficient more influential and sensitive to runoff depth and peak flow. The percentage impervious had $S_r$ of 0.96 on runoff depth and 0.72 on peak flow. Manning’s roughness coefficient for impervious area (N-Imperv) and Depth of depression storage on impervious area (Destore-Imperv) had negative $S_r$ values which indicate that the values of runoff depth and peak flow decrease with their increase in values (Chow et al., 2012).

A study conducted on modeling the quality and quantity of runoff in a highly urbanized catchment using storm water management model concluded that the depth of depression storage on impervious area and conduit roughness had the most influence on the hydrology and hydraulic component. Destore-Imperv was the most sensitive parameter in the determination of the total flow, and had a sensitivity coefficient value of 0.142. Condit roughness was highly sensitive to total flow and was the most sensitive parameter to peak flow (Li et al., 2016).

A research performed on sensitivity analysis in for a large basin in Tallinn, Estonia and found that the model is sensitive to the percentage of the impervious area for predicting both flow rate and peak flow. Impervious depression storage regulates the initial peak flow. Impervious surface roughness and width of catchment have weak connections to the model predictions (Maharjan et al., 2015). A sensitivity analysis performed for a large basin in Tallinn, Estonia found that the model is sensitive to the percentage of the impervious area for predicting both flow rate and peak flow (Maharjan et al., 2015). Impervious depression storage regulates the initial peak flow. Impervious surface roughness and width of catchment have weak connections to the model predictions (Maharjan et al., 2015). Previous studies using EPA SWMM have found that runoff flow depth is more sensitive to Width-K and N-Imperv and Destore-Imperv have negative coefficients which are similar to the results found for this study. The sensitive parameters were used to identify the values to be used for model calibration and validation.

### 4.1.3 Model calibration

The model was evaluated for the modelling capabilities through three indicators using Eq. 3-1, Eq. 3-2 and Eq. 3-3. The simulated and measured values of runoff quantity for a period from 1997 to 2005 were used and the results show the values $r^2$ of 0.72, E of 0.6 and d of 0.77. The values of the modelled and observed runoff depth and rainfall were plotted in Figure 4- 2.

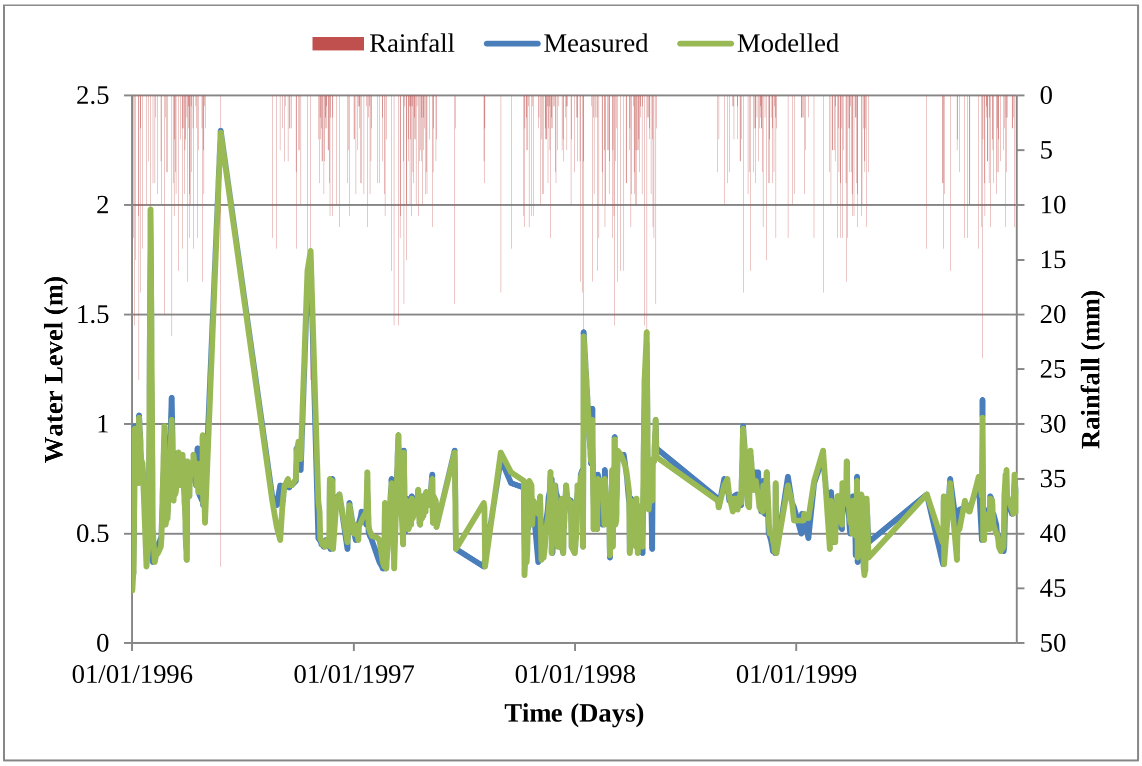

Figure 4-2: Runoff depth of measured and modelled values during calibration at Yanze Hydrological Station

The model performance was judged satisfactory for flow simulation at catchment scale for the values of $r^2$ greater than 0.6, NSE greater than 0.5 and d greater than 0.7 (Moriasi et al., 2015). The simulated runoff depths show good relationships with the measured values at Yanze Hydrological Station. The model is considered well calibrated for estimating the runoff quantity.

A research conducted on modeling the quality and quantity of runoff in a highly urbanized catchment using storm water management model resulted in calibration values of E greater than 0.87 and $r^2$ values of 0.86, 0.90, and 0.87 for three events. The runoff volume and peak flow had a good fit between the measured and simulated data (Li et al., 2016).

Continuous simulations were used for calibration and validation. Agreement between predicted and observed data was assessed using coefficients of determination $r^2$ and the Nash–Sutcliff model efficiency NSE coefficients. The calibration resulted in $r^2$ greater than 0.7 and E of 0.78 and 0.64 for runoff volume and peak flow, respectively (Rosa et al., 2015).

A study conducted on a long-term hydrological modelling of an extensive green roof by means of SWMM. The Model calibration and validation was evaluated based on the comparison of the observed and simulated runoff flow rates. In order to assess the model performance, the observation standard deviation ratio (RSR) and Nash–Sutcliffe efficiency index (NSE) were used. The calibration resulted in values of E ranging from 0.58 to 0.93 and RSR of 0.27 to 0.65 of flow rates (Cipolla et al., 2016). In the present study, the values of testing parameters from calibration were reasonable and in acceptable ranges.

### 4.1.4 Model validation

The input parameters that were derived in the calibration process were used to validate the model. The purpose of model validation is to confirm whether the input parameters are able to simulate new events. The simulated and measured values for runoff for a period from 2006 to 2017 were used. The results of model validation gave the values $r^2$ of 0.84; E of 0.72; and d of 0.8. The values of modelled and observed runoff depth and rainfall were plotted as shown in Figure 4- 3. The model performance is judged satisfactory for flow simulation at catchment scale for the values of $r^2$ greater than 0.6, NSE greater than 0.5 and d greater than 0.7 (Moriasi et al., 2015).

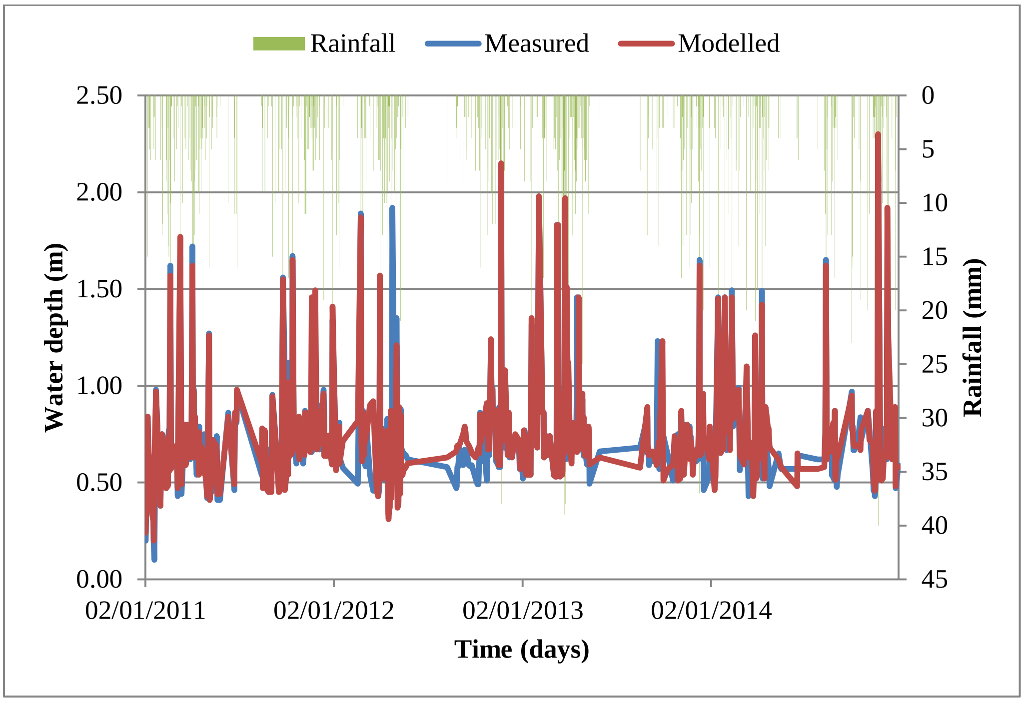

Figure 4-3: Runoff depth of measured and modelled values during validation at Yanze Hydrological Station

Generally, the model was found to be appropriate for runoff quantity modelling in Nyabugogo catchment.

A study on Calibration and validation of SWMM model in two urban catchments in Athens, Greece resulted in a validation showing the good fit between the measured and simulated values of runoff quantity with E of 0.93, d of 0.98 and $r^2$ of 0.96 (Kourtis, Kopsiaftis, et al., 2017). EPA SWMM was used to conduct a research on the rehabilitation of concrete canals in urban catchments using low impact development techniques. For the calibration and validation process, both the $r^2$ and NSE measures were used to comprehensively evaluate the model performance. The NSE values for the validation events ranged from 0.79 to 0.99 and the $r^2$ values ranged from 0.89 to 0.99 for peak runoff (Palanisamy et al., 2015).

A research conducted on a high resolution application of a storm water management model (SWMM) using genetic parameter optimization. The Model validation was evaluated using Nash-Sutcliffe efficiency NSE, the linear correlation coefficient LCC and the sum of squared errors SSE. The highest values of NSE equal to 0.95 and LCC of 0.97 for validation events were achieved (Krebs et al., 2013). In the present study, the values of testing parameters from validation were reasonable and in acceptable ranges.

### 4.1.5 Stormwater runoff characteristics of Nyabugogo catchment

The modelled stormwater runoff characteristics of Nyabugogo catchment are described by Figure 4-4 which illustrates the average monthly water depth for a period of 2011 to 2014.

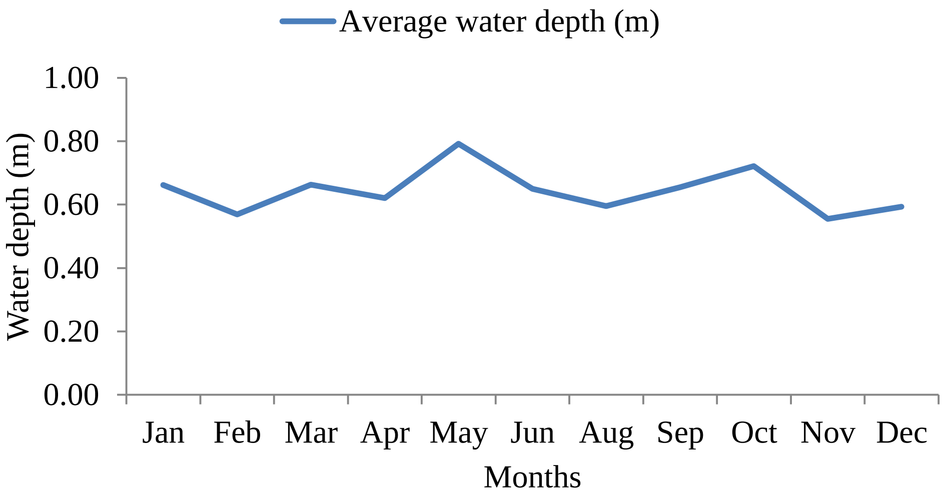

Figure 4-4: Average monthly water depth at Junction 44

The minimum and maximum daily and monthly water depths modelled for a period of 2011 to 2014, were illustrated in Figure 4-5 where the values greater than 2 m correspond to flooding.

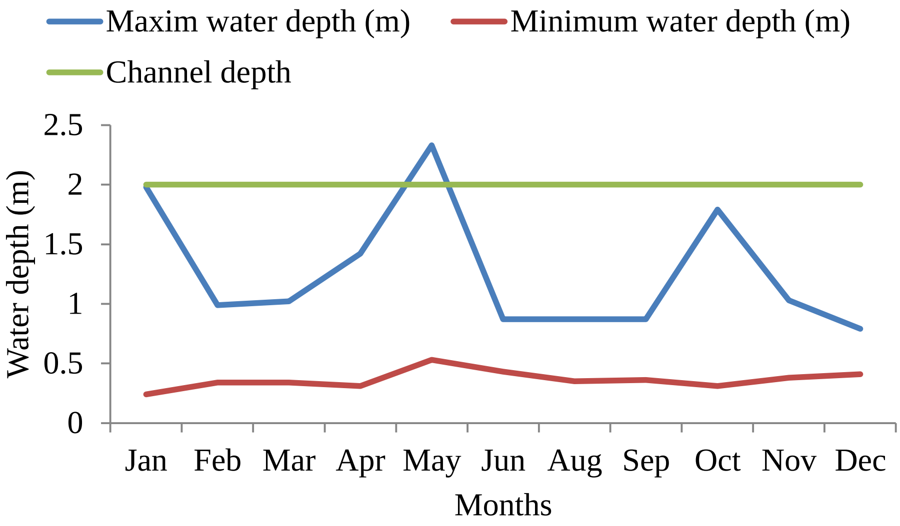

Figure 4-5: Monthly water depth at Junction 44

## 4.2 The performance of existing drainage systems in the Nyabugogo catchment

### 4.2.1 Design storms for evaluating drainage systems performance

The intensity-duration-frequency relationship for Rwanda established by (Wagesho et al., 2016) was used to get the design rainfall for Nyabugogo catchment and the Table 4-3 displays the design rainfall of 2, 5, 10, 25 and 50-year frequency return periods and 0.5, 1, 3, 6, 12 and 24 hours durations.

Table 4-3: Identified design storms (mm) with different return periods in Nyabugogo catchment

| Return Period (years) | Duration (hours) | | | | | |
|---|---|---|---|---|---|---|
| | 0.5 | 1 | 3 | 6 | 12 | 24 |
| 2 | 23.1 | 31.8 | 38.9 | 45.7 | 50.5 | 52.5 |
| 5 | 27.9 | 38.2 | 46.1 | 54.7 | 60 | 65 |
| 10 | 31.5 | 42.9 | 51.4 | 60.8 | 68.7 | 73.1 |
| 25 | 36.1 | 48.4 | 57.6 | 68.7 | 77.7 | 83.7 |
| 50 | 40.2 | 52.8 | 62.7 | 74 | 84.9 | 91.4 |
| 100 | 42.7 | 57.6 | 68.4 | 81 | 93.2 | 99.3 |

The design rainfalls were used to formulate scenarios in order to model the performance of existing drainage systems to manage stormwater runoff in Nyabugogo catchment. A research conducted on impact of urbanization on rainfall-runoff processes: case study in the Liang Shui river basin in Beijing, china used precipitation with different return periods: 2, 5, 20 and 100-year return periods as model input to analyse the changes of flood characteristics under different urbanized scenarios (Xu et al., 2016). A study on assessing the effectiveness of imperviousness on stormwater runoff in micro urban catchments by model simulation used EPA SWMM to model the effects of imperviousness on runoff. The rainfall with 3-year return period was used to establish the scenarios for modelling rainfall-runoff. The results showed that the impervious areas contributed a lot on both total and peak runoff depth (Yao et al., 2016).

A research conducted on reliability-based flood management in urban watersheds considering climate change impacts used EPA SWMM to simulate the rainfall-runoff processes in order to evaluate the reliability of an urban watershed located in the north-eastern part of Tehran, the capital of Iran. The scenarios were established under 5, 25, 50 and 100-year return periods in order to model the reliability of the system to flooding (Karamouz et al., 2013). The rainfall-runoff simulation for Nyabugogo catchment was conducted using the calibrated model.

### 4.2.2 Indicators for performance of drainage systems

The results of reliability, resiliency and vulnerability for Nyabugogo catchment drainage systems are presented from Figure 4-7 to Figure 4-13.

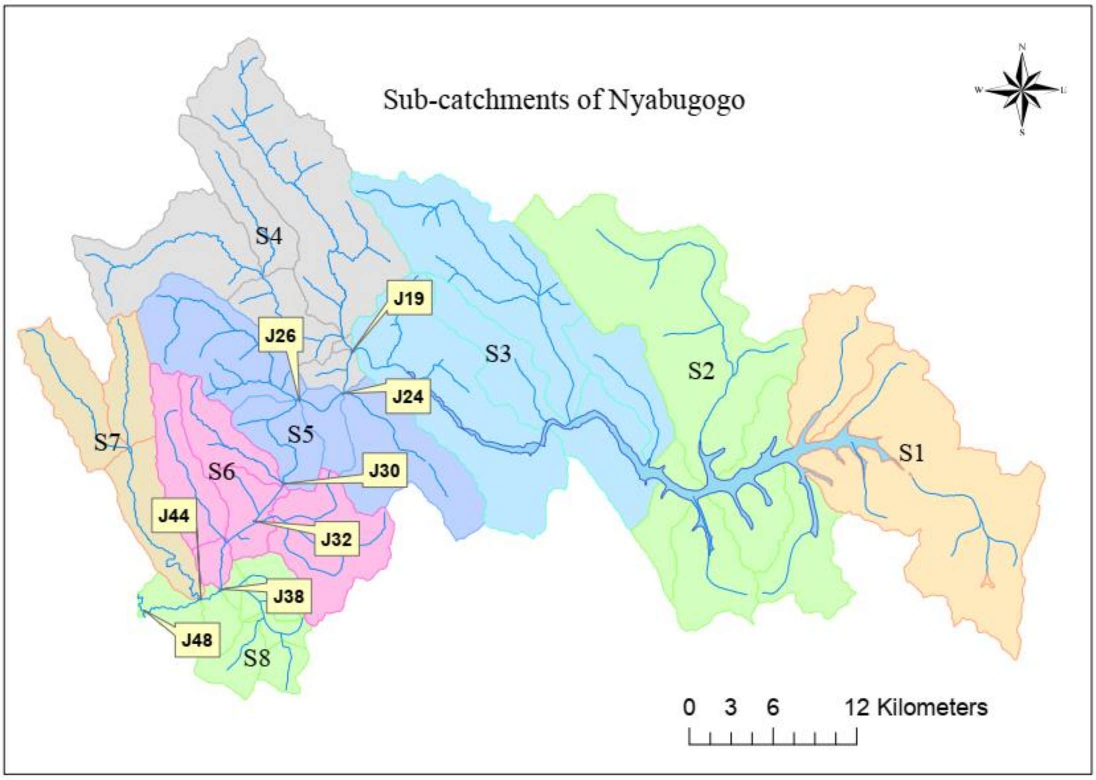

Figure 4-6: Junctions of Nyabugogo catchment

The scenario of design rainfall of duration of 3 hours gives a reduction in reliability from 67.6% to 22.7% as the design storm changed form from 2-year to 100-year return periods. The junctions J19, J24, J30, J32, J44 and J48 (Figure 4-7 and Figure 4-8) are the least reliable.

Other junctions represent good performance and act effectively in conveying the produced runoff.

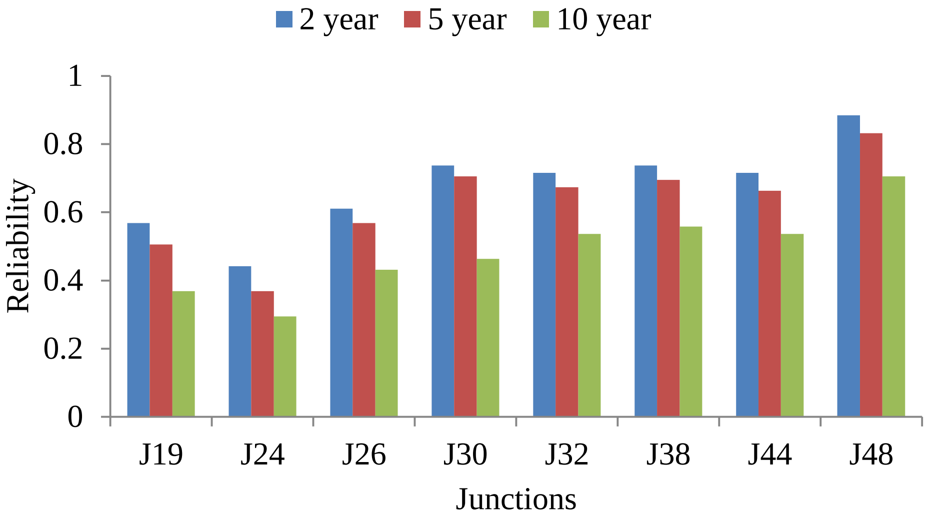

Figure 4-7: Simulated results of reliability under 2, 5 and 10-year return periods

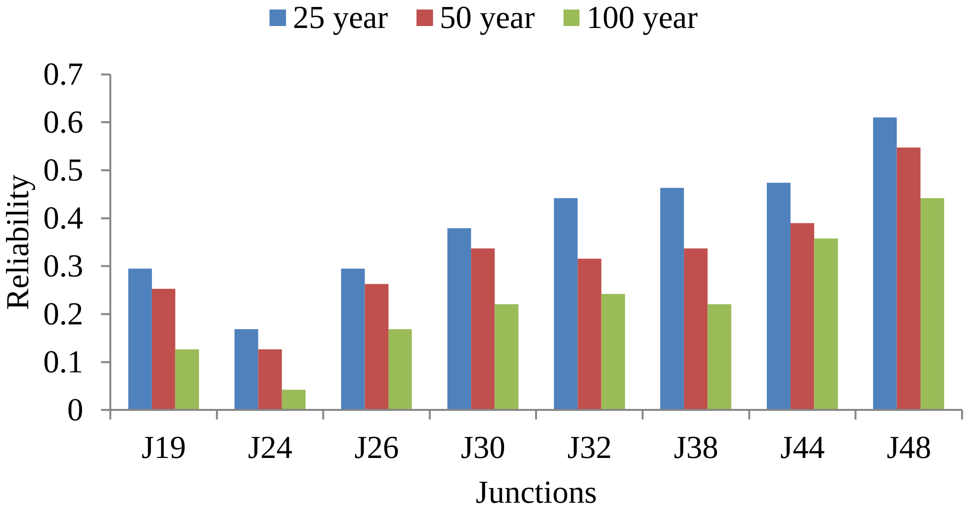

Figure 4-8: Simulated results of reliability under 25, 50 and 100-year return periods

A research conducted on reliability-based flood management in urban watersheds considering climate change impacts used EPA SWMM to simulate the rainfall-runoff processes in order to evaluate the reliability of an urban watershed located in the north-eastern part of Tehran, the capital of Iran. The reliability was tested considering both severity and duration of flooding. The results of the study showed that the flooding risks are increasing with design rainfall return periods (Karamouz et al., 2013).

The scenario of design rainfall of duration of 3 hours gives a reduction in resiliency from 3.9% to 1.4% as the design storm changed form from 2-year to 100-year return periods. The junctions J19, J24, J30, J32, J44 and J48 (Figure 4-9 and Figure 4-10) are the least resilient.

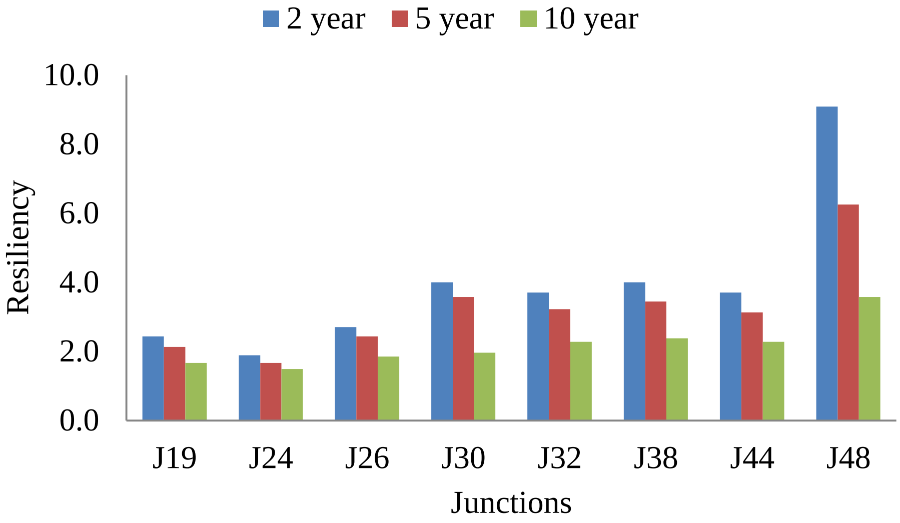

Figure 4-9: Simulated results of resiliency under 2, 5 and 10-year return periods

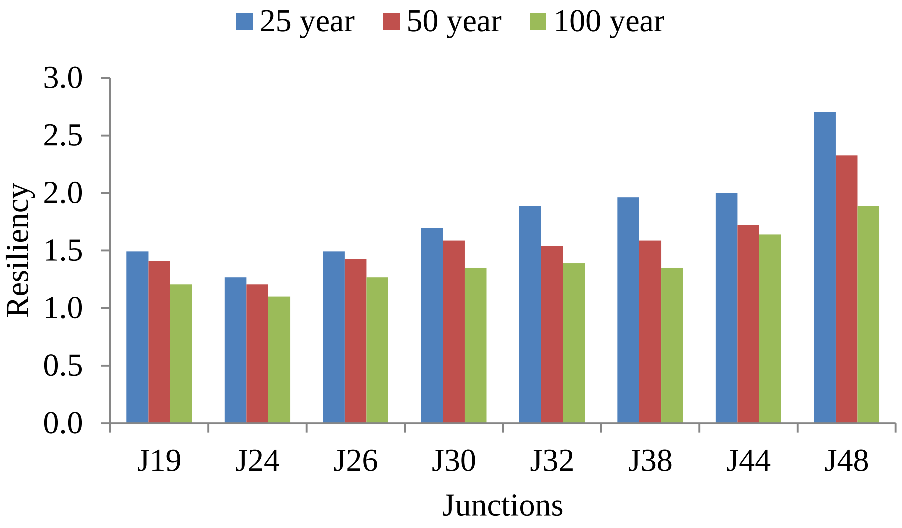

Figure 4-10: Simulated results of resiliency under 25, 50 and 100-year return periods

Other junctions represent good performance and act effectively in conveying the produced runoff. The results show that the remaining junctions in the study area are able to bounce back to its primary function after a failure occurs.

A study on assessing the impact of urbanization on storm runoff in a peri-urban catchment using historical change in impervious cover concluded that there a relative increase in peak flows and response time of a catchment is greatest at low levels of urbanization and that the introduction of storm water conveyance systems significantly increases the flashiness of storm runoff. The flashier response and higher peak flows reduce the performance of drainage systems. The research proposed the mitigation measures such as SUDS to contribute to runoff reduction in a natural manner (Miller et al., 2014).

The scenario of design rainfall of duration of 3 hours gives an increase in vulnerability from 31% to 72% as the design storm changed form from 2-year to 100-year return periods. The junctions J19, J24, J30, J32, J44 and J48 (Figure 4-11 and Figure 4-12) are the most vulnerable.

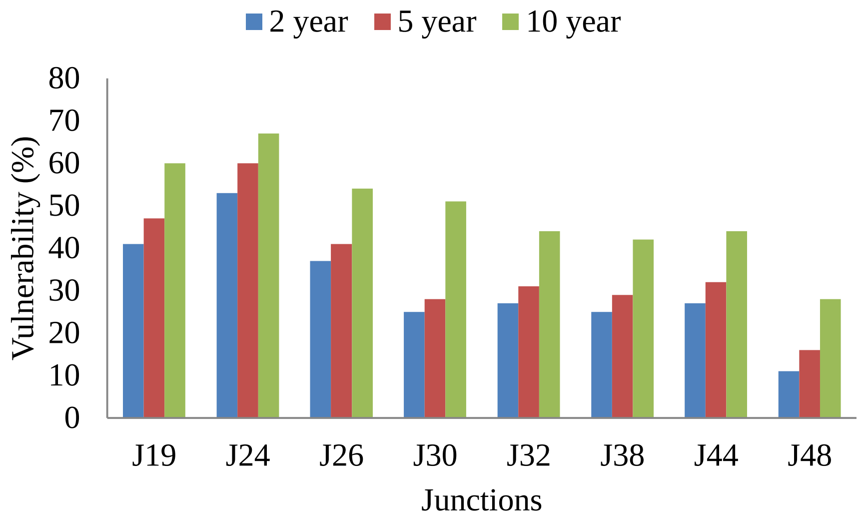

Figure 4-11: Simulated results of vulnerability under 2, 5 and 10-year return periods

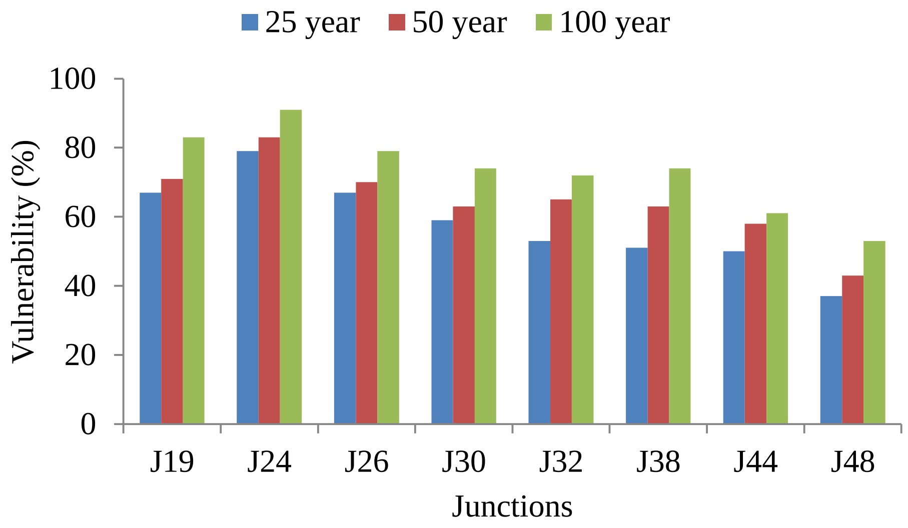

Figure 4-12: Simulated results of vulnerability under 25, 50 and 100-year return periods

Other junctions represent good performance and act effectively in conveying the produced runoff. The results show that the remaining junctions in the study area are less vulnerable.

A research on stormwater management and climate change: vulnerability and capacity for adaptation in urban and suburban contexts used EPA SWMM to assess the vulnerability of drainage systems to floods. A 10-year return period was used for scenario formulation. The vulnerability assessment resulted in identification of flooding locations and their increase related to return periods scenarios. The volume of flooding increased shapely with precipitation depth which showed a high vulnerability of drainage systems in the area studied (Moore et al., 2016).

The performance of drainage systems in Nyabugogo catchment was assessed based on the flooding time of the system and the results of performance of the system showed in decrease in reliability and resiliency and an increase in vulnerability as the return period of the design rainfall increased. Given the whole systems reliability, resiliency, and vulnerability, an average sustainability index for drainage system in the study area was 4%. The sustainability index of less than 10% is considered as poor (De Carvalho et al., 2009).

## 4.3 The effectiveness of infiltration-based techniques to mitigate floods in Nyabugogo catchment

The research investigated the effectiveness of infiltration-based techniques in Nyabugogo catchment comparing the scenarios with design storms and no infiltration-based techniques application and the scenarios with infiltration-based techniques application. They were evaluated both single and in combination in order to obtain the effectiveness of each and the effect of their combination on reducing runoff quantity and mitigating floods in Nyabugogo catchment. The main junctions of Nyabugogo catchment are displayed in Figure 4-6.

### 4.3.1 Impact of permeable pavements

The effect of permeable pavements on mitigating floods in Nyabugogo catchment was assessed by simulating scenarios which are based on 25, 50, 75 and 100% of impervious areas in sub-catchments where they are assigned. Comparing the scenario with no infiltration-based techniques and the scenario and application of permeable pavements to sub-catchments S5, S6 and S8 with 100%, the results showed good performance on reducing water depth (25.2% less compared to no application scenario using unit-area peak discharge as an indicator). The results of unit-area peak discharge are described in Figure 4-14.

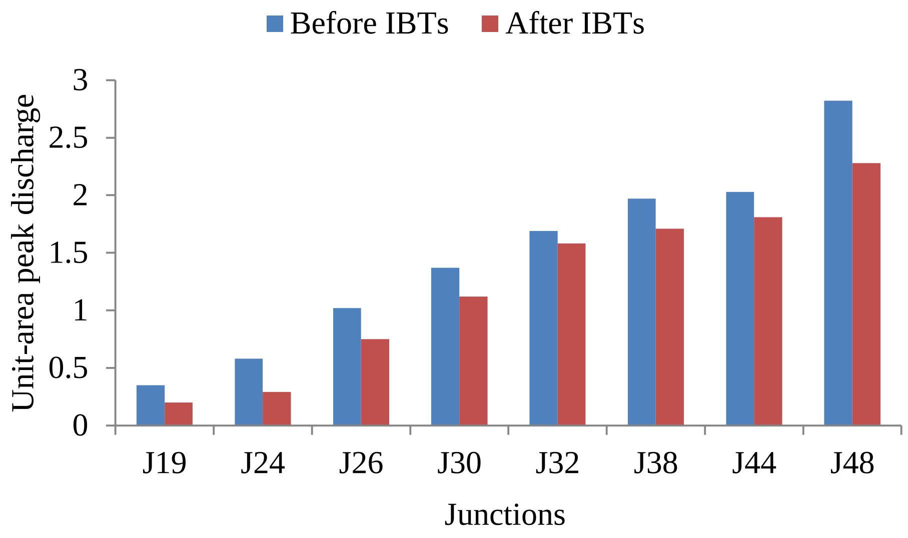

Figure 4-13: Simulated results of unit-area peak discharge comparing before and after IBTs use

A research on modeling flood reduction effects of low impact development at a watershed scale in central Illinois used the personal computer storm water management model to assess the floods reduction capabilities of many LIDs including permeable pavement and the simulation results indicated that 3 to 47% runoff reduction in the study watershed was achieved by a combination of LIDs and the floods were also reduced by 40%. This study showed that LIDs can be used to mitigate floods risk in urban catchments (Ahiablame et al., 2012).

A study on rainfall–runoff simulations to assess the potential of SUDS for mitigating flooding in highly urbanized catchments used EPA SWMM to show the potential benefits of using different types of SUDS in preventing flooding in comparison with the common urban drainage strategies consisting of sewer networks of manholes and pipes. The results demonstrated the usefulness of the systems which include permeable pavements in reducing the volume of water generated after a rainfall event and their ability to prevent localized flooding and surcharges along the sewer network (Jato-Espino et al., 2016). A research on low-impact development practices to mitigate climate change effects on urban stormwater runoff: Case Study of New York City used EPA SWMM to model the stormwater runoff and LID controls. A 2-year and 50-year return periods were used to formulate scenarios and the results of simulations showed that the LID controls could provide an average reduction of 41% in annual runoff volume. The permeable pavement was noted to have the greatest effect on peak flow reduction (Zahmatkesh et al., 2015).

Previous studies which include Ahiablame et al., (2012), Jato-Espino et al., (2016) Zahmatkesh et al., (2015) indicated the effectiveness of permeable pavements and appreciated the runoff reduction greater than 4%. In this research, permeable pavements have an effect on runoff reduction described by decrease of unit-area peak discharge with an average of 25.2 % and this has an impact on reducing floods risk in Nyabugogo catchment.

### 4.3.2 Impacts of vegetative swales

The contribution of vegetative swales on mitigating floods in Nyabugogo catchment was assessed by simulating scenarios which are based on 25, 50, 75 and 100% of impervious areas in sub-catchments where they are assigned. Comparing the scenario with no infiltration-based techniques and the application of vegetative swales to sub-catchments S1, S2, S3, S5, S6 and S8 with 100%, the results showed good performance on reducing water depth (8.4 % less compared to no application scenario using of runoff ratio as an indicator). The results of runoff ratio are described in Figure 4-15.

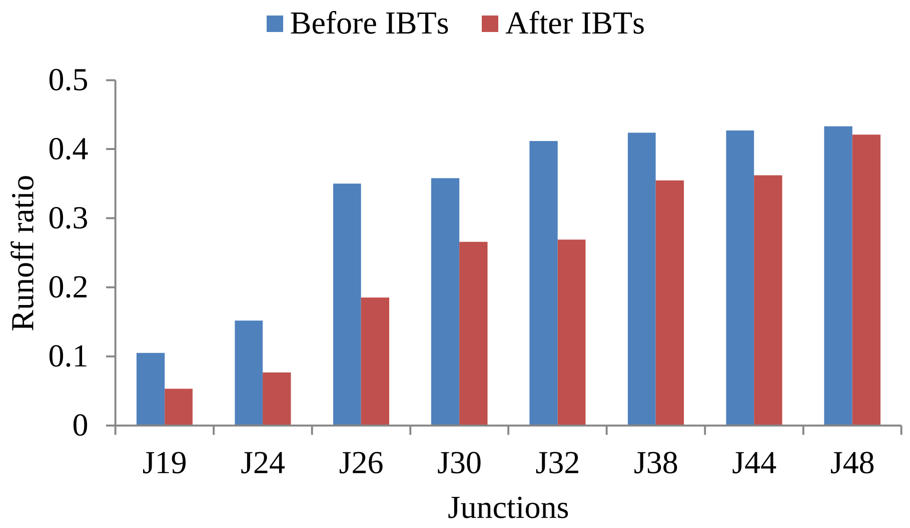

Figure 4-14: Simulated results of runoff ratio comparing before and after IBTs use

A research on the effects of low impact development on urban flooding under different rainfall characteristics analysed the effects of three LID techniques including vegetable swales and permeable pavements on urban flooding under different rainfall amounts and durations. The results obtained indicated that all LID scenarios with vegetative swales included, are more effective in flood reduction during heavier and shorter storm events than the conventional drainage systems. The study highlighted the necessity of combining the LID techniques to mitigate the risk of urban flooding due to heavier and longer storms effectively (Qin et al., 2013). In this research, vegetative swales reduced the runoff quantity by 8.4 % compared to no infiltration-based techniques scenario using runoff ratio as indicator.

### 4.3.3 Impacts of infiltration trenches

The contribution of infiltration trenches to mitigate floods in Nyabugogo catchment was assessed by simulating scenarios which are based on 25, 50, 75 and 100% of impervious areas in sub-catchments where they are assigned. Comparing the scenario with no infiltration-based techniques and the application of infiltration trenches to sub-catchments S4 and S7 with 100%, the results showed good performance on reducing water depth (19.2 % less compared to no application scenario using unit-area peak discharge). The results of unit-area peak discharge are described in Figure 4-16.

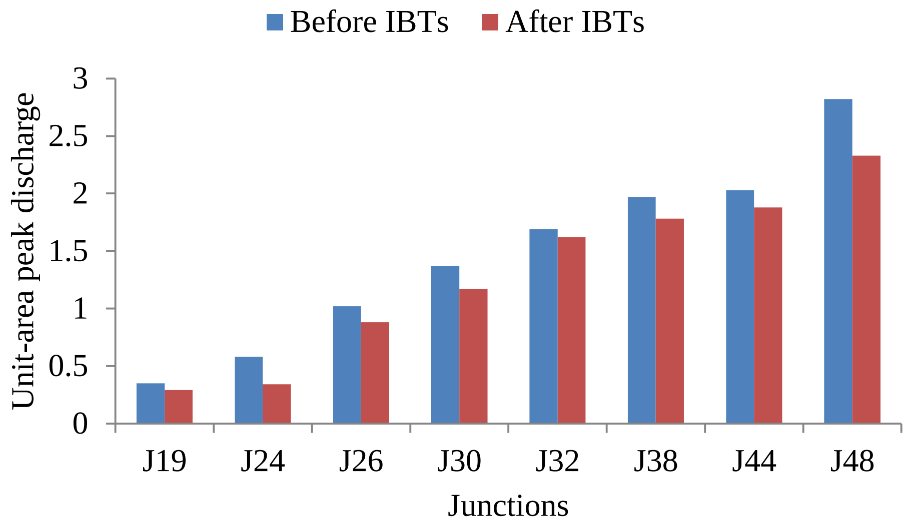

Figure 4-15: Simulated results of unit-area peak discharge comparing before and after IBTs use

A research on evaluation of flood runoff reduction effect of low impact development based on the decrease in CN: case studies from Gimcheon Pyeonghwa district, Korea; used EPA SWMM to evaluate the effects of many facilities including infiltration trench and detention pond on reducing runoff. The results of simulation showed a reduction of runoff up to 60% after the implementation of a combination of the facilities evaluated (Sin et al., 2014). The contribution of infiltration trenches on runoff reduction of 19.2% unit-area peak discharge compare to no infiltration-based techniques application has in impact on reducing flood risks in Nyabugogo catchment.

### 4.3.4 Impacts of bio-retention ponds

The effect of bio-retention ponds on mitigating floods in Nyabugogo catchment was assessed by simulating scenarios which are based on 25, 50, 75 and 100% of impervious areas in sub-catchments where they are assigned. Comparing the scenario with no infiltration-based techniques and the application of bio-retention ponds to sub-catchments S4 and S7 with 100%, the results showed good performance on reducing water depth (9.5 % less compared to no application scenario using R-B index as an indicator). The results of R-B index are described in Figure 4-15.

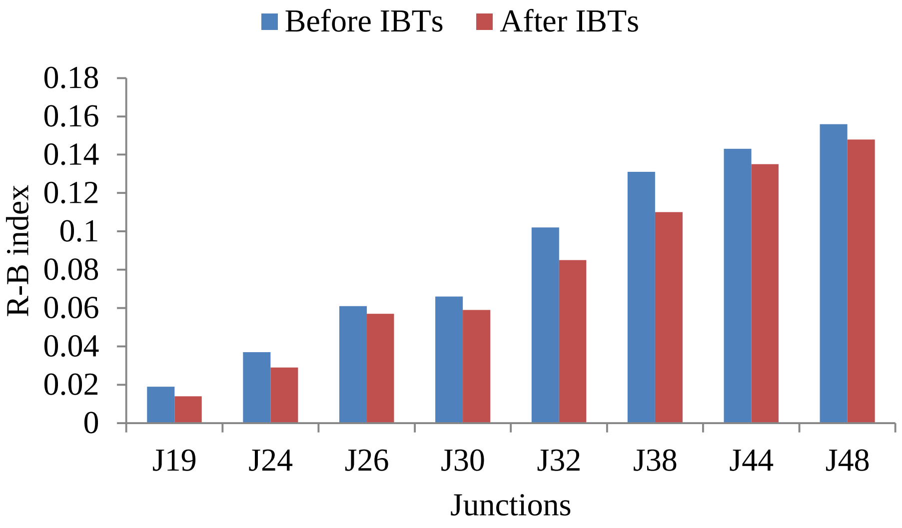

Figure 4-16: Simulated results of R-B index comparing before and after IBTs use

A study on assessing cost-effectiveness of specific LID practice designs in response to large storm events identified the optimal hydrological performance of different LID practices which include bio-retention ponds and porous pavement. EPA SWMM model was used to model different design storms were used for scenarios formulation and bio-retention ponds and porous pavements were found effective for peak flow reduction when the area of implementation is increased (Chui et al., 2016). A research carried out on enhancing a rainfall-runoff model to assess the impacts of BMPs and LID practices on storm runoff assess the effectiveness of BMPs and LID practices including bio-retention ponds. The simulations were done using 30 years of daily rainfall data and Curve Number method. The results highlighted BMPs and LID practices are effective to reduce runoff volume both separately and in series (Liu et al., 2015). In this research, bio-retention ponds have an effect on runoff reduction described by an average of 9.5 % decrease using R-B index and this have an impact on reducing floods risk in Nyabugogo catchment.

### 4.3.5 Impacts of global techniques to reduce runoff in Nyabugogo catchment

The effect of a combination of permeable pavements, vegetative swales, infiltration trenches and bio-retention ponds on mitigating floods in Nyabugogo catchment was assessed by simulating scenarios which are based on 25, 50, 75 and 100% of impervious areas in sub-catchments where they are assigned. Comparing the scenario with no infiltration-based techniques and the application of a combination of all four infiltration-based to sub-catchments of Nyabugogo and showed good performance on reducing water depth (average of 26.1% less compared to no application scenario using unit-area peak discharge as an indicator).

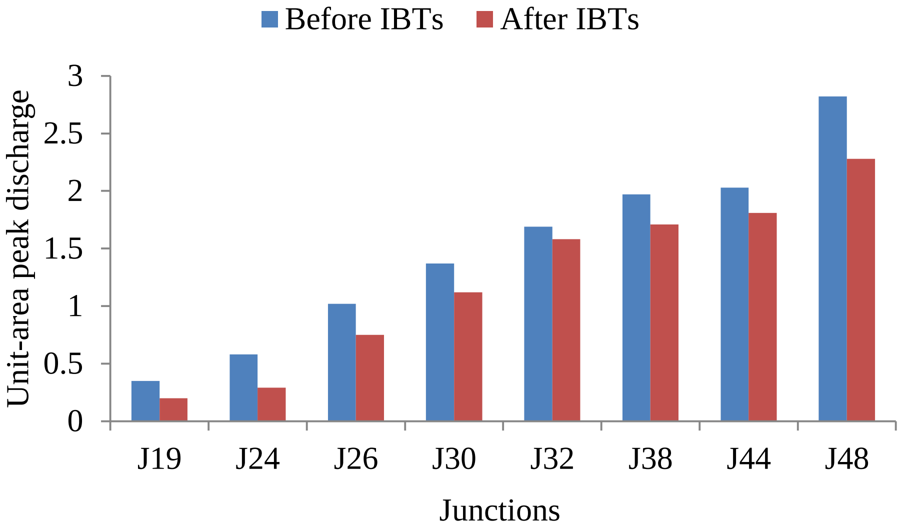

Figure 4-17: Simulated results of unit-area peak discharge comparing before and after IBTs use

A research on runoff control potential for design types of low impact development in small developing area using XPSWMM assessed the effect of runoff reduction from the combination of LID facilities and confirmed that a combination of facilities has about 10% or more of the peak runoff reduction than the single one. The infiltration-based facilities applied to the study area include permeable pavement and infiltration trenches and they have a high performance on runoff reduction (Kwak et al., 2016).

A study on hydrologic modeling of low impact development systems at the urban catchment scale used EPA SWMM to model the contribution of green roofs and permeable pavements to mitigate floods in urban areas under different return periods. The results showed a runoff volume reduction of 5% by the combination of green roofs and permeable pavements under a 10 year return periods (Palla et al., 2015).

Modeling results indicate that all four infiltration-based techniques significantly reduce the extent of flooding by an average of 26.1 % decrease and this have a contribution on reducing floods risk in Nyabugogo catchment. Previous studies including Palla et al. (2015) and Kwak et al. (2016) have appreciated a reduction of runoff quantity greater 5% and similar to Nyabugogo catchment study, a reduction of 26.1% is of great contribution.

# Chapter 5

# Conclusions and Recommendations

## 5.1 Conclusions

1. The model calibration and validation was achieved with values of $r^2$ greater than 0.6, NSE greater than 0.5 and d greater than 0.7 and resulted that the model is acceptable for runoff quantity modelling in Nyabugogo catchment.
2. The results of performance of the system showed in decrease in reliability and resiliency and an increase in vulnerability as the return period of the design rainfall increased.
3. Permeable pavements, vegetative swales, infiltration trenches and bio retention ponds reduced the runoff quantity by 25.2%, 8.4%, 19.2%, and 9.5%, respectively. The combination of all infiltration-based techniques showed a reduction of runoff quantity by 26.1 %. The model indicated that permeable pavement was the most effective system for reducing the extent and duration of flooding.

## 5.2 Recommendations

1. EPA SWMM model can be used for runoff modelling in catchment within the region of Nyabugogo catchment.
2. Further research on alternative methods of increasing the performance of the drainage systems is required.
3. Bio-retention ponds, infiltration trenches, permeable pavement and vegetated swales are recommended to contribute in solving the flooding problems in Nyabugogo catchment.

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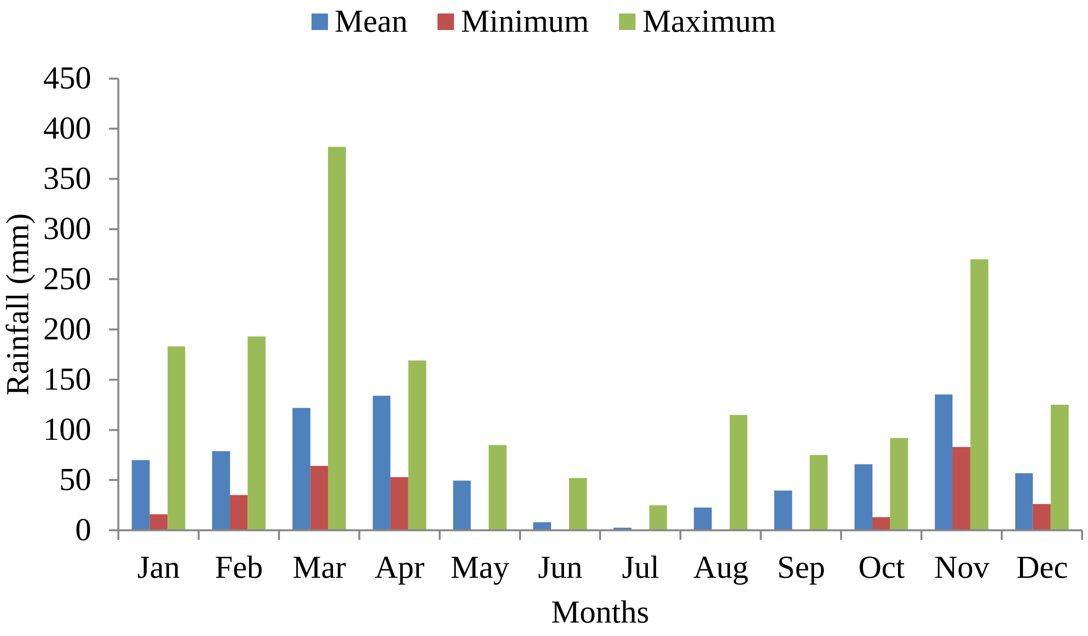
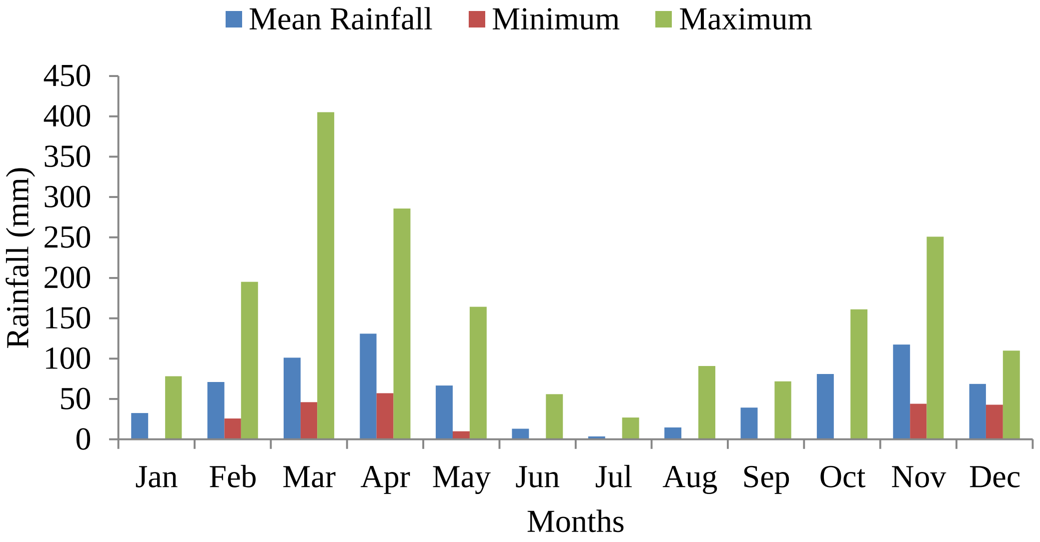
# Appendices

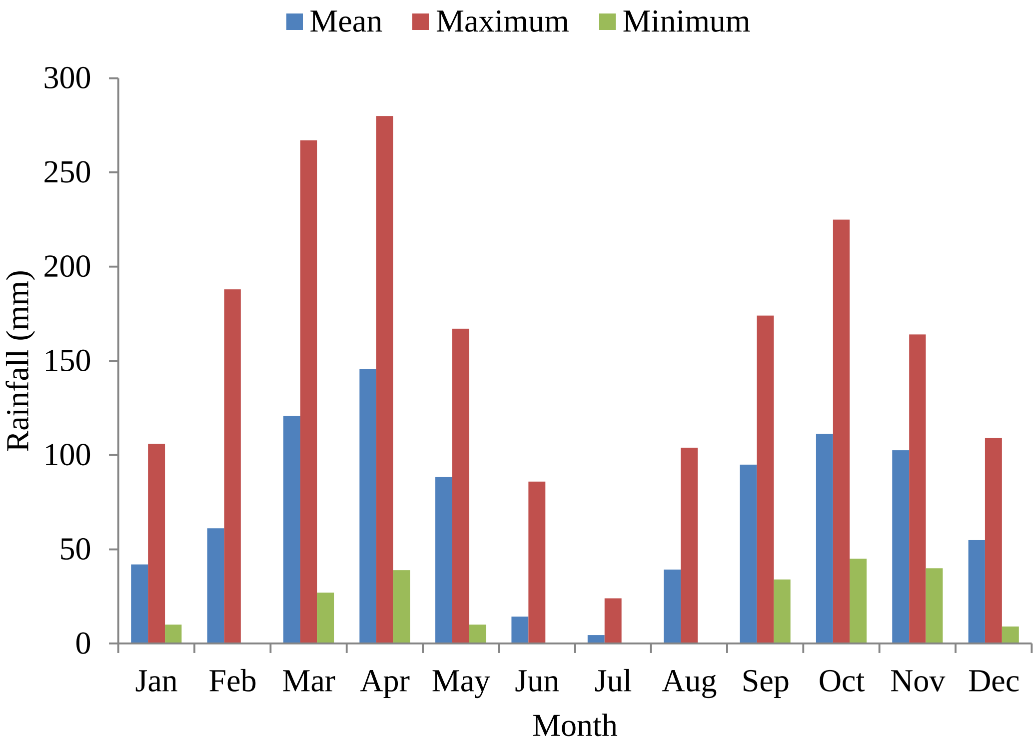
Appendix 1: Rainfall data of Kigali Airport station (1997-2017)



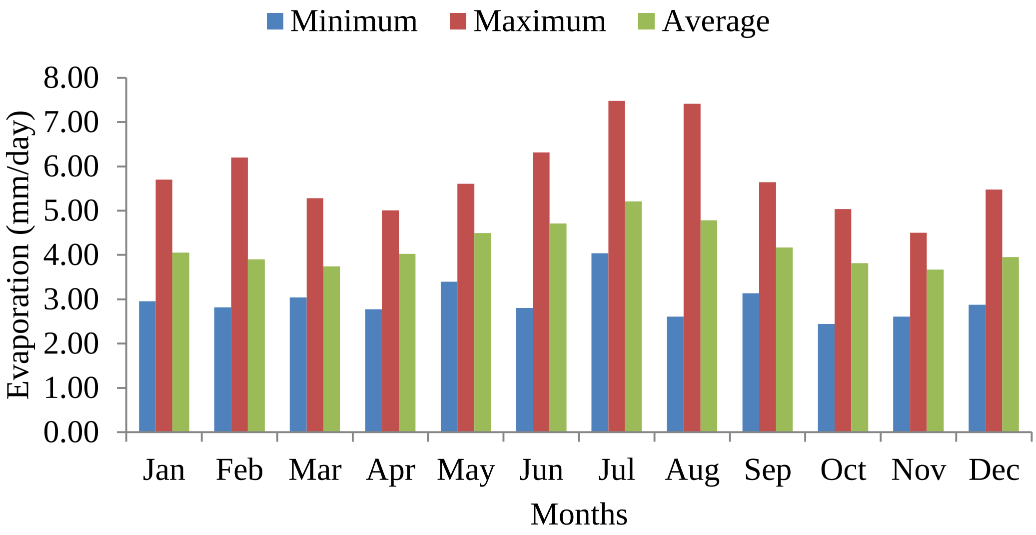
Appendix 2: Rainfall data of Gitega station (1997-2017)



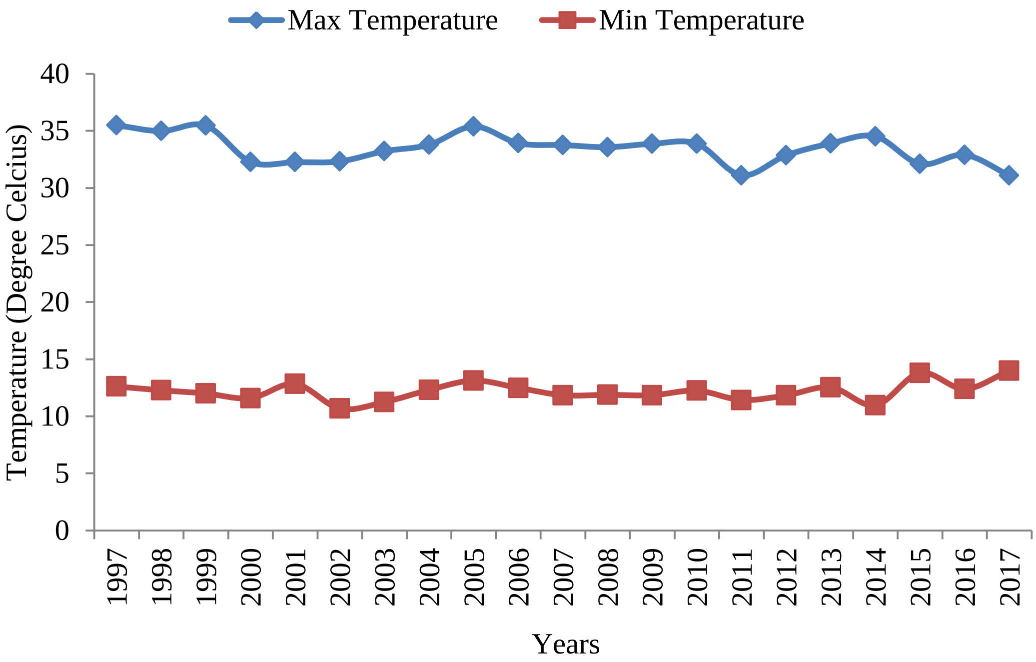
Appendix 3: Rainfall data of Byumba station (1997-2017)



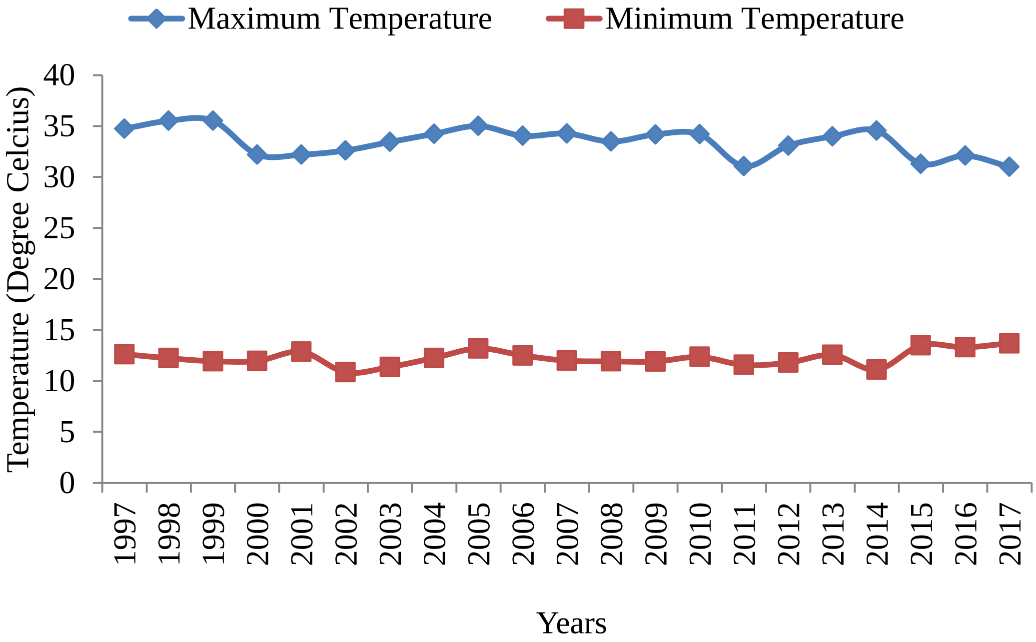
Appendix 4: Evaporation data of Kigali Airport station (1997-2017)



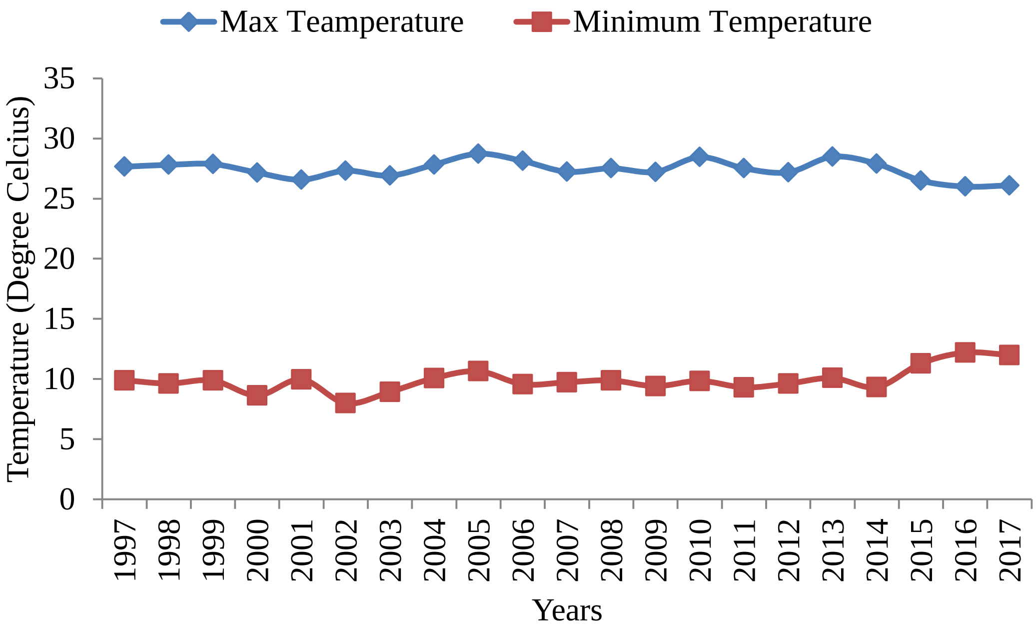
Appendix 5: Temperature data of Kigali Airport station



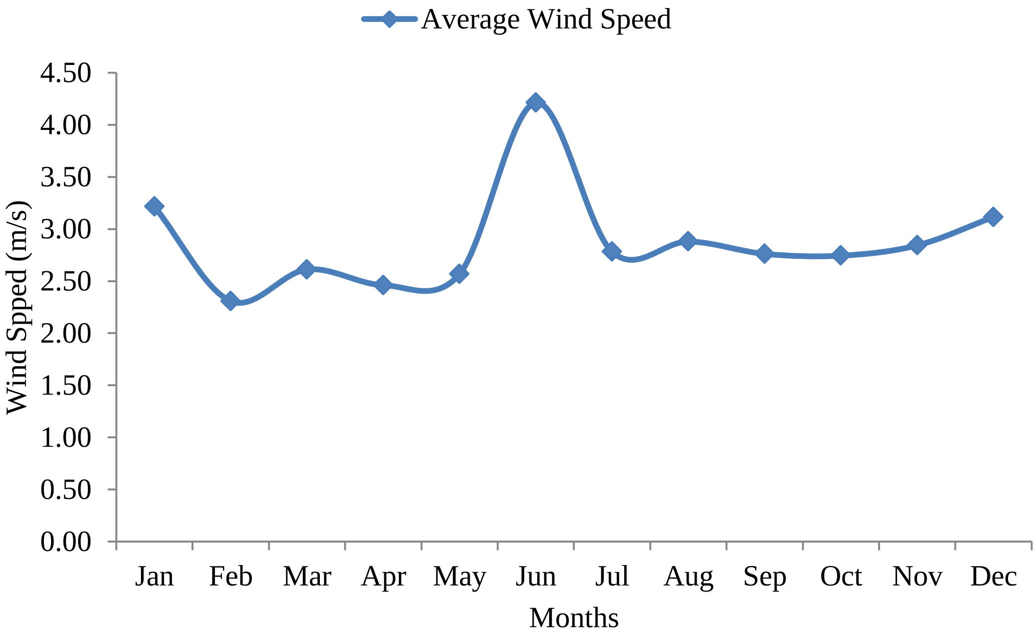
Appendix 6: Temperature data of Gitega station



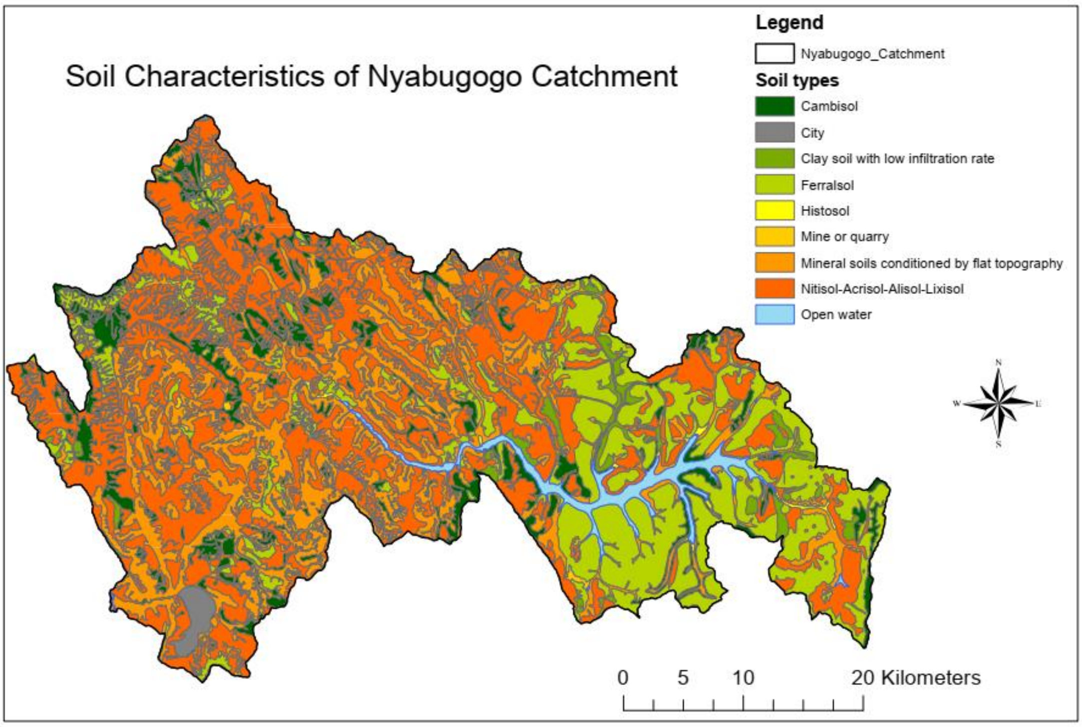
Appendix 7: Temperature data of Byumba station



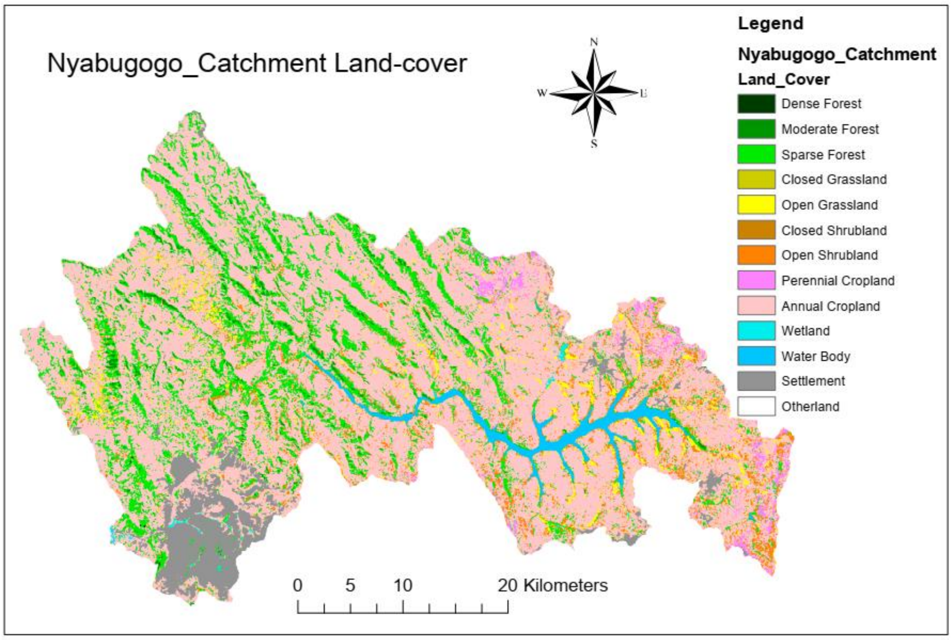
Appendix 8: Wind speed data of Kigali Airport station



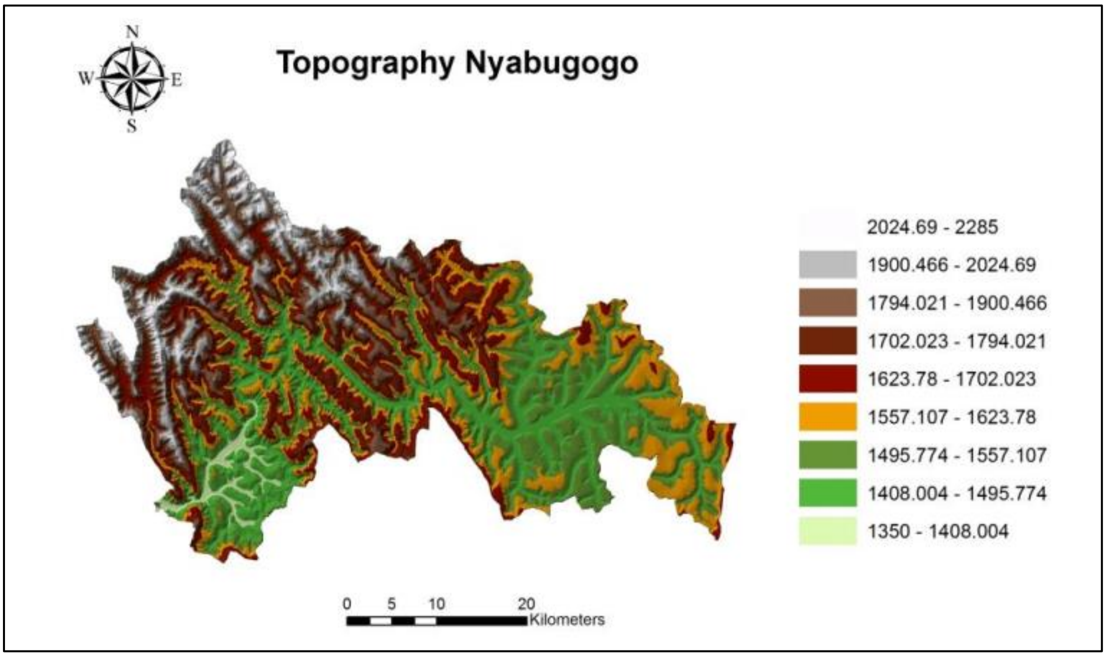
Appendix 9: Soil characteristics of Nyabugogo catchment



Appendix 10: Land-use of Nyabugogo catchment



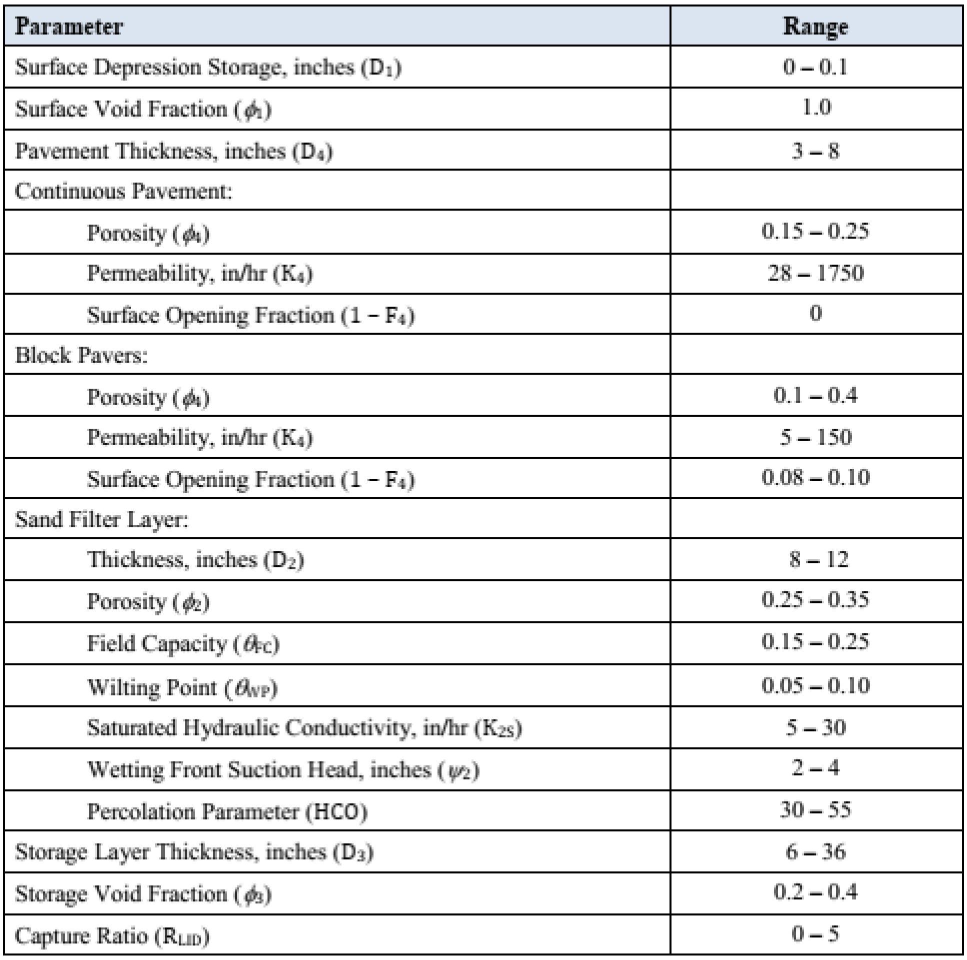
Appendix 11: Nyabugogo catchment topographic map



Appendix 12: Typical ranges for vegetative swale parameters (Rossman et al., 2016b)

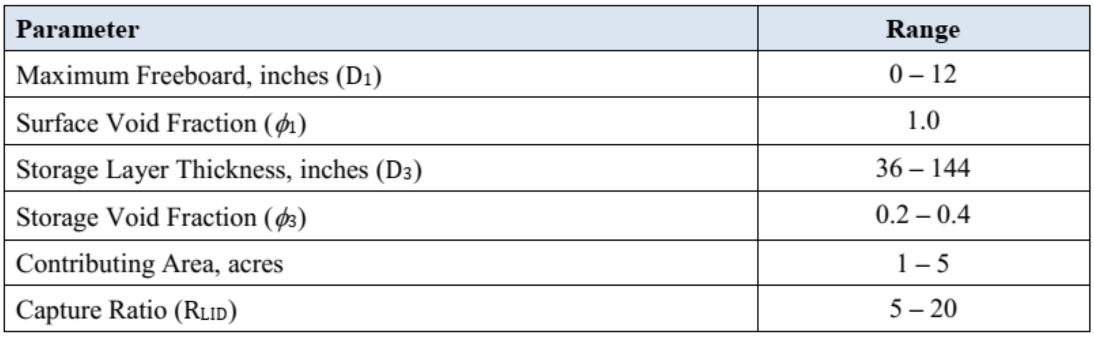
| **Parameter** | **Range** |
|---|---|
| Maximum Depth, feet ($D_1$) | 0.5 – 2.0 |
| Surface Void Fraction ($\phi_1$) | 0.8 - 1.0 |
| Bottom Width, feet ($W_X$) | 2.0 – 8.0 |
| Surface Slope, percent ($S_1$) | 0.5 – 3.0 |
| Side Slope, horizontal : vertical ($S_X$) | 2.5 : 1 – 4 : 1 |
| Surface Roughness ($n_1$) | 0.03 – 0.2 |
| Capture Ratio ($R_{LID}$) | 5 – 10 |

Appendix 13: Typical ranges for permeable pavement parameters (Rossman et al., 2016b)



| **Parameter** | **Range** |
|---|---|
| Surface Depression Storage, inches ($D_1$) | 0 – 0.1 |
| Surface Void Fraction ($\phi_1$) | 1.0 |
| Pavement Thickness, inches ($D_4$) | 3 – 8 |
| Continuous Pavement: | |
| Porosity ($\phi_4$) | 0.15 – 0.25 |
| Permeability, in/hr ($K_4$) | 28 – 1750 |
| Surface Opening Fraction ($1 - F_4$) | 0 |
| Block Pavers: | |
| Porosity ($\phi_4$) | 0.1 – 0.4 |
| Permeability, in/hr ($K_4$) | 5 – 150 |
| Surface Opening Fraction ($1 - F_4$) | 0.08 – 0.10 |
| Sand Filter Layer: | |
| Thickness, inches ($D_2$) | 8 – 12 |
| Porosity ($\phi_2$) | 0.25 – 0.35 |
| Field Capacity ($\theta_{FC}$) | 0.15 – 0.25 |
| Wilting Point ($\theta_{WP}$) | 0.05 – 0.10 |
| Saturated Hydraulic Conductivity, in/hr ($K_{2S}$) | 5 – 30 |
| Wetting Front Suction Head, inches ($\psi_2$) | 2 – 4 |
| Percolation Parameter (HCO) | 30 – 55 |
| Storage Layer Thickness, inches ($D_3$) | 6 – 36 |
| Storage Void Fraction ($\phi_3$) | 0.2 – 0.4 |
| Capture Ratio ($R_{LID}$) | 0 – 5 |

Appendix 14: Typical ranges for infiltration trench parameters (Rossman et al., 2016b)

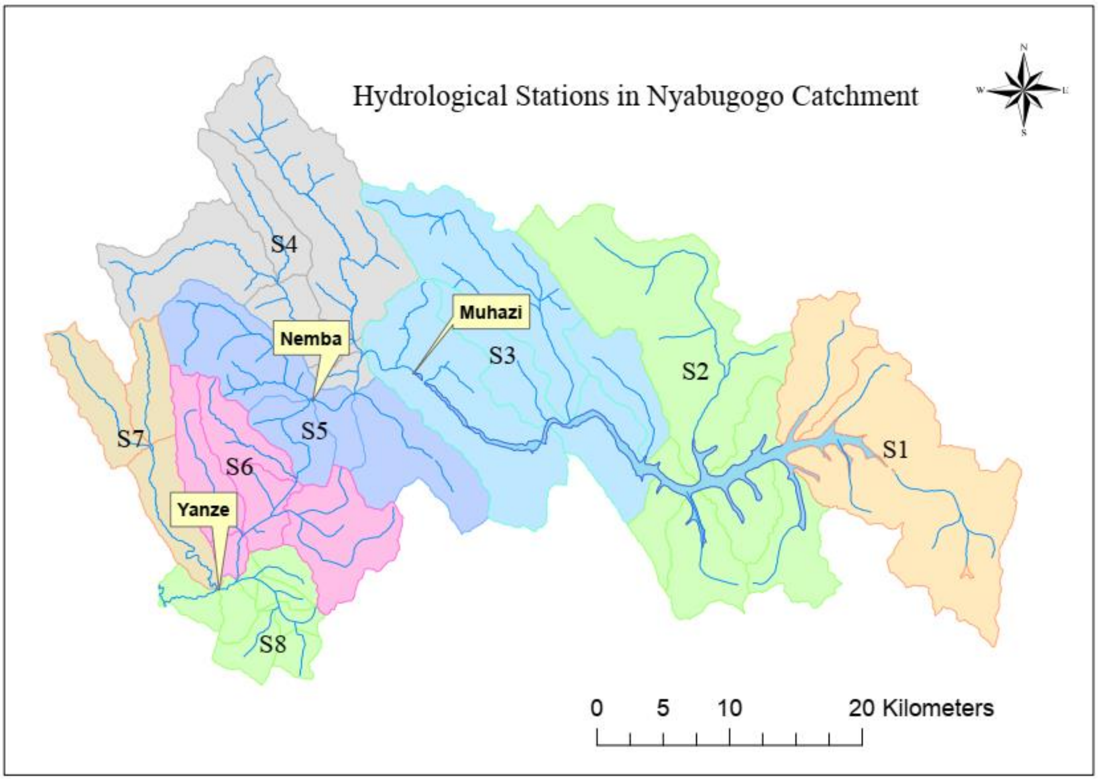


| **Parameter** | **Range** |
|---|---|
| Maximum Freeboard, inches ($D_1$) | 0 – 12 |
| Surface Void Fraction ($\phi_1$) | 1.0 |
| Storage Layer Thickness, inches ($D_3$) | 36 – 144 |
| Storage Void Fraction ($\phi_3$) | 0.2 – 0.4 |
| Contributing Area, acres | 1 – 5 |
| Capture Ratio ($R_{LID}$) | 5 – 20 |

Appendix 15: Typical ranges for bio-retention cell parameters (Rossman et al., 2016b)

| **Parameter** | **Range** |
|---|---|
| Maximum Freeboard, inches ($D_1$) | 6 – 12 |
| Surface Void Fraction ($\phi_1$) | 0.8 – 1.0 |
| Soil Layer Thickness, inches ($D_2$) | 24 – 48 |
| Soil Properties: | |
| Porosity ($\phi_2$) | 0.45 – 0.6 |
| Field Capacity ($\theta_{FC}$) | 0.15 – 0.25 |
| Wilting Point ($\theta_{WP}$) | 0.05 – 0.15 |
| Saturated Hydraulic Conductivity, in/hr ($K_{2S}$) | 2.0 – 5.5 |
| Wetting Front Suction Head, inches ($\psi_2$) | 2 – 4 |
| Percolation Decay Constant (HCO) | 30 – 55 |
| Storage Layer Thickness, inches ($D_3$) | 6 – 36 |
| Storage Void Fraction ($\phi_3$) | 0.2 – 0.4 |
| Capture Ratio ($R_{LID}$) | 5 – 15 |

Appendix 16: Hydrological Stations in Nyabugogo Catchment



Appendix 17: Meteorological Stations in Nyabugogo Catchment