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ASSESSING FLOOD RISK AND DEVELOPING A FRAMEWORK FOR A MITIGATION STRATEGY UNDER CURRENT AND FUTURE CLIMATE SCENARIOS IN NYABARONGO UPPER CATCHMENT, RWANDA

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DECLARATION AND RECOMMENDATION

DECLARATION

I declare that this research is my original work and has not been submitted to any other University for the award of any degree.

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RECOMMENDATION

This research has been submitted for examination with my approval as Supervisor.

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Dr. Tirusew Asefa

Courtesy Professor,

USF School of Global Sustainability

Assessing Flood Risk and Developing a Framework for a Mitigation Strategy under Current and Future Climate Scenarios in Nyabarongo Upper Catchment

ABSTRACT

Literally, Rwanda has experienced climate change and variability in terms of frequency, intensity, and persistence of extreme changes, such as floods and droughts as well. The occurrence of rainfall deficits and excess has meaningfully increased in recent years. Yet, these events have had serious impacts on the environment, economy and human lives. Overexploitation of soil and extensive erosion results in soil being washed down the hillsides into valleys causing extensive sedimentation of main rivers, such as Nyabarongo river, and other water-bodies. However, there is lack of knowledge on flood risk potential, flood damage and therefore no flood risk mitigation strategy.

The main objective of this study was to assess the flood risk and develop a framework for a mitigation strategy under current and future climate scenarios in the Nyabarongo Upper Catchment using a hydrological model. The hydrological data comprises precipitation and stream flow records for a period of 24 to 46 years, digital elevation model (DEM) dataset of cell 30-meter grid, land use/land cover datasets to create curve number (CN) values of the river catchment were used for hydrological modeling using ArcGIS. The SCS Curve Number method was used to perform Loss model, then SCS Unit Hydrograph for Transform model and Lag method for Routing model to compute the input basin and river reach parameter values for each sub-basin, for instance initial abstraction, curve number, imperviousness and lag time for both basin and river reach, in HEC-HMS to compute a 10-year, 50-year, 100-year, 250-year and 500-year flood for the entire catchment.

The catchment was delineated using the Digital Elevation Model and the whole catchment was divided into 4 sub-basins. The results of the analysis show that the upper left sub-basin (W500) has high flood magnitude of 1,128.4 m^3/sec compared to the 3 other sub-basins for a 10-year flood, the lower sub-basin (W360) is dominant for both a 50-year (21,054.7 m^3/sec) and 100-year flood (54,541.5 m^3/sec), and finally the middle sub-basin (W460) is leading at 27,467.7 m^3/sec of flood magnitude for a 250-year flood and at 836,578 m^3/sec of flood magnitude for a 500-year flood. As result, the integrated river basin approach, public awareness and public participation, land use, zoning and risk assessment along with early warning and forecast system were proposed as the best practices for the mitigation and adaptive management strategy in the catchment.

***Keywords**:* ArcGIS, HEC-HMS, Curve number, Flood discharge, Rwanda

RÉSUMÉ

Littéralement, le Rwanda a connu un changement climatique et une variabilité en termes de fréquence, d'intensité et de persistance de changements extrêmes comme les inondations et les sécheresses. L'apparition de déficits et d'excès de précipitations a considérablement augmenté au cours des dernières années. Pourtant, ces événements ont eu de sérieux impacts sur l'environnement, l'économie et la vie humaine. La surexploitation du sol et l'érosion étendue entraînent le ruissellement des cours d'eau dans les vallées entraînant une forte sédimentation des rivières principales telles que la rivière Nyabarongo et d'autres cours d'eau. Cependant, il manque de connaissances sur le potentiel de risque d'inondation, les dégâts causés par les inondations et d'une stratégie d'atténuation des risques d'inondation.

L'objectif principal de cette étude était de comprendre le risque d'inondation et d'élaborer un cadre pour une stratégie d'atténuation dans les scénarios climatiques actuels et futurs dans le Captage supérieur de Nyabarongo en utilisant le modèle hydrologique. Les données hydrologiques comprennent les enregistrements de précipitations et de flux d'écoulement pour une période de 24 à 46 ans, un modèle d'élévation numérique (DEM) de la grille de 30 mètres de cellule, des ensembles de données sur l'utilisation des terres et le recouvrement du sol pour créer des valeurs de nombre de courbes (CN) du bassin versant ont été utilisés pour la modélisation hydrologique à l'aide de l'ArcGIS. Nombre de courbes de la méthode du Service de conservation des sols (SCS) a été utilisée pour effectuer le modèle de perte, puis la méthode SCS de l'unité hydrographique pour le modèle de Transformer et la méthode décalage SCS pour le modèle de Routage pour calculer les valeurs des paramètres d'entrée du bassin et de la conduite de la rivière pour chaque sous-bassin, par exemple l'abstraction initiale, le nombre de courbes, l'imperméabilité et le temps de retard pour la conduite du bassin et de la rivière, dans HEC-HMS pour calculer une inondation de 10 ans, 50 ans, 100 ans, 250 ans et 500 ans pour l'ensemble du bassin versant.

Le bassin versant a été délimité en utilisant le modèle d'élévation numérique et le bassin versant entier a été divisé en 4 sous-bassins. Les résultats de l'analyse montrent que le sous-bassin supérieur gauche (W500) a une grandeur d'inondation élevée de 1,128,4 m^3/sec par rapport aux 3 autres sous-bassins pour une inondation de 10 ans, le sous-bassin inférieur (W360) est dominant pour une inondation de 50 ans (21 054,7 m^3/s) et 100 ans (54 541,5 m^3/s), et enfin le sous-bassin moyen (W460) mène à 27 467,7 m^3/s d'ampleur d'inondation pour une inondation de 250 ans et à 836 578 m^3/s d'ampleur d'inondation pour une inondation de 500 ans. En conséquence, l'approche intégrée du bassin hydrographique, la sensibilisation du public et la participation du public, l'utilisation des terres, le zonage et l'évaluation des risques ainsi que le système d'alerte précoce et de prévision ont été proposés comme les meilleures pratiques pour la stratégie d'atténuation et de gestion adaptative dans le bassin versant.

Mots-clés : ArcGIS, HEC-HMS, Numéro de courbe, Décharge d'inondation, Rwanda

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DEDICATION

To my loving brothers Epaphrodite IMFURAYACU and Jean Marie Vianney TEGERA.

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LIST OF SYMBOLS AND ABBREVIATIONS

AFS : Annual Flood Series

AMC : Antecedent Moisture Content

ARI : Average Recurrence Interval

ASCE : American Society of Civil Engineers

CN : Curve Number

DEM : Digital Elevation Model

EPA : Environmental Protection Agency

GDP : Gross Domestic Product

GIS : Geographic Information System

HEC-HMS : Hydrologic Engineering Center's Hydrologic Modelling System

HEC-RAS : Hydrologic Engineering Center's River Analysis System

I_a : Initial Abstraction

IDF : Intensity-Duration-Frequency

MIDIMAR : Ministry of Disaster Management and Refugee Affairs

MINIRENA : Ministry of Natural Resources

NLCD : National Land Cover Dataset

PMF : Probable Maximum Flood

Q_p : Peak Discharge

RMA : Rwanda Meteorology Agency

RNRA : Rwanda Natural Resources Authority

R(number) : Reach or River

RWFA : Rwanda Water and Forestry Authority

SCS : Soil Conservation Service

SWAT	: Soil and Water Assessment Tools
SWMM	: Strom Water Management Model
SVL	: Soil-Vegetation-Land
T_c	: Time of Concentration
USACE	: US Army Corps of Engineers
W(number)	: Sub-basin or sub-catchment or Watershed

CHAPTER 1 : INTRODUCTION

1.1. BACKGROUND INFORMATION

Flood is the most common form of natural disaster that disturbs human activities, cause loose of human lives and destroy properties (Asumadu-Sarkodie, et al., 2015). Besides, floods are caused by natural factors, such as topography, lithology and soil type, precipitation and river regime as well as tectonic activity, and anthropogenic factors, such as a change in land use, urbanization as well as deforestation. Consequently, the following sectors are likely to be affected, for instance, human settlement and shelter, health and nutrition, water and sanitation, education, agriculture and food, infrastructure, and further issues (MIDIMAR, 2014).

In addition, the flood is mostly due to natural environmental causes, together with characteristics of climate, hydrology and vegetation, and human activities, such as vegetation destruction, reclaiming land from lakes, the occupation of river and flood diversion zones in flood-prone areas (Li, et al., 2016). Climate irregularities, such as climate warming and precipitation inter-annual variability, and anthropogenic activities may affect hydrological processes and worldwide allocation patterns of water resources and then bring about changes in flood frequency and intensity (Jiang, et al., 2006; Kabanda & Palamuleni, 2013; Veijalainen, et al., 2010; Vormoor, et al., 2014). Flood disasters exhibit obvious inner-annual changes because of seasonal changes in precipitation and river flow (He, et al., 2009). When precipitation increases, river water levels will rise: this can lead to flooding and therefore regional disparities in flood disasters are affected by climate, hydrology, land cover, economy, and population in different countries (Li, et al., 2016).

However, the effects of climate change on hydrological extremes, in the form of floods, have not been appropriately understood at catchment scale in a different part of Africa (Ngongondo, et al., 2013). Once people develop within a watershed, the hydrologic cycle is affected (Gatwaza, et al., 2016) and therefore the increase in impervious or hard surfaces decreases the amount of water that soaks into the ground or infiltrates (Adrian & Pede, 2012; and Hategekimana, 2007). This increases the amount of surface runoff than if infiltration is significantly decreased, groundwater levels may decline, affecting stream flows especially during the dry season (Gatwaza, et al., 2016). In addition, Climate change is challenging the task of providing sufficient water and food by exacerbating the element of uncertainty and surprise, with increased frequency of water-related events such as dry spells, droughts, and floods. Therefore, conflicts between competing for sectoral uses of water, and between land use and terrestrial ecosystems upstream and downstream aquatic ecosystems are becoming more common and threaten both the internal and external security of many nations. The scenario looks bleak for Africa with projected shortfalls in agricultural production estimated at 50% due to the effects of expected climate change and variability by the year 2020 (Munyaneza, et al., 2011).

A Recent analysis of rainfall and temperature trends for Rwanda shows that rainy seasons are tending to become shorter with higher intensity leading to decrease in agricultural production and events such as droughts in dry areas and floods or landslides in areas experiencing heavy rains (RNRA, 2014). According to Rwanda's Second National Communication under the United Nations Framework Convention on Climate Change, monthly and annual total rainfalls recorded between 2004 and 2010 were generally lower than the average recorded between 1961 and 1990. Consequently, rainfall in Rwanda has become increasingly erratic and unpredictable. The monthly average temperature rises of 1.2°C between 1971 and 2009. Therefore, the temperature is expected to increase gradually in Rwanda during the 21st century from 0.75 to 3.25°C during the shorter dry season (December to February) and from 1 to 3.25°C during the long dry season (June-August) (MINIRENA, 2012).

Moreover, rainfall is projected to increase by 10% and 20% (of observed mean rainfall in 1961-1990) by the end of 21st century although model predictions are averages for long periods - daily, monthly and annual variability are therefore uncertain. Nevertheless, the models predict that despite the overall rise in rainfall, there is likely to be a decrease in the number of rainfall days with more dry spells in the rainy seasons and an increase in the frequency of torrential rain with daily rainfall sometimes exceeding the total monthly rainfall leading to an increasing incidence of floods, landslides, and soil erosion. On the other hand, many models indicate an intensification of heavy rainfall in the wet seasons creating a greater flood risk. Furthermore, the annual potential evapotranspiration is likely to increase every year reaching 1351 mm by 2020, 1432 mm by 2050 and 1682 mm by 2100 (MINIRENA, 2012).

Rwanda is among the slightest urbanized countries with an urban population of 28.8% of the total population, with a relatively high urbanization rate of 6.43% by 2015 (CIA, 2015) and it had a rapid population growth rate of about 2.4% in 2010-2015 (UNdata, 2016). About 80% of the population depends on agriculture, however, agricultural activities in Rwanda are largely subsistence-based and this, therefore, affects economic development. Due to the population increase in the highland areas, gradually marginal areas are being used for agriculture which has led to the degradation of the natural resources; and in degraded areas with poor vegetation cover and infertile soil, rainfall is lost almost completely through direct evaporation or uncontrolled runoff (Munyaneza, et al., 2016).

The Upper Nyabarongo catchment is mainly facing significance issues, such as soil erosion including riverbank erosion by agriculture and cattle in eight (8) districts, mining exploitation increasing siltation to rivers in six (6) districts, deforestation reducing the soil cover in four (4) districts, waste water management in two (2) districts and poor agricultural practices in two (2) districts. Therefore, these issues simply lead to the floods challenging in this particular catchment.

1.2. PROBLEM STATEMENT

Being a landlocked country, highly dense populated, more than 80% of households own less than 1 hectare of land in the rural areas by means of rain-fed agriculture and its socioeconomic indicators make Rwanda vulnerable to natural and anthropogenic risks. Recent years, Rwanda has also experienced climate change and variability in terms of frequency, intensity, and persistence of extreme changes, for instance, floods and droughts as well. The frequency of rainfall deficits reached 16%. The occurrence of rainfall deficits and excess has meaningfully increased in recent years. Yet, these events have had serious impacts on the environment, economy and human lives (MINIRENA, 2012).

In addition, overexploitation of soil and extensive erosion results in soil being washed down the hillsides into valleys causing extensive sedimentation of main rivers, such as Nyabarongo river, and other water-bodies. About 15 million tons of soil is lost annually that lead to decline in the country’s capacity to feed 40,000 people per year, as well as an annual economic loss of US$ 34,320,000 that is almost 2% of GDP equivalent due to unsustainable farming practices; more unplanned settlement in fragile and sensitive areas associated with land degradation including floods and landslides as well as high dependence on biomass fuels that contributes to deforestation and erosion of the hilly landscape (RNRA, 2014).

The Nyabarongo Upper catchment is strongly reliant on rain-fed agriculture about 2,560 km^2 or 76% of the catchment area. High slopes and persistent poor farming in the catchment are the key challenges of the rain-fed agriculture. At least 69.57% of the households raise livestock in the zero-grazing program. Land reclamation caused by agriculture, settlement and use of firewood for cooking are putting high pressure to the natural forests, such as Nyungwe, Mukura, Gishwati and Busaga forests. Moreover, in the same catchment, there are mining activities, agro-processing industries, four tea factories and one coffee factory as well as industry for soap, leather, ceramic and craft for Agaseke where they are considered as an important source of revenue and employment. The higher western part of the catchment is characterized by steep slopes, intensive rain-fed cultivation, and high population density; therefore, they are prone to severe soil erosion. Additionally, a collection of fuel wood has contributed to high rates of deforestation. The removal of trees and vegetation increases the effect of erosion and leads to land degradation. Moreover, this leads to flooding and yet there is lack of knowledge on flood risk potential, flood damage and consequently there is no flood risk mitigation strategy

The purpose of understanding this research is to assess the flood risk and develop a framework for a mitigation strategy under current and future climate scenarios in the Nyabarongo Upper catchment using a hydrological model.

1.3. OBJECTIVES OF THE STUDY

1.3.1. Main objective

The main objective of the study was to assess the flood risk and develop a framework for a mitigation strategy under current and future climate scenarios in the Nyabarongo Upper Catchment using a hydrological model.

1.3.2. Specific objectives

The specific objectives of the study are to:

i. To perform rainfall-runoff analysis (hydrological modeling) for Nyabarongo Upper Catchment;

ii. To establish flood hazard potential;

iii. To suggest measures to mitigate the risks and develop the adaptive management strategy.

1.4. RESEARCH QUESTIONS

i. How would rainfall-runoff relationship be in Nyabarongo Upper catchment?

ii. How would frequent flooding be in Nyabaronhgo Upper catchment?

iii. What can be the mitigation and adaptive management strategy for flood control in Nyabarongo upper catchment?

1.5. JUSTIFICATION

The study findings will provide a guideline for mitigation measures and adaptive management practices that will be incorporated in the catchment management plan under National Water Resources Master Plan and Ministry of Disaster Management and Refugee Affairs (MIDIMAR) as a means of disaster management in prone areas. The research will help to develop the sustainable technologies for enhancing flood control in the Upper Nyabarongo catchment and identify the opportunities among the different sectors. Use of the hydrological model, HEC-GeoHMS, will, therefore, help to explore the impacts of flood and develop the likely flood risks maps in the entire catchment.

1.6. SCOPE AND LIMITATIONS

The present study was focused on the establishment of flood hazard potential and vulnerability assessment and therefore the risk assessment in the Nyabarongo Upper catchment by estimating the probability of occurrence. The hydrological modeling was also used to simulate the floods risks in order to predict the most likely floods events as well as floods mitigation and adaptation measures. This research used the hydrological model such as HEC-GeoHMS together with ArcGIS for flood risk analysis.

1.7. EXPECTED OUTCOMES AND FINDINGS APPLICATION

The study findings will deliver a detailed report on digital elevation model (DEM), land use and land cover map of the study area as well as the overall agreement between predicted and measured runoff discharges, and prediction for the time and magnitude of hydrograph peaks and runoff volume. The study findings will establish flood hazard potential that shows the extent and depth of the expected 10, 50, 100, 250, and 500-year floods. The findings will also support in mapping the flood prone areas and in management and conservation practices to enhance efficiently the floods control in the Upper Nyabarongo catchment. The research findings will then propose the recommendations on possible sustainable management and conservation practices to control frequent flood events in the Upper Nyabarongo catchment.

1.8. THESIS STRUCTURE

The outline of this thesis report is composed of five chapters and is as follows:

- The first chapter provides the introduction of this study.

- The second chapter provides a literature review which illustrates the state of the art as far as studies like this one are concerned.
- The third chapter provides the research methodology and presents a description of the study area, the data used for this study with a discussion on their pre-processing.
- The fourth chapter presents and discusses the results.
- The fifth chapter provides a conclusion and few recommendations.

CHAPTER 2 : LITERATURE REVIEW

2.1. INTRODUCTION

A flood may be defined as an event when waters from a river, lake, ocean, or other surface water feature rise above normal limits (ASCE, 1995). Flooding is the greatest water-related natural disaster known to the human race. Flooding's human, material, and ecological costs can be overwhelming for sustainable development. Every year, Floods affect an estimated 520 million people across the world, that result in up to 25,000 annual deaths. Together with other water-related disasters, they cost the world economy some $50 to $60 billion a year. An estimated 96 percent of deaths related to natural disasters in the past decade occurred in developing countries with limited capacity to forecast and manage these disasters. Extensive urbanization, population growth in natural floodplains, every single increasing rate of deforestation, climate change, and rising sea levels are the key factors that rise the number of people vulnerable to a devastating flood (Ramesh, 2012).

In contrast, Floods also have beneficial, but seldom recognized, effects such as replenishing soil moisture, cleaning stream channels, depositing fertile fine sediments on agricultural lands, and restricting upstream movement of salt fronts in estuaries (ASCE, 1995). Furthermore, floods are natural phenomena, which contribute to the biodiversity and sustainability of ecosystems and to many human activities.

Both developed and developing countries have benefited from economic development in areas prone to flooding. Developing countries with mainly agricultural economies depend largely on their fertile floodplains for food security and poverty alleviation. The wetlands in floodplains contribute to biodiversity and also create employment opportunities. Therefore, precipitation as an important component of the hydrologic cycle bears a significant influence on hydrologic design and water resources management. The uncertainties associated with future climate change coupled with our inability to quantify these uncertainties from climate change models introduces additional complications on how we can adapt to future precipitation extremes and related drivers that influence future flooding mechanisms (Ramesh, 2012).

2.2. RAINFALL-RUNOFF ESTIMATION

2.2.1. Runoff estimation

Precipitation is an essential process for the generation of runoff at a catchment scale. The distribution of precipitation varies spatially and temporally to nature. Precipitation can be in the form of snow, hail, dew, rain, and rime (Quan, 2006). Rain is the only form of precipitation this study is considering. Therefore, there is a significant and unique relationship between precipitation and surface runoff (Kwaad, 1991). The process of runoff generation continues providing that rainfall intensity exceeds the actual infiltration capacity of the soil but stops the moment the rate of rainfall drops below the actual rate of infiltration.

2.2.2. Factors affecting Runoff

Apart from rainfall characteristics such as intensity, duration, and distribution, there are other specific factors; such as soil type, vegetation, slope and catchment size; which have a direct effect on the volume of runoff.

a. Type of soil

The soil is a complex, multiphase, heterogeneous system of various gases, liquids, and solids and as a result, the concept of soil can be interpreted in various ways. In surface water hydrology analysis, the most important soil properties are the amount and rate of passage of infiltrated rainfall through the surface layers of soil. In particular, the soil storage capacity requires a detailed look at the relationship of water content to the soil void space.

Baird et al. (1997) said that the runoff generation in the area is also associated with the porosity of a soil such as the peat soil layering as the deeper layers may be an important overall contributor to runoff. The highest infiltration capacities are observed in loose, sandy soils while heavy clay or loamy soils have considerable smaller infiltration capacities.

b. Vegetation

An area which is densely covered with vegetation produces less runoff than bare ground while the amount of rain lost to interception storage on the foliage depends on the kind of vegetation and its growth stage. Vegetation retards the surface flow particularly on gentle slopes, giving the more time to infiltrate and to evaporate (Wilfried, 2006). More significant is the effect the vegetation has on the infiltration capacity of the soil. A dense vegetation cover shields the soil from the raindrop impact which eventually will cause a breakdown of the soil aggregate as well as soil dispersion with the consequence of driving fine soil particles into the upper soil pores (Kobatake et al., 2000).

c. Slope and catchment size

Slope and catchment size influence the generation of surface runoff. Steep slopes in the headwaters of drainage basins tend to generate more runoff than the lowland areas. Overall mountain areas tend to receive more precipitation because they force air to be lifted and cooled. On gentle slopes, water may temporarily pond and later infiltrate, but in mountainsides, water tends to move downward more rapidly (Sharma et al., 1986).

Soils tend to be thinner on steep slopes, limiting storage of water, and where bedrock is exposed, little infiltration can occur. In addition, it was observed that the quantity of runoff decreased with increasing slope length. This is mainly due to lower flow velocities and subsequently a longer time of concentration (defined as the time needed for a drop of water to reach the outlet of a catchment from the most remote location in the catchment). The runoff efficiency (volume of runoff per unit of area) increases with the decreasing size of the catchment i.e. the larger the size of the catchment the larger the time of concentration and the smaller the runoff efficiency (Ben Asher, 1988).

The land use characteristics also contributed to the surface flow process whereby the infiltration excess flow is the main process in terms of runoff generation on degraded land while saturation excess overland flow is more relevant for agricultural land.

2.3. PRECIPITATION FREQUENCY ANALYSIS

The precipitation frequency analysis is used extensively for the design of engineering works that control storm runoff. These include municipal storm sewer systems, highway and railway culverts, and agricultural drainage systems. A common application of precipitation frequency analysis is the development of a design storm that is, a precipitation pattern used in water resource systems design.

The objective of precipitation frequency analysis is to develop useful relationships between four variables associated with precipitation events:

i. the size of the area of interest (km^2; often specified by a catchment area),

ii. the duration of interest (in hours),

iii. the frequency of occurrence, or "return interval," of the event (in years), and

iv. the precipitation accumulation (mm).

The most common way of presenting precipitation frequency analysis results is to represent rainfall accumulation in terms of the other three variables.

The connection between the probability of an event and return interval of an event is essential to precipitation frequency analysis and arises as follows. If an event has a probability of occurrence “p” for a year, then the return interval “T” is the average time (in years) between events and is given by “p^{-1}”. The 100-year storm, for instance, is the storm magnitude that is exceeded with probability 0.01 in any given year (ASCE, 1995).

2.4. FLOODS

2.4.1. Flood Characteristics

In general, the definition of floods stated above is unsatisfactory for engineering and related economic, financial, and social analyses. Therefore, Flood can be characterized by both:

- An "Annual Flood Series" (AFS) in which only the largest event (in terms of peak flow rate or volume) in a year is recognized. One flood is identified in each year even though the value may be smaller than the second or third largest value in some other years. Also, with the AFS on ephemeral streams, it is possible to have a year with a flood magnitude of zero.
- A "Partial Duration series" (PDS) in which all independent events exceeding a specified base magnitude are identified as floods regardless of the number of events in any given year. The base magnitude for a PDS is commonly established to identify an average of about three events per year as floods. Thus, the PDS provides a greater number of floods for the engineer to analyze (ASCE, 1995).

2.4.2. Causes of Floods and Flooding

Flood magnitude and frequency vary spatially and temporally. To assess the variability and to suggest appropriate solutions to flood problems requires a recognition of natural and man-made factors that affect floods. The major factors that affect river floods are as follow:

i. *Watershed Characteristics*: Size, shape, slope, and surface topography are watershed characteristics that affect floods. Larger watersheds produce larger floods of longer durations. These floods generally have lesser year-to-year variation in magnitudes than those from smaller watersheds. In general, a round watershed produces larger flood peaks than a long narrow one. A basin with a steep slope also produces larger flood peaks than basins with small slopes. Larger floods occur on basins with rocky or other impervious surfaces than basins with a deep and pervious soil cover.

ii. *Land Use Characteristics:* Forested and heavily vegetated drainage basins usually produce floods of smaller peaks and longer durations than comparable bare basins. The effects of a forest fire can significantly increase flood runoff. Construction of reservoirs usually reduces flood peaks downstream; however, small uncontrolled reservoirs on tributaries can disrupt natural runoff timing and cause an increase in flood peaks on the receiving stream depending on the positions of these reservoirs. Urban and suburban developments can have profound effects on flooding. Placement of impervious surfaces reduces infiltration. Construction of storm sewers and improvement of drainage channels, including streets with curbs and gutters, causes the rapid concentration of runoff. The result is usually a much larger flood peak with increased runoff volume during a shortened flow duration.

iii. *Precipitation*: Rainfall usually is the primary source of flood waters. Intense, short-duration thunderstorm rainfalls often cause severe floods on small streams. Larger streams usually experience the largest floods as a result of longer duration and wider spread storms. In addition to the magnitude, duration, and intensity of rainfall, other factors affect the magnitude and frequency of resulting floods. Seasonally, floods respond differently to comparable rainfalls because rainfall is intercepted by vegetation during growing seasons, infiltration is greater during dry seasons and frozen ground reduces infiltration. While rain falling on snow probably increases total runoff, it may either increase or decrease the peak magnitude.

iv. *Erosion and Sedimentation:* Erosion and sedimentation contribute to a large portion of annual damage losses due to floods. Floods carry sediments eroded from the watershed and scoured from the stream channel. As the flood waters recede, the sediment load is often deposited in the stream channel resulting in the reduction of the flow-carrying capacity of the stream. This can cause flooding of overbanks during subsequent storms.

v. *Dam Failure:* Though infrequently, dams and other water-retaining structures have failed and produced major floods causing severe loss of lives and properties. Although programs exist for inspection and maintenance of dams, a probability of dam failure remains (ASCE, 1995).

2.4.3. Flood magnitude measurement

There are different indices used to describe flood magnitude. Thus, there are:

i. An index that commonly identifies the magnitude of an event by the instantaneous maximum flow rate or flood "peak" in cubic meters per second (m^3/s) or cubic feet per second (cfs).

ii. The "peak stage," or maximum water surface elevation associated with a flood peak.

iii. At some stream gages, the instantaneous peak flow rates and stages are not measured. In such situations, the "maximum daily" flow rate and/or the associated stage is used. The maximum daily rate is the average rate over 24 hours and is always less than the peak rate. The difference between the peak and the maximum daily value is greater on small streams than on large ones.

In addition, Flood magnitude is sometimes described on the basis of likelihood of exceedance; such as the flood having a 4% chance of being exceeded in any year. The reciprocal of exceedance probability defines an average length of time, in years, between the occurrences of floods of a specified magnitude or larger. Due to this, it has become common to term the flood having a 4% chance of exceedance as the 25-year flood and the flood having a 1% chance of exceedance as the 100-year flood.

Moreover, facilities whose failure due to flood could endanger many lives or result in catastrophic economic losses are normally designed for probable maximum flood (PMF). The likelihood of experiencing a PMF in any future year cannot be properly determined with the current technique in statistical analysis, although it has been assumed to be as small as one in 1,000,000 (ASCE, 1995).

2.5. FLOOD ANALYSIS

Generally, flood analysis is performed to derive peak flow values or complete flood hydrographs at specific locations on streams. The watershed contributing runoff to the location of interest is determined from topographic maps. The derived peak flows and hydrographs are of limited use except they are associated with some measure of the probability of occurrence or physical meaning of the meteorological conditions associated with the floods. Exceedance probability (such as a 1% chance in any given year) combined with potential damages is the desirable approach for selecting a design flood; however, limitations on available data prevent reliability and accuracy in computing the exceedance probability of extremely rare flood events (ASCE, 1995).

2.5.1. Estimation of Flood Peak Discharge

The flood peak discharge is estimated using two (2) methods. They are:

i. Soil Conservation Service (SCS) curve number method which is commonly used for non-urban catchments.

ii. Rational formula method that is used for both urban flood designs and sometimes for non-urban catchments.

2.5.1.1. Soil Conservation Service (SCS) curve number method

To estimate flood runoff from a given storm involves estimating losses from the rainfall. The Soil Conservation Service (SCS) curve number method (SCS, 1969) is the most commonly used and simple method for practical applications. Fundamentally, it is based on accounting for infiltration losses from rainfall depending on the antecedent moisture content (AMC) and the soil type. The rainfall is assumed to occur uniformly over the entire watershed or catchment, during the storm. The fundamental basis for the SCS curve number method is that the runoff starts after initial losses due to abstractions, "I_a", are accounted for. These losses consist of interceptions due to vegetation and built area that prevent the rainfall from reaching the ground immediately after it occurs, surface storage consisting of water bodies such as lakes, ponds, and depressions, and infiltration. An assumption in developing the curve numbers is that the ratio of actual retention of rainfall in the watershed to potential retention, "S", in the watershed is equal to the ratio of direct runoff to rainfall minus the initial abstractions, I_a (before commencement of the runoff) (Mujumdar & Kumar, 2012).

The parameter "S" depends on the catchment characteristics of the soil, vegetation, and land constituting the soil–vegetation–land (SVL) complex (Singh, 1992), and the AMC. With a parameter, CN, to represent the relative measure of water retention on the watershed by a given SVL complex, the potential retention in a watershed with a given SVL complex is calculated using the following equation 2-1.

$$S = \frac{25400}{CN} - 254 \ (in\ Millimeters) \qquad \text{…………………….. Equation 2-1}$$

The parameter CN is called the curve number; it takes values between 0 and 100. The value of CN depends on the soil type and the AMC in the watershed. CN has no physical meaning. The equation for runoff (rainfall excess) is given as follow:

$$P_e = \frac{(P-0.2S)^2}{P+0.8S} \qquad \text{………………………..Equation 2-2}$$

Mujumdar & Kumar *(2012)* stated the points that must be kept in mind while using the SCS curve number method:

i. CN is a parameter that ranges from 0 to 100. A value of 100 indicates that all of the rainfall is converted into runoff and that there are no losses. Completely impervious and water surfaces are examples of this. For normal watersheds, CN< 100. A value of CN close to 0 indicates that almost all of the rainfall is accounted for losses, indicating highly dry conditions and therefore negligible runoff results.

ii. CN has no physical meaning. Since it is the only parameter used to compute the runoff from rainfall, it accounts for the combined effects of soil type, AMCs, and vegetation type on the runoff.

iii. The soil group is assumed to be uniform throughout the watershed. The rainfall is assumed to be uniformly distributed over the watershed.

iv. When a watershed consists of different soil types, AMCs, and vegetation types, a composite CN may be determined for the watershed, as an area-weighted CN.

v. The SCS method, when used to estimate runoff from rainfall that has actually occurred, may produce poor results and is rather heavily dependent on the AMCs assumed for the watershed. It is more useful for estimating design flood runoff resulting from a design storm.

vi. The SCS method may over-predict the volume of runoff in a watershed (Maidment, 1993).

vii. The method is generally used for non-urban catchments.

Soils are classified into four groups, A, B, C, and D, based on their runoff potential, with soil group A being the most porous, deepest, and least runoff-prone and soil group D being the shallowest, finest textures, and most runoff-prone. The hydrologic soils classification is described as follow:

- Group A: soils have low runoff potential and high infiltration rates even when thoroughly wetted They consist chiefly of deep, well to excessively drained sand or gravel and have a high rate of water transmission (greater than 0.30 in/hr).
- Group B: soils have moderate infiltration rates when thoroughly wetted and consist chiefly of moderately deep to deep, moderately well to well-drained soils with

moderately fine to moderately coarse textures. These soils have a moderate rate of water transmission (0.15 –0.30 in/hr).

- Group C: soils have low infiltration rates when thoroughly wetted, and consist chiefly of soils with a layer that impedes downward movement of water and soils with moderately fine to fine texture. These soils have a low rate of water transmission (0.05 to 0.15in/hr).
- Group D: soils have high runoff potential. They have very low infiltration rates when thoroughly wetted and consist chiefly of clay soils with a high swelling potential, soils with a high permanent water table, soils with a claypan or clay layer at or near the surface, and shallow soils over nearly impervious material. These soils have a very low rate of water transmission (0-0.05 in/hr) (WSDOT, 2014).

The AMC accounts for the moisture content in the soil preceding the storm for which the runoff is to be computed. The AMC of the watershed is classified into three groups, I, II, and III based on the rainfall in the previous 5 days and based on whether it is a growing season or a dormant season (Mujumdar & Kumar, 2012).

2.5.1.2. Rational Method

The Rational method has become widely used as a tool for drainage design, particularly for sizing water conveyance structures (Viessman, et al., 1989), especially in urban flood designs but it is also sometimes used for non-urban catchments for estimating peak runoff rate (Mujumdar & Kumar, 2012), and it was introduced in the USA in 1889. It is an empirically developed model, with simplifying assumptions including uniform rainfall with uniform intensity over the entire watershed for a duration equal to the time of concentration. The Rational Formula is expressed as follow:

$$Q_p = CIA \qquad \text{……………………………………………Equation 2-3}$$

Where Q_p is the peak discharge, I is the rainfall intensity, A is the area of the watershed, and C is a dimensionless runoff coefficient. Originally developed in FPS units, the formula may be used in SI units with appropriate units for Qp, I, and A. For example, if Qp is in m^3/s, I is in mm/hr, and A is in square kilometers, the rational formula may be written as

$$Q_p = 0.278CIA \qquad \text{……………………………………………Equation 2-4}$$

The rational formula is developed based on the assumption that the intensity of rainfall, I, is constant over the duration and that the peak flow occurs once the entire watershed starts contributing simultaneously to flow at the outlet of the watershed. This duration is the same as the time of concentration, T_c, defined in equation (2-5). Empirical expression commonly used to estimate the time of concentration for a watershed is the Kirpich formula (Kirpich, 1940), given below:

$$T_c = 0.0078L^{0.77}S^{-0.385} \qquad \text{.............………………………………}\textit{Equation 2-5}$$

Where L = length of channel/ditch from head water to outlet, ft

S = average watershed slope, ft/ft

The rational method is most commonly used for hydrologic designs, rather than for estimating peak flows from actual rainfall. The intensity of the rainfall for design purposes is obtained from the intensity–duration–frequency (IDF) relationship for the watershed. The frequency used to determine the intensity is the same as that required for the design flood. That is, the average recurrence interval (ARI) or the return period chosen for the hydrologic designs is used as the frequency in the IDF relationship. Duration of the design rainfall is generally taken as the time of concentration, T_c, for design purposes.

The coefficient of runoff, C, for a given watershed is a major source of uncertainty in the rational method. The coefficient, as seen from the rational formula, Equation 2.6a, aggregates the effect of soil type, AMC, vegetation, land use, degree of soil compaction, depression storage, catchment slope, rainfall intensity, proximity to water table, and other factors that determine the peak runoff for a given storm in a catchment. Suggested values for the coefficient "*C*" are given in Chow *et al.* (1988).

Mujumdar & Kumar *(2012)* stated the points that must be noted with respect to the rational formula method:

i. It is assumed in the rational formula that the frequency of the peak discharge is the same as the frequency of the rainfall.

ii. The runoff coefficient *"C"* is the same for storms of different frequencies.

iii. All losses are constant during a storm – the value of *"C"* does not change with hydrologic conditions (such as the AMC).

iv. As the intensity of the rainfall is assumed to be constant over the duration considered, the rational method is valid for relatively small catchments. Some investigators believe that the maximum area should be about 100 acres (about 40 ha) (Maidment, 1993).

v. The rational method is generally used for urban storm-water drainage designs. It is also used for small non-urban catchments to estimate peak flows. Where the catchment size is large, it is divided into sub-catchments to obtain the peak flows from each sub-catchment and then the resulting hydrographs are routed using flood routing procedures to obtain the peak flow at the outlet.

vi. To account for a nonlinear response of the catchment to increasing intensities of rainfall, the value of C is sometimes assumed to increase as ARI increases. Chow *et al.* (1988) provide a table of runoff coefficients for various return periods (average recurrence intervals).

vii. A probabilistic rational method (Maidment, 1993) may be used to obtain the runoff coefficient as a function of the ARI.

2.5.2. Flood routing

Flood routing is determining the track of the changes in depth and discharge, with time and along the length of the river as the flood wave crosses a section, the velocity (or discharge) and the depth of flow at that section change. The depth and discharge of the wave front itself change with time. A flood wave is, therefore, represented by a hydrograph, as shown in Figure 2-1. In actual fact, a flood travels along a river reach as a wave, with velocity and depth continuously changing with time and distance. While it is difficult to forecast with accuracy the time of occurrence and magnitude of floods, it is possible to estimate fairly accurately the movement of the flood wave along a river, once it is known that a flood wave is generated at some upstream location in the river. Such estimation is of immense practical utility, as it can be used in flood early warning systems (Mujumdar & Kumar, 2012).

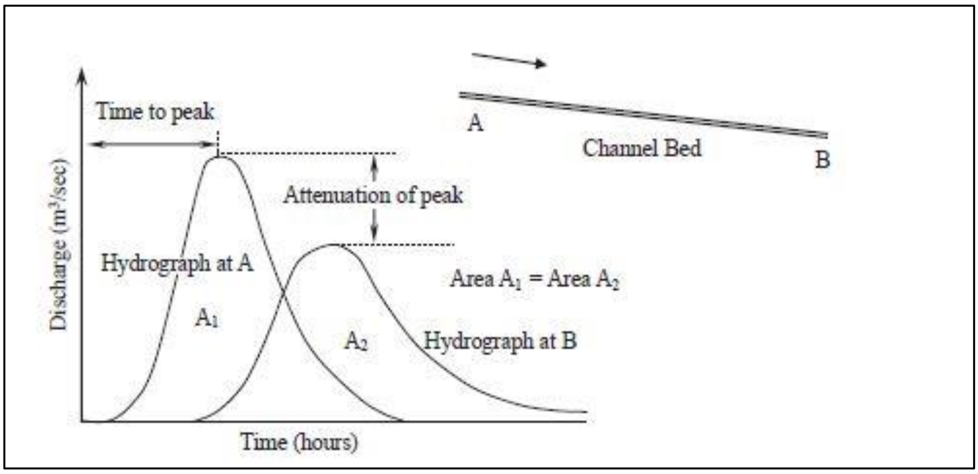

Figure 2-1: *Flood hydrographs* (Mujumdar & Kumar, 2012)

2.6. USE AND INTEGRATION OF GIS TECHNOLOGIES

Today, there are various hydrologic models with varying grades of data requirements that may be used for estimation of flood runoff, routing of flood hydrographs, and assessment of flood inundation, which may be done with a GIS interface. Hence, the hydrologic processes that occur in nature are distributed in the sense that the time and space derivatives of the processes are both important. The models can be classified as distributed and lumped depending on whether the models consider the space derivatives (distributed) or not (lumped). The semi-distributed models account for spatial variations in some processes while ignoring them in others. On the time scale, the models may be discrete or continuous time models (Mujumdar & Kumar, 2012).

In this study, HEC-HMS and HEC-RAS models (both developed by Hydrologic Engineering Centre, US Army Corps of Engineers), as well as the Soil and Water Assessment Tool (SWAT) and the Storm Water Management Model (SWMM) models, are discussed. These models are with GIS interface.

2.6.1. HEC-HMS MODEL

HEC-HMS is the Hydrologic Engineering Center's Hydrologic Modeling System, developed by the US Army Corps of Engineers (USACE). It is considered as the standard model in the private sector in the USA for the design of drainage systems, and for quantifying the effect of land use change on flooding (Singh & Woolhiser, 2002). It is designed to simulate the precipitation–runoff processes of dendritic watershed systems. The mass or energy flux in the hydrologic cycle in a watershed is represented with a mathematical model. In most cases, several model choices are available for representing each flux. Each mathematical model included in the program is typical of a particular environment (Mujumdar & Kumar, 2012).

The Hydrologic Modelling System (HEC-HMS) is designed to simulate the complete hydrologic processes of dendritic watershed systems. It includes many traditional hydrologic analysis procedures such as event infiltration, unit hydrographs, and hydrologic routing. It also includes procedures necessary for continuous simulation including evapotranspiration, snowmelt, and soil moisture accounting. Gridded runoff simulation can also be performed. Supplementary analysis tools are provided for parameter estimation, depth-area analysis, flow forecasting, uncertainty assessment, erosion and sediment transport, and nutrient water quality (USACE, 2016).

2.6.2. HEC-RAS MODEL

The Hydrologic Engineering Center's River Analysis System (HEC-RAS) software allows the user to perform one-dimensional steady and 1D and 2D unsteady flow river hydraulics calculations. HEC-RAS is an integrated system of software, designed for interactive use in a multitasking environment (USACE, 2016). It is developed by the Hydrologic Engineering Services of the USACE. HEC-RAS is useful in flood hydrology as a tool to carry out the flood routing, computations of backwater profiles, and gated operation of reservoirs to discharge flood waters (Mujumdar & Kumar, 2012).

The HEC-RAS system contains four (4) hydraulic analysis components for:

i. steady flow water surface profile computations;

ii. One and two-dimensional unsteady flow simulations;

iii. Movable boundary sediment transport computations; and

iv. Water temperature and constituent transport modeling

All four components use a common geometric data representation and common geometric and hydraulic computations routines. In addition to the four hydraulic analysis components, the system contains several hydraulic design features that can be invoked once the basic water surface profiles are computed.

The geometric data of the study area used in the model consist of connectivity information for the stream system, cross-section data, and data on hydraulic structures (bridges, culverts, weirs, etc.). The geometric data are drawn first in the river system schematic. Cross sections are ordered within a reach from the highest river station upstream to the lowest river station downstream. The flow data to be used in the model depend on the type of analysis to be performed: backwater computations, flood routing, reservoir operation, etc. The options for the results include graphic plots for cross sections, water surface profile, rating curves, X–Y–Z perspective, hydrographs, and tabular outputs at user specified locations (USACE, 2016).

2.6.3. SOIL AND WATER ASSESSMENT TOOL MODEL

The Soil and Water Assessment Tool (SWAT) is a river basin scale model developed by Dr. Jeff Arnold for the United States Department of Agriculture (USDA) Agricultural Research Service (Neitsch, et al., 2001). It can predict the impact of land management practices on water, sediment, and agricultural chemical yields in large complex watersheds with varying soils, land use, and management conditions over long periods of time.

SWAT is a physically based, distributed, continuous-time model that operates on a daily time scale. Physical processes associated with water movement, sediment movement, crop growth, nutrient cycling, etc. are directly modeled by SWAT.

For modeling purposes, a watershed is partitioned into a number of sub-basins, which are then further subdivided into hydrologic response units (HRUs). The use of sub-basins in a simulation model is particularly beneficial when different areas of the watershed are dominated by land uses and soils dissimilar enough in properties to impact hydrology. Simulation of the hydrology of a watershed is separated into two major parts in SWAT. The first part deals with the land phase of the hydrologic cycle, which considers the amount of water, sediment, nutrient, and pesticide loadings in each sub-basin. The second part deals with the routing phase that considers the movement of water and sediments through the channel network to the outlet (Mujumdar & Kumar, 2012).

2.6.4. STORM WATER MANAGEMENT MODEL

The US Environmental Protection Agency Storm Water Management Model (EPA SWMM) is a dynamic rainfall–runoff simulation model (Huber & Dickinson, 1988) used for simulation of runoff quantity and quality from predominantly urban areas. Although most commonly used in urban flood studies. The runoff component of SWMM operates on a collection of sub-catchment areas that receive precipitation and generate runoff and pollutant loads. The routing module of SWMM transports this runoff through a system of channels, storage/treatment devices, pumps, and regulators. 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 comprising multiple time steps. It is widely used for planning, analysis, and design related to storm water runoff, combined sewers, sanitary sewers, and other drainage systems primarily in urban areas (EPA, 2015).

The options available in the model for accounting for infiltration losses are the Horton model, the Green Ampt model, or use of the SCS curve number. Either the kinematic wave or the dynamic wave routing method may be chosen for flow routing. Details of rain gauges, sub-catchments, aquifers, and hydraulics (nodes, links, etc.) may be specified in the model.

The status report on a successful run of the model contains total precipitation quantity, losses, surface runoff, node depths, maximum depth of water and depth of water at different time steps in the simulation, nodes, and conduits flooded in case of flooding, and time of flooding. While extremely useful in urban flooding studies, SWMM may also be used for small watersheds where hydrologic homogeneity may be assumed (Mujumdar & Kumar, 2012).

CHAPTER 3 : MATERIALS AND METHODS

In this study, ArcGIS 10.2.1 with HEC-GeoHMS 10.2 extension and HEC-HMS 4.2 were used to perform the rainfall-runoff analysis (hydrological modeling) in order to establish the expected flood frequency and predict flood levels for estimating the probability of occurrence in the Nyabarongo Upper Catchment. This helped in determining the flood risks in the catchment with the purpose of recommending the possible measures to mitigate the risks socio-culturally, physically and by zoning in addition to develop the adaptive management strategy.

The methodological flow chart shown in Figure 3-1 describes the steps that were followed to achieve the main objective of the research project.

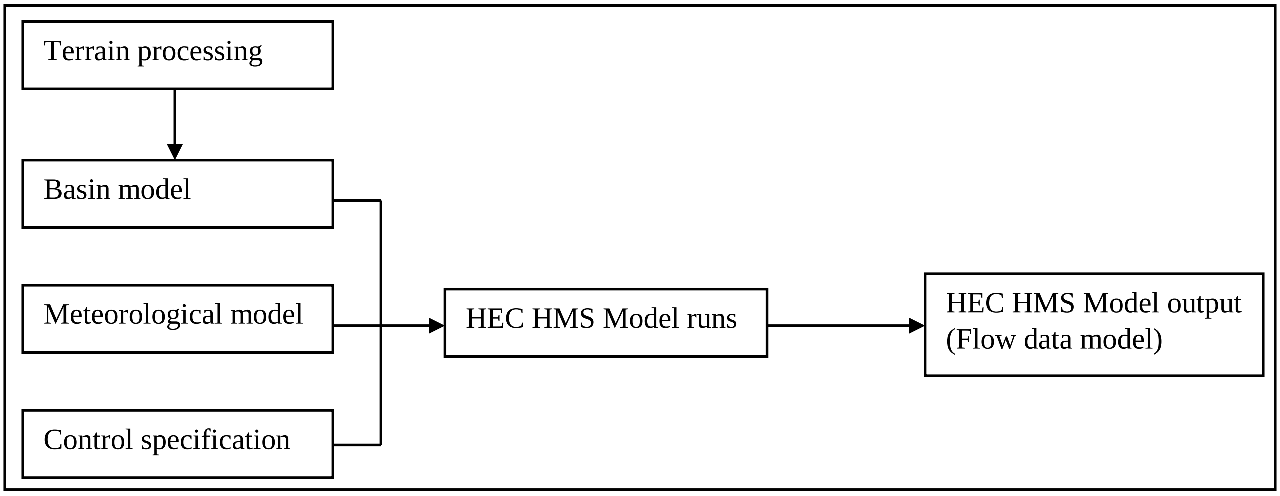

Figure 3-1: Methodological flow chart

3.1. DESCRIPTION OF THE STUDY AREA

3.1.1. General Background

The study was conducted in the eight (8) districts such as Karongi, Ngororero, Rutsiro, Huye, Nyanza, Ruhango, Muhanga, and Nyamagabe located in the Nyabarongo Upper catchment. The Nyabarongo Upper catchment is part of the Akagera river basin and Nile river basin as well and runs from South to North in the Western part of Rwanda and occupies the total area of 3,348 km^2 which represents almost 12.7% of the total surface of Rwanda (RNRA, 2015). The catchment is reputed to constitute the water tower of Rwanda and boosts 8 tributaries such as Mwogo river, Rukarara river, Mbirurume river, Mashiga river, Kiryango river, Munzanga river, Miguramo river and Santinsyi river. The Upper Nyabarongo springs from the confluence of the Mwogo and Mbirurume rivers and runs to the confluence with the Mukungwa river from where the Nyabarongo continues as the Lower Nyabarongo on its way to the Akagera river and Lake Victoria (RNRA, 2014).

The land morphology of a catchment is a crucial characteristic that determines a substantial part of its hydrological response to rainfall. The West of the catchment is of high altitude at 3,000 m (steep slopes) and the outflow of the catchment, which is the confluence of the Upper Nyabarongo with the Mukungwa river, is at 1400 m altitude (RNRA, 2016). The catchment watershed is subdivided into the granite basement aquifer in the Nile-Congo watershed in the West with a low water storage capacity and the quartzite and schist aquifer in the central part with intermediate storage and recharge conditions. The soil characteristics in the Upper Nyabarongo catchment show a high infiltration rate, the soils are dominants by deeply weathered, well drained, erodible tropical soils, strongly weathered soils with high content of kaolinite clay with iron and aluminum completed with young mineral soils. The rainfall pattern of the catchment shows high annual rainfall with the average annual rainfall varies approximately 1,365 mm/year (RNRA, 2016).

In the National Water Resources Master Plan of 2015, the annual resources assessment in the Nyabarongo Upper catchment demonstrates that the average annual rainfall is 1,365 mm/year, the average annual evaporation is 980 mm/year, annual surface water runoff is 385 mm/year, base flow is 34.2 m^3/sec, average annual groundwater recharge is 292 mm/year and groundwater volume storage is 24,110 million m^3 (RNRA, 2015). The population density in the catchment is about 352 inhabitants/km^2 which characterizes this catchment as highly dense populated compared to Rwanda's population density that is 415 inhabitants/km^2, the highest in Africa (RNRA, 2016; and REMA, 2015). The country census conducted in 2012 indicated that 320,682 people lived within the catchment with 6.7% living in urban areas and 93.3% living in rural areas.

Figure 3-2 and 3-3 show the location of the study area on the map of Rwanda and the river Nyabarongo Upper catchment.

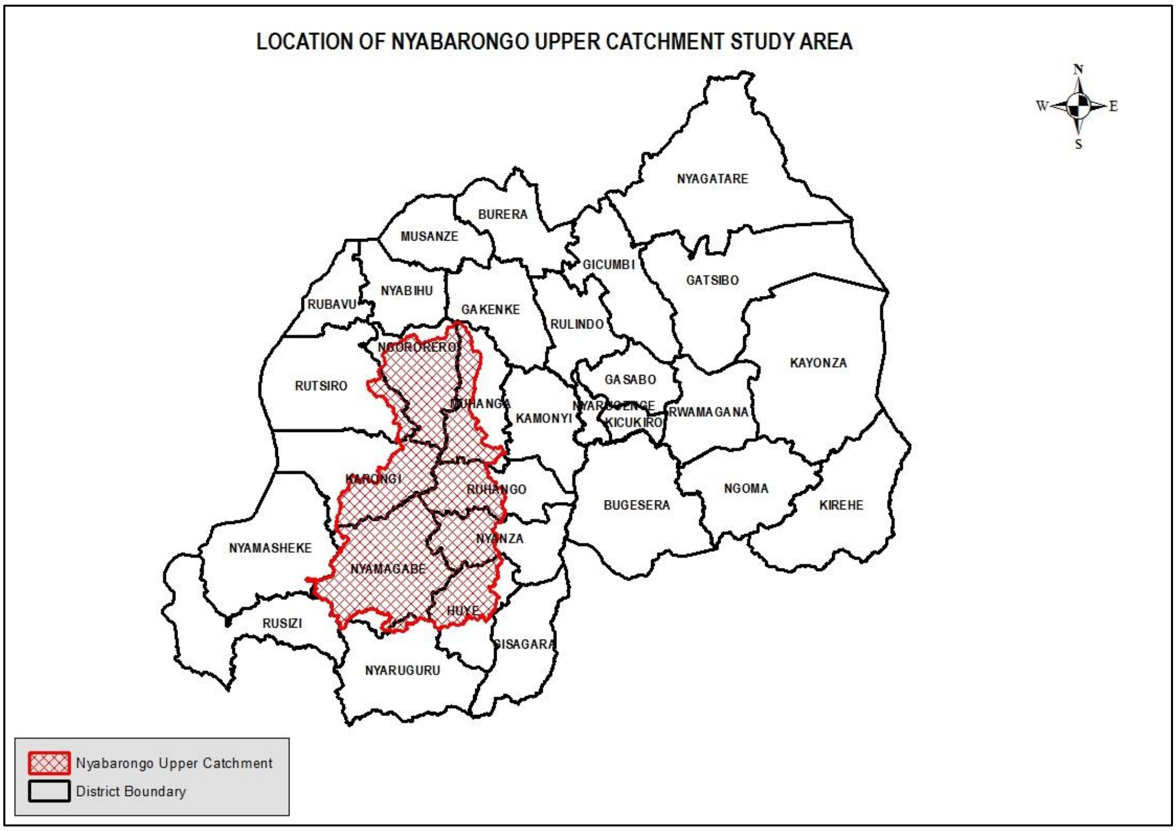

Figure 3-2: Location of Nyabaronho Upper catchment study area

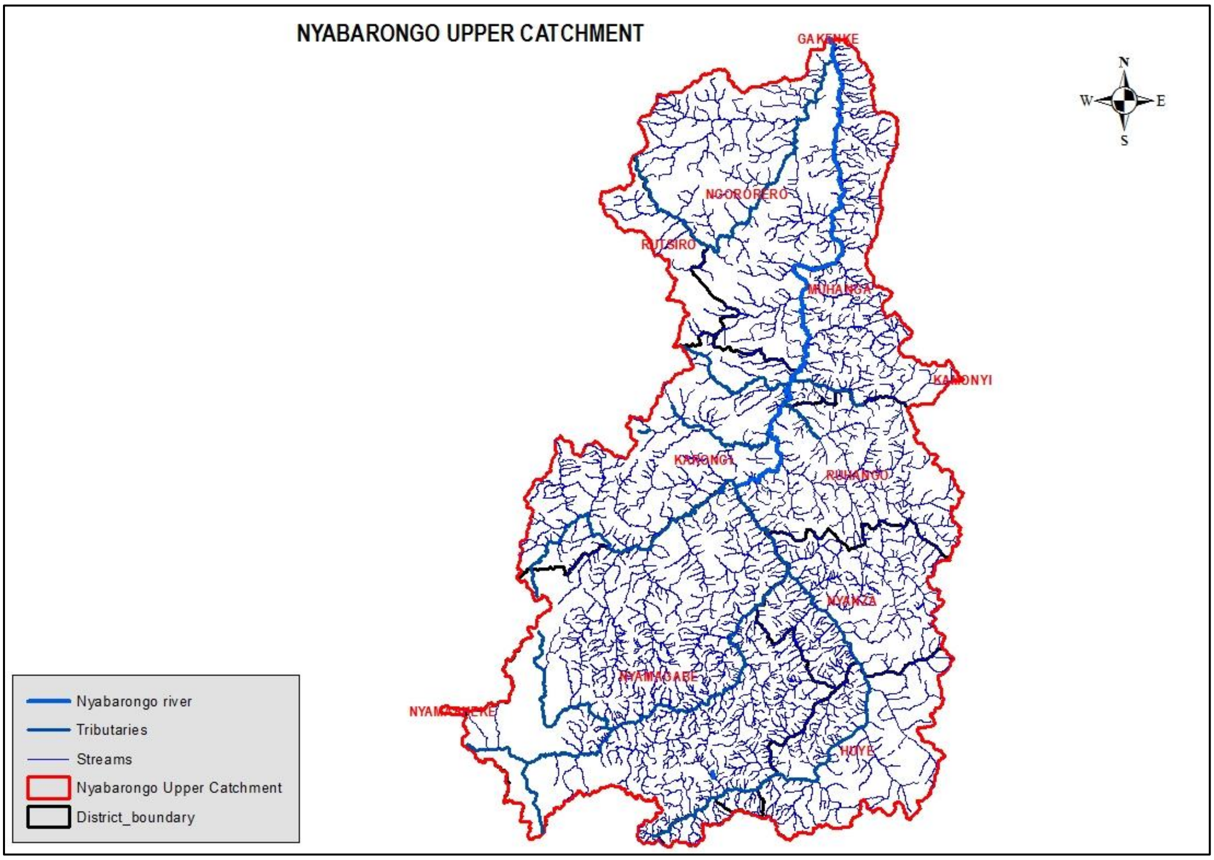

Figure 3-3: Nyabarongo Upper catchment with its drainage system

3.1.2. Nyabarongo Upper Catchment Physical characteristics

3.1.2.1. Topography and climate

The topography of Nyabarongo Upper catchment varies between the altitude of 1,396 and 2,950 meters and it is characterized by steep and moderately steep slopes in Northern-West, Southern-West and few areas Northern-East parts. Flat and gentle topography are dominant in the central and Eastern parts of the catchment.

The climate of Nyabarongo Upper catchment is similar to the Countrywide's that is a tropical temperate climate of around 20^0C and varies little throughout the year. Temperature observation data within the catchment indicates a maximum daily temperature of 25.3 °C and a minimum daily temperature of 14.6 °C in the western part of the catchment and a maximum daily temperature of 23.6 °C and a minimum daily temperature of 14.0 °C in the southern part of the catchment.

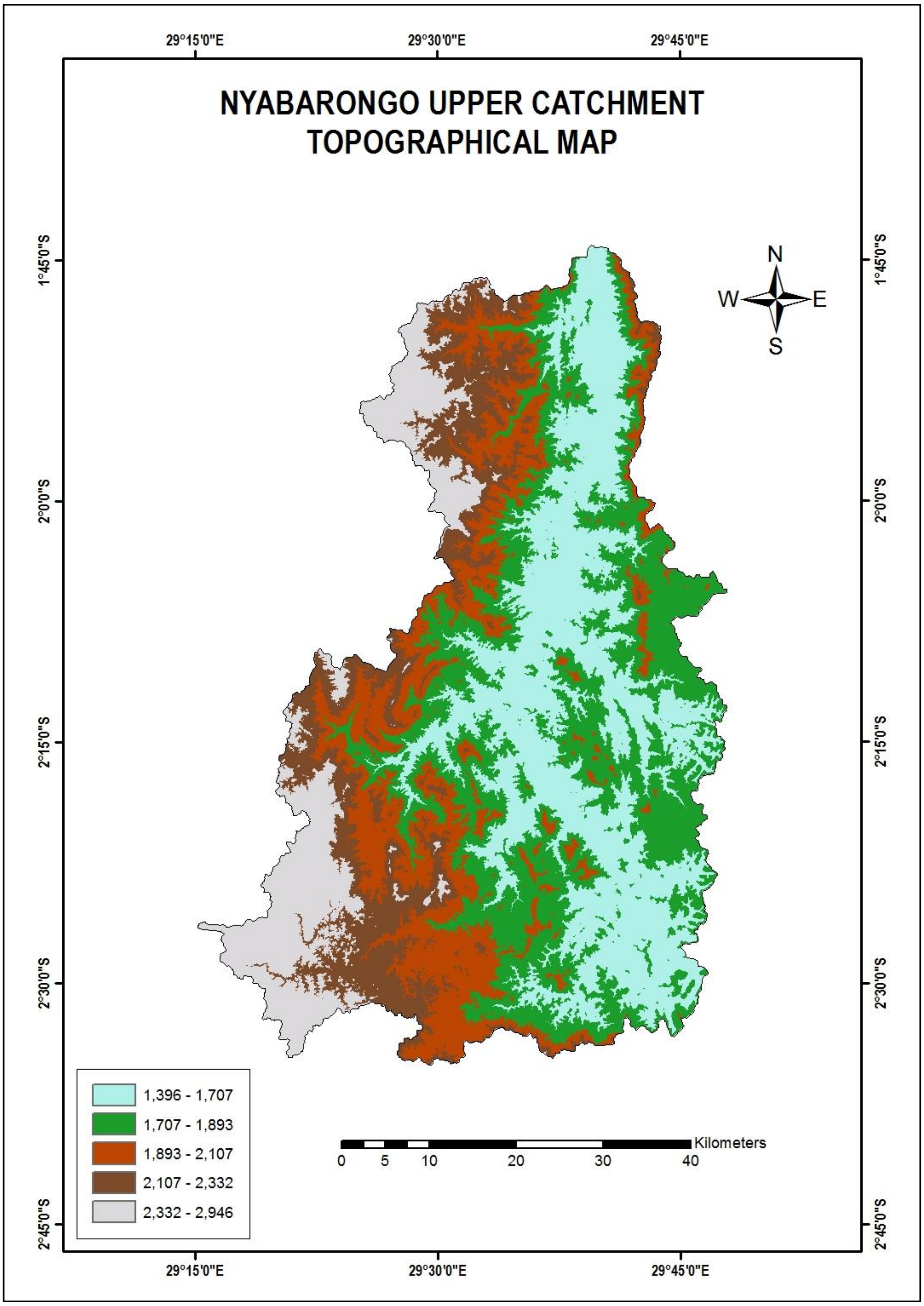

Figure 3-4: Nyabarongo Upper catchment topographical map

3.1.2.2.   Soils

In the Nyabaronga Upper catchment, eleven (11) predominant soil classes were identified that are Regosols, Acrisols, Alisols, Cambisols, Ferralsols, Gleysols, Histosols, Lixisols, Luvisols, Nitosols, and Vertisols. Therefore, Cambisols and Acrisols are the dominant soil type in the catchment (see Figure 3-5). In addition, eight (8) soil textures were found which are Clay, Clay Loam, Loam, Loamy Sand, Sand Clay, Sand Clay Loam, Sandy Loam, and Silt Loam. Thus, the dominant soil textures are Clay Loam, Sandy Clay Loam, and Sand Clay respectively (see Figure 3-6). As result, the soils in the catchment have very low infiltration rates and therefore, they have high runoff potential.

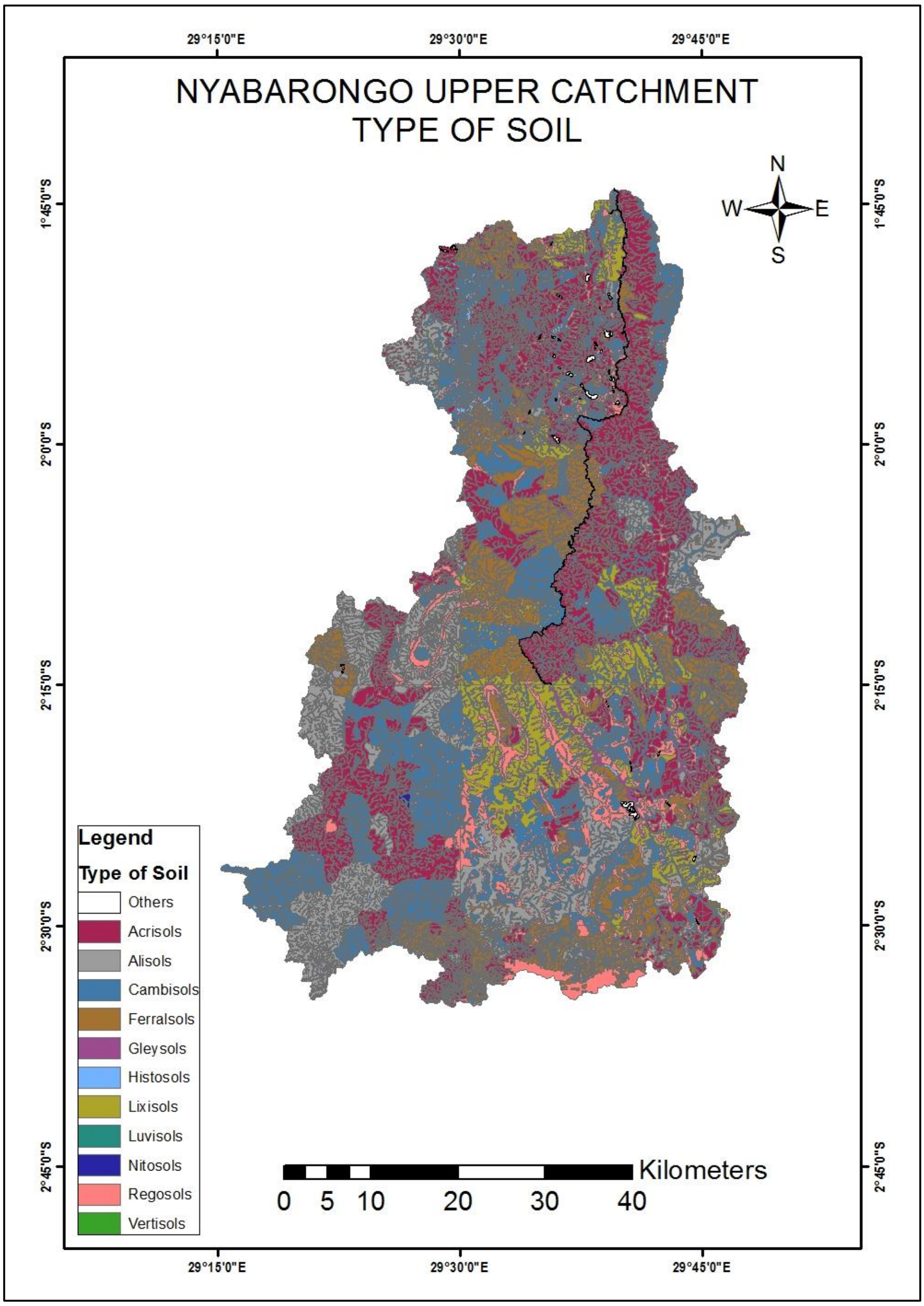

Figure 3-5: Soil map of Nyabarongo Upper Catchment

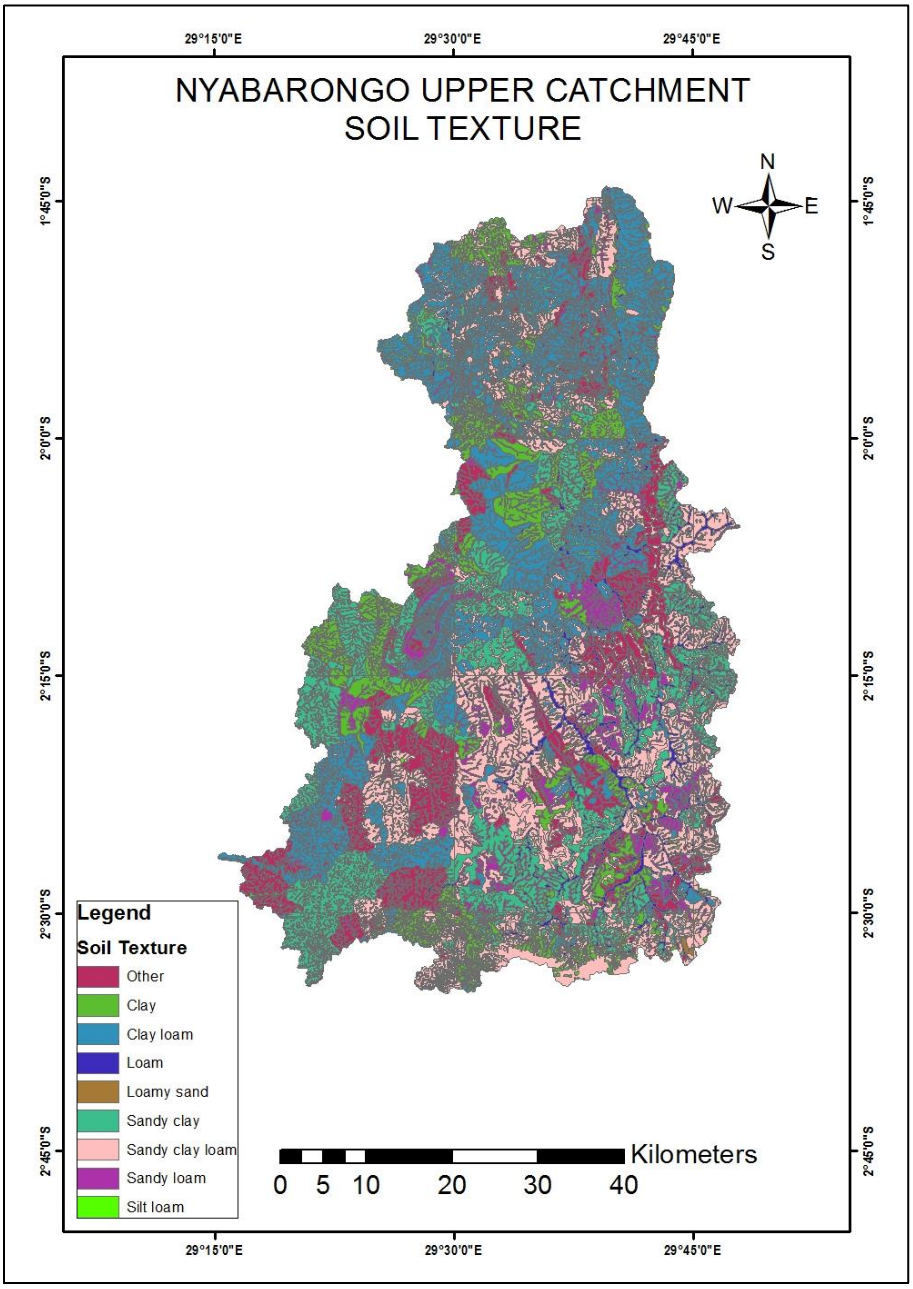

Figure 3-6: Major soil texture of Nyabarongo Upper Catchment

3.1.2.3. Land use/Land cover description

The Nyabarongo Upper Catchment is dominantly covered with Open Agriculture with an area coverage of about 241,886.18 ha (72.41%) followed by Natural Forest with an area coverage of 41,172.36 ha (12.33%), Closed Agriculture with 25,716.91 ha (7.7%), irrigation with 13,671.54 ha (4.09%), Open Land with 10,177.12 ha (3.05%), Built-up area with 1,339.71 ha (0.40%) and Forest plantation with an area coverage of about 76.86 ha (0.02%) (see Figure 3-7).

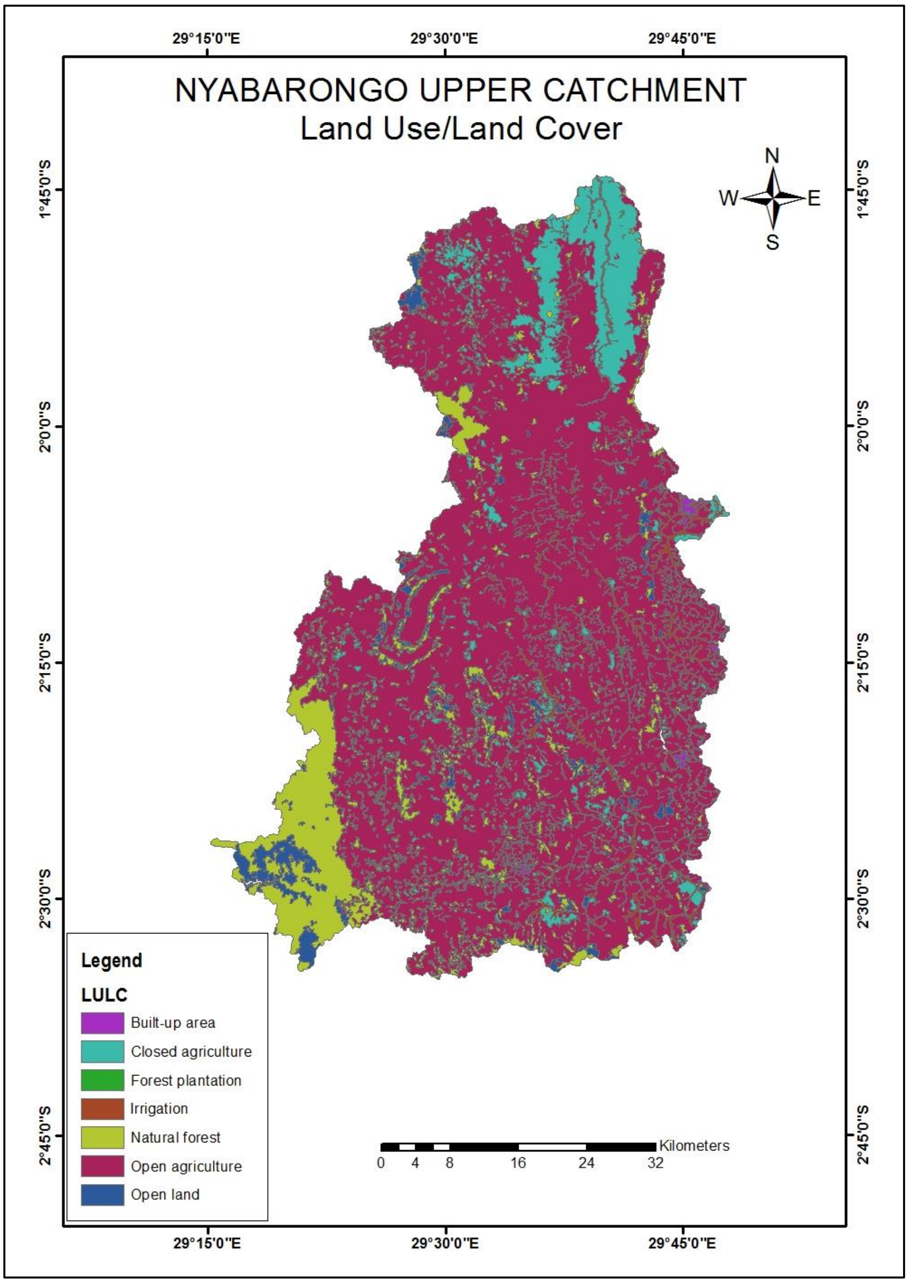

Figure 3-7: Land use / Land cover map of Nyabarongo Upper Catchment

3.2. DATA COLLECTION AND PRE-PROCESSING

3.2.1. Introduction

Regardless the behaviour and characteristics of the catchment, there are prone to severe erosion, high rates of deforestation as well as land degradation due to poor agricultural practices, illegal mining activities, overexploitation, high population density, poor drainage structure alongside the Nyabarongo river, socio-economic activities such as industries, water treatment, small hydropower, dam construction, and irrigation development over and above extreme excesses of precipitation caused by climate variability and topography (RNRA, 2014; and RNRA, 2016).

Nevertheless, they are following by trailing people's life, displacement of inhabitants, and socioeconomic damages.

Since the study was focused on assessing the flood risk as stated previously, the data collected for the years 1971 to 2017 were selected, processed and used in this research. The meteorological data were obtained from the Rwanda Meteorology Agency (RMA) and the hydrological data from the Rwanda Water and Forestry Authority (RWFA) under Ministry of Natural Resources (MINIRENA). The hydrological data used in the study comprises precipitation and stream flow records for a period of 24 to 46 years. The historical data were extracted from the hydrological data network of Rwanda Meteorology Agency and Rwanda Water and Forestry Authority. The data were divided into annual time-series for stream flow and precipitation for the whole Nyabarongo Upper catchment. The data provided good continuity and were chosen based on having few missing data records. A brief description of each gauge is presented in Table (3-1). The catchment was therefore divided into four sub-basins (W360, W460, W500, and W560), depending on topographical and meteorological features (see Figure 3-8).

This section provides a description of the data collected and all the methods used for their processing.

Table 3-1: Spatial and temporal information of 4 Nyabarongo Upper rain gauge stations and 4 streamflow stations comprised of Latitude, Longitude, Altitude (m) and period of records

Sub-basin ID	**Precipitation Station**	**Latitude**	**Longitude**	**Altitude (m)**	**Periods of records**
W360	Muramba Paroisse	29.6	-1.75	1950	1971-2017
W460	Rubengera MET	29.41	-2.05	1700	1991-2015
W500	Gikongoro MET	29.56	-2.46	1910	1990-2015
W560	Rubona Colline	29.76	-2.46	1706	1971-2015
Sub-basin ID	**Stream flow Station**				
W360	Nyabarongo_Outlet	463021	9808898	1400	1974-2010
W460	Nyabarongo_Mwaka	458147	9769624	1475	1971-2013
W500	Rukarara_Mudasomwa	439272	9728976	2010	1987-2012
W560	Mwogo_Nyabisindu	462631	9740792	1525	1972-2013

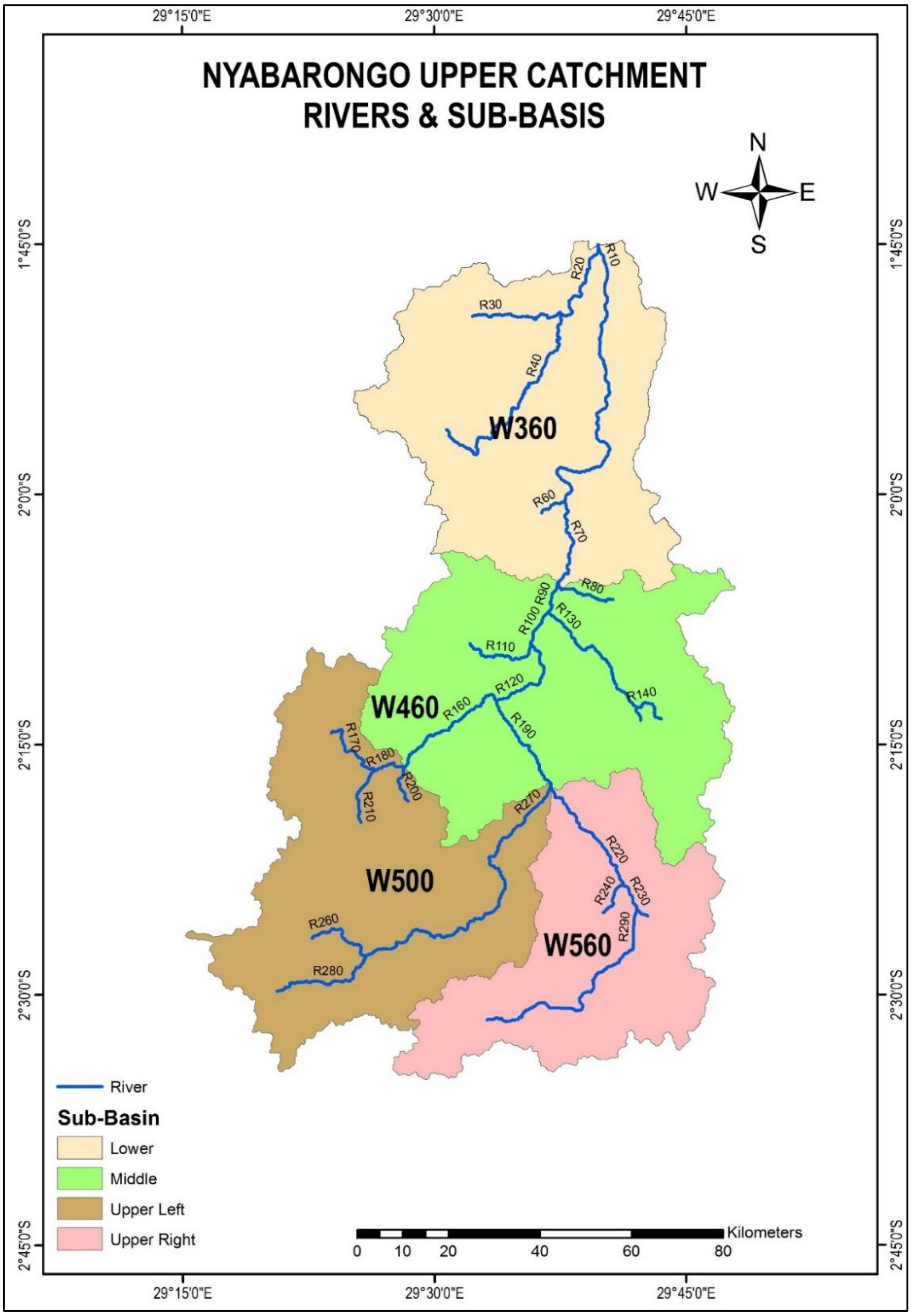

Figure 3-8: Nyabarongo Upper Catchment, its sub-basins, and its main rivers

3.2.2. Data processing tools

The data processing tools used to accomplish the research included: ArcGIS 10.2.1 (with ArcInfo, ArcCatalog, and extensions such as 3D analyst, spatial analysts), Arc Hydro tools (version that works with 10), HEC-GeoHMS toolbar (version that works with 10), HEC-HMS version 4.2 computer program, MS excel, Power point, and Word computer applications.

3.2.3. Hydrologic modelling

3.2.3.1. Terrain processing steps

Terrain processing involved using the DEM to create a stream network and catchments. The following steps were used for to create the input files for hydrologic modeling with HEC-HMS.

a. Pre-processing

All the steps in the Pre-processing menu should be performed in sequential order, from top to bottom and they must be completed to delineate the watershed for the HEC-HMS model. The used steps in the pre-processing are as follow: 1. Fill Sinks, 2. Flow Direction, 3. Flow Accumulation, 4. Stream Definition, 5. Stream Segmentation, 6. Catchment Grid Delineation, 7. Catchment Polygon Processing, 8. Drainage Line Processing, 9. Adjoint Catchment Processing performed in sequential order.

b. HEC-GeoHMS Project Setup

The HEC-GeoHMS Project Setup menu has tools for defining the outlet for the watershed and delineating the watershed for the HEC-HMS Project.

c. Basin Processing

The basin processing menu has features such as revising sub-basin delineations, dividing basins, and merging streams. Merge basins into 4 sub-basins (W360, W460, W500, and W560) was created.

d. Extracting Basin Characteristics

The basin characteristics menu in the HEC-GeoHMS Project view provide tools for extracting physical characteristics of streams and sub-basins into attributes tables. The used tools were:

- The River Length that computes the length of river segments and stores them in *RiverLen* field;
- The River Slope tool that computes the slope of the river segments and stores them in *Slp* field;
- The Basin Slope that computes average slope for sub-basins using the slope grid and sub-basin polygons and stores them in *BasinSlope* field.

- The Longest Flow Path that creates a feature class with polyline features and stores the longest flow path for each sub-basin.
- The basin Centroid that creates a centroid point feature class to store the centroid of each sub-basin. From different methods, this project used *Center of Gravity Method* that computes the centroid as the center of gravity of the sub-basin if it is located within the sub-basin. If the center is outside, it is snapped to the closest boundary.
- The Basin Centroid Elevation that computes the elevation for each centroid point using the underlying DEM.
- The Centroid Longest Flow Path that creates a new polyline feature class showing the flowpath for each centroid point along the longest flow path.

3.2.3.2. Digital Elevation Model (DEM)

The DEM of cell size of 30m by 30m was a fundamental dataset used for development of the catchment or basin model component in the HEC-HMS Model. This dataset was therefore useful in hydrological modeling and flood risk generation.

3.2.3.3. Land use/cover shape files

Land use/Land cover datasets were used to create a Curve Number (CN) grid file from which CN values of the river catchment basin were generated. The following Figure (3-9) describes clearly the creation of CN Grid in ArcMap.

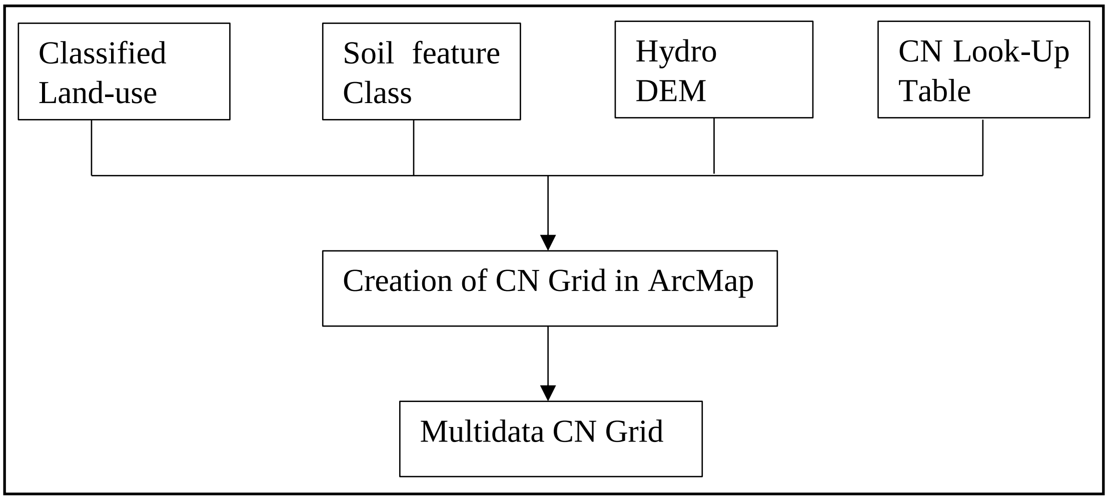

Figure 3-9: Creation of CN Grid in ArcMap

The steps used to create the CN Grid in ArcGIS (ArcMap) are as follow:

1. Preparing land use data for CN Grid

    - The original land use/cover grid was added with a unique symbology assigned to cells having identical numbers (see Figure 3-10 and Table 3-2).
    - The original land use/cover has 10 different categories which were used to reclassify the grid to reduce the number of land use classes to make the task easier. Therefore, the original land use/cover was reclassified into 4 major classes (see Figure 3-10 and Table 3-2).
    - Convert the reclassified land use grid into a polygon feature class which was merged with soil data.

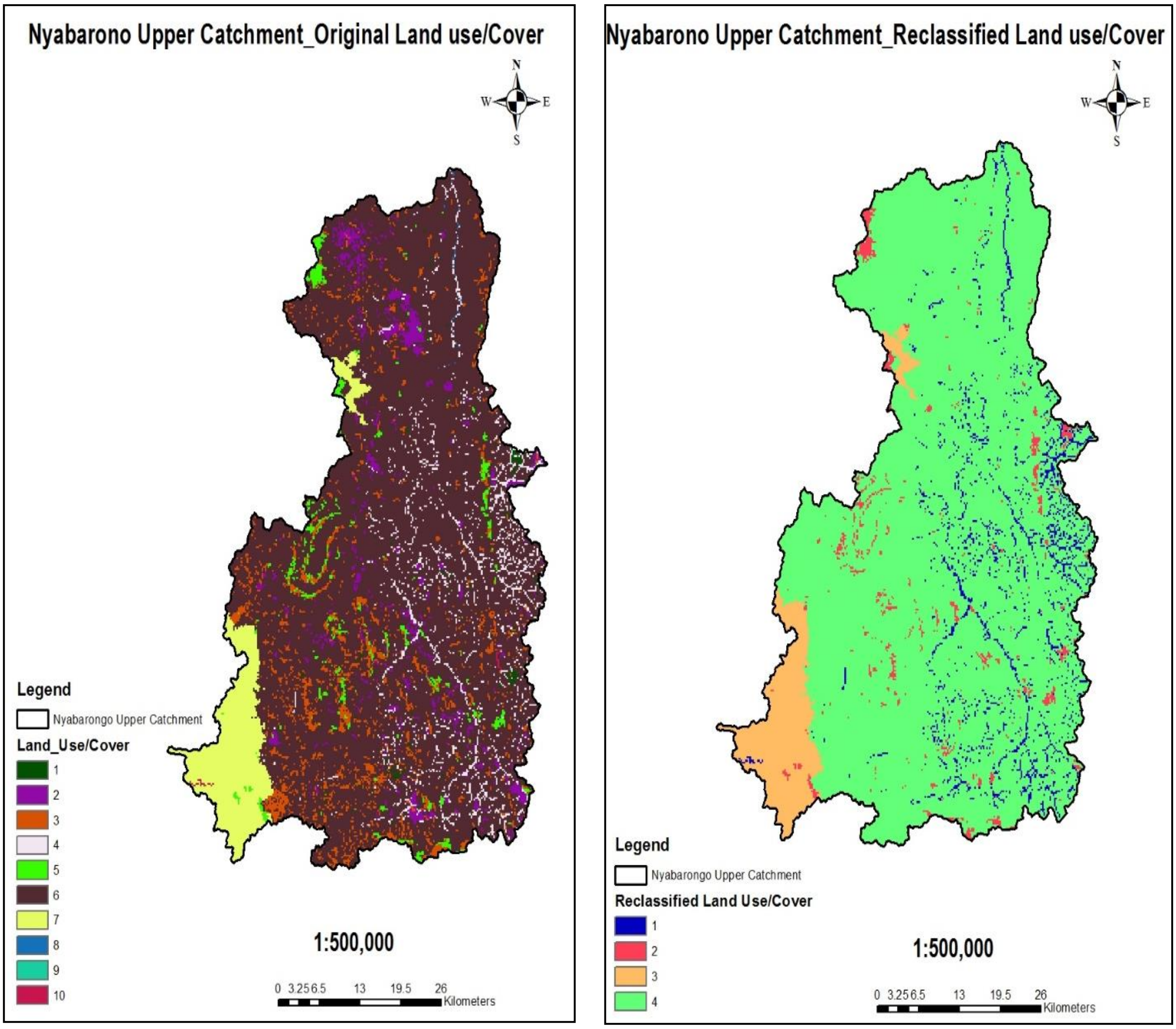

Figure 3-10: Original and Reclassified land use/cover

Table (3-2) below shows the description of the original and reclassified land use cover for the Nyabarongo Upper Catchment.

Table 3-2: Original and reclassified land use cover descriptions.

Original land use/cover		**Reclassified land use/cover**	
Land use code	**Description**	**Land use code**	**Description**
1	Built-up area	1	Water
2	Closed agriculture	2	Medium Residential
3	Forest plantation	3	Forest
4	Irrigation	4	Agricultural
5	Open land		
6	Open agriculture		
7	Natural forest		
8	Large river		
9	Dam		
10	March		

2. Preparing Soil data for CN Grid

    - The soil data feature from spatial feature dataset was added to map document,
    - Four more fields named PctA, PctB, PctC, and PctD were created in the soil data attribute table. For each feature (polygon) in PctA defines what percentage of area within the polygon has soil group A, PctB defines what percentage of area within the polygon will have soil group B and so on. If we have classifications such as these, we need to define how much area of a polygon is A/B/C/D. For Nyabarongo Upper catchment area we have only one soil group assigned to each polygon so a polygon with soil group “A” will have PctA = 100, PctB = 0, PctC = 0, and PctD = 0. Similarly, for a polygon with soil group D, only PctD = 100, and other three Pcts are 0. Then populate PctA, PctB, PctC, and PctD based on SoilCode for each polygon.

3. Merging of Soil and Land use data

    - The result of merge features inherits attributes from both Soil and Land use feature classes that were used as input to prepare a look-up table that has curve numbers for different combinations of land uses and soil groups. In this case, SCS curve numbers that are available from the literature were used.

4. Creating CN Look-up table
5. Creating CN Grid

- HEC-GeoHMS was used to create the curve number grid. HEC-GeoHMS uses the merged feature class and the lookup table (CNLookUp) to create the curve number grid.

3.2.3.4. Meteorological data

Frequency storm method was used to withstand extreme hydrologic events. Therefore, Meteorological data required as the HEC-HMS model input was the precipitation depths as a function of return period over the river catchment basin obtained from the rain-gauge point precipitation. The depths accumulated over twenty-four (24) hours duration as a function of the 10, 50, 100, 250, and 500-year return period of the storm events was determined using equation (3-1) shown (Butler & Davies, 2004). The duration for all the storm precipitation was chosen as 24 hours (one day). The design precipitation values obtained from the log – normal probability plots were used to determine the rainfall intensities for the 10, 50, 100, 250, and 500-year return period over 24 hours rainfall duration.

$d = i_{24} \times t$ ……………………………...*Equation 3-1*

Where d = Rainfall depth (mm) for duration time (t)

i_{24}= 24-hour rainfall intensity (mm/h)

t= rainfall duration time (h) (default values in the HEC-HMS set up)

The log-normal probability for the Maximum Annual Rainfall was given using MATLAB in order to predict the 10, 50, 100, 250 and 500-year return period for different rain-gauge stations (4) chosen and located in each and every sub-basin. The maximum annual rainfall is described in the Table (3-3) below.

Table 3-3: Maximum Rainfall in 24 hours with respect to the return period

		Maximum Rainfall over 24 hours (mm) per return period				
Sub-Basin ID	**Precipitation station**	**10-Year**	**50-Year**	**100-Year**	**250-Year**	**500-Year**
W360	Muramba_Paroisse	100	2,125	5,500	21,250	77,500
W460	Rubengera MET	52	1,085	4,033	22,873	85,000
W500	Gikongoro MET	145	1,088	2,575	8,050	19,000
W560	Rubona_Colline	103	1,376	4,200	18,200	55,850

The Tables 3-4 to 3-7 describes the design precipitation maximum depths as a function of 10, 50, 100, 250 and 500-year return periods for the 4 sub-basins (W360, W460, W500, and W560).

Table 3-4: Design precipitation maximum depths as a function of return periods for W360

Year (Rainfall)	**10-Year (100 mm)**	**50-Year (2,125 mm)**	**100-Year (5,500 mm)**	**250-Year (21,250 mm)**	**500-Year (77,500 mm)**
Rainfall intensity	4.17 mm/hr	88.54 mm/hr	229.17 mm/hr	885.42 mm/hr	3,229.17 mm/hr
Duration (hour)	Depth (mm)	Depth (mm)	Depth (mm)	Depth (mm)	Depth (mm)
0.08	0.35	7.38	19.10	73.79	269.10
0.25	1.04	22.14	57.29	221.36	807.29
1	4.17	88.54	229.17	885.42	3,229.17
2	8.34	177.08	458.34	1,770.84	6,458.34
3	12.51	265.62	687.51	2,656.26	9,687.51
6	25.02	531.24	1,375.02	5,312.52	19,375.02
12	50.04	1,062.48	2,750.04	10,625.04	38,750.04
24	100.08	2,124.96	5,500.08	21,250.08	77,500.08

Table 3-5: Design precipitation maximum depths as a function of return periods for W460

Year (Rainfall)	**10-Year (52 mm)**	**50-Year (1,085 mm)**	**100-Year (4,033 mm)**	**250-Year (22,873 mm)**	**500-Year (85,000 mm)**
Rainfall intensity	2.15 mm/hr	45.21 mm/hr	168.02 mm/hr	963.02 mm/hr	3541.67 mm/hr
Duration (hour)	**Depth (mm)**	**Depth (mm)**	**Depth (mm)**	**Depth (mm)**	**Depth (mm)**
0.083	0.18	3.77	14.00	80.25	295.14
0.25	0.54	11.30	42.01	240.76	885.42
1	2.15	45.21	168.02	963.02	3,541.67
2	4.30	90.42	336.04	1,926.04	7,083.34
3	6.45	135.63	504.06	2,889.06	10,625.01
6	12.90	271.26	1,008.12	5,778.12	21,250.02
12	25.80	542.52	2,016.24	11,556.24	42,500.04
24	51.60	1,085.04	4,032.48	23,112.48	85,000.08

Table 3-6: Design precipitation maximum depths as a function of return periods for W500

Year (Rainfall)	**10-Year (145 mm)**	**50-Year (1,088 mm)**	**100-Year (2,575 mm)**	**250-Year (8,050 mm)**	**500-Year (19,000 mm)**
Rainfall intensity	6.04 mm/hr	45.31 mm/hr	107.29 mm/hr	335.42 mm/hr	791.67 mm/hr
Duration (hour)	**Depth (mm)**	**Depth (mm)**	**Depth (mm)**	**Depth (mm)**	**Depth (mm)**
0.083	0.50	3.78	8.94	27.95	65.97
0.25	1.51	11.33	26.82	83.86	197.92
1	6.04	45.31	107.29	335.42	791.67
2	12.08	90.62	214.58	670.84	1,583.34
3	18.12	135.93	321.87	1,006.26	2,375.01
6	36.24	271.86	643.74	2,012.52	4,750.02
12	72.48	543.72	1,287.48	4,025.04	9,500.04
24	144.96	1,087.44	2,574.96	8,050.08	19,000.08

Table 3-7: Design precipitation maximum depths as a function of return periods for W560

Year (Rainfall)	**10-Year (103mm)**	**50-Year (1,376 mm)**	**100-Year (4,200 mm)**	**250-Year (18,200 mm)**	**500-Year (55,850 mm)**
Rainfall intensity	4.31 mm/hr	57.33 mm/hr	175 mm/hr	758.33 mm/hr	2,327.08 mm/hr
Duration (hour)	**Depth (mm)**	**Depth (mm)**	**Depth (mm)**	**Depth (mm)**	**Depth (mm)**
0.083	0.36	4.78	14.58	63.19	193.92
0.25	1.08	14.33	43.75	189.58	581.77
1	4.31	57.33	175.00	758.33	2,327.08
2	8.62	114.66	350.00	1,516.66	4,654.16
3	12.93	171.99	525.00	2,274.99	6,981.24
6	25.86	343.98	1,050.00	4,549.98	13,962.48
12	51.72	687.96	2,100.00	9,099.96	27,924.96
24	103.44	1,375.92	4,200.00	18,199.92	55,849.92

3.2.4. HEC-HMS Model input parameter values

The physical basin and river model parameter values were extracted from the attributes table of sub-basin 111 and River 111 layers in ArcGIS. Other required input basin and river reach parameter values are as shown in Table (3-8) below.

Table 3-8: Nyabarongo Upper HMS catchment basin model parameters

S/No	**Model**	**Method**	**Parameter values required and units**
1	Loss	SCS Curve Number	Initial abstraction (mm), Curve Number, imperviousness (%)
2	Transform	SCS Unit Hydrograph	Lag time (min)
3	Routing	Lag	Lag time (min)

The methods are described as follow:

a. *Loss model: SCS Curve Number Method*

   i. Initial abstraction parameter values for the sub-basins were estimated using the expression shown in Equation (3-8).

   ii. Basin Curve Number parameter values for each sub-basin were estimated during data processing using HEC-GeoHMS Software in ArcGIS environment. The values of Sub-Basin Curve Number were then extracted from the attributes table of Sub-basin data layer.

iii. Percentage imperviousness of each Sub-Basin was estimated using the expression shown in the Table (3-9) below.

Table 3-9: Percentage imperviousness of each sub-basin

S/N	Sub-basin ID	Imperviousness (%)
1	W360	7.47
2	W460	7.42
3	W500	7.17
4	W560	5.15

b. *Transform model: SCS Unit Hydrograph method*

Basin Lag time parameter values were computed during data processing using the HEC-GeoHMS application in ArcGIS environment and stored in the attributes table of Sub-Basin data layer. Basin Lag time in hours for each Sub-Basin was computed using Equation 3-2 (Matthew & James, 2013) and then converted to minutes by multiplying by sixty (60).

$$Lag = \frac{L^{0.8}(S+1)^{0.7}}{1900\ x\ Y^{0.5}} \quad \text{.................................} \ \textit{Equation 3-2}$$

Where S= Maximum retention

Lag= basin lag time (hours)

L= Hydraulic length of the watershed (longest flow path) (feet)

Y= Basin slope (%)

Table 3-10: Loss and Transform model parameter value estimates

Sub-basin ID	Basin Area (Km^2)	Basin CN	S	I_a (inches)	I_a (mm)	Basin Lag (Hours)	Basin Lag (minutes)
W360	916.50	83	2.05	0.41	10.40	3.44	206.64
W460	909.61	81	2.35	0.47	11.92	3.46	207.52
W500	879.56	79	2.66	0.53	13.50	4.32	259.25
W560	631.77	80	2.50	0.50	12.70	4.44	266.66

c. *Routing: Lag method*

Lag time (Δt) parameter values for the river reaches were computed as the travel time (K) of the flood wave through the river reaches using equation 8. For steeper streams, with well-defined channels, in Muskingum model, X will be closer to 0.5 and if X=0.50 then the travel time (K) in Muskingum model=Lag time (Δt) in the routing model (USACE, 2000). In Muskingum model, X is the dimensionless weight factor ranging between 0.0 and 0.50 (0.0 for a linear reservoir, 0.5 for a pure transmission reach).

$$H = z + \frac{P}{\rho g} + \frac{V^2}{2g} \quad \text{...Equation 3-3}$$

Where H= Total Energy Head (m)

Z= Potential head (m)

$P/\rho g$= Pressure head (m) with P (Pressure: N/m^2) and ρg (Unit Weight: N/m^3)

$V^2/2g$= Kinetic (Velocity) head (m) with V (Velocity of flow: m/sec) and g (Acceleration due to gravity (m/s^2)

The travel time K of the flood wave was estimated using Equation (3-4) expressed below:

$$K = \frac{L}{V} \quad \text{...Equation 3-4}$$

Where L=Length of the river reaches (m). River reach lengths were created after processing Nyabarongo Upper catchment DEM and stored in the river layer attributes table

V=Velocity of the flood wave through the reach (m/s) was obtained using Equation (3-5)

$$V = \frac{Q}{A} \quad \text{... Equation 3-5}$$

Where Q=flood discharge at the gauging station (m^3/s)

A=Cross section area at the gauging station (m^2).

The relationship between water level and discharge was estimated using the Rating curves. Rating curves usually comply with the Equation (3-6),

$$Q = C * (h + a)^N \quad \text{...Equation 3-6}$$

Where Q= Discharge (m^3/sec)

C= Calibration parameter (Unit)

h= Water level (m)

a= Water level at which discharge is zero (m)

N= Calibration parameter (Unit)

Table 3-11: Stream flows and their Rating Curve formulas used for each sub-basin

Sub-basin ID	Stream flow Station	Rating curve
W360	Nyabarongo_Outlet	$10.136*(1.57+H)^{1.751}$
W460	Nyabarongo_Mwaka	$7.286*(0.466+H)^{1.906}$
W500	Rukarara_Mudasomwa	$7.2627*(0.195+H)^{2.8}$
W560	Mwogo_Nyabisindu	$0.2396*(1.819+H)^{2.696}$

Table 3-12: Measured Flood discharge and the velocity of flood wave through the reach for the 4 sub-basins

Sub-basin ID	Flood Discharge (m^3/sec)					Flood wave Velocity (m/sec)				
	10 Year	50 Year	100 Year	250 Year	500 Year	10 Year	50 Year	100 Year	250 Year	500 Year
W360	387.50	20,150	107,500	1,000,000	5,500,000	2.2	10.3	21.25	52.4	104
W460	410	28,375	175,000	1,975,000	12,250,000	3.45	22	49	141	313.75
W500	93.75	8,325	57,500	739,250	5,100,000	1.08	5.22	10.3	25.2	49.65
W560	24.50	550	2,225	13,375	51,875	1.76	9.7	20.2	53.5	112

Lag time parameter values for the 10, 50, 100, 250 and 500-year storms respectively are shown in Table (3-13) below:

Table 3-13: Lag time parameter values for the Lag routing model

	10 yr Flood	**50 yr Flood**	**100 yr Flood**	**250 yr Flood**	**500 yr Flood**
Reach ID	Lag (min)	Lag (min)	Lag (min)	Lag (min)	Lag (min)
R10	0.12	0.02	0.01	0.00	0.00
R20	88.29	18.86	9.14	3.71	1.87
R30	93.68	20.01	9.70	3.93	1.98
R40	221.93	47.40	22.98	9.32	4.69
R60	25.70	5.49	2.66	1.08	0.54
R70	86.05	18.38	8.91	3.61	1.82
R80	36.43	5.71	2.57	0.89	0.40
R90	18.96	2.97	1.34	0.46	0.21
R100	19.83	3.11	1.40	0.49	0.22
R110	48.54	7.61	3.42	1.19	0.53
R120	54.91	8.61	3.87	1.34	0.60
R130	80.97	12.70	5.70	1.98	0.89
R140	22.27	3.49	1.57	0.54	0.24
R150	8.12	1.27	0.57	0.20	0.09
R160	75.40	11.82	5.31	1.84	0.83
R170	145.70	30.14	15.28	6.24	3.17
R180	60.03	12.42	6.29	2.57	1.31
R190	60.24	9.45	4.24	1.47	0.66
R200	72.09	14.91	7.56	3.09	1.57
R210	115.12	23.82	12.07	4.93	2.50
R220	236.23	48.88	24.77	10.12	5.14
R230	33.04	6.00	2.88	1.09	0.52
R240	43.85	7.96	3.82	1.44	0.69
R250	17.83	3.24	1.55	0.59	0.28
R260	142.41	29.46	14.93	6.10	3.10
R270	599.44	124.02	62.85	25.69	13.04
R280	212.59	43.98	22.29	9.11	4.62
R290	270.89	49.15	23.60	8.91	4.26

3.3. HEC-HMS MODEL DESCRIPTION

Hydrological modeling was performed using HEC-HMS computer software. HEC-HMS, developed by the US Army Corps of Engineers, is a numerical surface – water model (computer program) that simulates watersheds, channels, and water-control structure behavior, therefore predicting flow, stage, and timing (USACE, 2008). HEC – HMS model computes rainfall losses into the soil and converts excess rainfall to runoff, and routing (Maidment & Seth, 1999). HEC HMS has three major components (the basin model component containing information related to the physical attributes of the basin, such as areas, river reach connectivity and length; the precipitation model that hold precipitation data input files and control specifications section that contains information pertinent to the timing of the model such as when a storm occurred and what type of time interval one wants to use in the model). The empirical models that define the partitioning of rainfall into infiltration and runoff are as shown in Equations (3-7), (3-8), and (3-9) (USACE, 2000):

$$Q = \left(\frac{(P-0.2S)^2}{P+0.8S)}\right) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{Equation 3-7}$$

$$I_a=0.2S \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{Equation 3-8}$$

$$S = \left(\frac{1000}{CN}\right) - 10 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{Equation 3-9}$$

Where Q= runoff (in)

P= rainfall (in)

S= potential maximum retention

I_a= initial abstraction (in)

CN= runoff curve number value (CN values between 50 and 95 are appropriate for this equation

3.4. MODEL CALIBRATION

Model calibration is a systematic process of adjusting the model parameter values until model results match acceptable with the observed data. During this process, calibrated model parameters are not allowed to change. Actually, the basin and meteorological data models were imported into HEC-HMS application, then opened HEC-HMS, and selected File; browsed to Nyabarongo_Catchment.hms file and clicked Open. The two folders for Basin and Meteorological Models were added to the Watershed Explorer in HEC-HMS application. Five files were created for precipitation data input in the meteorological folder: 10, 50, 100, 250, and 500-year precipitation met files. Background file (sub-basin111) was also added from view, backgrounds maps, selecting a sub-basin111 file. The third folder for control specification was also added. Clicked on components, control specification manager and created a 3-day simulation run (starting date: 20 April 2017, starting time: 00:00 and ending date: 23 April 2017, ending time: 00:00, time interval for the hydrograph selected was 15 minutes) for the model.

Basin model parameter values were then entered as follows

i. *Loss model*: Clicked on parameters from the main project window, Loss, and then SCS Curve Number. Initial abstraction, basin Curve Number, and imperviousness (%) parameters (Table 3-10) were entered in the displayed window. Clicked apply and closed the window.

ii. *Transform model*: Clicked on parameters from the main project window, Transform, and then SCS Unit Hydrograph. Lag time (minutes) values (Table 3-10) were entered in the displayed window. Clicked apply and closed the window.

iii. *Routing model*: Clicked on parameters from the main project window, Routing, and then Lag. Lag time parameter values for 10, 50, 100, 250, and 500-year rainfalls (Table 3-11) were entered in the displayed window. Clicked apply and closed the window.

Selected compute from the main project window menu and then created simulation runs for 10, 50, 100, 250, and 500-year floods from the run manager. Changed default names of the runs (Run 1, 2, 3, 4, and 5) to Run 1 (10-year flood), run 2 (50-year flood), run 3 (100 years), run 4 (250-year flood), and Run 5 (500-year flood), clicked next to complete all the steps and finally clicked Finish to complete creating the runs one after the other. To run the model, selected compute, select run, and then computed the 10, 50, 100, 250, and 500-year floods by clicking the compute tab.

3.5. MODEL PERFORMANCE EVALUATION

The criteria used to evaluate the performance of the model was the overall agreement between predicted and measured runoff discharges, and the model' ability to predict time and magnitude of hydrograph peaks, and runoff volume. The model performance efficiency criteria, such as coefficient of determination R^2 and Nash–Sutcliffe model efficiency E (Nash & Sutcliffe, 1970) were used to evaluate the model simulations during the calibration periods. The R^2 value indicates the correlation between the observed and simulated values and *E* measures how well the plot of the observed against the simulated flows fits the 1:1 line. The R^2 coefficient is calculated using the Equation (3-10):

$$R^2 = \frac{\sum(Q_{obs} - Q_{obs\ avg}) * (Q_{sim} - Q_{sim\ avg})}{\sqrt{\sum(Q_{obs} - Q_{obs\ avg})^2 * (Q_{sim} - Q_{sim\ avg})^2}}$$

………………………… *Equation 3-10*

Where Q_{sim} is the simulated value, Q_{obs} is the observed value, $Q_{sim\ avg}$ is the average simulated value, and $Q_{obs\ avg}$ is the average observed value. The range of values for R^2 is 1.0 (best) to 0.0 (unacceptable). The *E* value is calculated using Equation 16. If the *E* value is less than or close to 0, the model simulation is unacceptable. The highest value of E is 1.0.

$$E = 1 - \sum \frac{(Q_{obs} - Q_{sim})^2}{\sum(Q_{obs} - Q_{obs\ avg})^2}$$

……………………………*Equation 3-11*

CHAPTER 4 : RESULTS AND DISCUSSION

4.1. FLOW RESULTS ANALYSIS

The Nyabarongo Upper Catchment HEC HMS model output flow data obtained were reasonable since the model was manually calibrated based on the observation of river flows at the gauging station. The following Tables 4-1, 4-2 and 4-3 describe the maximum annual flows based on recorded data (Table 4-1), the maximum flood estimated based on regression using plotting position technique (Table 4-2) and the simulated flows based on the physical characteristics of the catchment using the model (Table 4-3) for the four different sub-basins.

Table 4-1: Maximum annual flows based on historical data

Sub-basin ID	Maximum Annual flow (m^3/sec)	Period of records (Year)	Return period (Years)
W360	273.7	1974-2010	36
W460	230.59	1971-2013	42
W500	57.31	1987-2012	25
W560	25.37	1972-2013	41

Table 4-2: Maximum flood estimated based on regression using plotting position technique for the 4 sub-basins

Sub-basin ID	Flood Discharge (m^3/sec)				
	10 Year	**50 Year**	**100 Year**	**250 Year**	**500 Year**
W360	387.50	20,150	107,500	1,000,000	5,500,000
W460	410	28,375	175,000	1,975,000	12,250,000
W500	93.75	8,325	57,500	739,250	5,100,000
W560	24.50	550	2,225	13,375	51,875

Table 4-3: Simulated Peak discharge for the 4 sub-basins

Sub-basin ID	Flood Peak Discharge (m^3/sec)				
	10 Year	**50 Year**	**100 Year**	**250 Year**	**500 Year**
W360	807.5	21,054.7	54,541.5	210,752.5	768,634.1
W460	284.5	10,628.6	39,674.2	227,467.7	836,578.0
W500	1,128.4	10,192.3	24,268.8	75,960.4	179,303.4
W560	524.9	9,291.6	28,466.1	123,408.8	378,710.8

4.1.1. LOWER SUB-BASIN (W360)

The lower sub-basin (W360) is located at the downstream part of the catchment with Muramba_Paroisse precipitation station and Nyabarongo_Outlet stream flow station. The basin covers an estimated area of 916.5 Km^2 with curve number value of 83 and surface imperviousness of 7.47%. The basin slope is 36.14%. The maximum annual flow since 1974 to 2010 is 273.7 m^3/sec but during this period there were 11 years where no record (missing data) was taken due to some circumstances especially the war happened in Rwanda since 1990 and therefore in this study, they are considered as 0.1 m^3/sec for the model calibration to avoid misreading of Logarithm invalid value of zero. Consequently, using predict function to fit a generalized regression model, the estimated maximum flood for 10, 50, 100, 250 and 500 year-flood was 376.5 m^3/sec, 20,150 m^3/sec, 107,500 m^3/sec, 1,000,000 m^3/sec and 5,500,000 m^3/sec respectively.

Subsequently, by using the hydrological model (HEC-HMS) and considering its parameters, the simulated flow in the downstream of the catchment is estimated to 807.5 m^3/sec for 10-year flood, 21,054.7 m^3/sec for 50-year flood, 54,541.5 m^3/sec for a 100-year flood, 210,752.5 m^3/sec for 250-year flood and 768,634.1 m^3/sec for a 500-year flood.

Briefly, comparing flows based on statistical curve fit and that of simulated flows, there is a flow increase for both 10-year and 50-year flood but the flow decreases for 100-year, 250-year, and a 500-year flood. All flow values are greater than the observed maximum annual flow.

4.1.2. MIDDLE SUB-BASIN (W460)

The middle sub-basin (W460) is the central part of the catchment with Rubengera_MET precipitation station and Nyabarongo_Mwaka stream flow station. The sub-basin covers an area of 909.61 Km^2 with the curve number value of 81and surface imperviousness of 7.42%. The basin slope is 26.93%. Since 1971 to 2013, the maximum annual flow observed is 230.59 m^3/sec and 14 missing data was recorded and assumed to be 0.1 m^3/sec instead of being zero for the correction purposes. Thus, the same as in the Lower sub-basin, the estimated maximum flood is 410 m^3/sec for a 10-year flood, 28,375 m^3/sec for a 50-year flood, 175,000 m^3/sec for a 100-year flood, 1,975,000 m^3/sec for a 250-year flood and 12,250,000 m^3/sec for a 500-year flood.

Afterward, the simulated flows in the central part of the catchment are 284.5 m^3/sec, 10,628.6 m^3/sec, 39,674.2 m^3/sec, 227,467.7 m^3/sec and 836,578 m^3/sec for a 10-year, 50-year, a 100-year, a 250-year and a 500-year flood respectively.

In short, contrary to the previous sub-basin, the simulated flow decreases for 10-year, 50-year, 100-year, 250-year and 500-year flood but still, they are all higher than the maximum annual flow observed from Statistical Curve Fit.

4.1.3. UPPER SUB-BASINS (W500 & W560)

The upstream part of the catchment is divided into 2 sub-basins such as right (W560) and left (W500) sub-basins depending on the altitude. The upper left sub-basin is higher in elevation compared to the upper right sub-basin. (see Table 4-2). Two precipitation stations of Rubona_Colline and Gikongoro_MET and two stream flow stations of Mwogo_Nyabisindu and Rukarara_Mudasomwa were considered for upper right and left sub-basin respectively. The basin slope is 33.49% and 25.62% for upper left and right sub-basin respectively. The maximum annual flow recorded since 1987 until 2012 is 57.31 m^3/sec for the upper left sub-basin with 12 missing data and 25.37 m^3/sec from 1972 to 2013 for the upper right sub-basin with 15 missing data that was assumed to be 0.1 m^3/sec for the model calibration. The estimated maximum flood is 93.75 m^3/sec for a 10-year flood, 8325 m^3/sec for a 50-year flood, 57,500 m^3/sec for a 100-year flood, 739,250 m^3/sec for a 250-year flood and 5,100,000 m^3/sec for a 500-year flood in the upper left sub-basin whereas 24.5 m^3/sec for a 10-year flood, 550 m^3/sec for a 50-year flood, 2,225 m^3/sec for a 100-year flood, 13,375 m^3/sec for a 250-year flood and 51,875 m^3/sec for a 500-year flood in the upper left sub-basin.

Then, the simulated flows in the upstream part of the catchment are 1,128.4 m^3/sec, 10,192.3 m^3/sec, 24,268.8 m^3/sec, 75,960.4 m^3/sec and 179,303.4 m^3/sec for a 10-year, 50-year, 100-year, 250-year and 500-year flood respectively for the upper left sub-basin while in the upper right sub-basin the simulated flows are 524.9 m^3/sec for a 10-year flood, 9,291.6 m^3/sec for a 50-year flood, 28,466.1 m^3/sec for a 100-year flood, 123,408.8 m^3/sec for a 250-year flood and 378,710.8 m^3/sec for a 500-year flood.

Briefly, the simulated flows increase for 10-year and 50-year flood, and decrease for 100-year, 250-year and 500-year flood in the upper left sub-basin, although the increase in the upper right sub-basin for 10-year, 50-year, 100-year, 250-year and a 500-year flood.

4.2. FLOOD LEVELS AND FREQUENCY

4.2.1. A 10-Year Flood

The Figure (4-1) below shows a 10-year flood levels distribution for the whole Nyabarrongo Upper catchment.

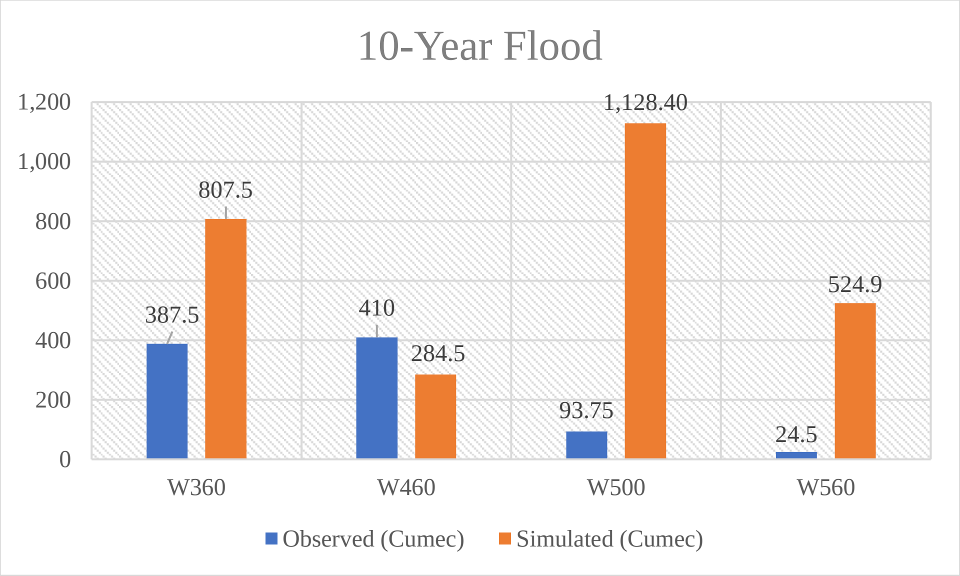

Figure 4-1: A 10-year flood Peak discharge for Nyabarongo Upper catchment

The upper left sub-basin (W500) has high magnitude of flood level of 1,128.4 m^3/sec contributing to the whole catchment followed by the lower sub-basin (W360) of 807.5 m^3/sec, then the upper right sub-basin (W560) of 524.9 m^3/sec and the middle sub-basin (W460) of 284.5 m^3/sec consecutively donating to the entire catchment.

4.2.2. A 50-Year Flood

The Figure (4-2) below demonstrates a 50-Year Flood Peak discharge for Lower, Middle, and Upper part of the catchment.

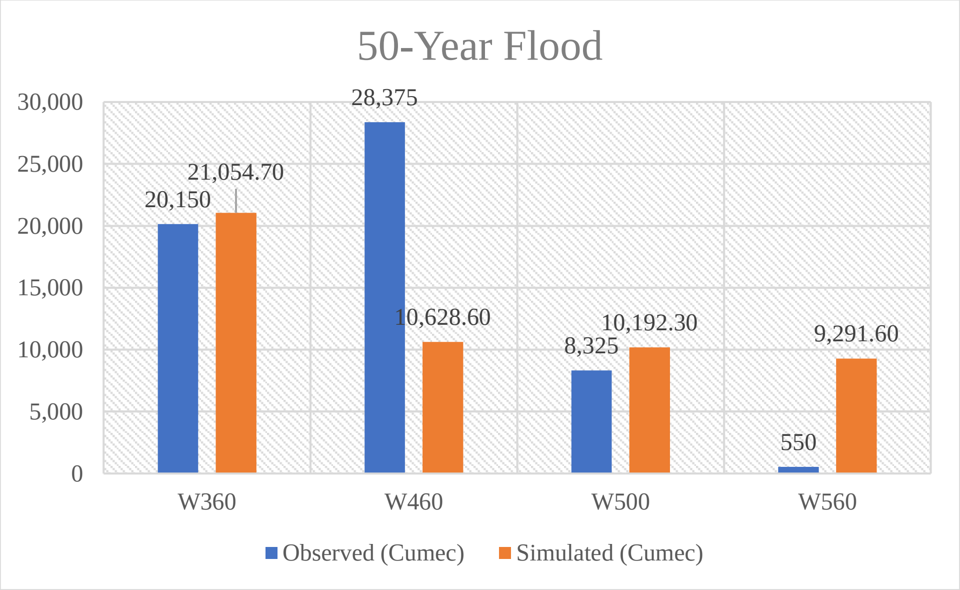

Figure 4-2: A 50-year flood Peak discharge for Nyabarongo Upper catchment

The downstream part (W360) of the catchment contributes high magnitude of flood level of 21,054.7 m^3/sec in the entire catchment followed by the central part (W460) of 10,628.6 m^3/sec, and then upstream part where the upper left sub-basin (W500) contributes 10,192.3 m^3/sec followed by the upper right sub-basin (W560) with 9,291.6 m^3/sec. This shows that the lower sub-basin (W360) is a receiving part of the whole catchment.

4.2.3. A 100-Year Flood

The following Figure (4-3) shows the magnitude of a 100-Year flood that occurs in the 4 sub-basins of the entire catchment.

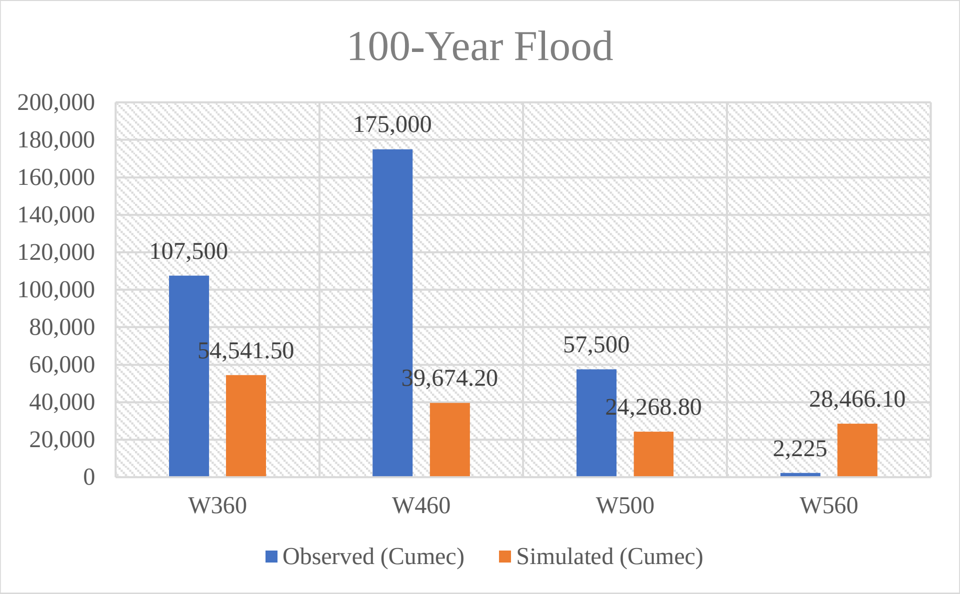

Figure 4-3: A 100-year flood Peak discharge for Nyabarongo Upper catchment

The above figure shows that the downstream part of the catchment (W360) contributes much more flood level of 54,541.5 m^3/sec compared to other 3 sub-basins. Therefore, the middle (W460), upper right (W560) and upper left (W500) sub-basins each contributes the flood magnitude of 39,674.2 m^3/sec, 28,466.1 m^3/sec, and 24,268.8 m^3/sec respectively in the entire catchment.

4.2.4. A 250-Year Flood

The Figure (4-4) below shows the extent of 250-Year flood levels for the Nyabarongo upper catchment.

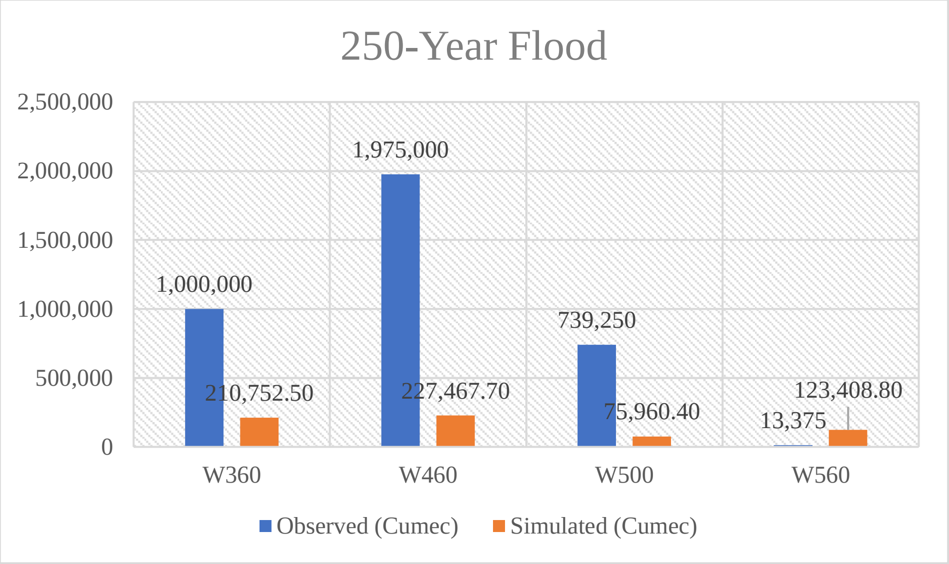

Figure 4-4: A 250-year flood Peak discharge for Nyabarongo Upper catchment

As it is shown in the figure above, the central part (W460) and the downstream part (W360) of the catchment are almost contributing the same flood magnitude in the entire catchment such that W460 has 227,467.7 m^3/sec and W360 with 210,752.5 m^3/sec. The upstream of the catchment contributes 123,408.8 m^3/sec of flood magnitude for the right part (W560) and 75,960.4 m^3/sec of flood level for the left part (W500) of the upstream part.

4.2.5. A 500-Year Flood

The Figure (4-5) below demonstrates the extent of a 500-Year flood magnitude for the Nyabarongo Upper catchment.

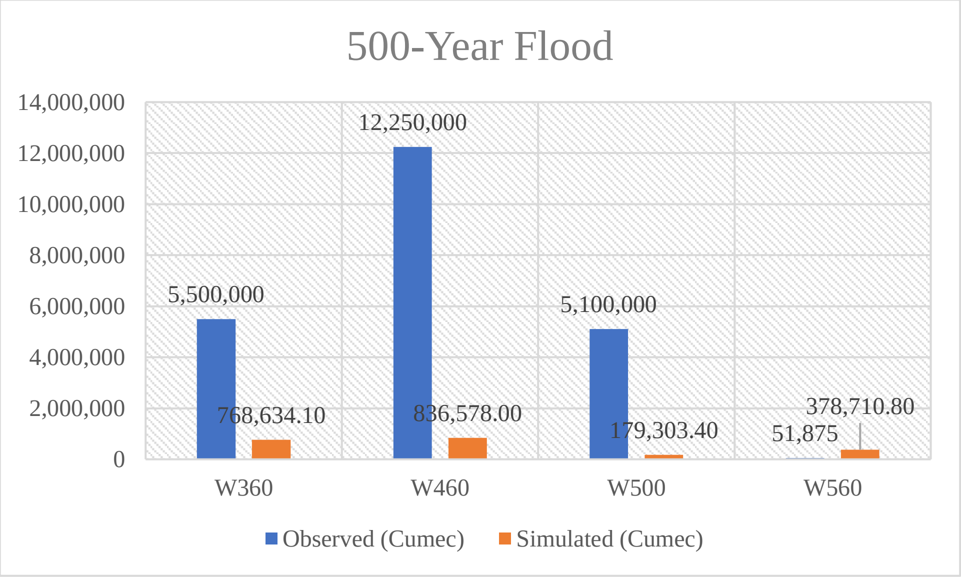

Figure 4-5: A 500-year flood Peak discharge for Nyabarongo Upper catchment

The central part (W460) and downstream part (W360) of the catchment have the highest flood magnitude of 836,578 m^3/sec and 768,634.1 m^3/sec respectively. Besides, the upstream of the catchment contributes the flood magnitude that is equivalent to 378,710.8 m^3/sec for the upper right sub-basin (W560) and 179,303.4 m^3/sec for the upper left sub-basin (W500).

Generally, a 250-Year and 500-Year flood have the same characteristics and behavior for the flood levels distribution in the entire catchment. Nevertheless, a 10-Year, 50-Year, and 100-Year flood behave differently.

4.3. PROPOSED MITIGATION AND ADAPTIVE MANAGEMENT STRATEGY

As it is discussed previously, there is a high probability of experiencing the high magnitude of the flood that can cause inundation in the Nyabarongo Upper catchment as the rainfall increases or fluctuations in climate variability as well as deficiency in land use management and land cover protection. In addition, there is mismanagement of precipitation stations and lack of historical data. Furthermore, there is the absence of studies on Flooding in the Nyabarongo Upper catchment itself but the same studies are being conducted in the other part of Rwanda and show that Rwanda is currently facing this issue.

The following best practices for mitigation and adaptation management should be taken into consideration for a proper management of the Nyabarongo Upper catchment to avoid inundation in the catchment area.

4.3.1. Integrated river basin approach

A. River basin approach

Experience has shown that effective measures for flood prevention and protection have to be taken to the level of river basins and that it is necessary to take into account interdependence and interaction of effects of individual measures implemented along water courses. Therefore, it is absolutely necessary to organize the water management systems and improve forecasting, flood defense measures and crisis management on a river basin basis, cutting across regional boundaries and country borders. This will be done in cooperation with the relevant organizations in the fields of hydrology and meteorology, mitigation planning, river control, civil protection and crisis management units.

B. Integrated approach

For flood prevention, protection and mitigation, a good combination of structural measures, preventive measures and operative measures during flood events are necessary. In some cases, even relocation of extremely endangered activities and buildings may be advisable. Development of preliminary flood protection strategy should include respectively evaluation of associated costs, technical feasibility assessment, environmental impact assessment, social acceptability and thus in a sustainable way by taking a river basin integrated and long-term view, probably of the order of 50 or 100 years.

Moreover, the reduction of flood risks has to be based on the principles of solidarity and precaution by not passing on water management problems and not passing on administrative responsibilities.

There is a need for interdisciplinary cooperation at all local levels for a coordination of sectoral policies regarding environmental protection, physical planning, land use planning, agriculture, transport and urban development, and a coordination regarding all phases of risk management. Therefore, a holistic approach is necessary throughout the river basin.

This would contribute to the implementation of a holistic approach with increased knowledge about responsibility, function, and capacity of the concerned parties, better understanding, and a better support for decision making.

C. Integrated and comprehensive action plan

All envisaged measures concerning flood prevention and protection should be compiled in a comprehensive action plan covering up to several decades. An integrated action plan for reducing flood damage must:

i. Draw long-term conclusions for preventive action in water management, land use, settlement policy, and finance,

ii. Define the scope of responsibilities in the flood protection system at levels of the government and local administration, responsibilities of public (individuals) and business companies.

iii. Such a plan is a tool which:

   a. ensures permanent and integrated planning of functions and use of the river basin,

b. specifies principles for its organization and coordinates investment activities and other activities affecting the river basin. It should also form conditions for ensuring the permanent harmony of all natural and cultural functions in the basin.

An effective cooperation between local authorities, the communities, water regulation enterprises and other interested parties, for instance by creating a local water commission, is more than needed for a regional coordination and the implementation of a holistic approach.

D. International and transboundary cooperation

Strengthening international cooperation aiming at securing a sustainable future for the river basin, especially in terms of shared approaches to river basin management, preparation of risk analyses and flood forecasts at transnational level, improving the coordination of the existing forms of assistance, sustainable use of biodiversity, is one of the components of an anticipatory approach.

The objective of an international cooperation is to develop joint documents specifying strategies and action programs aimed at improving protection against floods.

4.3.2. Public awareness and Public participation

A. Public awareness

It is the personal responsibility of anyone who lives and works by or on the river, and broader in the potential flooded area, to adapt his use of the water and all activities to flood risks. So, everyone must know the risk and take it into account appropriately when acting.

Problems associated with floods are often not sufficiently recognized and acknowledged. A communication plan to offer individuals an understanding of the nature and scope of these risks should be developed. Regional and municipal authorities will see to its continued and permanent implementation at the regional and local level in order to involve owners and administrators of properties, including organisations at levels of regions, districts, municipalities or individuals, and enable them to take preventive and protective actions by themselves and offer their opinions about the implementation of preventive measures for reduction of flood damages.

All measures linked to public information and awareness raising are most effective when they involve participation at all levels. Public participation in decision-making is a cornerstone of successful implementation of integrated and comprehensive action plans, both to improve the quality and the implementation of the decisions and to give the public the opportunity to express its concerns and to enable authorities to take due account of such concerns.

B. Public participation

The authorities should ensure that the information concerning flood prevention and protection plans is transparent and easily accessible to the public. This can achieve by:

i. Flood hazard maps point out areas at risk and are necessary for planning. Maps must be easily readable and show the different hazard levels. They are necessary for the coordination of different actions. They are a planning tool and ascertain that all actors have the same information on the spatial extent of a certain hazard. Flood maps should be used for the reduction of damage potential by integrating its outputs into spatial planning and emergency planning. Both types of utilization require that the flood hazard/zoning/risk maps should include the worst-case scenario as well.

ii. Information based on Geographic Information Systems (GIS) should be widely diffused and explained.

iii. Information and education must keep alive flood awareness. Flood marks placed in the communities and landscape remind the public of the danger and helpful for those not used to read maps. Citizens 'information desks, risk education in schools, flood marks on buildings and signs are also proved to be very helpful in many cases.

iv. The information should be disseminated early and actively, not just on request and be accompanied by the envisaged procedures for public participation

Moreover, the public should become aware that there is a need to adapt or even restrict uses, such as for industrial, agricultural, tourist or private purposes, in areas at risk of flooding to reduce the potential for damage. It will be essential to outline the likelihood of flooding and possible weak links in each flood protection measure and therefore increase the awareness of persons potentially at risk. Information about special measures required and restrictions on construction in flood areas should be easily accessible and easily understood. Competent authorities should, therefore, provide information on natural risks to be used in the context of real estate transactions, whether for sales or rentals.

Furthermore, the public should be encouraged to take their own flood prevention measures and be informed about how to act during flood events to protect oneself and one’s belongings. Practical guides for private individuals and municipalities should be published and disseminated on how to behave in that way. Moreover, in areas that are particularly threatened by flooding, a specific preparedness to alert, rescue and safety measures should be planned and implemented at all levels by maintaining regular basis and continuous ongoing training actions and a constant information strategy. This requires also that forecasts and related information are easily accessible and that real-time media coverage is ensured.

4.3.3. Land Use, Zoning, and risk assessment

In Nature, there is no flood damage. Floods only lead to damage when used by human beings are detrimentally affected. The more intensively and the less suitable the flood basin is used, the greater the potential for damage and then the actual damage when the flood occurs.

In addition, the water management policy must concentrate towards attaining an equilibrium stage between economic development and urbanization on the one hand and the needs to allocate more space to water for flow retardation and water retention on the other hand space that must be earmarked now. The exigencies of flood prevention must become one of the guiding principles in spatial planning.

A. Risk assessment means

Improve knowledge concerning extent and evolution of floods and water related problems, simulate different high-water incidences, study and compare zoning scenarios, and integrate this risk assessment, via identification and mapping of hazards and high-risk areas into land-use, emergency and rescue planning policies. At the same time, this would allow assessing effectiveness, thus priority of the flood protection measures along the whole longitudinal profile of a river, in view of informing the frontage population of the potential risks including remaining risks that occur, for example, as a result of a dam break, ice-jams or dyke break.

B. Preventive land use means

When identifying and designating areas prone to flooding, it should be borne in mind that they may require multi purpose and/or cross-sectoral action such as flood protection, nature conservation, and protection, protection of specific habitats and protection of sources of drinking-water supply. It is, therefore, necessary to consider everything that is in need of protection.

In addition, immediate flood plains should be identified and designated by law as priority sites for flood retention or to restore, as far as reasonable, mobility to waterways. The purpose is to discourage protective bank construction, embankments, impoundment and undermining, constructions or installations and, in general, any construction or works likely form an obstacle to the natural flow of waterways that cannot be justified by the protection of densely populated areas.

Also, stopping building development in the immediate areas at risk of floods, landslides or dam failures if an unacceptable risk to human lives or material damage exists, should be regulated. Exceptions should be restricted to those uses which are of stringent necessity. Adapting uses to the hazards in the potential flood plains in order to minimise the damage potential. Monitoring the building development in these areas and publishing the results in comparison with the former situation should be realized regularly.

Moreover, major installations, works, construction work and hazardous or hazard-prone activities and uses in designated areas should be subject to administrative permits or authorizations. Adaptation requirements, restrictions, and prohibitions should be based on among others risk assessments. Moreover, incorporation of an activity may not impede the retention, storage or drainage of water in the catchment area and should be guided by the underlying principle that water-related problems may not be passed downstream or from one part of the river basin to another.

Furthermore, vulnerability diagnoses should be generalised to existing industrial and commercial companies, real estate development managers, drinking water production or water treatment facilities, farms, etc located in flood-prone areas in order to assess the consequences of high water incidences and to propose measures enabling their reduction, produce flood emergency plans and develop the preparedness to the risk by training exercises.

Additionally, the most sensitive establishments, such as buildings, facilities, and installations whose operation is fundamental to civil safety, defense or maintaining public order, or whose failure presents a high risk to humans or presenting the same risks due to their socio-economic importance, must be implemented on the nearest no-risk-prone areas. Only activities that are inextricably tied to the water management system or cannot be implemented else-where for reasons of important societal interest should be permitted.

If, after an integrated assessment, a decision is made that has adverse consequences for (future) safety or exacerbates water-related problems, the measures that are required to keep the water management system in working order and offset the adverse effect of the measure under examination must be identified. The costs of these measures will in principle be borne by the initiator of the proposed activity.

As well, existing constructions at risk of flooding should be made flood compatible for all water-related problems. In many cases construction and reactive measures, with economic justification, can contribute more to damage reduction than all the natural water retention measures and technical flood protection together. In potential flood plains, the forward planning and approval stages of further construction work should take account of new and relative construction methods that incorporate the need to maintain space for water and address water-related problems. Thus, could finally lead to establishing mandatory construction standards for flood risk area.

Finally, Identify and reduce the vulnerability of existing infrastructures and all networks located in flood-prone areas (water supplies, energy systems, transportation and communication networks, public facilities, etc), and particularly transport network which may suffer massive interruptions or hinder the evacuation and the arrival of emergency services.

4.3.4. Early warning and forecast system

The possibility of climate change in decades to come further emphasizes the need for early warning and flood forecasting particularly in flood plain areas at immediate and high risk. Then, flood forecasting can be effectively combined with other measures for flood prevention such as retention, land use and structural Measures, flood emergency and public awareness.

Moreover, traditional measuring instruments such as rain gauges should play a fundamental role as far as possible. Broader information provided by innovative technologies, such as radar and numerical weather forecasts, will become more accessible. The traditional and the new technologies should coexist in an efficient manner and be used for mutual data verification and comparison. In addition, use historical information and experience to the maximum potential. Doing so can save lives, face, and resources.

Furthermore, a timely and reliable flood warning and forecasting system, depending upon consistent hydro-meteorological basins rather than on sectors, is one of the basic conditions for an improvement of the protection against floods. Therefore, an effective early warning and forecasting system for extending the reaction time should be supported by meteorological information and the earliest possible warning of extreme weather conditions.

Additionally, teams of forecasters should be, where possible, composed of meteorologists, hydrologists, hydraulicians and even crisis managers, capable of providing 24-hour a day, 365-day a year monitoring and forecasting. Thus, a compatible meteorological and hydrological information system and database, if possible with a fully automated data communication system, should be created for the entire river basin. However, experience shows that there is a need for redundancy in measuring and communications systems, particularly because of the adverse conditions encountered just during the most extreme events.

Flood forecasting models should also be worked out, verified and adopted and, if appropriate, harmonized by riparian countries, introduced and regularly improved for the catchment area of the main watercourse and its most important tributaries. That means particularly to harmonize the technical procedures for the hydrological and meteorological forecast, the procedure of use, store and exchange data between neighboring countries. And an effective and reliable system of flood forecasting and warning dissemination should be set up to inform, at respective level, flood authorities and citizens in threatened areas.

CHAPTER 5 : CONCLUSION AND RECOMMENDATIONS

This chapter describes the conclusion of this research. It concludes with the results and discussions and states the main contribution of this research by relating the findings to the research objectives. Finally, the recommendations and further research are given based on the discussion and findings of this research.

5.1. CONCLUSION

In this study, ArcGIS 10.2.1 with HEC-GeoHMS 10.2 extension and HEC-HMS 4.2 were applied to Nyabarongo Upper Catchment, and HEC-HMS model parameters for precipitation (frequency storm method), Loss (SCS Curve Number method) and Transform (SCS Unit Hydrograph method) were calibrated using the observed stream flows. The model performed reasonably well over the calibration period by reproducing the observed flow volumes and simulating the observed peaks in terms of timing and quantity.

Initially, the maximum annual flow for the lower, middle, and both upper left and right sub-basin in the Nyabarongo Upper catchment was 273.7 m^3/sec, 230.59 m^3/sec, 57.31 m^3/sec and 25.37 m^3/sec respectively and these were classified according to the spatial and temporal of precipitation and stream flow stations. Digital Elevation Model of 30x30m was used in hydrological modeling, and soil type and land use/cover to produce the curve number values for four sub-basins.

The HEC-HMS model was applied to four sub-basins and the model results were compared with Maximum flood estimated based on regression using plotting position technique and Maximum annual flows based on historical data for each sub-basin respectively; however, the model was not validated in a classical way due to the lack of reliable data. This is not a classical model validation; however, it provided further understandings into the model behavior and the model performance.

Therefore, depending on the performance of the HEC-HMS model, this study concluded that the plan works effectively in the Nyabarogo Upper catchment then requires being flexible in the framework’s structure for simulating the peak flows that predict flooding events in the coming years. In summary, the flexible models should probably work better in predicting flooding and providing the maps the flood prone-areas.

From the analysis made it is concluded that the flood magnitude of 807.5 m^3/sec for 10-year flood, 21,054.7 m^3/sec for 50-year flood, 54,541.5 m^3/sec for a 100-year flood, 210,752.5

m^3/sec for a 250-year flood, and 768,634.1 m^3/sec for 500-year flood resulted in the downstream of Nyabarongo Upper catchment. In addition, 284.5 m^3/sec for 10-year flood, 10,628.6 m^3/sec for 50-year flood, 39,674.2 m^3/sec for 100-year flood, 227,467.7 m^3/sec for 250-year flood, and 836,578 m^3/sec for 500-year flood were resulted in the middle area of the catchment. Moreover, 1,128.4 m^3/sec for 10-year flood, 10,192.3 m^3/sec for 50-year flood, 24,268.8 m^3/sec for 100-year flood, 75,960.4 m^3/sec for 250-year flood, and 179,303.4 m^3/sec for 500-year flood were resulted in the upper left part of the catchment. Furthermore, 524.9 m^3/sec for 10-year flood, 9,291.6 m^3/sec for 50-year flood, 28,466.1 m^3/sec for a 100-year flood, 123,408.8 m^3/sec for a 250-year flood, and 378,710.8 m^3/sec for 500-year flood resulted in the upper right part of the catchment.

Consequently, the integrated river basin approach, public awareness and public participation, land use, zoning and risk assessment along with early warning and forecast system were proposed as the best practices for the mitigation and adaptive management strategy for Nyabarongo Upper catchment.

5.2. RECOMMENDATIONS

In order to assess clearly the flood risk under current and future climate scenarios in the Nyabarongo upper catchment, this study recommends further study on establishing the expected flood risks (vulnerability and risks) and flood hazard potential (flood frequency and flood levels) by means of models that are able for River Analysis for instance HEC-RAS as it is discussed in chapter two. The study also recommends that Meteorological records for long period should be kept and filed safely to allow researchers doing their researches.

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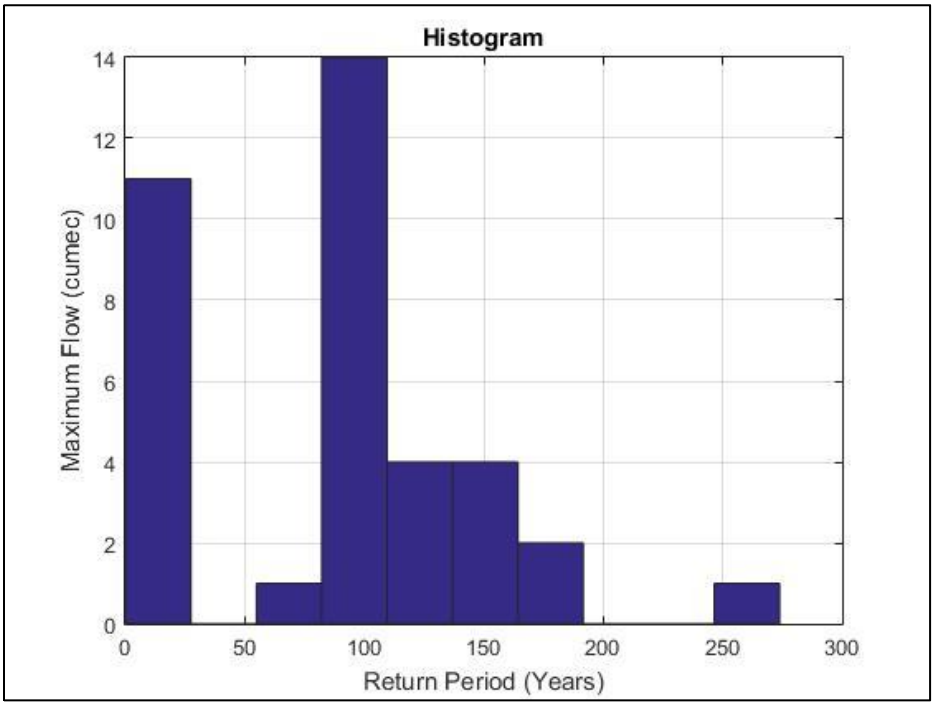
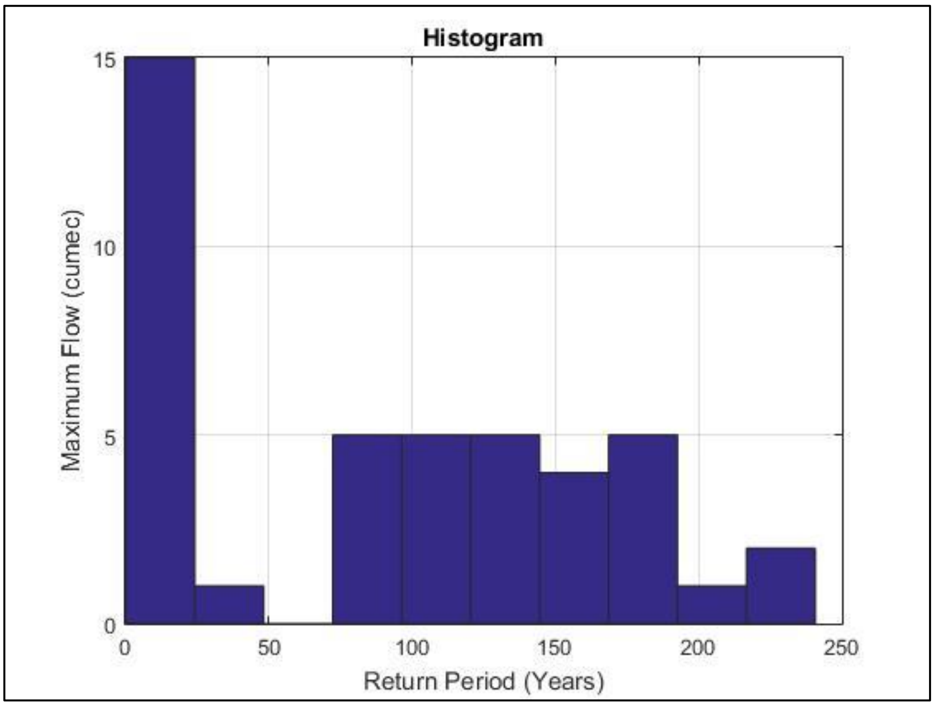
APPENDICES

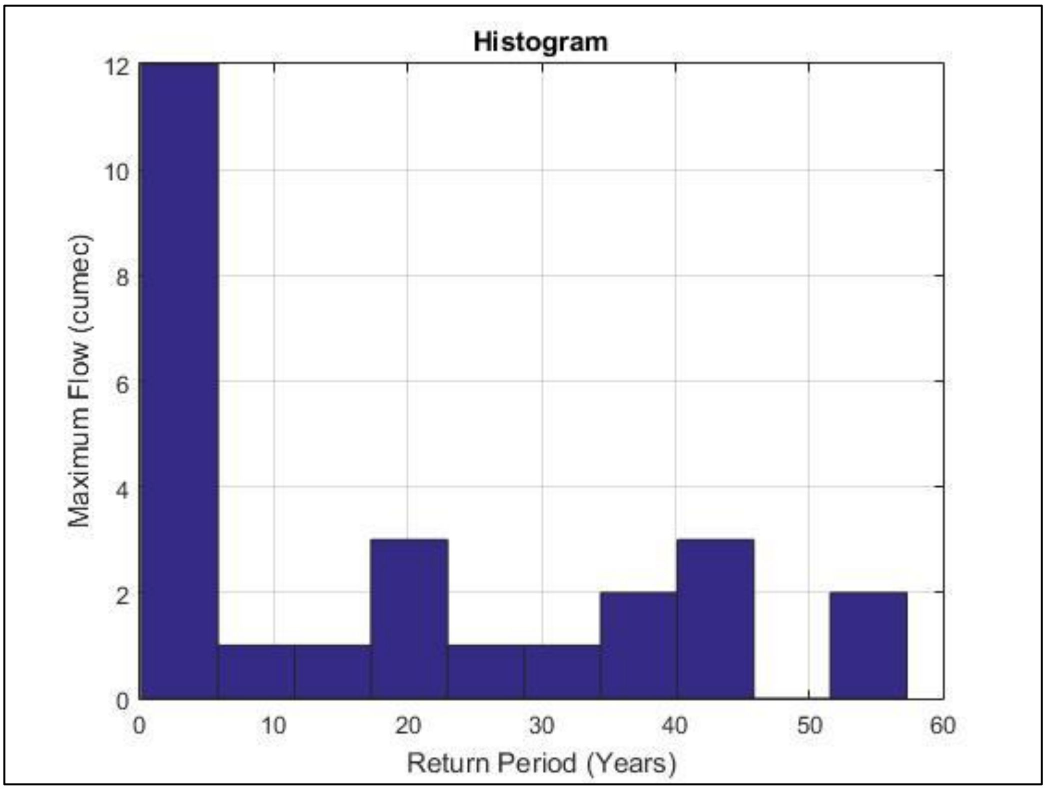
ANNEX 1: HISTOGRAM FOR BOTH USED STREAM FLOW AND PRECIPITATION STATIONS



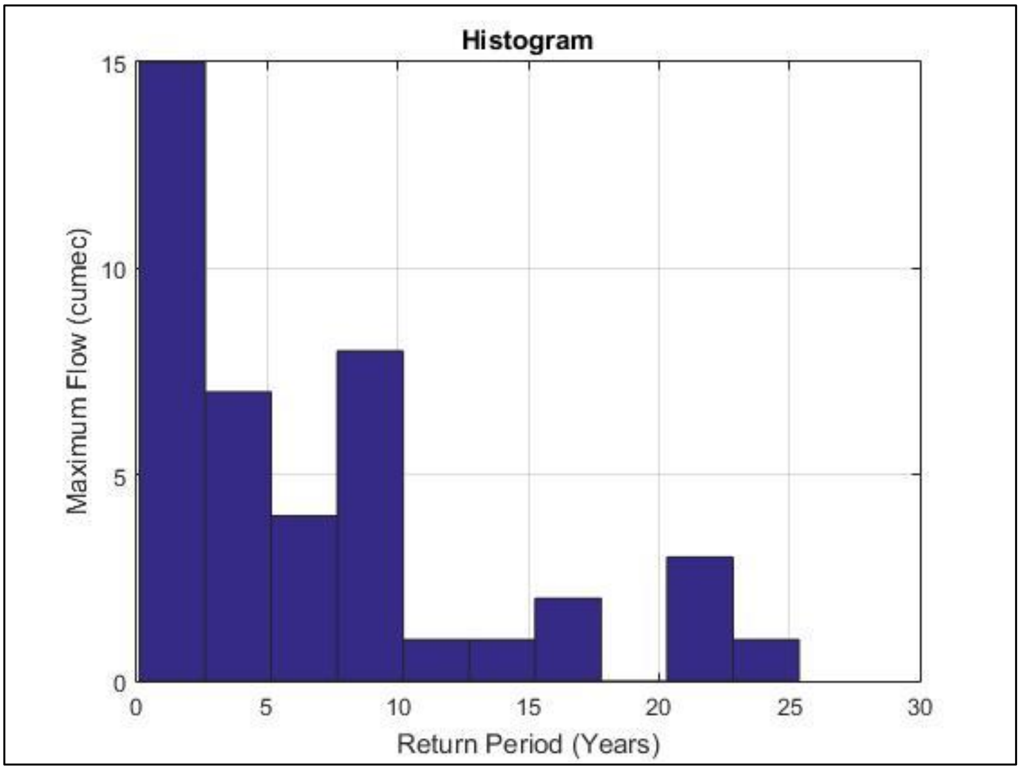
Histogram for Nyabarongo_Outlet streamflow station (W360)



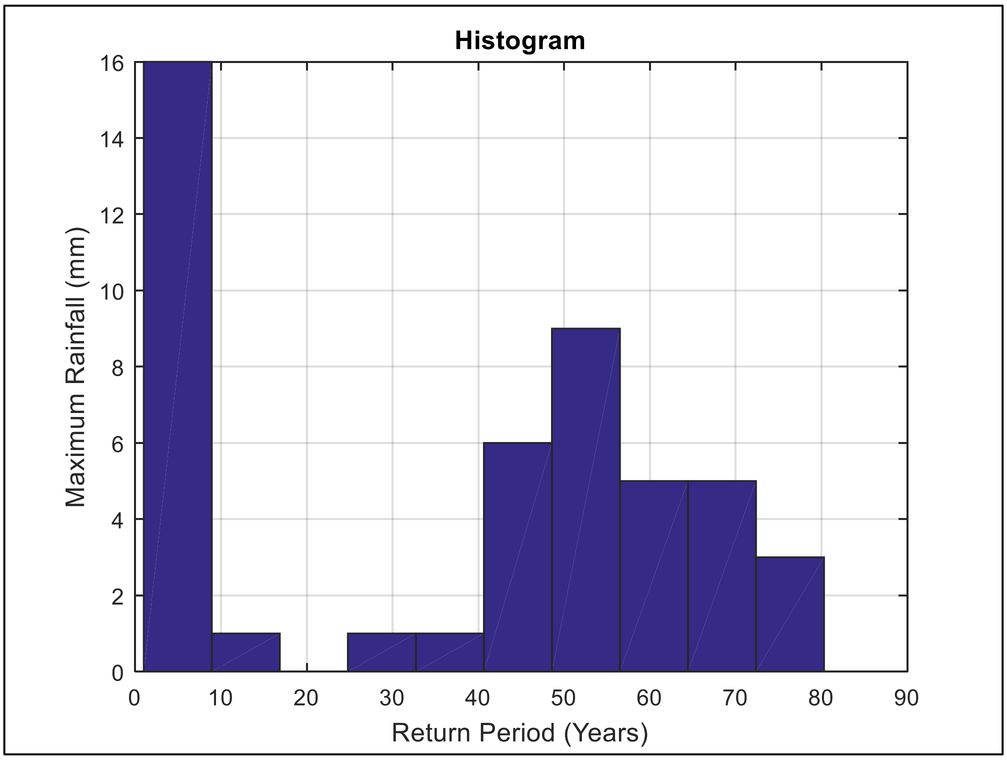
Histogram for Nyabarongo_Mwaka streamflow station (W460)



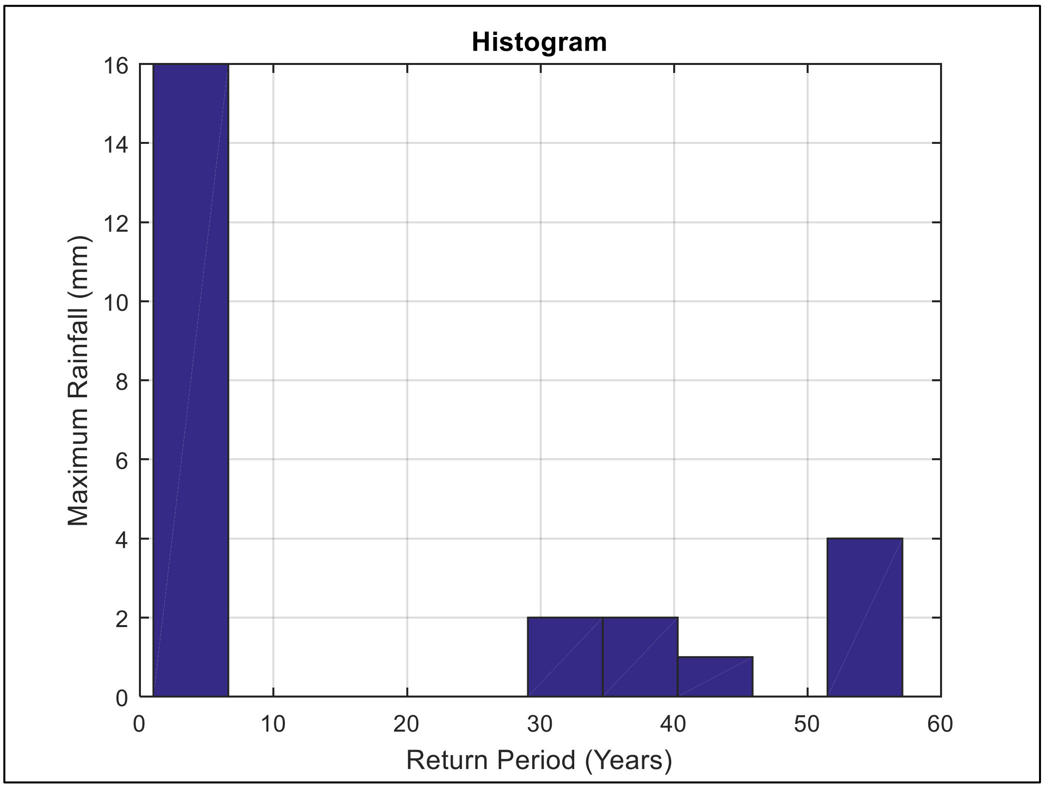
Histogram for Rukarara_Mudasomwa streamflow station (W500)



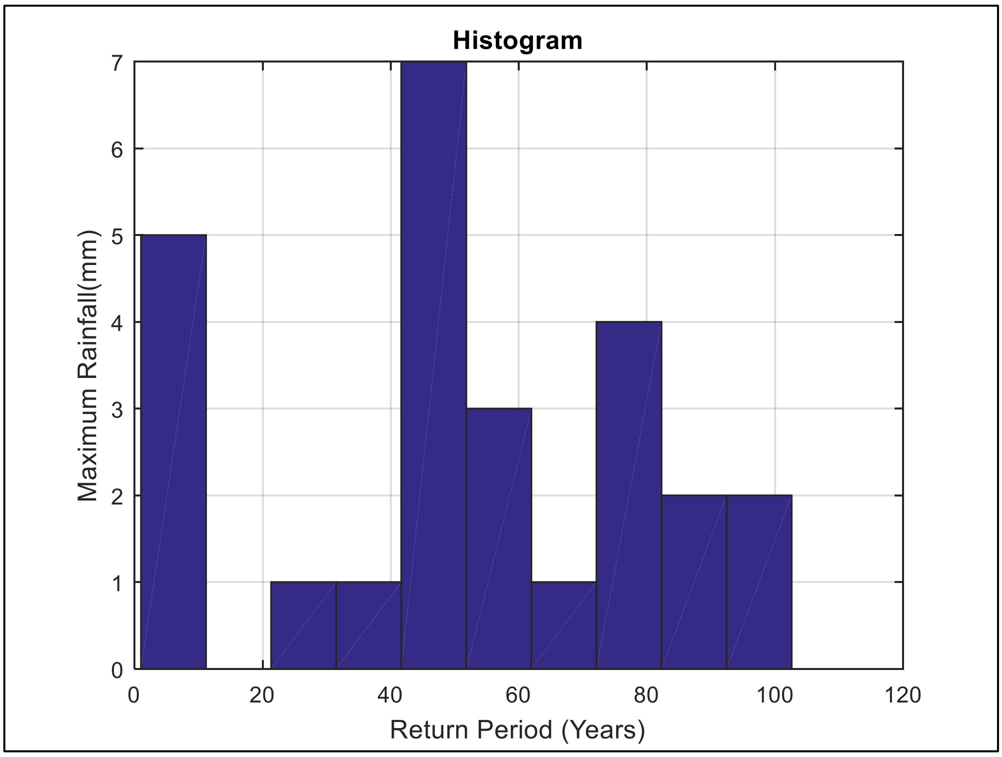
Histogram for Mwogo_Nyabisindu streamflow station (W560)



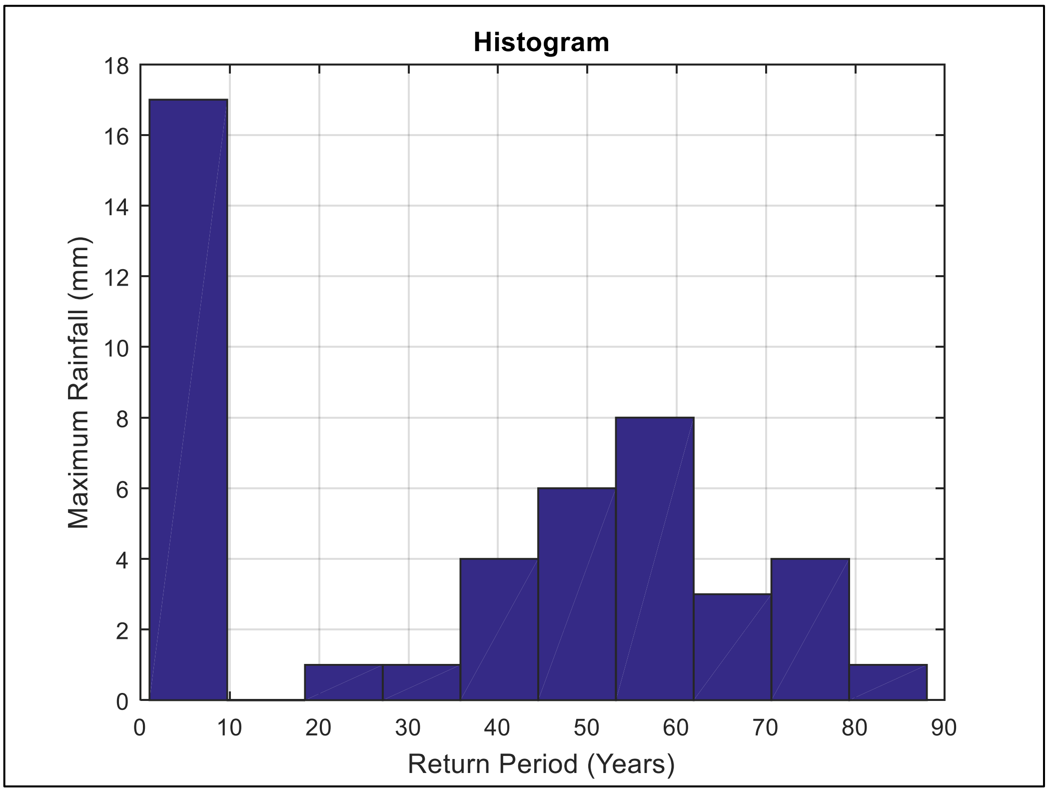
Histogram for Muramba_Paroisse precipitation station (W360)



Histogram for Rubengera_MET precipitation station (W460)

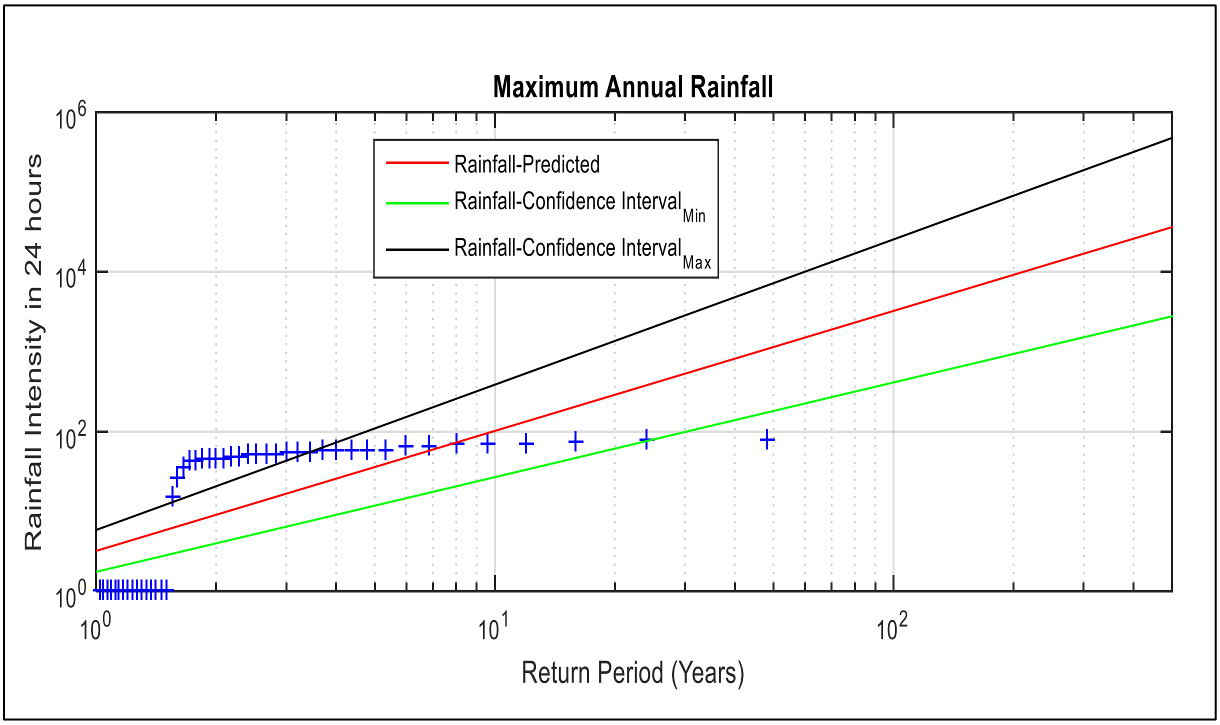


Histogram for Gikongoro_MET precipitation station (W500)

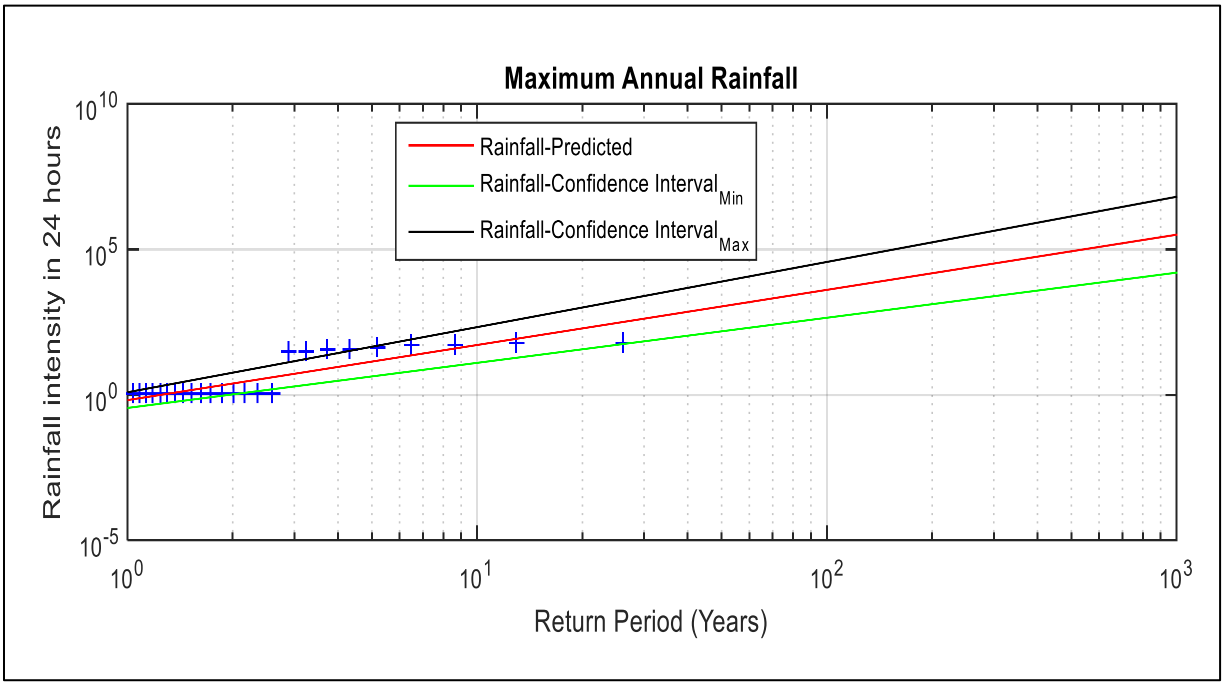


Histogram for Rubona_Colline precipitation station (W560)

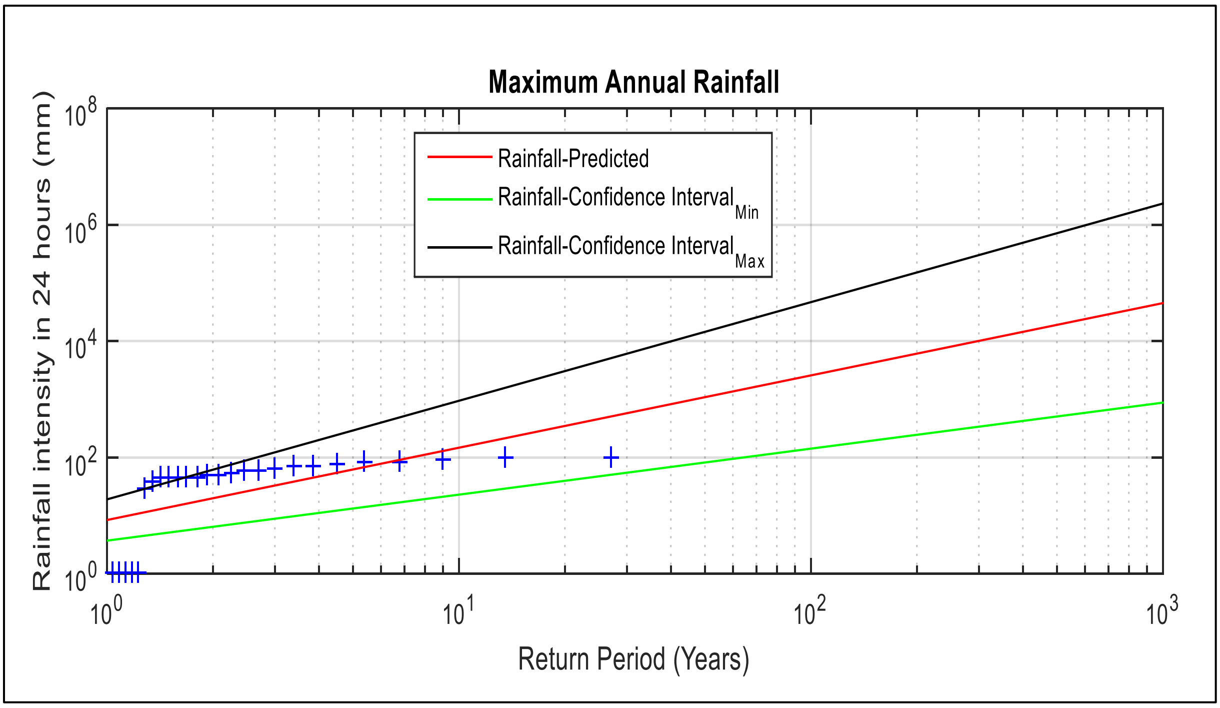
ANNEX 2: MAXIMUM ANNUAL RAINFALL PLOT FOR PRECIPITATION STATIONS



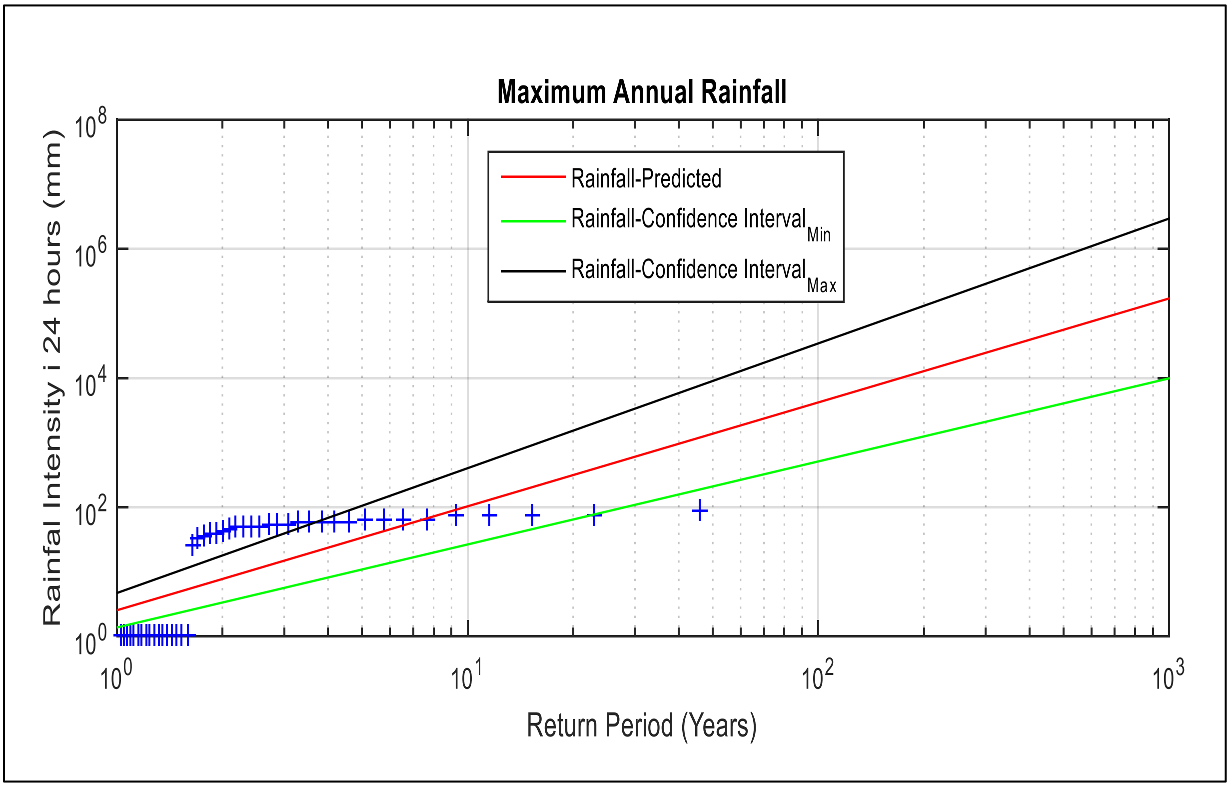
Maximum annual rainfall for Muramba_Paroisse precipitation station (W360)



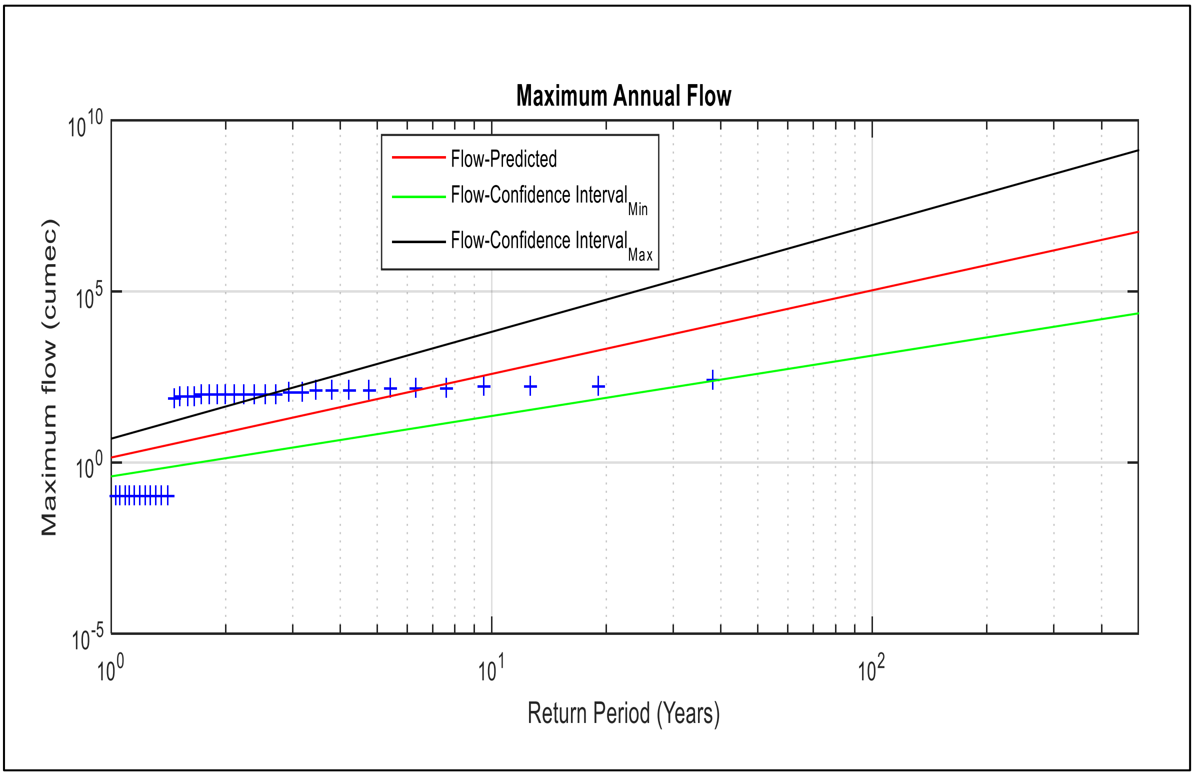
Maximum annual rainfall for Rubengera_MET precipitation station (W460)



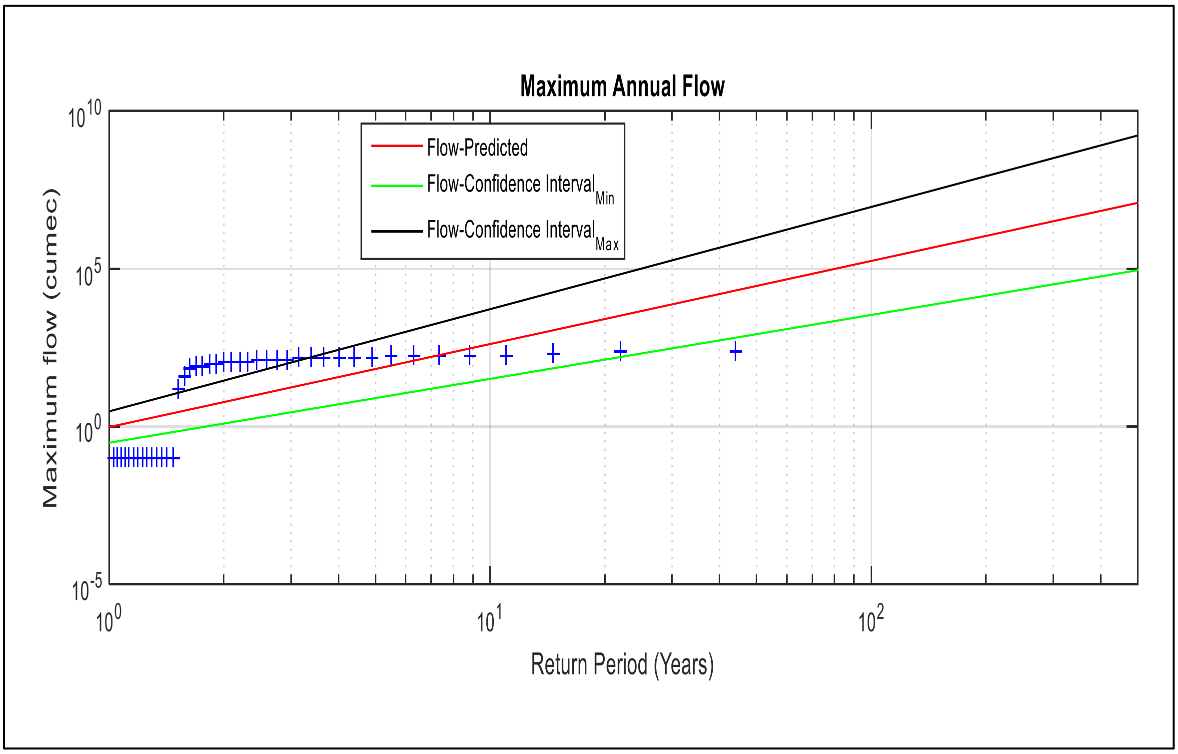
Maximum annual rainfall for Gikongora_MET precipitation station (W500)



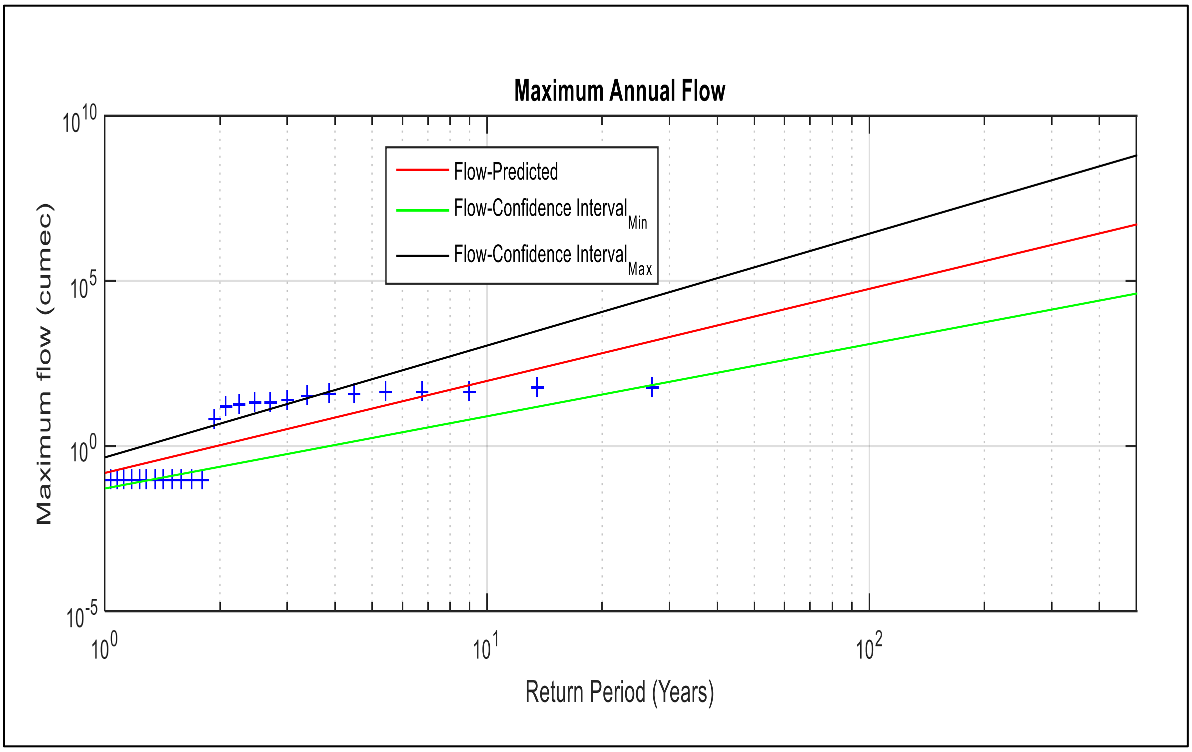
Maximum annual rainfall for Rubona_Colline precipitation station (W560)



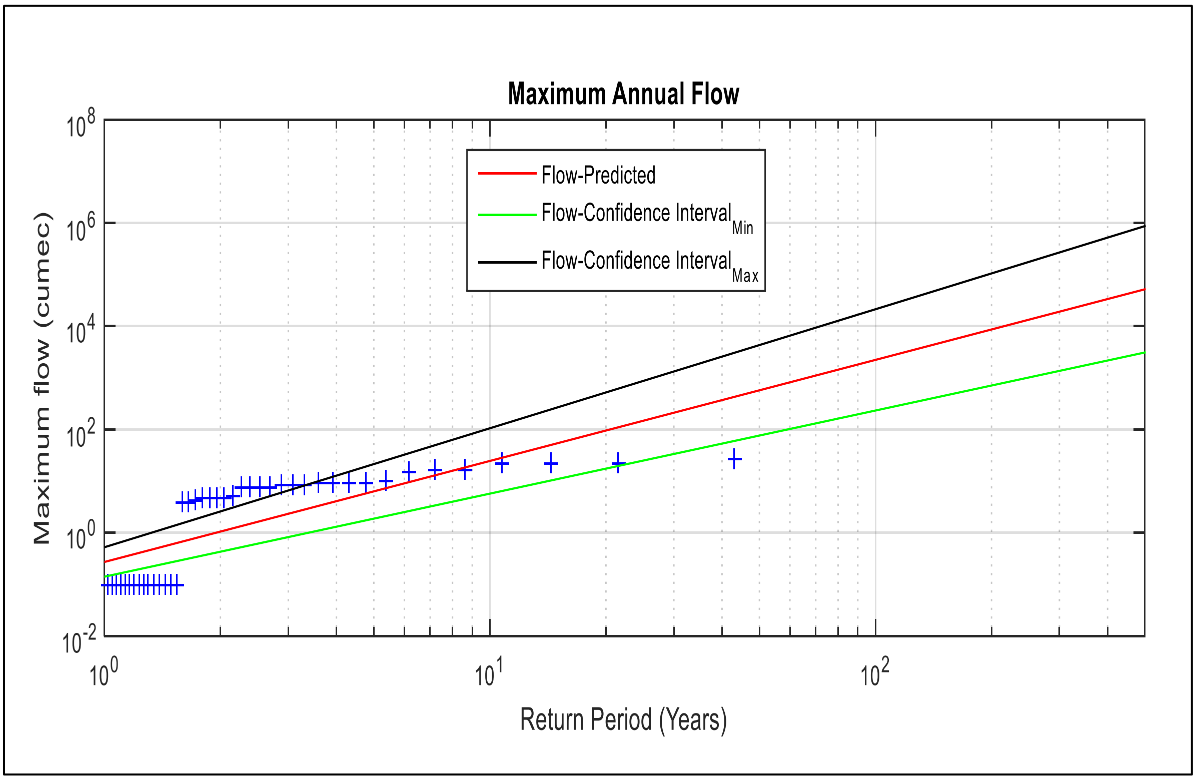
Maximum annual Flow for Nyabarongo_Outlet precipitation station (W360)



Maximum annual Flow for Nyabarongo_Mwaka precipitation station (W460)

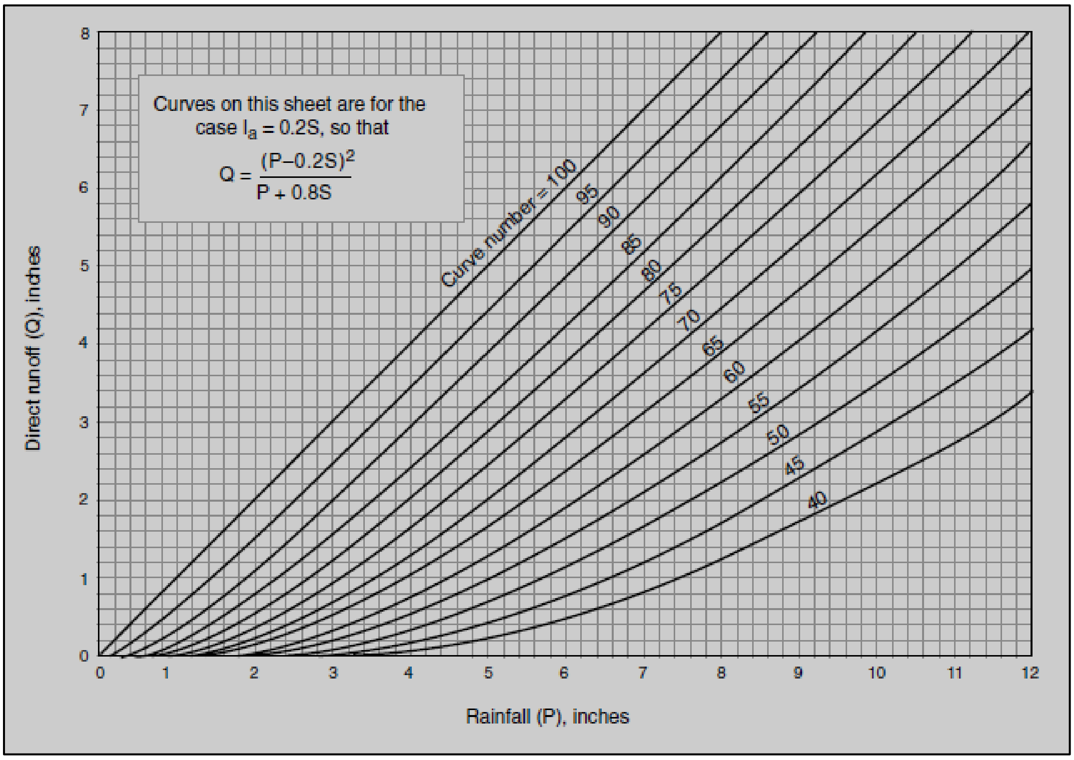


Maximum annual Flow for Rukarara_Mudasomwa precipitation station (W500)



Maximum annual Flow for Mwogo_Nyabisindu precipitation station (W560)

ANNEX 3. CURVE NUMBER DETERMINATION



Solution of runoff equation (TR-55, 1986)

Revised classification with the original 2001 NLCD classes *(Graham & Congalton, 2009)*

Original NLCD classification		**Revised classification (re-classification)**	
Number	*Description*	*Number*	*Description*
11	Open water	1	Water
90	Woody wetlands		
95	Emergent herbaceous wetlands		
21	Developed, open space	2	Medium Residential
22	Developed, low intensity		
23	Developed, medium intensity		
24	Developed, high intensity		
41	Deciduous forest	3	Forest
42	Evergreen forest		
43	Mixed forest		
31	Barren land	4	Agricultural
52	Shrub/scub		
71	Grassland/herbaceous		
81	Pasture/hay		
82	Cultivated crops		

TR-55 Runoff Curve Numbers for Urban areas (TR-55, 1986)

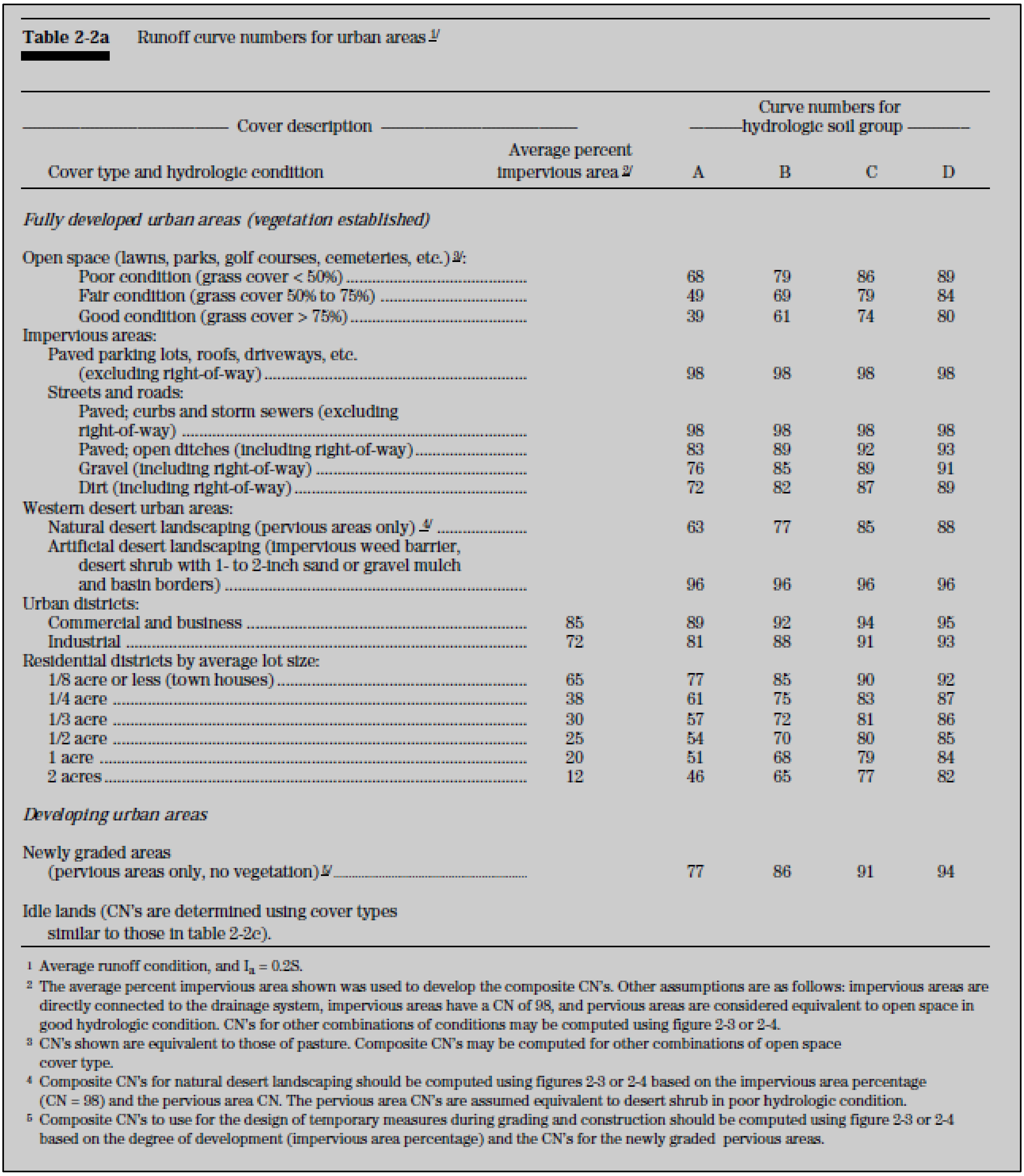


Table 2-2a Runoff curve numbers for urban areas [1]

Cover description		Curve numbers for hydrologic soil group			
Cover type and hydrologic condition	Average percent impervious area [2]	A	B	C	D
Fully developed urban areas (vegetation established)					
Open space (lawns, parks, golf courses, cemeteries, etc.) [3]:					
Poor condition (grass cover < 50%)		68	79	86	89
Fair condition (grass cover 50% to 75%)		49	69	79	84
Good condition (grass cover > 75%)		39	61	74	80
Impervious areas:					
Paved parking lots, roofs, driveways, etc. (excluding right-of-way)		98	98	98	98
Streets and roads:					
Paved; curbs and storm sewers (excluding right-of-way)		98	98	98	98
Paved; open ditches (including right-of-way)		83	89	92	93
Gravel (including right-of-way)		76	85	89	91
Dirt (including right-of-way)		72	82	87	89
Western desert urban areas:					
Natural desert landscaping (pervious areas only) [4]		63	77	85	88
Artificial desert landscaping (impervious weed barrier, desert shrub with 1- to 2-inch sand or gravel mulch and basin borders)		96	96	96	96
Urban districts:					
Commercial and business	85	89	92	94	95
Industrial	72	81	88	91	93
Residential districts by average lot size:					
1/8 acre or less (town houses)	65	77	85	90	92
1/4 acre	38	61	75	83	87
1/3 acre	30	57	72	81	86
1/2 acre	25	54	70	80	85
1 acre	20	51	68	79	84
2 acres	12	46	65	77	82
Developing urban areas					
Newly graded areas (pervious areas only, no vegetation) [5]		77	86	91	94
Idle lands (CN's are determined using cover types similar to those in table 2-2c).					

[1] Average runoff condition, and $I_a = 0.2S$.

[2] The average percent impervious area shown was used to develop the composite CN's. Other assumptions are as follows: impervious areas are directly connected to the drainage system, impervious areas have a CN of 98, and pervious areas are considered equivalent to open space in good hydrologic condition. CN's for other combinations of conditions may be computed using figure 2-3 or 2-4.

[3] CN's shown are equivalent to those of pasture. Composite CN's may be computed for other combinations of open space cover type.

[4] Composite CN's for natural desert landscaping should be computed using figures 2-3 or 2-4 based on the impervious area percentage (CN = 98) and the pervious area CN. The pervious area CN's are assumed equivalent to desert shrub in poor hydrologic condition.

[5] Composite CN's to use for the design of temporary measures during grading and construction should be computed using figure 2-3 or 2-4 based on the degree of development (impervious area percentage) and the CN's for the newly graded pervious areas.

TR-55 Runoff Curve Numbers for Cultivated agricultural lands (TR-55, 1986)

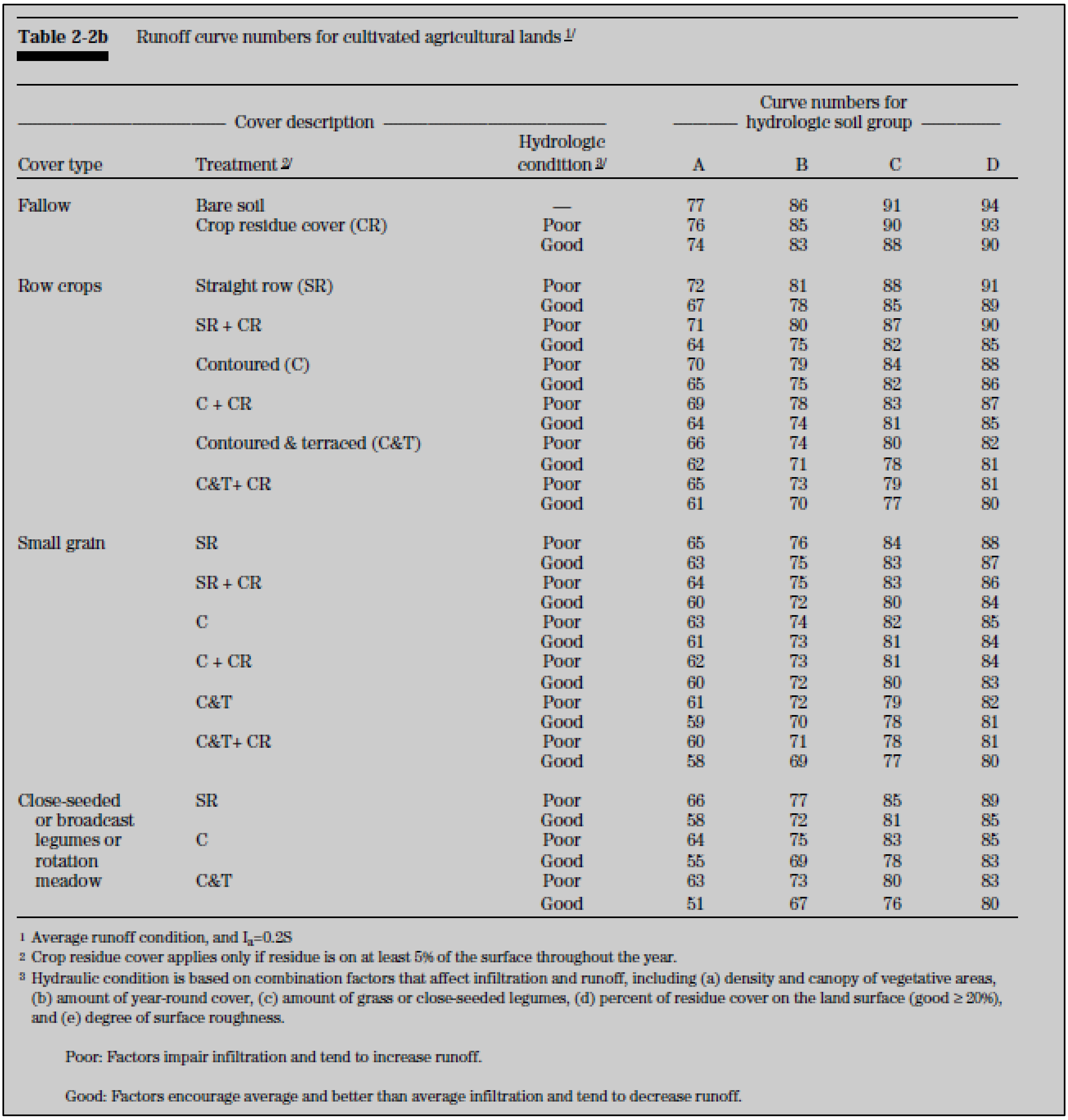


Table 2-2b Runoff curve numbers for cultivated agricultural lands [1/]

Cover description			Curve numbers for hydrologic soil group			
Cover type	Treatment [2/]	Hydrologic condition [3/]	A	B	C	D
Fallow	Bare soil	—	77	86	91	94
	Crop residue cover (CR)	Poor	76	85	90	93
		Good	74	83	88	90
Row crops	Straight row (SR)	Poor	72	81	88	91
		Good	67	78	85	89
	SR + CR	Poor	71	80	87	90
		Good	64	75	82	85
	Contoured (C)	Poor	70	79	84	88
		Good	65	75	82	86
	C + CR	Poor	69	78	83	87
		Good	64	74	81	85
	Contoured & terraced (C&T)	Poor	66	74	80	82
		Good	62	71	78	81
	C&T+ CR	Poor	65	73	79	81
		Good	61	70	77	80
Small grain	SR	Poor	65	76	84	88
		Good	63	75	83	87
	SR + CR	Poor	64	75	83	86
		Good	60	72	80	84
	C	Poor	63	74	82	85
		Good	61	73	81	84
	C + CR	Poor	62	73	81	84
		Good	60	72	80	83
	C&T	Poor	61	72	79	82
		Good	59	70	78	81
	C&T+ CR	Poor	60	71	78	81
		Good	58	69	77	80
Close-seeded or broadcast legumes or rotation meadow	SR	Poor	66	77	85	89
		Good	58	72	81	85
	C	Poor	64	75	83	85
		Good	55	69	78	83
	C&T	Poor	63	73	80	83
		Good	51	67	76	80

[1] Average runoff condition, and I_a=0.2S

[2] Crop residue cover applies only if residue is on at least 5% of the surface throughout the year.

[3] Hydraulic condition is based on combination factors that affect infiltration and runoff, including (a) density and canopy of vegetative areas, (b) amount of year-round cover, (c) amount of grass or close-seeded legumes, (d) percent of residue cover on the land surface (good ≥ 20%), and (e) degree of surface roughness.

Poor: Factors impair infiltration and tend to increase runoff.

Good: Factors encourage average and better than average infiltration and tend to decrease runoff.

TR-55 Runoff Curve Numbers for Other agricultural lands (TR-55, 1986)

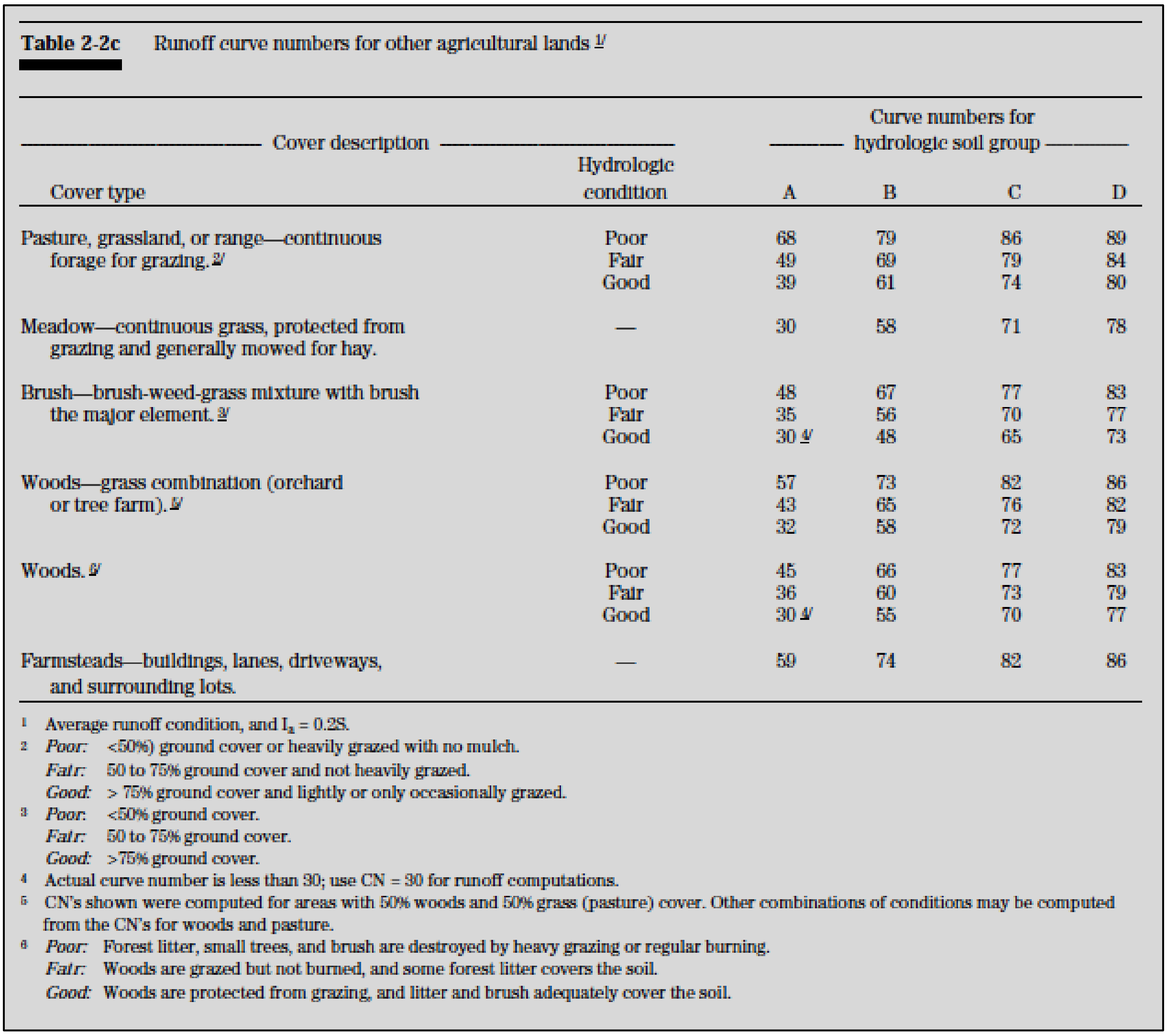


Table 2-2c Runoff curve numbers for other agricultural lands [1]

Cover description: Cover type	Cover description: Hydrologic condition	Curve numbers for hydrologic soil group: A	B	C	D
Pasture, grassland, or range—continuous forage for grazing. [2]	Poor	68	79	86	89
	Fair	49	69	79	84
	Good	39	61	74	80
Meadow—continuous grass, protected from grazing and generally mowed for hay.	—	30	58	71	78
Brush—brush-weed-grass mixture with brush the major element. [3]	Poor	48	67	77	83
	Fair	35	56	70	77
	Good	30 [4]	48	65	73
Woods—grass combination (orchard or tree farm). [5]	Poor	57	73	82	86
	Fair	43	65	76	82
	Good	32	58	72	79
Woods. [6]	Poor	45	66	77	83
	Fair	36	60	73	79
	Good	30 [4]	55	70	77
Farmsteads—buildings, lanes, driveways, and surrounding lots.	—	59	74	82	86

[1] Average runoff condition, and $I_a = 0.2S$.

[2] *Poor:* <50%) ground cover or heavily grazed with no mulch.
Fair: 50 to 75% ground cover and not heavily grazed.
Good: > 75% ground cover and lightly or only occasionally grazed.

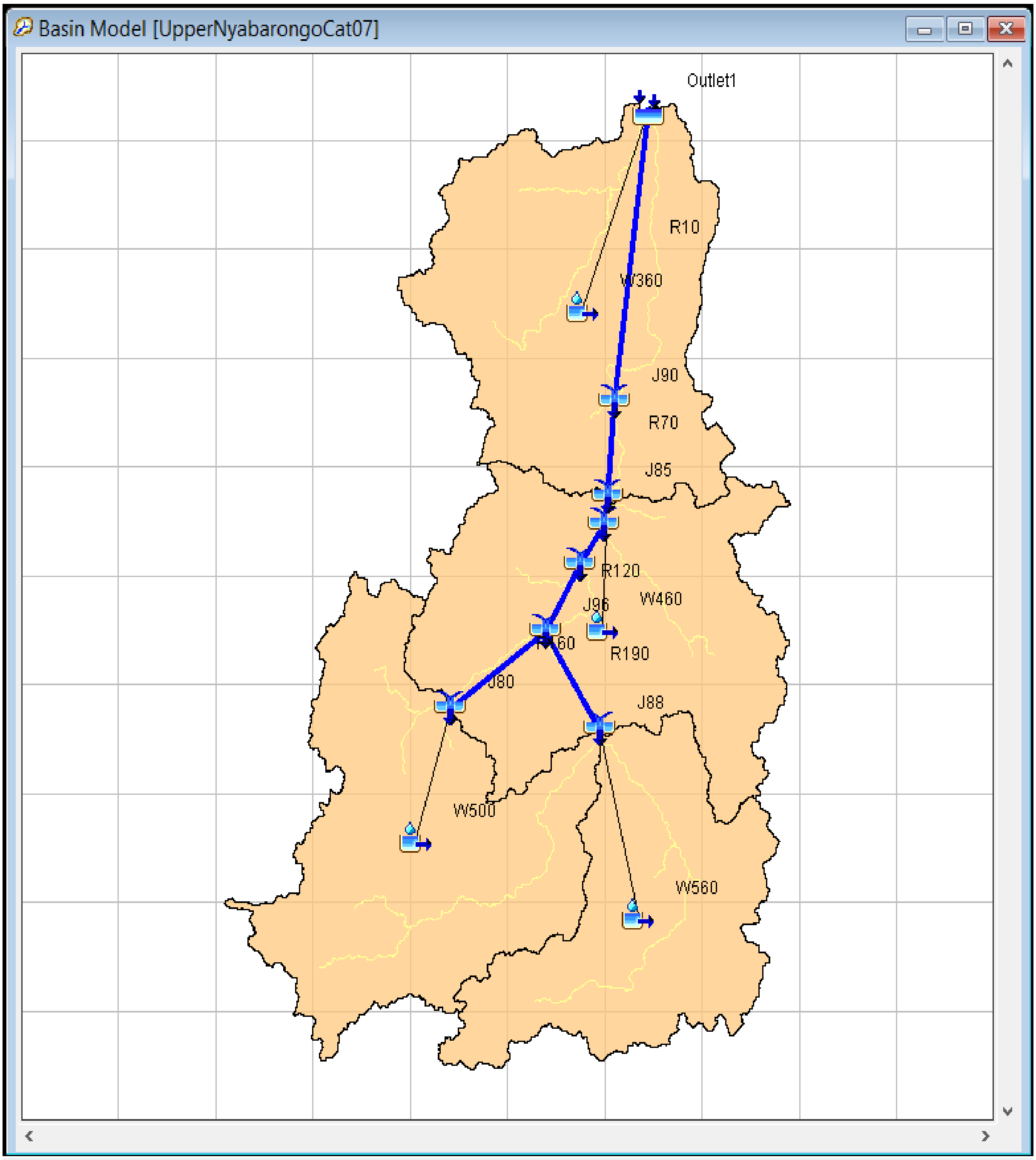
[3] *Poor:* <50% ground cover.
Fair: 50 to 75% ground cover.
Good: >75% ground cover.

[4] Actual curve number is less than 30; use CN = 30 for runoff computations.

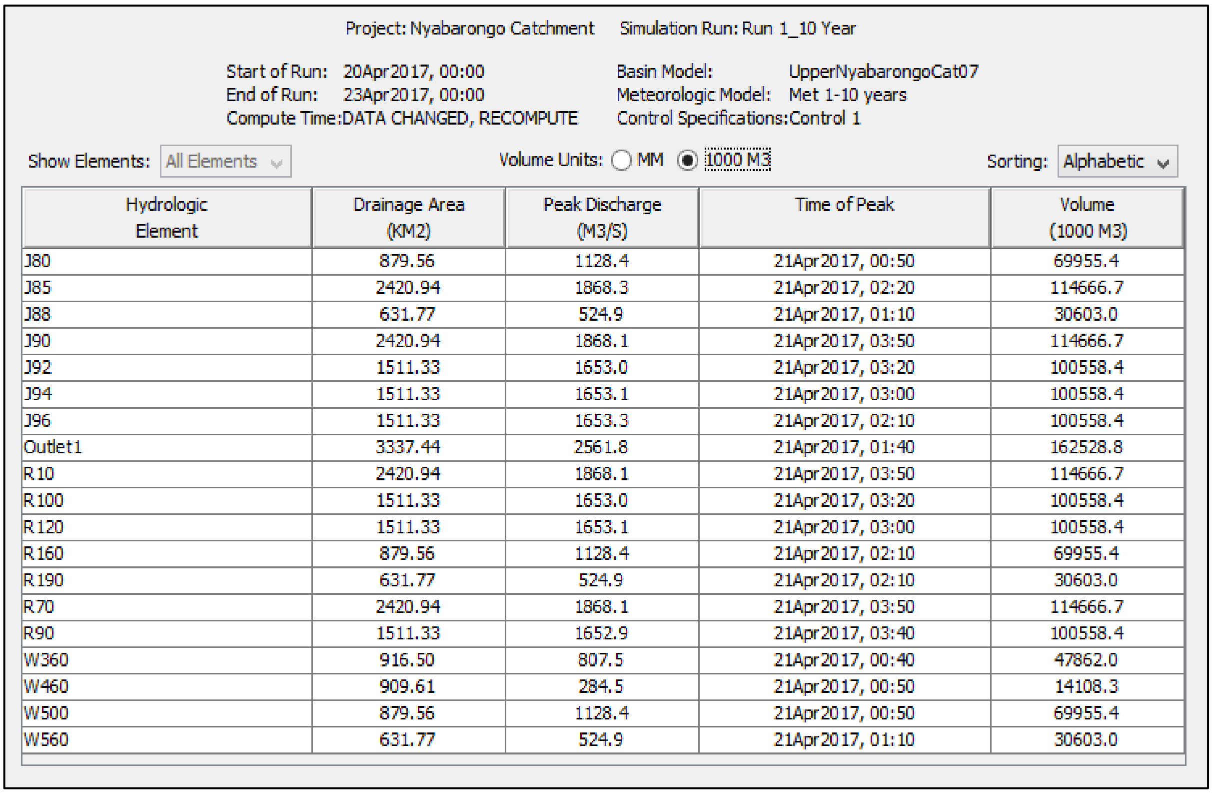
[5] CN's shown were computed for areas with 50% woods and 50% grass (pasture) cover. Other combinations of conditions may be computed from the CN's for woods and pasture.

[6] *Poor:* Forest litter, small trees, and brush are destroyed by heavy grazing or regular burning.
Fair: Woods are grazed but not burned, and some forest litter covers the soil.
Good: Woods are protected from grazing, and litter and brush adequately cover the soil.

ANNEX 4: HEC-HMS DESCRIPTION AND GLOBAL SUMMARY RESULTS



HEC-HMS Window



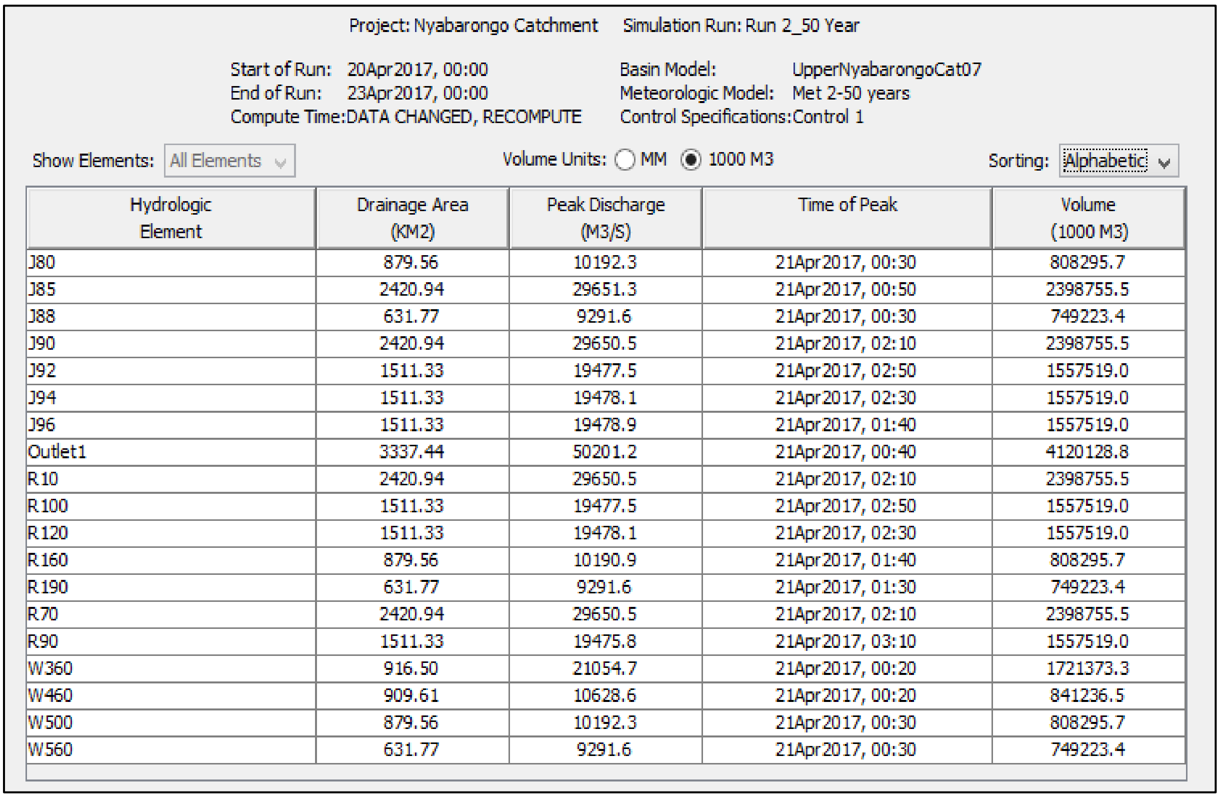
Project: Nyabarongo Catchment   Simulation Run: Run 1_10 Year

Start of Run: 20Apr2017, 00:00   Basin Model: UpperNyabarongoCat07
End of Run: 23Apr2017, 00:00   Meteorologic Model: Met 1-10 years
Compute Time:DATA CHANGED, RECOMPUTE   Control Specifications:Control 1

Show Elements: All Elements   Volume Units: ○ MM ● 1000 M3   Sorting: Alphabetic

Hydrologic Element	Drainage Area (KM2)	Peak Discharge (M3/S)	Time of Peak	Volume (1000 M3)
J80	879.56	1128.4	21Apr2017, 00:50	69955.4
J85	2420.94	1868.3	21Apr2017, 02:20	114666.7
J88	631.77	524.9	21Apr2017, 01:10	30603.0
J90	2420.94	1868.1	21Apr2017, 03:50	114666.7
J92	1511.33	1653.0	21Apr2017, 03:20	100558.4
J94	1511.33	1653.1	21Apr2017, 03:00	100558.4
J96	1511.33	1653.3	21Apr2017, 02:10	100558.4
Outlet1	3337.44	2561.8	21Apr2017, 01:40	162528.8
R10	2420.94	1868.1	21Apr2017, 03:50	114666.7
R100	1511.33	1653.0	21Apr2017, 03:20	100558.4
R120	1511.33	1653.1	21Apr2017, 03:00	100558.4
R160	879.56	1128.4	21Apr2017, 02:10	69955.4
R190	631.77	524.9	21Apr2017, 02:10	30603.0
R70	2420.94	1868.1	21Apr2017, 03:50	114666.7
R90	1511.33	1652.9	21Apr2017, 03:40	100558.4
W360	916.50	807.5	21Apr2017, 00:40	47862.0
W460	909.61	284.5	21Apr2017, 00:50	14108.3
W500	879.56	1128.4	21Apr2017, 00:50	69955.4
W560	631.77	524.9	21Apr2017, 01:10	30603.0

Global summary results of a 10-year flood (Run 1)



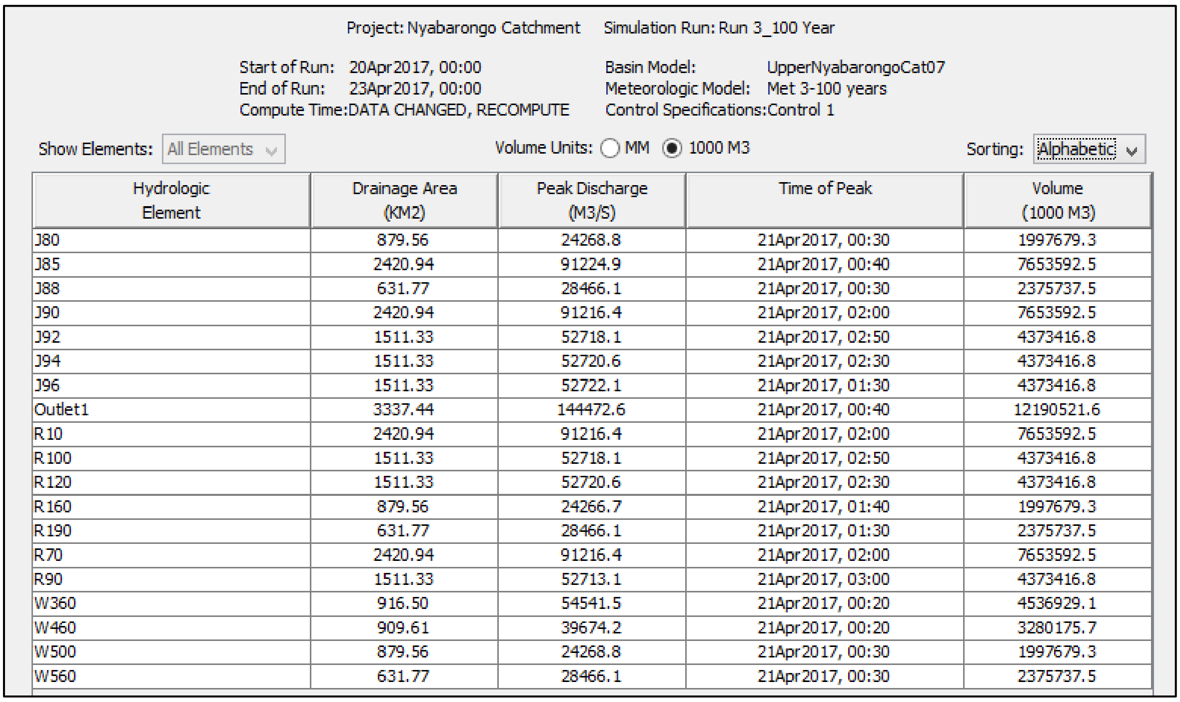
Project: Nyabarongo Catchment   Simulation Run: Run 2_50 Year

Start of Run: 20Apr2017, 00:00   Basin Model: UpperNyabarongoCat07
End of Run: 23Apr2017, 00:00   Meteorologic Model: Met 2-50 years
Compute Time: DATA CHANGED, RECOMPUTE   Control Specifications: Control 1

Show Elements: All Elements   Volume Units: ○ MM ● 1000 M3   Sorting: Alphabetic

Hydrologic Element	Drainage Area (KM2)	Peak Discharge (M3/S)	Time of Peak	Volume (1000 M3)
J80	879.56	10192.3	21Apr2017, 00:30	808295.7
J85	2420.94	29651.3	21Apr2017, 00:50	2398755.5
J88	631.77	9291.6	21Apr2017, 00:30	749223.4
J90	2420.94	29650.5	21Apr2017, 02:10	2398755.5
J92	1511.33	19477.5	21Apr2017, 02:50	1557519.0
J94	1511.33	19478.1	21Apr2017, 02:30	1557519.0
J96	1511.33	19478.9	21Apr2017, 01:40	1557519.0
Outlet1	3337.44	50201.2	21Apr2017, 00:40	4120128.8
R10	2420.94	29650.5	21Apr2017, 02:10	2398755.5
R100	1511.33	19477.5	21Apr2017, 02:50	1557519.0
R120	1511.33	19478.1	21Apr2017, 02:30	1557519.0
R160	879.56	10190.9	21Apr2017, 01:40	808295.7
R190	631.77	9291.6	21Apr2017, 01:30	749223.4
R70	2420.94	29650.5	21Apr2017, 02:10	2398755.5
R90	1511.33	19475.8	21Apr2017, 03:10	1557519.0
W360	916.50	21054.7	21Apr2017, 00:20	1721373.3
W460	909.61	10628.6	21Apr2017, 00:20	841236.5
W500	879.56	10192.3	21Apr2017, 00:30	808295.7
W560	631.77	9291.6	21Apr2017, 00:30	749223.4

Global summary results of a 50-year flood (Run 2)



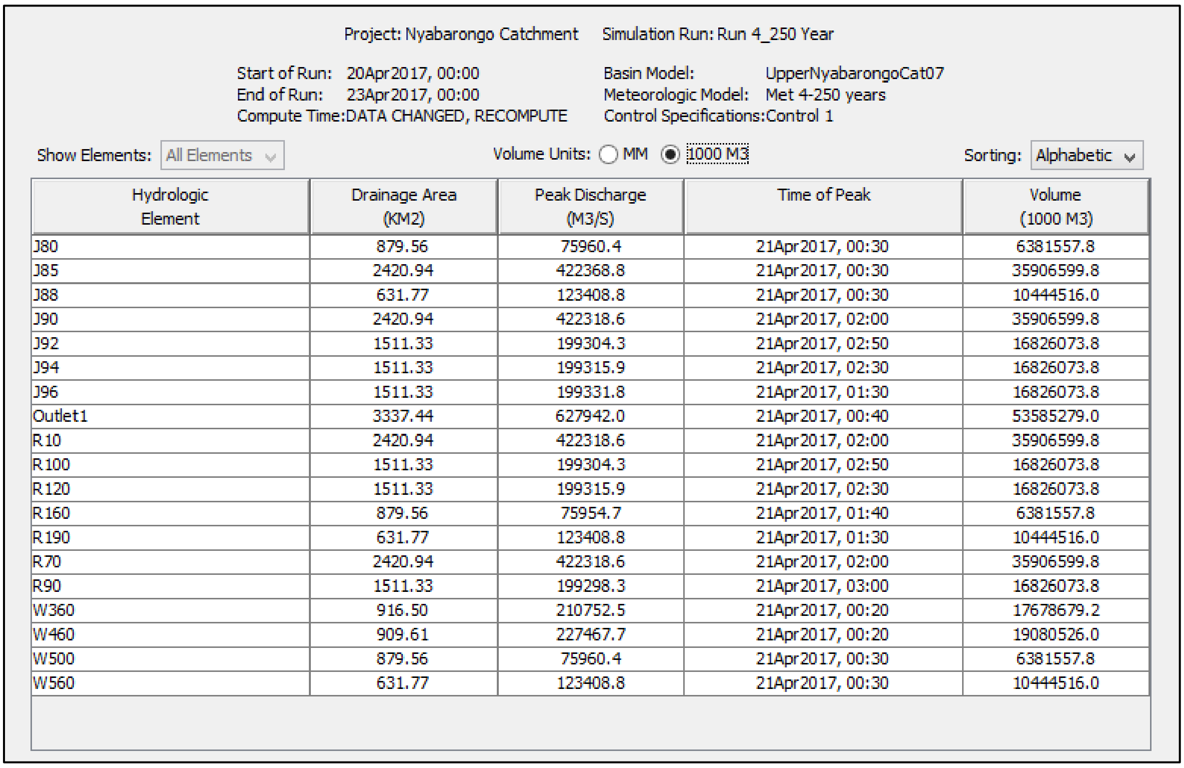
Project: Nyabarongo Catchment   Simulation Run: Run 3_100 Year

Start of Run: 20Apr2017, 00:00   Basin Model: UpperNyabarongoCat07
End of Run: 23Apr2017, 00:00   Meteorologic Model: Met 3-100 years
Compute Time: DATA CHANGED, RECOMPUTE   Control Specifications: Control 1

Show Elements: All Elements   Volume Units: ○ MM ● 1000 M3   Sorting: Alphabetic

Hydrologic Element	Drainage Area (KM2)	Peak Discharge (M3/S)	Time of Peak	Volume (1000 M3)
J80	879.56	24268.8	21Apr2017, 00:30	1997679.3
J85	2420.94	91224.9	21Apr2017, 00:40	7653592.5
J88	631.77	28466.1	21Apr2017, 00:30	2375737.5
J90	2420.94	91216.4	21Apr2017, 02:00	7653592.5
J92	1511.33	52718.1	21Apr2017, 02:50	4373416.8
J94	1511.33	52720.6	21Apr2017, 02:30	4373416.8
J96	1511.33	52722.1	21Apr2017, 01:30	4373416.8
Outlet1	3337.44	144472.6	21Apr2017, 00:40	12190521.6
R10	2420.94	91216.4	21Apr2017, 02:00	7653592.5
R100	1511.33	52718.1	21Apr2017, 02:50	4373416.8
R120	1511.33	52720.6	21Apr2017, 02:30	4373416.8
R160	879.56	24266.7	21Apr2017, 01:40	1997679.3
R190	631.77	28466.1	21Apr2017, 01:30	2375737.5
R70	2420.94	91216.4	21Apr2017, 02:00	7653592.5
R90	1511.33	52713.1	21Apr2017, 03:00	4373416.8
W360	916.50	54541.5	21Apr2017, 00:20	4536929.1
W460	909.61	39674.2	21Apr2017, 00:20	3280175.7
W500	879.56	24268.8	21Apr2017, 00:30	1997679.3
W560	631.77	28466.1	21Apr2017, 00:30	2375737.5

Global summary results of a 100-year flood (Run 3)



Project: Nyabarongo Catchment Simulation Run: Run 4_250 Year

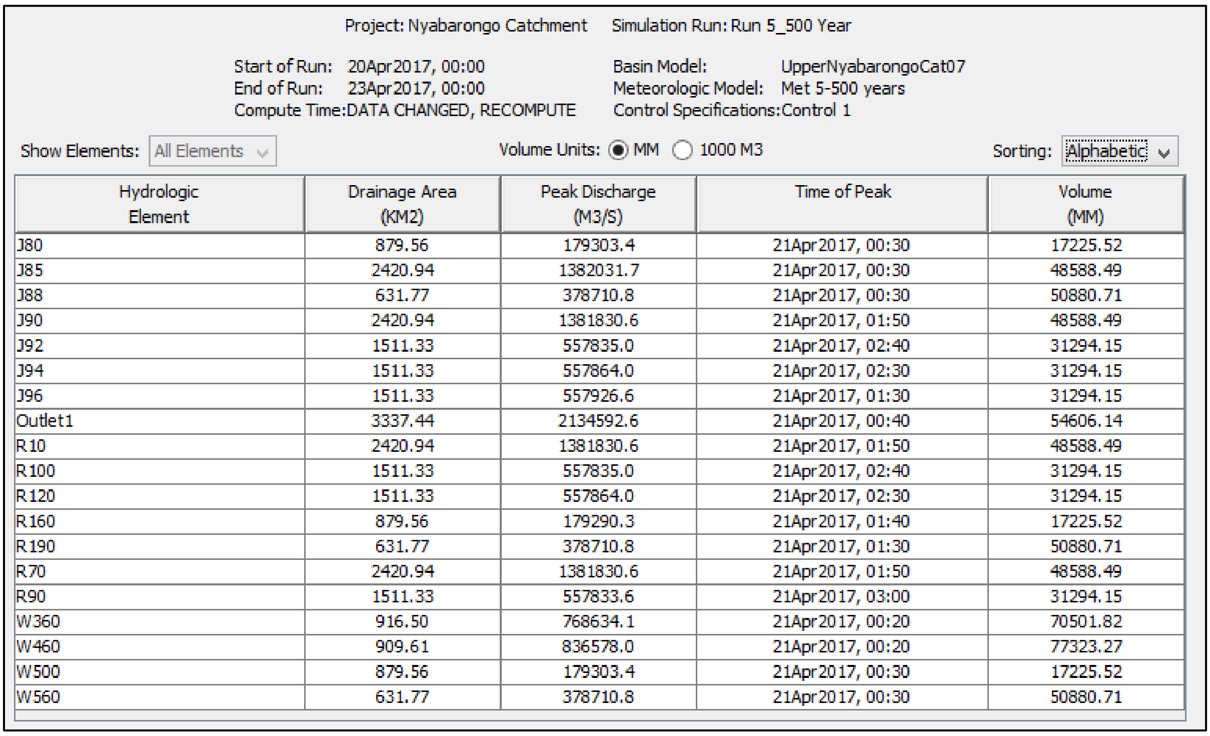
Start of Run: 20Apr2017, 00:00
End of Run: 23Apr2017, 00:00
Compute Time:DATA CHANGED, RECOMPUTE

Basin Model: UpperNyabarongoCat07
Meteorologic Model: Met 4-250 years
Control Specifications:Control 1

Show Elements: All Elements Volume Units: ○ MM ● 1000 M3 Sorting: Alphabetic

Hydrologic Element	Drainage Area (KM2)	Peak Discharge (M3/S)	Time of Peak	Volume (1000 M3)
J80	879.56	75960.4	21Apr2017, 00:30	6381557.8
J85	2420.94	422368.8	21Apr2017, 00:30	35906599.8
J88	631.77	123408.8	21Apr2017, 00:30	10444516.0
J90	2420.94	422318.6	21Apr2017, 02:00	35906599.8
J92	1511.33	199304.3	21Apr2017, 02:50	16826073.8
J94	1511.33	199315.9	21Apr2017, 02:30	16826073.8
J96	1511.33	199331.8	21Apr2017, 01:30	16826073.8
Outlet1	3337.44	627942.0	21Apr2017, 00:40	53585279.0
R10	2420.94	422318.6	21Apr2017, 02:00	35906599.8
R100	1511.33	199304.3	21Apr2017, 02:50	16826073.8
R120	1511.33	199315.9	21Apr2017, 02:30	16826073.8
R160	879.56	75954.7	21Apr2017, 01:40	6381557.8
R190	631.77	123408.8	21Apr2017, 01:30	10444516.0
R70	2420.94	422318.6	21Apr2017, 02:00	35906599.8
R90	1511.33	199298.3	21Apr2017, 03:00	16826073.8
W360	916.50	210752.5	21Apr2017, 00:20	17678679.2
W460	909.61	227467.7	21Apr2017, 00:20	19080526.0
W500	879.56	75960.4	21Apr2017, 00:30	6381557.8
W560	631.77	123408.8	21Apr2017, 00:30	10444516.0

Global summary results of a 250-year flood (Run 4)



Project: Nyabarongo Catchment Simulation Run: Run 5_500 Year

Start of Run: 20Apr2017, 00:00
End of Run: 23Apr2017, 00:00
Compute Time:DATA CHANGED, RECOMPUTE

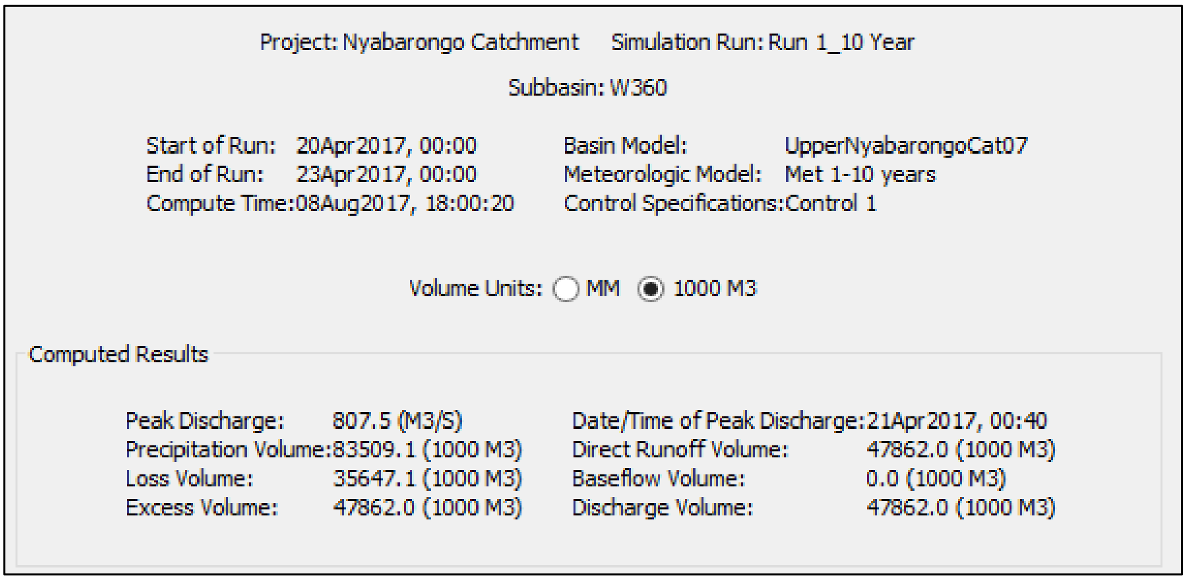
Basin Model: UpperNyabarongoCat07
Meteorologic Model: Met 5-500 years
Control Specifications:Control 1

Show Elements: All Elements Volume Units: ● MM ○ 1000 M3 Sorting: Alphabetic

Hydrologic Element	Drainage Area (KM2)	Peak Discharge (M3/S)	Time of Peak	Volume (MM)
J80	879.56	179303.4	21Apr2017, 00:30	17225.52
J85	2420.94	1382031.7	21Apr2017, 00:30	48588.49
J88	631.77	378710.8	21Apr2017, 00:30	50880.71
J90	2420.94	1381830.6	21Apr2017, 01:50	48588.49
J92	1511.33	557835.0	21Apr2017, 02:40	31294.15
J94	1511.33	557864.0	21Apr2017, 02:30	31294.15
J96	1511.33	557926.6	21Apr2017, 01:30	31294.15
Outlet1	3337.44	2134592.6	21Apr2017, 00:40	54606.14
R10	2420.94	1381830.6	21Apr2017, 01:50	48588.49
R100	1511.33	557835.0	21Apr2017, 02:40	31294.15
R120	1511.33	557864.0	21Apr2017, 02:30	31294.15
R160	879.56	179290.3	21Apr2017, 01:40	17225.52
R190	631.77	378710.8	21Apr2017, 01:30	50880.71
R70	2420.94	1381830.6	21Apr2017, 01:50	48588.49
R90	1511.33	557833.6	21Apr2017, 03:00	31294.15
W360	916.50	768634.1	21Apr2017, 00:20	70501.82
W460	909.61	836578.0	21Apr2017, 00:20	77323.27
W500	879.56	179303.4	21Apr2017, 00:30	17225.52
W560	631.77	378710.8	21Apr2017, 00:30	50880.71

Global summary results of a 500-year flood (Run 5)

Summary Table for Run 1 of W360



Project: Nyabarongo Catchment   Simulation Run: Run 1_10 Year

Subbasin: W360

Start of Run: 20Apr2017, 00:00
End of Run: 23Apr2017, 00:00
Compute Time: 08Aug2017, 18:00:20

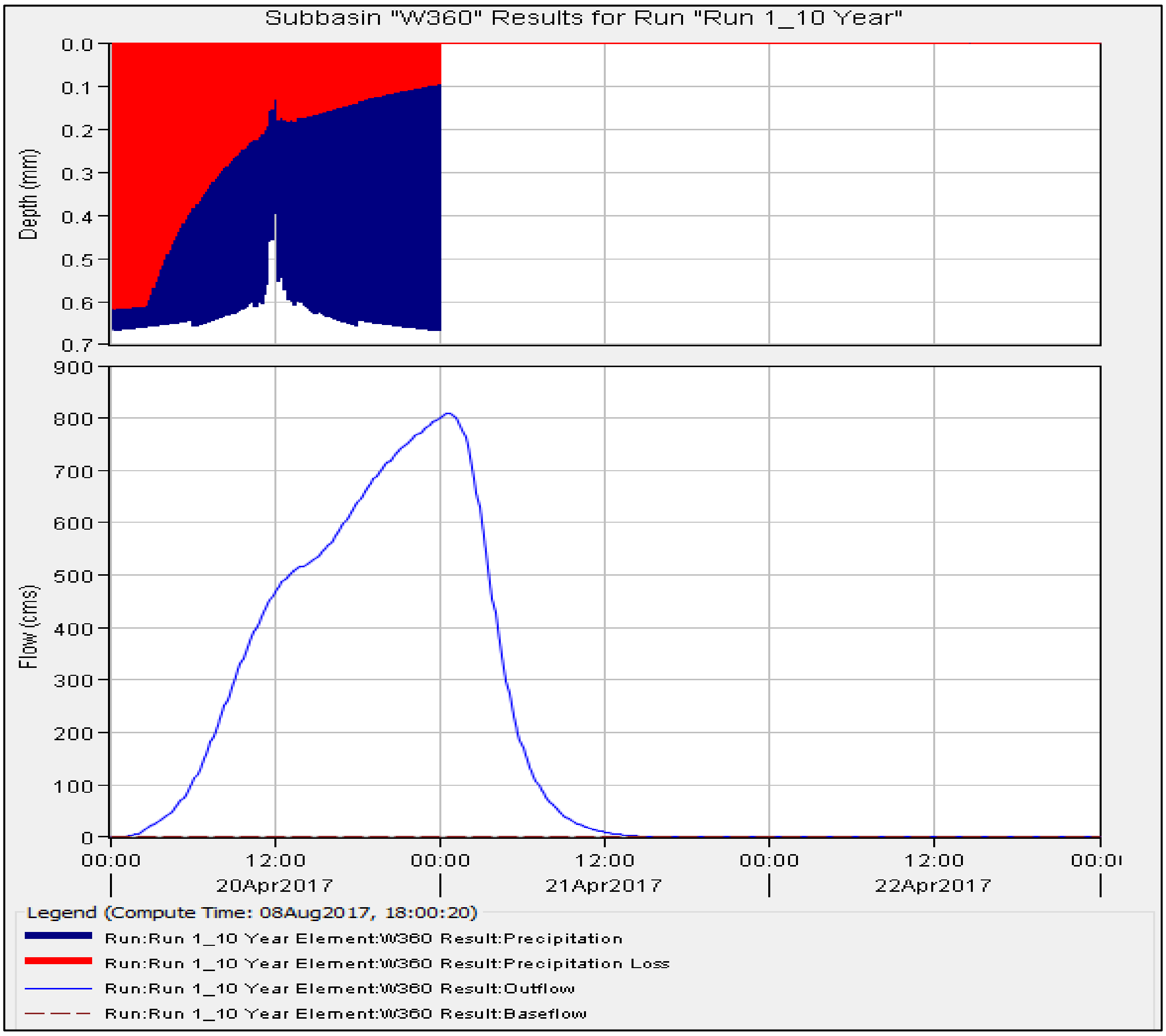
Basin Model: UpperNyabarongoCat07
Meteorologic Model: Met 1-10 years
Control Specifications: Control 1

Volume Units: ○ MM ● 1000 M3

Computed Results

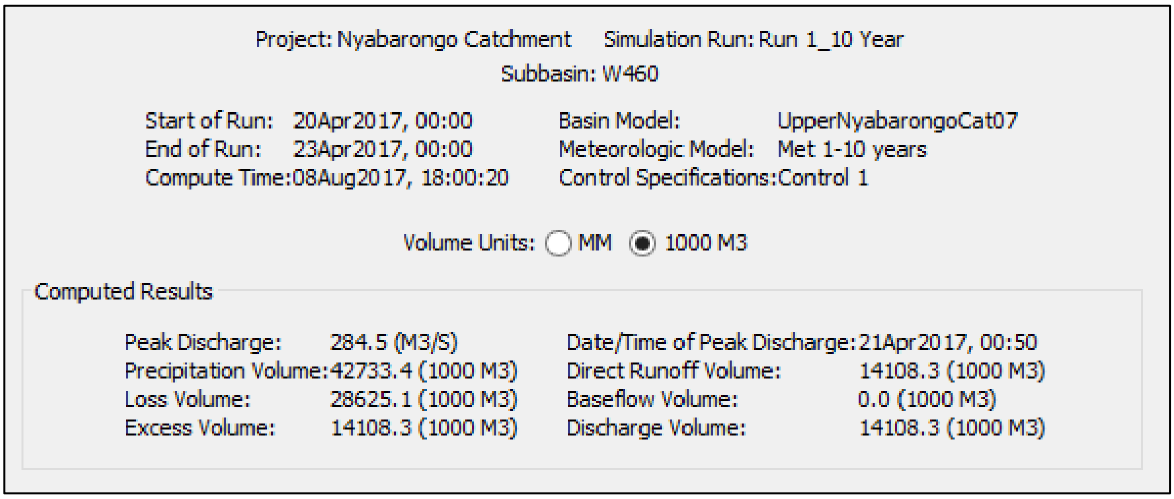
Peak Discharge: 807.5 (M3/S)
Precipitation Volume: 83509.1 (1000 M3)
Loss Volume: 35647.1 (1000 M3)
Excess Volume: 47862.0 (1000 M3)

Date/Time of Peak Discharge: 21Apr2017, 00:40
Direct Runoff Volume: 47862.0 (1000 M3)
Baseflow Volume: 0.0 (1000 M3)
Discharge Volume: 47862.0 (1000 M3)



Graph for Run 1 of W360

Summary Table for Run 1 of W460



Project: Nyabarongo Catchment   Simulation Run: Run 1_10 Year
Subbasin: W460

Start of Run: 20Apr2017, 00:00
End of Run: 23Apr2017, 00:00
Compute Time: 08Aug2017, 18:00:20

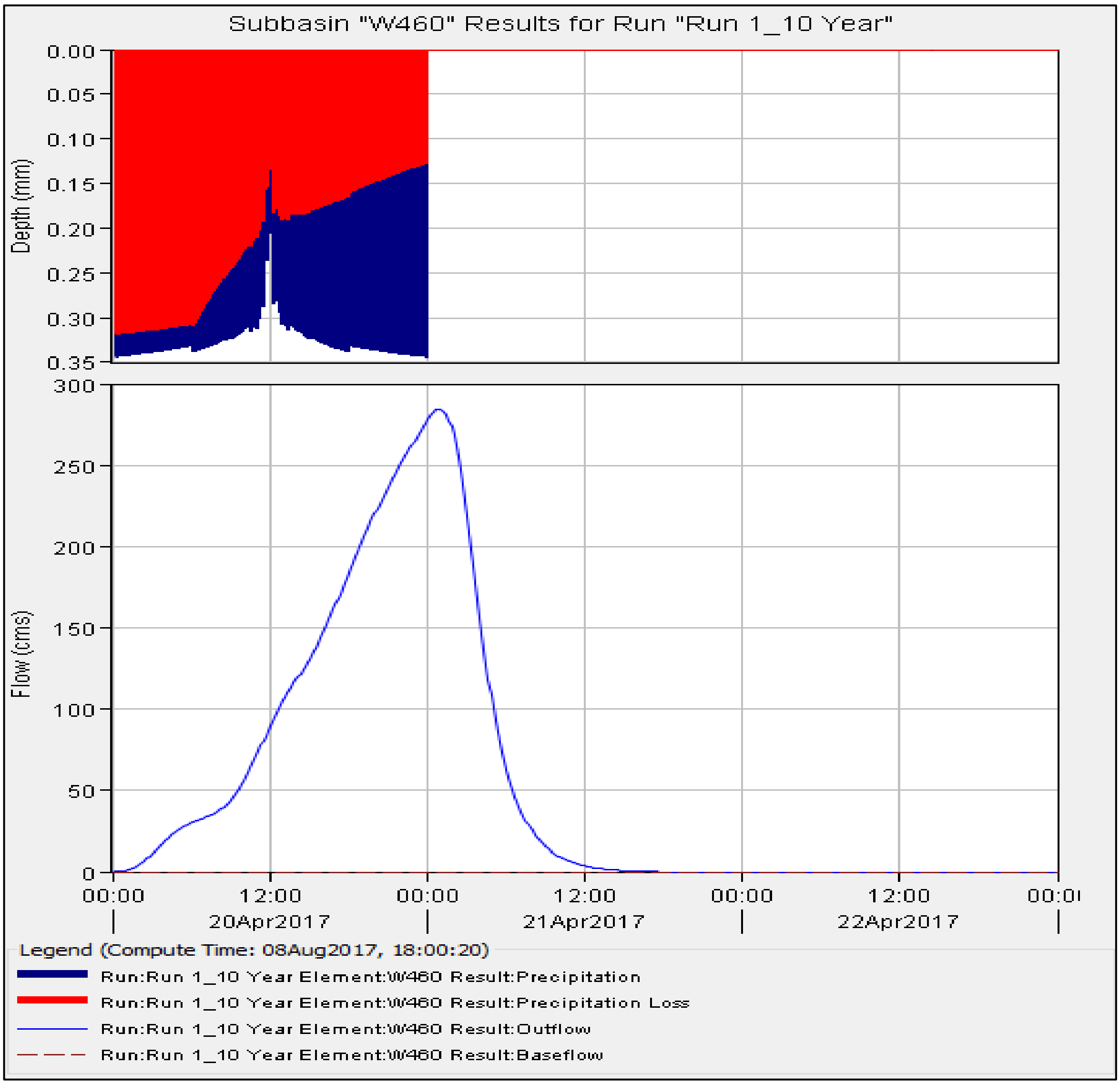
Basin Model: UpperNyabarongoCat07
Meteorologic Model: Met 1-10 years
Control Specifications: Control 1

Volume Units: ○ MM ● 1000 M3

Computed Results

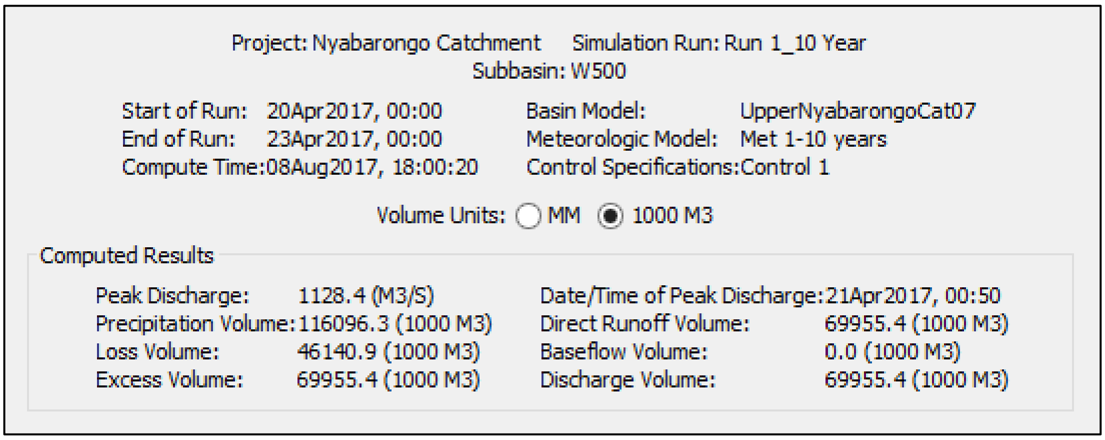
Peak Discharge: 284.5 (M3/S)
Precipitation Volume: 42733.4 (1000 M3)
Loss Volume: 28625.1 (1000 M3)
Excess Volume: 14108.3 (1000 M3)

Date/Time of Peak Discharge: 21Apr2017, 00:50
Direct Runoff Volume: 14108.3 (1000 M3)
Baseflow Volume: 0.0 (1000 M3)
Discharge Volume: 14108.3 (1000 M3)



Graph for Run 1 of W460

Summary Table for Run 1 of W500



Project: Nyabarongo Catchment Simulation Run: Run 1_10 Year
Subbasin: W500

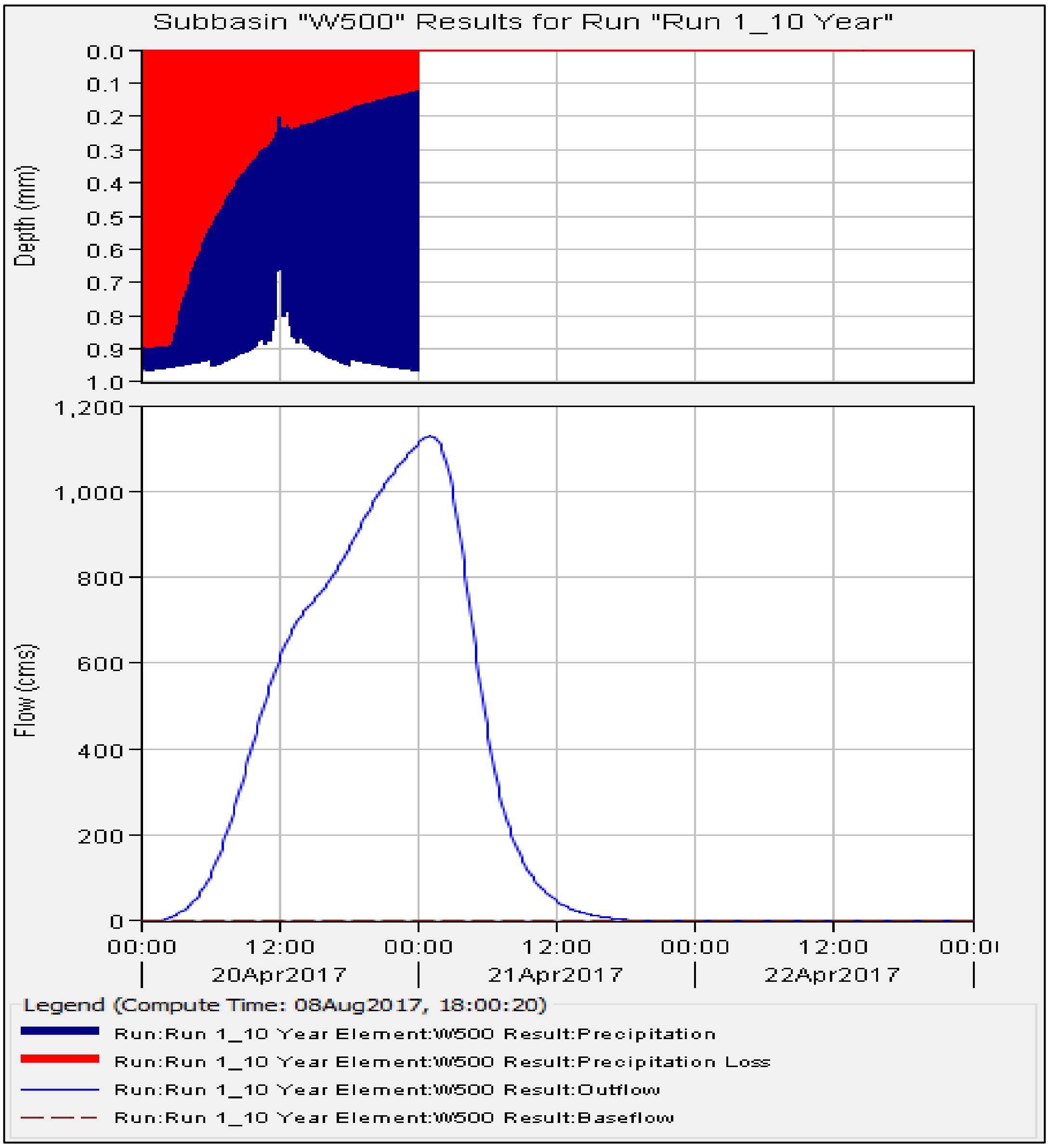
Start of Run: 20Apr2017, 00:00
End of Run: 23Apr2017, 00:00
Compute Time: 08Aug2017, 18:00:20

Basin Model: UpperNyabarongoCat07
Meteorologic Model: Met 1-10 years
Control Specifications: Control 1

Volume Units: ○ MM ● 1000 M3

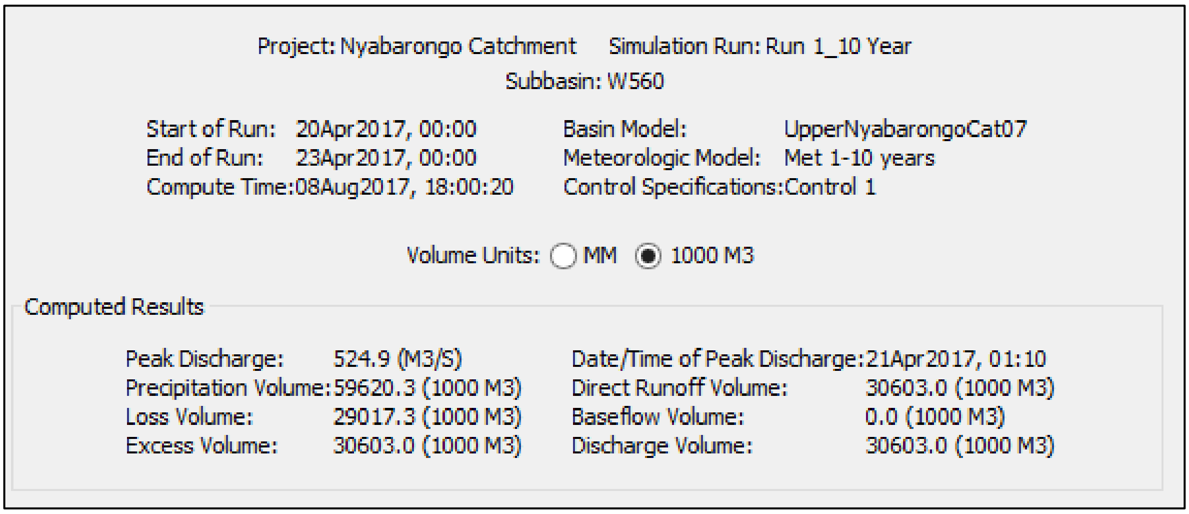
Computed Results

Peak Discharge:	1128.4 (M3/S)	Date/Time of Peak Discharge:	21Apr2017, 00:50
Precipitation Volume:	116096.3 (1000 M3)	Direct Runoff Volume:	69955.4 (1000 M3)
Loss Volume:	46140.9 (1000 M3)	Baseflow Volume:	0.0 (1000 M3)
Excess Volume:	69955.4 (1000 M3)	Discharge Volume:	69955.4 (1000 M3)



Graph for Run 1 of W500

Summary Table for Run 1 of W560



Project: Nyabarongo Catchment Simulation Run: Run 1_10 Year
Subbasin: W560

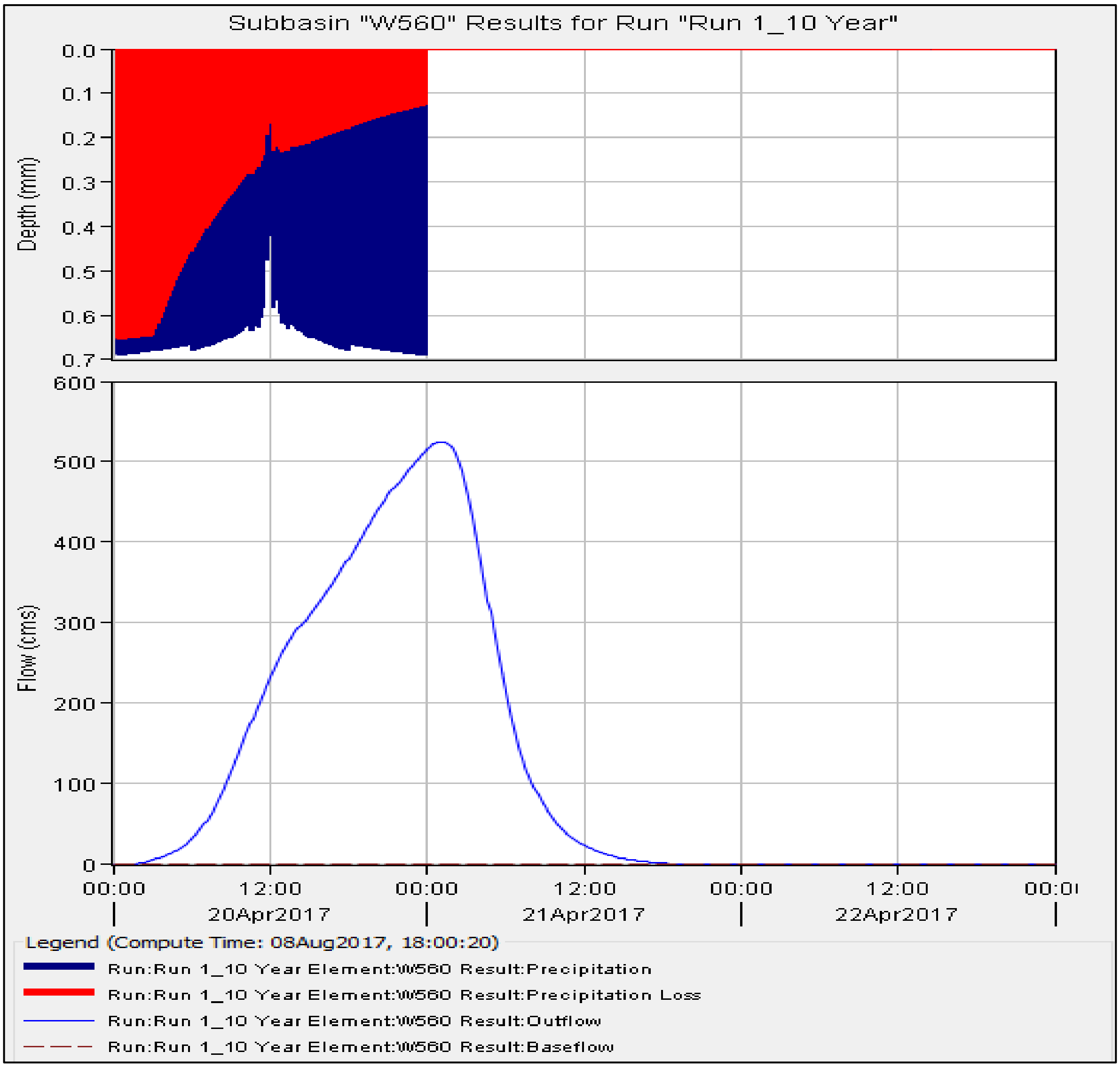
Start of Run: 20Apr2017, 00:00
End of Run: 23Apr2017, 00:00
Compute Time: 08Aug2017, 18:00:20

Basin Model: UpperNyabarongoCat07
Meteorologic Model: Met 1-10 years
Control Specifications: Control 1

Volume Units: ○ MM ● 1000 M3

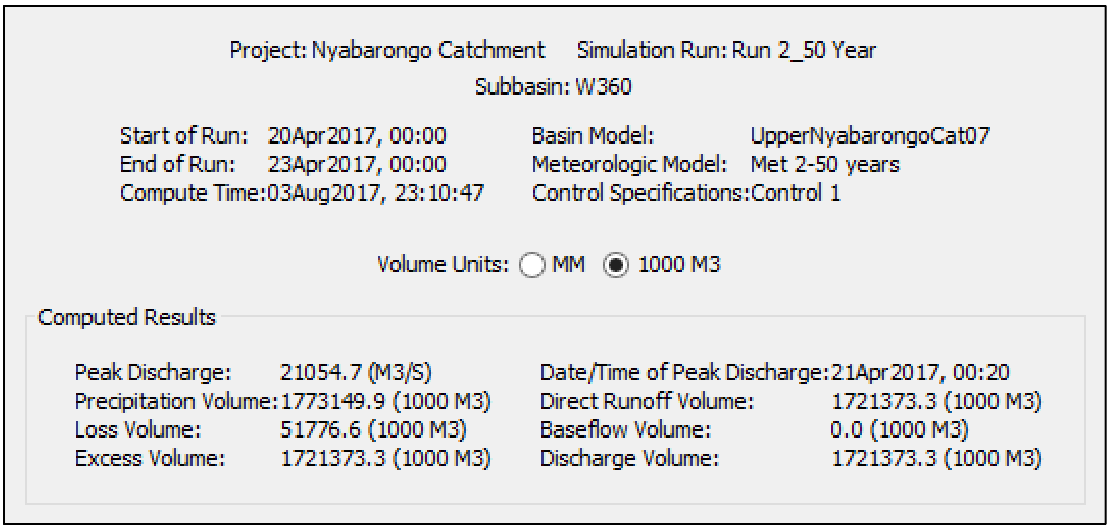
Computed Results

Peak Discharge:	524.9 (M3/S)	Date/Time of Peak Discharge:	21Apr2017, 01:10
Precipitation Volume:	59620.3 (1000 M3)	Direct Runoff Volume:	30603.0 (1000 M3)
Loss Volume:	29017.3 (1000 M3)	Baseflow Volume:	0.0 (1000 M3)
Excess Volume:	30603.0 (1000 M3)	Discharge Volume:	30603.0 (1000 M3)



Graph for Run 1 of W560

Summary Table for Run 2 of W360



Project: Nyabarongo Catchment   Simulation Run: Run 2_50 Year
Subbasin: W360

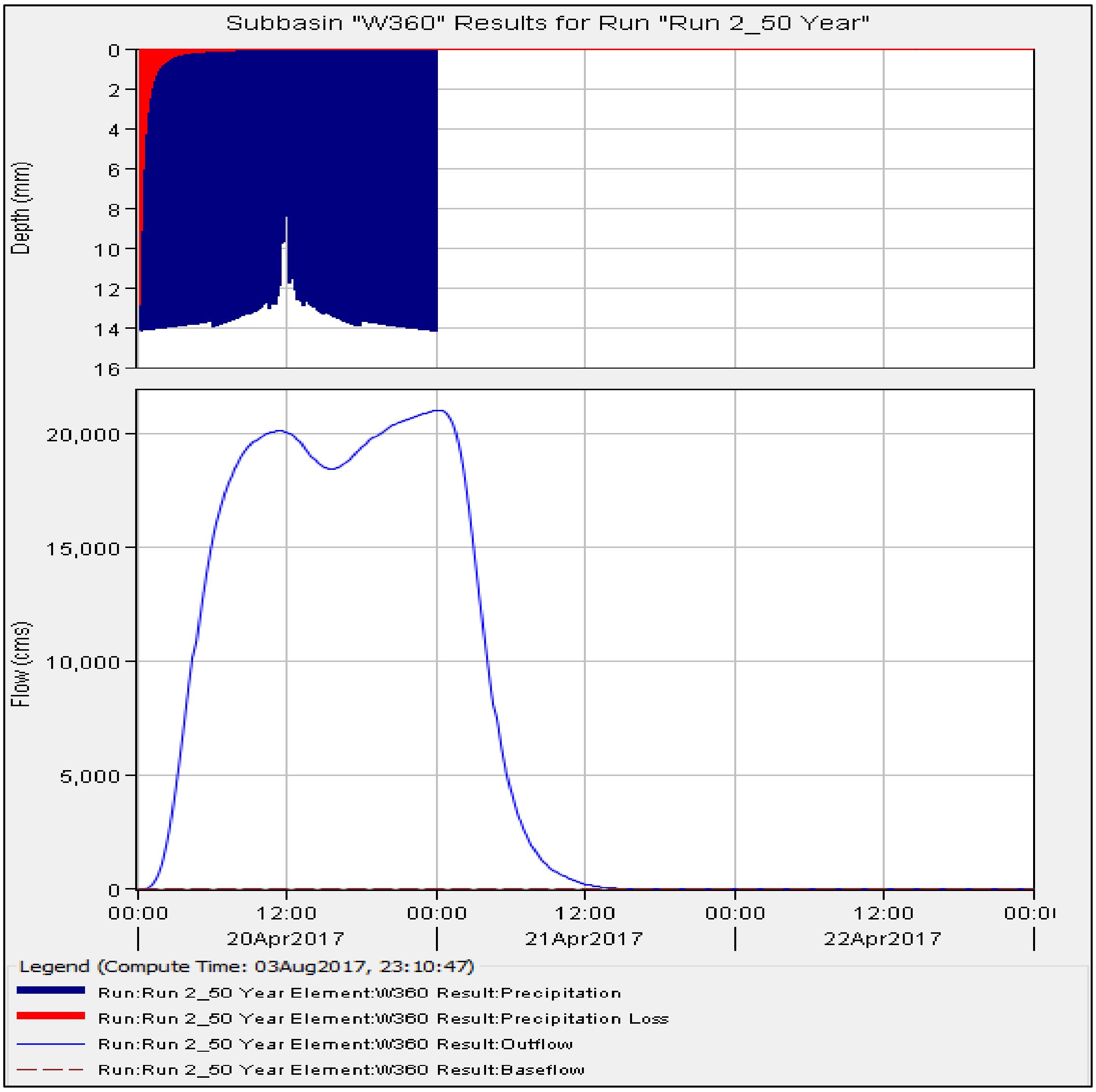
Start of Run: 20Apr2017, 00:00
End of Run: 23Apr2017, 00:00
Compute Time: 03Aug2017, 23:10:47

Basin Model: UpperNyabarongoCat07
Meteorologic Model: Met 2-50 years
Control Specifications: Control 1

Volume Units: ○ MM ● 1000 M3

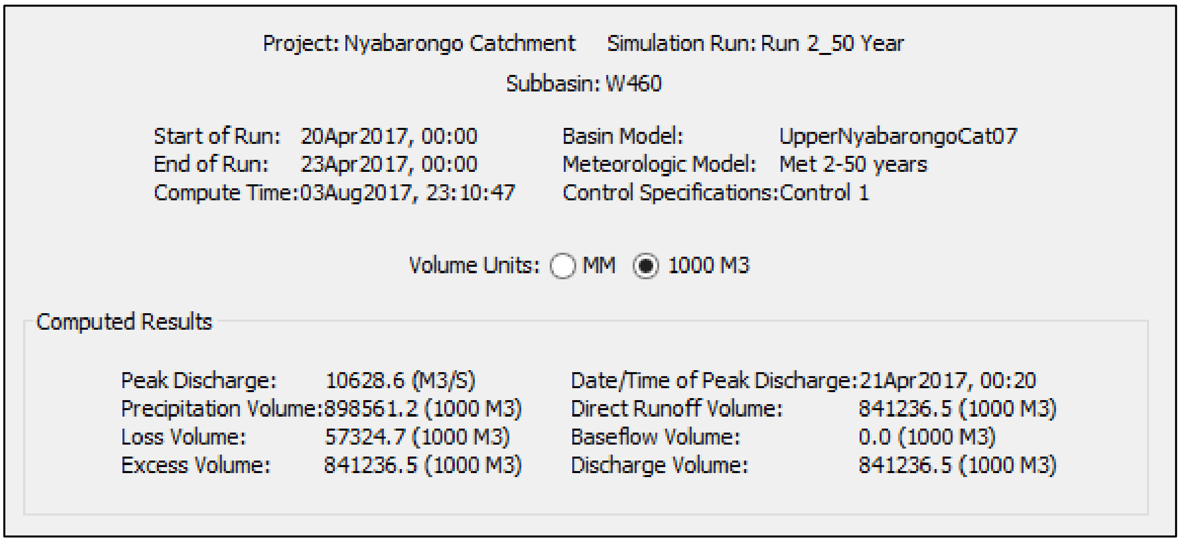
Computed Results

Peak Discharge:	21054.7 (M3/S)	Date/Time of Peak Discharge:	21Apr2017, 00:20
Precipitation Volume:	1773149.9 (1000 M3)	Direct Runoff Volume:	1721373.3 (1000 M3)
Loss Volume:	51776.6 (1000 M3)	Baseflow Volume:	0.0 (1000 M3)
Excess Volume:	1721373.3 (1000 M3)	Discharge Volume:	1721373.3 (1000 M3)



Graph for Run 2 of W360

Summary Table for Run 2 of W460



Project: Nyabarongo Catchment   Simulation Run: Run 2_50 Year

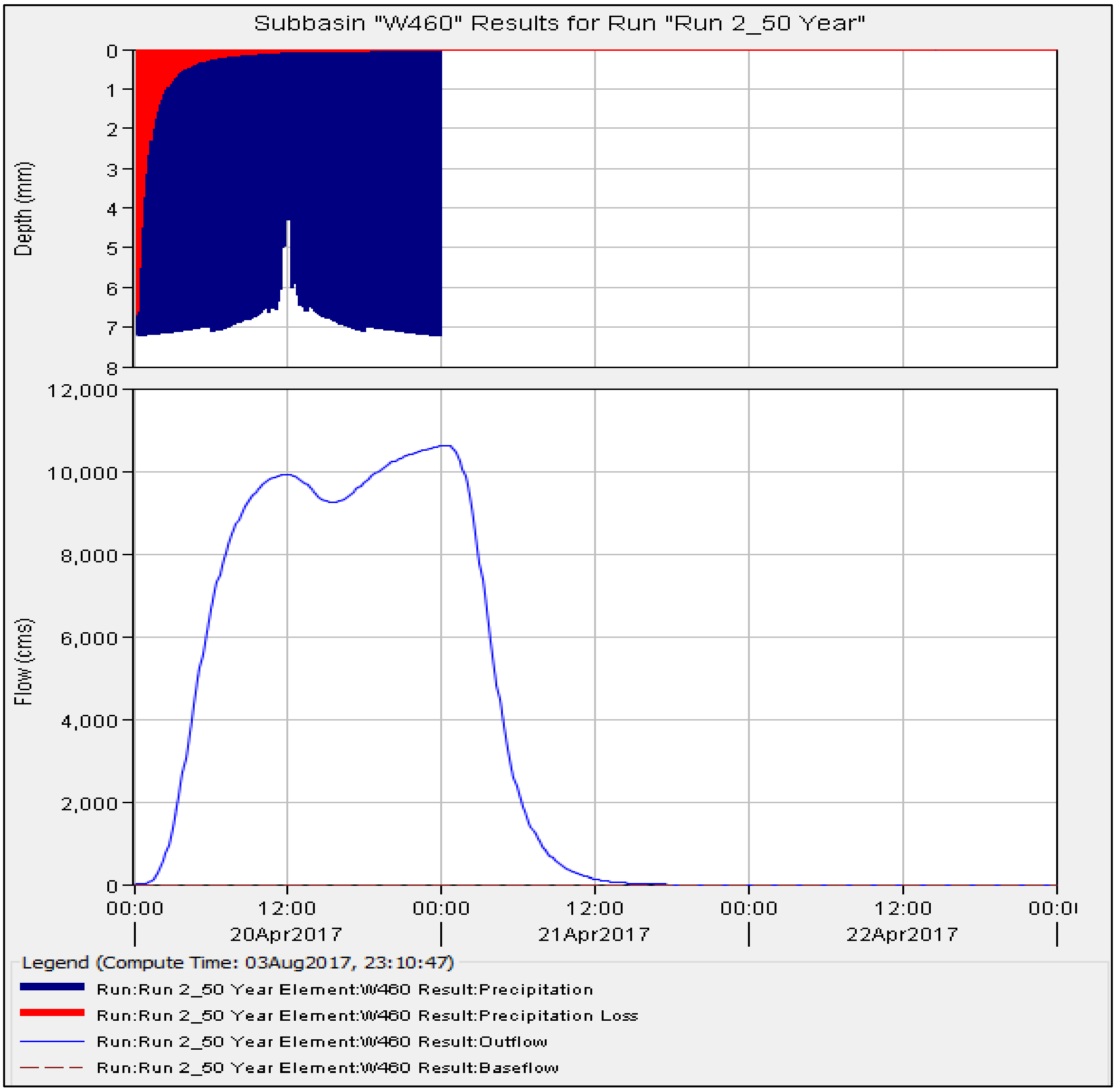
Subbasin: W460

Start of Run:	20Apr2017, 00:00	Basin Model:	UpperNyabarongoCat07
End of Run:	23Apr2017, 00:00	Meteorologic Model:	Met 2-50 years
Compute Time:	03Aug2017, 23:10:47	Control Specifications:	Control 1

Volume Units: ○ MM ● 1000 M3

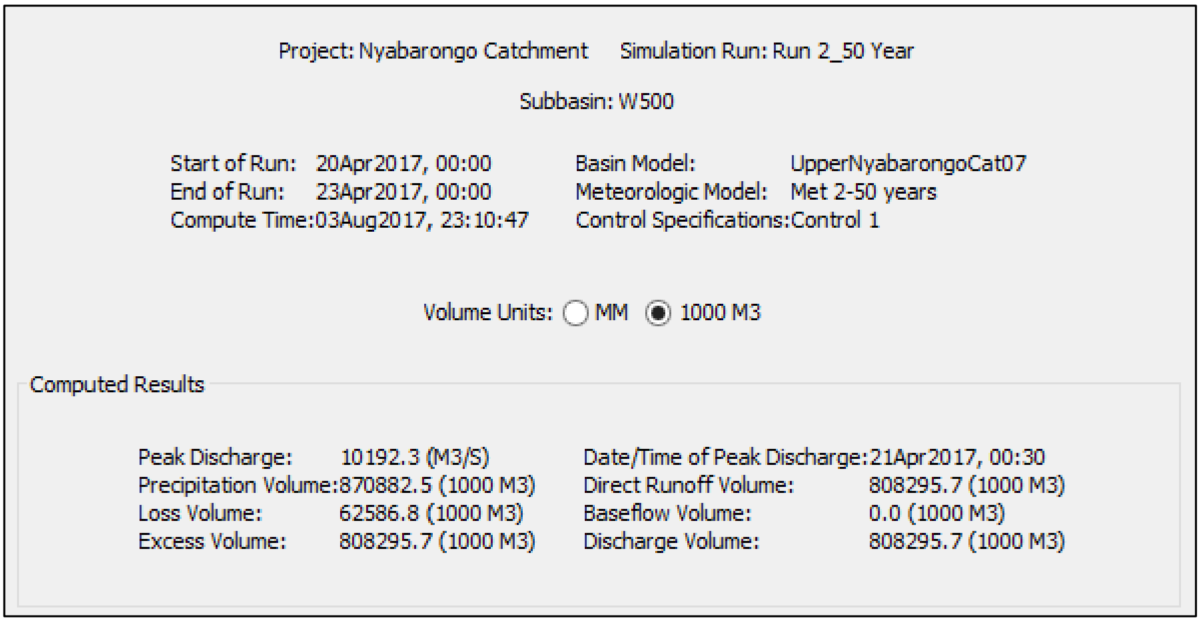
Computed Results

Peak Discharge:	10628.6 (M3/S)	Date/Time of Peak Discharge:	21Apr2017, 00:20
Precipitation Volume:	898561.2 (1000 M3)	Direct Runoff Volume:	841236.5 (1000 M3)
Loss Volume:	57324.7 (1000 M3)	Baseflow Volume:	0.0 (1000 M3)
Excess Volume:	841236.5 (1000 M3)	Discharge Volume:	841236.5 (1000 M3)



Graph for Run 2 of W460

Summary Table for Run 2 of W500



Project: Nyabarongo Catchment   Simulation Run: Run 2_50 Year

Subbasin: W500

Start of Run: 20Apr2017, 00:00
End of Run: 23Apr2017, 00:00
Compute Time: 03Aug2017, 23:10:47

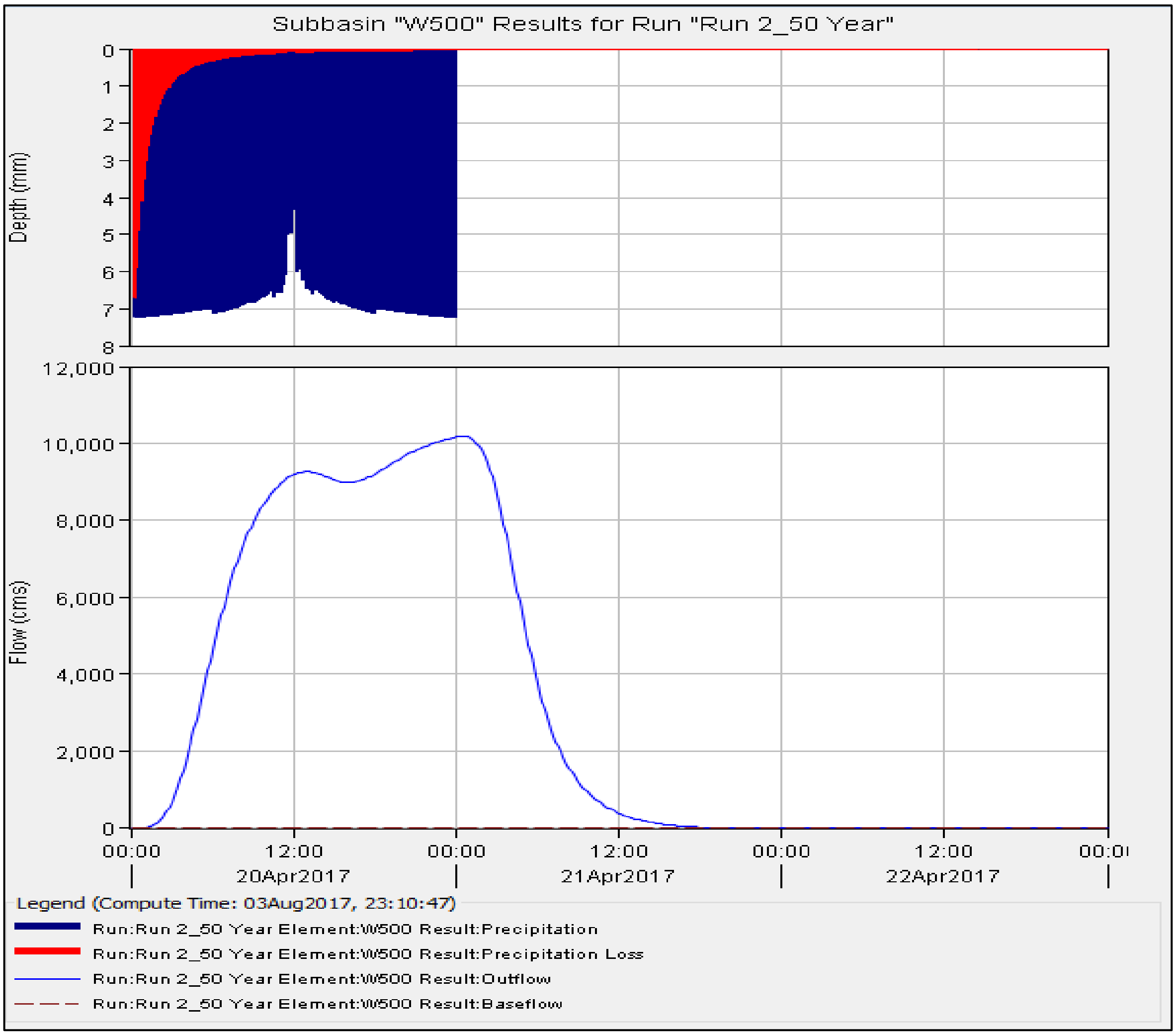
Basin Model: UpperNyabarongoCat07
Meteorologic Model: Met 2-50 years
Control Specifications: Control 1

Volume Units: ○ MM ● 1000 M3

Computed Results

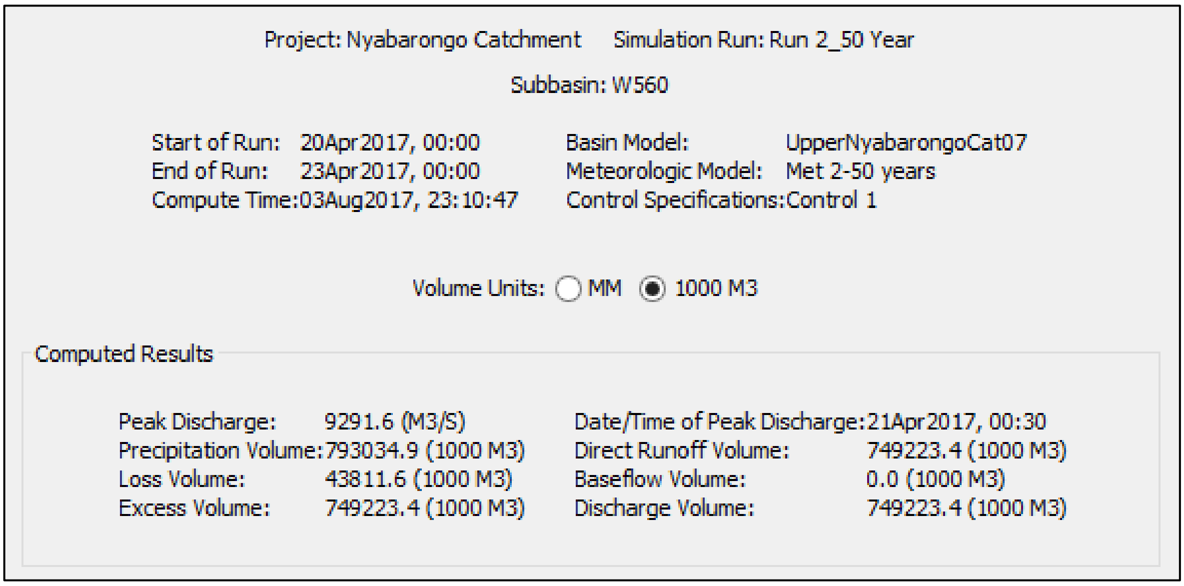
Peak Discharge: 10192.3 (M3/S)
Precipitation Volume: 870882.5 (1000 M3)
Loss Volume: 62586.8 (1000 M3)
Excess Volume: 808295.7 (1000 M3)

Date/Time of Peak Discharge: 21Apr2017, 00:30
Direct Runoff Volume: 808295.7 (1000 M3)
Baseflow Volume: 0.0 (1000 M3)
Discharge Volume: 808295.7 (1000 M3)



Graph for Run 2 of W500

Summary Table for Run 2 of W560



Project: Nyabarongo Catchment   Simulation Run: Run 2_50 Year

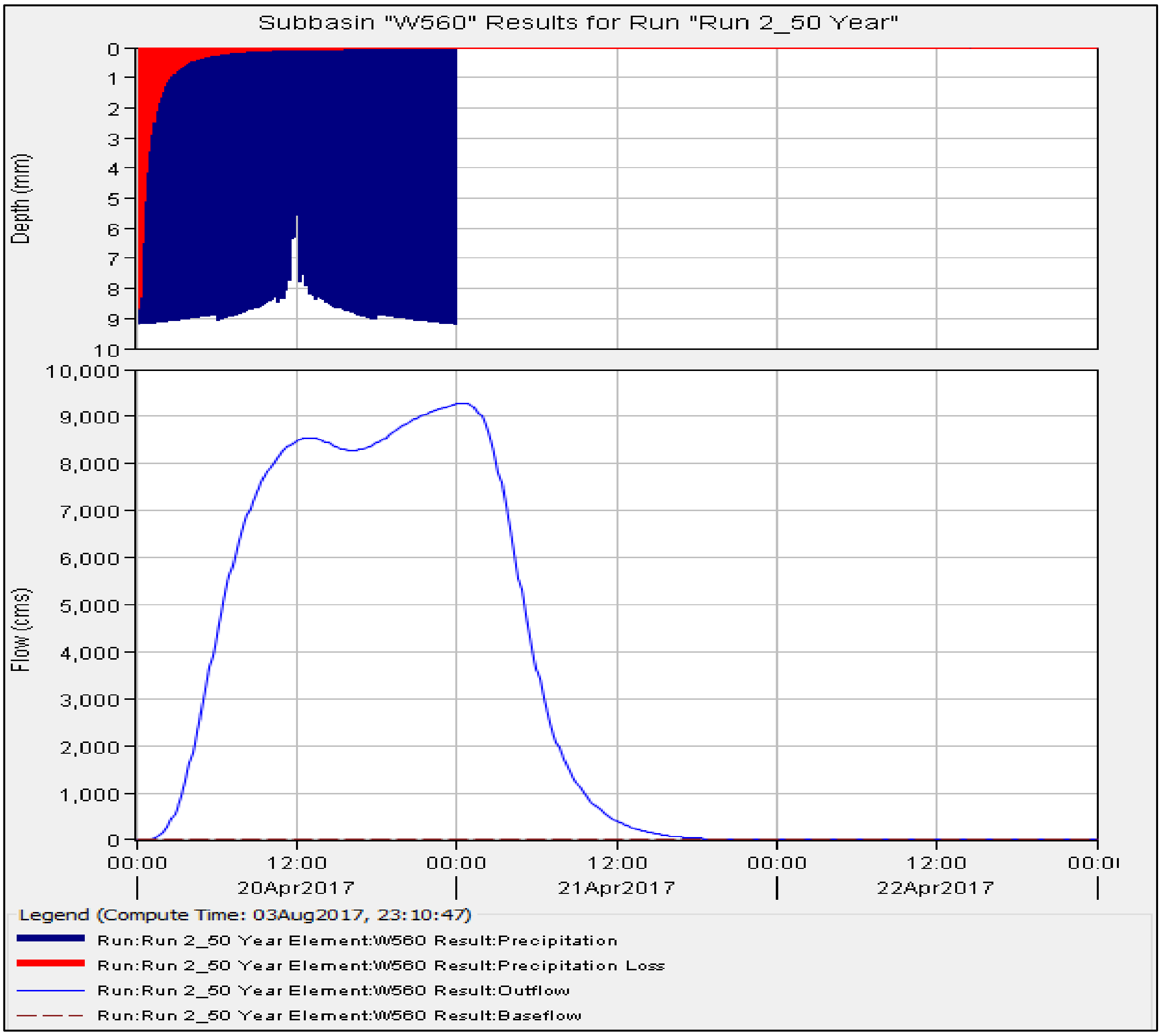
Subbasin: W560

Start of Run: 20Apr2017, 00:00   Basin Model: UpperNyabarongoCat07
End of Run: 23Apr2017, 00:00   Meteorologic Model: Met 2-50 years
Compute Time: 03Aug2017, 23:10:47   Control Specifications: Control 1

Volume Units: ○ MM ● 1000 M3

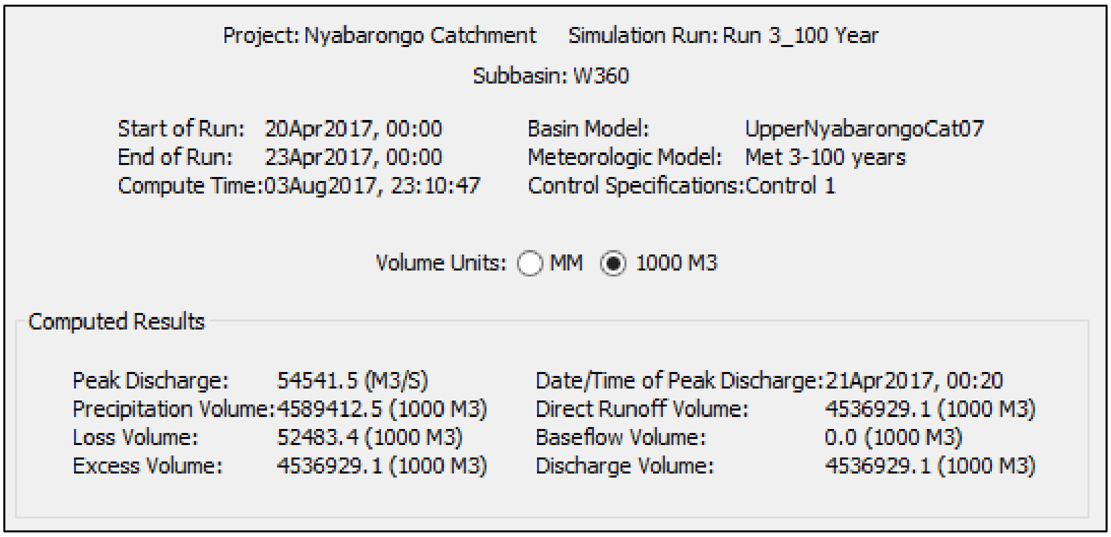
Computed Results

Peak Discharge: 9291.6 (M3/S)   Date/Time of Peak Discharge: 21Apr2017, 00:30
Precipitation Volume: 793034.9 (1000 M3)   Direct Runoff Volume: 749223.4 (1000 M3)
Loss Volume: 43811.6 (1000 M3)   Baseflow Volume: 0.0 (1000 M3)
Excess Volume: 749223.4 (1000 M3)   Discharge Volume: 749223.4 (1000 M3)



Graph for Run 2 of W560

Summary Table for Run 3 of W360


Project: Nyabarongo Catchment Simulation Run: Run 3_100 Year

Subbasin: W360

Start of Run: 20Apr2017, 00:00
End of Run: 23Apr2017, 00:00
Compute Time: 03Aug2017, 23:10:47

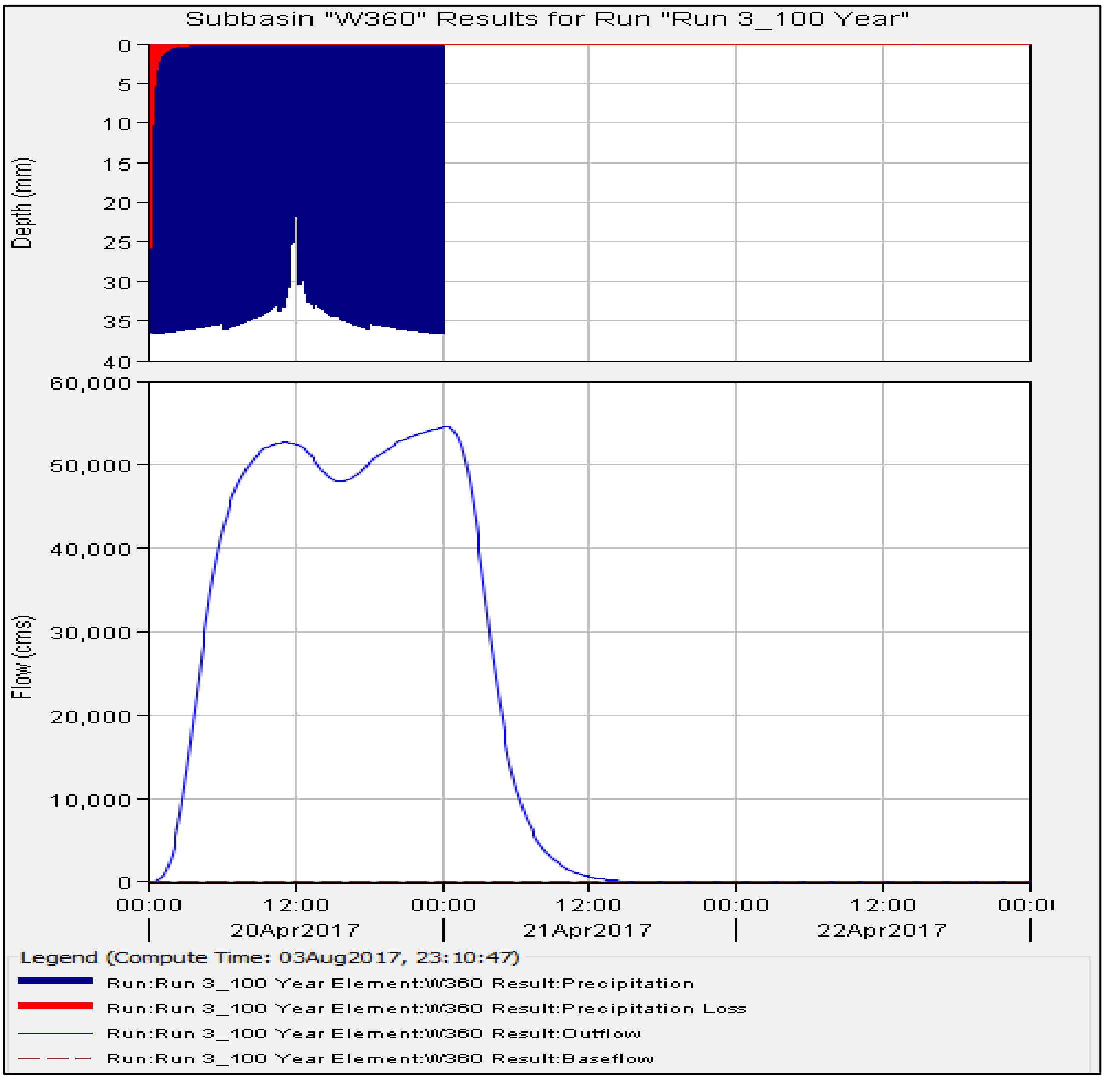
Basin Model: UpperNyabarongoCat07
Meteorologic Model: Met 3-100 years
Control Specifications: Control 1

Volume Units: ○ MM ● 1000 M3

Computed Results

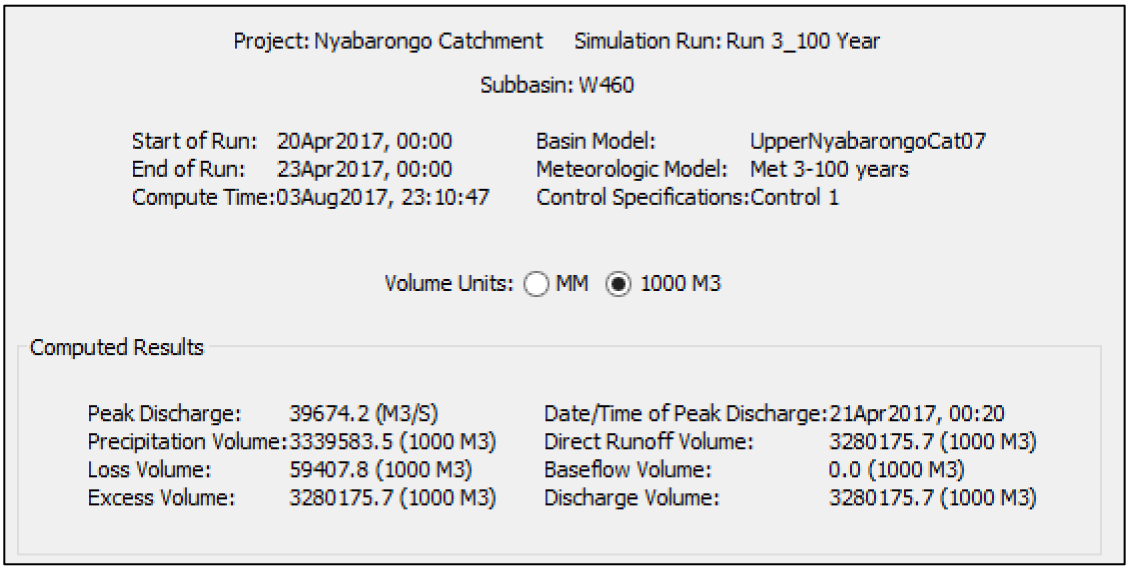
Peak Discharge: 54541.5 (M3/S)
Precipitation Volume: 4589412.5 (1000 M3)
Loss Volume: 52483.4 (1000 M3)
Excess Volume: 4536929.1 (1000 M3)

Date/Time of Peak Discharge: 21Apr2017, 00:20
Direct Runoff Volume: 4536929.1 (1000 M3)
Baseflow Volume: 0.0 (1000 M3)
Discharge Volume: 4536929.1 (1000 M3)



Graph for Run 3 of W360

Summary Table for Run 3 of W460



Project: Nyabarongo Catchment Simulation Run: Run 3_100 Year

Subbasin: W460

Start of Run: 20Apr2017, 00:00
End of Run: 23Apr2017, 00:00
Compute Time: 03Aug2017, 23:10:47

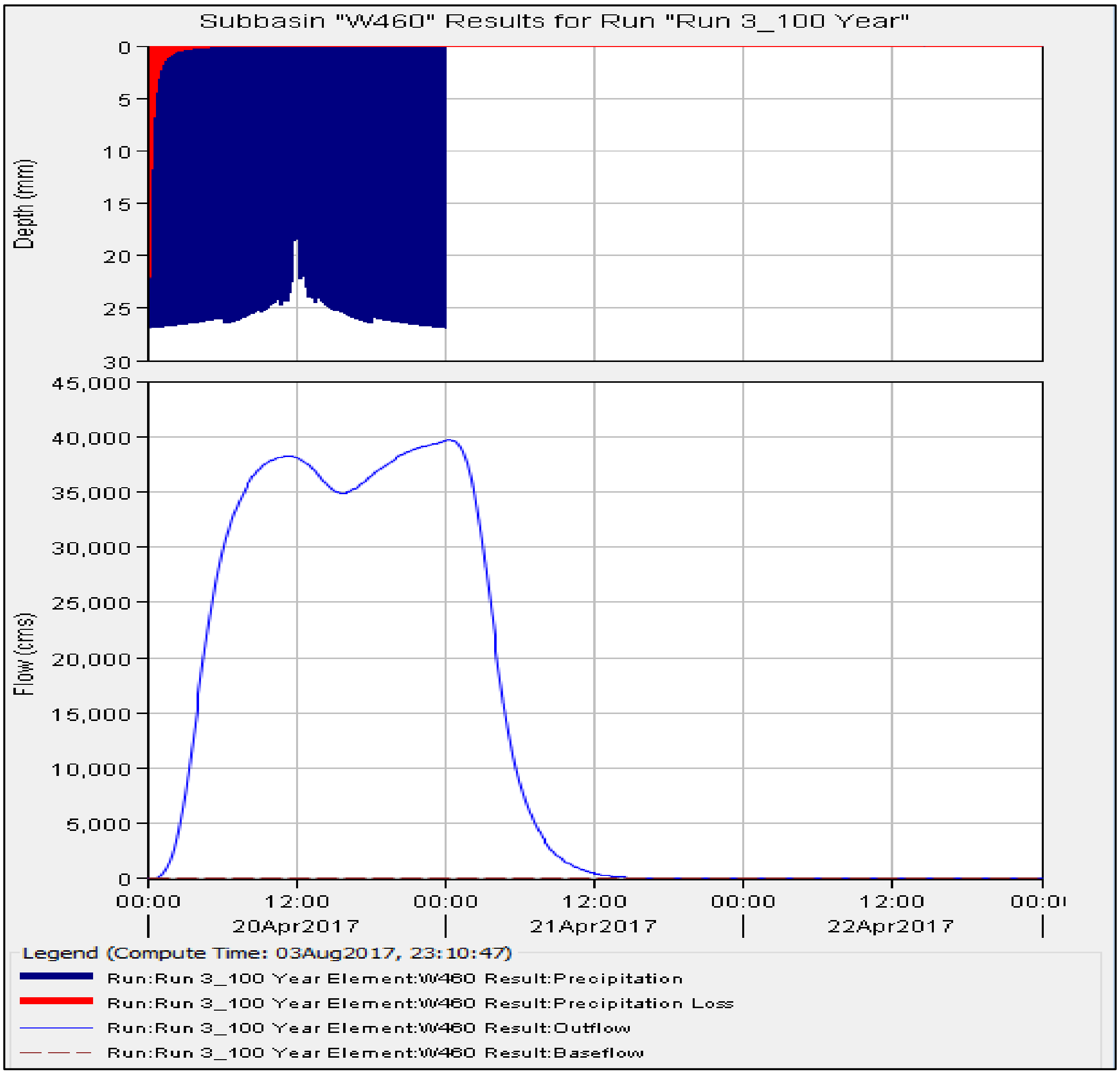
Basin Model: UpperNyabarongoCat07
Meteorologic Model: Met 3-100 years
Control Specifications: Control 1

Volume Units: ○ MM ● 1000 M3

Computed Results

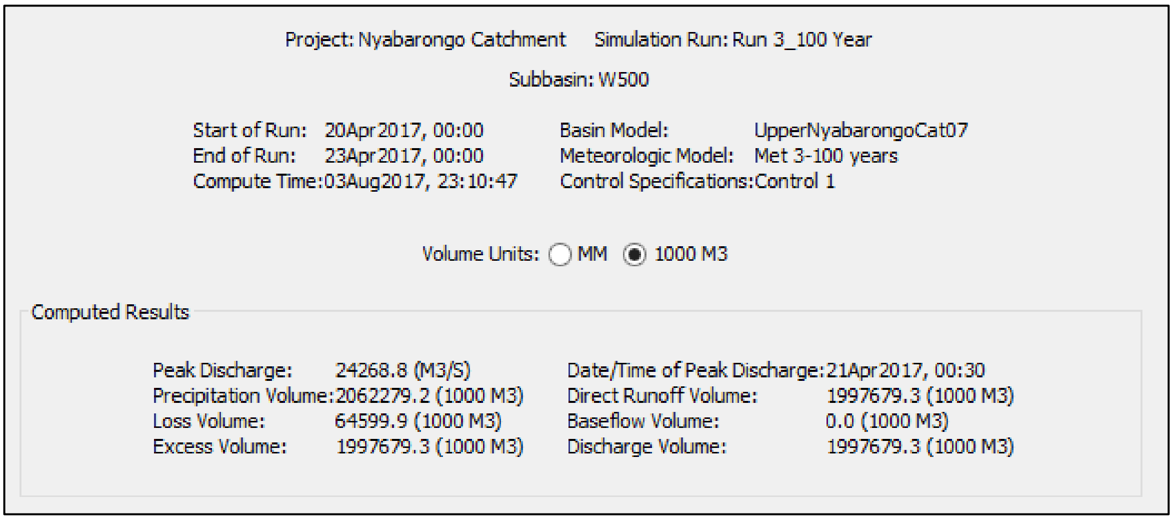
Peak Discharge: 39674.2 (M3/S)
Precipitation Volume: 3339583.5 (1000 M3)
Loss Volume: 59407.8 (1000 M3)
Excess Volume: 3280175.7 (1000 M3)

Date/Time of Peak Discharge: 21Apr2017, 00:20
Direct Runoff Volume: 3280175.7 (1000 M3)
Baseflow Volume: 0.0 (1000 M3)
Discharge Volume: 3280175.7 (1000 M3)



Graph for Run 3 of W460

Summary Table for Run 3 of W500



Project: Nyabarongo Catchment   Simulation Run: Run 3_100 Year

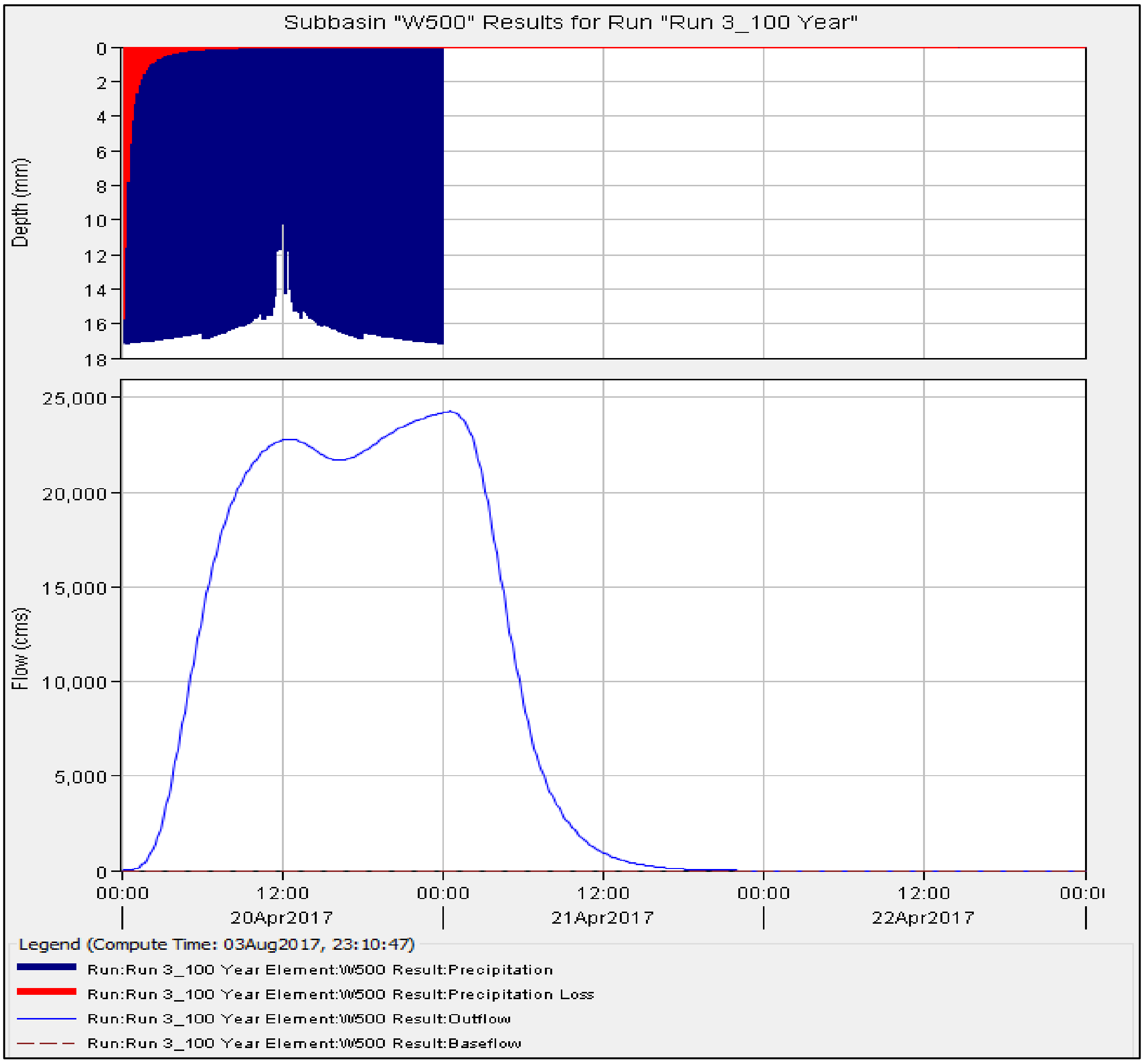
Subbasin: W500

Start of Run:	20Apr2017, 00:00	Basin Model:	UpperNyabarongoCat07
End of Run:	23Apr2017, 00:00	Meteorologic Model:	Met 3-100 years
Compute Time:	03Aug2017, 23:10:47	Control Specifications:	Control 1

Volume Units: ○ MM ● 1000 M3

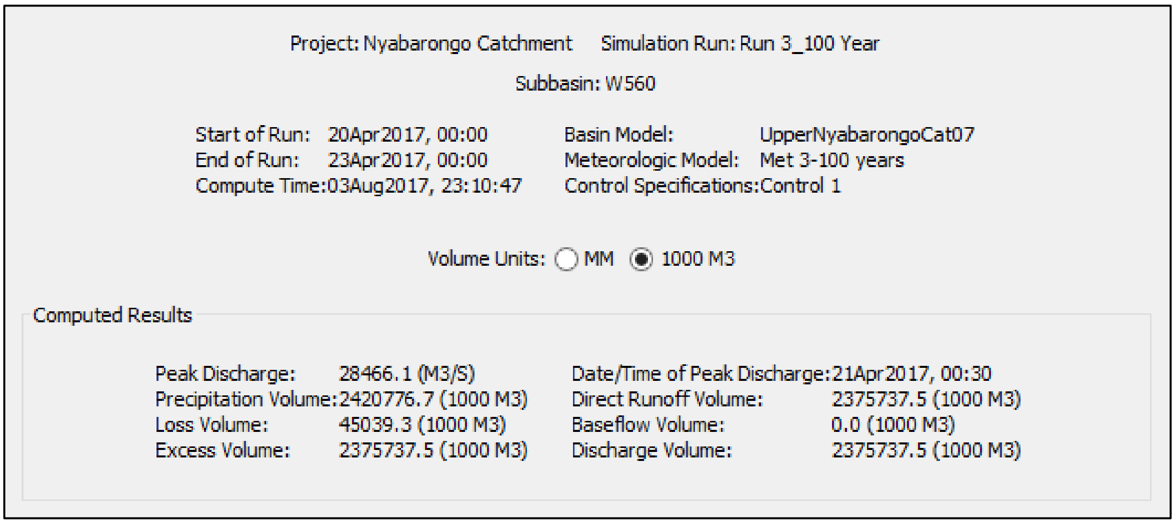
Computed Results

Peak Discharge:	24268.8 (M3/S)	Date/Time of Peak Discharge:	21Apr2017, 00:30
Precipitation Volume:	2062279.2 (1000 M3)	Direct Runoff Volume:	1997679.3 (1000 M3)
Loss Volume:	64599.9 (1000 M3)	Baseflow Volume:	0.0 (1000 M3)
Excess Volume:	1997679.3 (1000 M3)	Discharge Volume:	1997679.3 (1000 M3)



: Graph for Run 3 of W500

Summary Table for Run 3 of W560



Project: Nyabarongo Catchment Simulation Run: Run 3_100 Year

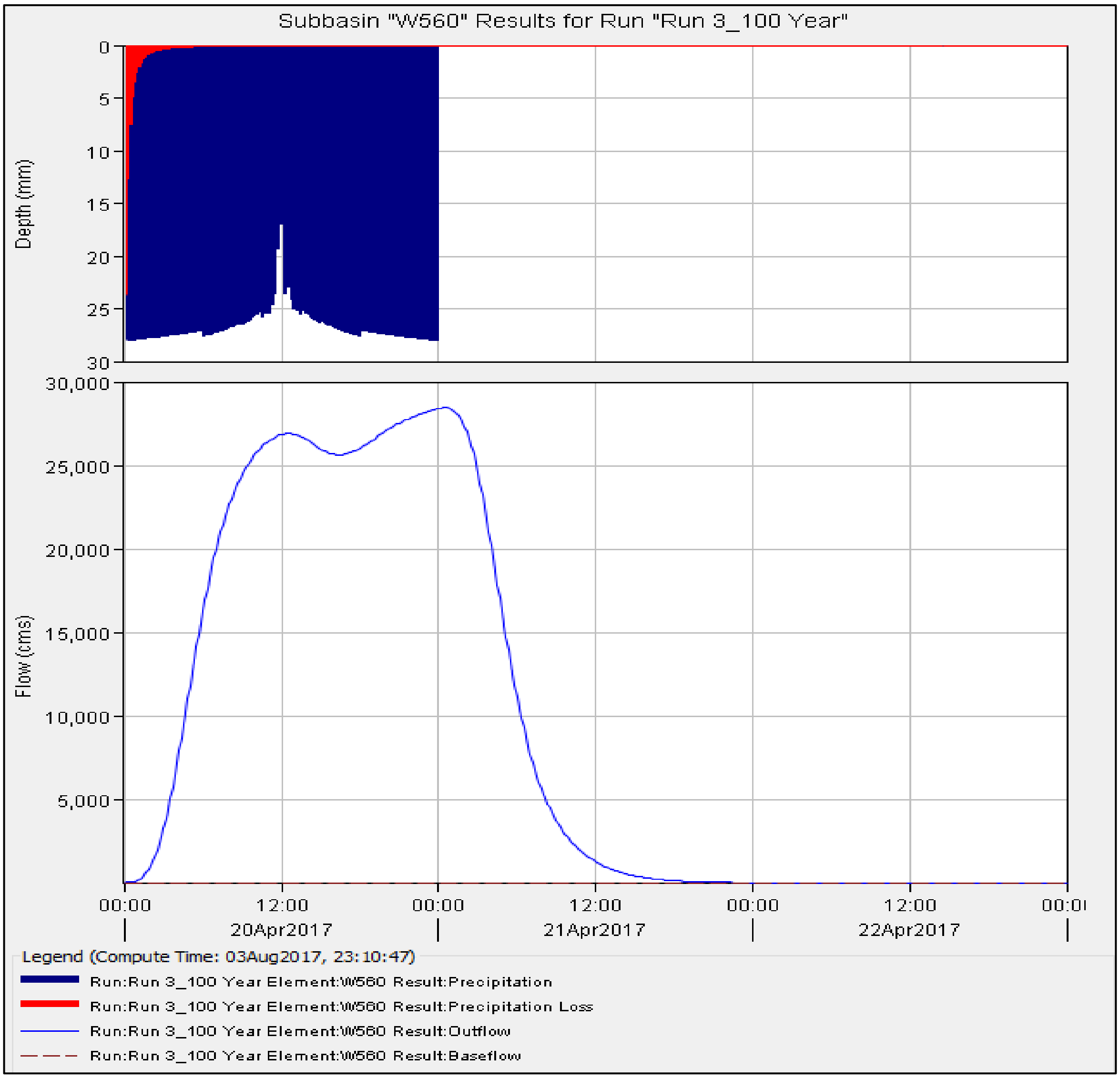
Subbasin: W560

Start of Run:	20Apr2017, 00:00	Basin Model:	UpperNyabarongoCat07
End of Run:	23Apr2017, 00:00	Meteorologic Model:	Met 3-100 years
Compute Time:	03Aug2017, 23:10:47	Control Specifications:	Control 1

Volume Units: ○ MM ● 1000 M3

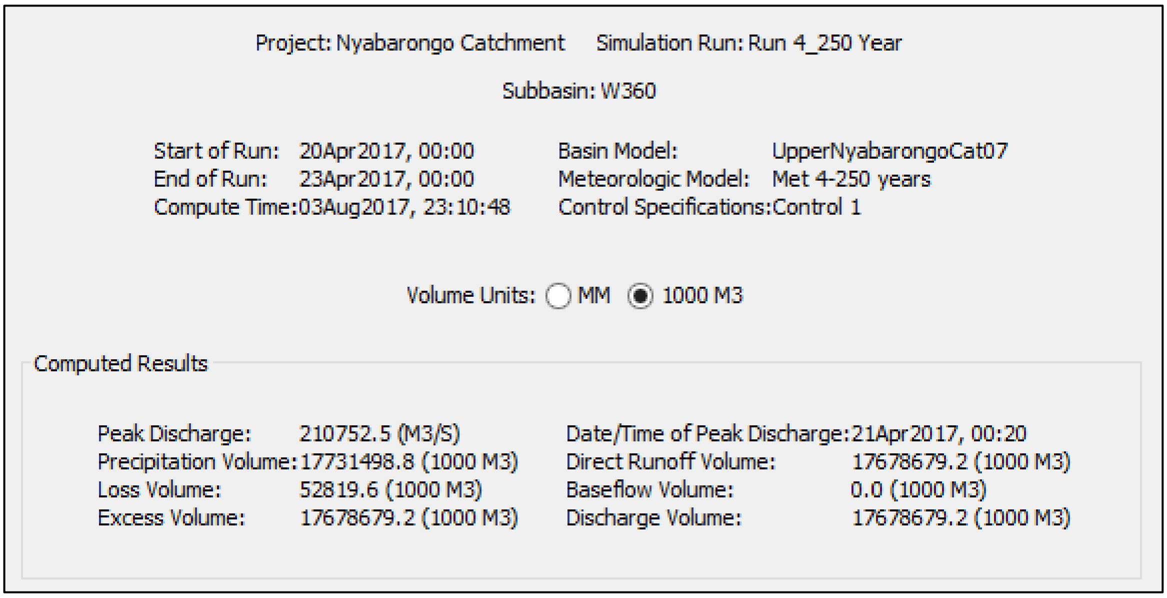
Computed Results

Peak Discharge:	28466.1 (M3/S)	Date/Time of Peak Discharge:	21Apr2017, 00:30
Precipitation Volume:	2420776.7 (1000 M3)	Direct Runoff Volume:	2375737.5 (1000 M3)
Loss Volume:	45039.3 (1000 M3)	Baseflow Volume:	0.0 (1000 M3)
Excess Volume:	2375737.5 (1000 M3)	Discharge Volume:	2375737.5 (1000 M3)



Graph for Run 3 of W560

Summary Table for Run 4 of W360



Project: Nyabarongo Catchment   Simulation Run: Run 4_250 Year

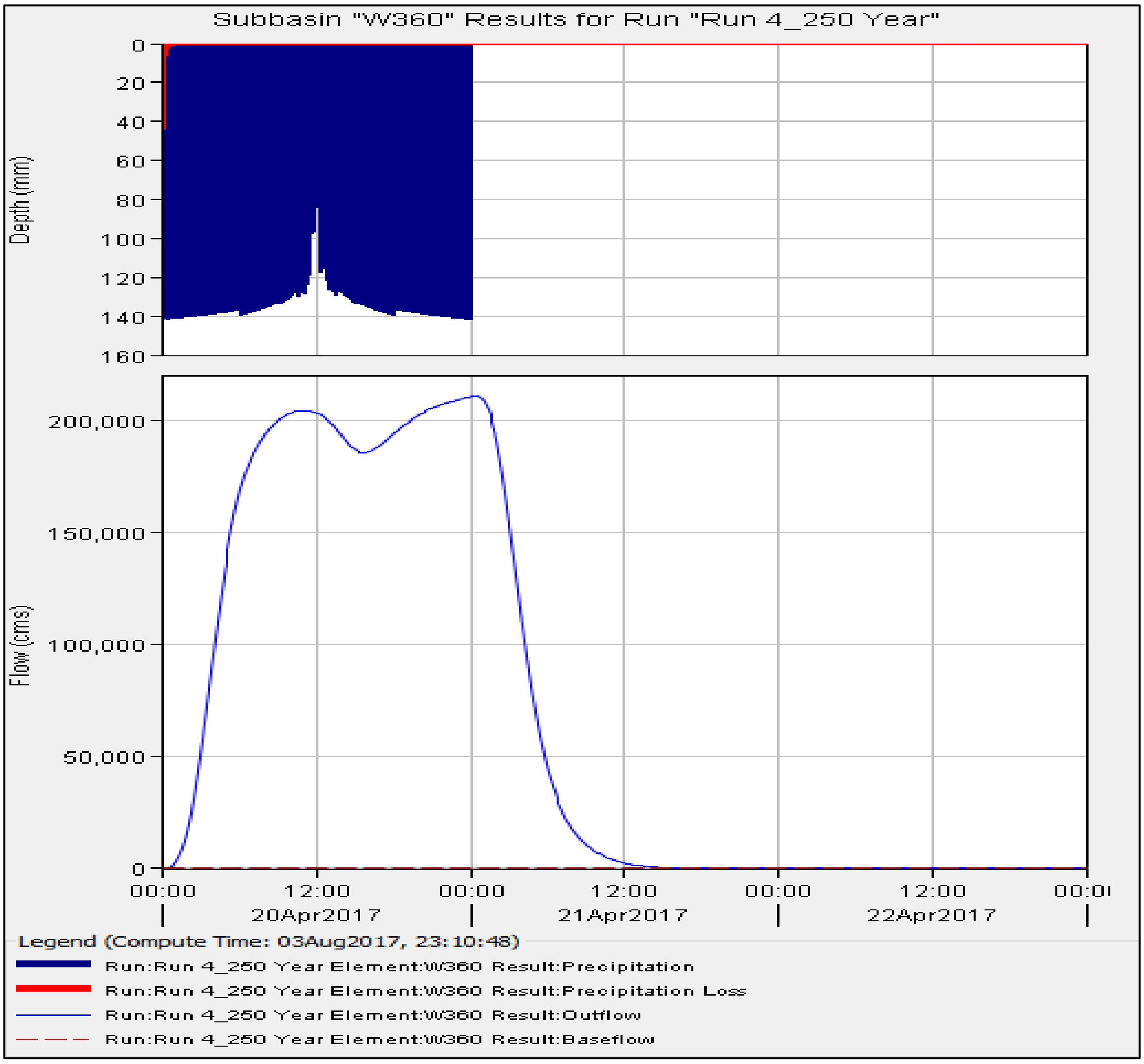
Subbasin: W360

Start of Run: 20Apr2017, 00:00   Basin Model: UpperNyabarongoCat07
End of Run: 23Apr2017, 00:00   Meteorologic Model: Met 4-250 years
Compute Time:03Aug2017, 23:10:48   Control Specifications:Control 1

Volume Units: ○ MM ● 1000 M3

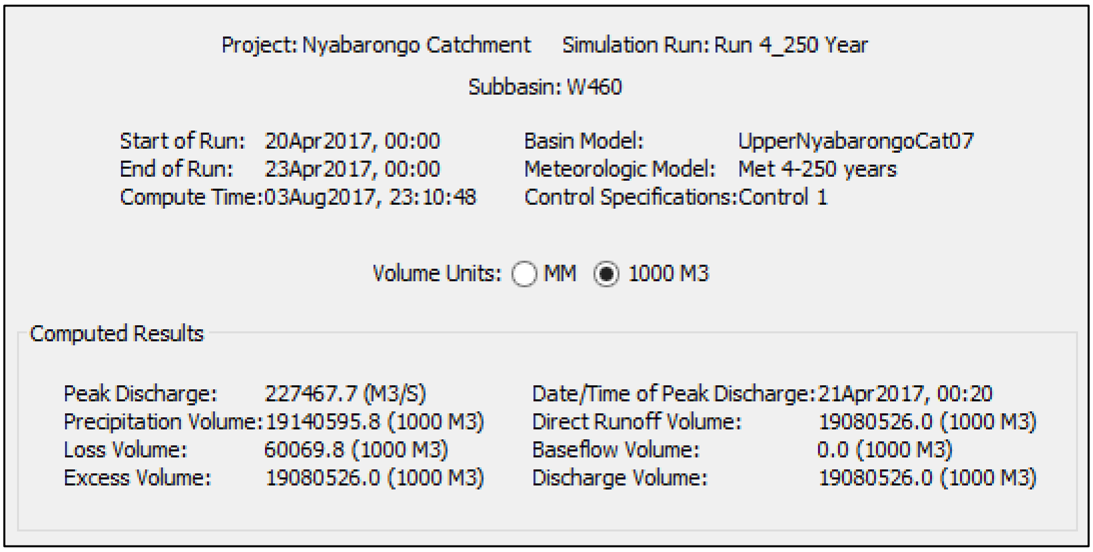
Computed Results

Peak Discharge:	210752.5 (M3/S)	Date/Time of Peak Discharge:	21Apr2017, 00:20
Precipitation Volume:	17731498.8 (1000 M3)	Direct Runoff Volume:	17678679.2 (1000 M3)
Loss Volume:	52819.6 (1000 M3)	Baseflow Volume:	0.0 (1000 M3)
Excess Volume:	17678679.2 (1000 M3)	Discharge Volume:	17678679.2 (1000 M3)



Graph for Run 4 of W360

Summary Table for Run 4 of W460



Project: Nyabarongo Catchment Simulation Run: Run 4_250 Year

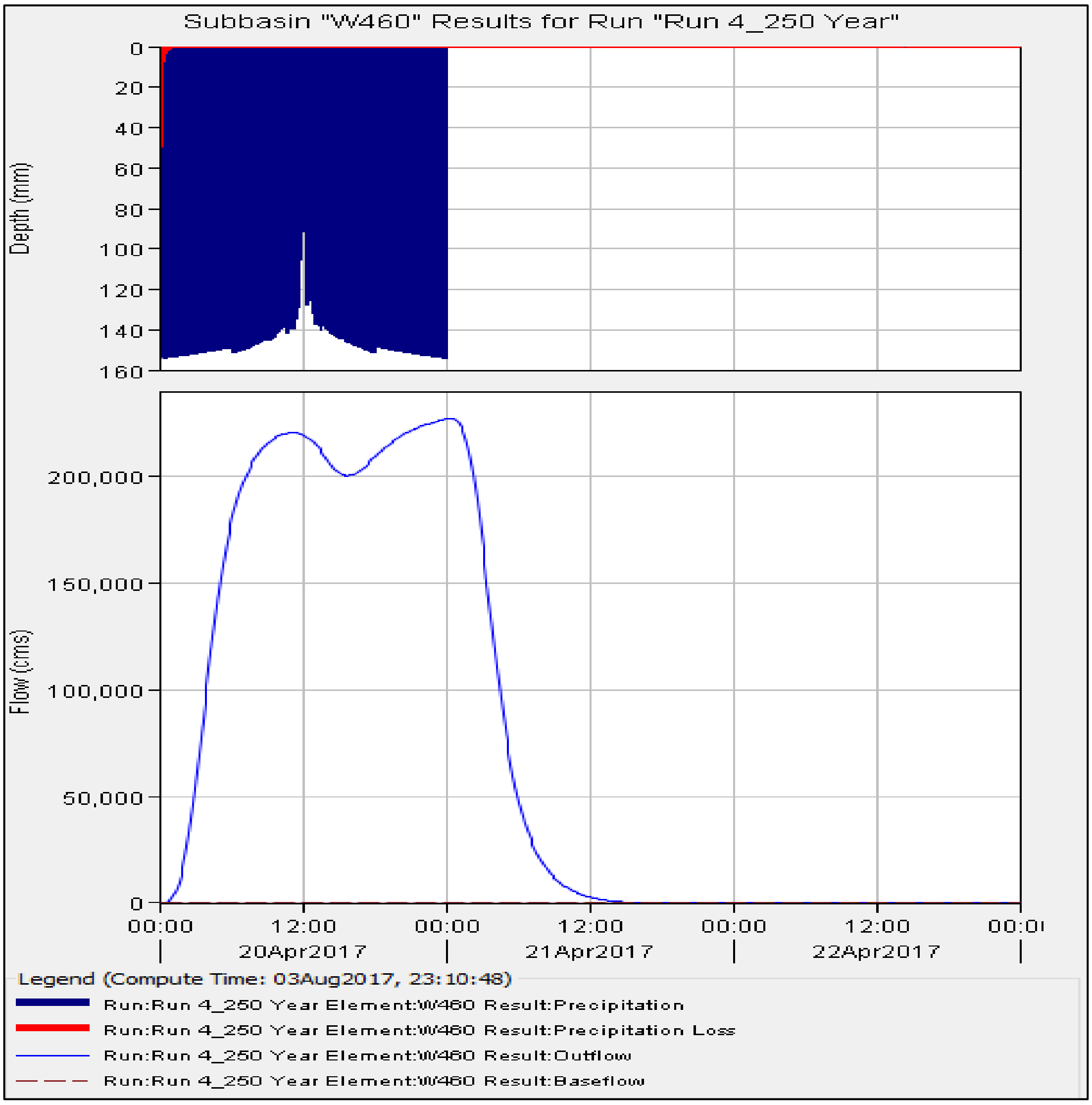
Subbasin: W460

Start of Run:	20Apr2017, 00:00	Basin Model:	UpperNyabarongoCat07
End of Run:	23Apr2017, 00:00	Meteorologic Model:	Met 4-250 years
Compute Time:	03Aug2017, 23:10:48	Control Specifications:	Control 1

Volume Units: ○ MM ● 1000 M3

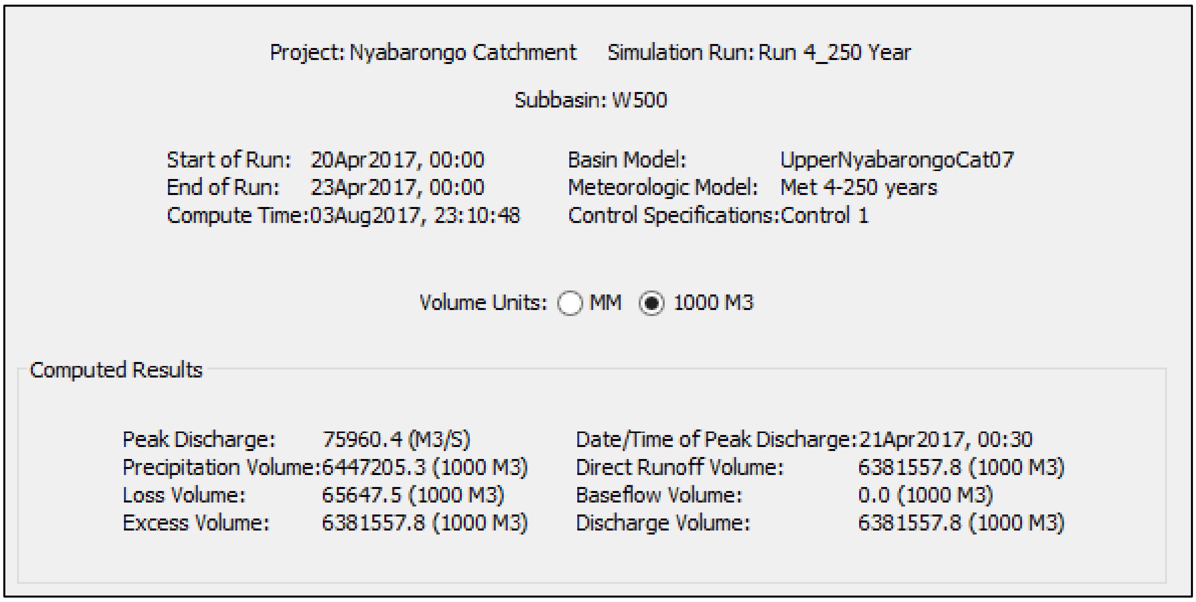
Computed Results

Peak Discharge:	227467.7 (M3/S)	Date/Time of Peak Discharge:	21Apr2017, 00:20
Precipitation Volume:	19140595.8 (1000 M3)	Direct Runoff Volume:	19080526.0 (1000 M3)
Loss Volume:	60069.8 (1000 M3)	Baseflow Volume:	0.0 (1000 M3)
Excess Volume:	19080526.0 (1000 M3)	Discharge Volume:	19080526.0 (1000 M3)



Graph for Run 4 of W460

: Summary Table for Run 4 of W500



Project: Nyabarongo Catchment Simulation Run: Run 4_250 Year

Subbasin: W500

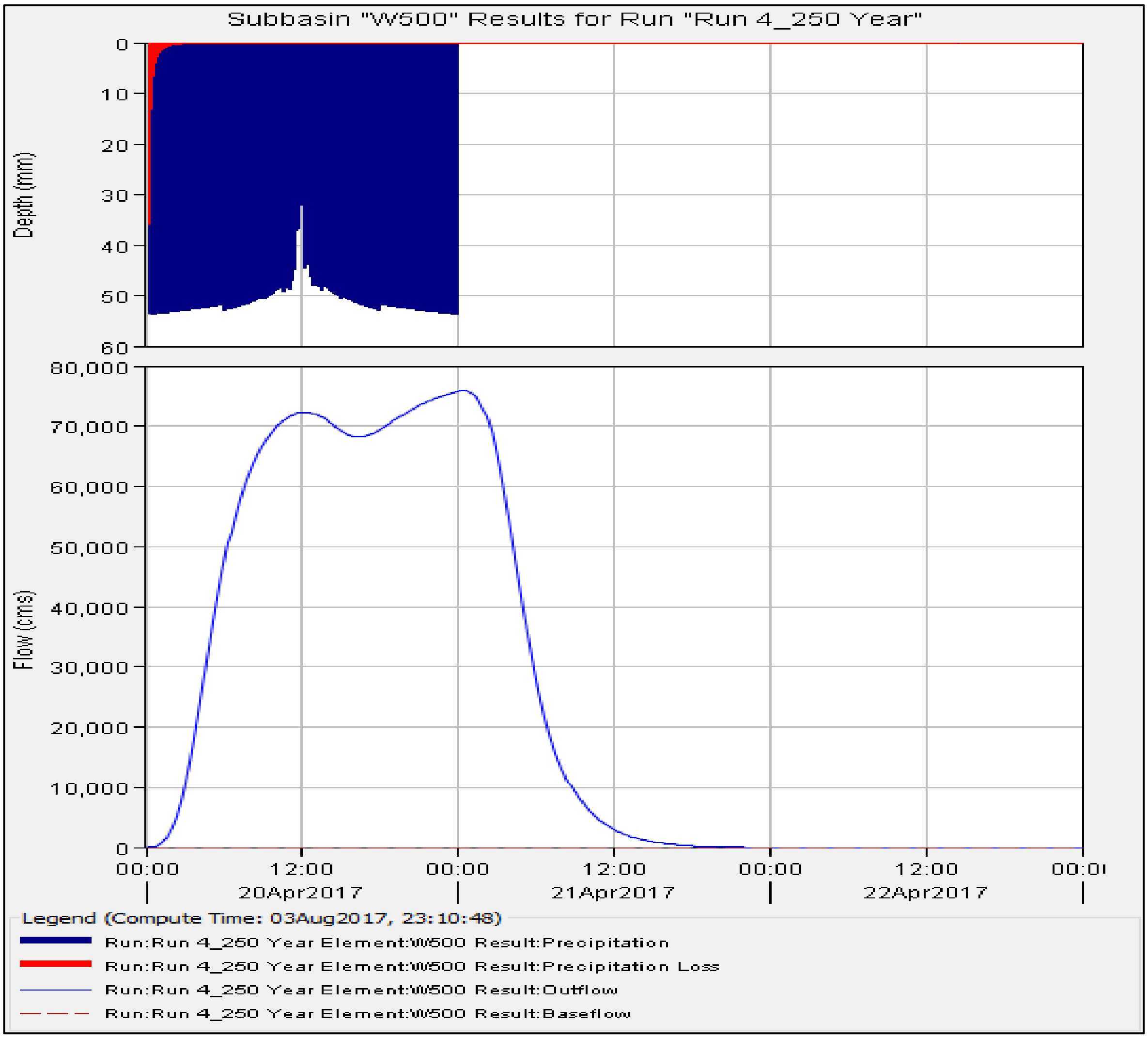
Start of Run: 20Apr2017, 00:00
End of Run: 23Apr2017, 00:00
Compute Time: 03Aug2017, 23:10:48

Basin Model: UpperNyabarongoCat07
Meteorologic Model: Met 4-250 years
Control Specifications: Control 1

Volume Units: ○ MM ● 1000 M3

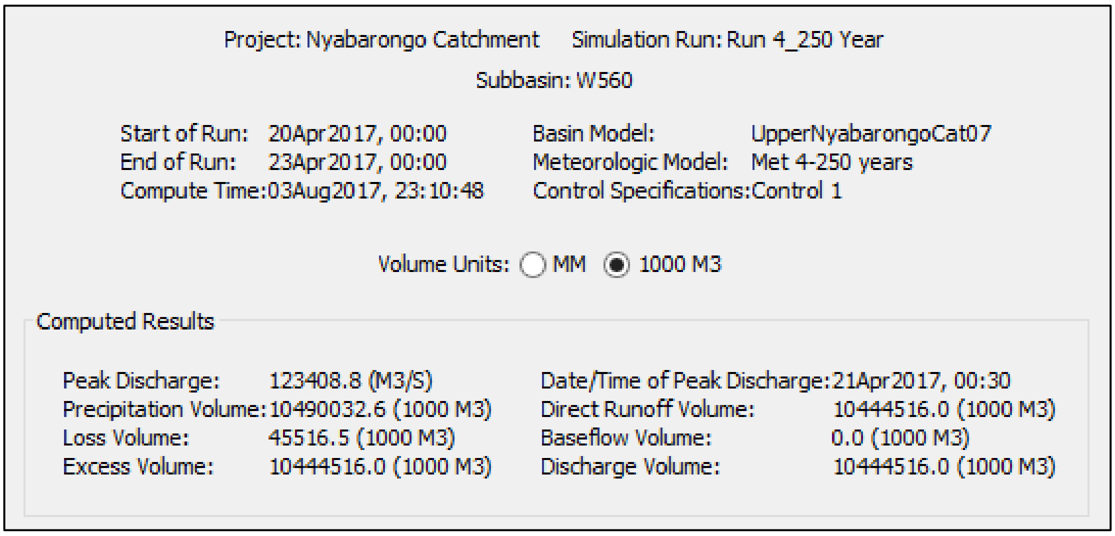
Computed Results

Peak Discharge:	75960.4 (M3/S)	Date/Time of Peak Discharge:	21Apr2017, 00:30
Precipitation Volume:	6447205.3 (1000 M3)	Direct Runoff Volume:	6381557.8 (1000 M3)
Loss Volume:	65647.5 (1000 M3)	Baseflow Volume:	0.0 (1000 M3)
Excess Volume:	6381557.8 (1000 M3)	Discharge Volume:	6381557.8 (1000 M3)



Graph for Run 4 of W500

Summary Table for Run 4 of W560



Project: Nyabarongo Catchment   Simulation Run: Run 4_250 Year

Subbasin: W560

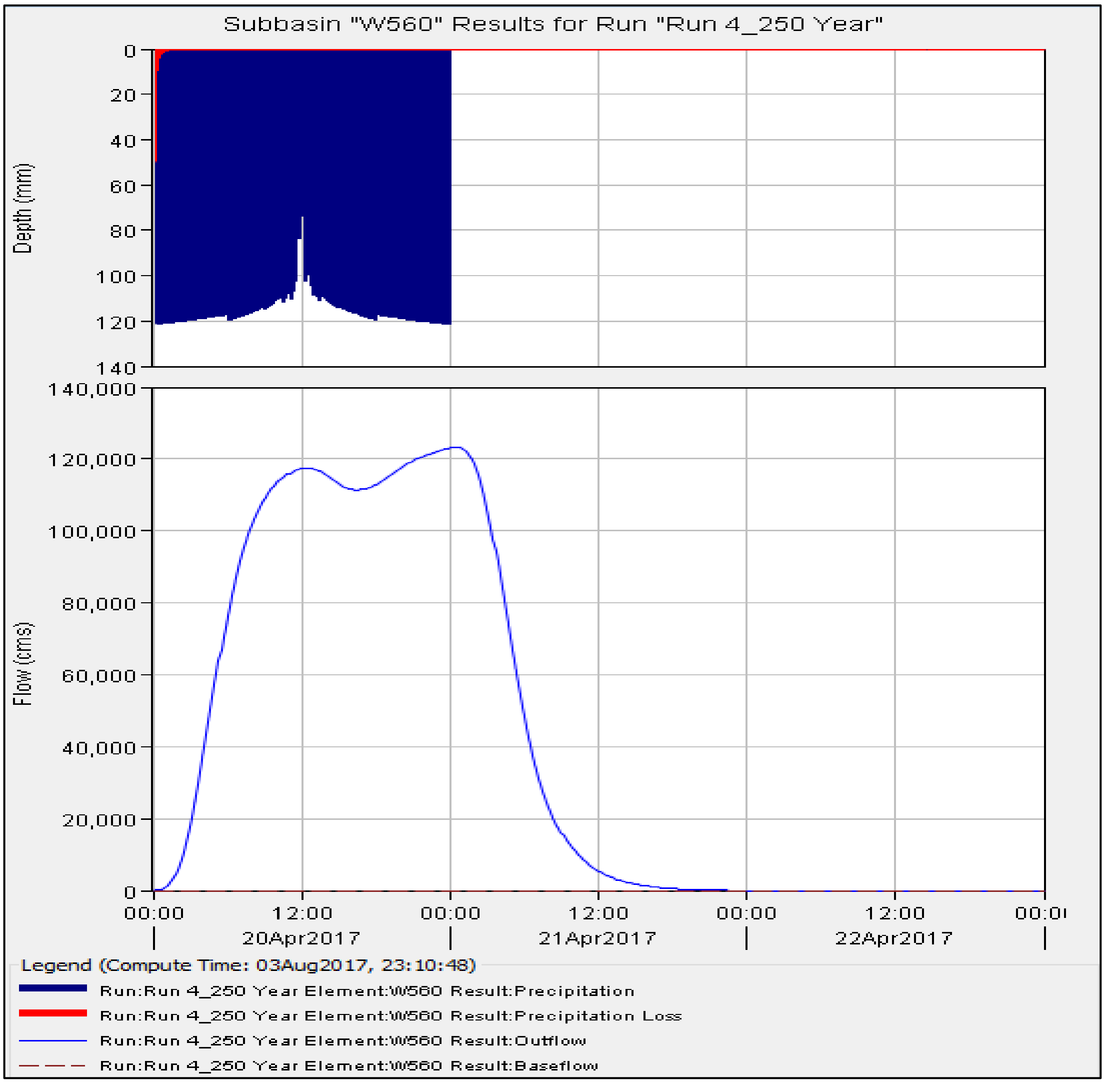
Start of Run: 20Apr2017, 00:00
End of Run: 23Apr2017, 00:00
Compute Time: 03Aug2017, 23:10:48

Basin Model: UpperNyabarongoCat07
Meteorologic Model: Met 4-250 years
Control Specifications: Control 1

Volume Units: ○ MM ● 1000 M3

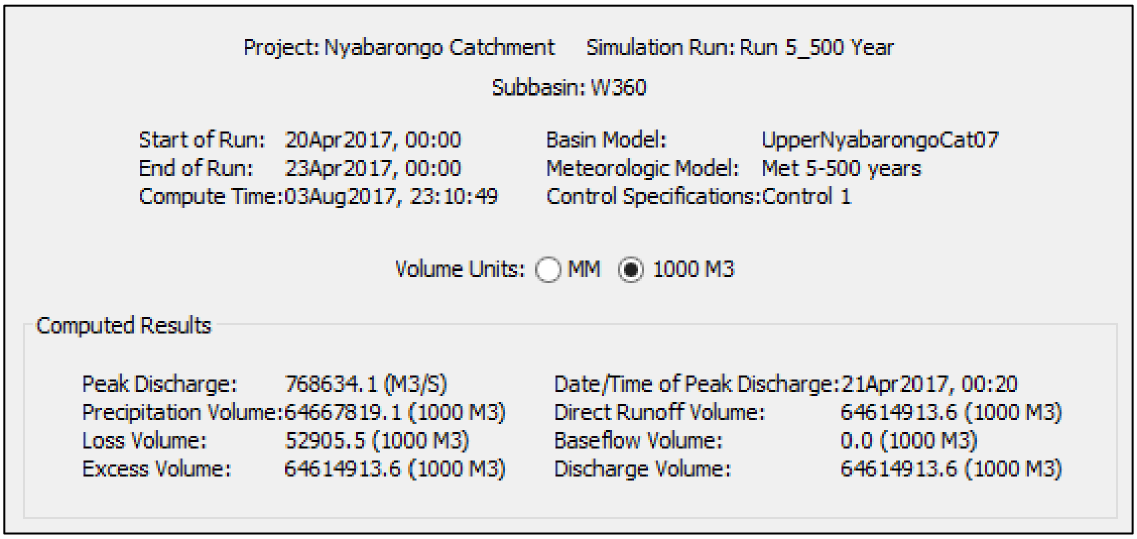
Computed Results

Peak Discharge:	123408.8 (M3/S)	Date/Time of Peak Discharge:	21Apr2017, 00:30
Precipitation Volume:	10490032.6 (1000 M3)	Direct Runoff Volume:	10444516.0 (1000 M3)
Loss Volume:	45516.5 (1000 M3)	Baseflow Volume:	0.0 (1000 M3)
Excess Volume:	10444516.0 (1000 M3)	Discharge Volume:	10444516.0 (1000 M3)



Graph for Run 4 of W560

Summary Table for Run 5 of W360



Project: Nyabarongo Catchment Simulation Run: Run 5_500 Year

Subbasin: W360

Start of Run: 20Apr2017, 00:00
End of Run: 23Apr2017, 00:00
Compute Time:03Aug2017, 23:10:49

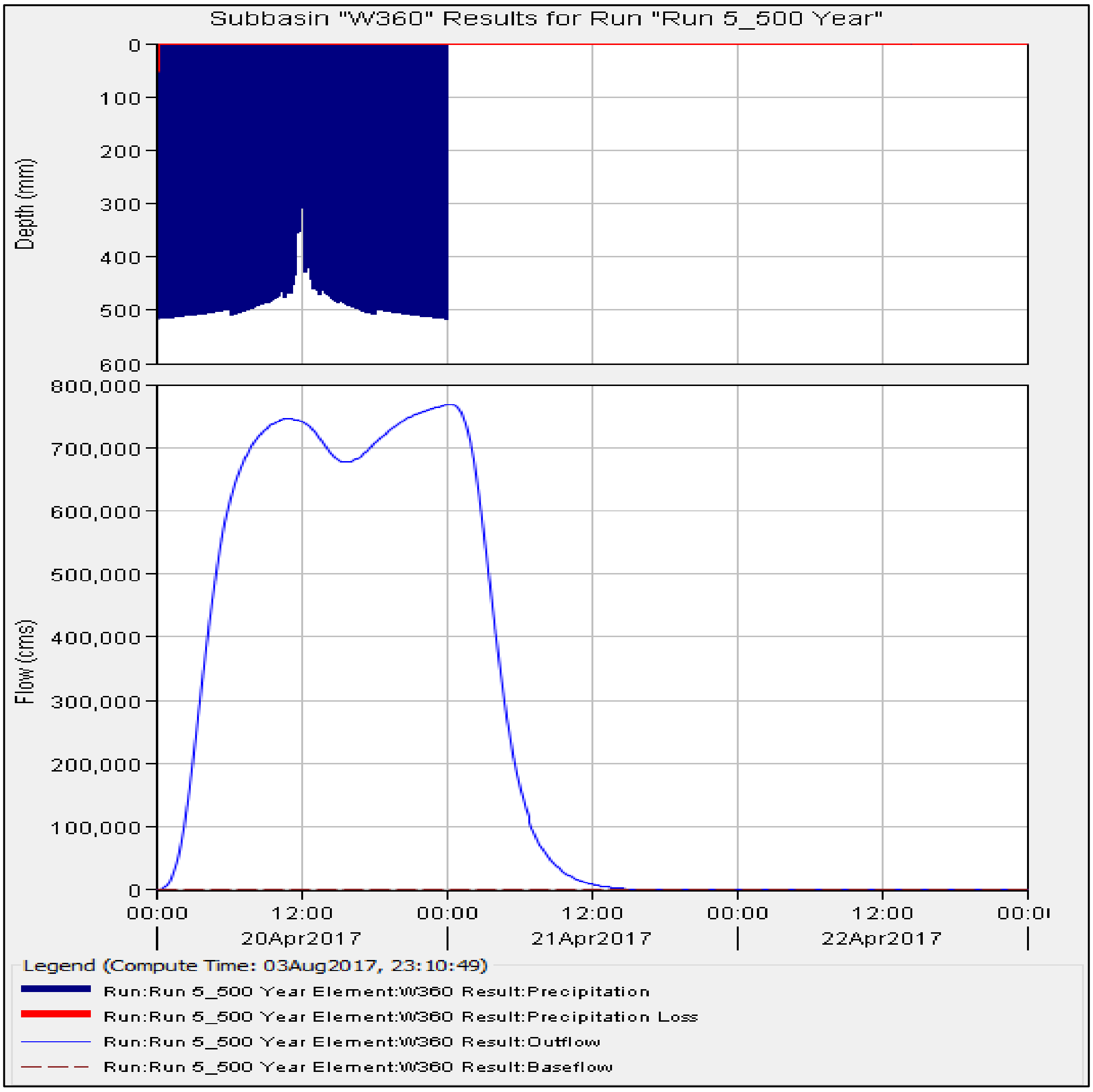
Basin Model: UpperNyabarongoCat07
Meteorologic Model: Met 5-500 years
Control Specifications:Control 1

Volume Units: ○ MM ● 1000 M3

Computed Results

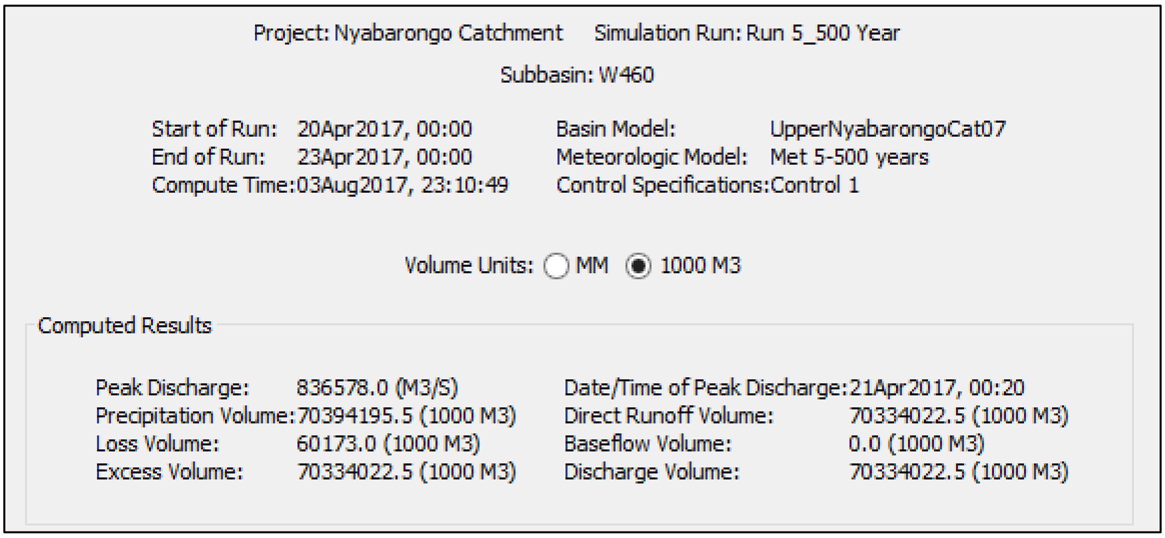
Peak Discharge: 768634.1 (M3/S)
Precipitation Volume:64667819.1 (1000 M3)
Loss Volume: 52905.5 (1000 M3)
Excess Volume: 64614913.6 (1000 M3)

Date/Time of Peak Discharge:21Apr2017, 00:20
Direct Runoff Volume: 64614913.6 (1000 M3)
Baseflow Volume: 0.0 (1000 M3)
Discharge Volume: 64614913.6 (1000 M3)



Graph for Run 5 of W360

TSummary Table for Run 5 of W460



Project: Nyabarongo Catchment Simulation Run: Run 5_500 Year

Subbasin: W460

Start of Run: 20Apr2017, 00:00
End of Run: 23Apr2017, 00:00
Compute Time: 03Aug2017, 23:10:49

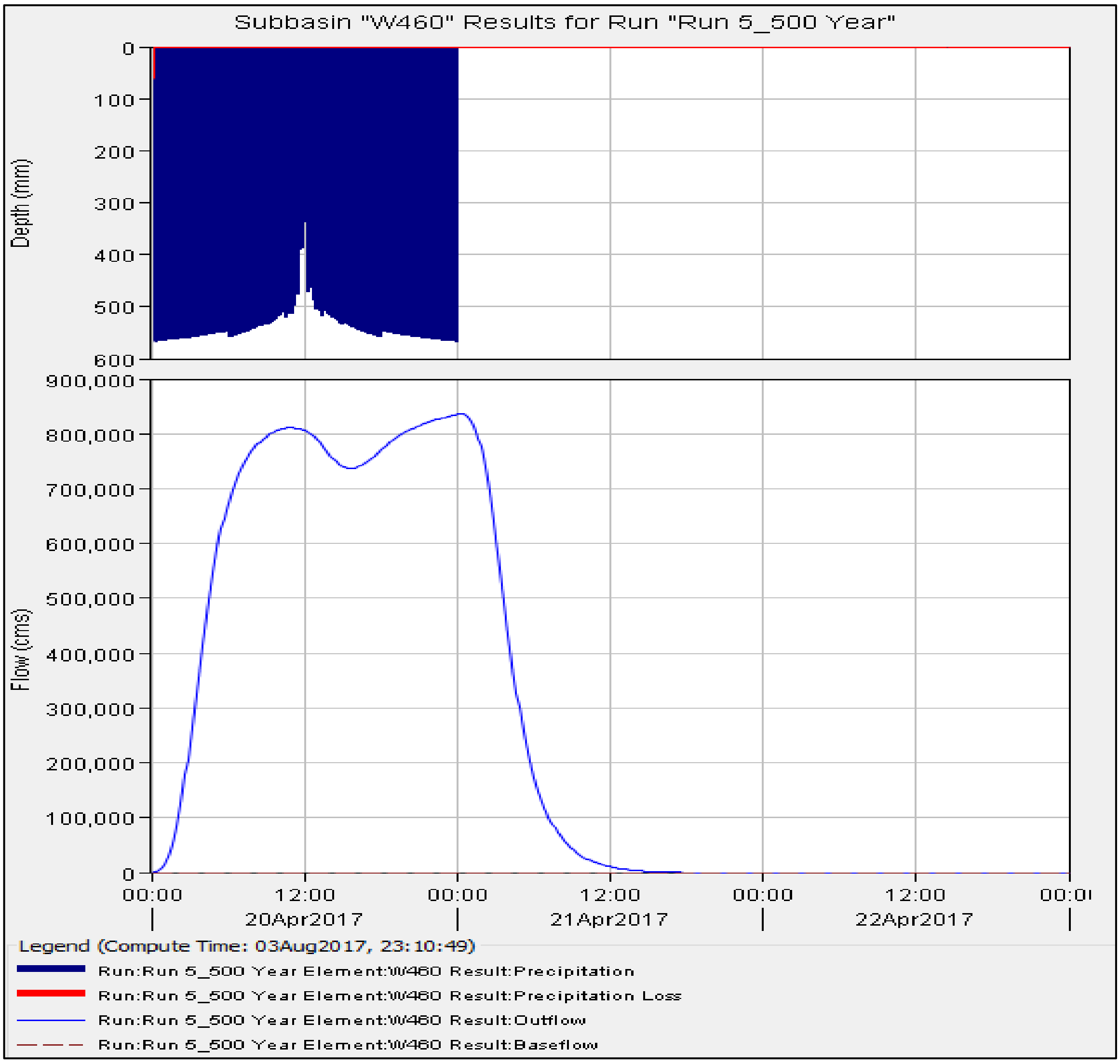
Basin Model: UpperNyabarongoCat07
Meteorologic Model: Met 5-500 years
Control Specifications: Control 1

Volume Units: ○ MM ● 1000 M3

Computed Results

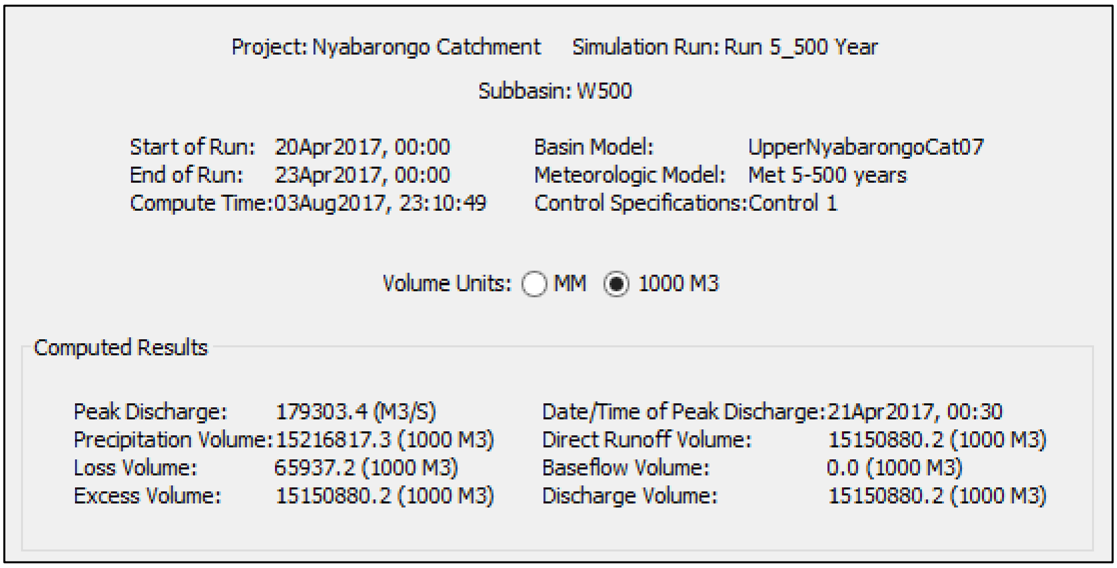
Peak Discharge: 836578.0 (M3/S)
Precipitation Volume: 70394195.5 (1000 M3)
Loss Volume: 60173.0 (1000 M3)
Excess Volume: 70334022.5 (1000 M3)

Date/Time of Peak Discharge: 21Apr2017, 00:20
Direct Runoff Volume: 70334022.5 (1000 M3)
Baseflow Volume: 0.0 (1000 M3)
Discharge Volume: 70334022.5 (1000 M3)



Graph for Run 5 of W460

Summary Table for Run 5 of W500



Project: Nyabarongo Catchment Simulation Run: Run 5_500 Year

Subbasin: W500

Start of Run: 20Apr2017, 00:00
End of Run: 23Apr2017, 00:00
Compute Time: 03Aug2017, 23:10:49

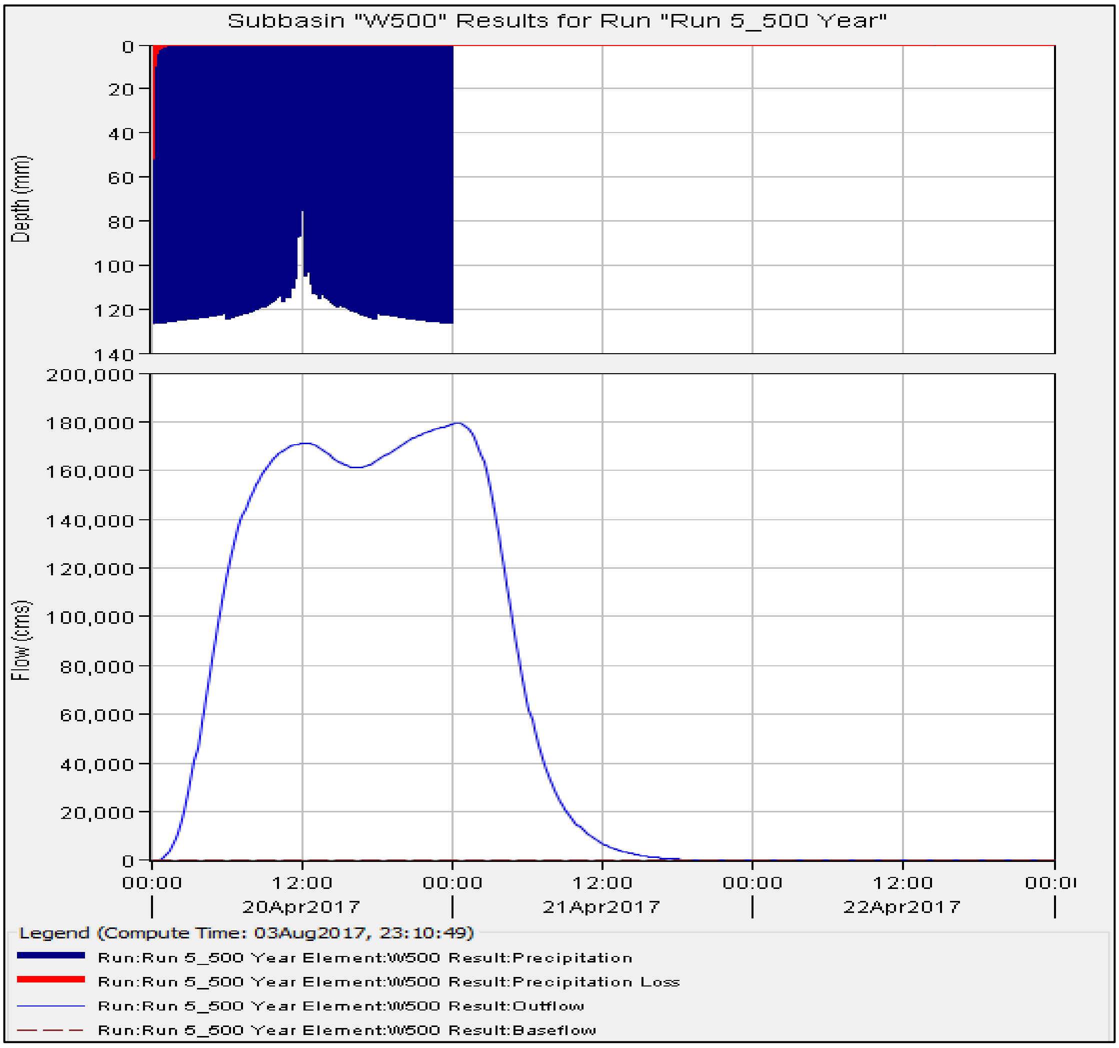
Basin Model: UpperNyabarongoCat07
Meteorologic Model: Met 5-500 years
Control Specifications: Control 1

Volume Units: ○ MM ● 1000 M3

Computed Results

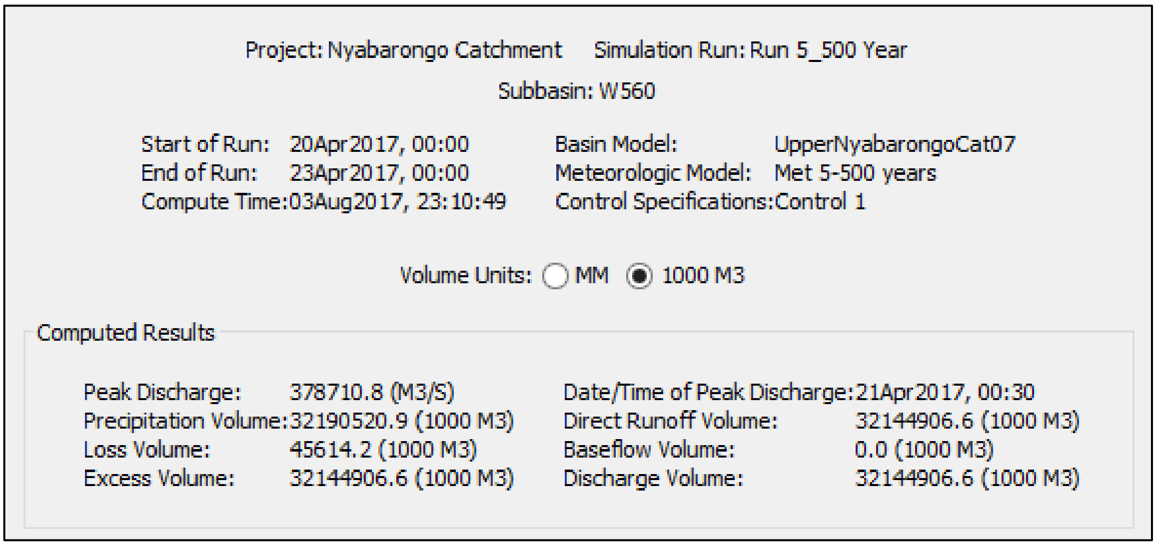
Peak Discharge: 179303.4 (M3/S)
Precipitation Volume: 15216817.3 (1000 M3)
Loss Volume: 65937.2 (1000 M3)
Excess Volume: 15150880.2 (1000 M3)

Date/Time of Peak Discharge: 21Apr2017, 00:30
Direct Runoff Volume: 15150880.2 (1000 M3)
Baseflow Volume: 0.0 (1000 M3)
Discharge Volume: 15150880.2 (1000 M3)



Graph for Run 5 of W500

Summary Table for Run 5 of W560



Project: Nyabarongo Catchment   Simulation Run: Run 5_500 Year

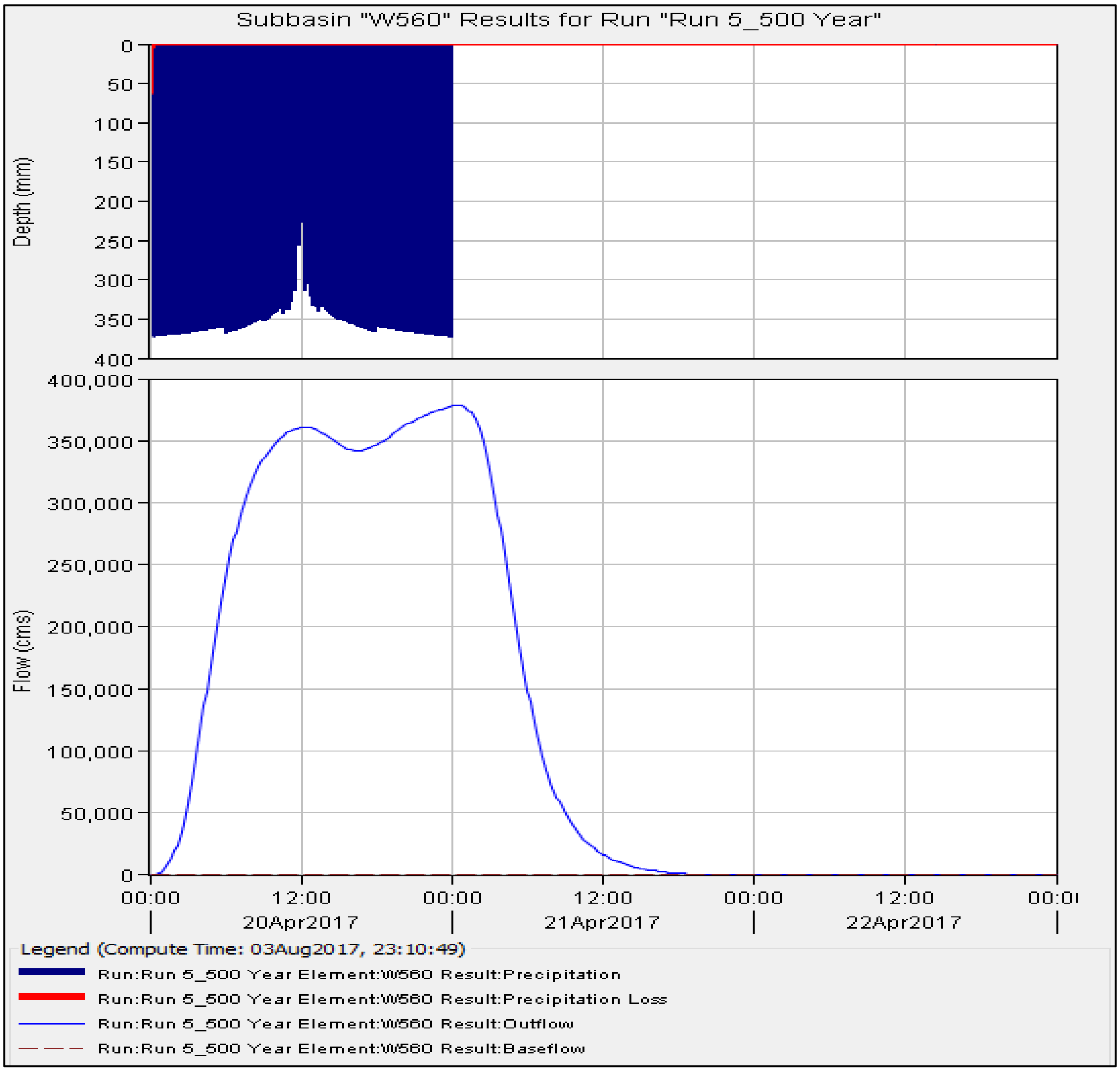
Subbasin: W560

Start of Run: 20Apr2017, 00:00   Basin Model: UpperNyabarongoCat07
End of Run: 23Apr2017, 00:00   Meteorologic Model: Met 5-500 years
Compute Time: 03Aug2017, 23:10:49   Control Specifications: Control 1

Volume Units: ○ MM ● 1000 M3

Computed Results

Peak Discharge: 378710.8 (M3/S)   Date/Time of Peak Discharge: 21Apr2017, 00:30
Precipitation Volume: 32190520.9 (1000 M3)   Direct Runoff Volume: 32144906.6 (1000 M3)
Loss Volume: 45614.2 (1000 M3)   Baseflow Volume: 0.0 (1000 M3)
Excess Volume: 32144906.6 (1000 M3)   Discharge Volume: 32144906.6 (1000 M3)



Graph for Run 5 of W560