PAN-AFRICAN UNIVERSITY

INSTITUTE FOR WATER AND ENERGY SCIENCES

Master Dissertation

Submitted in partial fulfillment of the requirements for the Master degree in

WATER ENGENEERING

Presented by

Sewanou Juferlin ***GBAGUIDI***

STATISTICAL ANALYSIS FOR FLOOD HAZARD ASSESSMENT UNDER CLIMATE CHANGE IN THE NIGER RIVER BASIN: CASE STUDY OF MEKROU RIVER SUB-BASIN (BENIN)

Defended on November 29, 2021 Before the following Committee:

Chair: Dr. Derdour Abdessamad (Naama University, Algeria)

Supervisor: Prof. Tirusew Asefa (University of Florida, USA)

Internal Examiner: Prof. Mahmoud Hasbaia (University of M’sila, Algeria)

External Examiner: Prof. John Mwangi Gathenya (Kenya)

DECLARATION

I, Sewanou Juferlin **GBAGUIDI**, attest that this thesis is my original work and has not been submitted to any other University for the award of any degree. I also attest that all information, material and results from other works presented here, have been fully cited and referenced in accordance with the academic rules and ethics.

Signed: Date:05/11/2021

Sewanou Juferlin **GBAGUIDI**

CERTIFICATION

This thesis has been submitted with my approval as the supervisor.

Signature: Date:28/11/2021

Tirusew Asefa

ACKNOWLEDGMENTS

I thank Almighty God for taking care of me throughout the duration of my studies and I would like to express my sincere thanks to PAU for granted me a scholarship to follow this master ‘s degree.

The sincerest thanks go to my supervisor, Professor Tirusew Asefa, for his guidance, unfailing support, constructive comments and for always being available to provide me with useful materials and information for the successful completion of this work. His presence kept me motivated in this study. Completion of this thesis work in the allowed timeline could not been achieved without his continuous and renewable support.

My grateful recognitions are passing to my families for their continuous advice, assistance and follow up in all of my moments. Mainly, my brothers, sisters, father and mother. May almighty God provide to you health and happiness. Thanks for being there.

Lastly but not least, I would like to express my warm feeling of appreciation and thank to my friends who were always available and made my stay unique.

ABSTRACT

Literally, West Africa 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. Niger River basin also experienced some negative effects of climate change. However, there is lack of knowledge on flood hazard potential in the basin and mostly in its sub-basins.

The main objective of this study was to assess the flood hazard occurrence under climate change in the Mekrou basin. Daily rainfall and stream flow data recorded over a 30-year period, 30-meter grid of digital elevation model (DEM) dataset, land use/land cover datasets to create curve number (CN) values of the river catchment were used for hydrological modelling 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 5-year, 10-year, 20-year, 30-year, 50-year and 100-year flood for the entire catchment.

The result reveals an increase in future quantile change compared to the historical quantiles. The change ranges between 9.09% and 57.29% for the period (2026-2055) and 21.12% to 75% for 2070-2099. Therefore, it is clearly indicated that flood frequency will increase in the middle and by the end of 21st century due to the climate change, in the Mekrou River basin.

It has been noticed that when the return period increase, the discharge quantiles increase too. That’s mean higher discharge will be recorded by 2100 compared to 2050 as well as the historical period (1983-2005) based on the result of the study.

Keywords: ArcGIS, HEC-HMS, Curve number, Climate change, Mekrou river basin.

RESUME

L'Afrique de l'Ouest a littéralement fait l'expérience du changement et de la variabilité climatiques en termes de fréquence, d'intensité et de persistance des changements extrêmes, tels que les inondations et les sécheresses. L'occurrence des déficits et des excès pluviométriques ont significativement augmenté ces dernières années. Ces événements ont eu de graves répercussions sur l'environnement, l'économie et les vies humaines. Le bassin du fleuve Niger a également subi certains effets négatifs du changement climatique. Cependant, il y a un manque de connaissances sur les risques d'inondation dans le bassin et surtout dans ses sous-bassins.

L'objectif principal de cette étude est d'évaluer les risques d'inondation liés au changement climatique dans le bassin de la Mekrou. Les données hydrologiques comprennent les précipitations et le débit des cours d'eau sur une période de 30 ans, les données du modèle numérique d'élévation d'une grille de 30 mètres, les données sur l'occupation des sols pour créer les valeurs du nombre de courbes (CN) du bassin versant de la rivière ont été utilisées pour la modélisation hydrologique en utilisant ArcGIS. La méthode du SCS curve number a été utilisée pour réaliser le modèle de perte, puis le SCS unit hydrographe pour le modèle de transformation et la méthode de Lag Time pour le modèle d'acheminement afin de calculer les valeurs des paramètres d'entrée du bassin et du tronçon de rivière pour chaque sous-bassin, par exemple le prélèvement initial, le numéro de courbe, l'imperméabilité et le temps de décalage pour le bassin et le tronçon de rivière, dans HEC-HMS pour calculer les inondations pour les périodes de retour, de 5ans, 10ans, 20 ans, 30 ans, 50 ans et 100 ans pour l’ensemble du bassin versant.

Le résultat révèle une augmentation de la fréquence d’occurrence des inondations future par rapport aux données historiques. Le changement varie entre 9,09% et 57,29% pour la période (2026-2055) et 21,12% à 75% pour 2070-2099. Par conséquent, il est clairement indiqué que la fréquence des inondations augmentera au milieu et à la fin du 21ème siècle en raison du changement climatique, dans le bassin du fleuve Mekrou.

Il a été remarqué que lorsque la période de retour augmente, les quantiles de débits augmentent également. Cela signifie qu'un débit plus élevé sera enregistré en 2100 par rapport à 2050 ainsi qu'à la période historique (1983-2005) selon les résultats de l'étude.

Mots clés : ArcGIS, HEC-HMS, Curve number, Changement climatique, Bassin du fleuve Mékrou.

Table of Contents

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS AND ACRONYMS

EM-DAT: CRED's Emergency Event Database

CRED: Centre for Research on the Epidemiology of Disasters

UNISDR: UN Office for Disaster Risk Reduction

NRB: Niger River Basin

IPCC: Intergovernmental Panel on Climate Change

RCP: Representative Concentration Pathway

UN: United Nations

USEPA: United States Environmental Protection Agency

WMO: World Meteorological Organisation

RGPH : Recensement Général de la Population et de l'Habitation

INSAE : Institut National de Statistiques Appliquées et de l'Economie

CHAPTER ONE

1. Introduction

1.1. Background Information

Floods are one of the most frequent and widely distributed type of destructive natural disaster. Throughout the world, flood causes significant damages by disrupting livelihoods. Its frequency is indeed higher than the frequency of other natural catastrophes such as extreme temperature, landslides, wildfire, earthquakes, drought, etc. According to EM-DAT classification (1995-2015) of natural hazards by disaster type, floods have the highest percentage (43%) of occurrence of all weather-related disasters (Figure 1) and affect 2.3 billion people (UNISDR, 2009).

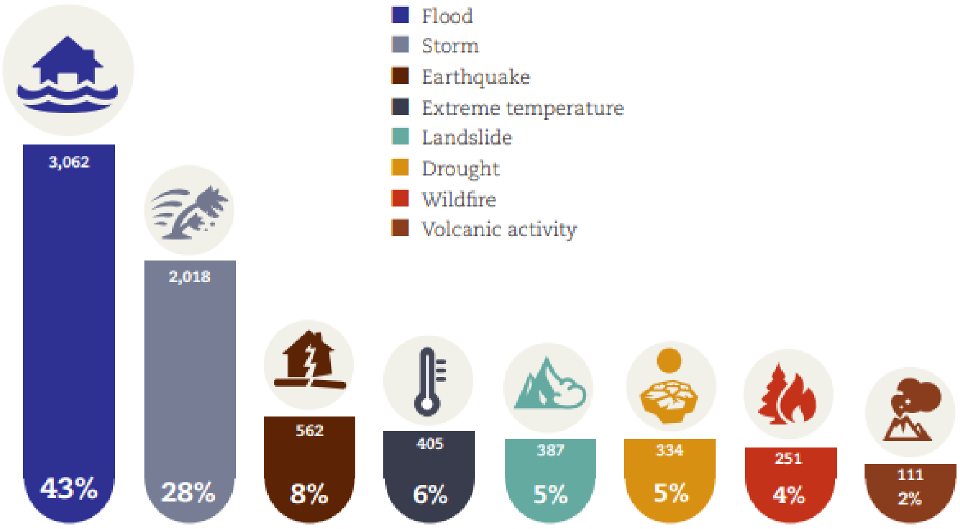

Figure 1:Percentage of occurrence of weather-related disasters. (UNISDR,2009)

Literature on the impact of climate change on pluvial floods (e.g., flash floods and urban floods) is scarce. Changes in climate variables pattern such as precipitation, temperature and evaporation, resulting from climate change, lead to the modification of the global water cycle and affect water resources (Bates & al., 2008). In addition to the projected changes in these variables, the climate change will also have implications on the extreme events. The AR4 also pointed to possible changes that may imply trends in flood occurrence with climate change.

The Niger River (4,200 km) is the third-longest river in Africa. It flows from the Guinean Fouta-Djalon Plateau after which it goes through vast flood plains in Mali (the Inner Delta) before resuming its path through Niger and Nigeria into the Atlantic Ocean. Over the past decade, several flooding events have affected the population living along the Niger River. The most recent one is currently happening in 2021 resulting in loss of lives, social disruption and damage to buildings and crops. Before this disaster, several flood events have been reported in the area with an enormous impact on the population living in the Niger River Basin (NRB) exacerbating the poverty-cycle in the region. The flood events of 2009, 2010 and 2020 affected 100,000 people, 1 million people and 2.2 million respectively (UN). The 2012 flood remains one of the most devastating floods in the region, with more than 10 million people being affected. The riparian country governments' disaster management approach has mostly been focused on the response to and recovery from the catastrophe. Less attention has been given to mitigation and adaptation measures in order to limit the impact of the floods on the population. This has left the population highly vulnerable to the disaster over time.

Niger River flows through West Africa, which is one of the regions in the continent that are most vulnerable to climate change (IPCC, 2012). Studies have reported that West Africa experienced above normal precipitation during June-September compared to the last 35 years as a result of the increased overall intensity of the monsoon season (Adegoke et al., 2019). In addition to these studies, the Fifth Assessment Report (AR5) by the Intergovernmental Panel on Climate Change (IPCC, 2014c) highlighted that flooding in West Africa are expected to increase by 20% over the next decades relative to the past (1986-2005) due to the impact of climate change which is likely become more severe by 2050. Also, the last two decades, the occurrence of extensive flooding has increased drastically in the Niger basin (Amogu et al., 2010; Library et al., 2014; Sighomnou et al., 2013). Very little research is currently being conducted in NRB on factors contributing to flood and the different ways to reduce the associated damages.

1.2. Problem statement

Located in West Africa precisely in the Northern region of Benin Republic, the Mekrou River Basin is one of the three sub-basins of the Niger River basin of Benin. As part of the Niger River Basin, the Mekrou river basin also experiences flooding (Figure 2) along the river during flood periods. Some studies have been carried out in the basin in order to better understand the flooding phenomenon occurring in the basin but also to have a tool to support risk management.

The low-lying areas that border Niger’s bed streams (Northern part of Mekrou River basin) is highly affected by the hazardous flood events and almost 90 % of the district is located in a flood hazard footprint and is consequently exposed to a high flood risk (Behanzin et al., 2016).

The maximum precipitation amounts of rainfall in 24, 48 and 72 consecutive hours in Mekrou River basin show an increasing trend over the period 2011–2100 regardless of the scenario and the future period (Obada et al., 2017).

Figure 2: Flood risk map of Mekrou River basin (Source, Mekrou Water4Growth)

1.3. Research objectives

1.3.1. Main objective

The overall objective of this research is to assess the flood hazard in the Mekrou River Sub-basin of Niger River basin using hydrological modelling and statistical analysis. The analysis will yield flood hazard assessment for the study area taking into consideration climate change.

1.3.2. Specific Objectives

- Develop under RCP 8.5 a physical based hydrological model with HEC-HMS software and simulate the future Rainfall-Runoff process over the Mekrou River Basin.
- Statistical analysis of extreme future discharge.
- Flood hazard assessment over Mekrou River catchment under climate change.

1.3.3. Research questions

- How well could we perform the simulating future discharge over the Mékrou River?
- What is the best statistical distribution which fit with the future discharge?
- What is the impact of climate change on flood frequency over the study area?

1.4. Limitations and assumptions

The present study focused on the flood hazard assessment in the Mekrou River basin. Its limitations and assumptions are listed below.

- The discharge and precipitation data used in hydrologic modelling were daily, and many data series had gaps.
- In HEC-HMS, different set of parameter values can give similar results during calibration of a model. The values chosen for the calibrated parameters may not necessarily have a physical reflection on the basin.
- The spatial distribution of gage stations for collection of climate and meteorological data was poor. This has resulted in lots of approximations in the analysis.
- The land use and land cover were supposed unchanged over the projected period.

1.5.Thesis outline

This thesis will be structured as the following way. The Chapter1 will provides the introduction which includes the general overview of the topic, the objectives and importance of the study. In Chapter 2, we will present the literature review including a thorough discussion about concepts relevant to this work. In chapter3, we will present the overview of the study area. The chapter4 will focus on the dataset used for modelling, the analysis and the methodology that has been adopted. The result of the analysis is presented in the chapter5 followed by the discussion. The chapter6 which is the last one will be dedicated to the conclusion and recommendations.

CHAPTER TWO

2. LITERATURE REVIEW

2.1. Introduction

The earth has experienced global warming in recent decades (IPCC, 2012). Thus, the average global temperature of the earth surface has increased by 0.85°C during the period 1880-2012 (AR5, 2013). These changes in climate systems have exacerbated changes in ecosystem functioning (Schickhoff et al., 2016; Shrestha et al., 2012) and these changes have led to the occurrence of many extreme events around the world (IPCC, 2014b, 2014a; Vargas et al., 2017). The frequency of extreme weather events (floods and droughts) has increased in many parts of the earth (Goswami et al., 2006; IPCC, 2014a; Schickhoff et al., 2016), while the number of rainy days has decreased(Rani & Sreekesh, 2019).

According to the UN-ESCAP report (2015), during the period 1970-2014, floods and storms account for about 64% of the 11,985 natural disaster events reported worldwide with a sharp increase in these numbers during the last decades. A flood is a very simple natural phenomenon that occurs when a body of water rises to overflow land that is not normally submerged (Llanbrynmair, 2016). In flood management several methods and models are used in order to determine the magnitude of flood occurrence in a specific area or river basin.

In this research, we are going to consider the influence of climate change on floods phenomenon in order to evaluate the future flood risk in the Mekrou River Catchment.

2.2. A GENERAL OVERVIEW ON CLIMATE CHANGE AND EXTREME WEATHER EVENTS

Average earth temperature has increased by 0.74^{0}C between 1906 and 2005(Bates & al., 2008). The warming of the earth's global temperature has disrupted many ecosystems and the hydrological water cycle. The resulting disruption has intensified the frequency of occurrence of extreme weather events (droughts, floods, heavy rainfall, heat waves, etc.). Extreme weather has always posed risks to human society and it is one way that people experience climate change.

2.2.1. Evidences for climate change

IPCC reports provide in different time period (past, present and future) the global climate trends. These reports are based on the findings of scientists who works through tangible evidences.

IPCC reports had been providing valuable information starting from First Assessment Report (FAR IPCC, 1990) to current Sixth Assessment Report (AR6 IPCC, 2021). Most reports were used their own scenarios, which are different to each other and/or are slightly similar for future climate change. However, all the reports have the same final conclusion, which is there was climate change in past, there is climate change currently and there will climate change in future.

All previous reports marked change of climate variables which contributes to climate change. Concentration of Co2 in the atmosphere would double in 2100 and average temperature will also increase between 1.4 to 5.8 ^{0}C on the same year. Due to risen in temperature, snow melt would be significantly accelerated which would contribute the rise of sea level and changing rainfall pattern up to 20%. Observations on past centuries showed changes are occurring in the different amount, intensity, frequency and types of precipitation (IPCC, 2007).

The presence of future climate change at global scale has been confirmed by different scientists and researchers. Climate change is expressed mainly by variability of rainfall and continued increment of temperature (Alexander et al., 2006; Kharin et al., 2013; Trenberth et al., 2003).

2.2.2. Global Circulation Model

Global or general circulation models (GCM) are large scale numerical models of the atmosphere and ocean circulation. They use hydrodynamic (Navier-stokes equations on Rotating sphere) with thermodynamics (radiation and latent heat) coupled together with atmospheric, ocean and other modelled aspects of the climate system to form a global climate model or earth system, model.

GCMs simulates the Earth’s climate system over time to compute atmospheric water vapor, ocean temperatures, greenhouse gas concentrations, annual and daily solar heating and describe how these components interact with each other to create complex climate variability and change (ARCC, 2014).

They are the main tools used to provide a reasonably accurate representation of global and continental scale climate information on average daily, monthly, seasonal, annual and longer time scales used for forecast and projection of impacts of anthropogenic greenhouse gases (GHGs) and aerosols on future climate.

2.2.3. Representative Concentration Pathways (RCP)

Representative Concentration Pathways (RCP) are the most recent generation of scenarios used for climate models. They take into account the variation in time and space in the concentrations of greenhouse gases and other pollutants resulting from anthropogenic activities, including changes in land use. The four RCPS are:

- **RCP 8.5: High emissions**: - consider a future with no policy changes in order to reduce greenhouse gaz emissions. Comparable SRES scenario : A1 F1

- **RCP 6**: Intermediate emissions: - consider the implementation of a range of technologies and strategies in order to reduce greenhouse gas emissions. Comparable SRES scenario : B2.

- **RCP 4.5**: Intermediate emissions: - consider a future with a number of relative ambitious of greenhouse gas emissions reductions. Comparable SRES scenario: B1

- **RCP 2.6**: Low emissions: - In order to reach such forcing levels, ambitious greenhouse gas emissions would be required over time.

2.2.4. Impact of Climate Change on Hydrology and Water Resources

Higher concentration of Greenhouse gases in atmosphere causes increase of both minimum and maximum temperature and variability of rainfall distribution and amount (Houghton et Al., 2001).Water cycle components such as precipitation and runoff; timely and spatial distribution of water and quantities are affected by climate change.

Changing of climate variables mainly temperature and precipitation are indicators of climate change. An increase of temperature leads increase of evaporation which causes water imbalance between surface and atmosphere. Changing in precipitation has negative impact on surface hydrology and water resources. The variation of precipitation also causes the occurrence of floods and droughts which affect the hydrology and water resources of a region. Climate change impact therefore affects discharge of rivers. Among many influences affecting stream flow, the weather parameters especially precipitation is the main factor.

2.2.4.1. Precipitation extremes and associated impacts

The oscillatory behaviours of climate variability over different time scales have enormous impact on regional hydrologic processes. It has been documented that the spatial and temporal variability of extremes precipitation for different storms durations in a tropical region is influenced by ENSO and AMO (Goly & Teegavarapu, 2013). Increased frequency of extreme precipitation (with reference to duration and intensity) will lead to a number of changes in various water resources sectors (USEPA, 2008). Some of the changes indicated are universal and are not limited to a specific region. Increased precipitation leads to an increase in pollution, erosion and sedimentation due to runoff (USEPA, 2008); increases in heavy precipitation, combined with land use changes (i.e., impervious surfaces), could increase urban flood risks and create additional design challenges and costs related to stormwater management (Field et al., 2010).

Frequent precipitation variability is capable of compromising wetlands by altering water level characteristics (timing, duration, depth); the limited adaptive capacity of wetlands makes them among the most vulnerable ecosystems to the effect of climate change (IPCC, 2008). Extreme precipitation events also lead to flooding events that impact water bodies by transporting increased loads of pollutants, overloading stormwater and wastewater systems, and facilitating ecological disturbances and biological invasions (IPCC, 2008). It is important to note that increased precipitation amounts may also lead to augmentation of water supply systems, which can be considered as a benefit in some sense. (Kundzewicz et al., 2008) indicate that water quality changes may be observed in the future as a result of overloading the capacity of water and wastewater treatment plants during extreme rainfall.

According to the IPCC (2007b), the frequency of heavy precipitation events has been increasing over most regions of the world, which is understandable given the warming of the earth and increases in atmospheric water vapour values. Based on a range of model estimates, it is likely that future tropical cyclone (typhoon and hurricane) intensities will increase, with higher maximum wind speeds and more precipitation associated with increasing trends in sea surface temperatures (SSTs) in the tropics (IPCC, 2007b). However, it is possible that global warming has had an impact on the 2004-5 event clusters in the mid-Atlantic as a whole.

2.2.5. Extreme Precipitation and floods in a changing climate

Evaluation of extreme precipitation events in relation to intensity, duration, and influences of climate variability and change is critical to address the issues of floods and flooding mechanisms under climate change scenarios. Precipitation measurement, instrumentation for estimation, monitoring network design, availability of data from different measurement devices, and assessment of long-term point and gridded data sets are essential for understanding variability of precipitation in space and time. The limitations of emerging precipitation measurement devices along with systematic and random errors need to be evaluated before data can be used for any analysis. Spatial precipitation analysis for continuous estimation is essential for establishment of homogeneous serially complete precipitation data sets that are used for climate change and trend analyses. Approaches that provide uncertainties in the estimates of missing data, multiple imputation mechanisms, and emerging methods that use data mining and other techniques to preserve site and regional statistics are critical. Assessment of hydrometeorological floods with links to extreme precipitation events, joint characterization of extreme precipitation and flooding events, and evaluation of the influence of climate change combined with anthropogenic activities are needed to address the causes of floods under changing climate.

Climate change projections of precipitation from GCMs, assessment of these projections, model selection, performance measures, and uncertainty assessment are important from the perspective of evaluating the most critical input to the hydrologic cycle. Internal modes of climate variability understood by teleconnections or oscillatory behaviours and their links to variability in extreme precipitation events need to be understood for effective intra-annual seasonal forecasts of hydrologic variables and for use in hydrologic design. Statistical data analysis using methods addressing the non-stationarity issues are essential for local, regional, and global variability of trends in precipitation extremes. Hydrologic design and water resources management that are climate change sensitive and sustainable are essential to mitigate the effects of catastrophic flooding mainly linked to extreme precipitation events. Stationarity is a contentious issue and has a profound impact on future hydrologic design and flood frequency analysis.

Precipitation is one of the most important components of the hydrological cycle. It has a strong influence on hydrological design and water resources management. Uncertainties about future climate conditions, 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. Measurements, estimation over different spatial and temporal scales, and understanding of the spatial and temporal variability of extreme precipitation events are therefore critical for future hydrologic design.

2.2.5.1. Precipitation and river regime

Precipitation regimes describing the distribution of precipitation totals on an annual basis were described by Shaw (1994) for eight regions around the world. Some of the regions were selected to coincide with the global precipitation regimes described by (Petterssen, 1958). According to Petterssen, the precipitation regimes can be divided into seven classes: (1) Equatorial (within a few degrees north and south of the Equator; (2) Tropical (between the Equator and tropics of Cancer and Capricorn); (3) Monsoon (within and outside the tropics in the Indian sub-continent on the east side of continents); (4) Subtropical (tropics to 30^{o} north and southwest side of continents); (5) Mediterranean (within 30^{o} to 40^{o} north and southwest side of continents); (6) Mid latitudes; and (7) Polar.

River regime refers to the expected pattern of river flow during a year (Shaw, 1994). Definition of river regimes requires long term flow data to obtain the general characteristics of the river flows. The river regime is the direct consequence of the climatic factors influencing the catchment runoff, and can be estimated from knowledge of the climate of a region. Classifications (Shaw, 1994) are possible based on two factors: temperature and rainfall. The temperature-dependent regimes are further categorized into glacial, mountain snowmelt, and plains snowmelt. The rainfall dependent regimes are divided into four types: equatorial, tropical, temperate oceanic, and Mediterranean.

2.2.5.2. Hydrometeorological aspects of floods

The meteorological systems are not enough to predict flooding. Other key components that must be included in the analysis are rainfall–runoff processes, surface and subsurface hydrologic conditions, and land-use properties. Also, the antecedent climate, the hydrologic factors, and the available reservoir storage affect the possible flooding in a basin (Dunne, 1983). The soil moisture, soil saturation, and groundwater levels (shallow groundwater tables) are determinant factors in flooding events. Saturated soils are not a required precursor to severe flooding.

Different types of rainfall events can be the cause of flooding in the same catchment area. Factors related to the seasons, as well as factors related to large-scale environments, determine the type of event that occur. Developing flood situations can be predictable or monitored on short meteorological and climatic time scales. Since many years, hydrological experts have been using time series of maximum flood data from gauges to assess the probability of occurrence of a flood of a given intensity. The intensities and durations of precipitation systems vary. This can be seen in the maximum flows of a given river. This produces mixed distributions defined by the hydroclimate in the overall probability density function of the peak flows (Hirschboeck, 1987a, 1987b). This approach combined with a statistical analysis of peak flows makes it possible to determine the types of weather systems that generate floods of a given magnitude. Furthermore, it can be used to estimate the causes of flood variations over time by different types of storms in several rivers in a region or by estimating in detail the flood chronology of a single river.(Hirschboeck, 1987b; Webb & Betancourt, 1992).

The shape, timing, and peak flow of a streamflow hydrograph are significantly influenced by spatial and temporal variability in rainfall and watershed characteristics such as land use. Studies have been carried out to investigate linkages between climate indices, streamflow, and precipitation. The hydrologic response of a watershed varies with the dynamics of the storm precipitation. Several studies have investigated the linkage between precipitation and the streamflow data by correlating the data using techniques such as the Mann– Kendall test and linear regressions (H.F. Lins & Slack, 1999; Harry F. Lins, 1997).

It is fundamental to explore the synergism between meteorological, climatic, hydrologic, and drainage basin factors as well as both the short-term meteorological and the long-term climatic processes in order to fully understand the causes of flood. Streamflow data have the advantage over rainfall data in that the complex variability of precipitation, evaporation, transpiration, land use, topography, and other physical characteristics of the region are reflected in the streamflow records (Sharif & Burn, 2009). It can be concluded that the common approach used to find the existing links between hydrologic events and flooding in populated and agricultural areas relies on the use of statistical methods.

2.2.5.3. Flooding Mechanisms

In general, floods fall into three major categories: (1) riverine flooding, (2) overland flooding, and (3) flash flooding. Riverine flooding is the most common of the flooding events. When a channel receives too much water during high storm events the excess water flows over its banks and into the adjacent area. Flooding that occurs along a stream or channel is called riverine flooding. In general, the terrain of the watershed determines the dynamics of riverine flooding. In relatively flat areas, floodwater may cover large areas of land for long periods of time. Flash floods usually occur in hilly areas and urban areas. Overland flooding or basin flooding is common in areas dominated by flat terrain. Overland flooding is defined as the increase in volume of water within a river channel and the overflow of water from the channel onto the adjacent floodplain. In many parts of the world, flooding occurs in combination with heavy rainfall on a large expanse of flat terrain during periods of high groundwater table. Figure 3 shows a general conceptual type of floods Adapted from (Díez-Herrero, Huerta, & Isidro, 2009)

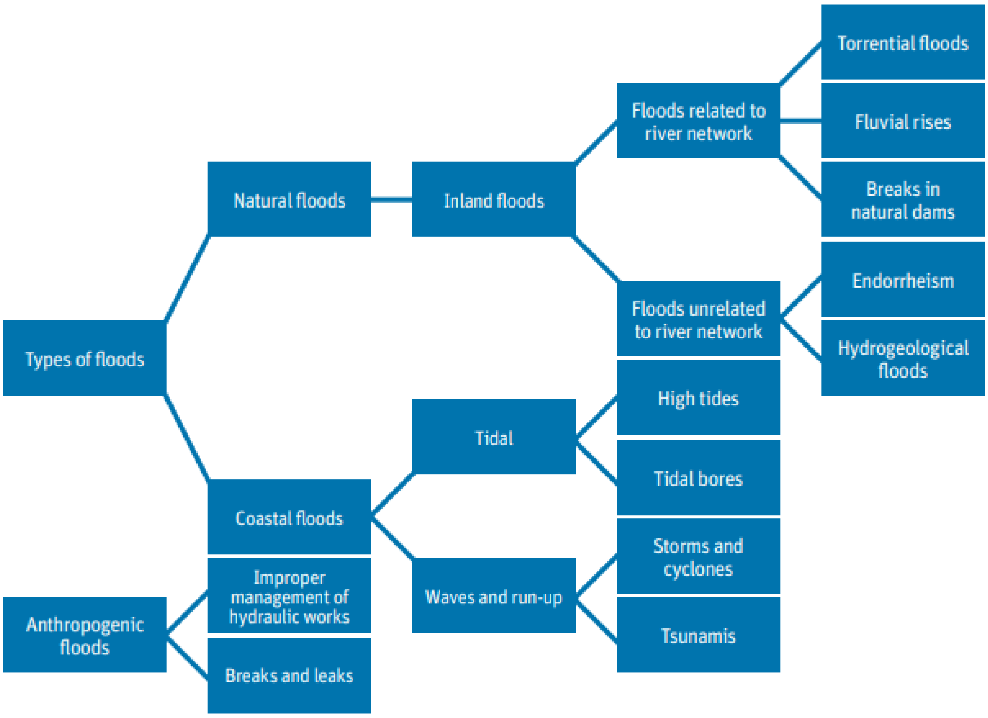

Figure 3:Different types of floods (Adapted from Díez-Herrero, Huerta, & Isidro, 2009)

2.2.5.4.Soil moisture contributions to flooding

Shallow groundwater table conditions can increase the available soil moisture and therefore lead to decrease in soil storage capacity and increase in peak flooding events due to wet AMC. (Fleming & Neary, 2004) has developed calibration methods and set up model parameters that are used in an ADM algorithm. When applied to a test catchment, the model performance indicates that the developed parameters and calibration methods work well when applied to the test catchment. In areas with a high-water table, the storage capacity of the soil is limited, and infiltration cannot occur for a long-time developed calibration methods and set up model parameters that are used in an ADM algorithm. Applied to a test catchment, the model performance indicates that the developed parameters and calibration methods work well. The model performance indicates that the developed parameters and calibration methods work well when applied to the test catchment. In areas with a high-water table, the storage capacity of the soil is limited, and infiltration cannot occur for a long time without complete saturation of the soil. In this case, infiltration stops, rainfall abstraction becomes zero and the intensity of the excess rainfall is equal to the intensity of the rainfall without complete soil saturation. In this case, infiltration stops, rainfall abstraction becomes zero and the intensity of the excess rainfall is equal to the intensity of the rainfall. Soil storage capacity, S, is calculated by using the following equation (Bedient et al., 2009):

$$S = L(\theta s - \theta i)$$

where L is depth of water table, θs is defined as saturated moisture content, while θi is supposed to be the initial moisture content. Available regional information on soil storage can be used in some areas for modelling purposes. The following equation is used to calculate the soil storage capacity using the curve number (CN):

$$S = (1000/CN) - 10$$

Initial abstraction is calculated using $I = 0.2S$. The Green–Ampt infiltration model can also be used for prediction of runoff (Manivannan et al., 2001). The Green–Ampt model predicts runoff volume more accurately than the Soil Conservation Service (SCS) CN method.

Groundwater table levels can influence the amount of soil moisture and ultimately the storage capacity. Gregory et al. (1999) used different methods to estimate soil storage capacity for stormwater modelling applications. They used the following equation to calculate the soil storage capacity:

$$S = aH^b$$

where H is the high-water table depth (groundwater table) in feet and S is the soil storage capacity in inches. Gregory et al. (1999) indicate that Soil storage capacity can be modified to better show development activity, and a 25% reduction in the original soil value can reduce voids due to compaction during earthmoving operations. By considering soil information and high-water table (HWT) conditions, the intrinsic relationship between soil water storage capacity and HWT can be defined. The relationship can then be used to determine the soil moisture capacity at different depths of the water table and the adjusted CNs are calculated. These adjusted numbers can then be used in methods that use the SCS CN approach for estimation of peak discharges.

2.2.6. Hydrological modelling

A model is a simplified representation of a real-world system (Gayathri, 2015). They are used for predicting system behavior and understanding various hydrological processes in a given area. The model giving results close to reality with the use of the least parameters is the best one. For simulation processes, hydrological models are an important tool for water and environment resource management. Nowadays, a wide variety of hydrological models are available with different data requirements and can be used for purposes such as flood runoff estimation, flood hydrograph routing and flood estimation, which can be done with a GIS interface (Icyimpaye, 2018).

Hydrological modelling is the use of physical or mathematical techniques to simulate the hydrologic cycle and its effect on a watershed. The purpose of using a model is to establish baseline characteristics whenever data is not available and to simulate long-term impacts that are difficult to calculate (Mkilima, 2018).

Hydrologic models help to simulate the rainfall-runoff process in order to inform hydrologist on “how much water, how often”. Rainfall events or simulations information are used to provide runoff characteristics including peak flow, flood hydrograph and flow frequencies (Georgia stormwater Management Manual G1).

2.2.6.1. Class of usual model

The two main classes of rainfall-runoff models are:

- **Lumped**: Lumped models consider the catchment area as a single unit. Simplified processes are used to carry out the calculations using mean surface processes. The resulting flow value applies only to the watershed outlet (the most downstream modelled point in the river system). Well-known lumped models include TR-55 and other unit hydrograph-based methods.

- **Distributed:** Distributed models take into account spatial variability of data for processes such as precipitation, infiltration, interception, interflow, infiltration and baseflow, estimating discharge or other variables. This type of model is more flexible and can be more accurate, but it requires much more data than lumped models. Distributed models are generally intended for use at a given scale, such as small urban catchments (SWMM, GSSHA, Vflo, OpenLISEM) or large river basins (VIC). When properly used, flow estimates at different locations in the river system can be obtained with most distributed models.

HEC-HMS is one of the popular models that partitions the catchment into several sub-catchments, each of the sub-catchments is then represented using a defined storm runoff model. The results of the individual runoff models can then be cumulated to assess the response of the catchment at various points. In this way, it is possible to combine some of the advantages of lumped and distributed models.

2.2.6.2. Model and software description

In this study, we have used mainly two open-source software which are ArcGIS and HEC-HMS. HEC-HMS is used for hydrologic while ArcGIS is used as a platform for generating physical basin models for HEC-HMS through the interfacing hydrological extensions HEC-GeoHMS.

2.2.6.3. ArcGIS : HEC-GeoHMS

HEC-GeoHMS is a toolkit that serves as an interface between the GIS and HEC-HMS. It is used to create hydrological data that can be used directly with HEC-HMS. It is used to visualize spatial information, use DEMs (Digital Elevation Models) and GIS to extract physical characteristics of watersheds. It also allows for spatial analysis and delineation of subbasins and rivers to develop hydrological parameters as input to hydrological models (Fleming et. al., 2013). In this study, we used HEC-GeoHMS version 10.8.

2.2.6.4. Rainfall Runoff Model: HEC-HMS

Developed by the U.S. Army Corps of Engineering's Hydrologic Engineering Center, the Hydrologic Modelling System (HEC-HMS) is an open-source software package that simulates the hydrologic cycle of a watershed by describing its physical and meteorological properties. The schematic representation of the runoff process reproduced by HEC-HMS is shown in Figure 4. Several options for mathematical models of the different hydrological components for conceptualizing the behavior of a catchment are incorporated in the HEC-HMS program. The program uses various models to reproduce the representation of each component of the runoff process, such as the runoff volume estimation model, the direct runoff/baseflow/channel flow model, as well as other alternative models to account for cumulative losses, e.g., the SCS CN loss model: the SCS CN loss model. Then, by removing the losses (infiltration, storage, interception, evaporation, etc.) from the precipitation, it determines the runoff volume. In this research, HEC-HMS 4.7.1 version is the one used.

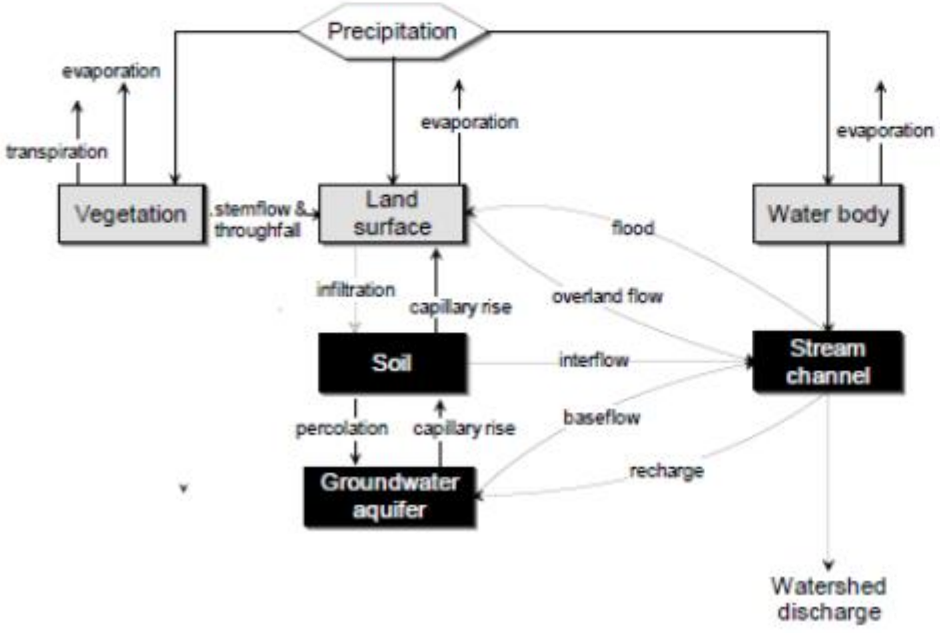

Figure 4:System diagram of runoff process (Feldman, 2000)

HEC-HMS model includes different components which are:

- Basin Models: hydrologic elements (such as: reach, subbasins, reservoirs, junctions) with the physical basin as well as the drainage network of the catchment are included in basin models.
- Meteorological Models: components related to meteorological information's such as temperature, precipitation, humidity, sunshine is computed in meteorological model. In HEC-HMS, there is many varieties of options to define each meteorological element.
- Control Specification: it allows to define the simulation parameters which are: Starting date and time, ending date and time and computational time step.
- Timeseries Data: in this part, the time series data for every meteorological elements defined in meteorological model are computed. Data related to streamflow can be computed for the calibration and simulation of the developed model. It is possible to supply manually to the software or in the form of HEC-DSS, the Hydrologic Engineering Center Data Storage System.
- Paired Data: this option allow to input Meteorological data in tabular/graphical format and it is called paired data. (Scharffenberg, 2016).

In HEC-HMS, the hydrological procedure which convert excess rainfall into runoff runs through four processes: loss, transform, baseflow and transform. These processes are described as following:

- **Loss method: Soil Conservation Service (SCS) curve number**

The estimation of rainfall losses allows the runoff from a given storm to be estimated. One of the simplest and most commonly used methods for practical applications is the Soil Conservation Service (SCS) curve number method (SCS, 1969). Depending on the soil type and the antecedent moisture content (AMC), it takes into account infiltration losses due to precipitation. During the storm, the precipitation is assumed to be distributed over the entire catchment area. The SCS curve number method is mainly based on taking into account the initial losses due to abstractions, "Ia", before the runoff starts. These losses include: interceptions due to built-up areas and vegetation that do not allow precipitation to reach the ground directly after it has occurred, storage surfaces constituted by water bodies such as ponds, lakes, and depressions, and infiltration. In developing the curves, one of the assumptions is that the ratio of the retention of precipitation in the catchment to the potential retention, "S", in the catchment is equal to the ratio of direct runoff to rainfall minus the initial abstractions, Ia (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.

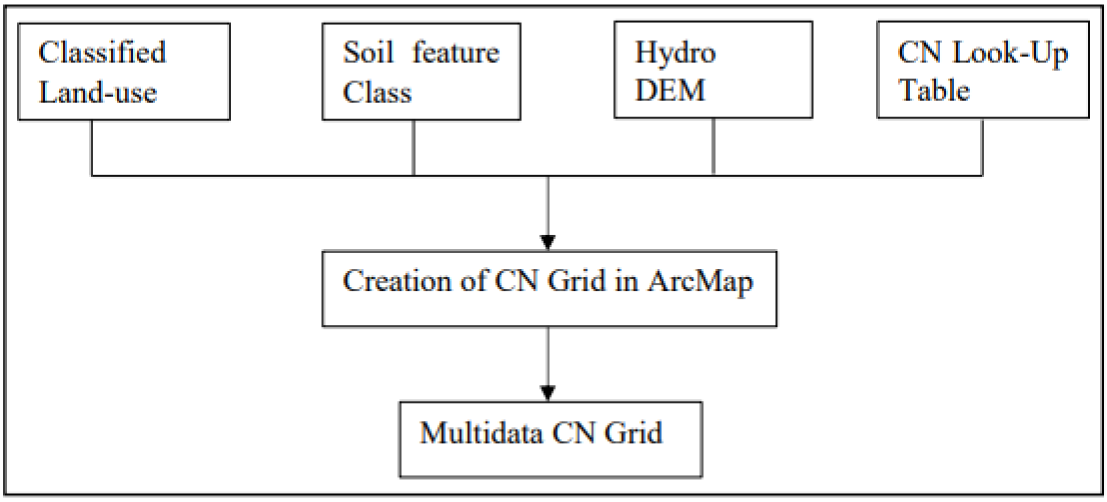

Figure 5:Procedure of creation of CN Grid (with ArcMap)

- **Transform method**

The principle of the unit hydrograph is the basis for calculating the overflow runoff at the catchment and the basis for the transformation method. The unit hydrograph can be considered as the runoff hydrograph produced by the excess precipitation per unit depth in the basin. Theories of the unit hydrograph are that (i) the excess precipitation and the runoff produced are directly proportional to each other, (ii) the excess precipitation is distributed uniformly in time and space over the catchment and (iii) the runoff produced from a given excess precipitation is independent of the time of occurrence and the previous moisture content (Subramanya, 2008).

For this study, the transformation method which has been used is SCS Unit Hydrograph. The resulting runoff hydrograph from this model is described by properties of unit hydrograph using one or more equations of the parameters involved. The peak of unit hydrograph and its time of peak is given by following equations.

$Up = 2.08 * (A/Tp)$ and

$Tp = (\Delta t/2) + tlag$

where, Up = Peak of unit hydrograph, A = Area of watershed, Tp = Time of peak, ∆t = Excess precipitation duration and tlag = Basin lag (Feldman, 2000).

Basin lag is defined as the time difference between the peak of unit hydrograph and centroid of the associated excess rainfall hyetograph which is shown in the Figure 6 below.

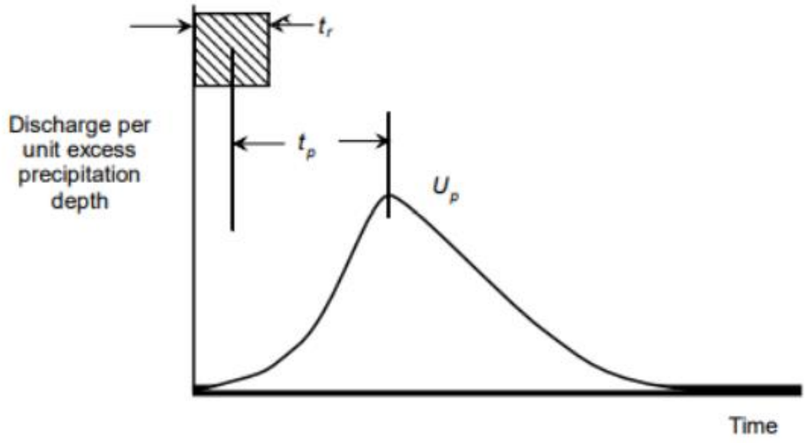

Figure 6: Unit Hydrograph (Feldman, 2000)

On this figure, tp = time of peak, Up = Peak of unit hydrograph and tr = rainfall duration. (Feldman, 2000)

- **Base-flow Method**

In HMS, subsurface flow in the watershed is represented by a baseflow. It is comprising interflow and flow in groundwater aquifer. In case of short rainfall event, the contribution of baseflow can be ignored. But because of the recession limb of hydrograph, the base-flow contributes significantly in flood volume in case of long rainfall event. (Cunderlik and Simonovik, 2004).

The Mekrou River catchment baseflow has not been taken into consideration in this research.

- Route Method

Flood routing is the tracking of changes in depth and flow over the length of the river as a function of time. The velocity and depth of the flow vary according to the cross-sectional area through which the flood wave passes. The characteristics of the wave (depth and discharge) also change with time. In fact, a flood moves along a stretch of river like a wave, whose speed and depth change continuously with time and distance. Although it is difficult to accurately predict the timing and magnitude of floods, it is possible to estimate the movement of the flood wave along a river fairly accurately, once it is known that a flood wave is generated at some point upstream of the river. This kind of estimation is of great practical use, as it could be used in flood early warning systems (Mujumdar & Kumar, 2012).

2.2.6.5. HEC-HMS Model Efficiency criteria

2.2.6.6.Model evaluation Statistic (Standard Regression)

- **Pearson's correlation coefficient (r) and coefficient of determination (R2):** Pearson's correlation coefficient (r)and coefficient of determination (R2) describe the degree of collinearity between simulated and measured data. The correlation coefficient, which ranges from −1 to 1, is an index of the degree of linear relationship between observed and simulated data. If r = 0, no linear relationship exists. If r = 1 or −1, a perfect positive or negative linear relationship exists. Similarly, R2 describes the proportion of the variance in measured data explained by the model. R2 ranges from 0 to 1, with high-er values indicating less error variance, and typically values greater than 0.5 are considered acceptable (Santhi et al.,2001, Van Liew et al., 2003). Although r and R2 have been widely used for model evaluation, these statistics are over-sensitive to high extreme values (outliers) and insensitive to additive and proportional differences between model predictions and measured data (Legates and McCabe, 1999).

- **Nash-Sutcliffe efficiency (NSE):** The Nash-Sutcliffe efficiency (NSE) is a normalized statistic that determines the relative magnitude of the residual variance ("noise") compared to the measured data variance ("information") (Nash and Sutcliffe, 1970). NSE indicates how well the plot of observed versus simulated data fits the 1:1 line. NSE is computed as:

$$\mathrm{NSE} = 1 - \left[\frac{\sum_{i=1}^{n} (Y_i^{obs} - Y_i^{sim})^2}{\sum_{i=1}^{n} (Y_i^{obs} - Y^{mean})^2} \right]$$

where Yi obs is the ith observation for the constituent being evaluated, Yi sim is the ith simulated value for the constituent being evaluated, Ymean is the mean of observed data for the constituent being evaluated, and n is the total number of observations.

NSE ranges between −∞ and 1.0 (1 inclusive), with NSE = 1 being the optimal value. Values between 0.0 and 1.0 are generally viewed as acceptable levels of performance, whereas values.

- **RMSE-observations standard deviation ratio (RSR):** RMSE is one of the commonly used error index statistics (Chu and Shirmohammadi, 2004; Singh et al., 2004; Vasquez-Amábile and Engel, 2005). Although it is commonly accepted that the lower the RMSE the better the model performance, only Singh et al. (2004) have published a guideline to qualify what is considered a low RMSE based on the observation’s standard deviation. Based on the recommendation by Singh et al. (2004), a model evaluation statistic, named the RMSE-observations standard deviation ratio (RSR), was developed. RSR standardizes RMSE using the observations standard deviation, and it combines both an error index and the additional information recommended by Legates and McCabe (1999). RSR is calculated as the ratio of the RMSE and standard deviation of measured data, as:

$$\mathrm{RSR} = \frac{\mathrm{RMSE}}{\mathrm{STDEV}_{obs}} = \frac{\left[\sqrt{\sum_{i=1}^{n} (Y_i^{obs} - Y_i^{sim})^2} \right]}{\left[\sqrt{\sum_{i=1}^{n} (Y_i^{obs} - Y^{mean})^2} \right]}$$

RSR incorporates the benefits of error index statistics and includes a scaling/normalization factor, so that the resulting statistic and reported values can apply to various constituents. RSR varies from the optimal value of 0, which indicates zero RMSE or residual variation and therefore perfect model simulation, to a large positive value. The lower RSR, the lower the RMSE, and the better the model simulation performance.

- **Percent bias (PBIAS):** Percent bias (PBIAS) measures the average tendency of the simulated data to be larger or smaller than their observed counterparts (Gupta et al., 1999).

  The optimal value of PBIAS is 0.0, with low-magnitude values indicating accurate model simulation. Positive values indicate model underestimation bias, and negative values indicate model overestimation bias (Gupta et al., 1999). PBIAS is calculated with:

$$\text{PBIAS} = \left[\frac{\sum_{i=1}^{n} \left(Y_i^{obs} - Y_i^{sim}\right) * (100)}{\sum_{i=1}^{n} \left(Y_i^{obs}\right)} \right]$$

  PBIAS values for streamflow tend to vary more, among different autocalibration methods, during dry years than during wet years (Gupta et al., 1999). This fact should be considered when attempting to do a split-sample evaluation, one for calibration and one for validation.

CHAPTER THREE

3. STUDY AREA

3.1. General overview of Mekrou River Catchment

Mékrou River catchment (between 1°30’ and 2°15’ East Longitude and 10°20’ and 11°30’ North Latitude) is a sub-basin of the Niger River located in the Northern part of Benin Republic. It covers a total area of 10 635 km2, about 3 % of the total area of Niger basin surface. Mekrou River catchment is shared by three countries Benin (80 % of the basin territory), Burkina Faso (10 %), and Niger (10 %) (Figure 7). In Benin, it covers five main municipalities, i.e., Kouandé, Kérou, Péhunco, Banikoara and Karimama.

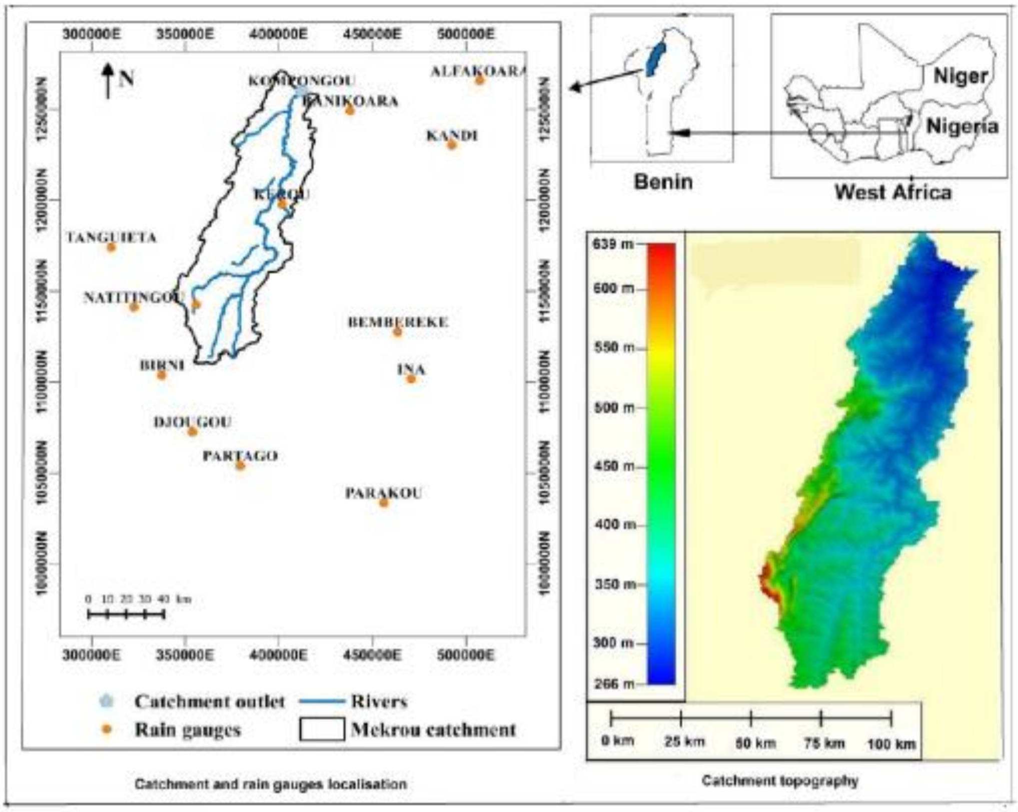

Figure 7:Mekrou River catchment

3.2.Climatic Features

The Mekrou river basin is located in a climatic zone characterised by a rainy season and a long dry season from December to April. The average annual maximum rainfall in the southern region is around 1300 mm while in the northern region it is around 500 mm. Generally, the wet season covers the months of June to September with an average cumulative rainfall of 700mm.

The warmest months are April and the coldest are September. The average annual temperatures vary according to the period and the region. Thus, the annual maximum varies from 35-40 ˚C and the annual minimum varies from 15-19 ˚C with an average that is between 26-30˚C.

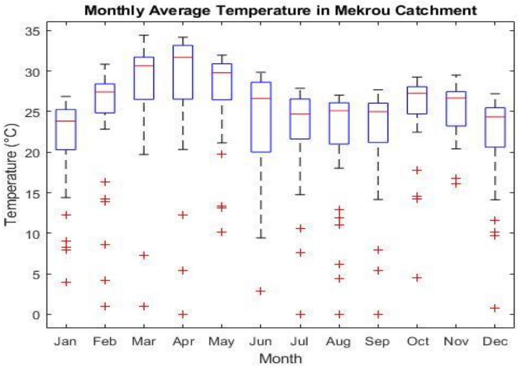

Figure 8: Monthly average temperature in Mekrou Catchment (1980-2020).

3.3. Population and Economics activities

Rainfed agriculture is the main economic activity of the communities living in Mekrou river catchment. Because of the high annual variability of precipitation and the lack of water storage infrastructures in the basin, the vulnerability of this activity to extreme climate events such as drought and flooding is high.

According to the RGPH-4 of INSAE in 2013, the population of the basin is more than 548,213. They live in high density by grouping area and in addition to the rainfed agriculture, they practice: fishing, livestock and the transformation of some local products such as the shea, groundnut, etc.

3.4. Vegetation and Soil

In this dry continental area, the vegetation is dominated by savannas, divided into tree and shrub savannas with a strong agricultural influence. There are forest galleries along the watercourses. Classified forests cover a large area of the basin, especially the Pendjari wildlife park, which is the refuge of warthogs, monkeys, buffaloes, lions, elephants, etc.

The most dominant type of soil in the basin is ferruginous on crystalline bedrock. In the northern part of the basin, it is the Niger Valley and its tributaries where there is sandy and ferruginous clay.

CHAPTER FOUR

4. MATERIALS AND METHODS

This chapter gives a detailed information about the datasets required to answer the research questions outlined in Chapter 1. It provides the methodology adopted in this study and highlight the stepwise procedures for the hydrological modelling.

4.1. Data acquisition for Hydrologic Modelling

There are different types of data (climatic data, hydrological data, Climate model data, etc.) used in the framework of this research. All these data have been collected in order to be used as input for HEC-HMS hydrological model.

- Digital Elevation Model (DEM)

DEM (Digital Elevation Model) is the topographic representation of the study area features. For Mekrou River catchment, a 30m spatial resolution DEM was downloaded from (http://srtm.csi.cgiar.org) in decimal degree and datum WGS84. The DEM acquired for the study areas were refined using tools ArcGIS and HEC-GeoHMS tools.

- Land use and Soil cover

Land use Land cover map

The global LULC map of the catchment region was obtained from Institut Geographic National (IGN) of Benin. These data were then exported to ArcGIS in order to extract the study area from the global map. Afterwards, a symbology has been performed in order to obtain the final lulc shapefile maps of the study area (see Figure 9).

Soil type and soil cover

The global Soil cover map of the catchment region was obtained from Office Béninoise de Recherches Géologiques et Minières. As the lulc data, the global map of soil type and soil cover were exported to ArcGIS in order to clip the study area. A symbology has been performed afterwards in order to obtain the soil type map of the study area.

Figure 9: Land use/Land cover Map of the study area

- Climatic data

Climatic data includes precipitation, humidity and temperature data. Climate data for the study area were obtained from National Meteorological Service of BENIN. The timeseries available data were collected for Natitingou and Kandi synoptic weather station. However, these data contain were not complete and contained some missing data which has been fulfilled by using the mean imputation method.

- Hydrological data

For the calibration of hydrological model, the daily streamflow data have been used. In case of Mekrou river, there are two discharge gauging stations along the river stretch namely Kérou and Kompougou. For this study, only the daily flow data of Kompougou gauge station has been obtained from Benin General Directorate of Water.

- Climate model data (GCMs and RCM)

The simulated data are future (RCP8.5 scenarios) precipitation, humidity and temperature projection data of one regional climate model (SMHI-RCA4) obtained from the CORDEX

Africa project. Its characteristics are shown in Table 1. The future projections, i.e., RCP8.5 scenarios, are considered over the period from 2026 to 2099. The data bias was corrected using the Empirical Quantile Mapping Method.

Table 1:Main characteristics of RCMs data

Model (RCM)	Institution	Driving GCM	Horizontal Resolution	Simulation Period
RC4	SMHI	CSIRO-QCCCE	50km	1950-2100

4.2.Methodology

4.2.1. Hydrological model development

Rainfall runoff modelling was carried out with HEC-HMS 4.7.1 and its ArcGIS extension HEC-GeoHMS.

A schematic diagram (Figure 10) gives an overview of the working mechanism of rainfall runoff model.

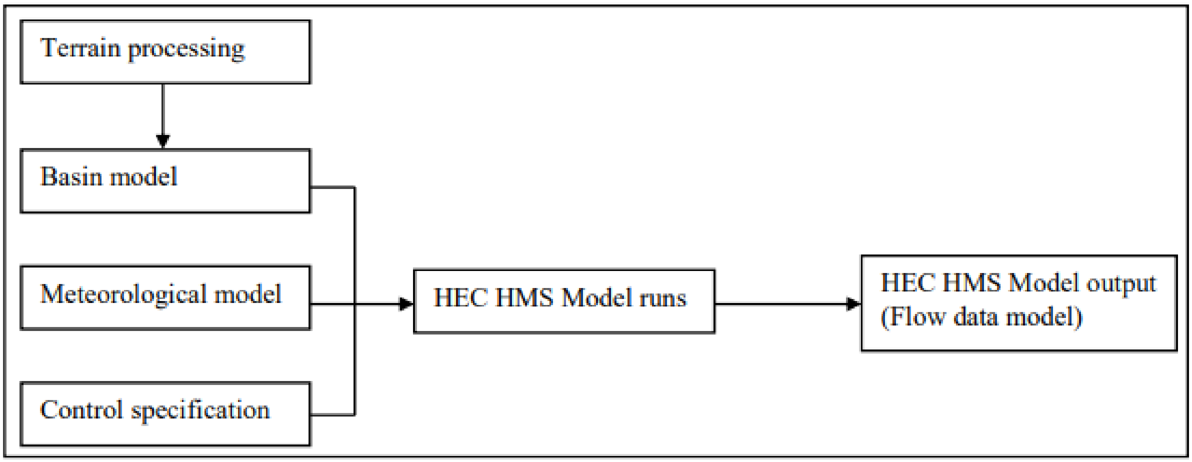

Figure 10:Schematic approach of Rainfall-Runoff modelling

Nevertheless, the version of HEC-HSM model, every Rainfall Runoff Modelling run with that software follows three steps which are categorised as:

- Creation of the basin model,
- Development of the hydrological parameters,
- Hydrological modelling and simulation.

a- Creation of the basin model

Terrain Pre-processing

Before carrying out terrain pre-processing, HEC-HMS project has been created and the coordinate system of the input terrain data DEM was defined using HEC-HMS 4.7.1 GIS tools. After this process, the DEM was pre-processed to derive sub-basins and drainage network of the catchment. The steps included: Pre-process sinks, Pre-process Drainage.

Basin processing

The terrain pre-processing is followed by the basin processing. At this step, Identify Streams, Break Point Manager and Delineate Elements have been used in order to create the hydrologic modelling system of the study area. Through these tools, the study area basin has been defined, the hydrologic network with different streams and also the outlet.

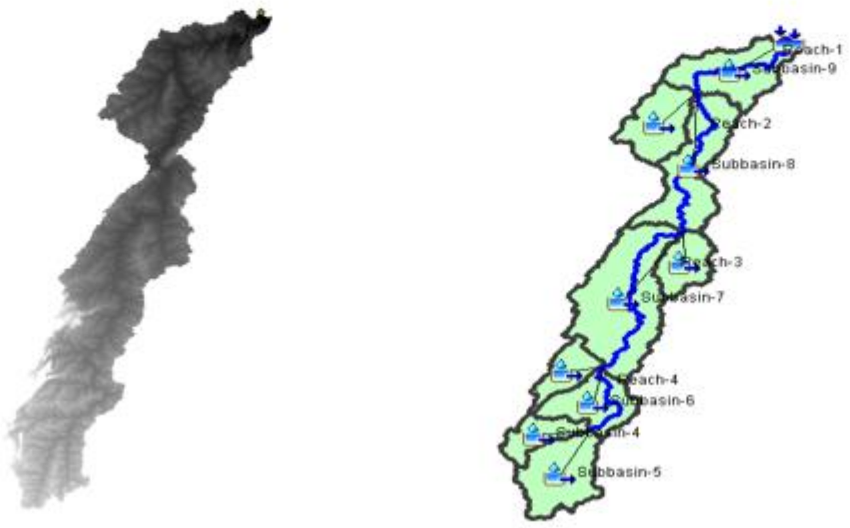

Figure 11: Left-Raw DEM of Mekrou River Catchment (downloaded from USGS website and modified by the author). Right-Hydrologic modeling system of Mekrou River Catchment by HEC-HMS

b- Development of the hydrological parameters

At this step, the values of every hydrological process involved in modelling are parameterise. The land and soil use data for each sub-basin were used for the estimation of the hydrological parameters. Several steps are involved in the development of the hydrological parameters. Table2 shows different HSM parameters use for this study.

Table 2:HSM parameters use for this study

HSM processes	Method
Loss	SCS Curve number
Transform	SCS Unit Hydrograph
Routing	Muskigum

b-1. Parameters estimation

- **Loss-Model-Soil conservation Service Curve Number**

The loss models in HEC-HMS were calculated by subtracting the volume of water that was intercepted, infiltrated, stored, evaporated or transpired to the rainfall water volume. For the estimation of the direct Runoff for a design precipitation, the method of Soil Conservation Service Curve Number loss (SCS Curve number) were used.

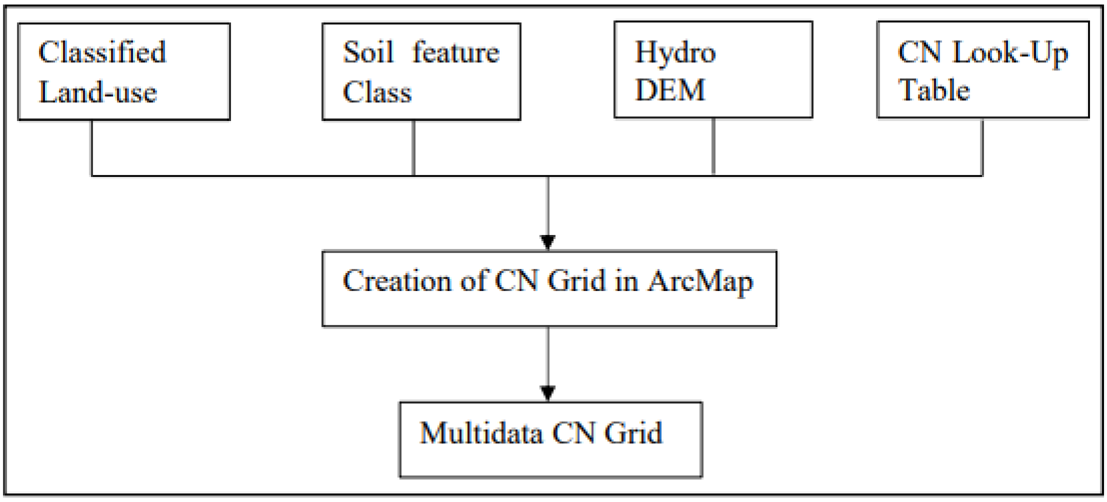

Figure 12:Procedure for the creation of CN Grid in ArcMap

For the loss model, the SCS-CN has two parameters: the curve number (CN) and the initial abstraction (Ia). The default initial abstraction ratio was equal to 0.2 but then varied after the model calibration. The CN (Figure 13) is a function of land use and soil type estimated by using the HEC-GeoHMS toolkit of Arc Map 10.5. The percentage of imperviousness for each sub-basin was assumed to be 0% (the entire catchment was assumed to be completely pervious). The CN values for each sub-basin were calculated by using the Mean statistical grid value in ArcMap. The formula driving by that calculation is:

$$\mathrm{CN} = \frac{\sum \mathrm{A_i CN_i}}{\sum \mathrm{A_i}}$$

where Ai is the area (km2) of the sub-basin and CNi is the corresponding curve number.

Ia (mm) is obtained by multiplying the loss coefficient by the potential abstraction S (mm). The potential abstraction (S) is a function of CN and calculated by using the formula:

$$\mathrm{S} = \frac{25,400}{\mathrm{CN}} - 254$$

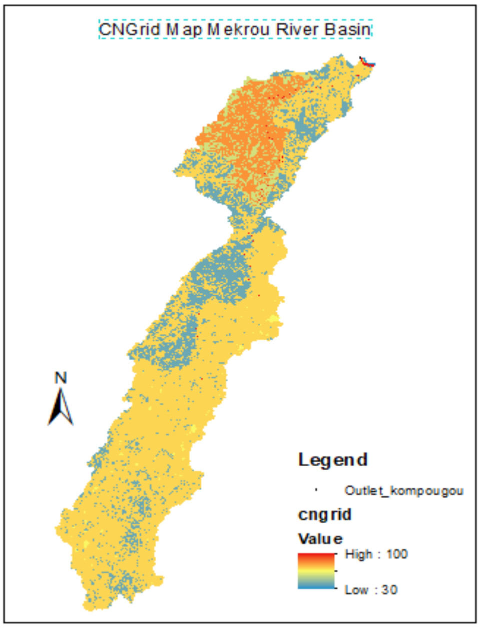

Figure 13:Curve Number Grid of Mekrou River Catchment (Generated with ArcMap)

- **Transform Model—Soil Conservation Service Unit Hydrograph Method**

The direct runoff process of the excess rainfall in the catchment area is simulated by the transformation prediction models of the HEC-HMS software. Through this process, the excess rainfall is transformed into point runoff. To transform the excess rainfall into runoff, the SCS unit hydrograph model was used during the analysis of the study data.

The basin lag time parameter values have been calculated during data processing by means of the HEC GeoHMS application and stored in the attributes' table of the sub-basin data layer. Basin lag times were initially calculated in hours for the sub-basins by using and were then converted to minutes when used with HEC-HMS.

$$\mathrm{Lag} = \frac{(S+1)^{0.7} L^{0.8}}{1900 * Y^{0.5}}$$

where S = maximum retention (mm) as defined above, lag = basin lag time (hour), L= hydraulic length of the catchment (longest flow path) (feet) and Y = basin slope (%). Table 4 shows the Loss and Transform Model parameter value estimations.

- **Routing: Muskingum Method**

As the flood runoff moves through the channel reach, it weakens because of the channel storage effects. The routing model available in the HEC-HMS software for this scenario was the Muskingum method.

The Muskingum method is one of the most common lumped flow routing techniques. In this model, two parameters (X and K), was required for the calibration. X is a dimensionless weight, which is a constant coefficient that varies between 0 and 0.5, where X is a factor representing the relative influence of flow on storage levels. It can be assumed that the value equals 0.1 as an initial value of the calibration parameters, which was corrected during the calibration process. The parameter K has a time and it value ranges from 1 to 5 h. K is directly related to the delay between discharge peaks. K is estimated using:

$$K = \frac{L}{V_w}$$

where Vw is the flood wave velocity, which can be taken as 1.5 times the average velocity, and L is the reach length. The average velocity was obtained from the stream gauging sites. The value of K was used also in the calibration process within short limits based on K estimation until the simulated hydrographs approached the observed ones.

The hydrological modelling system of the HEC-HMS software was used to simulate the rainfall runoff process of the catchments. The pre-processed model as a catchment file made with HEC-GeoHMS was imported into the HEC-HMS software. These HEC-HMS input data are essential to perform the rainfall-runoff modelling.

The calculated parameters, such as loss parameters (curve number, initial abstraction and percentage of imperviousness), transform parameters (lag time) and routing parameters (k and x), were added to the sub-basins and the reaches either manually from the GIS attribute tables. The precipitation, temperature, evaporation and discharge gauge data were added as time series using the time series data manager.

Three files were created for rainfall data input in the meteorological folder, corresponding to the hydrological year intervals 1982-1984, 2007-2009 and 2010-2011. For the control run, daily rainfall was started on January 1st at 00:00 and ended on December 31st at 00:00. The selected time interval for the hydrograph was of one day for the three corresponding hydrological years.

4.2.2. Flood hazard assessment

The main goal of flood risk assessment is to be able to determine the probability that a flood of a given intensity will occur over a long period of time. After the risk assessment, it would be possible to estimate this probability over long periods of time ranging from a few years to decades in order to assist in the planning of risk management activities. Generally speaking, the depth and horizontal extent of floodwaters are referred to as intensity. However, the flow velocity as well as the duration of the flooding are also other intensity parameters that can be useful depending on the situation.

4.2.3. Flood frequency analysis

Flood frequency analysis is defined as an estimate of how often a given flood flow will recur. This kind of estimation is necessary for the hydraulic calculation of a river and the creation of a flood map. In order to carry out the analysis, a probability model has to be adapted to the extreme annual values of floods recorded over a long period of time in the catchment area. Once the model parameters are established, they can be used for the prediction of extreme events with a large recurrence scale (Pegram and Parak, 2004).

Among the river hydrology studies, flood frequency analysis is one of the important, which could be conducted based on maximum instantaneous flow (Ntajal, 2016).

According to (Khaliq et al., 2006), there are three steps in frequency analysis:

- selecting a suitable Probability Distribution Function (PDF);
- estimating the parameters of PDF based on samples;
- assessing the uncertainty of objective of interest in prescribed confidence level.

Flood frequency analysis is the procedure of obtaining the relationship between flood quantiles and their non-exceedance probability using extreme value theory.

The magnitude of the T-year flood at a site is the amount of streamflow that has a probability 1/T of being exceeded in any one year.

- Using either the Annual Maximum Series (AMS) or Peak Over Treshold (POT) methods/ Partial Duration Series (PDS), a selection of values from the streamflow series can be considered peak events (Claps & Laio, 2003).

4.2.4. Probability distribution

For accurate hydrologic analysis of flooding there are different probability distributions method used to estimate extreme rainfall such as Beta –P; Generalized extreme value (GEV), Gumbel, Weibull, Beta-k, Generalized Logistic (GLO), Generalized Pareto (GPA), Log-Pearson Type III, Pearson Type III and Generalized Normal, GNO, (Icyimpaye, 2018).

The generalized extreme value (GEV), of which extreme value type I (EV I), EV II, and EV III are special cases, and the generalized Pareto distribution (GDP) are frequently used when analysing data in the context of extreme value theory (Ghorbani, Ruskeep, Singh, & Sivakumar, 2010). The EV I or Gumbel distribution is commonly used for the distribution of annual maxima of stream flows, though the Person type 3 or log-normal is also common. It is indeed the most widely used distribution to model extremes in hydrology (Koutsoyiannis, 2004). The EV III distribution is used for annual low flows. The most common approaches are the annual maximum series (AMS) method and the Peak-over-threshold (POT) or Partial duration series (PDS) method. Among the many probability distributions, the ones that are commonly used are Pearson type III, Weibull, Generalized Extreme Value distributions, Gumbel which seem to adequately fit peak, rainfall and stream-flow (Ghorbani et al., 2010).

4.2.5. HYFRAN-PLUS Software

HYFRAN software is especially designed for extreme value for Hydrological Frequency Analysis (HFA) . HYFRAN software version 1.1 (Salaheddine & Bobée, 2015) is the one used in this study. It is a tool developed by Canadian Developer used to fit statistical distributions (Alib et al., 2016). For flood analysis, the maximum annual flow is often considered. However, HYFRAN allows to fit different statistical distributions. To any dataset of extreme values in areas with different time steps, provided that observations are Independent and Identically Distributed (IDD). The “comparison” option allows to compare several fittings to choose which is the most adequate to represent the studied dataset.

The fittings can be compared using criteria or graphics.

Graphic: It is possible to compare the results of several different fits (2 or 5) using either Normal or Gumbel probability paper.

Criteria: Two criteria are available, these are the Akaike (AIC) and Bayesian information Criteria (BIC) (Ehsanzadeh et al., 2010). Criteria can be reliably used in climate statistics to assist in finding the best distribution to use to fit the given data. These tests describe the differences between the observed data values, and the expected values from the distribution being tested (Millington, Das, & Simonovic, 2011).

$\mathrm{AICj} = -2ln(Lj) + 2pj$

Where pj is the number of estimated parameters, and Lj is the likelihood function and n is the sample size.

The Bayesian criterion (BIC) is based on the discrepancy between the model and the parent distribution in a Bayesian framework (Schwarz, 1978). BIC can be computed according to the following relationship:

$\mathrm{BIC} = -2\ ln(Lj) + ln(n)pj$

CHAPTER FIVE

5. RESULT AND DISCUSSION

5.1. HEC-HMS model set-up

5.1.1. Model Calibration

Calibration of the model is a process of setting model parameters so that the simulated results match with the observed data and it is done after making a comparison between the simulated and observed discharge results. The model is calibrated by using the daily rainfall data from the hydrological year intervals 1982-1984. Manual calibration was applied to estimate the values of the different parameters. The optimal values of the Muskingum Model parameters (K, X) were obtained by comparing the observed and simulated flows, while the parameters of the Loss Model and the Transform Model were calculated.

Table 3:The estimation of Loss and Transform Model parameter values.

Name	CN	L(km)	Y	S	L(ft)	Y(%)	Lag(hr)
Basin1	81.77	59.57	0.01726	56.60	195440.2	1.726	116.9174
Basin2	82.20	48.40	0.01719	55.00	158807.4	1.719	97.28462
Basin3	81.37	266.05	0.02576	58.12	872880.6	2.576	322.6652
Basin4	81.40	134.60	0.01922	58.04	441609.5	1.922	216.3706
Basin5	81.15	97.93	0.02059	58.96	321324.6	2.059	163.8695

Basin6	81.98	71.63	0.02479	55.81	235031.3	2.479	111.9642
Basin7	80.03	142.10	0.02059	63.34	466214.5	2.059	231.8702
Basin8	79.74	134.60	0.01922	64.50	441609.5	1.922	232.6932
Basin9	80.94	97.93	0.02059	59.79	321324.6	2.059	165.4396

Satisfactory results are obtained as shown by Table 4, where the objective function, Nash-Sutcliff Efficiency coefficient (NSE) is relatively high reaching the value of 0.70. In addition, coefficient of determination is 0.8 PBIAS is 0.75. These performance results are above the normal reference (see 2.2.6.6) and shows that HEC-HMS model can significantly well simulate the discharge in Mekrou river basin over the calibration period 1982 to 1984.

Table 4: HEC-HMS model efficiency results for the calibration period

Goodness of fit	Calibration results
Model efficiency (Nash-Sutcliffe E)	0.7
Coefficient of determination (R2)	0.8
Percent bias (PBIAS)	0.75

5.1.2. Model Validation

Following the satisfactory calibration results, the HEC-HSM hydrological model was validated with the calibration parameters. Two independent periods (2007-2009 and 2010-2011) were used to validate the model. Validation also shows satisfactory results (Table 5); according to the goodness of fit criteria for the validation periods 2007-2009 and 2010-2011 where NSE, R^2

are greater than 0.70. While the Percent bias (PBIAS) is respectively: 0.62 and 0.68 (those values are lower than the calibration values but still fitting the goodness criteria.)

Table 5:HEC-HMS model efficiency results for the validation period

Validation Period	Goodness of fit	Validations results
2007-2009	Model efficiency (Nash-Sutcliffe E)	0.71
	Coefficient of determination (R2)	0.78
	Percent bias (PBIAS)	0.62
2010-2011	Model efficiency (Nash-Sutcliffe E)	0.75
	Coefficient of determination (R2)	0.70
	Percent bias (PBIAS)	0.68

5.2. Climate model data processing

After the validation of the Rainfall-Runoff model over the Mekrou river catchment, the parameters used for calibration and validation have been used to simulate the future discharge.

After simulation, the time series discharge has been extracted and the Maximal Annual discharge sorted for the two future projected period. Table 6 show the simulated Maximum annual for the simulated future periods.

Table 6:Simulated annual maximum future discharge (2026-2055)

Year	Discharge(m^3/s)	Year	Discharge(m^3/s)	Year	Discharge(m^3/s)
2026	225.5	2036	254.8	2046	253
2027	224.1	2037	253.3	2047	283.1
2028	181.5	2038	236.6	2048	333.4
2029	168.4	2039	370.8	2049	221.5
2030	232	2040	286.5	2050	279.1
2031	253.7	2041	317	2051	229.5
2032	207.1	2042	157.7	2052	334.1
2033	293.1	2043	278.6	2053	286.3
2034	219.7	2044	349.9	2054	286.1
2035	248.5	2045	257.3	2055	276.8

Table 7:Simulated annual maximal discharge (2070-2099)

Year	Discharge(m^3/s)	Year	Discharge(m^3/s)	Year	Discharge(m^3/s)
2070	251.9	2080	283.6	2090	281.4
2071	249.9	2081	281.7	2091	314
2072	202.6	2082	263.1	2092	370.3
2073	188.1	2083	411.6	2093	246.8
2074	258.4	2084	319.4	2094	311.2
2075	282.3	2085	352.1	2095	255.5
2076	230.9	2086	176	2096	370.8

2077	327	2087	309.4	2097	319.1
2078	245.6	2088	388.6	2098	319.1
2079	276.6	2089	285.8	2099	308.4

5.3. Flood frequency analysis

5.3.1. Probability distribution with Hyfran software

Flood frequency analysis were carried out using Hyfran-Plus software. It allows to analyse the relationships between flood quantile and its frequency of occurrence. Three probability distributions (GEV, Gumbel and Lognormal) were used and the corresponding BIC and AIC for 100 years return period were computed and in Table 8.

5.3.2. Best fitting probability distribution

After the reviewing the results of the distributions used and the corresponding performance criteria (Table 8 and Table 9), It can be noticed that for the historical period of 1982- 2011, and future periods (2026-2055; 2070-2099), Lognormal distribution presents the lower BIC and AIC compared to the Generalized Extreme value (GEV) and Gumbel. Figure 14 shows a well fit of the observation points for the Lognormal distribution. The probability distribution which has the lower BIC and AIC is the one fitting better the data series. Hence, Lognormal distribution fits the best the discharge series for both historical and projected discharge/ HEC-HMS outputs.

Table 8:Comparaison criteria of the distribution for 100 years return period

Probability Distribution	Parameter of estimation	From 2026-2055			From 2070-2099		
		XT	BIC	AIC	XT	BIC	AIC
GEV	Weighted moments	381.278	329.902	325.699	423.374	335.906	331.703

Gumbel	Weighted moments	428.079	331.096	328.294	475.206	337.180	334.378
Lognormal	Maximun likelihood	408.406	327.569	324.766	453.202	333.585	330.783

Table 9:Comparaison criteria of the distribution for 100 years return period (Observed)

Probability Distribution	Parameter of estimation	From 1982-2011		
		XT	BIC	AIC
GEV	Weighted moments	303.196	338.217	334.014
Gumbel	Weighted moments	373.880	335.639	332.486
Lognormal	Maximun likelihood	341.724	335.289	332.486

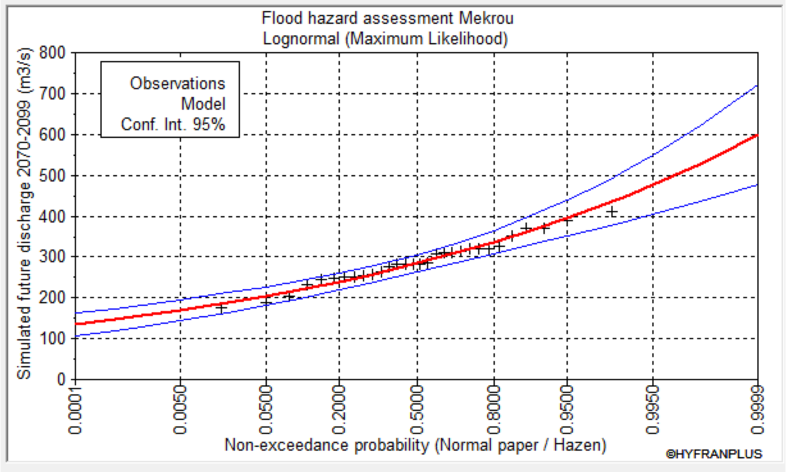

Figure 14:Probability distribution Lognormal (Maximum Likehood) for T=100

5.3.3. Climate change impact on flood frequency

Understanding the climate change impact on the hydrologic cycle evolution is one of the major challenges for water resources management. Recent climate changes have had serious impacts on the magnitude and frequency of floods in many regions of the world (IPCC, 2014). The results analysis of future flood frequency under climate change in Mekrou river catchment are presented in this section. The probability of non-exceedance (q), the flood quantile (XT) as well as the corresponding return period (T), for the historical (1982- 2011) and future periods (2026-2055; 2070-2099). Those results were obtained from Lognormal distribution (Maximum Likelihood) with Hyfran-Plus software.

Table 10:Discharge frequency analysis and Percentage of change in future floods

Return Period	Probability of non-exceedance	XT			CHANGE (%)	
		1982-2011	2026-2055	2070-2099	2026-2055	2070-2099
100	0.99	374	408	453	9.09	21.12
50	0.98	331	386	429	16.61	29.60
30	0.9667	300	370	410	23.33	36.66
20	0.95	275	356	395	29.45	43.64

10	0.9	234	331	367	41.45	56.83
5	0.8	192	302	336	57.29	75

To reduce the uncertainties in climate model simulations, Hydrological model, downscaled RCMs data, Hyfran software, the analysis was concentrated on change in quantiles which is common in scenario analysis (Hounkpè et al., 2015) rather than absolute values. The change in flood frequency over the future periods (2026-2055; 2070-2099) is presented in Table 10. The result reveals an increase in future quantile change compared to the historical quantiles. The change ranges between 9.09% and 57.29% for the period (2026-2055) and 21.12% to 75% for 2070-2099. Therefore, it is clearly indicated that flood frequency will increase in the middle and by the end of 21st century due to the climate change, in the Mekrou River basin.

It has been noticed that when the return period increase, the discharge quantiles increase too. That’s mean higher discharge will be recorded by 2100 compared to 2050 as well as the historical period (1982-2011) based on the result of the study.

CHAPTER SIX

6. Conclusions and recommendations

6.1. Conclusions

The Niger is a transboundary river located in West Africa; it is the third-longest river in Africa, exceeded only by the Nile and the Congo River, it floods annually causing material damage and most alarming the loss of human lives. Studies have shown an increase of the frequency and the magnitude of floods in the NRB over the decades (Geo, 2015). Even though extreme events cannot be prevented, a better understanding of the risk pose by such events is the first stage in building the resilience of the community.

The main objective of this study was to access the flood hazard events under climate change through Rainfall-Runoff modelling. Hydrological model (HEC-HMS) of Mekrou River basin (Sub-basin of Niger river basin) were developed to study the effect of climate change on future flood frequency.

HEC-HMS model version 4.7.1 was calibrated over the period 1982- 1984 and validated on 2007-2009 and 2010-2011. Satisfactory results were obtained during the calibration and validation periods. Once the model has been calibrated and validated, it has been used to simulate future Rainfall-Runoff process over the Mekrou River basin. RCP8.5 bias corrected metrological data download from CORDEX Africa website and downscaled at basin level. The Annual maximal discharge provided by the output data of the hydrological model were used as input for HYFRAN-PLUS software for the future flood frequency analysis over the study area.

The result of flood hazard assessment under climate change (RCP8.5) revealed that the future quantile of flood frequency will increase compared to the historical quantiles. For the period of (2026-2055), the percentage of change ranges between 9.09% and 57.29% while from 2070-2099, its ranges between 21.12% to 75%. So, according to the result, flood frequency will increase in the middle and the end of 21st century due to the climate change. Similar result were found by (Obada et al., 2017) who reported that the projected future discharge (2011-2100) of the Mekrou River through four hydrological models under climate change will increase for different projected periods compared to the baseline period (1981-2010).

6.2. Recommendations

The result of this study needs to be improved by future research in the study area. Flood risk assessment in the study area could help to better understand flood events and its impact in the catchment. It will be an important tool to support decision taking. Furthermore, land use and land cover dynamics should be taken into consideration in order to produce more accurate results for projected period.

REFERENCES

Adegoke, J., B. Y., Sylla, M. B., Taylor, C., & & Klein, C. (2019). *Chapter 1 : On the 2017 Rainy Season Intensity and Subsequent Flood Events Over West Africa.*

Alexander, L. V., Zhang, X., Peterson, T. C., Caesar, J., Gleason, B., Klein Tank, A. M. G., Haylock, M., Collins, D., Trewin, B., Rahimzadeh, F., Tagipour, A., Rupa Kumar, K., Revadekar, J., Griffiths, G., Vincent, L., Stephenson, D. B., Burn, J., Aguilar, E., Brunet, M., … Vazquez-Aguirre, J. L. (2006). Global observed changes in daily climate extremes of temperature and precipitation. *Journal of Geophysical Research Atmospheres*, *111*(5). https://doi.org/10.1029/2005JD006290

Amogu, O., Descroix, L., Yéro, K. S., Breton, E. Le, Mamadou, I., Ali, A., Vischel, T., Bader, J. C., Moussa, I. B., Gautier, E., Boubkraoui, S., & Belleudy, P. (2010). Increasing river flows in the Sahel? *Water (Switzerland)*, *2*(2), 170–199. https://doi.org/10.3390/W2020170

AR5. (2013). *AR5 Climate Change 2013: The Physical Science Basis — IPCC*. https://www.ipcc.ch/report/ar5/wg1/

Bates & al. (2008). *Climate Change and Water Technical Paper of the Intergovernmental Panel on Climate Change*.

Behanzin, I. D., Thiel, M., Szarzynski, J., & Boko, M. (2016). *GIS-Based Mapping of Flood Vulnerability and Risk in the Bénin Niger River Valley*. *6*(3).

Dunne, T. (1983). Relation of field studies and modeling in the prediction of storm runoff. *Journal of Hydrology*, *65*(1–3), 25–48. https://doi.org/10.1016/0022-1694(83)90209-3

Field, T., Diego, M., & Hernandez-Reif, M. (2010). Preterm Infant Massage Therapy Research: A Review. *Infant Behavior & Development*, *33*(2), 115. https://doi.org/10.1016/J.INFBEH.2009.12.004

Fleming, M., & Neary, V. (2004). Continuous Hydrologic Modeling Study with the Hydrologic Modeling System. *Journal of Hydrologic Engineering*, *9*(3), 175–183. https://doi.org/10.1061/(ASCE)1084-0699(2004)9:3(175)

Goly, A., & Teegavarapu, R. S. V. (2013). Assessment of various statistical downscaling methods for downscaling precipitation in Florida. *World Environmental and Water Resources Congress 2013: Showcasing the Future - Proceedings of the 2013 Congress*, 1086–1098. https://doi.org/10.1061/9780784412947.105

Goswami, B. N., Venugopal, V., Sangupta, D., Madhusoodanan, M. S., & Xavier, P. K. (2006). Increasing trend of extreme rain events over India in a warming environment. *Science*, *314*(5804), 1442–1445. https://doi.org/10.1126/SCIENCE.1132027

Hirschboeck, K. K. (1987a). *and Atmospheric Circulation Anomalies*. 23–56.

Hirschboeck, K. K. (1987b). *Hirschboeck, K.K., 1987. Hydroclimatically•defined mixed distributions in partial duration flood series, in Singh, V.P., ed., Hydrologic Frequency Modeling, D. Reidel Publishing Company, 199•212.* 199–212.

Houghton et Al. (2001). C Limate C Hange. *SciencesNew York*, *November 2014*, 30–30. http://www.metoffice.gov.uk

Hounkpè, J., Diekkrüger, B., Badou, D. F., & Afouda, A. A. (2015). Non-stationary flood frequency analysis in the Ouémé River Basin, Benin Republic. *Hydrology*, *2*(4), 210–229. https://doi.org/10.3390/HYDROLOGY2040210

IPCC. (2012). *Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change.*

IPCC. (2014a). Climate change 2014: impacts, adaptation, and vulnerability. Part A: global and sectoral aspects. Contribution of working group II to the fifth assessment report of the intergovernmental panel on climate change. *Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, PartA.*

IPCC. (2014b). Climate change 2014: Impacts, adaptation, and vulnerability. Part B: regional aspects. Contribution of working group II to the fifth assessment report of the intergovernmental panel on climate change. *Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, PartB.*

IPCC. (2014c). *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*

[Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

Kharin, V. V., Zwiers, F. W., Zhang, X., & Wehner, M. (2013). Changes in temperature and precipitation extremes in the CMIP5 ensemble. *Climatic Change*, *119*(2), 345–357. https://doi.org/10.1007/S10584-013-0705-8

Kundzewicz, Z. W., Mata, L. J., Arnell, N. W., DÖLL, P., Jimenez, B., Miller, K., Oki, T., ŞEN, Z., & Shiklomanov, I. (2008). The implications of projected climate change for freshwater resources and their management. *Hydrological Sciences Journal*, *53*(1), 3–10. https://doi.org/10.1623/HYSJ.53.1.3

Library, W. O., Panthou, G., Vischel, T., & Lebel, T. (2014). Short Communication Recent trends in the regime of extreme rainfall in the Central Sahel. *INTERNATIONAL JOURNAL OF CLIMATOLOGY Int. J. Climatol*, *34*, 3998–4006. https://doi.org/10.1002/joc.3984

Lins, H.F., & Slack, J. R. (1999). Streamflow trends in the United States. *Geophysical Research Letters*, *26*(2), 227–230.

Lins, Harry F. (1997). Regional streamflow regimes and hydroclimatology of the United States. *Water Resources Research*, *33*(7), 1655–1667. https://doi.org/10.1029/97WR00615

Llanbrynmair, M. D. N. (2016). Book reviews: Ward, R. 1978: Floods, a geographical perspective. London: Macmillan. 244 pp. £8.95 cloth, £3.95 paper: *Http://Dx.Doi.Org/10.1177/030913337900300318*, *3*(3), 467–468. https://doi.org/10.1177/030913337900300318

Manivannan, S., Ramaswamy, K., & Shanthi, R. (2001). Predicting runoff from tank catchments using Green-Ampt and SCS runoff curve number models. *International Agricultural Engineering Journal*, *10*(1–2), 57–69.

Obada, E., Alamou, E. A., Zandagba, J., Chabi, A., & Afouda, A. (2017). Change in future rainfall characteristics in the Mekrou catchment (Benin), from an ensemble of 3 RCMs (MPI-REMO, DMI-HIRHAM5 and SMHI-RCA4). *Hydrology*, *4*(1). https://doi.org/10.3390/hydrology4010014

Petterssen, S. (1958). Introduction to meteorology. By Sverre Petterssen, New York (McGraw-

Hill), 1958. Pp. ix, 327, 213 Figs.; 14 Tables; 52s. 6d. *Quarterly Journal of the Royal Meteorological Society*, *85*(363), 78–78. https://doi.org/10.1002/QJ.49708536319

Rani, S., & Sreekesh, S. (2019). Evaluating the Responses of Streamflow under Future Climate Change Scenarios in a Western Indian Himalaya Watershed. *Environmental Processes*, *6*(1), 155–174. https://doi.org/10.1007/S40710-019-00361-2

Schickhoff, U., Bobrowski, M., Böhner, J., Bürzle, B., Chaudhary, R. P., Gerlitz, L., Lange, J., Müller, M., Scholten, T., & Schwab, N. (2016). Climate Change and Treeline Dynamics in the Himalaya. *Climate Change, Glacier Response, and Vegetation Dynamics in the Himalaya: Contributions Toward Future Earth Initiatives*, 271–306. https://doi.org/10.1007/978-3-319-28977-9_15

Sharif, M., & Burn, D. (2009). Detection of linkages between extreme flow measures and climate indices. *World Academy of Science, Engineering and Technology*, *36*, 873–878. https://doi.org/10.5281/zenodo.1063248

Shrestha, U. B., Gautam, S., & Bawa, K. S. (2012). Widespread climate change in the Himalayas and associated changes in local ecosystems. *PloS One*, *7*(5). https://doi.org/10.1371/JOURNAL.PONE.0036741

Sighomnou, D., Descroix, L., Genthon, P., Mahé, G., Moussa, I. B., Gautier, E., Mamadou, I., Vandervaere, J. P., Bachir, T., Coulibaly, B., Rajot, J. L., Issa, O. M., Abdou, M. M., Dessay, N., Delaitre, E., Maiga, O. F., Diedhiou, A., Panthou, G., Vischel, T., … Hiernaux, P. (2013). La crue de 2012 à Niamey: Un paroxysme du paradoxe du Sahel? *Science et Changements Planetaires - Secheresse*, *24*(1), 3–13. https://doi.org/10.1684/SEC.2013.0370

Trenberth, K. E., Dai, A., Rasmussen, R. M., & Parsons, D. B. (2003). The changing character of precipitation. *Bulletin of the American Meteorological Society*, *84*(9), 1205-1217+1161. https://doi.org/10.1175/BAMS-84-9-1205

UNISDR. (2009). *THE HUMAN COST OF WEATHER RELATED DISASTERS*.

Vargas, C. A., Lagos, N. A., Lardies, M. A., Duarte, C., Manríquez, P. H., Aguilera, V. M., Broitman, B., Widdicombe, S., & Dupont, S. (2017). Species-specific responses to ocean acidification should account for local adaptation and adaptive plasticity. *Nature Ecology* *and Evolution*, *1*(4). https://doi.org/10.1038/S41559-017-0084

Webb, R. H., & Betancourt, J. L. (1992). Climatic variability and flood frequency of the Santa Cruz River, Pima County, Arizona. *Water Supply Paper*. https://doi.org/10.3133/WSP2379