



**UNIVERSITY OF NAIROBI**

**CLIMATE CHANGE IMPACTS ON WATER  
RESOURCES OVER THE UPPER TANA CATCHMENT  
OF KENYA**

**BY**

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**REG: I56/76205/2014**

**A Dissertation Submitted in Partial Fulfillment of the Requirements for the Award of  
the Degree of Master of Science in Meteorology of the University of Nairobi**

**AUGUST, 2016**

## Declaration

This dissertation is my original work and has not been presented for the award of a degree in the University of Nairobi or any other University.

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## **Dedication**

I dedicate this dissertation to my mother for her constant support and prayers, my entire family, who heartened me to work hard in order to accomplish the best.

## **Acknowledgment**

I wish to thank the Almighty God for helping me through the entire MSc. Study and through my project work. Secondly, I wish to express my heartfelt appreciation to Dr. Mutemi, Dr. Opere and Professor Mutua for their valuable guidance and advice which contributed to the completion of my project work.

Very special thanks to the University of Nairobi for offering me a partial scholarship and the WaSo project under the coordination of Professor Mutua for offering me a financial and career opportunity support. I also appreciate the entire staff of the Department of Meteorology, University of Nairobi for their support during the period of my study.

I would also like to thank my classmates and friends for their support and finally to my family members for their inexorable support during my study period.

## Abstract

The hydrological regimes and cycles within a certain watershed can be altered by the global climate variability and change. This alteration adversely impacts on environmental sustainability, water resources, agriculture and ecosystems. The Upper Tana Catchment in Kenya is the source of the upstream flows of the large Tana River basin. It is also a home to the major hydropower dams in Kenya and so it is the power house for the electricity supply in the country. This therefore makes the catchment one of the most important water areas in the country. Understanding and prediction of connections between the water systems and climate change are the primacy science essential and challenge areas. The study aimed at establishing the probable future status of Upper Tana Catchment water resource availability under different future climate scenarios through modeling framework.

Observed datasets for temperature and rainfall used were acquired from the Kenya Meteorological Department (KMD) and river discharge data used were from the Ministry of Water and Irrigation (MWI). The KMD and MWI datasets were for the period 1951-2014 and 1963-2000 respectively. SWAT data input comprised of Digital Elevation Model (DEM) with a 90m resolution topography data from Shuttle Radar Topography Mission (SRTM). The Land Use data were acquired from the United States Geological Survey (USGS) and soil data from Kenya Soil and Terrain (KENSOTER). The climate projection datasets for the RCP4.5 and RCP8.5 were obtained from IGAD Climate Prediction and Application Centre (ICPAC) for the period 2006-2100.

The data were subjected to various methods in order to define the temporal patterns of climatic and hydrological characteristics at specific locations within the study area. Trend analysis with test using Mann-Kendall (MK) was applied in analyzing the past, current and future climate and water resource status over the catchment. To assess the changes in the rainfall and surface air temperature the Gaussian Kernel density distribution was used. The period 2021-2100 was divided into three climatic periods from 2021-2040, 2051-2070 and 2081-2100. These are the climate in the 30's, 60's and 90's respectively with 20 years of data each. The climatological periods were used analyze the climate projection. The baseline period was taken to be from 1995 to 2014 against which comparison was made.

Results show that rainfall is generally increasing gradually and that the future temperatures are also expected to rise at an alarming rate over the catchment in both RCPs. However, a

greater rate of increase in temperature was observed in RCP8.5 compared to RCP4.5. To evaluate how change in climate may influence the water resources within the Upper Tana, the outputs as shown by changes in the water yields from calibrated and confirmed Soil and Water Assessment Tool (SWAT) were used.

Due to variations in the projected precipitation and temperature in both space and time, different hydrological implications are likely to be caused by climate change. Based on temperature (minimum and maximum) and rainfall changes, the climate change effects on water yields were simulated on a monthly basis. A baseline period of 1970 to 1989 for the observed river flows for the station 4ED03 was used to assess how the water yields over the Upper Tana catchment will be impacted by climate change. This was analyzed against the simulated future river flows for the period 2021-2040, 2051-2070 and 2081-2100.

Results suggest a future increase in the long term yields of water related to the baseline period from January to March for the three climatic phases in RCP4.5 climate change scenario. A reduction in future water yields for MAM rainfall season is depicted in all the climatic periods while a future increase in the water yields in the OND rainfall season. The same tendency of decrease in the future long term water yields during the long rains and an increase in the future water yields in the short rains was also observed in the RCP8.5 climate change scenario for the three climatic periods. Due to precipitation and temperature variations, water yields will be altered by the changes in the climate in the long term. The variation in the river flows during rainy seasons over the catchment has implications on the water quantity and quality, agriculture, energy production sectors and needs for the aquatic habitat.

The results from the study may perhaps enlighten decision making in water sector in terms of development projects implementation in both short and long terms and also strategic planning. These results can also be used in management of water resources and disaster control in the water sector. In understanding the extent of vulnerability of the Upper Tana Catchment water resources to the climate change impacts, policy makers can also use the results from this study. This will help in coming up with suitable mitigation and adaptation approaches. The use of integrated hydrological modeling in impact assessment and the inclusion of other factors that cause imbalance in the water should be enhanced in the Upper Tana Catchment.

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## **LIST OF ACRONYMS**

AR: Assessment Report

CCCMA: Canadian Centre for Climate Modeling and Analysis

CDF: Cumulative Distribution Function

CFCs: Chlorofluorocarbons

CH<sub>4</sub>: Methane

CO<sub>2</sub>: Carbon dioxide

CORDEX: Coordinated Regional Climate Downscaling Experiments

DEM: Digital Elevation Model

ECMWF: European Centre for Medium-Range Weather Forecasting

EPA: Environmental Protection Agency

ERA -Interim: ECMWF Re-Analysis Interim

GCMs: General Climate Models

GHGs: Greenhouse Gases

GOK: Government of Kenya

GIS: Geographical Information System

GW: Groundwater Contribution

H<sub>2</sub>O: Water

HCFCs: Hydro-chlorofluorocarbons SF<sub>6</sub>

HEP: hydroelectric power

HFCs: Hydro-fluorocarbons

HRUs: Hydrological response units

ICPAC: Intergovernmental Authority on Development Climate Prediction and Applications Centre

IPCC: Intergovernmental Panel on Climate Change

ISRIC: International Soil Reference and Information Centre

ITCZ: Inter-tropical Convergence Zone

KENSOTER: Kenya Soil and Terrain Database

KMD: Kenya Meteorological Department

KSS: Kenya Soil Survey

LULC: Land-use/Land-cover

LULCCS: Land-use/Land-cover Classification Systems

MAM: March-April-May

MRDA: Ministry of Regional Development Authorities

MIROC: Model for Interdisciplinary Research On Climate

MOHC: Met Office Hadley Centre

MPI: Max Planck Institute

MWI: Ministry of Water and Irrigation

NCC: Norwegian Climate Center

NO<sub>2</sub>: Nitrous oxide

NOAA: National Oceanic and Atmospheric Administration

OND: October –November- December

PFCs: Per-fluorocarbons

RCM: Regional Climate Models

RCs: Representative Concentration Pathways

SDGs: Sustainable Development Goals

SF<sub>6</sub>: Sulfur hexafluoride

SRES: Special Report on Emission Scenarios

SWAT: Soil and Water Assessment Tool

UNEP: United Nation Environmental Programme

USGS: United States Geological Survey

UTC: Upper Tana Catchment

WGS: World Geodetic System

WMO: World Meteorological Organization

WRMA: Water Resource Management Authority

# CHAPTER ONE

## 1.0 INTRODUCTION

The background, problem statement, objectives, justification and the area of study are presented in this chapter.

### 1.1 Background of the study

Variations and change in climate in the past has influenced and will continue influencing the availability and spatial spreading of natural resources, human economy and ecosystems (IPCC, 2014). The main contributors in the significant changes in global climatic patterns are the increasing concentrations of atmospheric greenhouse gases (GHGs), which subsequently leads to global warming (IPCC, 2014; Xu *et al.*, 2011). Changes in the climate patterns affect the access and availability of various crucial natural resources with water resources among the top. The adeptness of the people for the majority of the sub-Saharan Africa countries to meet their water needs is a crucial issue. According to Xu *et al.*, 2013, populations whose livelihoods profoundly depend on sectors that are climate-sensitive such as forestry, water resources and agriculture are the key victims of the climate change impacts.

Water resources have a very vital role in socio-economic development. However, increase in population growth and climate change has threatened its availability (Musau *et al.*, 2015). The population of the world has generally been increasing which in turn has caused increase in the use of non-renewable energy by a factor of 30 (Karamouz *et al.*, 2011). The industrial production has also increased 50 times since last century hence increasing the demand for quality water (Karamouz *et al.*, 2011).

Projected climate changes are expected to cause significant consequences in the alterations of the availability of water resources (Kingston & Taylor, 2010; IPCC, 2014). Variability in the hydrological cycle will have effects in the timing and magnitude of runoff, ecosystem dynamics, social and economic systems. The magnitude and spatial distribution of the changes in climatic variables and the characteristics of the area, clearly defines severity of the impacts on water resources at local level. Various studies also associate the vulnerability of communities and ecosystems to these impacts (Matondo *et al.*, 2004; Hagg *et al.*, 2007; Kingston *et al.*, 2011)



Evapotranspiration and precipitation are the two vital hydrologic variables that can be altered by changing temperature. According to Chien *et al.*, 2013, precipitation and temperature are the dominant climate variables whose long term changes have potential hydrological impacts and have a significant challenge for water resource scheduling and management. Understanding the interaction of climate and water resources can help researchers and policy makers in reducing the undesirable climate change effects by introducing viable water management strategies (WMO 2008; Musau *et al.*, 2015).

The United Nations' Economic, Social and Cultural Rights Committee in 2015 accredited the access to freshwater as a universal human right. Regardless of this global recognition of the importance of water resources to both flora and fauna, water availability remains a challenge to the most population of the world. Therefore, it is evident that water resource is a global concern. To ensure sustainable fresh water availability for present and future generations to address the Sustainable Development Goal (SDG) of Clean Water & Sanitation, there must be continuous studies to provide knowledge on how the changing climate and increasing water demands are expected to impact on the available water resources (UNEP, 2015).

The major water towers in Kenya are the Aberdare Ranges, Mount Kenya, Mount Elgon, Cherangani hills and the Mau Complex. The existence of these natural resources is affected by various factors including encroachment by people and uncontrolled utilization of these resources. In addition climate change is a paramount threat to variety of ecosystems including the water resources. However, water stress is not only driven by supply issues, but also how these water resources are managed

The per capita water availability of Kenya is approximately 650 m<sup>3</sup> which is below the global benchmark of 1000 m<sup>3</sup> and this makes Kenya to be referred as a water scarce country (WRMA, 2009). Due to issues such as climate change, environmental degradation and population growth the situation could even get worse. According to Mogaka *et al.*, 2009 the combined water demand is predicted to upsurge and hence reduce the amount of water that is available per capita. Thus, the country needs to invest adequately in the water storage capacity.

In the Upper Tana Catchment(UTC), occurrence of extreme hydrological conditions with appalling consequences for the nearby populations have already uncovered the vulnerability of human and natural systems to hydrological changes (Jacobs *et al.*, 2007). This area

contributes a significant proportion of stream flow volume of the large Tana River since it forms the upper reaches of the river. However, the hydrological processes within the catchment are likely to be influenced by change in climate perhaps increasing the vulnerability of communities to extreme events. For disaster preparedness, structural development and irrigation planning it is crucial to evaluate the probable impacts of climate change on water resources. The study sought to evaluate the prospective effects of climate change on water yields in Upper Tana Catchment. This was done through assessment of changes in simulated water yields under two different climate scenarios using the (SWAT). The already downscaled dataset for the two future climate scenarios from the finest climate model was used in the analysis as input to the hydrological model.

## **1.2 Statement of the problem**

According to IPCC, 2014 synthesis report, climate change is happening owing to human (or anthropogenic) factors and its impacts are being felt at global, regional and even at local levels. Impacts on water resources due to changes in climate can be substantial in causing changes in the precipitation amount and timing. Diverse water balance and climate models have been developed in climate change impact evaluation on water resources.

Regardless of growing concern in the assessment of effects on water resources owing to climate change, underlying uncertainties are challenges accompanying the model of hydrological reactions to climate change. These uncertainties are as a result of model adjustment, calibration procedure and errors in model structure in the case of stable climate conditions and/or the physical characteristics (Bastola *et al.*, 2011; Brigode *et al.*, 2013). Conversely, uneven resolution of the climate models, in terms of how they represent the processes of the atmosphere, different results from the downscaling techniques are of major concern in the case of climate change (Ficklin *et al.*, 2009; Chiew *et al.*, 2010; Teng *et al.*, 2011; Xu *et al.*, 2011; Braga *et al.*, 2013). Studies have clearly shown that uncertainties from hydrological models are less significant than those from GCM outputs (Arnell, 2011; Chen *et al.*, 2011; Teng *et al.*, 2012).

The Upper Tana Catchment (UTC) is very crucial as it forms the upper reaches of the large Tana River. The catchment contributes a substantial percentage of stream flow volume. Change of climate may probably influence the hydrological course within the catchment. Water scarcity and community vulnerability to extreme climate change implications maybe

perhaps increased. Consequently, assessment of probable effects on water resources due to climate change is crucial for structural development, readiness to disasters and irrigation planning.

This study seeks to evaluate the possible impacts of global climate change on water resources at basin scale through a modeling framework since the area has not received adequate attention in evaluation on how the water resources maybe impacted by climate change. The modeling framework used comprised of applying outputs of climate change models as inputs to a river basin hydrologic model (Soil and Water Assessment Tool (SWAT)). Climate change scenario data for the best climate model was used to run the calibrated and validated SWAT model.

### **1.3 Objectives**

The overall objective of this study was to evaluate the likely future status of Upper Tana Catchment water resource availability under different future climate scenarios. This was attained through the following specific objectives:

- a) To assess the climate and hydrological characteristics of the Upper Tana Catchment.
- b) To evaluate the future climate scenarios over the Upper Tana catchment for the period 2030's, 2060's and 2090's relative to base period 1995-2014.
- c) To simulate the stream flow patterns of the catchment under different climate scenarios following the representative concentration paths (RCPs) 4.5 and 8.5 (RCP4.5 and RCP8.5)

### **1.4 Hypothesis**

If precipitation and temperature which are the dominant climate variables are responsible for the amount of water that ends up in to the river channel within the upper Tana catchment, then their changes will lead to alterations in the water yields in the catchment.

### **1.5 Justification of the study**

The River Tana is the largest and one of the most important rivers in Kenya. The total catchment area is 100,000 km<sup>2</sup>, which is 16% of Kenya territory (MRDA, 2011). It is however divided into upper, middle and lower catchments with areas of 10%, 16% and 74% respectively of the total Tana River area (MRDA, 2011). The river and its catchment is an

important driver of Kenya's economy as it provides the hydroelectric power (HEP) projects. The Masinga dam is strategically located on the Upper Tana catchment outlet and controls the flow of water to the reservoirs downstream (Jacobs *et al.*, 2007). The river also serves as the key source of water to the surrounding population for; agriculture, domestic use and industrial use, food inform of fish, transport and communication, wastewater disposal and recreation,(Jacobs *et al.*, 2007). Therefore, the Tana River is key to social-economic growth and development.

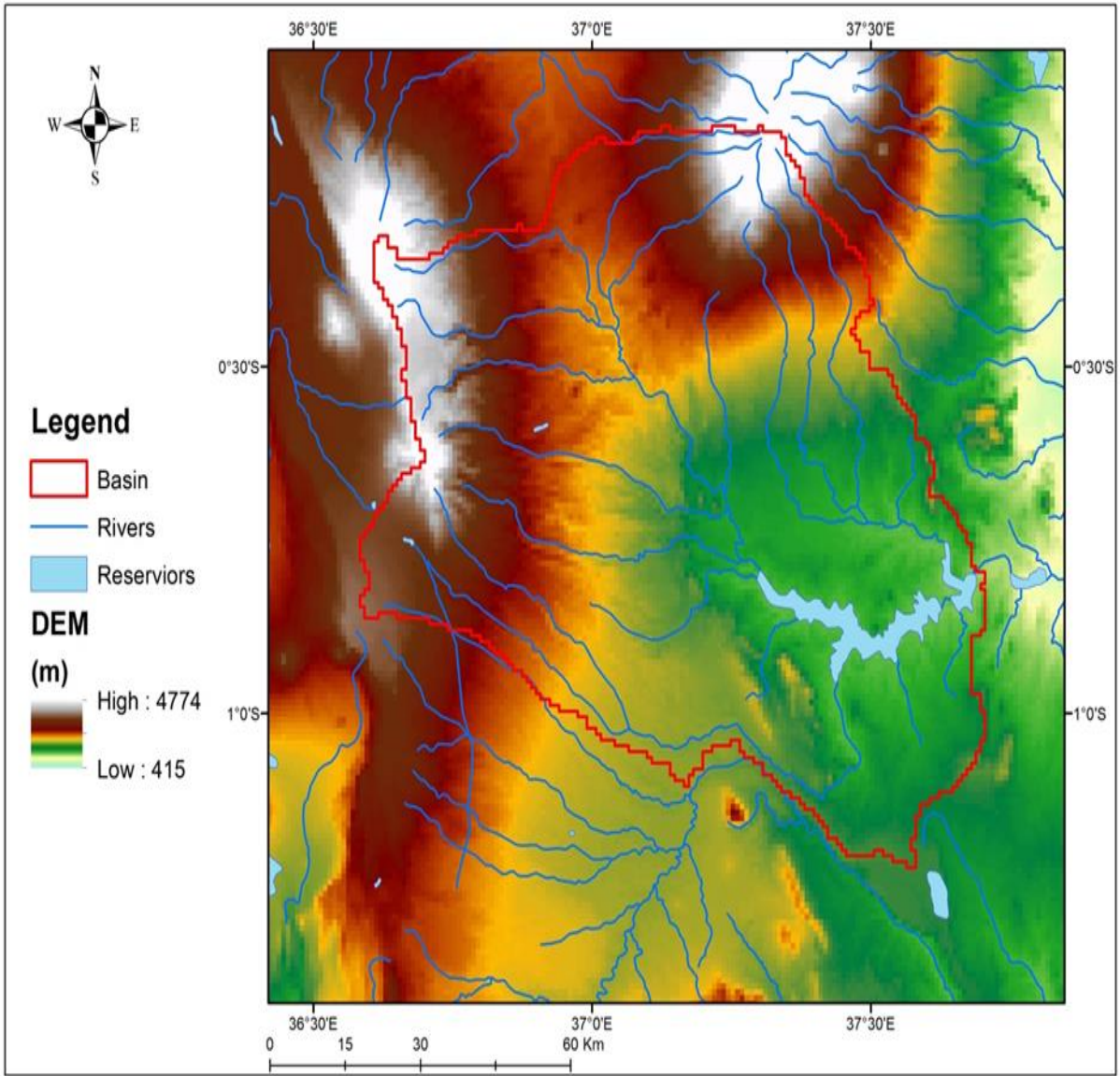
Hydropower capacity of the river is severely constrained by the reduced flow levels during dry season. The Masinga dam along the river produces 65% of the country's HEP (Jacobs *et al.*, 2007) and therefore reduced flow levels will impact negatively on the proposed hydropower generation. Change in climate is increasing fast and extreme weather events in the future are expected to be more recurrent and life-threatening than current (Ahrens, 2009). Escalation of poverty and food insecurity intensifies the exposure of the communities that live in this region to climate change implications.

Assessment of the potential climate change impacts on water resources is therefore central for irrigation scheduling, alertness to disasters and development of structures (Musau *et al.*, 2015). This study therefore was intended to enhance the understanding of various climatic scenarios on water resources by assessing the influences on water resources in Upper Tana Catchment of Kenya caused by climate change.

## **1.6 Area of study**

### **1.6.1 Location**

The central concentration of the study is the Upper Tana Catchment (UTC) as shown in Figure 1, an area that comprises the cities of Thika, Nyeri and Embu. It is located to the northeast of Nairobi. From the Mt. Kenya and the Aberdare Range slopes within the region in focus originate the major tributaries that feed the large Tana River. The Tana River travels nearly 1,000 km and discharges in the Indian Ocean on the eastern coast of Kenya shown in Figure 2.



**Figure 1: Location of the Upper Tana Catchment with elevation, streams derived from DEM for the River Basin**

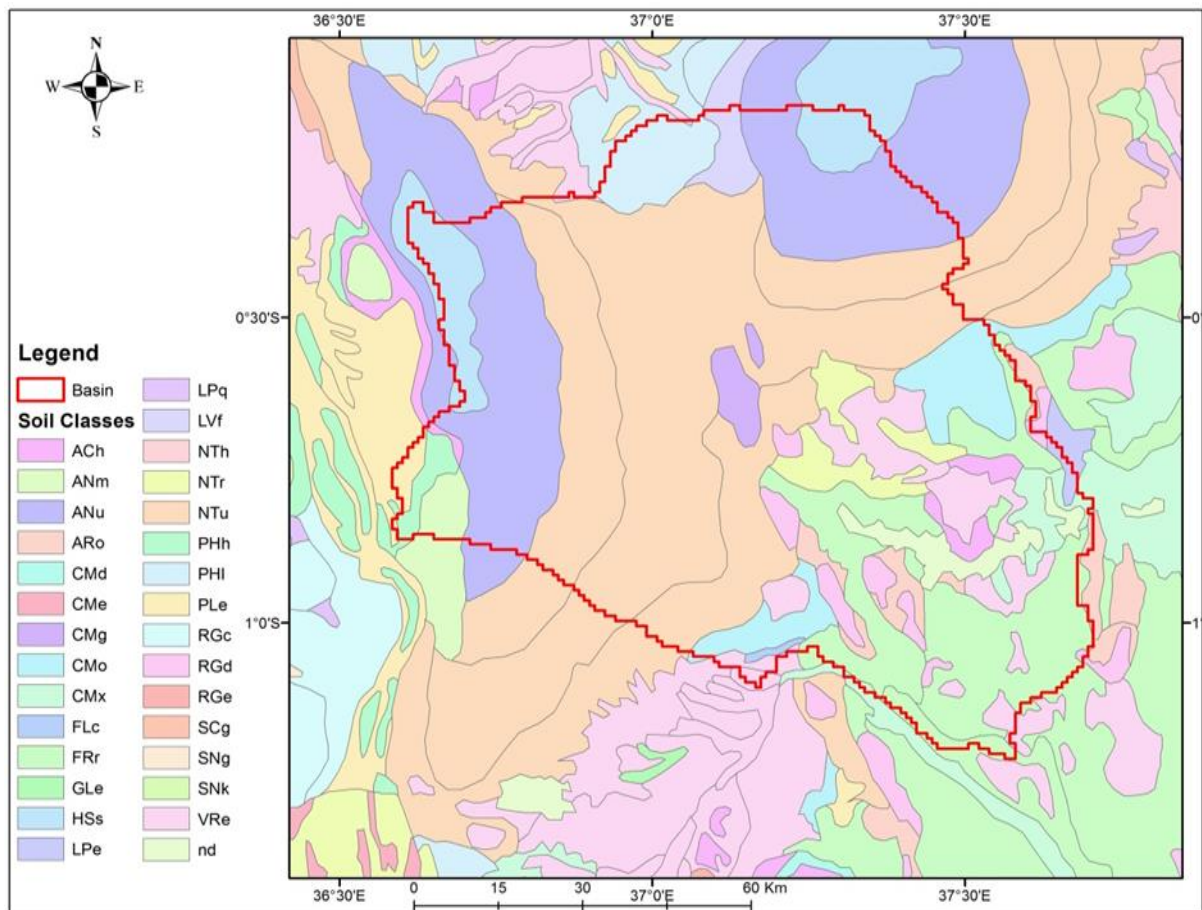




Figure 2: The Tana River Basin (Source MRDA, 2011)

### 1.6.2 Size and Topography of the study area

The size, soil type, topography and the geology of an area are among the key factors that determine the amount of rainfall that translates to runoff (Arnold *et al.*, 1998; Cadol *et al.*, 2012). The Tana River is a key resource for hydroelectric power and water for the region and Kenya at large. The entire catchment has an area of nearly 100,000 km<sup>2</sup> (MRDA, 2011). The Upper Tana Catchment has an area of approximately 10,000 km<sup>2</sup> and elevation that ranges from 500 m near the Kamburu Dam to 4800 m on Mt. Kenya. Rainfall, land use and soils follow this broad elevation gradient (MRDA, 2011). Each elevation level of the catchment comprises of different types of soil as shown in Figure 3.

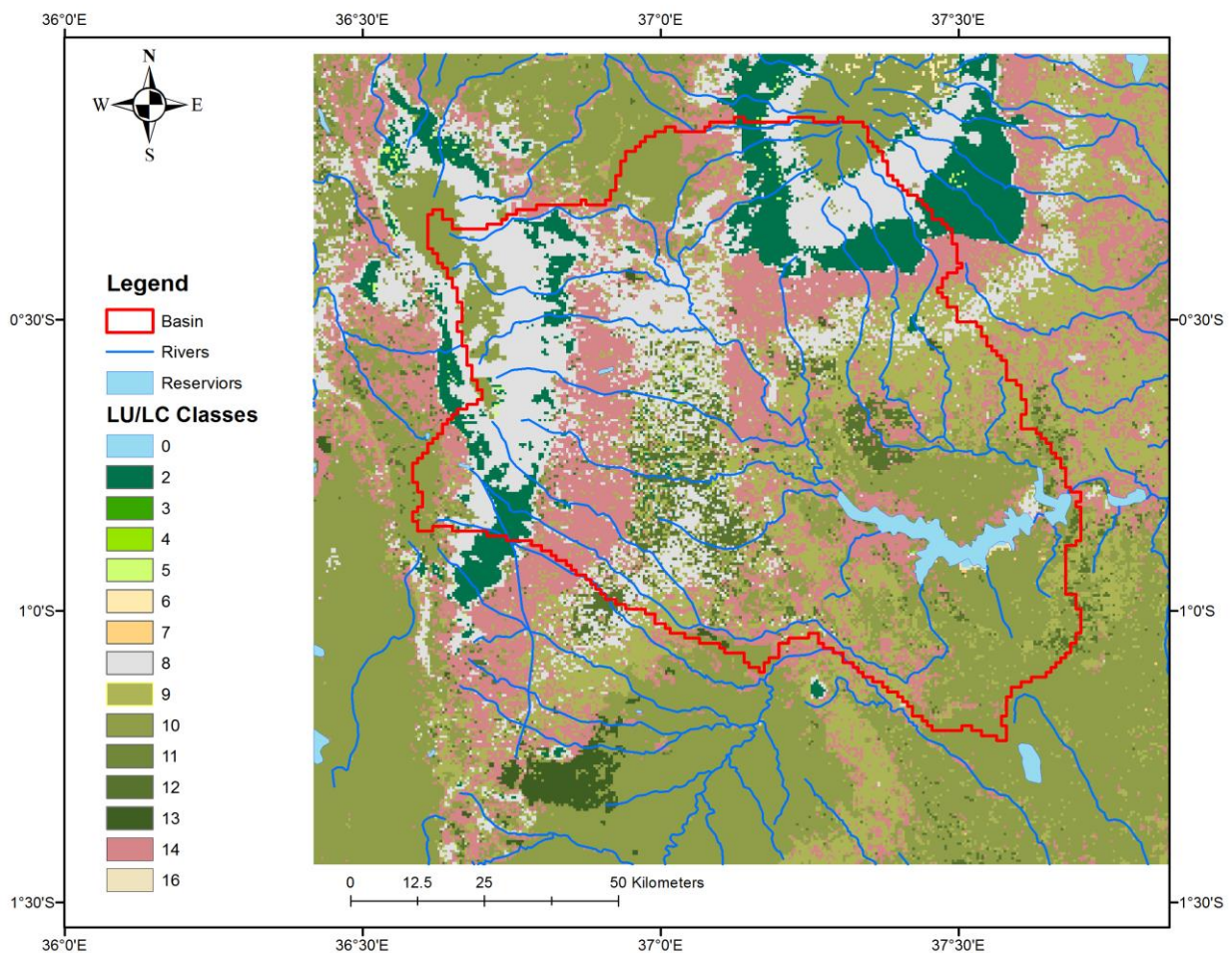


**Figure 3: Soil classes within the upper Tana catchment indicating a distinct soil or a connotation of soils. Source: Kenya Soil and Terrain Database**



### 1.6.3 Land use

The water yields of a certain catchment are greatly influenced by the type of land use through dynamics of evapotranspiration, evaporation and interference of the canopy (Wang *et al.*, 2010; Cadol *et al.*, 2012; Rwigi, 2014). Cropland agriculture, forests and rangelands are the major land uses within the study area as indicated in Figure 4. Tea cropping and forests dominate the higher elevations of the study area. However, agriculture is most intensive at mid-elevations where by various crops are grown which comprises maize, beans coffee, napier grass, and bananas. Less agriculture and livestock grazing occurs at the lower elevations of the study area (Jacobs *et al.*, 2007).



**Figure 4: Major land uses/land cover within the study area (Source: USGS)**



**Table 1: Landuse/ landcover classes over the Upper Tana Catchment (Source: USGS)**

0	Water
2,3,4 and 5	Evergreen broadleaf, deciduous needle leaf, deciduous broadleaf Forests and mixed forests respectively.
6 and 7	Closed and open Shrublands respectively
8	Woody Savannas
9	Savannas
10	Grasslands
11	Permanent Wetland
12	Croplands
13	Built-Up area
14	Cropland/Natural Vegetation
16	Barren or Sparsely Vegetated

#### **1.6.4 Climate**

The climate of the Tana River Basin, like the whole of East Africa region, is determined by interaction between the Monsoonal Winds, the Inter-tropical Convergence Zone (ITCZ), the El Niño/Southern Oscillation (ENSO), extra-tropical systems (St. Helena, Mascarene, Arabian and Azores), the Indian Ocean Dipole (IOD), the Quasi-biennial Oscillation (QBO), and meso-scale circulations (Omeny *et al.*, 2006; Ngaina & Mutai, 2013).

The movements of the ITCZ control the direction of the seasonal monsoon winds (Nicholson & Yin, 2002; Ngaina & Mutai, 2013). Westward monsoons sweep humid maritime air inland during the wet seasons. These are interchanged by easterly dry-season winds, which bring arid continental air masses to the East African region (Okoola, 1996). Extended droughts or excessive rains are often caused by irregularities in the monsoon pattern.

The long rains occurring in March-April-May (MAM) and the short rains in October-November-December (OND) are the two rainy seasons that are experienced in most parts of Kenya. A comparable altitude gradient as that of soils is followed by the rainfall over the basin. The Aberdare Ranges and Mt. Kenya receives beyond 1,800mm/yr of rainfall (Otieno *et al.*, 2000). 1,000 to 1,800mm/yr of rainfall is experienced in mid elevations. Below 1,000m elevation level, the region experiences rainfall less than 700 mm/yr which mainly favors livestock grazing rather than intensive agriculture (Otieno *et al.*, 2000).

### **1.6.5 Hydrological Characteristics**

Seasonal variations in river flows are prevalent even at elevations greater than 1,800 m which is associated with high rainfall. There exist dry periods within the two distinct wet periods which have rainfall pattern of total duration each of three months. The Supply of water during the dry periods is not adequate to meet the high demand of water both for urban needs, irrigation and continuous electric power generation. According to Jacobs *et al.*, 2007, the seasonal fluctuation in streamflows led to the construction of the Masinga Dam which also regulates the water flow to the Kamburu, Gitaru, Kindaruma and Kiambere dams downstream.

Siltation problems in the Tana River reservoirs are easily recognized. During rainy season, one can easily identify amount of silt being transported downstream from the rivers draining in the Aberdare foothills (Otieno *et al.*, 2000). Increased demand of land for settlement and farming as a result of hasty population growth within the catchment, natural vegetation has been rigorously cleared. Furthermore, felling of trees for charcoal burning and overgrazing in the lower areas within the surroundings of Masinga dam has accelerated soil erosion (Gichuki *et al.*, 2000).

The completion of Masinga dam and the impounding of the reservoir were effected when sedimentation complications were eminent. However, no relevant action was put taken along the reservoir and upstream for sedimentation reduction. The hesitancy in solving the problem of sedimentation satisfactorily has led to development of large gullies measuring 15m to 30m in depth alongside the reservoir (Jacobs *et al.*, 2007). This is dominant during the rainy seasons at a time when Tana River overflows its banks and floods the plains.

## **CHAPTER TWO**

### **2.0 LITERATURE REVIEW**

#### **2.1 Climate Change aspects**

The cognizance of the level to which the society, environment and economy can be affected by the change of climate has increased. Increasing greenhouse gases concentration mainly carbon dioxide has led to the observed long-term climate change globally, regionally and also at local scales. These encompass changes in timings and amounts of precipitation, temperatures, extreme weather like droughts and heavy precipitation, wind patterns and heat waves (IPCC, 2014). Precipitation patterns are influenced by moisture availability and circulation patterns of the atmosphere and are unevenly distributed across the globe. These patterns of precipitation are anticipated to change since the temperature is changing and it influences the moisture availability and the atmospheric circulation patterns.

The changes comprise of the amount, frequency intensity and nature of precipitation. In most parts of Northern Europe, North America and South America, precipitation has increased and decreased in most of Africa, the Mediterranean and southern Asia (Trenberth & Shea 2006; IPCC 2014). The world leading international organizations in climate change research associate climate change to human causes through activities that increases emissions of heat-absorbing GHGs (IPCC, 2014). These emissions change the composition of atmosphere and vary the natural climate witnessed over a relatively longer time periods. Climate change is the state variation of the climate that can be predictable by mean fluctuations or the inconsistency of its characteristics and that takes longer period, normally decades or longer (IPCC, 2014).

##### **2.1.1 Source and Emission of Greenhouse Gases**

The anthropogenic activities that contribute to climate change mostly encompass the emissions of greenhouse gases (GHGs) which trap heat. These GHGs include methane (CH<sub>4</sub>), carbon dioxide (CO<sub>2</sub>) and nitrous oxide (NO<sub>2</sub>). GHGs such as CO<sub>2</sub> and CH<sub>4</sub> absorb energy emitted on earth's surface, and this prevents or reduces the loss of heat to space. Therefore, these gases form a blanket near earth's surface rising the average temperature of the earth's climate system. This process is called greenhouse effect (IPCC, 2014).

The major cause of global warming is CO<sub>2</sub>. Its main source is increased and continuous burning of fossil fuels for electricity generation (30% of 2014 greenhouse gas emissions), transportation (26% of 2014 greenhouse gas emissions), industrial (21% of 2014 greenhouse gas emissions) and household uses (12% of 2014 greenhouse gas emissions) (Pachauri *et al.*, 2014). 57% of the global CO<sub>2</sub> is produced from fossil fuel use while 17% of CO<sub>2</sub> is from decay of biomass and 8% of CO<sub>2</sub> is from unknown sources. 8, 14, and 1% of the total GHG emitted is contributed by NO<sub>2</sub>, CH<sub>4</sub> and fluorinated gases respectively (IPCC, 2014; Oluwatomiwa, 2014).

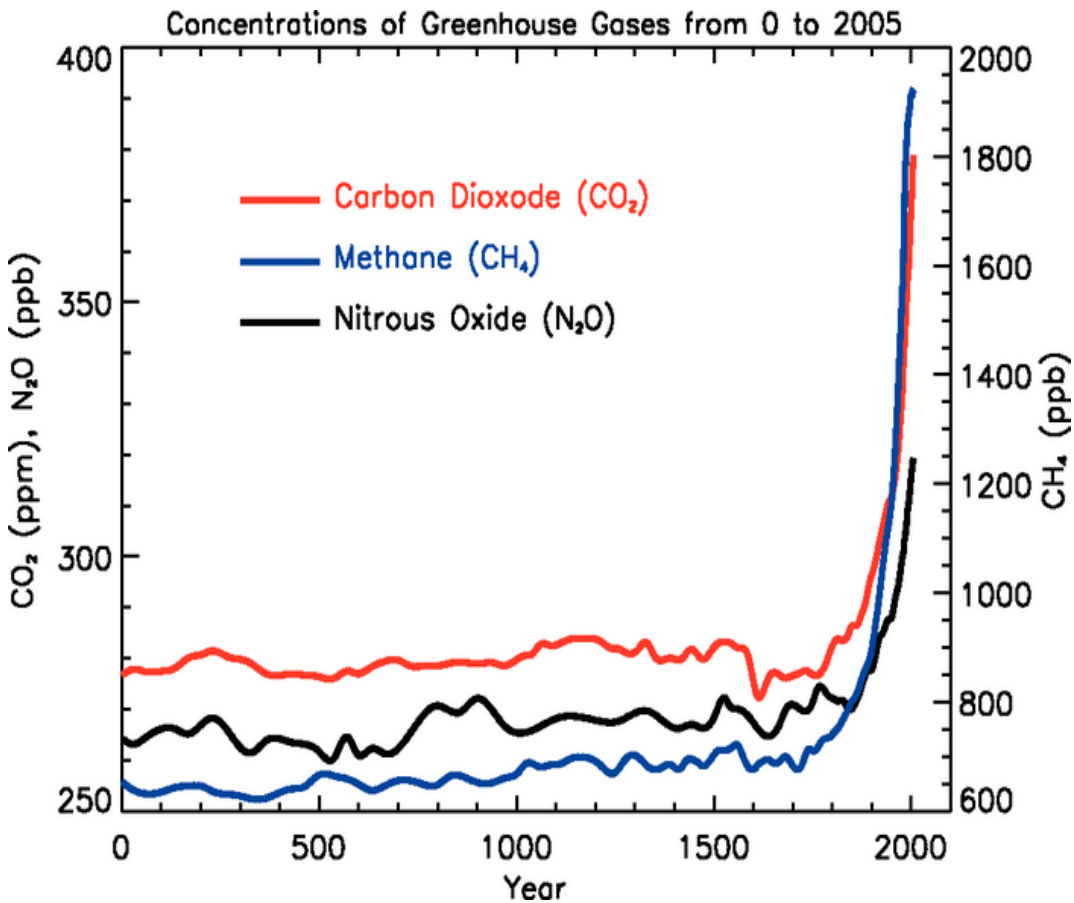
Recent research works reliably show that the CO<sub>2</sub> emissions primarily from the combustion of fossil fuel on a global scale have constantly increased (Karl *et al.*, 2009; Schnoor, 2010; IPCC, 2014). In the previous several decades, 20% of CO<sub>2</sub> brought about by human activities stemmed from deforestation and associated agricultural practices, while about 80 percent emissions were produced from fossil fuels burning, globally (Forster *et al.*, 2007; Mach & Mastrandrea, 2014).

The CO<sub>2</sub> concentration in the atmosphere has increased by roughly 35 percent since the beginning of industrial revolution (IPCC, 2014). During the biological carbon cycle, plants take up the CO<sub>2</sub> from the atmosphere which helps in the process of CO<sub>2</sub> sequestration. CH<sub>4</sub> results from production and transport of natural gas, coal, oil. Another factor that contributes to the emission of methane to a greater extent is waste decay in municipal solid waste landfills and agricultural practices such as livestock farming (IPCC, 2014). Another GHG is NO<sub>2</sub> which is emitted during industrial activities, fossil fuels combustion and solid waste as well as in agricultural related activities such as raising livestock (IPCC, 2014).

Fluorinated gases (F-gases) which are emitted from a range of industrial processes that are applied in fire extinguishers, pesticides, coolants, foaming agents, aerosol propellants and solvents, include hydrofluorocarbons (HFCs), Chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), sulfur hexafluoride (SF<sub>6</sub>), and perfluorocarbons (PFCs) also cause greenhouse effect (Pachauri *et al.*, 2014; IPCC, 2014).

Ozone (O<sub>3</sub>) is another considerable GHG with a short atmospheric lifetime produced when nitrogen oxides and explosive organic compounds reacts with sunlight (IPCC, 2014). Tropospheric ozone is a major pollutant which adversely affects respiratory health of living organisms and damages plants and ecosystems (Pinto *et al.*, 2010; IPCC, 2014). Nevertheless, water with its short lifetime in the atmosphere is another factor that is considered as the most ample GHG contributing to the natural greenhouse effect. Temperature generally controls the

concentration of water vapor globally which in turn influences precipitation and evaporation rates. The emission of water vapour on a global scale is not fundamentally influenced generally by human induced emission (Rothausen & Conway, 2011; IPCC, 2014). Major greenhouse gas concentrations are shown Figure 5.



**Figure 5: Concentrations of Greenhouse Gases from 0 to 2005 (Source: IPCC, 2014)**

### 2.1.2 Naturally Driven Climate Change Aspects

The volcanic eruptions and the sun are among the major natural factors contributing to global climate change (IPCC, 2014). The energy output of the sun has followed its historical cycle of 11- years of small ups and downs without any significant increment. This is as was measured by satellites since 1979 several decades ago. Though the above stated natural influences cannot substantially give details on the global warming in latest decades, there has existed a minor cooling influence over this period as a result of their net effect on climate (Hansen *et al.*, 2006; IPCC, 2014). On thousands of year's timescales, the unhurried variations in the earth's orbit around the Sun and its tilt in the direction of or away from the Sun are also a natural influence on climate, (Kaufmann *et al.*, 2011; Burck *et al.*, 2014; Mach & Mastrandrea 2014).

### **2.1.3 Climate Change Indicators**

Climate, generally defined by the temperature and precipitation characterizes an enduring average condition of the weather in a given place. Weather can change within a few minutes or hours, but development of changes in climate is over longer time periods, i.e., decades to centuries). The warming of the climate system is undisputable, a statement from the Fifth Assessment Report of IPCC (2014). This is a claim deduced from observations of rising average sea level, prevalent melting of snow and ice and rise in overall average air and ocean temperatures.

The emission GHGs which trap heat into the atmosphere continuously and increasingly is basic but not the sole source of increase in temperature and global warming (Karl *et al.*, 2009; IPCC, 2014; Mach & Mastrandrea, 2014). Since the 1970's there has been noticeable increase in average surface temperature extending from 0.31- 0.51°F per decade. (Haeberli *et al.*, 2007; Rothausen & Conway, 2011)

The accessibility of water for use in the industries and households, agricultural purposes and drinking water is generally affected by the rainfall and snowmelt timing (Mimikou *et al.*, 2000; Philippart *et al.*, 2011). Plant types and animals that can survive in a particular region heavily depend on the rate of precipitation (IPCC, 2014). The effect of climate change varies globally with the unstable wind patterns and shifting ocean currents that drive climate system of the world (IPCC, 2014). This causes some areas to experience increased precipitation while others decreased precipitation (Funk & Brown, 2009; EPA, 2011). Moreover, higher temperature causes more evaporation reducing the amount of water available regardless of an increased precipitation (Melillo *et al.*, 2014; Martens, 2014; Schewe *et al.*, 2014; IPCC, 2014).

## **2.2 Climate Change impacts**

### **2.2.1 Impacts on Water Quantity**

For human survival and sustenance, water as a natural resource is very crucial. Water is also important for energy production, agricultural science, manufacturing, recreation and navigation (Karl *et al.*, 2009; Melillo *et al.*, 2014). These natural water resources include ocean, seas, lakes, underground aquifers and rivers (Furniss, 2010).

The hydrologic cycles and regimes within watersheds are altered by the climate change at global scale and also local scale which undesirably impacts forests, water resources, sustainable agriculture, environment and ecosystems (Poff *et al.*, 2002; Karl *et al.*, 2009; Chien *et al.*,

2013; Rwigi, 2014). Runoff is one of the significant components of water resources and will be affected by changes in the climate in terms altering of precipitation and temperature. Quite several researches are steered towards evaluation of climate change effects on runoff due to the importance of runoff for water supply (Githui *et al.*, 2009; Faramarzi *et al.*, 2010; Mango *et al.*, 2011). Demand for water could likely be increased by change in climate while the supply is being reduced (IPCC 2014; Melillo *et al.*, 2014).

The amount of water that is available for recharge will also be affected by reduced precipitation or increased evaporation and runoff which are as result of changes in the water cycle (Mach & Mastrandrea, 2014). Temperature changes, fire or pest outbreaks that lead to changes in soils and vegetation which in turn leads to changes in the rates evaporation and infiltration are also likely to affect recharge (Bates *et al.*, 2008). More frequent and larger floods in semi-arid and arid areas may likely increase the groundwater recharge (Bates *et al.*, 2008).

Lastly, extreme weather conditions for instance drought caused by the stretched imbalance between precipitation and evaporation, is another resulting impact of climate change (Melillo *et al.*, 2014). Increasing demand for drinking water which accompanies the more rates of urbanization will put stress on the existing water sources (Bates *et al.*, 2008).

### **2.2.2 Impacts on Water Quality**

When considering the human health, ecosystems and their survival, the quality of water becomes a very important issue (Quansah *et al.*, 2008; Melillo *et al.*, 2014). Regions expected experience increased rainfall intensity due to climate change, the water quality could depreciate. The increased runoff in rivers could lead to washing human and animal waste, sediment, trash, nutrients, pollutants and other materials into water supplies, making them insecure or requiring water treatment process before use (Parry *et al.*, 2007; Ebi *et al.*, 2008). The same could cause problems in water treatment plants and sewer systems as these infrastructures can be overwhelmed by the increased volumes of water and materials (Mimikou *et al.*, 2000; Karl *et al.*, 2009; EPA, 2011).

Sea level upsurge caused by climate change may also affect freshwater resources along the coasts (Karl *et al.*, 2009; Mach & Mastrandrea 2014). Availability of dissolved oxygen in water is an indispensable resource for various living things, and also for self-purification abilities of rivers. However, increased temperatures in the water could compromise its availability (Mimikou *et al.*, 2000; Karl *et al.*, 2009).

The Upper Tana Catchment experiences a substantial threat of point and non-point pollution emanating from human activities, (Maingi & Marsh, 2002; Dijkshoorn *et al.*, 2011; Knoop *et al.*, 2012). Nation's largest water quality deprivation is the non-point source pollution and is linked to why the apportioned water quality principles for various activities like recreational activities or fishing are not met by a greater percentage of rivers, lakes etc. (Maingi & Marsh, 2002; Kauffman *et al.*, 2014). The principal source of non-point source pollution is agriculture (Hunink, *et al.*, 2012; Melillo *et al.*, 2014).

### **2.2.3 Impacts on Agriculture**

Climate change has adverse impacts on the agricultural sector. Warmer temperatures may decrease crop yields and also could favor a quick growth of some crops (Mach & Mastrandrea, 2014). Like in the case of crops like grains, there is decline in the quantity of crop produced in a farm because of reductions in the extent of time the seed have to develop and mature, (EPA, 2011; Mach & Mastrandrea, 2014).

Water availability, soil nutrients and optimal temperature of the crop for reproduction and growth, controls the effects as a result of increased temperature (Mogaka, 2006; Kauffman *et al.*, 2014). Agricultural activities largely depend on water resources. Farming in the upper Tana will become altered due to climate change and this will affect economic growth of the country. Crop yield is also affected by higher atmospheric concentrations and extreme weather conditions e.g. flood and drought (Funk & Brown, 2009). Human health and livestock can also be negatively impacted by increased temperatures in the form of heat waves (Githeko & Woodward, 2003; Nardone *et al.*, 2010; Ouma, 2015).

## **2.3 Future climate scenarios**

Representative Concentration Pathways (RCPs) are the four new greenhouse gas concentration trajectories embraced by the IPCC, 2014 in its fifth Assessment Report (AR5). These define four likely climate futures in the coming years which are considered potential depending on the amount of emitted greenhouse gases. These pathways are applied in climate modeling and research and replace the projections on Special Report on Emission Scenarios (SRES) published in 2000 (Moss *et al.*, 2008). RCP2.6, RCP4.5, RCP6.0, and RCP8.5 are termed after probable variety values of radiative forcing +2.6, +4.5, +6.0, and +8.5 W/m<sup>2</sup> correspondingly, relation to pre-industrial values in the year 2100 (Van Vuuren *et al.*, 2011; IPCC, 2014).

The RCPs are comprised of extensive variety of possible changes of anthropogenic (i.e., human) Greenhouse Gases (GHG) emissions in the future (Ebi *et al.*, 2014). The global annual

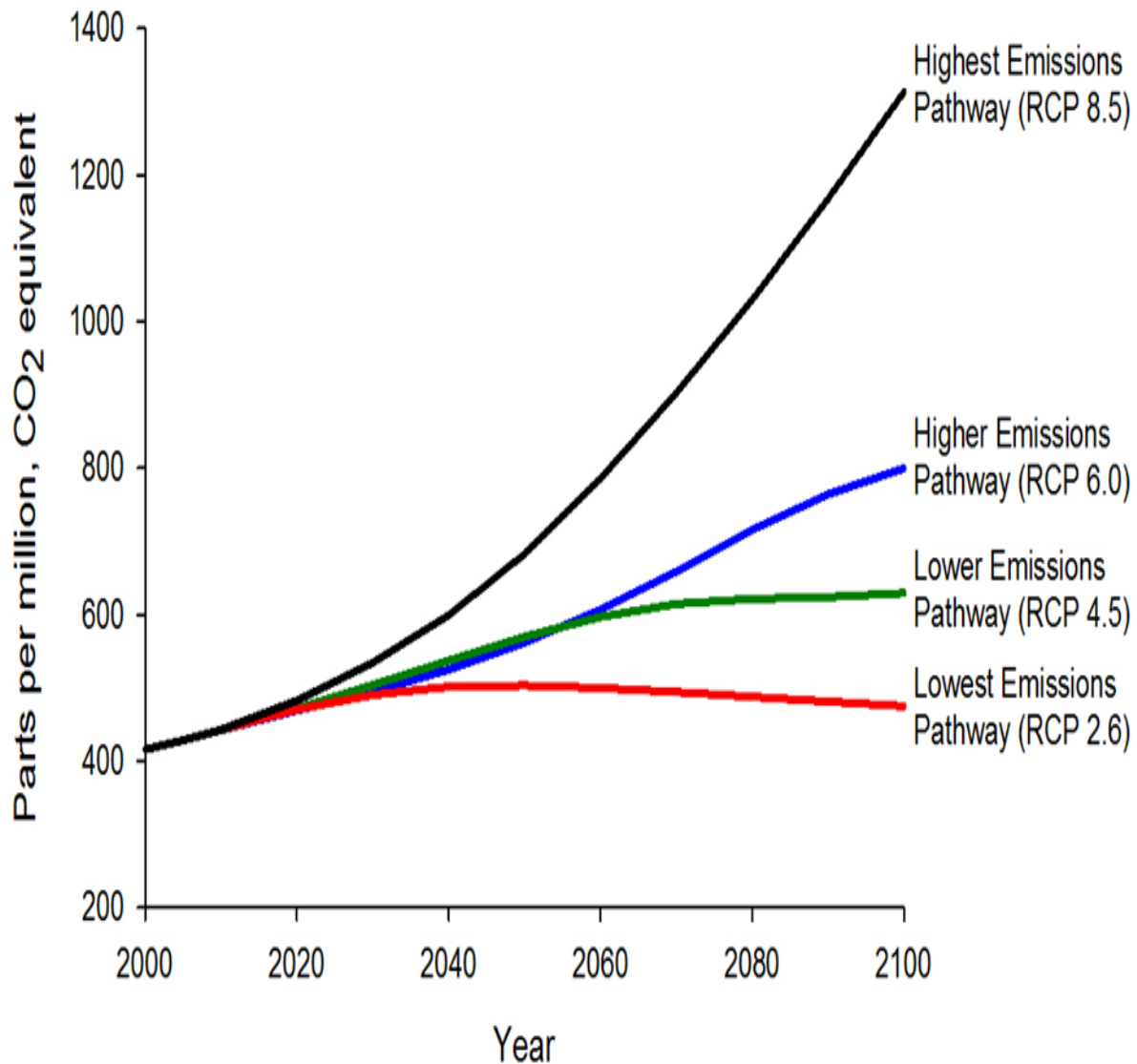


emissions of GHGs from 2010-2020 (as per CO<sub>2</sub>-equivalents) will peak with a substantial decline of emissions thereafter is assumed in the RCP2.6 (Meinshausen *et al.*, 2011; IPCC, 2014). Emissions peak around 2040 in the RCP 4.5 and then decline (Meinshausen *et al.*, 2011; IPCC, 2014). Around 2080 there is a peak in the emissions in RCP6.0 and then decline and in RCP8.5, continuous rise of emissions throughout the 21st century (IPCC, 2014). 2046-2065 and 2081-2100 are the mid and late 21st century averages respectively and projections established on the RCPs 21st century. Table 2 below shows the global mean sea level rise and global warming projections from the IPCC AR5 relative to sea levels and temperatures in late 20th to early 21st centuries. Projected Atmospheric Greenhouse Gas Concentrations are shown in Figure 6.

**Table 2: AR5 global warming projections (Source: IPCC, 2014)**

<b>AR5 global warming rise (°C) projections</b>		
	2046 to 2065	2081 to 2100
Scenario	possible range and average	possible range and average
RCP2.6	1.0 (0.4-1.6)°C	(0.3-1.7)1.0°C
RCP4.5	(0.9-2.0)1.4°C	(1.1-2.6)1.8°C
RCP6.0	(0.8-1.8) 1.3°C	(1.4-3.1)2.2°C
RCP8.5	(1.4-2.6)2.0°C	(2.6-4.8)3.7°C

## Projected Atmospheric Greenhouse Gas Concentrations



**Figure 6: Projected Atmospheric Greenhouse Gas Concentrations (Source: IPCC, 2014)**

A rise of 0.3 to 4.8 °C in the global mean temperature is expected across all RCPs by the late-21st century. A change in climate beyond the 21st century is also projected by the AR5. Continual net negative anthropogenic GHG emissions are assumed by the prolonged RCP2.6 pathway after the year 2070 (Ebi *et al.*, 2014, Pachauri *et al.*, 2014). "Negative emissions" occur when in overall, more GHG is absorbed from the atmosphere than it is release by humans. According to Pachauri *et al.*, 2014 a persistent anthropogenic GHG emission is assumed by the stretched RCP8.5 pathway after 2100.

### **2.3.1 Low Carbon Pathway for Development in Kenya**

A development path pointed at creation of a prosperous country with a high quality of life is set out by the Kenya Vision 2030. Climate Change Action Plan of Kenya encourages people-centered development and supports determinations towards the accomplishment of Vision 2030. This ensures movement of the country towards long-term development goals guided by the climate change actions (GOK, 2010; GOK, 2013). The country has preferred an incorporated low carbon climate resilient pathway which emphasizes on sustainable development, adaptation and mitigation (Parry *et al.*, 2012; Ngaira & Omwayi, 2012).

Kenya considers that climate change and action on development are interlinked. The country recognizes that increasing the ability of the country to adapt to climate change, in as low carbon as possible will help achieving the Vision 2030 goals and sustainable development (GOK, 2010). Kenya considers a low carbon development pathway crucial which climate resilient for addressing the risks and threats posed by climate change on development visions and livelihoods. Investments made to meet Vision 2030 goals are destabilized by the changes in climate. Increased strength and occurrences of extreme weather occasions such as droughts and floods, the rising of average temperatures, varying rainfall patterns are some of climate change indicators. Droughts and floods have interference with the on the economy, water resources, infrastructure, food security and environment.

In the water sector, a low carbon climate resistant pathway can have significant viable benefits and contribute to enhanced management of water resources in Kenya. Proposed interventions in this sector are mainly environmental including growing tree covers to 10% of the entire land area as a goal indicated in Kenya's constitution. Actions intended towards increase in the forest cover have indispensable low carbon and climate resilience benefits. Landslides, flooding, erosion and increased sediment discharge into rivers can be barred by forests.

Loss of rainwater from the ecosystem can be decelerated by forests hence contributing to water availability. Recently, the country has taken measures towards restoration and afforesting of the key water towers and water catchments. Additionally, conservation of the forests has biodiversity benefits and may contribute to enhancement of livelihoods. According to Ngaira & Omwayi (2012), refurbishment of forests on ruined lands is an imperative low carbon climate resilient action which has a mitigation potential of over 30 MtCO<sub>2e</sub> a year in 2030.

## **2.4 Hydrologic Modeling**

Hydrologic modeling is an approach where mathematical equations or programming approach, are applied to simulate the behavior of watershed, hydrologic processes, physical responses of a watershed for a given input like the rainfall (Miller *et al.*, 2007; Pechlivanidis *et al.*, 2011). Hydrological models are required in the environmental applications like the prediction of flood, water resources planning, climate modeling and water quality modeling (Pechlivanidis *et al.*, 2011). Hydrological models represent part of the hydrological cycle. These models can be used to simulate the physical courses of a certain catchment that control the transformation of precipitation to runoff or water yields (Droogers *et al.*, 2006).

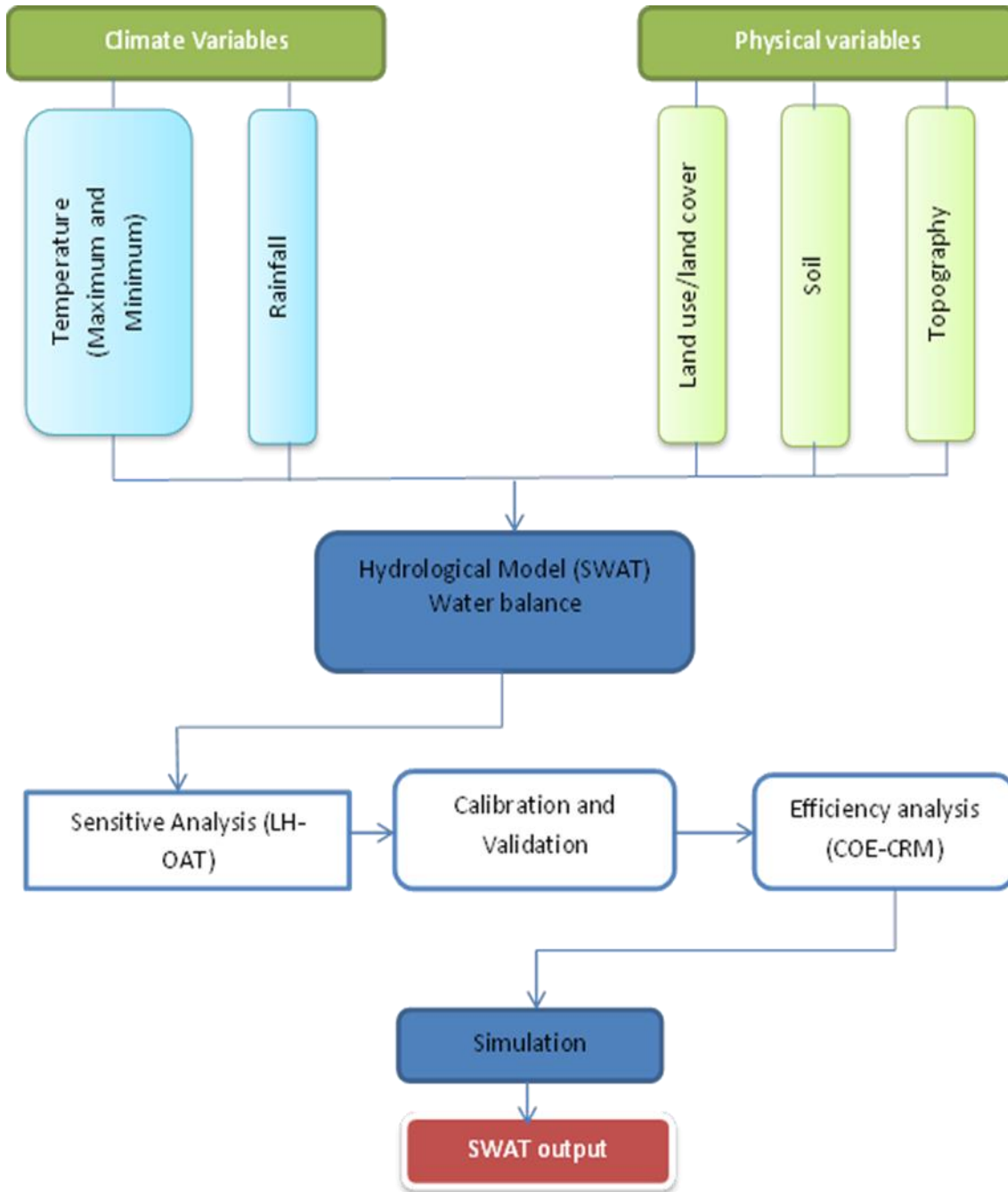
The topography, landuse/landcover and soil are the main physical parameters which determine the amount of precipitation that translates to runoff or stream flow. These parameters are mostly used for understanding the hydrologic processes in a certain catchment (Arnold *et al.*, 2012). Temperature and precipitation are the most crucial climatological inputs that are essential for the calibration and validation of hydrological models (Akhtar *et al.*, 2009; Rwigi, 2014).

In evaluation of impacts on water yields on the Upper Tana Catchment due to changing climate the study applied two diverse future climate scenarios. The simulated water yields are compared with the observed discharge to evaluate the change. This assessment was accomplished through the use of SWAT. This model has been demonstrated to be an operational tool to be applied in assessing water resource issues at small and wide scales in various environmental conditions across the world (Arnold *et al.*, 2012; Oluwatomiwa, 2014). A brief explanation of the model is given below.

### **2.4.1 Soil and Water Assessment Tool (SWAT)**

This is computationally efficient and physical based hydrological model that can be applied at watershed scale or an extended river basin (Arnold & Fohrer, 2005; Arnold, 2012). SWAT is applied in projection of management practices of land on water, changes in climate and the effects on water, agricultural chemical yields and sediment over certain period (Neitsch *et al.*, 2011; Arnold, 2012). A platform whereby GIS and the Hydrologic model are integrated is provided by SWAT. Various studies have proven SWAT model to be a flexible tool that can be used in the simulation of numerous watershed issues (Githui, 2008; Faramarzi *et al.*, 2010; Kilonzo *et al.*, 2012). Water yields, ground water flows, weather, evapotranspiration, surface runoffs, reservoir storage are among the products of the SWAT model.

Reasons which led to the use of SWAT model in the study includes; its capability to use data that is readily available. Once operating in areas with insufficient or undependable data it is an advantage essentially. Secondly, SWAT model is capable of running simulations of vast management practices or basins economically hence it is computationally efficient. SWAT requires precise data about land management practices, vegetation, topography, soil properties and weather to simulate the physical processes related to movements of sediments, crop growth, nutrient transportation and water movement. The application of the SWAT model may perhaps be grouped into six steps namely: data preparation, watershed delineation, Definition of the HRUs, sensitivity analysis, Model calibration and validation and uncertainty analysis (Neitsch *et al.*, 2011, Kilonzo *et al.*, 2012). The flowchart displaying the modeling phases are shown in Figure 7.



**Figure 7: SWAT Modeling process, inputs and output**

### 2.4.1.1 Data preparation

The use of SWAT as a hydrological modeling tool necessitates the use of comprehensive spatially unambiguous sets of data on land cover and topography, soils classifications, hydrological data and Climate data on daily time step (Schuol *et al.*, 2008; Neitsch *et al.*, 2011;Mango *et al.*, 2011; Nakaegawa & Wachana 2012). Improving on the landuse/ landcover and weather dataset in this study increased the efficiency of the modeling effort however the soil data was a challenge.

### **2.4.1.2 Watershed Delineation and Definition of hydrological response units (HRUs)**

It is essential to develop physical properties of the basin. This is so because the direction and the rate of flow over the surface of land are influenced by basin's topography (Arnold *et al.*, 2012; Shrestha *et al.*, 2013). To delineate the area of interest, the SWAT uses Digital Elevation Model which gives the height at certain spatial resolution of precise points and this is done under the ArcGIS environment. Exploration of the land surface features and drainage patterns are provided (Arnold *et al.*, 2012).

To delineate the catchment and the sub- catchments, DEM was used and this was accomplished through various steps which include: DEM setup, definition of the stream network, definition of inlets and outlets, selection of the watershed outlets and calculation of sub basin parameters. HRUs are areas within a sub-basin possessing distinctive land use management, soil attributes and slope characteristics. HRUs are used by SWAT tool for description of land complexity within sub-basins (Neitsch *et al.*, 2011; Arnold *et al.*, 2012).

### **2.4.1.3 Model calibration and validation**

Calibration encompasses adjusting parameters in a model to best capture the local conditions hence minimizing the model output uncertainties before putting it in to use. For the model to be in a position to be used for a certain assessment it has to be calibrated and validated for the existing conditions (Arnold *et al.*, 2012). To be sure that the model can make satisfactorily accurate simulations a process known as validation is done (Arnold *et al.*, 2012).

Three crucial steps are followed in the process of calibration and validation: first, a portion of the observed data is selected, secondly, the model is allowed to run with the given known inputs and then comparing the output with observed data. In SWAT model a sensitivity analysis has to be performed to choose sensitive parameters for calibration purposes. This is done until goodness of fit to observation is acceptable (Neitsch *et al.*, 2011; Rwigy, 2014). The third step is where by the model with the calibrated parameters is run with remaining portion of the observed data (Kilonzo *et al.*, 2012; Bosshard *et al.*, 2013; Rwigy, 2014). Automatic scheme which is inbuilt in the SWAT2012 and manual schemes for calibration are available in the SWAT model (Lam *et al.*, 2010; Arnold *et al.*, 2012).

Coordinated Regional Downscaling Experiments (CORDEX) provides new climate change model outputs which have not yet been applied in evaluating the impacts of climate change on water resources in Upper Tana catchment. This study uses the CORDEX products to drive

SWAT hydrological model. The SWAT outputs were used to analyze how changes in climate will impact on the Upper Tana Catchment water yields.



## CHAPTER THREE

### 3.0 DATA AND METHODOLOGY

This section presents the methods and the data that were used in the analysis to get results and in achieving the objectives of the study.

#### 3.1 Data

The data used in this study consist of rainfall, temperature (maximum and minimum) at monthly time series, daily stream flow data, and climate projection data (RCP4.5 and RCP8.5). Below are comprehensive description of the datasets and their sources.

##### 3.1.1 Observed climate and stream flow data

Rainfall and temperature datasets for the period 1951 to 2014 from the Kenya Meteorological Department (KMD) on a monthly time scale were used. Daily discharge datasets for the period of 1963 to 2000 from Ministry of Water and Irrigation (MWI) were also used. These datasets were processed to get the monthly for the case of discharge data, and seasonal, annual and long-term mean values for all the datasets.

##### 3.1.2 Digital Elevation Model (DEM)

A 90m resolution DEM was downloaded from the Shuttle Radar Topography Mission (SRTM). In order to be applied into the SWAT model the DEM was projected to the World Geodetic System of 1984 (WGS84) World Mercator.

##### 3.1.3 Land use / land cover data

Different processes within a watershed like surface runoff, evapotranspiration, erosion among others are affected by the management of the land and land use type. A collection of 10 years (2001-2010) LULC data from the USGS describe the type of land cover, and are 5.1 MCD12Q1 land cover data. For every pixel, the land cover classification with main general confidence from 2001-2010 is selected in generation of the map as described in Broxton *et al.*, 2014. Reclassification is done to match classes that are corresponding to the LULC in the SWAT database. Bushland (shrubs), water, urban, forest and cropland distributed into crops essentially denoted by tea plantations and annual plants were the main landuse classes. Due to the fact that plots are left barren for part of the year as a result of the yearly cycle the annual crops undergo that leaves this distinction for cropland was established.

### **3.1.4 Soil data**

Nature and conditions soils affect how river basin responds to a certain rainfall event greatly (Shrestha *et al.*, 2013). Soil properties such as the hydraulic conductivity, moisture content availability, physical properties, bulk density, chemical composition, organic carbon content and texture, for the different layers of each specific soil type are required by SWAT model (Setegn, 2008). Data that facilitated in defining the soil units was obtained from the KENSOTER database established by Kenya Soil Survey (KSS) together with the International Soils Reference and Information Centre (ISRIC). Soil data set for the Upper Tana Catchment was projected to WGS84 World Mercator to overlay the DEM layer.

### **3.1.5 Climate data**

SWAT model requires climate data inputs in daily time series. These datasets comprises of wind speed, evapotranspiration, rainfall, temperature and humidity data. The observed weather variables from Embu, Thika and Nyeri stations used were the daily precipitation and air temperature (minimum and maximum) from 1970-2000 obtained from Kenya Meteorological Department. This aided in setting up the SWAT project for the Upper Tana Catchment.

### **3.1.6 Climate projection data sets**

The World Climate Research Program (WCRP) initiated the CORDEX RCPs climate scenario runs which were forced by lateral and surface boundary condition from the European Centre for Medium Range Weather Forecasting (ECMWF) Interim Re-Analysis using the region of Africa (Endris *et al.*, 2013). A 50 km resolution was used to perform CORDEX-African domain simulation and the experimental data are available for the period 1989-2008 (Endris *et al.*, 2013).

These pathways have been provided by the CORDEX (near-term and long-term modelling experiment) datasets for the regional climate modelling and research (Moss *et al.*, 2010; Van Vuuren *et al.*, 2011). The climate change projection datasets for the period 2006 to 2100 were obtained from ICPAC data repository. Simulated daily and monthly rainfall, minimum and maximum temperature from the CORDEX models (RCP4.5 and RCP8.5) were used in this study.

## 3.2 METHODOLOGY

In this section, the methods that were used in the study are discussed. These methods include those that were used to organize the data to meet the needs of the study such as estimating missing records and examination of the quality of the records used in the study. The other methods focused on the specific objectives of the study that included: Correlation analysis, Regression analysis, Graphical methods, Cumulative distribution, Gaussian Kernel distribution, and Mann Kendall method.

### 3.2.1 Estimation of missing data

Gaps that are found in most of the climatological records must be filled before such data is used for any scientific research. Standards for the World Meteorological Organization (WMO) for estimating missing data is that, the missing data of a station should be less than 10% of the total records (WMO, 1966).

There are several techniques for estimating missing data including; the arithmetic mean, Thiessen polygon method, Isohyetal method, the isopleths method, finite differencing method, Correlation method and regression method (Nyakwada *et al.*, 2009; Little & Rubin, 2014). The arithmetic method which was used in this study is discussed here.

#### 3.2.1.1 Arithmetic mean method

$$X_{Aj} = \frac{X_{Bj}}{\bar{X}_B} \cdot \bar{X}_A \dots\dots\dots (1)$$

Where  $X_{Aj}$  is the missing record of station A in the  $j^{\text{th}}$  year,  $X_{Bj}$  the record for station with reliable records (B) in year j, and  $\bar{X}_A$  and  $\bar{X}_B$  are the long-term averages for stations A and B, respectively based on the period of records available at A. Long period of records and relatively homogeneous distribution of station in the catchments are required in this method to enable it generate stable averages for individual stations. Such a network could include all the best-correlated neighboring stations, which are required to estimate the missing records (WMO, 1966; Nyakwada *et al.*, 2009; Vicente-Serrano *et al.*, 2010)

The understanding of a neighboring station which is best correlated to the station with missing data is however required in the use of arithmetic mean method to estimate missing data for any station. Therefore, the first step is to identify a neighboring station, which has the

highest correlation with the station with missing records (WMO, 1966; Nyakwada *et al.*, 2009)

### 3.2.1.2 Correlation analysis

Correlation coefficient was used to quantify the degree of relations between pairs of variables. When the correlation value is +1, it indicates perfect positive linear relationship and if it is -1, it signifies a perfect negative linear relationship (Indeje & Semazzi, 2000; González-Rouco *et al.*, 2001; Nyakwada *et al.*, 2009). The period with complete data was correlated with the neighboring station using Equation 2.

$$r_{xy} = \frac{\frac{1}{N} \sum_{i=1}^N (x_i - \bar{x})(y_i - \bar{y})}{\left[ \frac{1}{N} \sum_{i=1}^N (x_i - \bar{x})^2 \cdot \frac{1}{N} \sum_{i=1}^N (y_i - \bar{y})^2 \right]^{1/2}} \dots\dots\dots (2)$$

Where,  $r_{xy}$  is the correlation coefficient between the values of the two stations,  $N$  is the total number of years with complete records,  $x_i$  is the available datasets for station with missing data,  $\bar{x}$  is the mean of the available data for the same station,  $y_i$  is the dataset for the neighboring station with complete records and  $\bar{y}$  is the long-term mean of the station with complete records.

To test the significance of the correlation coefficient, the student T-test was used by comparing the t-statistic as given by Equation 3. Correlation coefficient is significant if the t computed is more than the tabulated t value for a given value of confidence.

$$t_{n-2} = r \sqrt{\frac{(n-2)}{1-r^2}} \dots\dots\dots (3)$$

Where,  $n$  represents the length of the data that were used,  $n-2$  is the degrees of freedom,  $t_{n-2}$  is the value of the confidence level computed from the correlation coefficient and  $r$  is the correlation coefficient.

### 3.2.2 Data quality

Most climatological records are characterized by inconsistencies, which could be as result of instrument changes, changes in gauge location or surrounding conditions or changes in observation procedures (Sahin & Cigizoglu, 2010). Methods used in data collection, estimation of missing records, transmission and processing could have associated errors and this may cause the heterogeneity of the records (González-Rouco *et al.*, 2001). Therefore, before such datasets are used in any climatological analysis it is advisable to check for the quality of those climatological records. The single and double-mass curves methods are the most commonly used methods of testing the quality of data. In this study the mass curves analysis and pettitt's test were used.

Cumulative climatological records are plotted against time in the mass curve analysis. The patterns of these graphs can be used to test for the quality of the records. For nearly homogeneous records, a single straight line is obtained. Other patterns indicate that the records are heterogeneous. Records that are heterogeneous, the next step would be to correct for heterogeneity. Double mass curve is the commonly used method to adjust heterogeneous records which applies the same principles as those of single mass curves. In double-mass curve analysis, cumulative values of the heterogeneous records are plotted against the cumulative values of records from a homogeneous station or parameter.

The Pettitt's test on the other hand is a nonparametric test that entails no assumption about the distribution of data. The Pettitt's test embraces tank-based Mann-Whitney test which allows identification of the time when a shift in the records occurred. To discover a single change-point in hydrological or climate series with continuous data set the method is commonly applied (Pettitt, 1979)

Pettitt's test is established on the rank,  $r_i$  of the  $Y_i$  and does not consider the normality of the series and it's given by Equation 4 and 5 below.

$$X_y = 2 \sum_{r=1}^y r_i - y(n + 1), \quad y = 1, 2, \dots, n \quad \dots \dots \dots (4)$$

Where the break occurs at year  $k$  is given by

$$X_k = \max_{1 \leq y \leq n} |X_y| \dots \dots \dots (5)$$

**Table 3: 5% and 1% critical values for  $X_k$  of Pettitt test as a function of n**

<b>n</b>	<b>20</b>	<b>30</b>	<b>40</b>	<b>50</b>	<b>70</b>	<b>100</b>
1%	71	133	208	293	488	841
5%	57	107	167	235	393	677

### **3.2.3 Assessing the Climate and Hydrological characteristics of Upper Tana Catchment**

This objective was achieved by analyzing the past and present trends in rainfall, surface air temperature (maximum and minimum) and Discharge. In this study several methods were adopted which included the normal density distribution, time series analysis and Mann-Kendall test.

#### **3.2.3.1 Density distribution**

Under the density distribution the annual totals of the observed rainfall were calculated for the three stations (Embu, Nyeri and Thika). The annual average of the maximum and minimum temperature was determined. This was used to show the distribution of rainfall and air temperature over the catchment which helped in understanding the past and present climate characteristics of the study area. Normal density distributions often represent real-valued random variables with unidentified distributions. It is shown by Equation 6 below.

$$f(x | \mu, \sigma^2) = \frac{1}{\sqrt{2\sigma^2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \dots\dots\dots (6)$$

Where:

$\mu$  represents the expectation of the distribution (median, mode and mean),  $\sigma$  is the standard deviation and  $\sigma^2$  is variance.

#### **3.2.3.2 Time Series Analysis**

Graphical methods include the time series analysis with the trend test for the observed (rainfall and temperature) for the period 1951 -2014 and discharge data for the period 1963-1990. The annual totals for rainfall were computed and plotted, while for the case of temperature, the annual average minimum, mean and maximum temperatures were

computed. To analyze the past and current state of the stream flow within the catchment, the mean annual discharge for the four gauge stations were plotted.

In Hydrological analysis, time series analysis is an important tool (McSweeney *et al.*, 2010; Rwigi, 2014). It is mainly applied in detecting the trends and shifts, cycles and seasonality in hydrological records. It can also be applied in forecasting hydrological events, and if need be filling in missing records by extension like in the case of short records (McSweeney *et al.*, 2010; Rwigi, 2014).

In this study Time series analysis were used in determination of the past and current trends of the rainfall, minimum, maximum and mean temperatures over the study area. This method has been applied in various research works (Koutsoyiannis, & Montanari, 2007; McSweeney *et al.*, 2010; Shanafield *et al.*, 2011; Rwigi, 2014; Imdadullah, 2014)

### 3.2.3.3 Mann Kendall method

Mann-Kendall test was used to analyze the trends in rainfall and surface air temperature using Equation. 8. Long term climatic changes could introduce trends in hydrologic data. Catchments response to effective rainfall could be changed due to the changes in land cover which introduces trends in the stream flow.

In detecting trend in datasets there are many parametric and nonparametric methods available for use. Simple linear regression analysis which assumes constant variance, normality of errors and true linearity of relationships is one of the most useful parametric methods that are used to detect trend. However, in this study the trend in time series of different datasets was determined by Mann-Kendall trend test given by Equation7 and 8, below.

$$\tau = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sgn}(x_j - x_i) \dots\dots\dots (7)$$

Where  $n$  is the length of the data set,  $x_j$  are the sequential values, , and

$$\text{sgn}(\theta) = \begin{cases} 1 & \text{if } \theta > 0 \\ 0 & \text{if } \theta = 0 \\ -1 & \text{if } \theta < 0 \end{cases} \dots\dots\dots (8)$$

This test was suggested by Mann in 1945 and it has been widely used (Yue *et al.*, 2002; Hamed, 2008; Mondal *et al.*, 2012; Ngaina & Mutai, 2013; Nasrollahi *et al.*, 2015; Ouma 2015).

In this test,  $\tau$  is the test statistic. When the value of  $\tau$  is positive, it gives a positive trend and negative trend when  $\tau$  gives a negative value. In this study, the level of significance of 0.05 (P-value=0.05) was used. If their P-value was equal to or less than 0.05 (P-value  $\leq$  0.05) the trend tests were considered significant.

### **3.2.4 Evaluation of the future climate change scenarios over the upper Tana catchment**

Different models have their own strengths and weaknesses (Endris *et al.*, 2013). To achieve this specific objective, the performance of each model used in the study was evaluated against observation. An ensemble of the models was also computed and its performance evaluated together with the models against the observation. In order to assess the performance of the models against observations, in an attempt to identifying the best model that mimics the observation, the study used the following methods: Correlation analysis, Cumulative Distribution Function (CDF) and Boxplot.

To achieve this specific objective, the chosen model was then subjected to further analysis which involved Time series analysis and Gaussian kernel method.

#### **3.2.4.1 Cumulative Distribution Function (CDF)**

A distribution of a variable  $X$  when evaluated at  $x$  is the likely that  $X$  will take a value equal or less than  $x$  in statistics or even in probability theory. It is described by Equation 9 below.

$$F_X(x) = P(X \leq x) \dots \dots \dots (9)$$

The area under the probability density function from negative infinity to  $x$  represents a continuous distribution. Cumulative distribution functions can also elaborate the distribution of multivariate random variables (Piani *et al.*, 2010; Xue *et al.*, 2011)

#### **3.2.4.2 Boxplot**

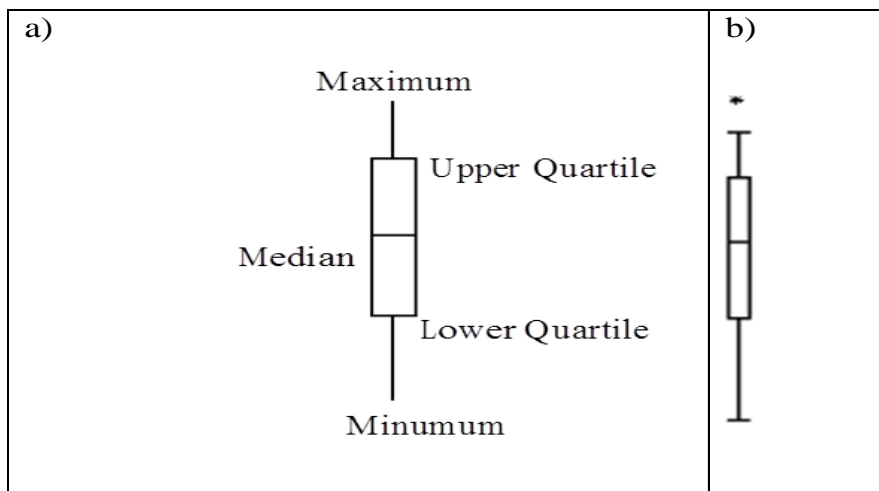
To detect patterns hidden in a group of numbers, an exploratory data analysis is applied which involves the use of statistical techniques. "Box plot," is one of these techniques (Härdle & Simar, 2012; Spitzer *et al.*, 2014). It is used to visually compare and summarize groups of data. The symmetry, level and spread of data distribution can be displayed by the box plot which uses the approximate quartiles, median and lowest and highest data points (Kampstra, 2008; Krzywinski & Altman, 2014). The box shows the lower and upper quartiles



while the interior of the box indicates the inner quartile range. The Lines (also termed as whiskers) are stretched to either maximum or minimum values in dataset (Kampstra, 2008; Krzywinski & Altman, 2014). A crossbar drawn at the middle of the box shows the median of the dataset. It is illustrated by Figure 8.

Subject to the use of the plot and the data it is demonstrating, the choice of the extent of the range-line, indication of outliers, width and fill of the box may vary. In the cases where only these distinctive values need to be analyzed, Box plot provides a more straightforward way which reduces representation afforded by the 5-number summary way to compare datasets. This method has been applied in various studies (Tebaldi *et al.*, 2004; Sun & Genton, 2012; Krzywinski & Altman, 2014).

In this study the Box plot was applied to evaluate the performance of the various chosen models and their ensemble against the observations. Annual totals of the historical rainfall simulations dataset were computed which were compared with the historical annual totals of the observed data.



**Figure 8: The anatomy of a box plot (a) and the box plot (b)**

### 3.2.4.3 Gaussian kernel method

Then the chosen model dataset was subjected to further analysis which involved, Time series analysis with a trend test using the Mann Kendall test which have been explained in the sub-section 3.2.3.2 and 3.2.3.3 respectively. This sub-section describes the Gaussian kernel method that was also used to achieve this specific objective. This method is represented by Equation 10 below.

$$g_y(\mathbf{fs}) = \sum_{t=1}^T \frac{1}{h^N} K\left(\frac{y_t - \mathbf{fs}}{h}\right) \dots \dots \dots (10)$$

Where,  $\mathbf{fs}$  is the random variable,  $h$  is a scaling factor (Bandwidth),  $N$  is sample number and  $K$  represents the Kernel (Bessa *et al.*, 2012; Mohseni *et al.*, 2014).

Total annuals of the projected rainfall and the annual mean temperatures for both the minimum and maximum temperature for the two climate change scenarios were computed. This was also done for the observed rainfall and temperature. The Gaussian kernel method was used with the future non-overlapping climatic periods which were 2021-2040, 2051-2070, and 2081-2100, to analyse future climate change for rainfall and temperature over the study area under the climate change scenarios (RCP4.5 and RCP8.5). This method has been applied in several studies in analysing the future climate status (McCabe *et al.*, 2014; Mohseni *et al.*, 2014; Chen *et al.*, 2015; Chu *et al.*, 2015; Van Ackooij & Minoux, 2015)

### **3.2.5 Projection of stream flow patterns under climate change scenarios**

This study examined the water yields under different climate change scenarios (RCP4.5 and RCP8.5) on the Upper Tana catchment in Kenya through the use of SWAT model which is physically based hydrological model (Bouraoui *et al.*, 2002; Neitsch *et al.*, 2011; Arnold *et al.*, 2012).

#### **3.2.5.1 SWAT model set up**

Using the DEM, the Upper Tana Catchment was delineated and stream network/flow was defined. Hydrologic Response Units (HRUs) were then computed and defined from the land use, soils and elevation data. The particular hydrologic process and response at every geographic point within the research basin are determined by the HRU. Climate data (rainfall, maximum and minimum temperature) was then uploaded into the SWAT model. The inbuilt SWAT database was used to generate the related atmospheric and weather variables like relative humidity, solar radiation, wind speed, etc. for the catchment (Lam *et al.*, 2010).

Preprocessed geospatial and the collected data were written into the SWAT Model. For performance efficiency, calibrated and validated processes were done. The model was allowed to run at the one selected outlet 4ED03 after loading all the necessary data into the SWAT model. The initial runs are necessary to determine if the model is suitable. The

hydrological balance for each HRU was simulated according to water balance equation suggested by the Arnold *et al.*, (1998).

$$SW_t = SW_0 + \sum_{i=1}^t (R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}) \dots \dots \dots (10)$$

Where t (day) is the time.  $SW_t$  final soil water content in mm,  $SW_0$  (mm) expresses initial soil water content,  $R_{day}$  (mm) is amount of rainfall,  $Q_{surf}$  (mm) surface runoff amount,  $E_a$  (mm) quantity of evapotranspiration,  $W_{seep}$  (mm) water amounts from soil profile entering the vadose zone and  $Q_{gw}$  (mm) return flow amount all on day i.

Water yield is the overall quantity of water from certain HRU which moves in to the main channel during the time step and is estimated the by the model.

### 3.2.5.2 SWAT Model Calibration and Validation

In SWAT model calibaration, the parameters are adjusted within their physical acceptable range in such a way that practical agreement between simulated and observed streamflows is accomplished. After the model is calibrated, it's performance is validated where by the calibrated model is run with a different data set without adjusting the parameters that were set during calibration process (Dile *et al.*, 2013).

In the model sensitivity analysis One-Factor-At-a-Time method was used (Kilonzo *et al.*, 2006, Schuol *et al.*, 2008; Abbaspour *et al.*, 2009; Lam *et al.*, 2010). Manual calibration helper and auto-calibration are the two available tools in SWAT. Manual calibration was used where the parameters were adjusted one by one until a better  $R^2$  was achieved between the simulated and observed streamflow.

Adjusting parameters that are sensitive and affect surface runoff until a reasonable  $R^2$  is achieved calibrates the surface runoff part of the streamflow (e.g., Ch\_N2 – Manning's 'n' value of the channel, soil evaporation compensation factor -Esco and CN2 – Initial SCS runoff curve number for moisture condition II, and I). By modifying the sensitive parameters which affect the contribution of groundwater, calibration of base-flow parameters e.g., coefficient of groundwater 'revap' (GW\_REVAP), and depth of water inception in the shallow aquifer necessitating return flow (GWQMN) was done when a reasonable coefficient of determination was obtained.

The adjustments of the parameters are done concurrently since varying parameters that disturb the base flow can interfere with the simulation of surface runoff. Other parameters affecting the hydrograph outline include baseflow alpha factor (Alpha\_BF), effective hydraulic conductivity in main channel (Ch\_K), lag coefficient of surface runoff (Surlag) and groundwater delay time (GW\_DELAY) (Neitsch *et al.*, 2011; Arnold *et al.*, 2012).

Auto-calibration process of the model was performed after the initial values were fixed to be the manually calibrated parameter values. The model was run from 01 January 1970 to 31 December 2000. The observed discharge for period 1990-1992 was used to calibrate the model and from 1993-1995 were used to validate the model. Hydrological graphs were developed and coefficient of determination used to evaluate the model performance.

### 3.2.5.3 Coefficient of Determination ( $R^2$ )

R-squared ( $R^2$ ) is a value that is generally computed as a measure of how well the observed values are replicated by simulated values as explained by the proportion of total variations by the model (Moriassi *et al.*, 2007; Rwigi 2014). Statistically the  $R^2$  is computed as a comparison of the variability of the estimation error ( $SS_E$ ) with the variability of the original value ( $SS_T$ ) using Equation 11.

$$R^2 = 1 - \frac{SS_E}{SS_T} \dots\dots\dots (11)$$

Where  $SS_T$  is the total sum of squares and  $SS_E$  is the sum of squared errors.

The model output is considered satisfactory if  $R^2$  approaches 1 as a result of small  $SS_E$ . Values reflected by the trend line help in the estimation of the coefficient of determination which is a number between 0 and 1 that reveals how closely the simulated values agree to the actual observed (Muthama *et al.*, 2008; Jain *et al.*, 2010).

### 3.2.5.4 Impacts of Climate Change on Water Yields

By adjusting the climatic inputs in the SWAT model, impact assessment of climate change on water yields can be accomplished. Simulated water yields under the two future scenarios (RCP 4.5 and 8.5) were evaluated relative to the observed monthly discharge for the gauge station 4ED03. This was done through graphical methods. Regression graphs of the annual totals of the observed for the period 1970- 1989 were compared with those of the simulated

water yields for the 2021-2040, 2051-2070, 2081-2100 from the two climate change scenarios.

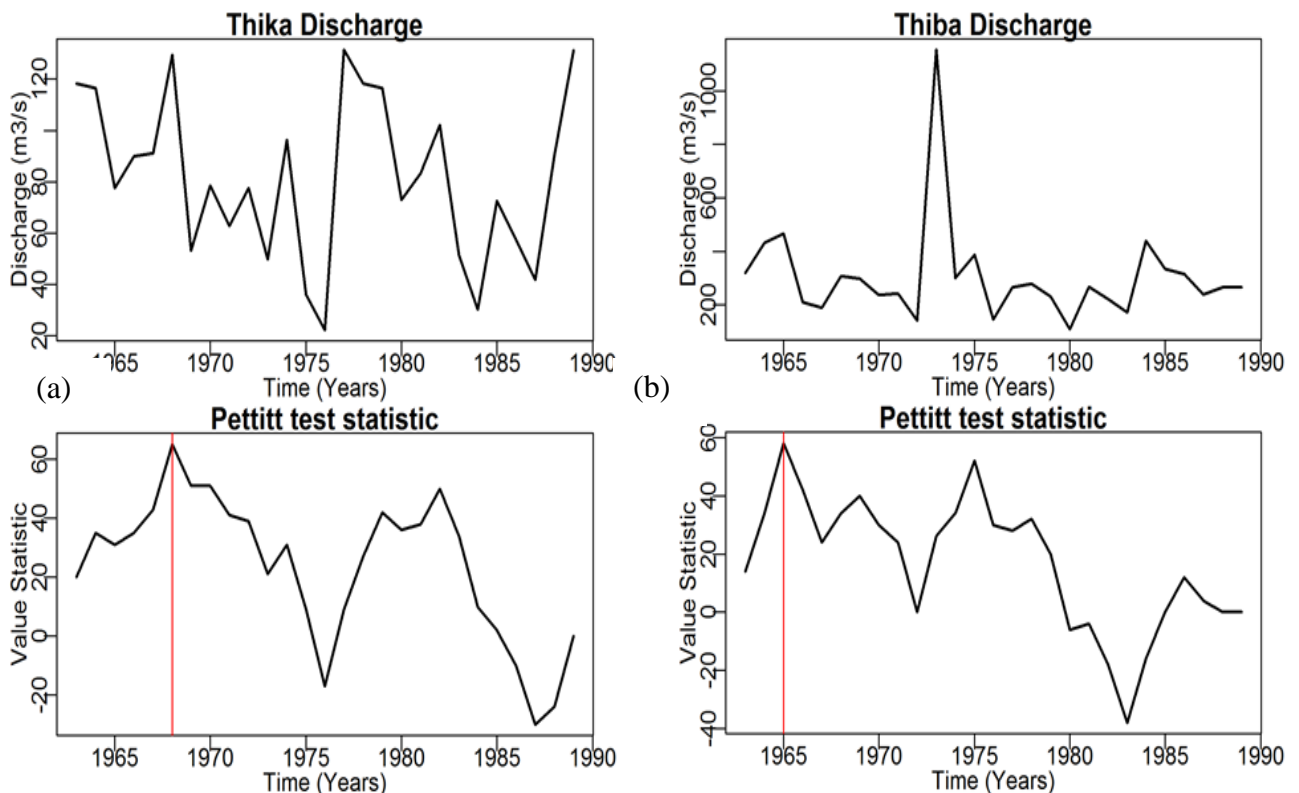
## CHAPTER FOUR

### 4.0 Results and Discussion

This chapter presents the results and discussion from the various methods that aided in achievement of the objectives in the study.

### 4.1 Data Quality Control

In any analysis determination of the quality of observed records is an important step. The observed datasets used in the study encompasses stream flow, rainfall, temperature (maximum and minimum). The consistency of these datasets was established. Results from the single mass curve indicated that datasets were homogeneous. The data sets were again subjected to pettitt test to test for the homogeneity. From the Figure 9 below it is clearly shown that the discharge data for Thika and Thiba gauge stations were homogeneous. All the data sets were found to be homogeneous.



**Figure 9: Annual discharge time series and corresponding homogeneity test series for (a) Thika and (b) Thiba during the years 1963 to 1990**

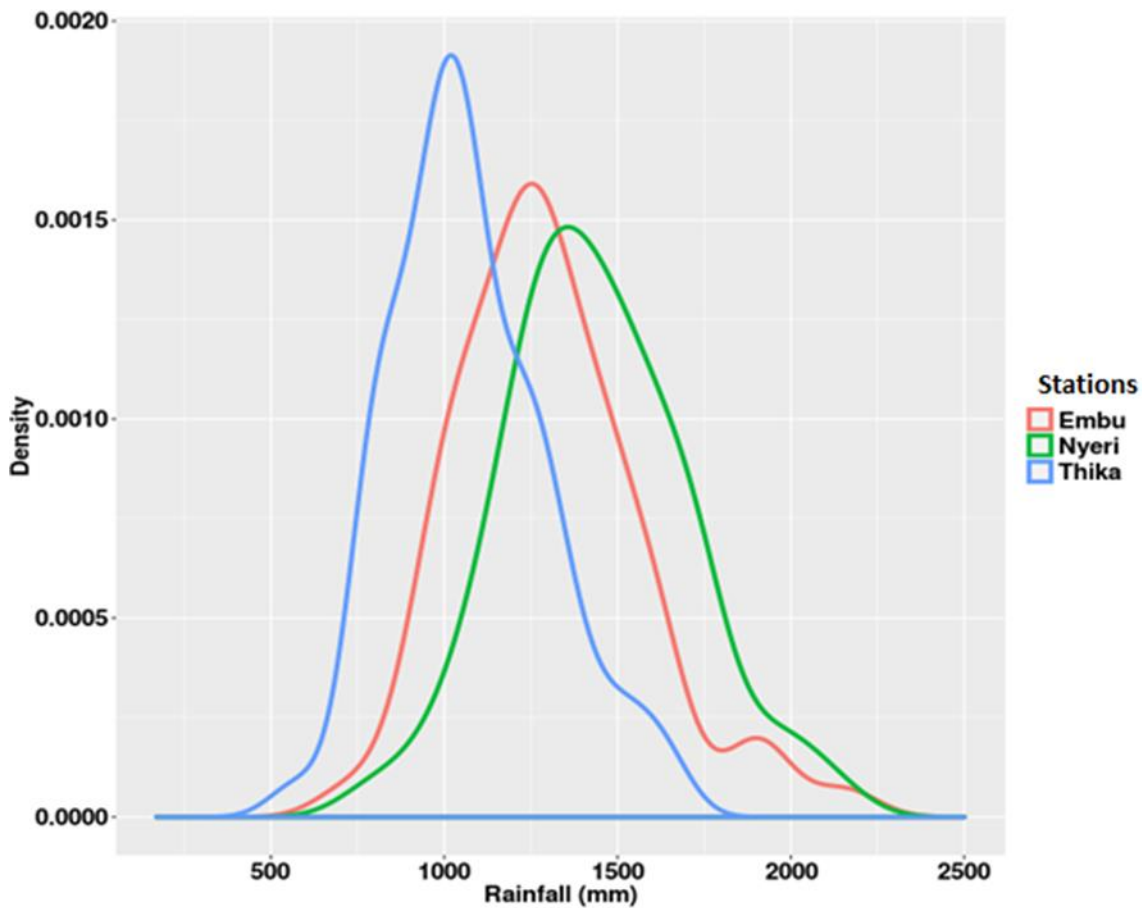
## **4.2 Assessing the Climate and Hydrological characteristics of Upper Tana Catchment**

The discussion on the distribution of rainfall, surface air temperature and discharge for the study area are presented in this section. Trends in rainfall mean and minimum maximum surface air temperature and also the relationships between rainfall and discharge over the Upper Tana Catchment are also presented.

### **4.2.1 Rainfall distribution over the Upper Tana catchment**

The distribution of annual total rainfall in Figure 10 shows Embu and Thika stations are skewed to right with maximum annual totals greater than 2000mm. However, Thika station had a maximum less than 2000mm. On the other hand, annual total rainfall distribution for Nyeri station is normally distributed with maximum amount greater than 2000mm. A study by Ngaina *et al.*, (2014) over the Tana catchment indicated that mean rainfall over the catchment is between 300-500mm.

Otieno *et al.*, (2000) found out the over the Upper Tana River Basin rainfall follows a similar elevation gradient as that of soils. In higher elevations more than 1800 mm/yr of rainfall is received, the mid elevations receive rainfall ranging from 1000-1800 mm/yr and at lower elevations, rainfall of less than 700 mm/yr is received.

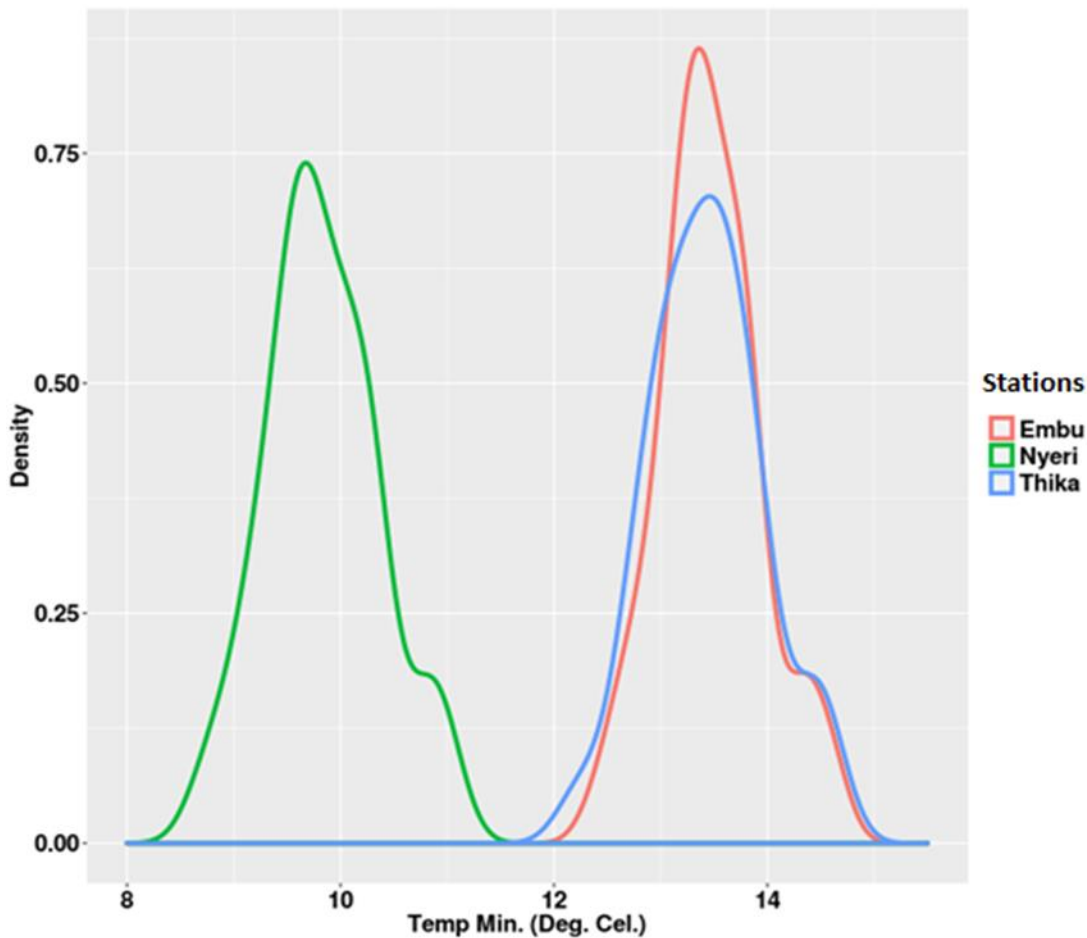


**Figure 10: Density distribution of total annual rainfall over the study area for the period 1951-2014**

#### **4.2.2 Temperature distribution over the study area**

Results for the annual average minimum, mean and maximum temperature are presented in this section. Figure 11 shows density distribution of annual average minimum temperature for the stations used in the area of study. Embu, and Thika have their distributions skewed to the left. This indicates that these stations mostly record extreme high minimum temperatures greater than  $14^{\circ}\text{C}$  as compared to Nyeri with its temperature distribution skewed to the right. Therefore, Nyeri minimum temperatures have a tendency to fall in the lower extremes about  $9^{\circ}\text{C}$ .



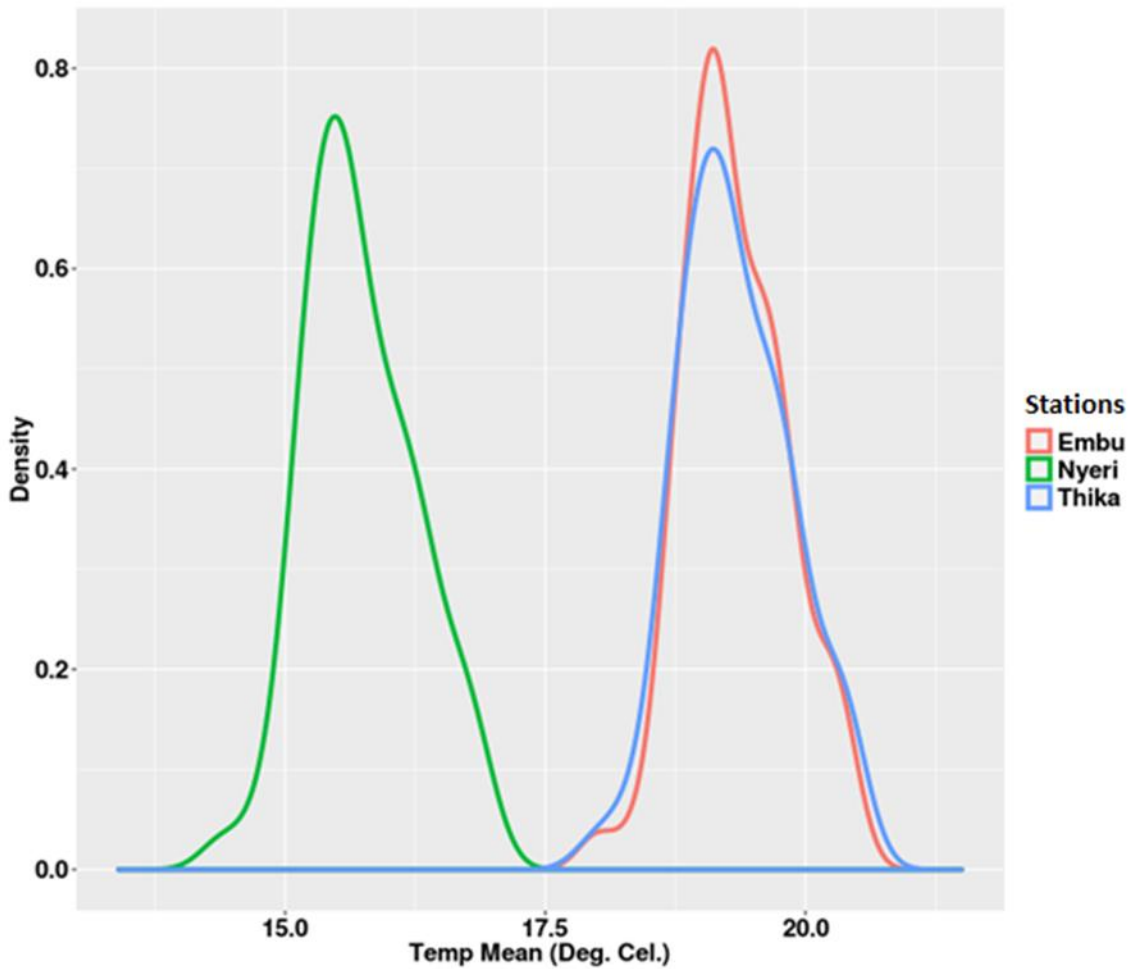


**Figure 11: Density distribution of annual average Minimum temperature over the Upper Tana Catchment for the period 1951-2014**

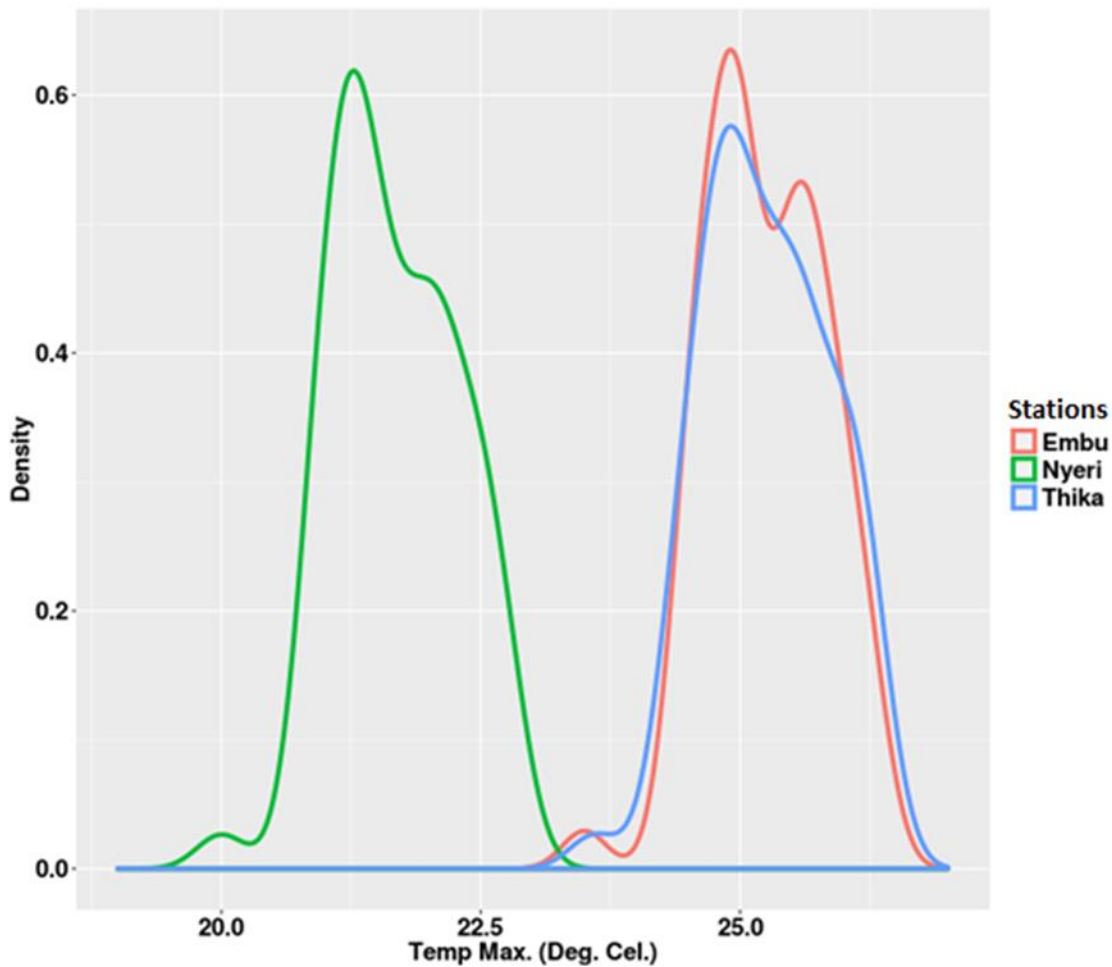
In Figure 12, it is evident the same distribution pattern for the annual average minimum temperature is observed for the annual average mean temperature. Nyeri has a distribution that favors high frequency of lower temperatures with the mode distribution of 15.5°C. On the other hand, Embu and Thika have high frequency of higher temperatures as compared to Nyeri, with their extremes reaching beyond 20°C.

Unlike the annual average minimum and mean temperatures, the annual average maximum temperatures have a peculiar distribution as given in Figure 13. The distribution of Embu has two distinct peaks. This is a clear indication that temperatures over these stations may have undergone significant changes over time. In addition, their distributions are skewed to the left, an indication that, these regions rarely record low temperatures, especially below 24°C. Both Nyeri and Thika have a unimodal distribution. However, the distribution for Nyeri is nearly Gaussian while that of Thika is skewed to the left.

In overall, both rainfall and temperature distributions show that Nyeri experiences a strong orographic modification of its microclimate due to the presence of Mt. Kenya. Its rainfall is normally distribution unlike the rest of the stations which show skewness. Therefore, rainfall over Nyeri has not experienced any significant changes over the period of study. In terms of temperature, only a few high extreme values are recorded over this station compared to Thika and Embu which has extremes in the lower category.



**Figure 12: Density distribution of annual average Mean temperature over the Upper Tana Catchment for the period 1951-2014**

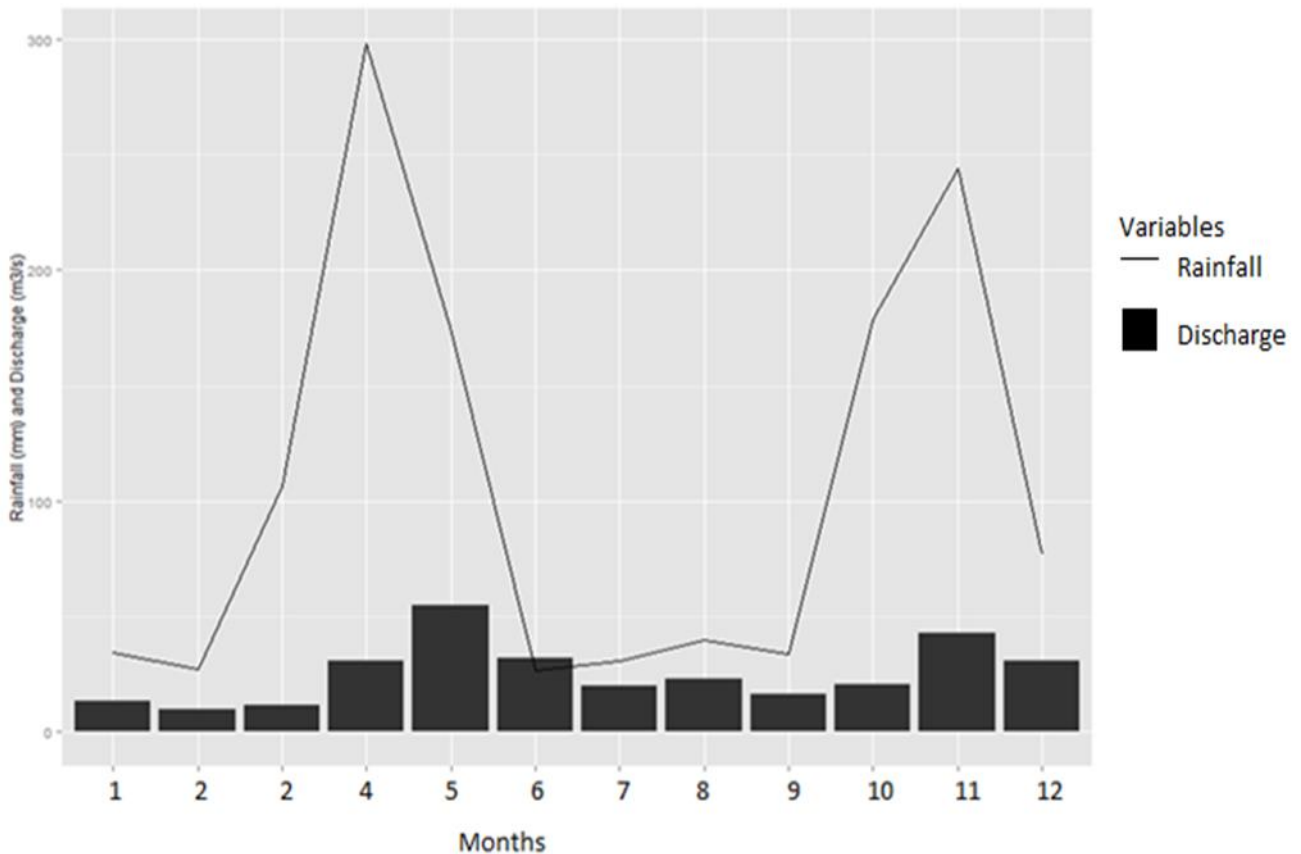


**Figure 13: Density distribution of annual average Maximum temperature over the Upper Tana Catchment for the period 1951-2014**

### **4.2.3 Relationship between observed rainfall and Discharge in the study area**

The analysis for the long term monthly rainfall and how they relate with the long term discharge for the three station used in the catchment are presented in this section. In determining catchment hydrology the rainfall intensity and distribution is a critical component. The time series represents the rainfall and the bars represents the discharge. Decrease in the annual rainfall rates and temperature increase indicates the most complicated hydrological processes.

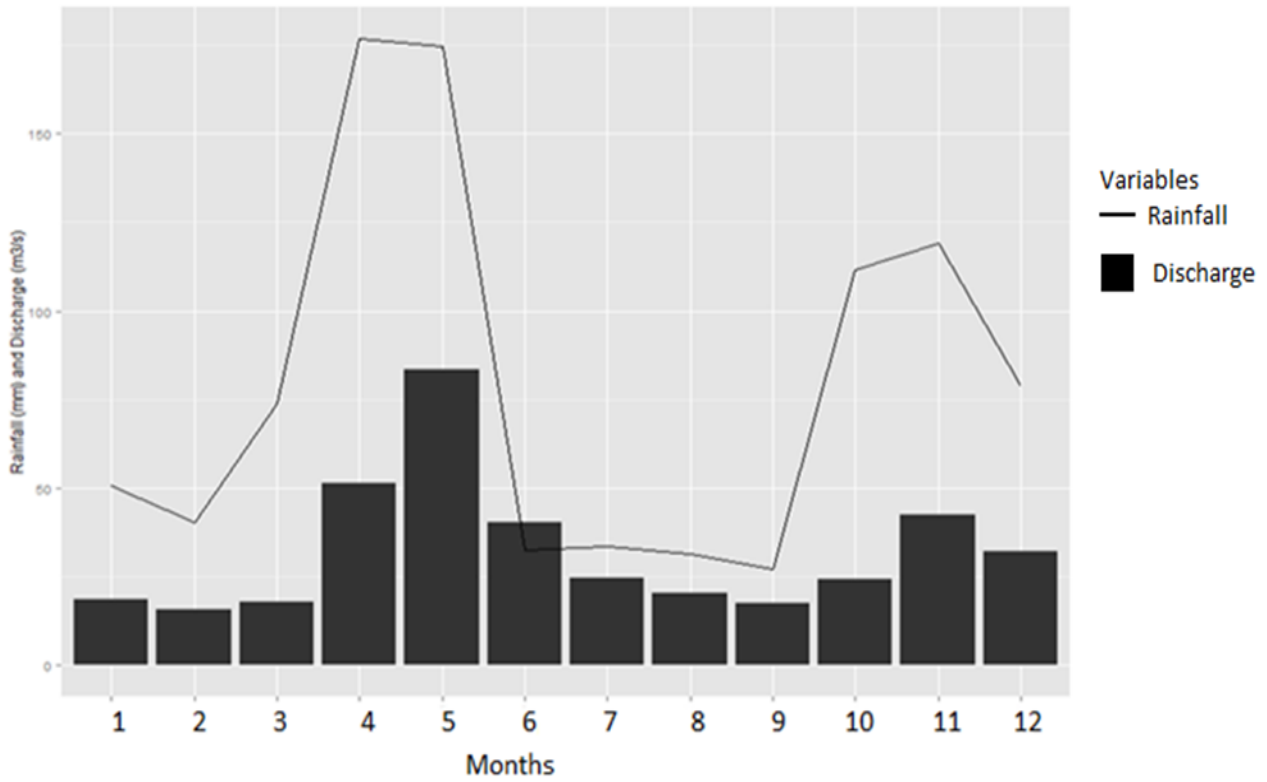
The long term averages of the rainfall over the Embu Station in Figure 14 shows that it receives high amounts of rainfall as compared to the Thika and Nyeri stations as shown in Figure 15 for Nyeri and Figure 16 for Thika. The Embu station showed increased records of the long term average rainfall. The peak over this station occurred in May for the MAM rainfall season. This was followed by another minor peak in the month of August and another in November



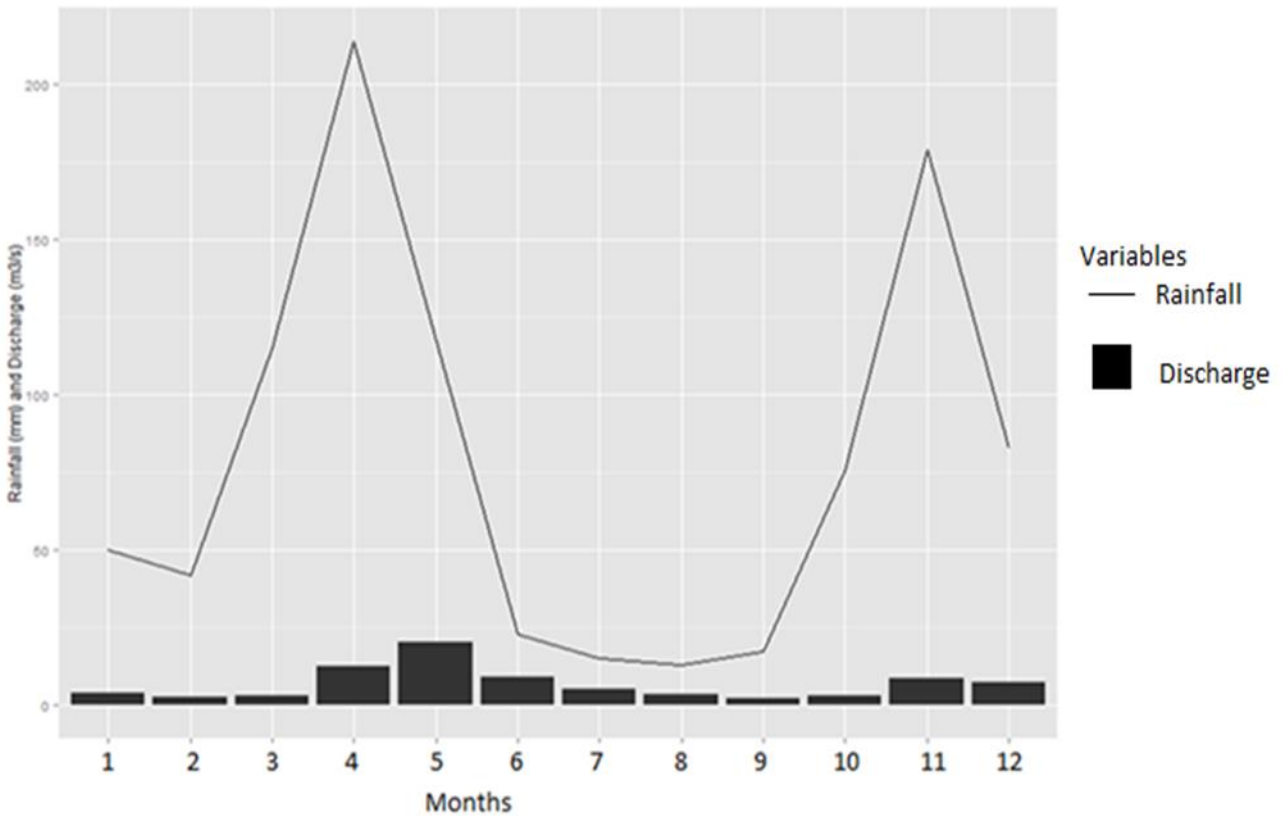
**Figure 14: Relationship between long term monthly rainfall over Embu station and long term River discharge for the period 1963-1990**

The Nyeri station clearly displays two rainfall seasons with the main rainfall season in March-April-May (MAM) where peak rainfall occurs in May and another peak occur in November for the OND rainfall season. The Thika station displayed only two peaks, one on the month of May and another one in November. This confirms that the Nyeri and Thika stations have bimodal pattern of rainfall though the Thika station showed low records in the long term rainfall. The Embu station on the other hand showed a trimodal pattern of rainfall.

The long term variations in the recorded rainfall over the catchment are a result of orographic influence from the Aberdare Ranges and Mt. Kenya (Otieno *et al.*, 2000; Jacobs *et al.*, 2007). The rainfall and discharge depict the same regimes; there exist a difference in the peaks of the rainfall regimes and the discharge.



**Figure 15: Relationship between long term monthly rainfall over Nyeri station and long term River discharge for the period 1963-1990**



**Figure 16: Relationship between long term monthly rainfall over Thika station and long term River discharge for the period 1963-1990**

#### 4.2.4 Trend analysis of rainfall, temperature and discharge

The significance test of trends of the annual rainfall, temperature and also the annual and seasonal discharge over the study area was done through Mann Kendall trend method. The results from the trend analysis are presented in this section.

In Figure 17, the rainfall indicates a general negative trend over all stations except for Thika station. In addition, the rate of change is evidently lower over Thika station as compared to the rest of the stations. However, as noted in Table 4 which has the summary of the trends in the rainfall, minimum, mean and maximum temperature, the rainfall trends are statistically not significant for all stations. If the p-value is less than or equal to 0.05 the trend is regarded significant.

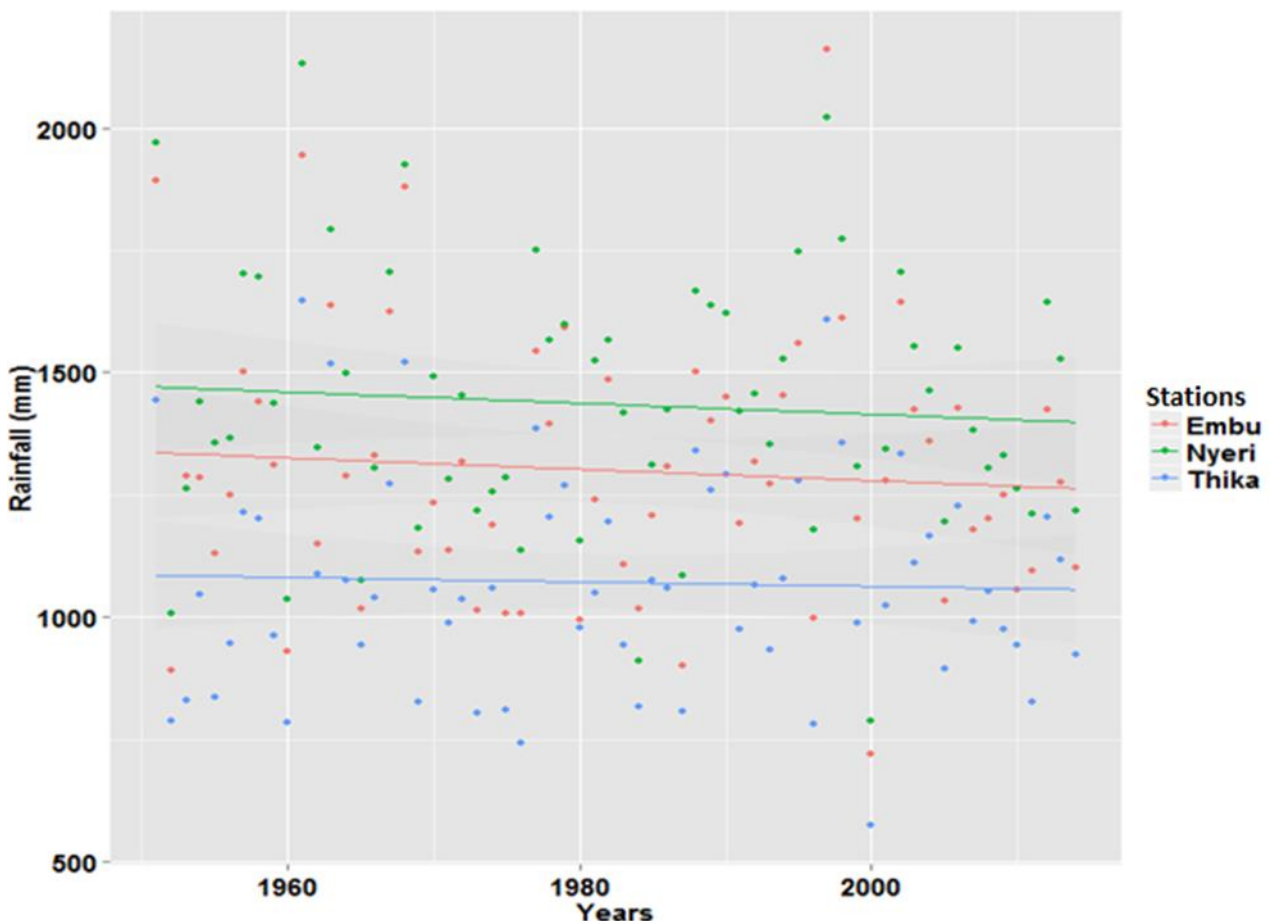


Figure 17: Trend analysis of the annual rainfall for Embu, Nyeri and Thika for the period 1951-2014

**Table 4: Trends in the annual rainfall totals, annual average temperature (minimum and maximum) for different stations for the period 1951 to 2014**

<b>Variables</b>	<b>tau</b>	<b>p-value</b>
Embu.PRE	-0.037	0.672
Nyeri.PRE	-0.034	0.698
Thika.PRE	0.001	0.995
Embu.MIN	0.434	0.000
Nyeri.MIN	0.454	0.000
Thika.MIN	0.411	0.000
Embu.MAX	0.413	0.000
Nyeri.MAX	0.440	0.000
Thika.MAX	0.405	0.000

A study by Bunyasi, (2012) showed that the average annual precipitation in the Upper Tana Catchment is gradually declining. This shows that the negative trend of rainfall over these regions is therefore sufficiently large enough to impact some applications that are dependent on rainfall like the water resources. This in turn influences the type of agriculture practiced and hence land use type. It generally affects the hydrological cycle over the catchment.

The temperature in Figures 18, 19 and 20 for minimum, mean and maximum temperatures respectively depicts a clear positive trend over all stations. The rates of change are in the range of about 0.4 as shown by Table 7. This indicates that temperature variables over the given stations are increasing in nearly a uniform rate. The trends of temperature are statistically significant. The findings by Omondi *et al.*, (2014) found out that temperatures in Kenya are generally increasing.

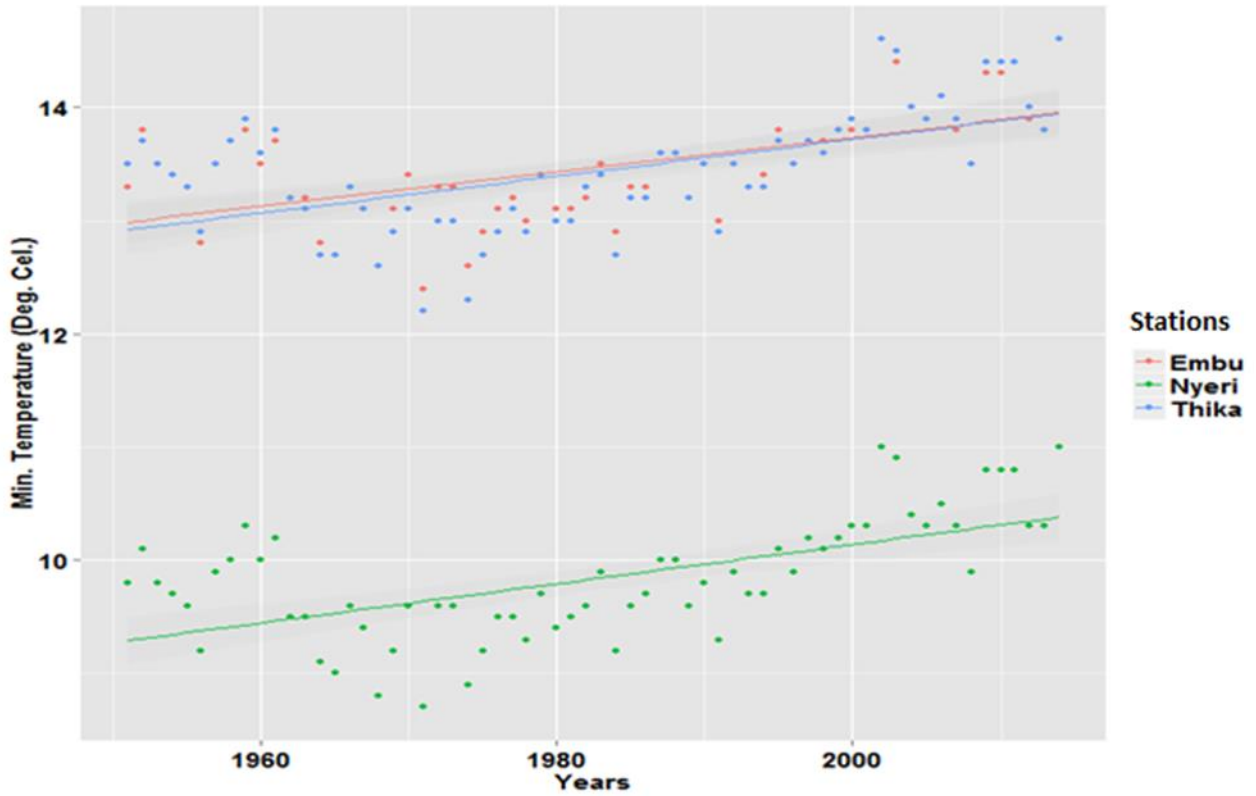


Figure 18: Trend analysis of the annual Minimum temperature for Embu, Nyeri and Thika for the period 1951-2014

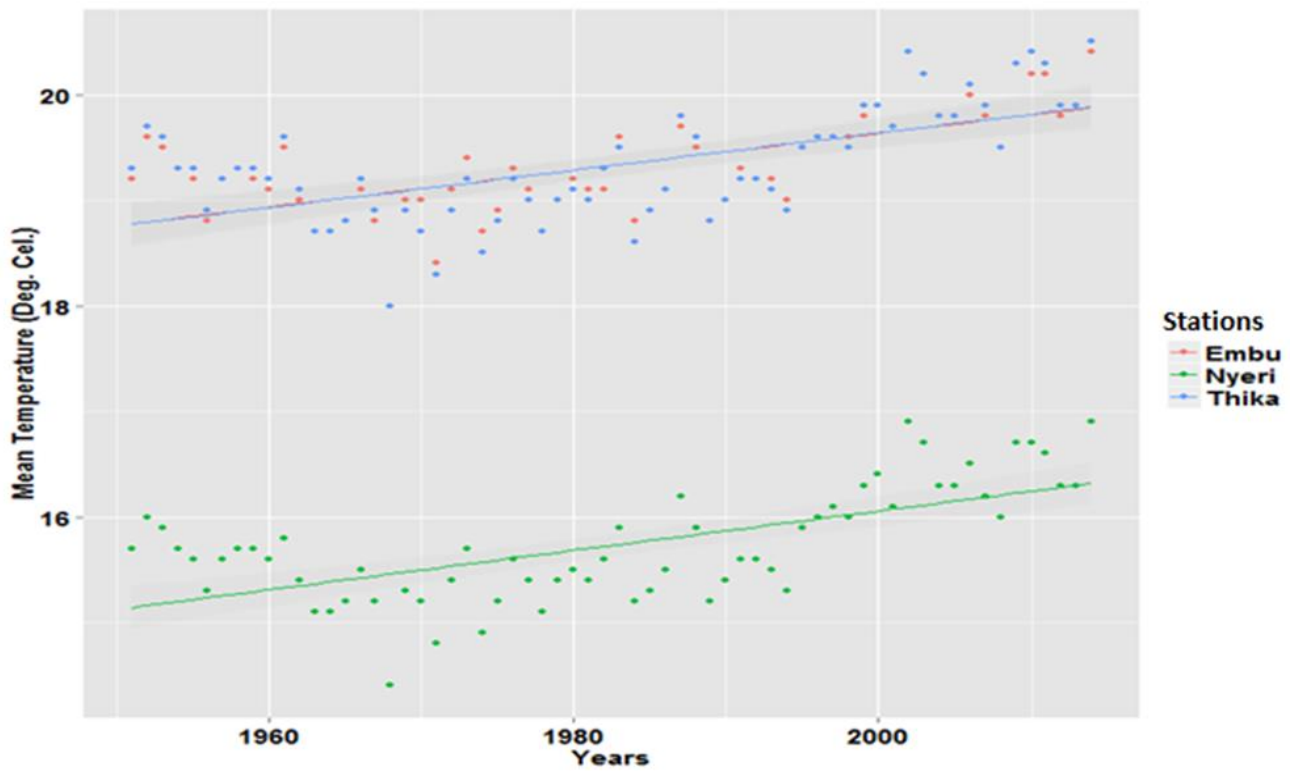
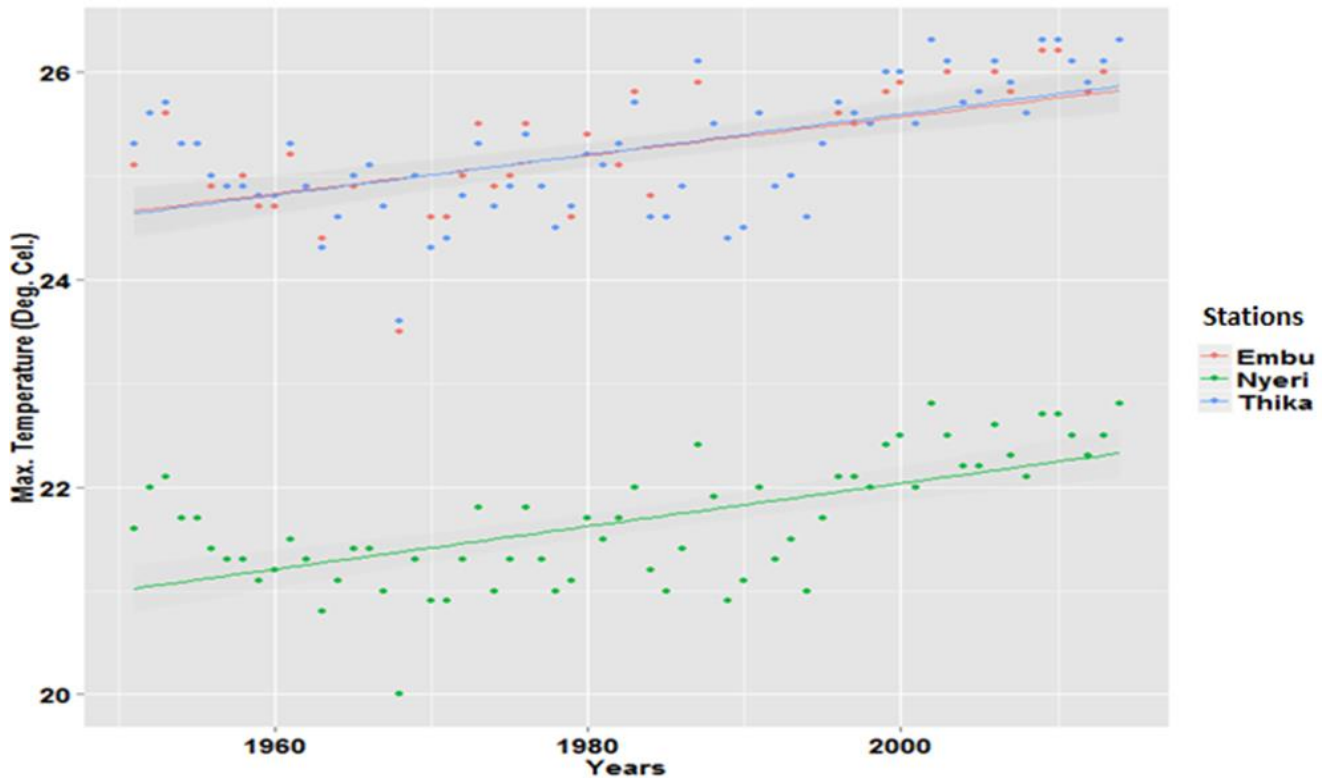


Figure 19: Trend analysis of the annual average Mean temperature for Embu, Nyeri and Thika for the period 1951-2014

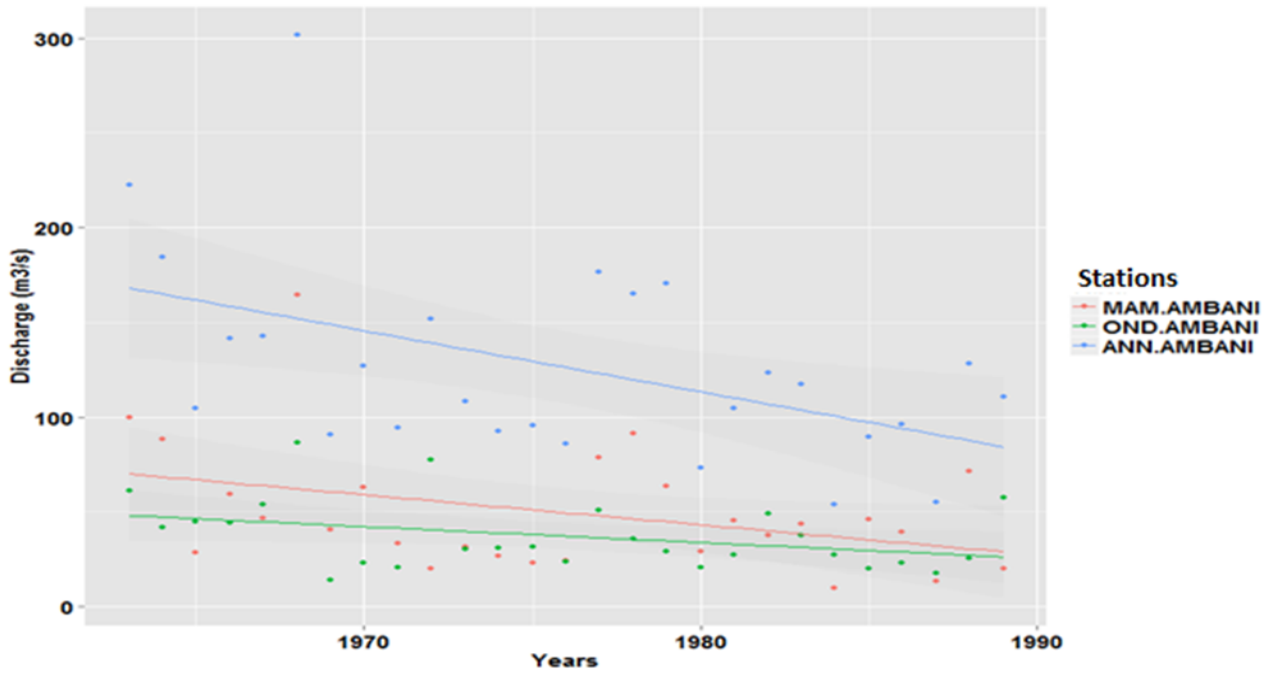




**Figure 20: Trend analysis of the annual average Maximum temperature Embu, Nyeri and Thika for the period 1951-2014**

A study by Bunyasi, (2012) also found out an increasing trend in the average mean temperature over the Upper Tana Catchment. It is worth to note that given the high rate of change, the impact of the increasing temperatures on both ecosystems and human activities may be sufficiently large. Water yields would be reduced by the increasing temperature which causes increased evapotranspiration rates. The rising temperature in the upper catchment coupled with decreasing precipitation trends would result into reduced water supply.

The discharge trends at the given gauging stations were also analyzed at seasonal and annual time scales. Over the Ambani River gauging station in Figure 21, discharge trends were decreasing for MAM, OND and annual analysis. The rate of decrease is however great for annual and least for MAM. During all time scales however; the trends were not statistically significant except for the annual analysis of the Ambani river gauge station as shown by Table 5.



**Figure 21: Trend analysis of the Discharge over the Ambani River gauge station for the period 1963-1990**

**Table 5: Trend in the Annual and seasonal discharge for the period 1963-1990**

Variables	tau	P-Value
MAM.AMBANI	-0.248	0.073
OND.AMBANI	-0.254	0.067
ANN.AMBANI	-0.297	0.032
MAM.MARAGUA	-0.174	0.211
OND.MARAGUA	0.06	0.677
ANN.MARAGUA	-0.145	0.297
MAM.SAGANA	-0.054	0.707
OND.SAGANA	-0.06	0.677
ANN.SAGANA	-0.054	0.707
MAM.THIBA	-0.017	0.917
OND.THIBA	-0.06	0.677
ANN.THIBA	-0.105	0.453
MAM.THIKA	-0.148	0.288
OND.THIKA	0.006	0.983
ANN.THIKA	-0.16	0.251

In Figure 22, the trends over Sagana River gauging station were decreasing over all timescales just like those over the Thika River gauging station in Figure 25. The trends over the Maragua River gauging station also showed a decreasing trend for MAM and the annual analysis while that of OND indicated no trend as shown in Figure 23. In Figure 24 which gave the analysis for the discharge in the Thiba River gauging station, the trends for MAM and OND indicated no trend, while a decreasing trend was shown in the annual analysis.

Bunyasi, (2012) and Onywere, (2013) found that inflows to Masinga reservoir which is served by the discharges from the analyzed river gauge stations in the area of study had a decreasing trend. Oludhe, (2011) also found that there exists a higher variability in streamflow during the OND season. Increasing temperature and decreasing amounts of rainfall are in line with depicted trends in the streamflow in the catchment.



**Figure 22: Trend analysis of the Discharge over the Sagana gauge station for the period 1963-1990**



Figure 23: Trend analysis of the Discharge over the Maragua gauge station for the period 1963-1990

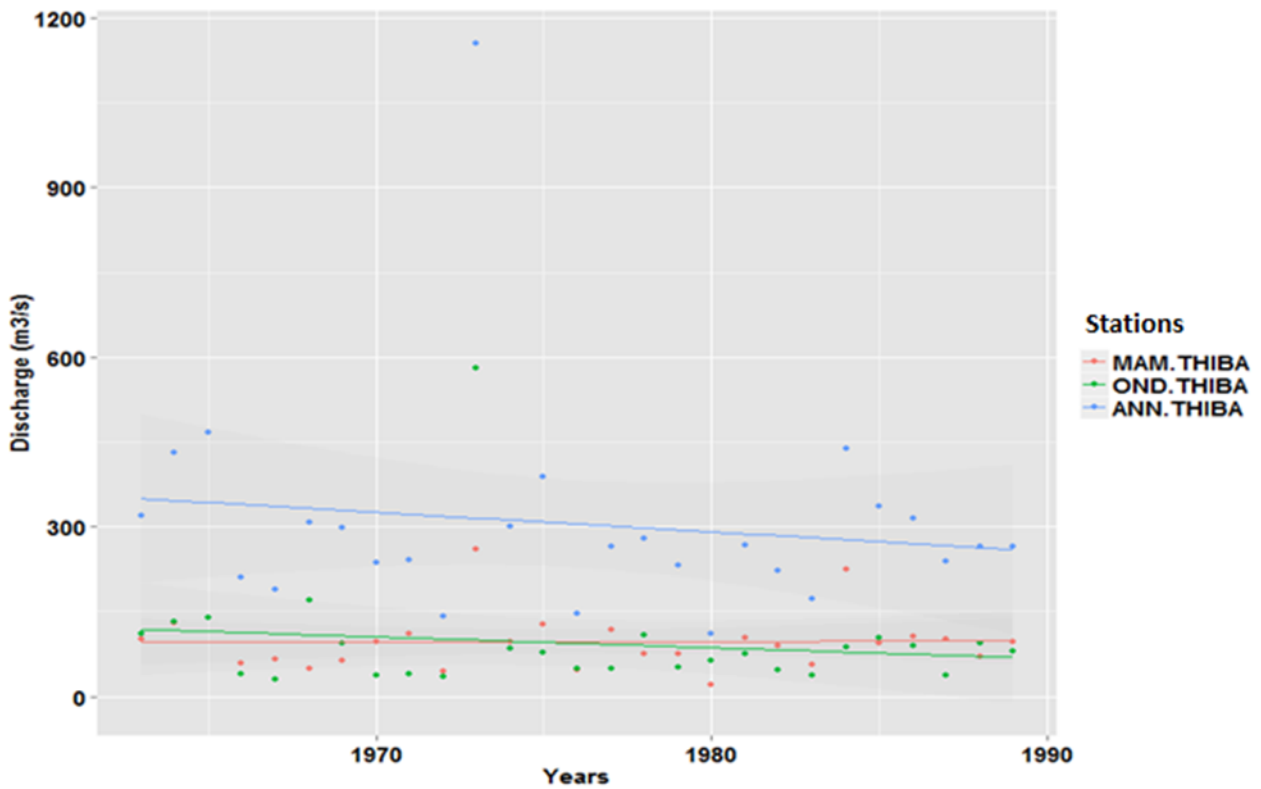


Figure 24: Trend analysis of the Discharge over the Thiba gauge station for the period for the period 1963-1990

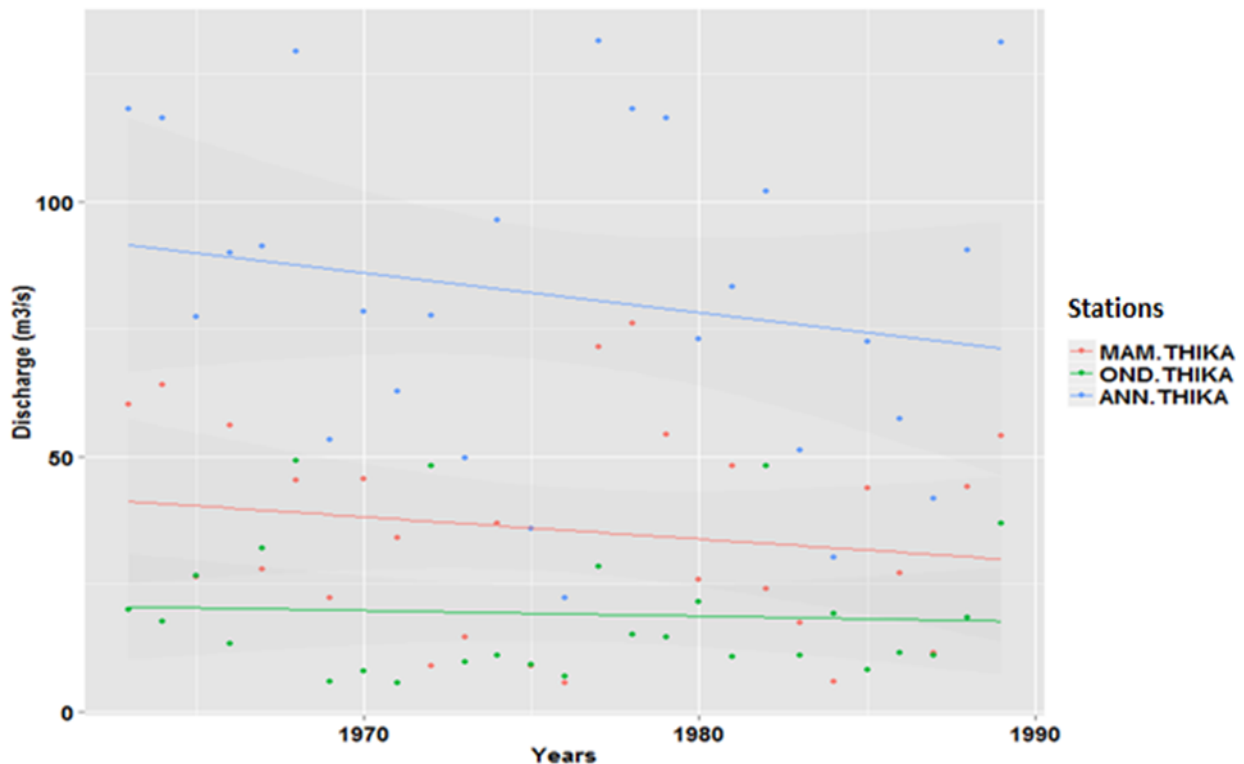


Figure 25: Trend analysis of the Discharge over the Thika gauge station for the period 1963-1990

#### 4.2.5 Evaluation of projected rainfall and temperature for the period 2021-2100 relative to base period 1995-2014

##### 4.2.5.1 Performance of the CODEX RCMs and the ENSEMBLE against observed data

Correlation analysis, box plot and cumulative distribution were used in the evaluation of the performance of the six models and their average in relation to the observed data. The results of the correlation analysis of the annual total rainfall over the Upper Tana Catchment are shown in Table 6 below. When the correlation value is +1, it denotes a positive linear relationship and if it is -1, it denotes a negative linear relationship. In the results, MIROC, MOHC and NCC showed a negative relation while CCCMA, MPI, NOAA and ENSEMBLE indicated a positive relation though in both cases the correlation was low. Using the correlation analysis method CCCMA, MPI and ENSEMBLE had the best data set which performed well against the observed.

**Table 6: Correlation analysis of the CORDEX RCMs, Ensemble of all RCMs and observed data for the period 1951-2005 over the study area**

Var1	Var2	value
CCCMA	OBS	0.44
MIROC	OBS	-0.11
MOHC	OBS	-0.25
MPI	OBS	0.47
NCC	OBS	-0.08
NOAA	OBS	0.25
ENSEMBLE	OBS	0.58

A box plot of the rainfall datasets was also plotted to investigate the distribution of rainfall as depicted by the models, the observed and the ensemble of the six models, Figure 26. The distribution of the observed data indicated that the annual total rainfall is distributed between 1000 and 1500 mm. This distribution was depicted by most of the models except the MIROC and MOHC. The position of the lower and the upper percentiles was not replicated by most of the models. The median value of the observed annual total rainfall was approximately 1250 mm which was also shown well by the MPI model. Using the box plot method, the MPI model replicated the observed dataset best. Figure 27 shows the analysis for the best performing model using a cumulative distribution. At this stage the MPI model data set was confirmed to replicate the observed annual total rainfall over the study area.

The performance of CORDEX RCMs in East Africa was also done by Endris *et al.*, (2013) it was found that multi-model ensemble models the rainfall over Eastern Africa well. Also Ouma, (2015) established that ensemble and the MPI had higher skill of simulating the observed rainfall over Turkana, Marsabit, Samburu and Isiolo counties.

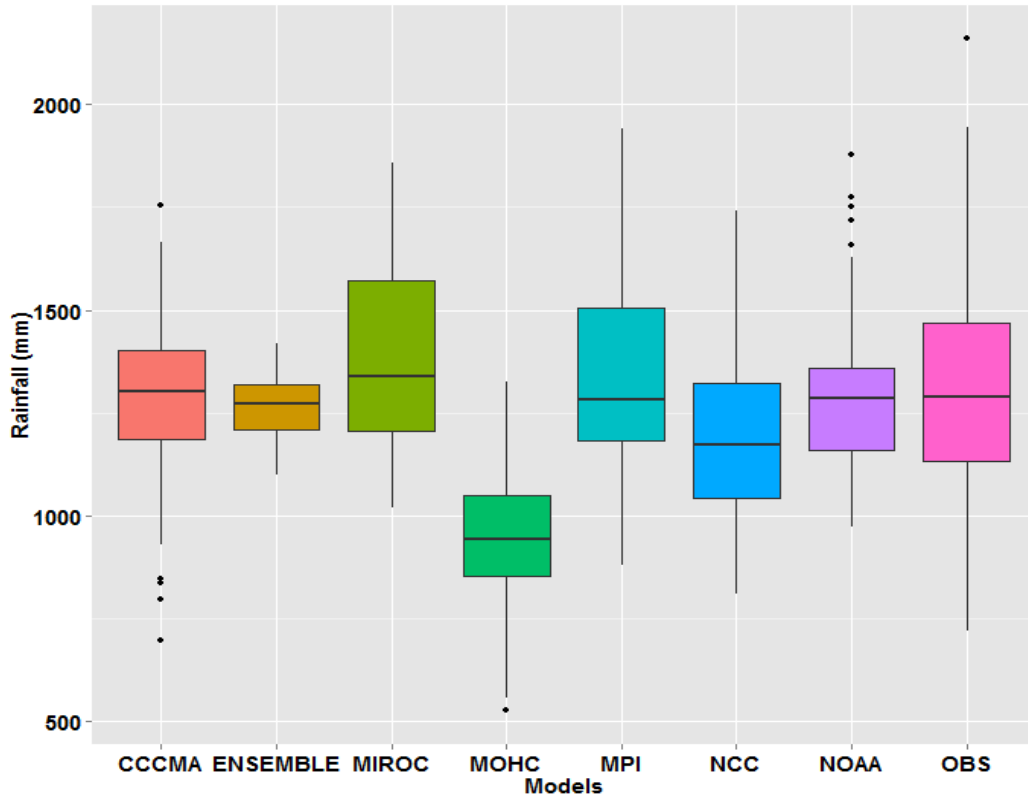


Figure 26: Boxplot of the CORDEX RCMs, Ensemble of all RCMs and observed data for the period 1951-2005 over the study area.

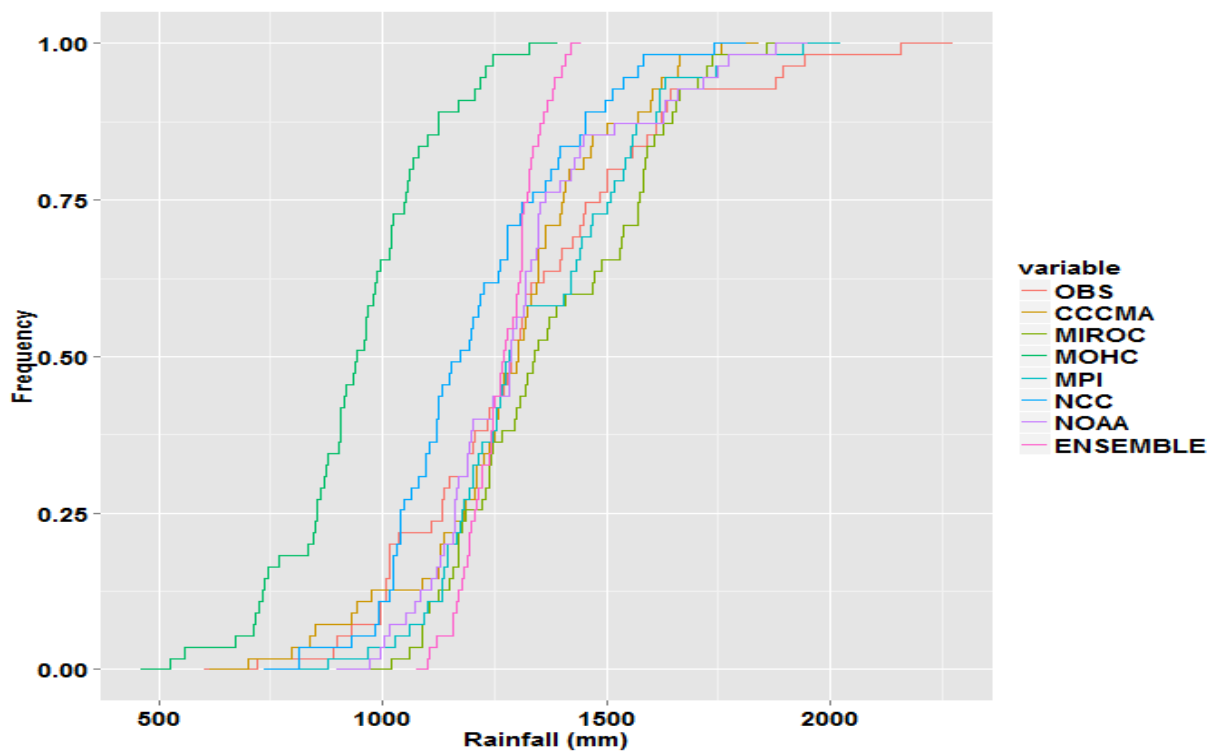


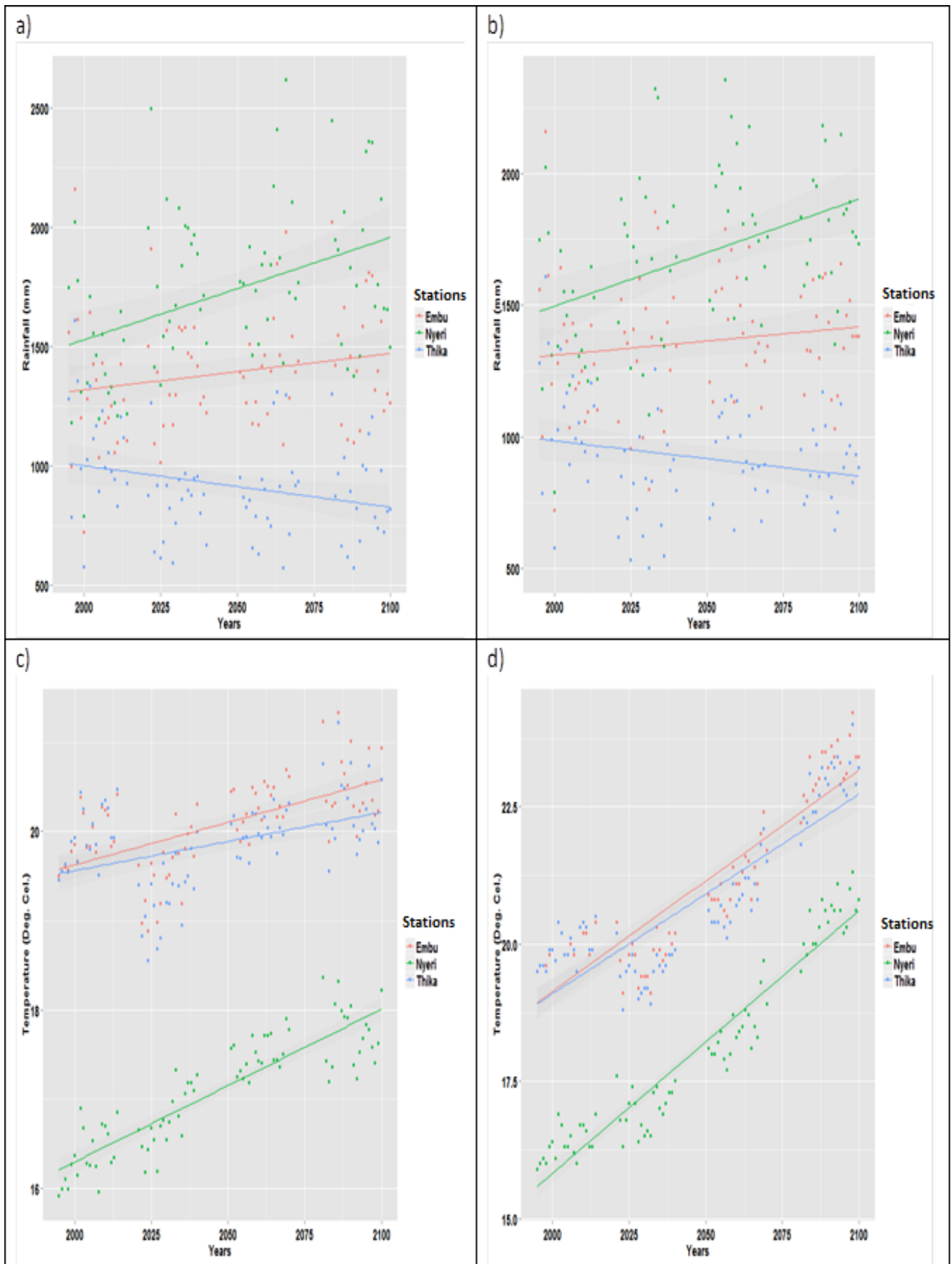
Figure 27: Cumulative distribution of the CORDEX RCMs, Ensemble of all RCMs and observed data for the period 1951-2005 over the study area.

#### **4.2.5.2 Future climate scenarios relative to the baseline period**

In this section the best model dataset was then subjected to trend analysis and Gaussian Kernel distribution methods. The future climate change scenarios of annual rainfall and temperature distribution for three future climatological periods (2021-2040, 2051-2070, and 2081-2100) for RCP 4.5 and RCP 8.5 relative to the baseline period 1995-2014 in Upper Tana Catchment were analysed.

The trend analysis for the future changes in annual rainfall and mean temperature using the non-overlapping climatic periods relative to the baseline period for Embu, Thika and Nyeri is shown in Figure 28. The trends in rainfall for RCP 4.5 and RCP 8.5 indicate an increasing trend in the Nyeri and Embu stations and a decreasing trend in Thika station. This has the implication that rainfall is generally increasing gradually over the catchment in both RCPs as shown in Figure 28 (a and b). Figure 28 (c and d) shows that the future temperature is also expected to rise at an alarming rate in both RCPs. However the rate of increase in temperature in RCP 8.5 is higher than that in the RCP 4.5.

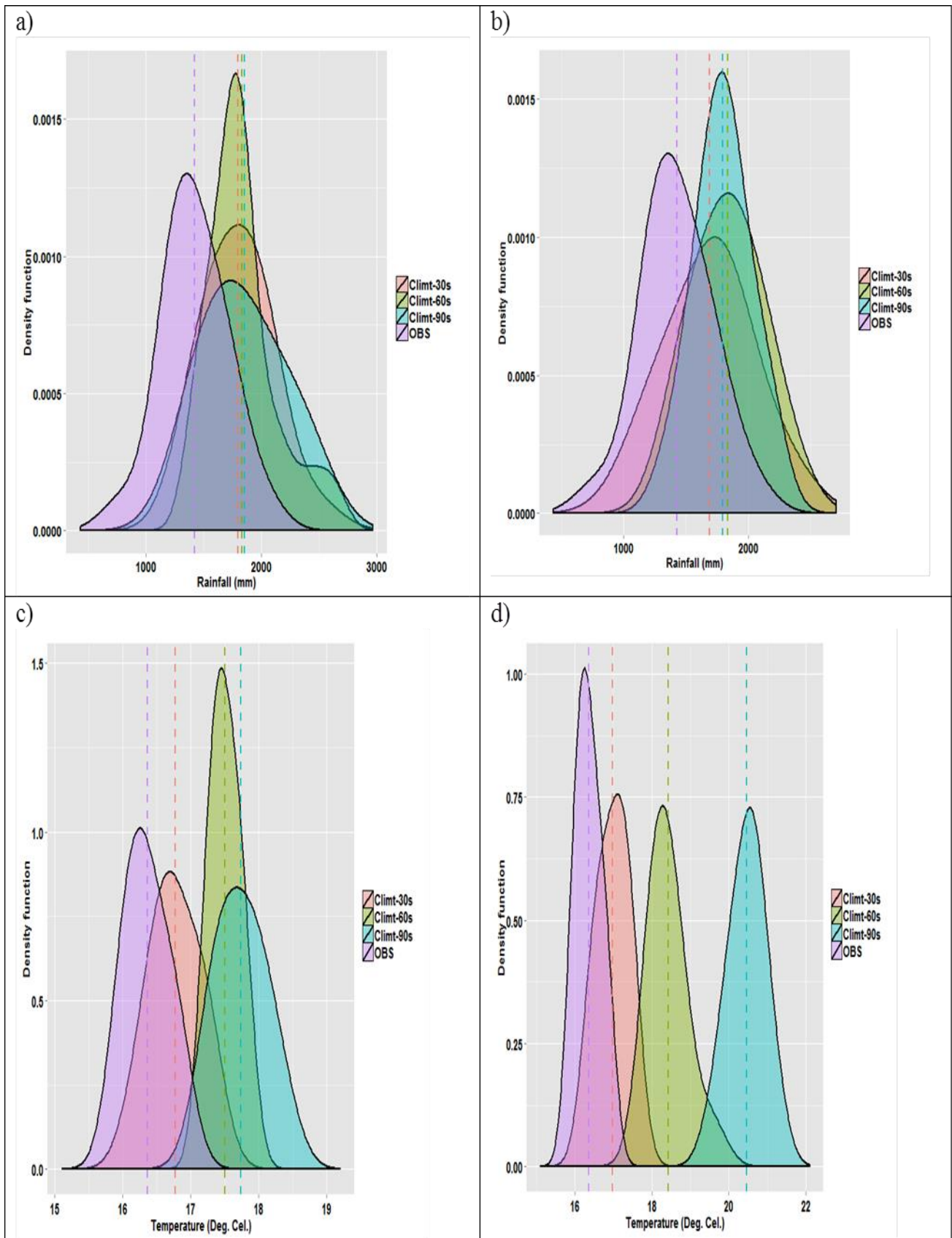




**Figure 28: Trend Analysis of Rainfall (a and b) and Mean Temperature (c and d) for the for RCPs 4.5 and 8.5 respectively over the study area**

In IPCC custom, a change in state of the climate identified statistically by changes in the mean of its properties and that continues for an extended period of more than a decade is referred to as climate change. In this study the change in mean was used in the analysis of the climate projections. Gaussian kernel distribution was used to analyze future changes in annual rainfall and mean temperature for climate in the 30's, 60's, and 90's using a baseline period from 1995-2014 of observed annual total rainfall.

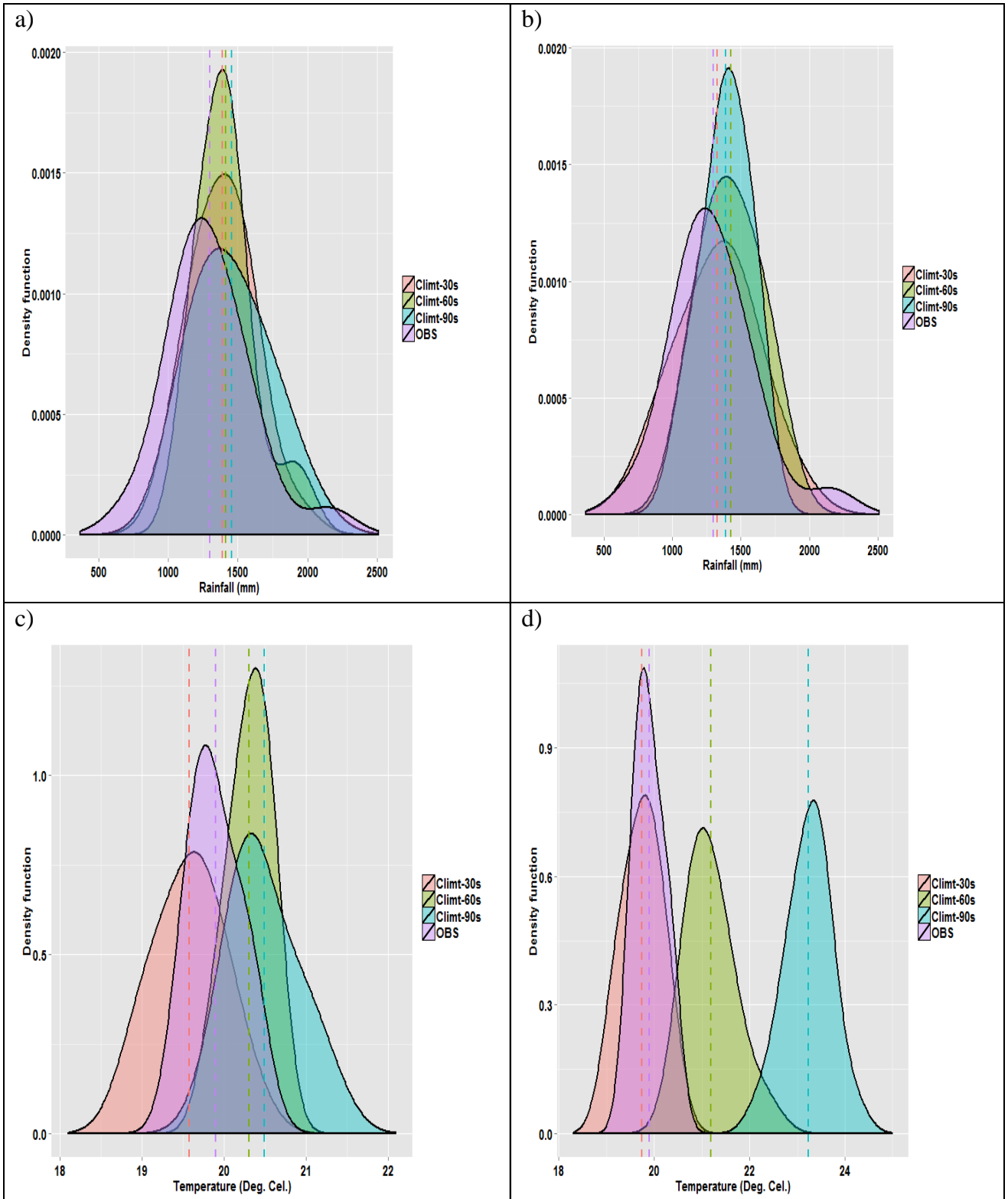
In Figure 29 (a and b) Results showed a general increase of about 30% in annual total precipitation for all the climatic periods for the two RCPs and annual average temperature increase of about 1°C for all the climatic periods for RCP 4.5 and in climate at 30's, 60's for RCP 8.5 Figure 29 (c and d). However, an increase of 3°C was shown in the climate at 90's for RCP 8.5. This change was relative to the baseline period over Nyeri station.



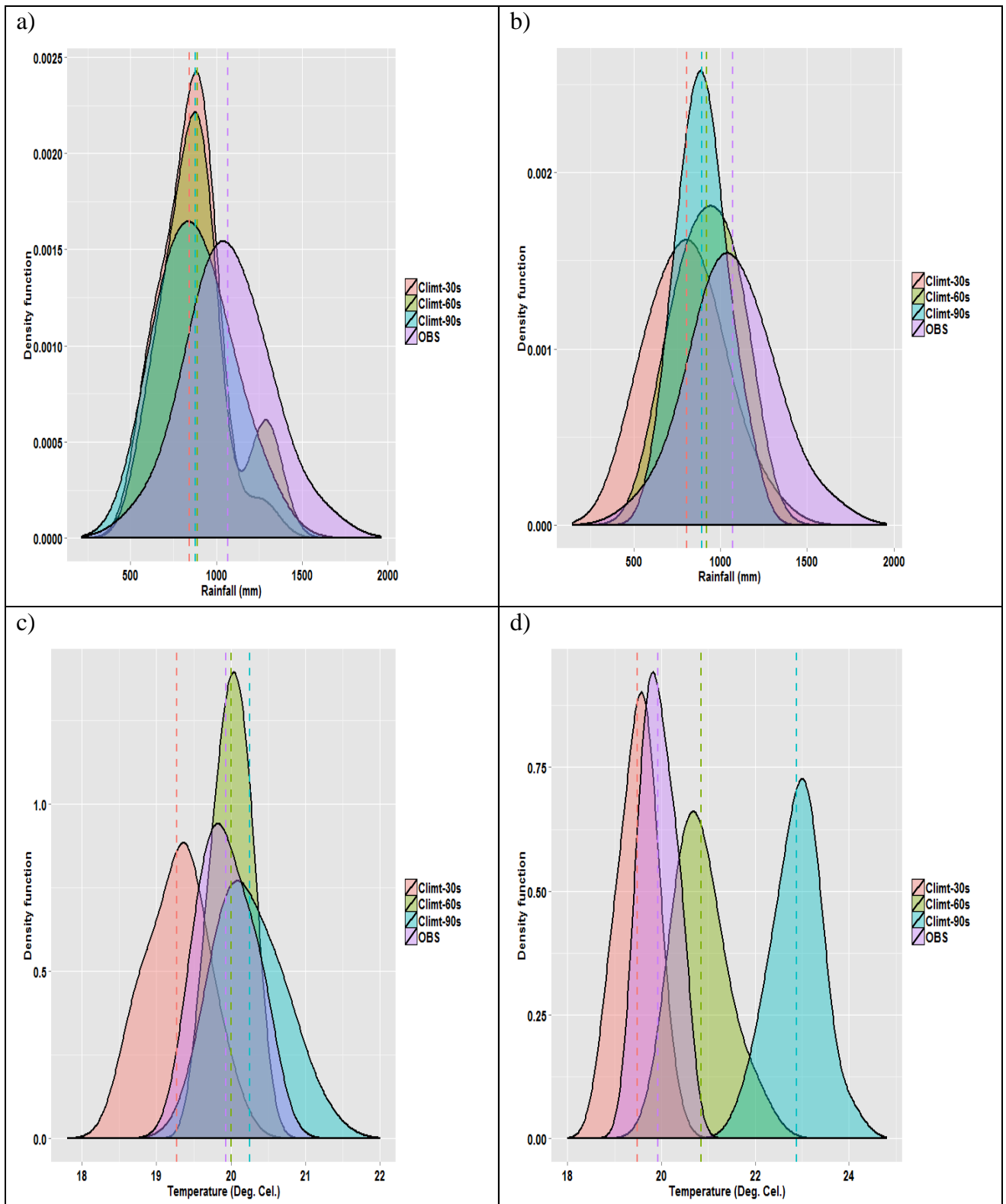
**Figure 29: Gaussian distribution of Rainfall for RCP4.5 (a) and RCP8.5 (b) and Mean Temperature for RCP4.5 (c) and RCP8.5 (d) for Nyeri station**

Over Embu station, relative to the observed annual rainfall an increase of about 10% for the two RCPs in all the climatic periods was observed as shown in Figure 30 (a and b), however, in Figure 30 (c and d) shows a decrease of about  $-0.5^{\circ}\text{C}$  in the annual temperature in the climate at 30's and an increase  $1^{\circ}\text{C}$  in the climate in 60's and climate in 90's for both RCPs.

Thika station on the other hand indicated general decrease of -20% in the annual rainfall for all the climatic periods in RCP4.5 and RCP8.5 relative to the baseline period as presented in Figure 31 (a and b). In Figure 31 (c and d) the annual temperature indicates a decrease of about  $-0.5^{\circ}\text{C}$  in the climate at 30's and an increase of  $2^{\circ}\text{C}$  in the climate in the 60's and 90's for the two climate change scenarios. Extreme weather events like droughts and floods, increased evaporation rates, low rainfall intensity, alteration in the rainfall seasons are some of the events related to climate change. Global warming effects are confirmed by increase in the catchment temperatures. Increasingly unpredictable weather patterns are as result of Climate change.



**Figure 30: Gaussian distribution of Rainfall and RCP4.5 (a) and RCP8.5 (b) and Mean Temperature for RCP4.5 (c) and RCP8.5 (d) for Embu station**



**Figure 31: Gaussian distribution of Rainfall RCP4.5 (a) and RCP8.5 (b) and Mean Temperature for RCP4.5 (c) and RCP8.5 (d) for Thika station**

## 4.2.6 Projected stream flow patterns under climate change scenarios for RCP4.5 and RCP8.5

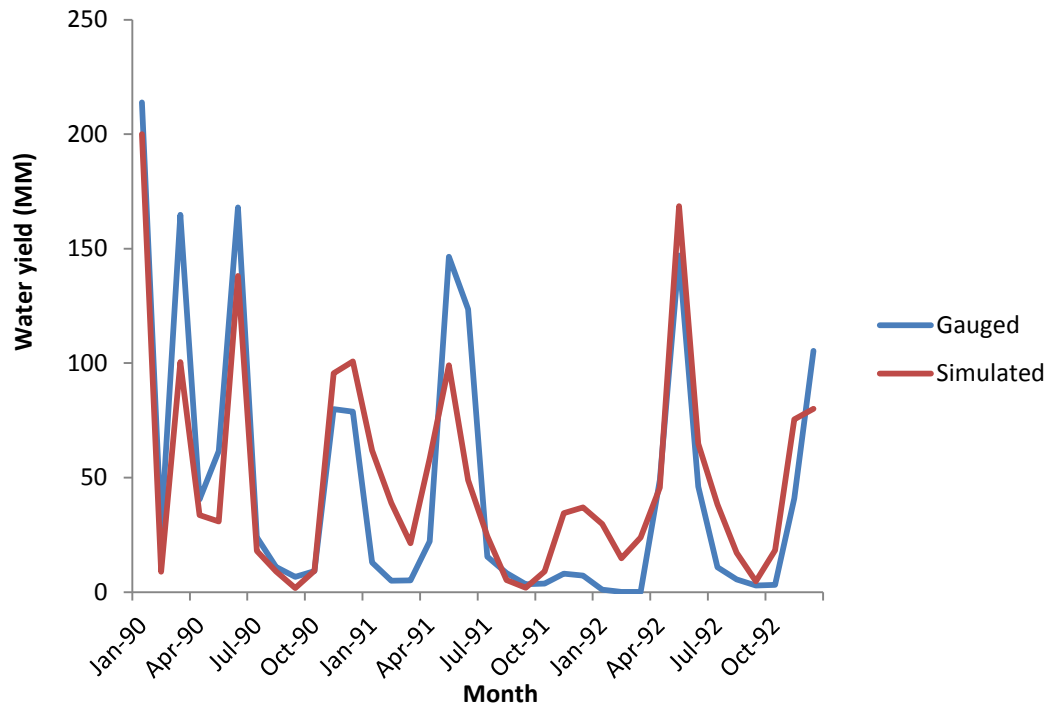
### 4.2.6.1 Hydrological modelling

Upper Tana Catchment resulted in 19 sub-basins and 59 HRUs from the watershed delineation and HRU definition with an area of 9625.208 km<sup>2</sup>. From the parameter estimation, the sensitivity values showed that Gw\_Delay (groundwater delay time), baseflow alpha factor (Alpha\_Bf), Groundwater “revap” coefficient (Gw\_Revap), CN2 (curve number for moisture condition-II), Esco (soil evaporation compensation factor) and Surlag (surface runoff lag coefficient) were most sensitive.

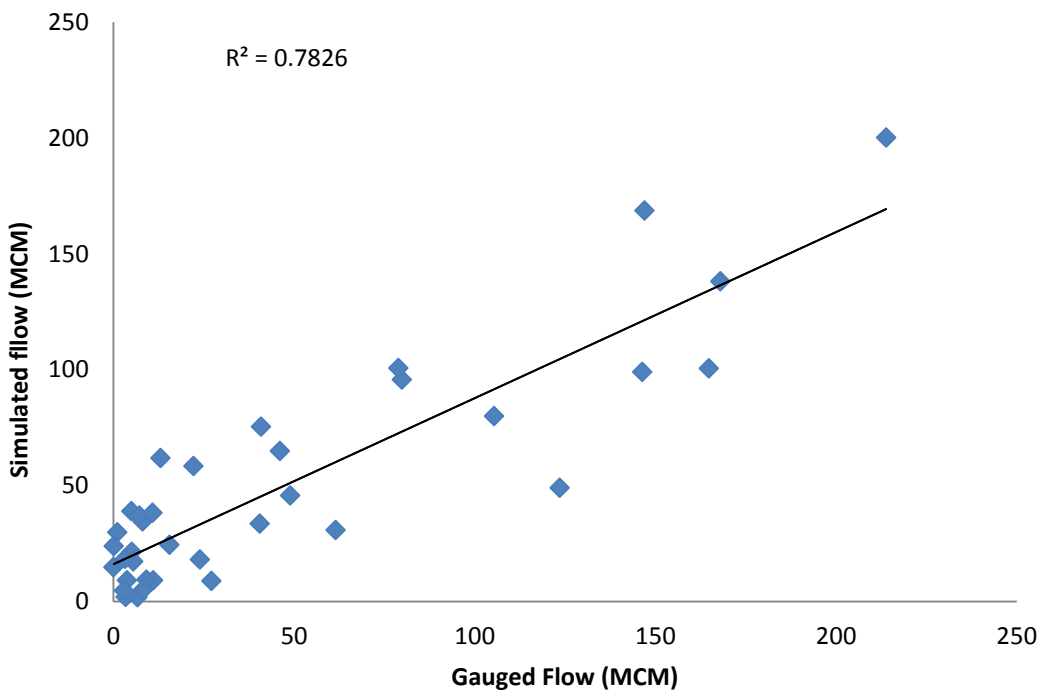
**Table 7: SWAT model calibration Parameters**

Parameter	Range
Gw_Delay	0-150
Alpha_Bf	0-1
Gw_Revap	0.0-21
Cn2	-20% - +20%
Esco	0-1
Surlag	0-20

Studies done using Coefficient of Determination ( $R^2$ ) consider a range from 0-1, with values greater than 0.5 usually considered acceptable (Geza *et al.*, 2009; Musau *et al.*, 2015). Figure 32 and 34 shows the results from the calibration and validation process respectively. A reasonable agreement was found to exist between monthly simulated stream flows and observed flows from the value of Coefficient of Determination ( $R^2 = 0.7826$ ) as indicated in Figure 33 for the calibration period. Results from the validation process also indicated ( $R^2 = 0.8708$ ) as shown in Figure 35. The model represents well the hydrological characteristics of the catchment as shown by the values of  $R^2$  results of the calibration and validation processes and therefore it was used for further analysis.

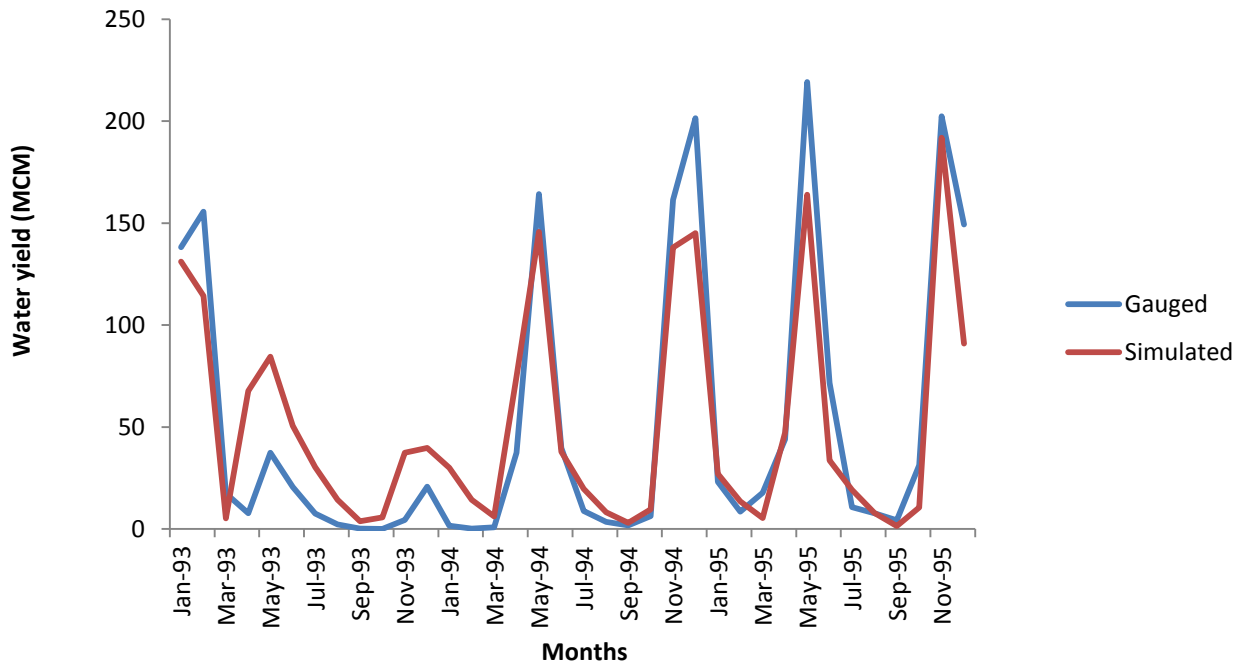


**Figure 32: Simulated and Gauged flows during the calibration period (1990-1992)**

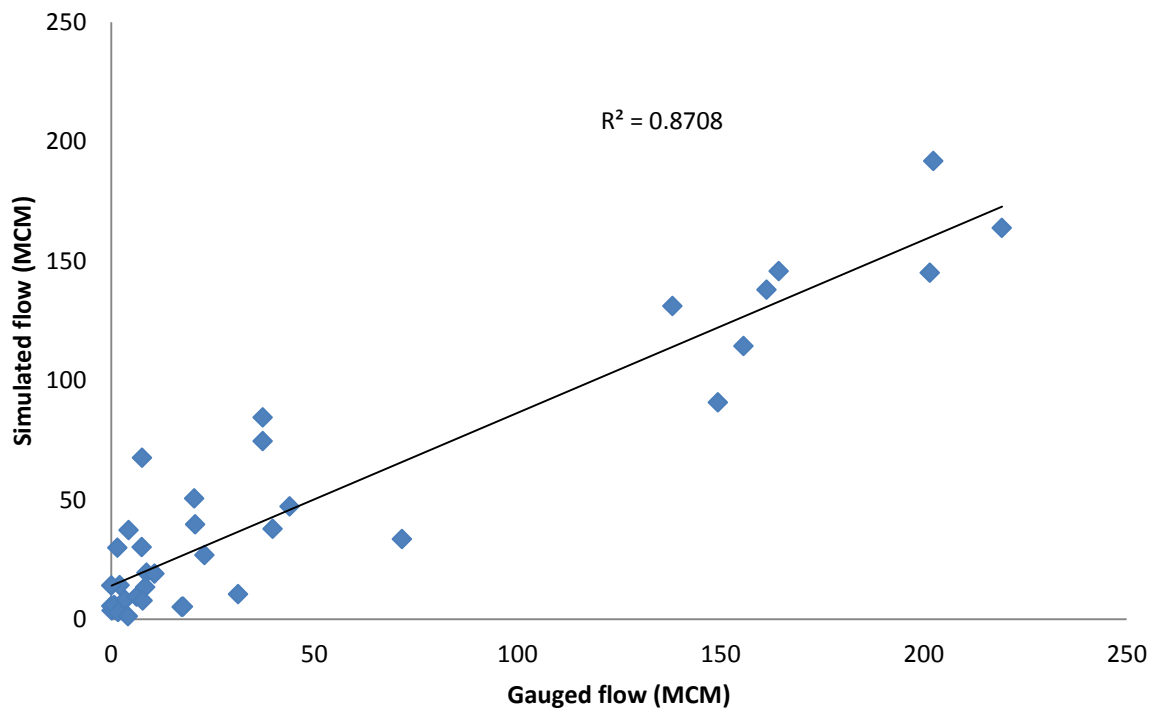


**Figure 33: Simulated and Gauged flows during the calibration period (1990-1992)**





**Figure 34: Simulated and Gauged flows during the Validation period (1993-1995)**



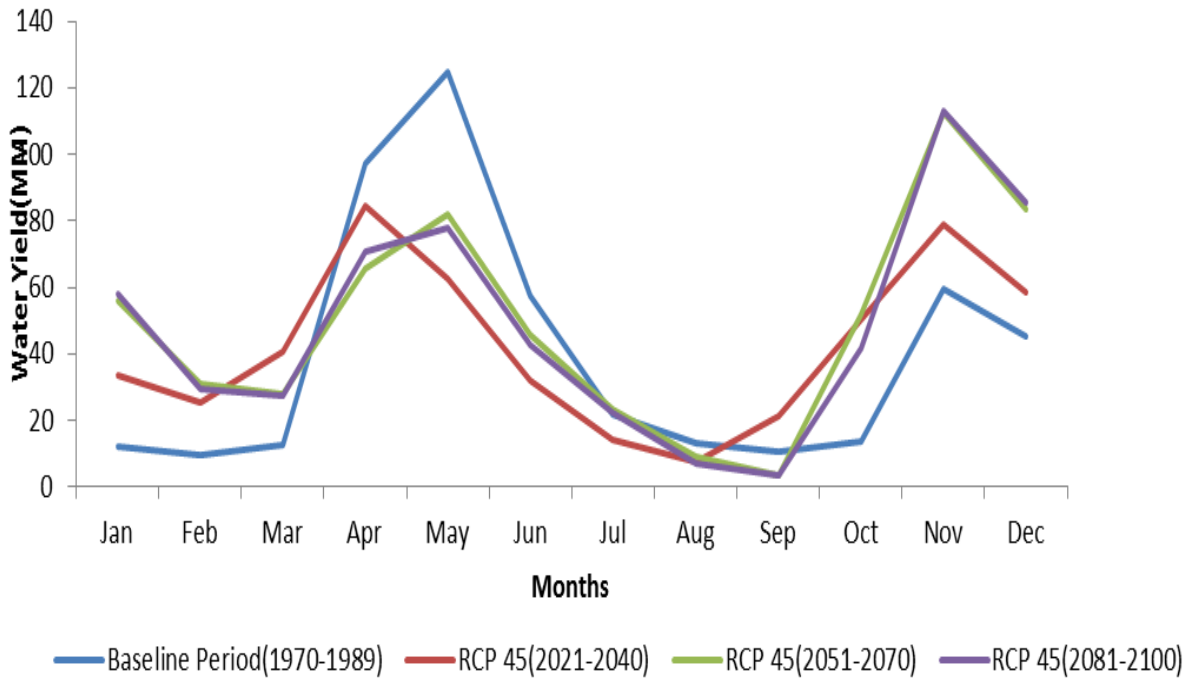
**Figure 35: Simulated and gauged flows during the Validation period (1993-1995)**

#### **4.2.6.2 Impacts of Climate change on water yields**

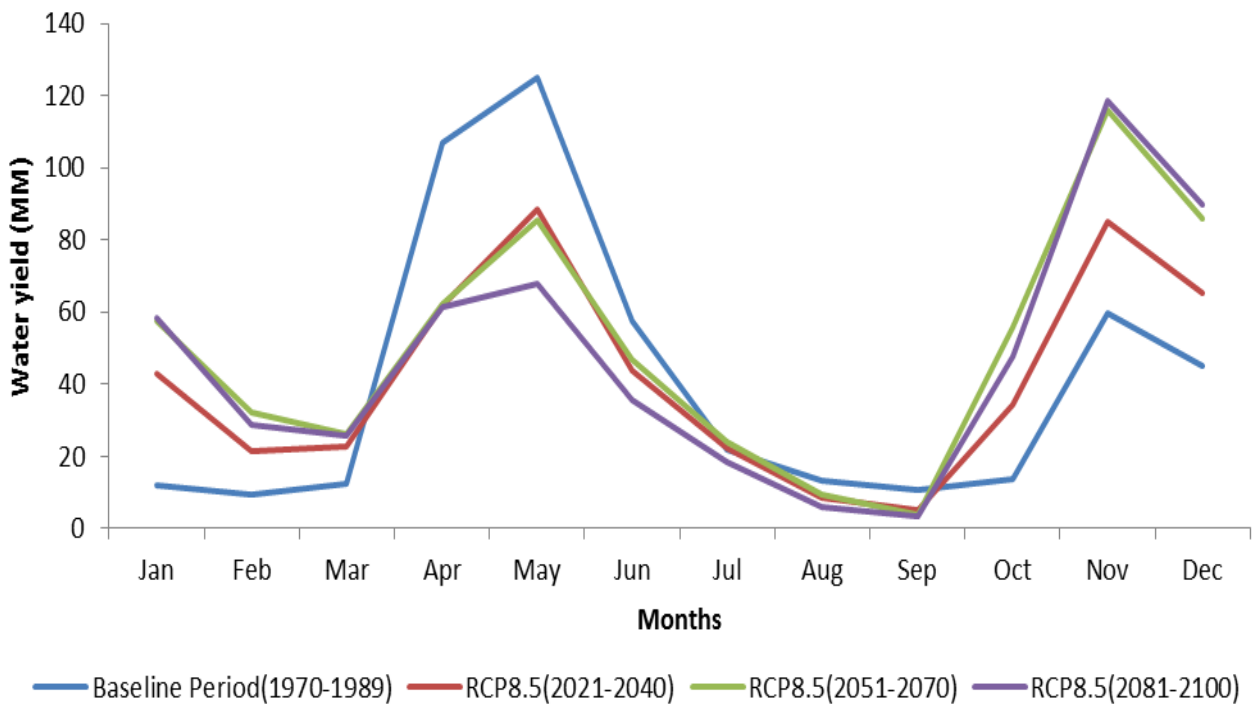
Due to the variations in the projected precipitation and temperature in both space and time different hydrological impacts are likely caused by the climate change. The impact of climate change on water yields was simulated based on the rainfall and (minimum and maximum) temperature changes on monthly basis. To assess how the water yields will be impacted by climate change over the upper Tana catchment, a baseline period of the period 1970-1989 for the observed river flows for the station 4ED03 was used. This was analyzed against the simulated future river flows for the period 2021-2040, 2051-2070 and 2081-2100.

Figure 36 shows an increase in the long term water yields for the three climatic periods relative to the baseline period in the months of January, February and March for the RCP 4.5 climate scenario. A decrease in the water yields for MAM rainfall season is depicted in all the climatic periods while an increase in the water yields in the OND rainfall season. The same tendency of decrease in the long term water yield during the long rains and an increase in the water yields in the short rains was also observed in the RCP 8.5 climate scenario for the three climatic periods as shown in Figure 37.

Due to variability in precipitation and temperature the impacts of climate change will affect the water yields in the long term. The river flows in the rainy seasons over the catchment are varied. This has implications on the quantity and quality of water, on the agriculture, in the energy production sectors and needs for the aquatic habitat.



**Figure 36: Baseline and simulated mean monthly Water yields for RCP 45 for 4ED03 Gauge Station**



**Figure 37: Baseline and simulated mean monthly Water yields for RCP 85 for 4ED03 Gauge Station**

## CHAPTER FIVE

### 5.0 Conclusions and Recommendations

The conclusion and recommendation of the study is presented in this chapter.

#### 5.1 Conclusions

From this study the distribution of precipitation and temperature shows temporal and spatial variations. Discharge volumes in any catchment are highly depended on the Precipitation, temperature and evaporation rates among other factors. The increase in rainfall does not necessarily lead to increased river flows because the increase in the temperature causes increase in the evapotranspiration rates. The current status shows that the rainfall trends have been gradually decreasing over the catchment and the temperatures have a significant increasing trend too. There exist a strong relationship between these climate variables and the water yields. This implies that the water resources over the catchment have been negatively affected by these changes as shown by decreasing trends in the river discharge.

The intensity of the climate change varies on spatial and also on temporal basis. MPI Regional Climate Model was found to replicate the observations quite well and was used in the future climate analysis. A significant increase in the future temperatures over the Upper Tana catchment for the two climate scenarios was observed. The future rainfall status also depicts an increasing trend in some stations and a decreasing trend in other stations for climate at 30's, 60's and 90's as compared to the base period 1995-2014.

Using SWAT model on the Upper Tana Catchment, the probable impacts of climate change on the water yields in the catchment were evaluated. The period 1990-1992 of the observed discharge was used for the calibration process of the model and 1993-1995 was used for the validation process. From the coefficient of determination used to test the suitability of the model to be used for further analysis, the SWAT model was found to capture well hydrological processes in the Catchment.

The trend in projected changes in precipitation dictates the projected changes in water yields. Projected changes in the water yields show high uncertainty during the short and long rains periods. These changes will certainly have implications on the social-economic development over the area, and will also impact on the water yields downstream.

## **5.2 Recommendations**

### **5.2.1 Recommendations to the water sector and policy makers**

The results of this study is a basis for informed decision in the water sector in terms of short and long term implementation of development projects and also strategic planning policies. These results can also be used in the water sector for water resources management and disaster risk reduction.

The results can be used by policy makers in understanding the vulnerability level of the Upper Tana Catchment to climate change impacts; this will help in coming up with suitable mitigation and adaptation approaches.

### **5.2.2 Recommendations to the researchers**

The use of an integrated hydrological modeling in impact assessment and the inclusion of other factors like land cover/land use changes and population increase that cause imbalance in the water should be enhanced in the Upper Tana Catchment.

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