DEMOCRATIC AND POPULAR REPUBLIC OF ALGERIA

Ministry of Higher Education and Scientific Research

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PAN AFRICAN UNIVERSITY

Institute for Water and Energy Sciences (Incl. Climate Change)

ASSESSING THE IMPACT OF CLIMATE CHANGE ON HYDROPOWER GENERATION IN KENYA

A Case Study of Upper Tana River Basin

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Master in ***Water Engineering track***

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A master research thesis submitted to the Pan African University in partial fulfillment for the requirements of the Master of Science Degree in Water Engineering of Pan African University Institute of Water and Energy Sciences (Including Climate Change)

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DECLARATION AND RECOMMENDATION

DECLARATION

I declare that this proposal is my original work, and that it has not been wholly or in part presented for award of any degree in any University known to me.

Signature: __________________________ Date: ______________________

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RECOMMENDATION

This proposal is the candidate's original work and has been prepared with our guidance and assistance. It is presented for examination with our approval as official University Supervisors.

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ABSTRACT

Hydropower is currently Kenya's second most dominant source of renewable electrical energy accounting for close to 49 per cent of power supply. The main source of hydropower in Kenya is the seven forks dams located in the Upper Tana river basin. Among the hydropower dams, Masinga Dam serves as a storage reservoir, controlling hydrology through a series of downstream hydro-electric reservoirs. The operation of Masinga dam is therefore crucial in meeting the power demands for the country, thus contributing significantly to the country's economy. The main resource for hydropower generation is runoff which hugely depends on precipitation. Temperature and precipitation effects from global climate change could alter future hydrologic conditions in the upper Tana River basin and, as a result, hydropower generation. This research thesis is therefore a study that aims to assess the changes in hydropower generation in Kenya as a result of the changing climate, with a focus on the seven forks hydropower project. A simple approach assumes that hydropower systems will reduce generation if water supply reduces, and vice versa. The study uses a 30-year climate data to establish the precipitation trend and runoff variations of the study area. Based on the runoff changes, hydropower generation is estimated by relating the runoff changes to hydropower generation potential. The ArcSWAT model has been used for runoff analysis and simulation. ArcSWAT ArcGIS extension is a graphical user interface for the SWAT model developed to predict the impact of land management practices on water, sediment, and agricultural chemical yields in large, complex watersheds with varying soils, land use, and management conditions over long periods of time. The model is physically based and computationally efficient, uses readily available inputs and enables users to study long-term impacts. The results show that climate change is affecting the stream flow of the Upper Tana basin and hence leading to reduction in hydropower generation due to reduced or increased reservoir storage.

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ABBREVIATIONS

IPCC	Intergovernmental Panel for Climate Change
GHGs	Green House Gases
CC	Climate Change
NEMA	National Environment Management Authority
WRMA	Water Resources Management Authority
KMD	Kenya Meteorological Department
WRI	World Resource Institute
SWAT	Soil and Water Assessment Tool
MT	Mount
KPLC	Kenya Power and Lightening Company
MW	Megawatts
GWh	Gigawatt hours
HEP	Hydro-electric Power
CEC	Cation exchange capacity
CERF	Central Emergency Response Fund.

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CHAPTER ONE

INTRODUCTION

1.1 Background information

Climate change refers to a change in state of the climate that can be identified by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer (IPCC, 2007). Climate change already affects physical processes in many parts of the world, leading to changes in temperature and rainfall patterns, in wind direction and increased intensity and frequency of extreme events like droughts, floods and cyclones (Trenberth *et al.* 2007). Climate change may be due to internal processes and/or external forcings. Some external influences, such as changes in solar radiation and volcanism, occur naturally and contribute to the natural variability of the climate system. Other external changes, such as change in the composition of the atmosphere that began with the industrial revolution, are the result of human activity.

Climate change is one of the world's greatest challenges of the 21st century, there is unanimous consensus in the scientific community that the world is going to get warmer in the future and the average weather patterns are expected to take a major shift (Godbole, 2014). A more variable climate is expected to be a direct result of increase in atmospheric concentrations of greenhouse gases resulting from human activities (Pilesjo and Al-Juboori, 2016). Unequivocal evidence from in situ observations and ice core records shows that the atmospheric concentrations of important greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) have increased over the last few centuries (IPCC, 2013). Carbon dioxide and many other greenhouse gases occur naturally in the atmosphere and are important in keeping the earth warm. Anthropogenic sources of greenhouse gases have increased since the industrial revolution which has resulted into a significant increase in greenhouse gases concentrations in the atmosphere, this trend is expected to continue over the next century which will result into major rise in temperature greater than any time in the past (Pilesjo and Al-Juboori, 2016).

Climate change is viewed as a critical factor in water resources availability due to the fact that it has a direct interrelation with hydrology. Major attributes of climate change include temperature rise reducing flora and fauna resources and change in rainfall intensity and runoff trends exacerbates water stress. This heightens global fresh water resources distribution which varies greatly in space and time due to the unreliable and erratic spatial-temporal distribution (Bunyasi *et al.*, 2013). Knowledge about flow regime in river basins has a capital importance for a variety of practical applications, especially for watershed management and water sustainable use. The hydrological regime plays a crucial role in determining the biotic composition, structure and function of river basins. A full understanding of surface water availability and seasonality should drive us towards a rational use of the water resource, aimed to satisfy anthropogenic needs, warranting, at the same time, sufficient resources to support ecosystems services (Pumo *et al.*, 2016).

Changes in the hydrological cycle due to climate change can lead to diverse impacts and risks, and they are conditioned by and interact with non-climatic drivers of change and water management responses. Water is the agent that delivers many of the impacts of climate change to society, for example, to the energy, agriculture, and transport sectors. Even though water moves through the hydrological cycle, it is a locally variable resource, and vulnerabilities to water-related hazards such as floods and droughts differ between regions. (IPCC, 2014). Information on stream flow can be used to predict surface runoff, reliable prediction of surface runoff from rainfall in a catchment is essential for several purposes in watershed management. Prediction of both volume and rate of runoff from a watershed is vital in the design of hydraulic structures including soil and water conservation, rainwater harvesting, flood control and hydroelectric power generation structures (Obiero *et al.*, 2011).

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Over the past decade, the assessment of climate change impacts on water resources has been a major research effort. Climate change is expected to affect the hydrological cycle, and consequently, water balances and local water supplies. Predicting water availability under changing climatic conditions and hydrological variations, for both short-term and long-term, are essential for many social, economic and environmental sectors such as agriculture, industry, and biodiversity conservation (Li, *et al.*, 2016). Climate change can cause significant impacts on water resources by resulting changes in the hydrological cycle. For instance, the changes in temperature and precipitation can have a direct consequence on the quantity of evapotranspiration and on both quality and quantity of the runoff component. Consequently, the spatial and temporal availability of water resources, or in general the water balance, can be significantly affected which in turn affects agriculture, industry and urban development.

The hydrologic system, which basically consists of the circulation of water between the oceans and the atmosphere is an essential part of the global climate system. Changes in global climate are believed to have a significant impact on hydrological regimes and also bring about significant changes in severity and frequency of droughts and floods. Snows and glaciers in Mount Kenya and Kilimanjaro which acts a major water towers are quickly receding due to continued rise in temperatures in the past century, the changing temperatures have been attributed to climate change (Droogers, 2009). Climate change has also led to decreased river flows especially during the dry seasons which has severely affected hydropower generation across the country (Bunyasi, 2012).

As the evidence for human induced CC becomes clearer, so too does the realization that its effects will have impacts on socioeconomic systems and terrestrial ecosystems (Maran *et al.*, 2013). An increasing number of evidences of glacier retreats and snowfall decrease have been observed in many mountainous regions in these years, thus suggesting that climate modifications may seriously affect stream flow regimes, in turn threatening the availability of water resources useful to agriculture, forestry, tourism, and hydropower generation.

Hydropower, largely considered as a clean renewable energy source, has provided many economic and social benefits to many countries in the world, such as improving domestic energy supply, providing energy security and services, stimulating national economic development, and increasing economic growth. Hydropower is the main form of renewable source of energy world over and is increasing, the world's hydropower installed capacity and output increased by over 5.3 % from the year 2009 to 2010 (Hamududu and Killingtveit, 2012). Hydropower supplies about 50% of electricity in 66 countries and 90% in 24 countries globally. In Africa, it's recorded that the effects of climate change are severely affecting hydropower plants especially in areas that experience low annual rainfall (Bunyasi *et al.*, 2013). Hydropower generation makes a substantial contribution to today's world electricity demands and it is the main form of renewable source of energy over the world. Hydropower accounts for 49% of installed electricity capacity in Kenya with almost all hydropower being generated by the seven forks scheme (Droogers *et al.*, 2006).

The IPCC in its AR4 report concluded that climate change is occurring faster than earlier reported. Many future climate scenarios point to the fact that the climate is changing rapidly although there are many arguments over the causes of these changes. Climate change will result in changes in various river flow conditions such as timing and quantity, sediment load, temperature, biological/ecosystem changes, and fish responses. Climate change and the resulting changes in precipitation and temperature regimes will affect hydropower generation. It is reported that hydropower systems with less storage capacities are more vulnerable to climate change, as storage capacity provides more flexibility in operations (Kumar *et al.*, 2009). Although hydropower systems may benefit from more storage and generation capacity, expansion of such capacities may not be economically and environmentally justified. These changes would affect hydropower generation in all regions of the world. Given the significant role of hydropower, the assessment of possible impacts of climate changes on regional discharge regimes and hydropower generation is of interest and importance for management of water resources in power generation.

Hydropower generation is progressively becoming susceptible to climate change related events and resultant processes like reduced reservoir storage capacity due to siltation (Walling, 2008). Climate change has led to more pronounced droughts in the past years which has led to decreased river flows especially during the dry seasons which has severely affected hydropower generation across the country. In addition to its impacts on snow and glacier, the continued rise in temperature have also increased the direct evaporation rates from the hydropower water reservoirs which is negatively affecting power generation. (Bunyasi, 2012)

Simulating the impact of climate change on runoff has been realized in recent years. By applying projected climate scenarios into a validated hydrological model, hydrologists could assess potential variation tendencies of flow components in the future. However, the nature is a multi-component system, so the variations concern with this system is regularly complicated and difficult to predict accurately. Evidently, this work contains several sources of uncertainty. The uncertainty depends on both climate data and simulated hydrologic regimes (Duong Vo *et al.,* 2015).

This research thesis therefore, by applying a calibrated and validated physically based hydrological model over the upper Tana basin (UTB), seeks to identify the effects of climate change on hydrology of the UTB in eastern Kenya. This is achieved through examining the streamflow changes in the basin and possible changes in reservoir storage as a direct impact of rainfall variability and increasing temperatures in the region and hence establish the expected changes in hydropower generation.

1.2 Statement of the Problem

Atmospheric concentrations of greenhouse gases have been increasing rapidly over the decades (IPCC, 2007). This increase has been mainly attributed to human activities. The composition f of the atmosphere has thus changed and the change is expected to continue in the future. Changes in atmospheric concentrations of greenhouse gases are capable of affecting the earth's surface climate and can have possible consequences on both man-made and natural resources and there by affecting the well-being of humans through its impact on important sectors such as health, transport, agriculture, industry, energy and water resources.

Hydropower is the main form of renewable source of energy world over. In Kenya, the effects of climate change are severely affecting hydropower plants especially in areas that experience low annual rainfall. Lack of adequate water in river flows especially during dry season is severely impacting hydropower generation, leading to either reliance on diesel power or power rationing which adversely affects environment and distracts investment plans and economic growth. Modern developments, changing life styles and population growth have greatly increased water demand. With a forecasted future water crisis, meeting the water demands of the increasing population in the Upper Tana basin is closely tied to understanding and the development of surface water resources in order to prevent their depletion. Climate change is putting further constraints on the water resources because of changes in spatial and temporal distribution of rainfall received in the area. Therefore, there is a need to assess the impact that climate change will have on water resources which is critical in evaluating future risks of droughts, floods, threats to food security, and the reliability of hydropower generation.

Kenya's National electricity peak demand is growing fast from 1,072 MW in 2008/2009 to 1,173MW in 2009/2010 and 1,191 MW in 2012 (GoK, 2011; GoK, 2009). Kenya lacks sufficient power generation reserve margin to meet its ever rising national power demand. To meet its increasing energy demands, Kenya is heavily relying on diesel power. Diesel generators are both expensive and subjective to global fuel prices fluctuation, and have severe environmental effects. Due to this Kenya's electricity tariff is about 15 US cents per kWh while other tariffs in the region are at as low as 5.0 US cents per kWh (GoK, 2009) disadvantaging Kenya regionally.

Hydropower generation depends on availability of water, which in turn depends on the prevailing climate. Fluctuations in temperature and rainfall can affect evapotranspiration rates which in turn can determine the stream flow and hydropower generation. Effects of climate change can bring a significant impact on water resources by causing changes in type, quantity and the timing of precipitation. These precipitation changes have a direct impact on the quantity and duration surface runoff and stream flow, which has in effect a direct relation to the amount of water available in hydroelectric dams. For better planning, it is important to understand how the changing climate will impact on the hydropower generation and energy potential of Kenya. This study therefore focuses on the impacts of climate change on the water resources and hydropower generation in Kenya.

1.3 Objectives

1.3.1 Broad objective

The broad objective of this research is to assess the impact of climate change on stream flow in the upper Tana basin and simulate its consequent impact on hydropower generation.

1.3.2 Specific objectives

i. To determine the temperature and precipitation trends in the upper Tana river basin from 1983 to 2013.
ii. To determine the river flow regime from 1983 to 2013 for upper Tana River basin.
iii. To determine the relationship between river flow regimes and hydropower generation.
iv. To simulate future river flow regimes and assess their impact on hydropower generation using the ArcSWAT model.

1.4 Research questions

The study is designed to address the following research questions which will be explored throughout the thesis:

i. How has temperature and precipitation of the upper Tana river basin changed between 1983 and 2013?
ii. How is the river flow regime for upper Tana River basin from 1983 to 2013?
iii. What is the impact of river flow regime to hydropower generation in the upper Tana basin?
iv. What are the expected future impacts of climate change on hydropower generation in Kenya?

1.5 Scope of Study and limitations

The study aims to fulfil the objectives through literature review on climate change and its impacts on river flow regime and hydropower generation studies. A particular study area in Kenya has been selected and meteorological and hydrological data collected. The selected study area is the upper Tana river basin with an estimated surface area of 12,500 square kilometers. The meteorological data included the precipitation and temperature records from different recording stations across the study area while the hydrological data included the stream flow and stage at several gauging stations along the river Tana and its tributaries. Analysis was done on the quality of the data and a method developed to fill missing values. A rainfall runoff model was selected for the study and any other data required to set the model acquired, finally the model was calibrated and validated and then used to compute streamflow scenarios for the future. Based on the results, a correlation between river flow regime, climate change and hydropower generation was established.

The limitation of this study is that meteorological and gauging stations are not uniformly distributed throughout the catchment area and therefore assumptions have been made and trial-error methods adopted where necessary. This study also focuses majorly on the impacts of climate change without analyzing in depth the impacts of land use, population change and sedimentation which could also affect the river flow regimes and reservoir capacity in the study area.

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CHAPTER TWO

LITERATURE REVIEW

2.1 Climate and climate change

Climate is defined as a statistical description of weather of a region in terms of its mean and variability of the parameters, for example temperature and precipitation over a long period of time of that region, typically 30 years (Harvey *et al.*, 1997). On the other hand, The United Nations Framework Convention on Climate Change (UNFCCC), defines climate change as the change observed over comparable periods in composition with the global atmosphere in addition to the natural variability. This change is mainly due to direct or indirect human activity. Climate change is caused by emissions of greenhouse gases into the atmosphere mainly through human activities disrupting atmospheric balance and global warming and heating of the earth's surface.

A large amount of observations gives a picture of global warming and other changes in the climate system. Changes in the climate occur as a result both of internal variability within the climate system and external factors (both natural and anthropogenic). The major influence of external factors is related to the increasing concentrations of greenhouse gases which affect the atmospheric absorption properties of longwave radiation, thereby leading to increased radiative forcing that tend to warm the lower atmosphere and the earth's surface (Solomon *et al.*, 2007).

The increase in atmospheric temperatures due to emissions of greenhouse gases (GHGs) has led to global warming. According to IPCC (2007), the warming is not only unequivocal, but it is increasingly clear that most of the warming that has occurred over the last 50 years is due to anthropogenic causes. As a result, significant changes in physical and biological systems are occurring on all continents and in most oceans (Rosenzweig *et al.*, 2008). The GHGs form an invisible film over the atmosphere which traps heat leading to increasing atmospheric temperatures and global warming. This has triggered change in climate which has become a major challenge to human existence and survival. The largest contributors of GHGs include carbon dioxide and water vapour (NEMA, 2013). Climate change is caused predominantly through human induced activities especially the combustion of fossils fuels, deforestation to support both agriculture and settlements and other land use changes. It is estimated that the concentration of carbon dioxide has increased in the atmosphere from 270 ppm to 370 ppm over the past several decades (NEMA, 2013). Scholes and Biggs, 2004 states that climate change poses serious threats to development, particularly in sub-Saharan Africa.

Carbon dioxide (CO_2) is the most important anthropogenic GHG; its annual emissions grew by about 80% between 1970 and 2004. The long-term trend of declining CO2 emissions per unit of energy supplied reversed after 2000 (IPCC, 2007). The Earth's climate system is powered by solar radiation. Approximately half of the energy from the Sun is supplied in the visible part of the electromagnetic spectrum. As the Earth's temperature has been relatively constant over many centuries, the incoming solar energy must be nearly in balance with outgoing radiation. Of the incoming solar shortwave radiation (SWR), about half is absorbed by the Earth's surface. The fraction of SWR reflected back to space by gases and aerosols, clouds and by the Earth's surface is approximately 30%, and about 20% is absorbed in the atmosphere (IPCC, 2007).

Based on the temperature of the Earth's surface the majority of the outgoing energy flux from the Earth is in the infrared part of the spectrum. The longwave radiation (LWR, also referred to as infrared radiation) emitted from the Earth's surface is largely absorbed by certain atmospheric constituents: water vapour, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and other greenhouse gases (GHGs); and clouds, which themselves emit LWR into all directions. The downward directed component of this LWR adds heat to the lower layers of the atmosphere and to the Earth's surface. The dominant energy loss of the infrared radiation from the Earth is from higher layers of the troposphere. The Sun provides its energy to the Earth primarily in the tropics and the subtropics; this energy is then partially redistributed to middle and high latitudes by atmospheric and oceanic transport processes (IPCC, 2013). In recent years, evidence of the man-made origin of climate change (CC) are becoming more and more frequent and, similarly, data of related impacts on terrestrial ecosystems and the socio-economic system are arising from several fields. Not all geographic areas, however, will suffer the same consequences, and it has been recognized that some regions are potentially more vulnerable than others, both for their physical and anthropic characteristics. Mountains are recognized as one of the most sensitive environment, with significant potential impacts on the people who live there (Maran *et al*, 2013). Schipper and Pelling, (2006) argues that climate change due to the increase of greenhouse gas emissions is considered to be one of the major challenges to the human beings in the 21st century.

According to the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC, 2007), by the end of the 21st century, the average global surface temperature is likely to increase by 1.1 to 6.4°C and global average sea level rise of between 0.18 m and 0.59 m relative to 1980–1999. It will lead to changes in precipitation, atmospheric moisture, increase in evaporation and probably raise the frequency of extreme events. The consequences of these phenomena will influence on many aspects of human society, such as the reduction of agriculture production, increase risk to animals, destruction of infrastructure, damage to socio-economic, enhanced water conflicts, poverty and war. Stern (2008) showed that if we do not act, the overall costs and risks of climate change will be equivalent to losing at least 5% of global GDP each year, starting from now and keep losing. If a wider range of risks and impacts is taken into account, the estimated damage could rise to 20% of GDP or more. There is therefore a need to have a robust and accurate estimation of variation of natural factors due to climate change, at least in the hydrological cycle and flooding events, to provide a strong basis for mitigating the impacts of climate change and adapt to these challenges (Duong Vo *et al.*, 2015)

2.2 Overview of climate in Kenya

Kenya is located on the eastern part of the African continent. It lies across the equator at latitude of 4° North to 4° South and Longitude 34° East to 41° East. The country is bordered by Sudan and Ethiopia in the north. Somalia to the east while Indian Ocean borders the country in the south-eastern part. To the southwest of the country lies Tanzania while to the west lies Lake Victoria and Uganda. The country has a total area of 582,650 square kilometers of which 13,400 square kilometers is occupied by inland water. The country has a 536km coastline (NEMA, 2013).

Kenya's climate is fairly warm throughout most of the country. Most of the country has a tropical climate. Exceptions to this are the coastal belt and the northern parts, which are generally arid and hot. It is hot and humid at the coast, temperate inland and very dry in the north and northeast parts of the country. There are two rainy seasons; the long rains occur from April to June and short rains from October to December. (Bunyasi, 2012). The rainfall is sometimes heavy and when it does come, it often falls in the afternoons and evenings. The hottest period is from February to March and coldest in July to August. Over two-thirds of the country receives less than 500mm of rainfall per year and 79% has less then 700mm annually. Only 11% of the country receives more than 1000mm per year. The mean annual rainfall shows a wide spatial variation, ranging from about 200mm in the driest areas in northwestern and eastern parts of Kenya to the wetter areas with rainfall of 1200-2000 mm in areas bordering Lake Victoria and Central Highlands east of the Rift Valley (Geertsema *et al.,* 2011).

Kenya like other countries in the world is experiencing adverse effects of climate change. This is because only 20% of the territorial surface area in Kenya is classified as highly potential area receiving high amounts of rainfall to support agricultural productivity. The largest part of the country comprising of over 88% of the total territorial area is arid and semi-arid lands (ASALs) with minimal annual rainfall ranging from 200-850mm. (NEMA, 2013). However, over 80% of the total population occurs within the potential areas while only 20% of the population occurs in the vast ASALs. NEMA, 2013 further states that climate change has caused negative socio-economic effects across most sectors with the most vulnerable being agriculture and livestock, forestry, water, health, fisheries, energy, tourism as well as physical and social infrastructure. Some of the general adverse effects of climate change experienced in Kenya include variations in weather patterns, frequent and prolonged droughts and diminishing water resources.

In 2005-2006 Kenya faced a serious humanitarian crisis following the failure of several cycles of rain, particularly the October to December short rains in 2005 (Oludhe, *et al.,* 2006). 3.5 million people were affected by the drought and required humanitarian assistance. The worst affected communities were the pastoralists in the northeast of Kenya, where in some areas 70% of the livestock died. As a consequence, a high number of pastoralists moved to settlements closer to urban areas, increasing significantly household vulnerability and dependence on food aid.

All of Africa is likely to warm during this century and the warming is likely to be larger than the global annual mean warming throughout the continent and throughout the seasons. Annual precipitation is likely to decrease in most of Africa, however in East Africa and Kenya an increase in mean annual rainfall is projected (IPCC, 2007). The IPCC, 2007 further states that for East Africa a temperature increase of 3.2 °C is predicted for 2080-2099, a precipitation increase of 7% and an increase in extreme wet events by 30% based on a 21 climate model average for the A1B scenario. The increase in rainfall in East-Africa is robust across the ensemble of models. A total of 18 out of 21 models predict an increase in precipitation in this region.

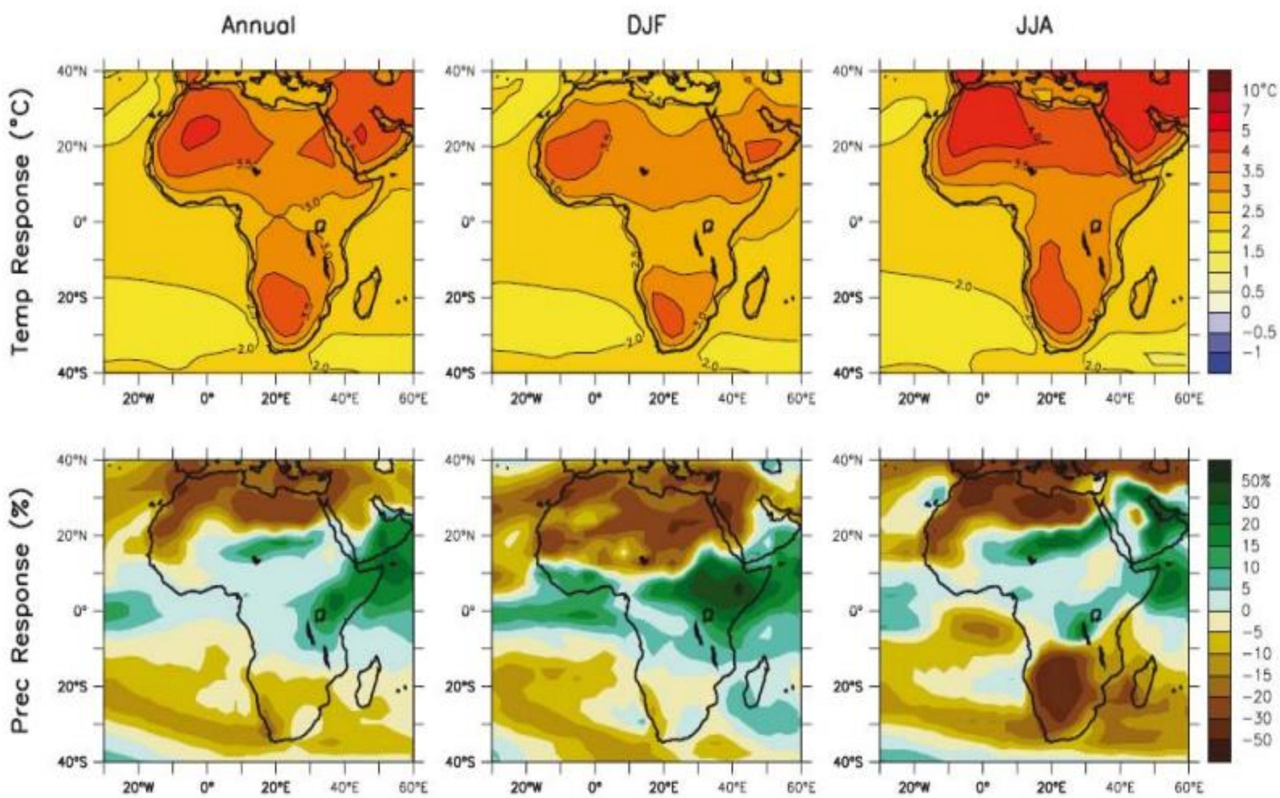

Figure 2. 1: Temperature and precipitation changes over Africa from the MMD-A1B simulations. Top row: Annual mean, DJF and JJA temperature change between 1980 to 1999 and 2080 to 2099, averaged over 21 models. Middle row: same as top, but for fractional change in precipitation. (Source: IPCC 2007).

A study done by Ogutu *et al.*, (2007) examined the influence of the El Nino-southern Oscillation on rainfall and temperature and Normalized Difference Vegetation Index fluctuations in the Mara-Serengeti ecosystem and it is anticipated that climate change will accelerate habitat desiccation and deterioration of vegetation quality. Generally, the reduction of precipitation brought about a reduction in available water in the watersheds reducing base flows to very low levels. The research also found out that increasing temperature reduces the water availability to some degree by increasing evapotranspiration in the watershed thus reducing amount of water and discharge.

Mango *et al.*, (2010) investigated the impact of land use and climate change on the hydrology of the Mara river basin using the SWAT model. Using regional climate projections documented in IPCC Fourth Assessment Report: Climate Change 2007 for climate scenario analysis, the research found out that minimum changes in temperature and precipitation for each seasons of the year, resulted in 25.34% reduction in stream flow.

2.3 River flow regime

Knowledge about flow regime in river basins has a capital importance for a variety of practical applications, especially for watershed management and water sustainable use. The hydrological regime plays a crucial role in determining the biotic composition, structure and function of river basins. A full understanding of surface water availability and seasonality should drive us towards a rational use of the water resource, aimed to satisfy anthropogenic needs, warranting, at the same time, sufficient resources to support ecosystems services (Pumo *et al.*, 2016)

The stream flow response to rainfall depends on the catchment attributes that include the physiographic, underlying geology, vegetation cover and rainfall amount, intensity, and frequency. The interaction between these attributes and the nature of the response are variable in space and time and induce complexity which cannot yet be predicted in hydrology. River flow regime is one of the means that addresses the complexity of stream flow response through the process of systematically organizing streams, rivers or catchments into groups that are most similar with respect to their flow characteristics The natural flow of a river varies on time scales of hours, days, seasons, years, and longer. Many years of observation from a streamflow gauge are generally needed to describe the characteristic pattern of a river's flow quantity, timing, and variability. River flow regimes show regional patterns that are determined largely by river size and by geographic variation in climate, geology, topography, and vegetative cover. For example, some streams in regions with little seasonality in precipitation exhibit relatively stable hydrographs due to high groundwater inputs, whereas other streams can fluctuate greatly at virtually any time of year (LeRoy Poff *et al.*, 1997).

Streamflow regime in a river is highly dependent on different climatic factors, among which the most important is surely the precipitation, in terms of frequency, intensity and seasonal distribution of rainfall events. According to Pumo, *et al.*, (2016), the cause–effect relationship between precipitation and discharge becomes more noticeable in non-perennial rivers, where streamflow mainly relies on surface runoff. Thus, the study of the hydrological regime under transient climate conditions results particularly relevant in ephemeral river basins, where the variations in streamflow characteristics strongly depend on the underlying precipitation patterns.

Different flow regime patterns can be treated as some "preferred states" of the runoff system, which are more or less stable. Under the influence of changing climatic conditions, a flow regime might destabilize and turn over to another one with sometimes quite different seasonal patterns of high and low water, thus disturbing the established hydro-ecological conditions and water uses. The importance of such a change will clearly depend on the sensitivity of a certain regime pattern to the changing climate (Krasovskaia, 2002).

Five critical components of the flow regime regulate ecological processes in river ecosystems: the magnitude, frequency, duration, timing, and rate of change of hydrologic conditions (Walker *et al.*, 1995). These components can be used to characterize the entire range of flows and specific hydrologic phenomena, such as floods or low flows, that are critical to river ecosystems. Furthermore, by defining flow regimes in these terms, the ecological consequences of particular human activities that modify one or more components of the flow regime can be considered explicitly (LeRoy Poff *et al.*, 1997)

Flow regime classification is achieved commonly on the basis of stream flow characteristics using hydrologic indices with five stream flow components; magnitude, frequency, duration, timing, and rate of changes of flows. In most of the studies, the hydrological indices of the rivers are calculated from a time series data recorded at gauging stations. Statistical similarities in hydrological indices are then used to group gauging stations with similar flow regimes. The use of a flow regime classification is maximized when class membership is extrapolated to ungauged locations. In several recent studies, temporal flow data have been combined with spatial environmental and physical data of watersheds in statistical classifications that were used to predict river flow regimes for ungauged watersheds (Berhanu *et al.,* 2015).

All river flow derives ultimately from precipitation, but in any given time and place a river's flow is derived from some combination of surface water, soil water, and groundwater. Climate, geology, topography, soils, and vegetation help to determine both the supply of water and the pathways by which precipitation reaches the channel. Variability in intensity, timing, and duration of precipitation (as rain or as snow) and in the effects of terrain, soil texture, and plant evapotranspiration on the hydrologic cycle combine to create local and regional flow patterns. (LeRoy Poff *et al.,* 1997).

Climate change has the potential to alter substantially river flow regimes by shifting the timing of river flow regimes (Arnell *et al*, 2013). Streamflow regime in a river is highly dependent on different climatic factors, among which the most important is surely the precipitation, in terms of frequency, intensity and seasonal distribution of rainfall events. The cause–effect relationship between precipitation and discharge becomes more noticeable in non-perennial rivers, where streamflow mainly relies on surface runoff. Thus, the study of the hydrological regime under transient climate conditions results particularly relevant in ephemeral river basins, where the variations in streamflow characteristics strongly depend on the underlying precipitation patterns (Pumo *et al.,* 2016)

Climate change is projected to have significant fallout upon streamflow regimes worldwide. Since the beginning of climate change literature, researchers investigated on potential impacts on streamflow regimes, which, in turns, could affect water resources availability and riparian ecosystems existence in some vulnerable areas

In a research done in the Rhine river basin by Middelkoop *et al*, 2001, in the German Middle Mountains, the catchments demonstrated only a minor seasonal shift in river flow as a result of climate change. This was due to the fact that changes in runoff are controlled by the balance between increased precipitation on the one hand, and increased evapotranspiration rates due to higher temperatures on the other hand. This balance depends both on the expected climate changes and on the present climate and land use. In the investigated cases, the accelerated evapotranspiration seems to counterbalance the higher precipitation, resulting in a slight reduction of average runoff during winter, and a much greater reduction during summer. Depending on the severity of net precipitation shortage in summer, the soil water deficit at the end of summer becomes larger, and results in a considerable time lag (weeks to months) until it is recharged by precipitation. Peak flows resulting from heavy rainfall and convective thunderstorms, however, are expected to increase.

In addition, Nepal (2016) argues that even when the precipitation of Koshi basin remained constant, there was a slight increase in discharge in the rivers during the same period. This has been attributed to increased rates of snowmelt due to increase in temperatures and also reduction of snowfall and thus change in the amount of snow available to contribute to snowmelt. Increased evapotranspiration may also play a role. Nepal (2016) further adds that climate change can have impact on different components of runoff. The most visible impact is on surface runoff, which is usually increased with respect to baseline. There are two possible reasons: (a) increased precipitation in the monsoon season when the rainfall–runoff coefficient is high due to the saturated soil conditions and (b) increased number of extreme precipitation events which also result in higher runoff. The interflow is also increased slightly. In contrast, the base flow is projected to decrease, this can be explained by the increase in surface runoff, which implies reduced infiltration.

Climate change may alter the entire energy balance at the basin scale, inducing significant changes in the evapotranspiration processes. The increase in the air concentration of CO_2, on the one hand, induces a temperature increase, which implies an increment also in the atmospheric evaporative demand, while, on the other hand, it is expected to induce a reduction in plants stomatal conductance to water vapor (Moratiel *et al.*, 2011). Alterations of the leaf stomatal conductance with increasing CO_2, could potentially reduce the energy used in evaporating processes, also modifying the mechanism of stomatal regulation. This phenomenon could partially counterbalance the effects on evapotranspiration induced by the temperature increment (Pumo *et al.*, 2016).

2.5 Climate change and hydropower

Hydropower is a renewable energy source where power is derived from the energy of moving water from higher to lower elevations. It is a proven, mature, predictable and price competitive technology. Hydropower has the best conversion efficiency of all known energy sources (about 90% efficiency, water to wire). It also has the highest energy payback ratio. Hydropower requires relatively high initial investment, but has the advantage of very low operation costs and a long lifespan. Life-cycle costs are deemed low. (Kumar *et al.*, 2009)

The hydro-electric power generation provides the major source of energy in Kenya, however, climate change has led to reduced amounts of rainfall and its reliability often resulting in failed seasons. The level of hydro-electric power generation in existing facilities has fallen far below the national requirements. (NEMA, 2013). Hydropower is a source of clean renewable energy, and it does not produce any greenhouse gas emissions. However, there are social, environmental, and economic impacts associated with harnessing hydropower. Hydropower has been heavily exploited in most developed countries with countries like the USA at 70% capacity. Hydropower is often the key to economic success in developing countries. (Chiang *et al.*, 2013). In Africa, it's recorded that the effects of climate change are severely affecting HEP plants especially in areas that experience low annual rainfall. For instance, the early 1970s Sahel drought was devastating and yet recurrence of such events are on the increase as witnessed in the mid-1980s, 2000 and 2009 in Kenya (UNDP, 2007).

Masinga dam is the largest Dam of the Seven Forks Hydro-Electric Power (HEP) project with a design capacity of 1,560 million m3. It has a full operation surface area of 125 Km2 and was commissioned in 1981. Masinga catchment covers about 6,255 Km^2. Roles of the dam include hydropower generation with an installed capacity of 40 MW, regulating water flow into subsequent dams and controlling downstream flooding. Figure 2.1 shows the hydropower stations located in the upper Tana river basin with their installed capacity and years of commissioning.

Station	**Installed capacity (MW)**	**Year Commissioned**
Masinga power station	40	1981
Kindaruma power station	72	1968
Kiambere power station	168	1988
Kamburu power station	100	1974
Gitaru power station	225	1999

Table 2. 1: Hydropower Output Capacity of the Commissioned Plants

(Source; Bunyasi, 2012)

As the evidence for human induced CC becomes clearer, so too does the realization that its effects will have impacts on socioeconomic systems and terrestrial ecosystems. Maran *et al.*, (2013) argues that an increasing number of evidences of glacier retreats and snowfall decrease have been observed in many mountainous regions in these years, thus suggesting that climate modifications may seriously affect stream flow regimes, in turn threatening the availability of water resources useful to agriculture, forestry, tourism, and hydropower generation.

A study done in Iraq by Pilesjo and Al-Juboori (2016) found out that the runoff-rainfall processes non-linear nature will hit hydropower severe by changes in climate given a reduction in rainfall by 10% gives a 25 to 50% loss in hydropower generation. As a result of temperature increase of a few degrees, a severe impact of higher evapotranspiration on hydropower might result in a substantial decrease in generated electricity. In general, increases in climate variability will lead to a lower energy security. The potential for hydroelectric generation approximately follows runoff. A more accurate estimate of climate impacts on hydropower would involve assessment of hydro plants cost, the government's and international organizations policies and the economic development of the country.

Hydropower potential depends on topography and volume, variability and seasonal distribution of runoff. An increase in climate variability, even with no change in average runoff, can lead to reduced hydropower production unless more reservoir capacity is built. Generally, the regions with increasing precipitation and runoff will have increasing potential for hydropower production, while regions with decreasing precipitation and runoff will face a reduction in hydropower potential. (Kumar *et al*, 2009). Among the issues that are most relevant in the study of CC, hydropower plays a double role. On one hand, it will be affected by the change in water feeding hydropower plants and it calls for some measures to manage these changes (adaptation). On the other hand, as one of the major renewable energy source, it makes sense to support and increase its production in order to reduce the human induced CC (Maran *et al.*, 2013).

Raje and Mujumdar, (2009) evaluated climate change impacts on reservoirs performance and adaptive strategies for the future. They used three climate scenarios of A2, A1B, and B1, and three GCMs: CGCM2, MIROC3.2 medium resolution, and GISS model with conditional random fields (CRF) to downscale the GCMs. They found that hydropower generation and reliability will decrease in the future. Reservoir operations were analyzed using rule curves, which describe frequency and severity of flood events as well as demand satisfaction. Mean monthly storage and, therefore, power generation is predicted to decline in future years. To provide better assessments, sub-daily simulations are suggested. Nonetheless, with annual demand increasing, optimal operative policies indicate a balance between increased power reliability, and reduced irrigation reliability. All adaptive policies can offset performance decrease but are ultimately limited by overall water balance deficits of the future.

The resource potential for hydropower is currently based on historical data for the present climatic conditions. With a changing climate, this potential could change due to:

i. Changes in river flow (runoff) related to changes in local climate, particularly on precipitation and temperature in the catchment area. This may lead to changes in runoff volume, variability of flow and in the seasonality of the flow, for example by changing from spring/summer high flow to more winter flow, directly affected the potential for hydropower generation.
ii. Changes in extreme events (floods and droughts) may increase the cost and risk for the hydropower projects:
iii. Changes in sediment loads due to changing hydrology and extreme events. More sediment could increase turbine abrasions and decrease efficiency. Increased sediment load could also fill up reservoirs faster and decrease the live storage, reducing the degree of regulation, increasing flood spill and decreasing generation.

Table 2. 2: Regional hydropower potential (2009)

Region	Technically Feasible Potential (Twh/y)	Capacity Potential (MW)	Installed Capacity (MW)	2009 Generation (Thh/y)	Capacity Factor	Feasible Capacity Increase
Africa	1750	424,277	23,482	98	0.47	1925
Asia	6800	1,928,286	401,626	1514	0.40	670
Oceania	200	55,351	13,370	37	0.41	408
Europe	1140	352,804	179,152	542	0.37	214
North America	1510	360,397	169,105	689	0.48	225
Latin America	2968	596,185	139,424	671	0.57	464
Total/Average	14368	3,722,930	776,760	3551	0.44	

Impact of climate change on water resources

Water is an extremely important resource in Kenya and is the lifeline of its ecosystems. It is used for agriculture, industry, power generation, livestock production, and many other important activities. However, only 1.9 percent of Kenya is covered by water (Mango *et al.*, 2010), most of which is supplied by the country's rivers most of which are concentrated in the highlands. Kenya is also categorized as a water scarce country based on the average per capita water availability and this is a major challenge to the country in several ways.

Observational records and climate projections provide abundant evidence that water resources are vulnerable and have the potential to be strongly impacted by climate change, with wide-ranging consequences for human societies and ecosystems (Bates *et al.*, 2008). Numerous internal and external feedback paths occur between anthropogenic impairment of the water cycle and the environmental resources of the atmosphere, soils and the biosphere. Even without the additional stress of climate change, water security already is one of the most pressing issues in developing countries (Ozor and Urama, 2010).

Kenya is classified by the United Nations as a chronically water-scarce country, with poor replenishment rate. The country's natural endowment of freshwater is highly limited, with an annual renewable freshwater supply of about 647m^3 per capita significantly below the 1,000m^3 per capita set as the marker for water scarcity (Mogaka, *et al.*,2006*)*. The current level of development of water resources in Kenya is very low. The country's water resources are unevenly distributed in both time and space in five drainage basins namely Lake Victoria, Rift Valley, Athi River, Tana River, and Ewaso Ng'iro. The severe weather events like frequent and prolonged droughts and floods, which have been attributed to climate change, will severely affect freshwater availability. Major rivers including the Tana, Athi, Sondu Miriu, Ewaso Ngiro and Mara have experienced severe reduced volumes during droughts and many seasonal ones have completely dried up.

Water is fundamental to human life and many other social, economic and industrial activities. It is required for agriculture, industry, ecosystems, energy, transportation, recreation and waste disposal (Chaulagain, 2006). Therefore, any changes in hydrological system and water resources could have a direct effect on the society, environment and economy. Water resources are influenced by various social, technical, environmental and economic factors. Climate change is just one of many pressures that hydrological systems and water resources are facing (IPCC, 2007). Climate change is having a multitude of immediate and long-term impacts on water resources in African countries. These include flooding, drought, sea-level rise in estuaries, drying up of rivers, poor water quality in surface and groundwater systems, precipitation and water vapour pattern distortions, and snow and land ice mal-distribution. These effects when compounded together have devastating impacts on ecosystems and communities, ranging from economic and social impacts to health and food insecurity, all of which threaten the continued existence of many regions in Africa (Ozor and Urama, 2010).

According to climate model analyses, the number of people at risk due to water scarcity increases rapidly with rising temperatures towards the second half of the century, with impacts in arid and semi-arid regions expected to be much larger than the global averages suggest (Parry *et al.*, 2001). Therefore, in Kenya, a country under water stress, climate change is expected to exacerbate the situation. Changes in the hydrological cycle due to climate change can lead to diverse impacts and risks, and they are conditioned by and interact with non-climatic drivers of change and water management responses. Water is the agent that delivers many of the impacts of climate change to society, for example, to the energy, agriculture, and transport sectors. Even though water moves through the hydrological cycle, it is a locally variable resource, and vulnerabilities to water-related hazards such as floods and droughts differ between regions. Anthropogenic climate change is one of many stressors of water resources. Non climatic drivers such as population increase, economic development, urbanization, and land use or natural geomorphic changes also challenge the sustainability of resources by decreasing water supply or increasing demand.

Uncertainties in projected changes in the hydrological systems arise from internal variability in the climatic system, uncertainty in future greenhouse gas and aerosol emissions, the translations of these emissions into climate change by global climate models, and hydrological model uncertainty. Projections become less consistent between models as the spatial scale decreases. The uncertainty of climate model projections for freshwater assessments is often taken into account by using multimodel ensembles (Bates *et al.*, 2008).

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CHAPTER THREE

MATERIALS AND METHODS

3.1 Study area

3.1.1 Location

The Tana river basin covers nearly 21 % of the total national landmass of Kenya, and has an aerial coverage of about 126,927 km2 (Agwata, 2006; NEMA, 2013). River Tana is the main river in the basin and it flows for about 1200 meters from the central Kenya highlands to Indian Ocean and it is the lifeline of the seven forks hydroelectricity power project. Five major reservoirs have been built on the upper reaches: Kindaruma in 1968, Kamburu in 1975, Gitaru in 1978, Masinga in 1981, and Kiambere in 1988 (Figure 3.2). Together, these provide three quarters of Kenya's electricity and regulate the river flow. The upper Tana River basin covers the Aberdares highlands and Mount Kenya and is situated north west of Nairobi with a surface area of approximately 12,500km^2. The Masinga dam is the largest reservoir of the Seven Forks hydropower project and therefore most important in controlling the Tana River system and the seven forks hydropower project.

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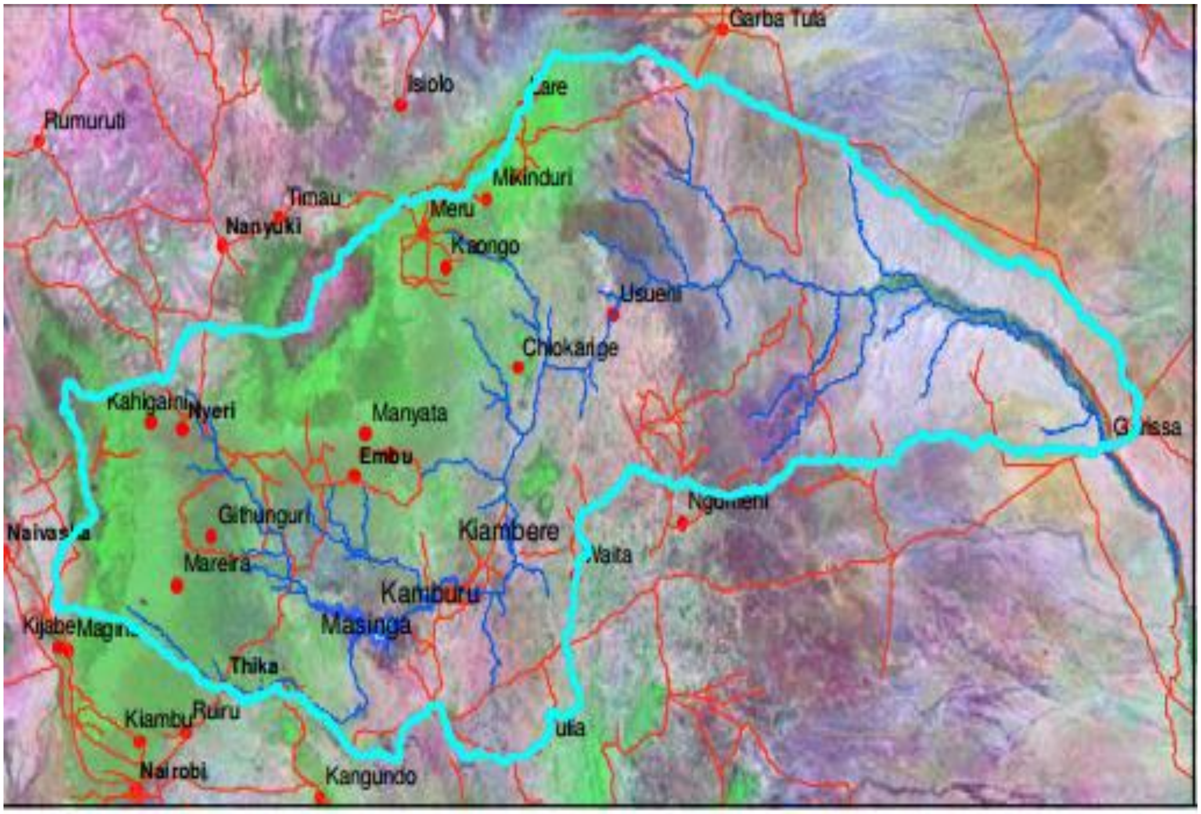

Figure 3. 1: Landsat image of Tana basin (Source: Droogers, et al., 2006)

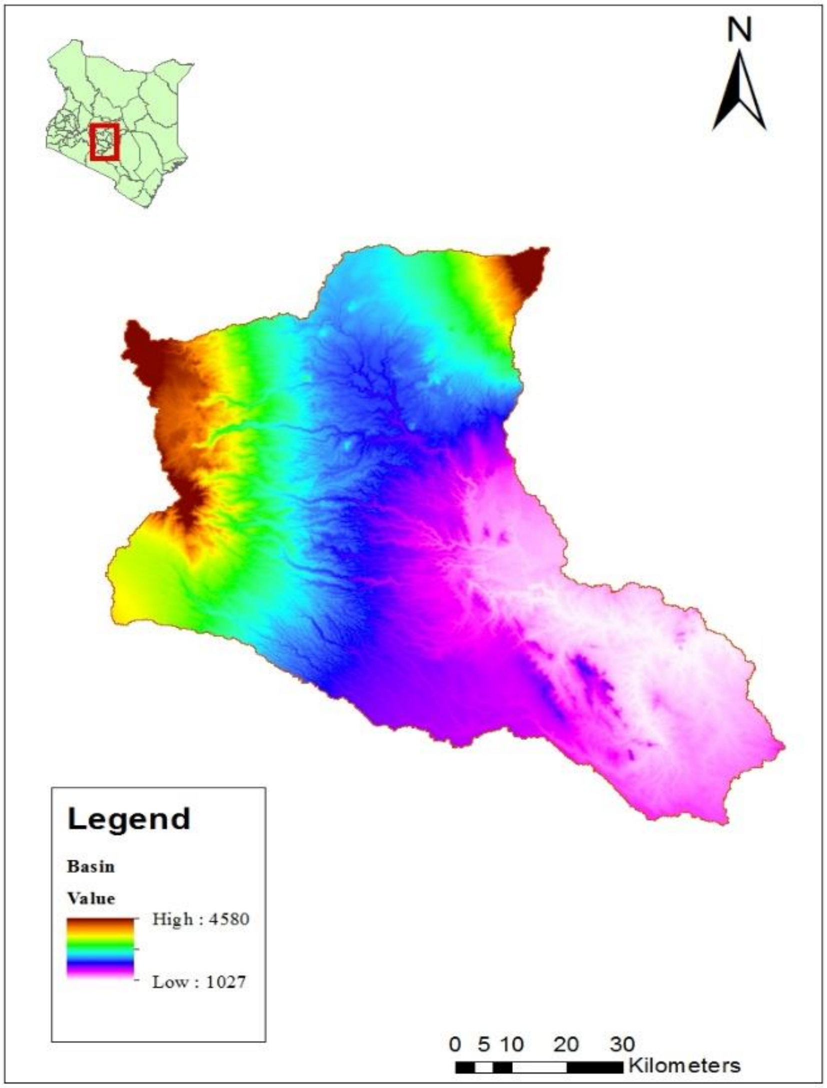

Figure 3. 2: Elevation and relative location of Masinga catchment

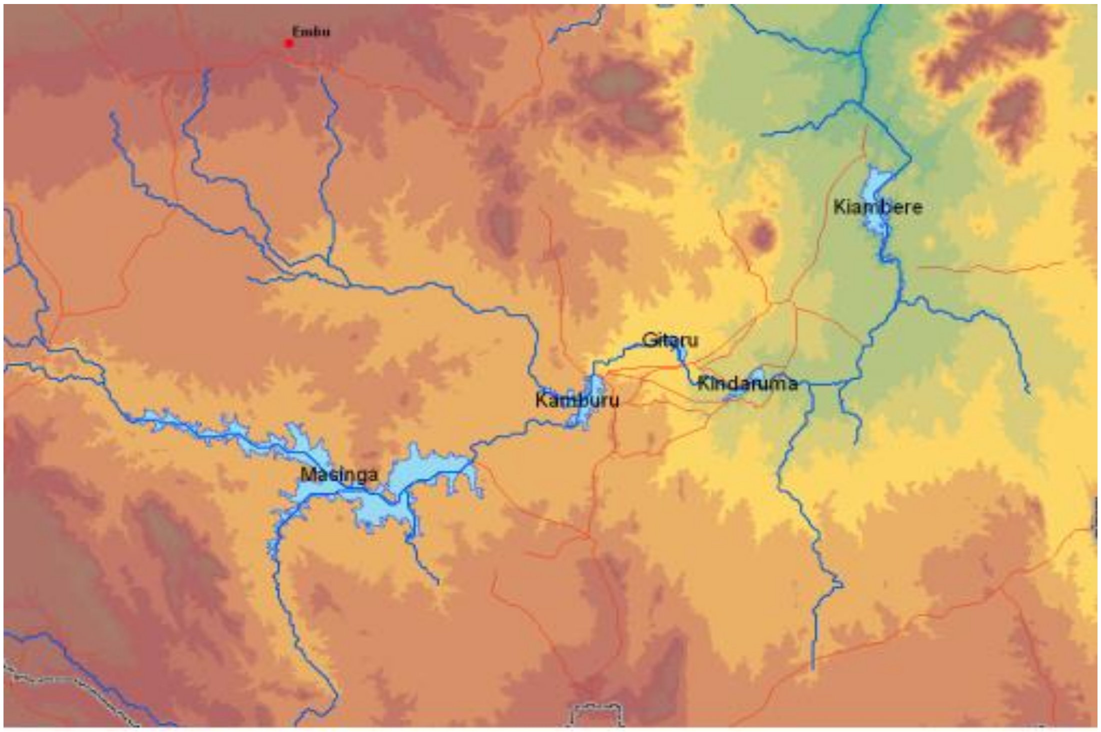

Figure 3. 3: Relative location and size of the hydropower plants

(Source: Droogers, et al., 2006)

3.1.2 Topography

The main topographic features in the catchment area are the Mount Kenya and the Aberdare ranges. Elevation ranges from 5199m towards the peak of Mt. Kenya to 400m in the east of the catchment. The southern slopes of Mt. Kenya and the eastern slopes of the Aberdare ranges are the main sources of rivers draining into the seven forks dam projects. Towards Mt. Kenya and the Aberdare ranges, the topography is rugged and sloping towards the Tana basin allowing for construction of hydroelectric dams. The slopes in the catchment are characterized by deeply dissected ridges and valleys which vary in altitude between 1,500m up to 2,400m, these dissections are further eroded by the rivers and runoff through erosion forming parallel valleys and ridges (Bunyasi, 2013).

3.1.3 Geology and soils

The geology of the upper Tana can broadly be divided into volcanic rocks in the north and west and pre-cambrian basement complex in the south-east. Other geologic formations of limited extend include igneous intrusions of granite and dolerite and an area of quaternary sandstone between Murang'a and Sagana. The catchment has a broad range of soil types with varying water retention ability. Lithosols and Histosols occur at the highest altitudes in the Aberdare range, with Humic Andosols at slightly lower elevations. Nitosols are found in the mid-elevations and Vertisols in the lower elevations.

3.1.4 Climate

The climate ranges from semi-arid in the east to humid in the west. Generally, the area has a bimodal rainfall pattern with four fairly distinct seasons. The long rains occur between March and May while the short rains during September and November. The long rains and short rains are separated by about three dry months. Rainfall varies between 600mm in the eastern part of the watershed to over 2000mm on the Aberdare mountains. The maximum and minimum mean annual temperature varies between 25.5 – 31.00C and 21.0 – 24.00C respectively.

3.1.5 Land use

Agricultural activities are being practiced in the western area of the catchment where rainfall is higher, the rest of the area is used for grazing with only scattered cultivation. Maize, sisal, tea and coffee are the major crops grown in the area. Crop husbandry is low with only a few cases where physical conservation measures have been applied.

3.2 Determination of Precipitation and Temperature Trends

Precipitation and temperature trend analysis was carried out through acquisition of rainfall and temperature data for the period 1983 to 2013 across several locations in the study area. For the temperature, minimum, maximum and mean monthly and yearly temperatures were calculated and plotted against time and the resulting trend observed and analysed. The mean monthly and yearly precipitation data collected at several rainfall stations in the study area were plotted against time and the precipitation trend analysed. The trends in precipitation and temperature were used as indicators of climate change in the upper Tana River basin.

3.2.1 Data required for study area

Climate data of the study area was obtained from the Kenya Meteorological Department (KMD), the data acquired include precipitation and temperature records for the 1983-2013 period. Water Resources Management Authority, (WRMA), provided data on Tana river flow discharge and stage at different locations along the Tana river, while the Masinga dam reservoir levels were acquired from Kenya electricity generating company, KenGen. Data on soils, land use and topography was downloaded from World Resource Institute (WRI), website.

3.2.2 Filling of missing data

Every data series must be complete before the input to any hydrological model. Data missing can happen due to several reasons like gauge problem, difficulty in reading daily data, personal mistakes in storage, poor storage system and so on. The data series collected from WRMA and Ministry of Water, Kenya had so many missing values and mostly on a long regular series of more than 90 regular days and sometimes a year of missing data. Random missing data were filled by simple interpolation while the long missing series were estimated using data from nearby stations.

3.3 Determination of Tana River Flow Regime.

The natural flow of a river varies on time scales of hours, days, seasons, years, decades and longer. To describe the characteristic pattern of the river flow, many years of observation from a streamflow gauge are generally needed. A 30-year stream discharge data for the upper Tana was obtained from the Ministry of Water and the Water Resources Management Authority (WRMA). Flow changes within the 30-year period were analysed and discharge trends plotted. For determination of the variations in the river flow regime over the 30-year duration, the study period was divided into three 10-year periods starting from the initial study year, 1983 and ending in 2013. The flow regime of different streams in the watershed was established and therefore a general trend of stream flow over the study period established. The mean flow and the minimum peak flow was also determined. The ArcGIS software was used for analyses of catchment characteristics.

3.3.1 Time Series Hydrographs

Daily and monthly river flow data for various gauging stations across the basin (1983-2013), were plotted against time to obtain time series hydrographs. These hydrographs are important in obtaining the baseline scenarios that can be used to assess the future effects of flows on hydropower generation in the upper Tana River basin.

3.4 Relating River Flow Regime to Hydropower

Data on hydropower generation from 1990 to 2013 was obtained from KPLC and KenGen. The corresponding reservoir levels were established for each specific amount of power generated from the hydropower stations. A trend for hydropower generation over the same period was also established. Water resource availability changes were converted and linked to changes in hydropower generation. The runoff is assumed to be the main determinant of limitation to hydropower generation. On average, runoff can be thought of as the difference between the precipitation and evaporation over long periods of time. The analysis methodology is based on the fact that hydropower generation is a function of flow (Q, in m^3/s), Head (H, in m) and efficiencies. Assuming that the changes in water resources will impact hydropower generated in the future, the most varying factor will be the flow. The approach is based on the fact that the current hydropower generation system may only be limited by water availability. The main assumption is that if water supply reduces, the hydropower systems will likewise reduce generation and vice versa, assuming that current systems can be upgraded. With this approach, changes in annual and monthly mean flows are the main predictors of hydropower generation. A relationship will then be established between the hydropower generation and stream flow trends.

3.4.1 Discharge versus hydropower generation analysis

Hydropower technology allows for the transformation of about 90 per cent of kinetic energy of flowing water into electricity. A flow rate of about 4000 liters per second is used to produce one kilowatt of electricity, assuming there is a vertical difference in elevation of 100m. Due to the fact that hydropower generation needs a continuous flow of water with minimum sedimentation, major dam constructions are usually necessary, particularly on rivers with high fluctuations in flow. Reservoirs created by damming of rivers regulate the river flow and also act as sediment settlement tanks. Constructing a dam across a river also causes a change in downstream river flow regime and water quality.

Generally, high amounts of precipitation in an area leads to high stream flow rates and consequently higher hydropower generation since the reservoirs will be constantly full of water, and therefore the channel flow and the power production will be positively correlated. However, deviations from these expectations do occur and are usually attributed changing climate and activities upstream the dam, including land use practices, that lead to poor vegetation cover and hence accelerated runoff or reduced flows due to diversion of water to other point uses such as irrigation.

3.5 Simulation of River Flow Regimes and its Impact on Hydropower Generation

The ArcSWAT model was selected as the model for simulation of future stream flow charactteristics. Soil, land use and slope characteristics of the study area were processed using the ArcSWAT model. The model was calibrated and validated in order to be representative of the real watershed characteristics. Future river flow scenarios were them simulated based on the predicted climate change scenarios for the upper Tana river catchment. Climate scenarios are used to provide quantitative assessments of climate impacts and can be defined as possible representation of future climate which have been developed to be used exclusively in conjunction with investigating the potential impacts of anthropogenic climate change (IPCC,2007).

General Circulation Models (GCMs) are currently the most advanced tools available for simulating the response of the global climate system to changing atmospheric composition. In general, the GCM is a numerical representation of the atmosphere and its phenomena over the entire Earth and it incorporates a variety of fluid-dynamical, chemical or even biological equations (IPCC,2007). The GCM is run using different climate change scenarios and produces outputs of annual and seasonal averages, which enable the determination of the likely changes in precipitation, temperature and runoff as a result of these scenarios taking place.

Climate models and scenarios were selected to obtain projections of future climate change in the study area. Appropriate climate models and scenarios were identified through literature review. The climate models were then used to generate future climate ensembles for emission scenarios from the Special Report on Emission Scenarios (SRES) by the Intergovernmental Panel on Climate Change (IPCC). According to Mango, *et al.*, (2010), climate change is predicted by GCMs and therefore, in assessing the climate impacts of smaller basins, downscaling approaches should be adopted. Downscaling is a means of relating large scale atmospheric predictor variables to local- or station- scale meteorological series (Mango, *et al.*, 2010). Future climate projections need to be spatially downscaled from low-resolution General Circulation Models (GCMs) to a scale usable for the watershed level analysis.

3.5.1 Model Review

There are numerous hydrologic models that can be and have been applied for climate change impact analysis and hydrology. Understanding of future climate change on the hydrological cycle within a watershed scale is crucial for water resources planning. This makes the selection of hydrologic modeling technique crucial to the validity and accuracy of results. Impacts of climate change on the hydrological behavior of a particular watershed are only meaningful if the physical, spatial, and hydrological cycles are accurately represented (Kienzle *et al.*, 2012). Some models which have been applied in assessment of impacts of climate change on water resources are discussed below.

i) Variable Infiltration Capacity (VIC)

The Variable Infiltration Capacity is a macro scale hydrology model which uses GCM outputs to produce hydrology and water resources results (Christensen et al., 2004). VIC is a gridded model driven by precipitation, temperature and wind time series. It models soil moisture processes and evapotranspiration, surface runoff and baseflow, and snow accumulation and melt. The model uses a cell-based routing technique to simulate streamflow at specified junctures in the system (Liang et al., 1994). It can run at daily and sub-daily time steps for an energy or water balance analysis.

ii) The HBV model

The HBV model is a conceptual model developed by Dr. Sten Bergstrom at Swedish Meteorological and Hydrological Institute (SMHI), during early 1970s. It has then been widely used and revised several times.

The model treats catchment as a single unit without consideration of spatial distribution within the catchment thus is also a lumped model though the snow routine is distributed. Inputs for the model are observed precipitation, temperature and potential evapotranspiration. The model has a fixed structure but contains a number of parameters for a catchment which are mostly to be determined through calibration. The model then computes snow accumulation, snow melt, and actual evapotranspiration, storage in soil moisture, groundwater and runoff from the catchment.

iii) Watershed Assessment Resources Management Framework (WARMF)

The Watershed Assessment Resources Management Framework is a decision support system for water management. It is a GIS-based physical watershed model integrating models databases, and graphical software using data from meteorological, air quality, point source, diversion, and reservoir data propel the model engine. WARMF is a seamless river basin model comprised of catchment, river, lake and reservoir segments for soil and surface hydrology evaluation based on physical principles. The river basin serves as an interconnected reactor of vegetation, land surface, soil layers, river segments and lakes, routing movement to evaluate infiltration, evapotranspiratio n, stream flow, daily runoff and shallow ground water flow. The hydrology budget is calculated by the water balance which analyzes precipitation and irrigation water infiltration to the land layer, percolation out of the layer, lateral in/outflow and evapotranspiration (Geza et al., 2009). Individual catchments can be divided into five soil layers. WARMF is a dynamic simulation model and can run at daily time steps to analyze the water balance for watersheds to produce runoff, soil hydrology, ground water lateral flows, stream flows, and point source loads, if necessary.

iv) Soil and Water Assessment Tool (SWAT)

SWAT is a river, basin, or watershed scale model that analyzes the impact of land management practices on water, sediment and agricultural chemical yields (http://swat.tamu.edu). It is frequently used with differing soils, land use patterns, and management conditions in large and complex watersheds for long term impact analysis. It is physically-based, using weather, soils, topography, and vegetation properties to drive a continuous time model for long-term yield. SWAT models watershed even when monitoring data is unavailable, and is capable of quantifying change in input data for impact analysis. It is computationally and fiscally efficient.

v) Hydrological Simulation Program- Fortran (HSPF)

HSPF is a widely used program simulating watershed hydrology and water quality for conventional and toxic organic pollutants. It is a physical, continuous, distributed parameter watershed model. HSPF simulates runoff, sediment, and water quality. The watershed is divided into catchments based on climate stations and soils types. Each catchment includes landuse data and soil classification. It analyzes the fate and transport of contaminants while calculating water quantity and quality at any point in the watershed. The total load from HSPF includes the contribution from groundwater and overland flow (Geza and McCray, 2009). The model has some groundwater transport routine but is not sufficient in its analysis.

vi) Areal Nonpoint Source Watershed Environmental Response Simulation (ANSWERS)

The Areal Nonpoint Source Watershed Environmental Response Simulation (ANSWERS) model was jointly developed by Purdue University and the Environmental Protection Agency(EPA). ANSWERS is a single-event, distributed-parameter model to simulate hydrology, sediment transport, and routing through a basin. The size of the basin is limited to 10,000 ha, which is further subdivided into smaller independent elements. (Saenyi, 2002)

vii) Water Evaluation And Planning system (WEAP)

WEAP is a Windows-based decision support system for water resource managers and policy decision-makers to analyze long-term decision planning (www.weap21.org). It contains a GIS-based, graphical interface. WEAP simulates water supply and demand, runoff, evapotranspiration, infiltration, irrigation needs, instream flow requirements, groundwater and storage analysis. Pollution creation, treatment, discharge and stream quality, and reservoir operations under possible varying scenarios of policy, hydrology, climate, land use, technology and socio-economic factors.

3.5.2 Model selection

The Soil Water Assessment Tool (SWAT) was chosen for hydrological modeling in the watershed under study using the ArcGIS 2012. SWAT is a watershed scale model developed to predict the impact of land management practices on water, sediment and agricultural chemical yields with varying soils, land use and management conditions over long periods of time.

One basis for model selection was due to its worldwide use for variety of applications. The model has in the recent past gained significant publicity having been used widely for various applications world over with notable success with recent applications in the Nilotic catchments that include Kenya, Tanzania, Ethiopia, Uganda, among others (Obiero, *et al.,* 2011). SWAT has gained international acceptance as a robust interdisciplinary watershed modeling tool as evidenced by international SWAT conferences, hundreds of SWAT related papers presented at numerous scientific meetings, and many articles published in peer reviewed journals. The SWAT model is computationally efficient and able to run simulations of very large basins or management practices without consuming large amounts of time and expenses compared to lumped, conceptual or fully distributed, physically based models (Mulungu and Munishi, 2007). The model also has a weather simulation model that generates daily data for rainfall, solar radiation, relative humidity, wind speed and temperature from the average monthly variables of the data that provides a useful tool to fill in gaps in daily data in the observed records. This enables SWAT to model ungauged watersheds and more importantly, quantify the impact of scenarios such as changes in land use, land management practices and climate on water quality and quantity. SWAT is capable of modeling changes in land use and management practices, can model variety of catchment areas ranging from a few hectares to thousands of square kilometers and performs long term simulations. Besides, the model is freely available and can be downloaded from the internet. The model website has a well-developed system for support to model users.

The model is in the public domain and therefore available without many restrictions. The model has options for daily, monthly and yearly time step simulations that can be carried out without altering the input data. Model predictions are spatially distributed thereby providing spatial information regarding upstream sources of modeled quantities.

3.5.3 SWAT Model Description

The ArcSWAT ArcGIS extension is a graphical user interface for the SWAT model. ArcSWAT ArcGIS extension is a graphical user interface for the SWAT2005 which is evolved from AVSWAT which is an ArcView extension developed for an earlier version of SWAT (Setegen, *et al.*,2008). SWAT is a river basin, or watershed scale model developed to predict the impact of land management practices on water, sediment, and agricultural chemical yields in large, complex watersheds with varying soils, land use, and management conditions over long periods of time. SWAT operates on a daily time step and is designed to predict the impact of land use and management on water, sediment, and agricultural chemical yields in ungauged watersheds (Arnold, *et al.*, 2012). The model is physically based and computationally efficient, uses readily available inputs and enables users to study long-term impacts.

Physically based, spatially distributed hydrological models are an effective means to assess the impacts of climate change on hydrological response, as they are able to capture the spatial variability of hydrological processes throughout complex watersheds (Kienzle, 2012). The main components of the model include hydrology, soil temperature and properties, weather, plant growth, nutrients, pesticides, bacteria and pathogens, and land management. The ArcSWAT model is continuous time, spatially distributed model designed to simulate water and sediments transport on catchment scale on daily time steps. It uses hydrologic response units that consist of specific land use, soil and slope class within the watershed. The model estimates relevant hydrologic components such as evapotranspiration, surface runoff and peak rate of runoff, groundwater flow and sediment yield for each HRUs unit.

Conceptually, SWAT divides a watershed into sub-watersheds. Each sub-watershed is connected through a stream channel and further discretized into Hydrologic Response Units (HRUs). A HRU is a unique combination of soil and vegetation type in a sub-watershed that consist of homogeneous land use, management, topographical, and soil characteristics. The HRUs are represented as a percentage of the sub watershed area and may not be contiguous or spatially identified within a SWAT simulation. Alternatively, a watershed can be subdivided into only sub watersheds that are characterized by dominant land use, soil type, and management. (Arnold, *et al.*, 2012). ArcSWAT simulates the hydrological variables and runoff results at the HRU level and aggregates these results to the catchment scale by applying a weighted average to the HRU results. The runoff is routed to obtain the total runoff for the watershed at the outlet (Devkota and Gyawali, 2015).

The driving force behind all the SWAT processes is the water balance, this is due to the fact that water balance impacts plant growth, movement of sediments, pesticides, nutrients, and also pathogens. Simulation of watershed hydrology is separated into two phases, the land phase, which controls the amount of water, sediment, nutrient, and pesticide loadings to the main channel in each sub-basin, and the routing phase, which is the movement of water, pesticides, nutrients and sediments through the channel network of the watershed to the outlet. The hydrologic model simulated by the ArcSWAT model is based on the water balance equation;

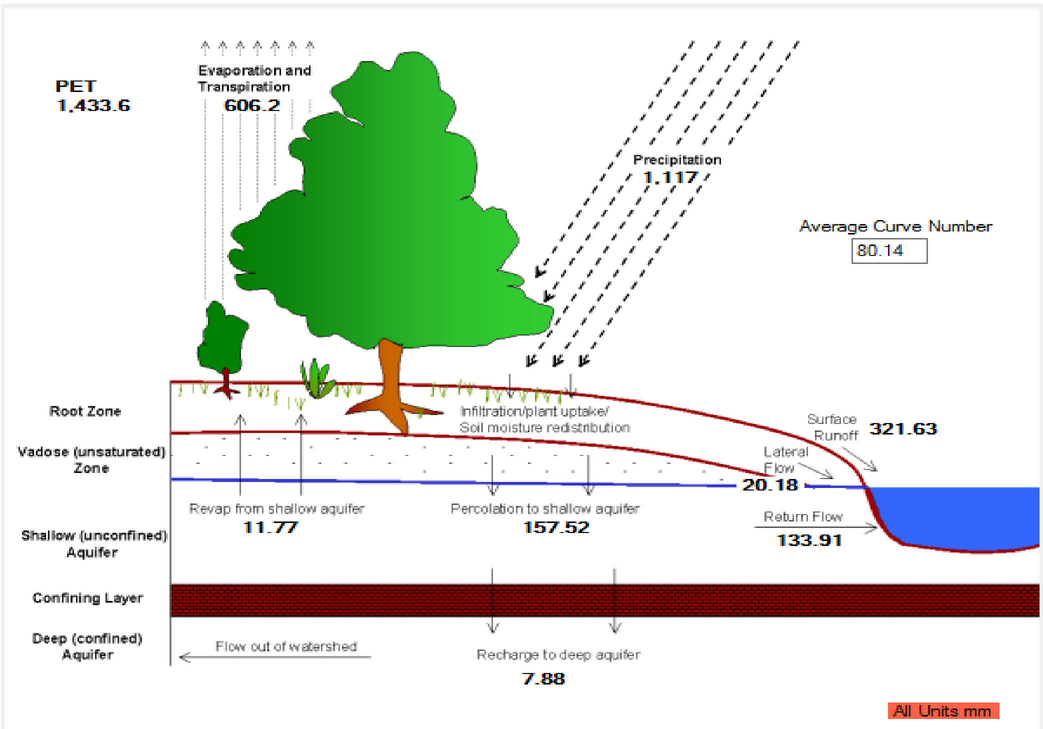

Figure 3. 4: Water balance schematic

$$SW_t = SW_o + \sum_{i+1}^{t}\{R_{day} - Q_{surf} - E_a - W_{seep} - Q_{qw}\} \quad (3.1)$$

Where SW_t is the final soil water content (mm), SW_o is the initial water content in day *i* (mm), R_{day} is the amount of precipitation in day *i* (mm), Q_{surf} is the amount of surface runoff in day *i* (mm), E_a is the amount of evaporation in day *i* (mm) , W_{seep} is the amount of water entering the vandose zone in day *i* (mm) and Q_{qw} is the amount of return flow in day *i* (mm). The hydrologic cycle is climate driven and provides moisture and energy inputs, such as daily precipitation, maximum/minimum air temperature, solar radiation, wind speed, and relative humidity, that control the water balance.

The SWAT model is capable of reading this observed data directly from files or generate simulated data at runtime from observed monthly statistics. Soil temperature is computed because it impacts water movement and the decay rate of residue in the soil and snow is computed when temperatures are below freezing point. Hydrologic processes simulated by SWAT include canopy storage, surface runoff, infiltration, evapotranspiration, lateral flow, tile drainage, redistribution of water within the soil profile, consumptive use through pumping (if any), return flow, and recharge by seepage from surface water bodies, ponds, and tributary channels. SWAT uses a single plant growth model to simulate all types of land cover and differentiates between annual and perennial plants (Arnold, *et al.*, 2012).

Once the loadings of water, sediment, nutrients, and pesticides from the land phase to the main channel have been determined, the loadings are routed through the streams and reservoirs within the watershed. The water balance for reservoirs includes inflow, outflow, rainfall on the surface, evaporation, seepage from the reservoir bottom, and diversions. Two methods are used for surface runoff estimation in SWAT i.e. the SCS curve number and Green-Ampt infiltration. This study is based on the use of curve number for surface runoff and hence stream flow simulation. The SCS curve number is a function of land use, soils permeability and the antecedent soil water conditions. The SCS curve number method is described by equation 3.3.2

$$Q_{surf} = \frac{(R_{day} - I_a)^2}{(R_{day} - I_a + S)} \tag{3.2}$$

In which, Q_{surf} is the accumulated runoff or rainfall excess (mm), R_{day} is the rainfall depth for the day (mm), S is the retention parameter (mm), and I_a is the initial abstractions which includes surface storage, interception and infiltration prior to runoff (mm). The retention parameter, S is defined by the following equation.

$$S = 25.4\left(\frac{100}{CN} - 10\right) \tag{3.3}$$

Where CN id the curve number for the day. Ia is usually approximated as 0.2S and therefore equation 3.2 becomes

$$Q_{surf} = \frac{(R_{day}-0.2S)^2}{(R_{day}+0.8S)} \tag{3.4}$$

Runoff occurs only when the rainfall depth for the day (R_{day}) is less than the initial abstractions. Figure 3.5 presents a graphical solution to different curve numbers for equation 3.3.4

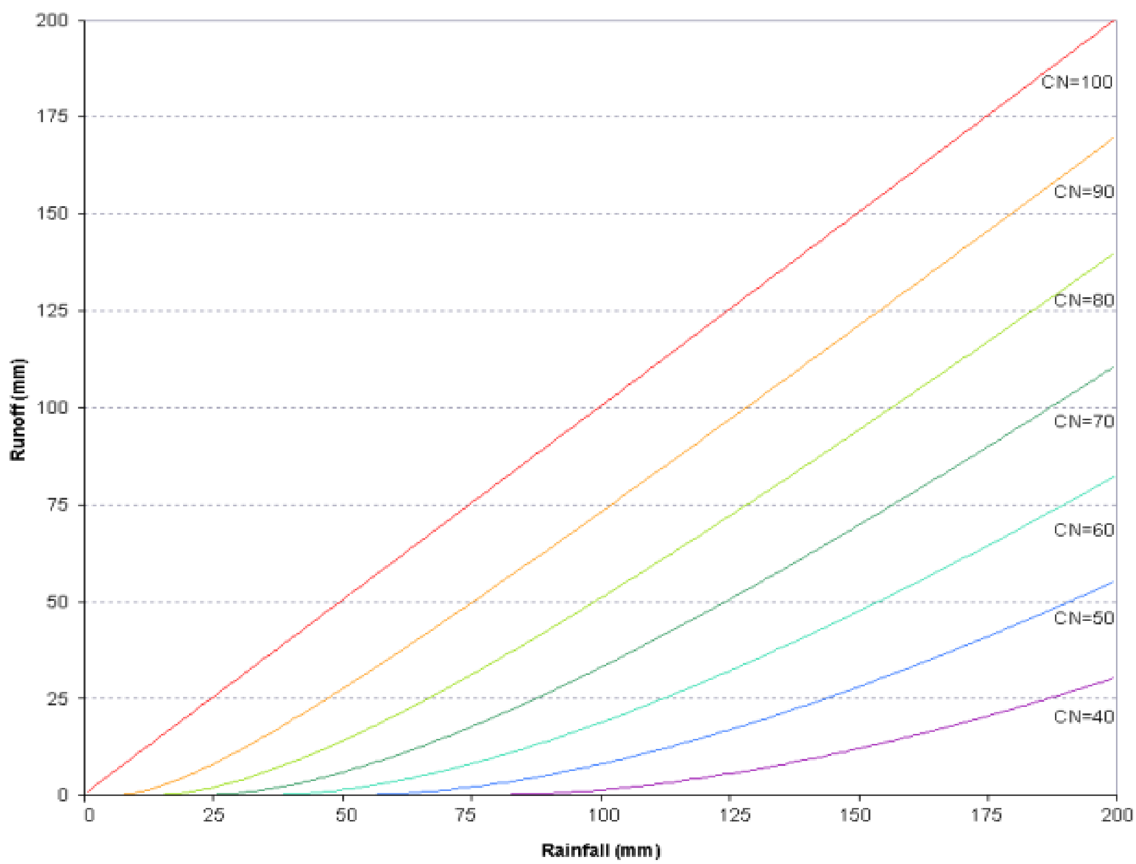

Figure 3. 5: Relationship of rainfall to runoff in SCS curve number method

Source; Arnold, et al., 2009

SCS defines three antecedent moisture conditions; I-Dry (Wilting point), II- Average moisture and III- Wet (Field capacity). The curve number for the moisture conditions can be calculated by the following equations;

$$CN_1 = CN_2 - \frac{20*(100-CN_2)}{(100-CN_2+exp[2.533-0.0636*(100-CN_2)])} \quad (3.5)$$

$$CN_3 = CN_2 * exp[0.00673 * (100 - CN_2)] \quad (3.6)$$

Where CN_1 is the curve number for moisture condition I, CN_2 the curve number for moisture condition II and CN_3 the curve number for moisture condition III.

The Green & Ampt equation was developed to predict infiltration assuming excess water at the surface at all times. The equation assumes that the soil profile is homogenous and antecedent moisture is uniformly distributed in the profile. (Arnold, *et al.*, 2009) The model assumes that as the water infiltrates, the soil above the wetting front is completely saturated and there is a sharp break in moisture content at the wetting front. The infiltration rate id defined by

$$f_{inf,t} = K_e \left\{1 + \frac{\varphi_{wf}*\Delta\theta_v}{F_{inf,t}}\right\} \quad (3.7)$$

Where f_{inf} is the infiltration rate at time t (mm/hr), Ke is the effective hydraulic conductivity (mm/hr), φ_{wf} is the wetting front matric potential (mm), $\Delta\theta_v$ is the change in volumetric moisture content across the wetting front (mm/mm) and F_{inf} is the cumulative infiltration at time t, (mm).

For simulation, a watershed is subdivided into a number of homogenous sub basins (hydrologic response units or HRUs) having unique soil and land use properties. The input information for each sub basin is grouped into categories of weather; unique areas of land cover, soil, and management within the sub basin; ponds/reservoirs; groundwater; and the main channel or reach, draining the sub basin (http://www.brc.tamus.edu/swat). The loading and movement of runoff, sediment, nutrient and pesticide loadings to the main channel in each sub basin is simulated considering the effect of several physical processes that influence the hydrology.

3.5.4 Model Input

The GIS input needed for the ArcSWAT interface include the Digital Elevation Model (DEM), soil data, land use and stream network layers. Data on weather and river discharge were also used for prediction of streamflow and calibration purposes. Topography was defined by a DEM that describes the elevation of any point in a given area at a specific spatial resolution. A 90 m by 90 m resolution DEM was downloaded from SRTM (Shuttle Radar Topography Mission) website on 20 February 2016 and projected using Arc GIS 10.2 software package. The DEM is one of the essential spatial inputs which was used to delineate the watershed and to analyze the drainage patterns of the land surface terrain. Sub basin parameters such as slope gradient, slope length of the terrain, and the stream network characteristics such as channel slope, length, and width were derived from the DEM. The surface area of the basin as calculated by the model was 7,026 km^2, SWAT divided the watershed into 37 sub basins and 309 hydrologic response units as shown in the Figure 3.6.

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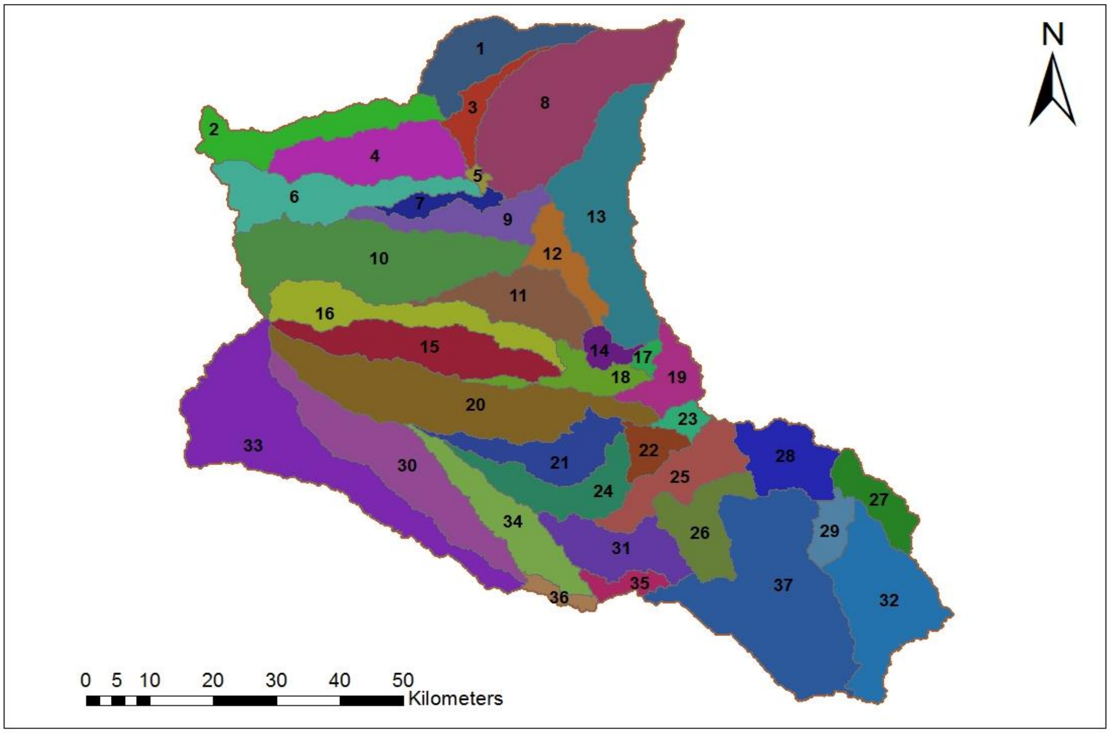

Figure 3. 6: Masinga basin sub catchments

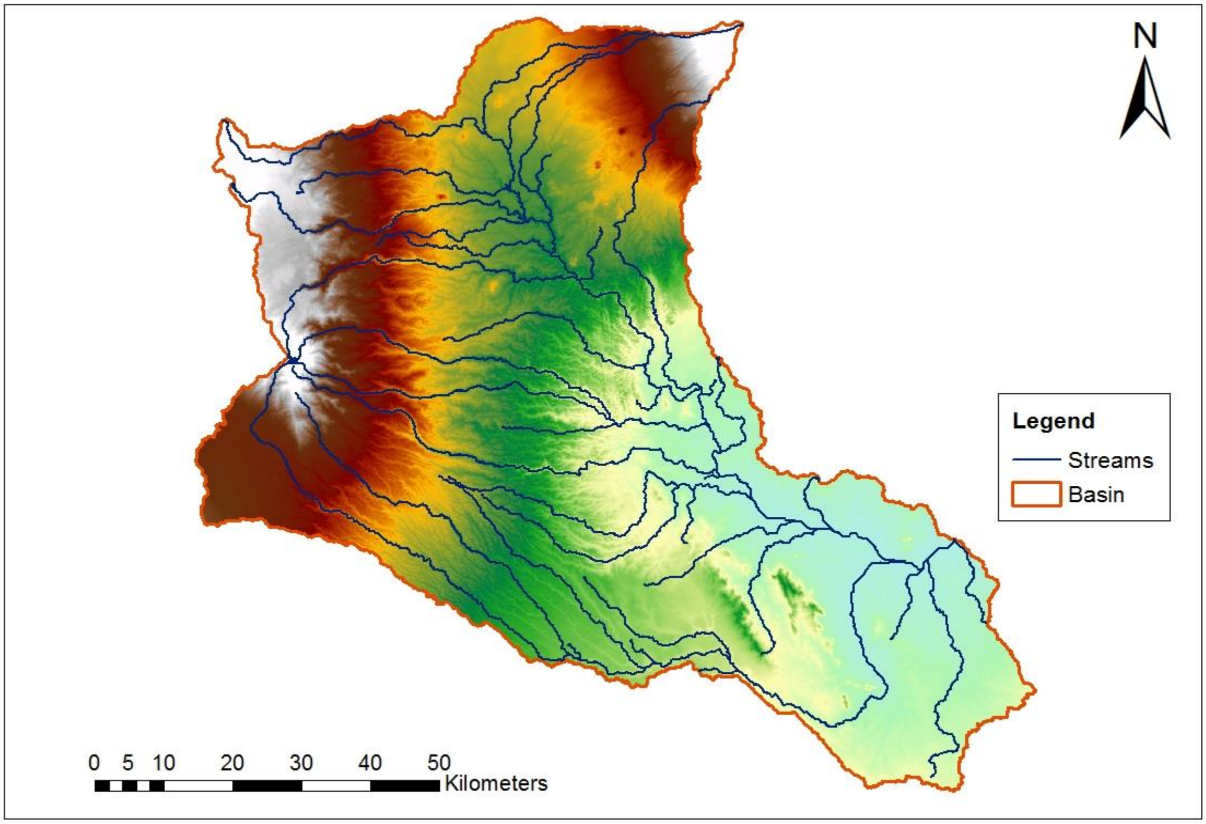

Figure 3. 7: Stream network

3.5.5 Soil data

SWAT model requires different soil textural and physicochemical properties such as soil texture, available water content, hydraulic conductivity, bulk density and organic carbon content for different layers of each soil type. Data for soil included the shape file soil map extracted from the soil map of Kenya available from Kenya Soil Survey (KSS). For each of the soil units in the study area, the soil physical and chemical properties were determined from the corresponding soil unit identified from the table of the soil properties. Table 3.2 shows some soil types and properties.

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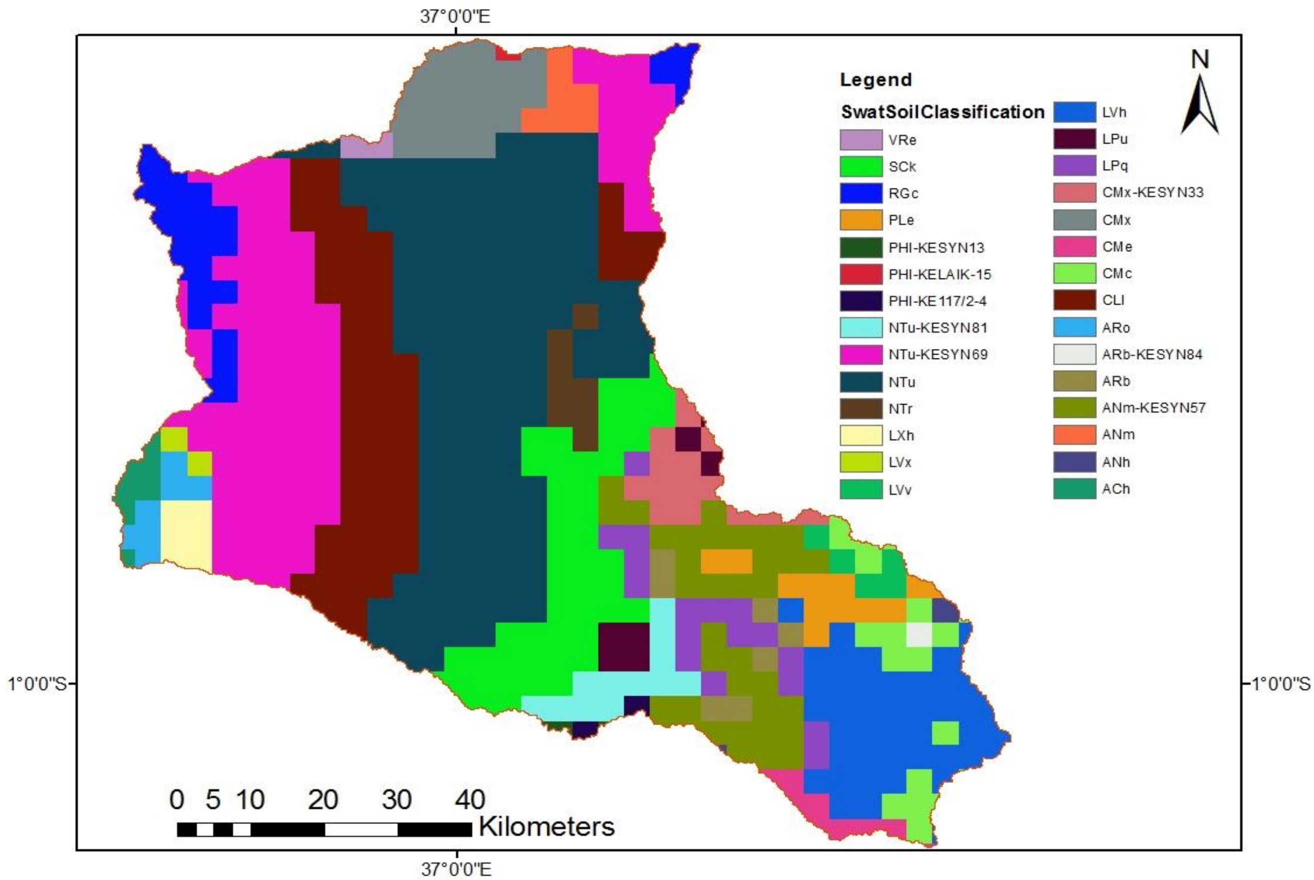

Figure 3. 8: Soil map of Masinga dam catchment

Table 3. 1: Soils description

Soil code	Soil name	%sand	%silt	%clay	CEC	Bulk density	TAWC
NTu	Nitosols	7	31	62	21.4	1.10	23
HSs	Histosols	30	56	14	15	0.36	35.0
VRe	Vertisols	30	30	40	40	1.49	12
ANm	Andosols	59	20	21	33	1.13	17.0
PHI	Phaeozem	24	17	59	14	1.10	11.0

3.5.6 Land use

Land use is one of the most important factors that affects surface erosion, runoff, and evapotranspiration in a watershed. The land use shapefile of the study area was downloaded from MWI. The reclassification of the land use map was done to represent the land use according to the specific land cover types such as type of crop, pasture and forest.

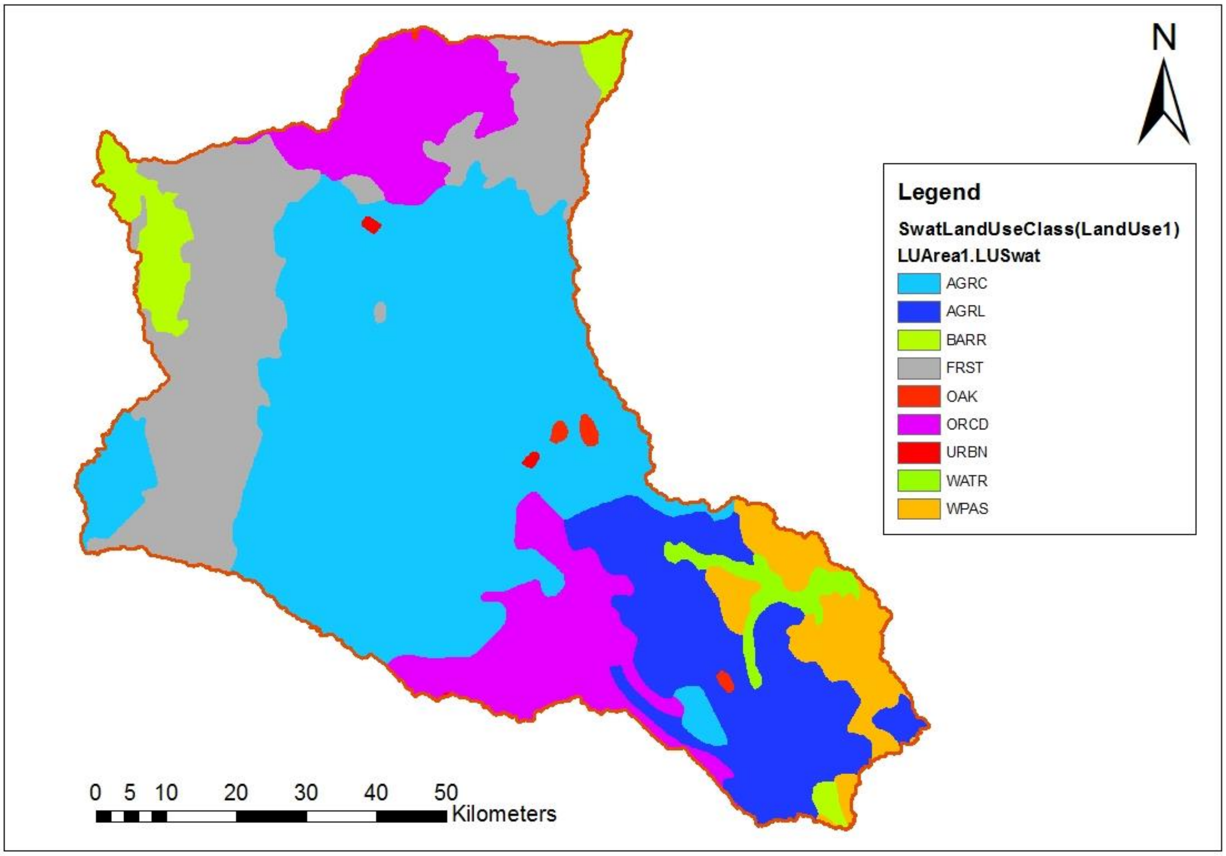

Figure 3. 9: Land use map for Masinga dam basin

3.5.7 Weather data

SWAT requires daily meteorological data that can either be read from a measured data set or be generated by a weather generator model. The weather generator provides input data to SWAT being statistical parameters derived from the weather information. The weather generator data was derived from the thirty years daily data (1983-2013) on rainfall, minimum temperature, maximum temperature, relative humidity, wind speed, solar radiation and dew point temperature. The data output included the following for precipitation:

i. Average monthly precipitation (PCP_MM).

ii. Standard deviation for precipitation (PCPSTD).
iii. Skew coefficient (PCPSKW).
iv. Probability of a wet day following a dry day (PR_W1).
v. Probability of a wet day following a wet day (PR_W2)
vi. Average number of days of precipitation in month(PCPD).

Similar information was also determined for other weather variables. The weather variables used in this study for driving the hydrological balance are daily precipitation, minimum and maximum air temperature for the period 1983 to 2013. These data were obtained from KMD for stations located within and around the watershed.

3.5.8 Discharge data

Daily river discharge values the Masinga catchment were obtained from the WRMA and the Ministry of Water. These daily river discharges were used for model calibration and validation.

3.5.9 Model simulation run

Having successfully loaded the required data, the model was able to run and produce the necessary output information on streamflow on a daily, monthly or yearly basis.

3.5.10 Model Setup

The model setup involved five steps: (1) data preparation; (2) sub basin discretization: (3) HRU definition; (4) parameter sensitivity analysis; (5) calibration and uncertainty analysis. Hydrological modeling using SWAT requires the use of detailed spatially explicit datasets on land morphology or topography, land use or land cover, soil classification and parameters for hydrological characteristics, and climate and hydrological data on a daily time-step (Schuol *et al.*, 2007).

The DEM, Land cover and soil datasets were projected to Arc 1960 UTM Zone 37S by use of ArcGIS 10.2. Arc 1960 UTM Zone 37S is the Transverse Mercator projection parameters for

Kenya. Using the DEM, the watershed was delineated by the use of ArcSWAT extension in the ArcGIS software. The watershed delineation process includes five major steps, DEM setup, stream definition, outlet and inlet definition, watershed outlets selection and definition and calculation of sub basin parameters. The model first defines flow direction and accumulation which is then used for stream network and outlets development. Upon selection of preferred basin outlet position, the model was able to delineate the watershed using the DEM and also develop sub basins. The sub basin parameters including area, perimeter and mean elevation were then calculated. In order to be incorporated into the ArcSWAT model, the Land use/Land cover spatial data sets were reclassified into SWAT land cover/plant types. A user look-up table was created to identify the SWAT code for the different categories of land cover/land use on the map as per the required format. The soil map was linked with the user soil database which is a soil database designed to hold data for soils not included in the United States. Subdividing the sub watershed into areas having unique land use, soil and slope combinations makes it possible to study the differences in evapotranspiration and other hydrologic conditions for different land covers, soils and slopes.

The soil, land use and slope datasets were imported overlaid and linked with the ArcSWAT databases. To define the distributions of HRUs both single and multiple HRU definition options were tested. For multiple HRU definition the ArcSWAT user's manual suggests that a 20 percent land use, a 10 percent soil and 20 percent slope threshold are adequate for most applications. To identify the most reasonable threshold level in the area the suggested threshold and other land use, soil and slope combinations scenarios were tested. These were 20% - 10% - 20%, 10% - 20% - 10%, 10% - 10% - 20%, 20% - 20% - 10%, and 25% - 30% - 20%. Each scenario was arranged in order of land use percentage over sub basin area, soil class percentage over land use area and slope class percentage over soil area. For example, if a 20% soil area is defined in HRU distribution, only soils that occupy more than 20% of a sub watershed area are considered in HRU distributions. Land uses, soils or slope that cover a percentage of the sub basin area less than the threshold level were eliminated. After the elimination processes the area of the land use, soil or slope is reallocated so that 100 percent of the land area, soil or slope in the sub basin is included in the simulation.

The ArcSWAT model to run, it requires input of meteorological data on daily time step. The weather parameters include precipitation, temperature, relative humidity and solar radiation for the study area over the study period. In absence of consistent daily data, the model is able to simulate the weather data using the weather generator model. The weather generator model requires input of average monthly weather data.

3.5.11 Model Calibration and Validation

SWAT input parameters are process based and must be held within a realistic uncertainty range. The first step in the calibration and validation process in SWAT is the determination of the most sensitive parameters for a given watershed or sub watershed. The user determines which variables to adjust based on expert judgment or on sensitivity analysis. Sensitivity analysis is the process of determining the rate of change in model output with respect to changes in model inputs.

Sensitivity analysis in practical sense helps determine the predominant processes for the component of interest. Two types of sensitivity analysis are generally performed: local analysis, which entails changing one value at a time, and global sensitivity analysis, which involves allowing all parameter values to change. The two procedures, however, may yield different results. Sensitivity of one parameter often depends on the value of other related parameters; hence, the problem with one-at-a-time analysis is that the correct values of other parameters that are fixed are never known (Arnold, *et al.,* 2012). The disadvantage of the global sensitivity analysis is that it needs a large number of simulations. Both procedures provide insight into the sensitivity of the parameters and are necessary steps in model calibration.

The parameter sensitivity analysis was done using the SWATCUP interface for the whole catchment area. Ten hydrological parameters were tested for sensitivity analysis for the simulation of the stream flow in the study area. Here, the default lower and upper bound parameter values was used. SWATCUP is a freely available computer program, which calibrates the swat model by linking it to several calibration algorithms. It provides user-friendly interface for sensitivity analysis, calibration and validation of the SWAT model output.

Parameter sensitivities are determined by calculating a multiple regression system as shown in equation 3.8, which regresses the latin hypercube generated parameters against the objective function values

$$g = \alpha + \sum_{i=1}^{m} \beta_i b_i \qquad (3.8).$$

A t- test is then used to identify the relative significance of each parameter, b_i. The t-stat is the coefficient of the parameter divided by its standard error. It is used as measure of the precision with which the regression coefficient is measured.

The second step is the calibration process. Calibration is an effort to better parameterize a model to a given set of local conditions, thereby reducing the prediction uncertainty. Model calibration is performed by carefully selecting values for model input parameters (within their respective un-certainty ranges) by comparing model predictions for a given set of assumed conditions with observed data for the same conditions. The final step is validation for the component of interest (streamflow, sediment yields, etc.). Model validation is the process of demonstrating that a given site-specific model is capable of making sufficiently accurate simulations, although “sufficiently accurate” can vary based on project goals (Refsgaard, 1997). Validation involves running a model using parameters that were determined during the calibration process, and comparing the predictions to observed data not used in the calibration.

The calibration and validation procedures should be ideally process and spatially based, while taking into account input, model, and parameter uncertainties. Streamflow is a good example of a process-based calibration, this is because streamflow processes are comprised of the water balance in the land phase of the hydrology, including evapotranspiration, lateral flow, surface runoff, return flow, tile flow, channel transmission losses, and deep aquifer recharge. If data are available for each of these processes, they should be calibrated individually. If a longer time period is available for hydrology than water quality data, it is important to use all the hydrology data available for calibration and validation to capture long-term trends. This process-based calibration should be done at the sub watershed or landscape level to ensure that variability in the predominant processes for each of the sub watersheds is captured instead of determining global (watershed-wide) processes (Arnold, *et al.*, 2012).

Calibration and validation are typically performed by splitting the available observed data into two datasets: one for calibration, and another for validation. Data are most frequently split by time periods, carefully ensuring that the climate data used for both calibration and validation are not substantially different, i.e., wet, moderate, and dry years occur in both periods.

The calibration and uncertainty analysis were done using Sequential Uncertainty Fitting algorithm, SUFI-2. In the SUFI-2 algorithm, uncertainty in parameters accounts for all sources of uncertainties such as uncertainty in driving variables for example, rainfall, conceptual model parameters and the measured data. Propagation of the uncertainties in the parameters leads to uncertainties in the model output variables, which are expressed as he 95 per cent probability distributions which are calculated at the 2.5% and 97.5% levels of cumulative distribution of an output variable generated by the propagation of the parameter uncertainties (Abbaspour, 2015).

Another measure quantifying the strength of a calibration or uncertainty analysis is the r-factor which is the average thickness of the 95PPU band divided by the standard deviation of the measured data. The goodness of calibration and prediction uncertainty is judged on the basis of the closeness of the p-factor to 100% (i.e., all observations bracketed by the prediction uncertainty) and the r-factor to 1. The r-factor is calculated by Equation 3.9

$$r-factor = \frac{p-factor}{\sigma_{obs}} \tag{3.9}$$

Where σ_{obs} is the standard deviation of the observed data.

The metrics and methods used to compare observed data to model predictions are also important. Multiple graphical and statistical methods could be used, such as coefficient of determination, time-series plots, Nash-Sutcliffe efficiency (NSE; Nash and Sutcliffe, 1970), and percent bias.

Coefficient of Determination (R2) and Nash–Sutcliffe Simulation Efficiency (ENS) were used as the goodness of fit measures during calibration and validation of the model. Coefficient of determination (R2) and Nash-Sutcliffe coefficient (NSE) are calculated by equation 3.10 and 3.11 respectively.

$$R^2 = \frac{\left[\sum_i (Q_{m,i}-\bar{Q}_m)(Q_{s,j}-\bar{Q}_s)\right]^2}{\sum_i (Q_{m,i}-\bar{Q}_m)^2 \sum_i (Q_{s,j}-\bar{Q}_s)^2} \tag{3.10}$$

$$NSE = 1 - \frac{\sum_i (Q_m - Q_s)^2}{\sum_i (Q_{m,i}-\bar{Q}_m)^2} \tag{3.11}$$

In which, Q_m is the measured discharge, Qs is the simulated discharge, $\bar{Q}_m$ is the average measured discharge and $\bar{Q}_s$ is the average simulated discharge.

After setting up and running of the ArcSWAT model, the default simulations of stream flow, using the default parameter values, were done in the upper Tana river basin for the calibration period (1983- 2013). In this study, SWAT Calibration Uncertainty Program, SWAT-CUP was used for calibration and validation of the SWAT model. The default simulation outputs obtained by the model were compared with the observed streamflow data. The data for period 2008 to 2013 was used for model calibration and validation. After the completion of the validation exercise, the final parameter values were incorporated into the SWAT model for further applications.

3.5.12 Climate Change Scenarios

For the climate change scenarios in this study, regional projections of climate change were based on a research carried out by Gosling *et al.*, (2011): Climate: Observations, projections and impacts. The regional averages of temperature and precipitation projections were developed from a set of 21 CMIP3 models, which were statistically downscaled for the year 2100 for different scenarios for Kenya. Climate models are used to understand how the climate will evolve over time and typically represent the atmosphere, ocean, land surface, cryosphere, and biogeochemical processes, and solve the equations governing their evolution on a geographical grid covering the globe. Some processes are represented explicitly within climate models, large-scale circulations for instance, while others are represented by simplified parameterisations (Gosling *et al.*, 2011). The projections were done under the A1B SRES scenario. GCM‟s are numerical coupled models that represent various earth systems including the atmosphere, oceans, land surface and sea-ice and offer considerable potential for the study of climate change and variability. Scenarios are neither predictions nor forecasts, they are images of the future, or alternative futures (Mango, *et al.*, 2010).

The SRES scenarios are grouped into four scenario families (A1, A2, B1 and B2) that explore alternative development pathways, covering a wide range of demographic, economic and technological driving forces and resulting GHG emissions. The SRES scenarios do not include additional climate policies above current ones. The emissions projections are widely used in the assessments of future climate change, and their underlying assumptions with respect to socio-economic, demographic and technological change serve as inputs to many recent climate change vulnerability and impact assessments.

As described in IPCC Fourth Assessment Report: Climate Change (2007), the A1 storyline assumes a world of very rapid economic growth, a global population that peaks in mid-century and rapid introduction of new and more efficient technologies. A1 is divided into three groups that describe alternative directions of technological change: fossil intensive (A1FI), non-fossil energy resources (A1T) and a balance across all sources (A1B). B1 describes a convergent world, with the same global population as A1, but with more rapid changes in economic structures toward a service and information economy. B2 describes a world with intermediate population and economic growth, emphasizing local solutions to economic, social, and environmental sustainability. A2 describes a very heterogeneous world with high population growth, slow economic development and slow technological change. No likelihood has been attached to any of the SRES scenarios. The climate scenarios explored were then carried out by adjusting the monthly precipitation and temperature files in the model database and running the simulations with the best parameters acquired from the calibration process.

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CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Temperature and precipitation trends from 1983 to 2013.

Specific climate change indicators and their effects on hydropower output based on the Masinga dam reservoir have been summarized in the table below. The table represents the catchment average maximum, minimum, and mean annual temperatures in degrees Celsius, the average annual rainfall intensity in millimeters and the reservoir inflow from upstream rivers in cubic meters per second.

Table 4. 1: Climate change indicators in Masinga catchment

Year	**Mean Min Annual Temperature** (°C)	**Mean Max Annual Temperature** (°C)	**Mean Annual Temperature** (°C)	**Mean Annual Precipitation** (mm)	**Reservoir inflows** (m^3/s)
1983	14.54	24.84	19.45	90.88	65.30
1984	13.88	24.57	19.15	78.27	33.00
1985	13.70	23.71	18.15	107.43	80.20
1986	13.83	24.31	19.45	100.58	70.90
1987	14.23	25.02	19.00	81.70	54.70
1988	14.53	24.12	20.80	157.00	93.80
1989	13.88	23.25	18.70	112.35	90.20
1990	14.00	23.88	18.70	143.41	120.10
1991	14.13	24.40	18.70	80.91	58.70
1992	14.19	24.34	19.20	85.59	55.60
1993	14.03	23.82	18.40	86.97	58.10
1994	14.23	24.40	19.35	133.46	83.70
1995	14.11	23.88	19.30	120.56	88.50
1996	14.01	24.12	18.50	73.29	46.40
1997	14.39	25.05	20.00	138.98	111.80
1998	14.43	24.06	19.95	133.98	157.5
1999	14.25	24.78	19.35	104.10	48.10

2000	13.85	25.38	18.75	41.62	21.40
2001	14.56	24.70	19.46	96.96	60.40
2002	14.62	24.46	19.60	145.57	85.40
2003	14.14	24.96	19.37	115.37	90.60
2004	14.30	24.88	19.90	97.42	51.90
2005	14.18	24.85	19.70	79.38	48.30
2006	14.28	24.80	19.30	148.30	76.20
2007	14.49	24.66	19.10	95.37	37.00
2008	14.13	24.69	18.90	84.41	35.20
2009	14.74	25.58	20.05	86.56	22.80
2010	14.75	24.72	20.00	92.06	98.60
2011	14.67	25.31	19.95	103.12	66.10
2012	14.38	25.08	19.85	128.87	52.60
2013	13.45	24.87	18.54	81.74	32.50

4.1.1 Temperature trends

Over the past three decades, the mean monthly and annual temperatures in Masinga catchment shows an increasing trend. Based on table 4.1, the mean maximum and minimum annual temperature trends indicate that the catchment temperatures are rising at 0.030°C and 0.010°C respectively from 1983 to 2013 (Figure 4.1 and 4.2).

The table 4.1 also indicates a decadal mean annual temperature increase of 0.18°C as shown in Figure 3.3, if sustained; this temperature rise would yield to a 1.8°C rise in mean temperatures in about 100 years. The increase in Masinga catchment temperature is a complex phenomenon which can be attributed to both natural processes and anthropogenic activities. It is important to note the fact that increased temperatures would equivocally yield greater surface evaporation rates, diminishing surface water availability and soil moisture changes. According to Arnel and Reynard (1993) research findings, potential evapotranspiration simulations showed that based on temperature rise only, evapotranspiration in England and Wales would increase by over 10% by 2050.

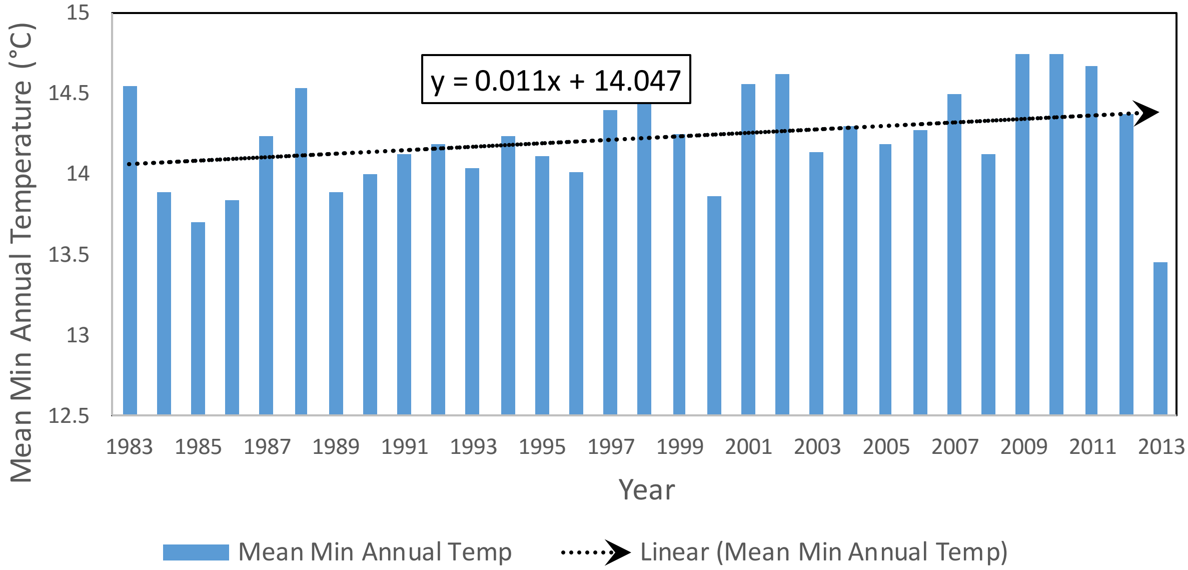

Figure 4. 1: Annual Mean Minimum Temperatures in Masinga catchment

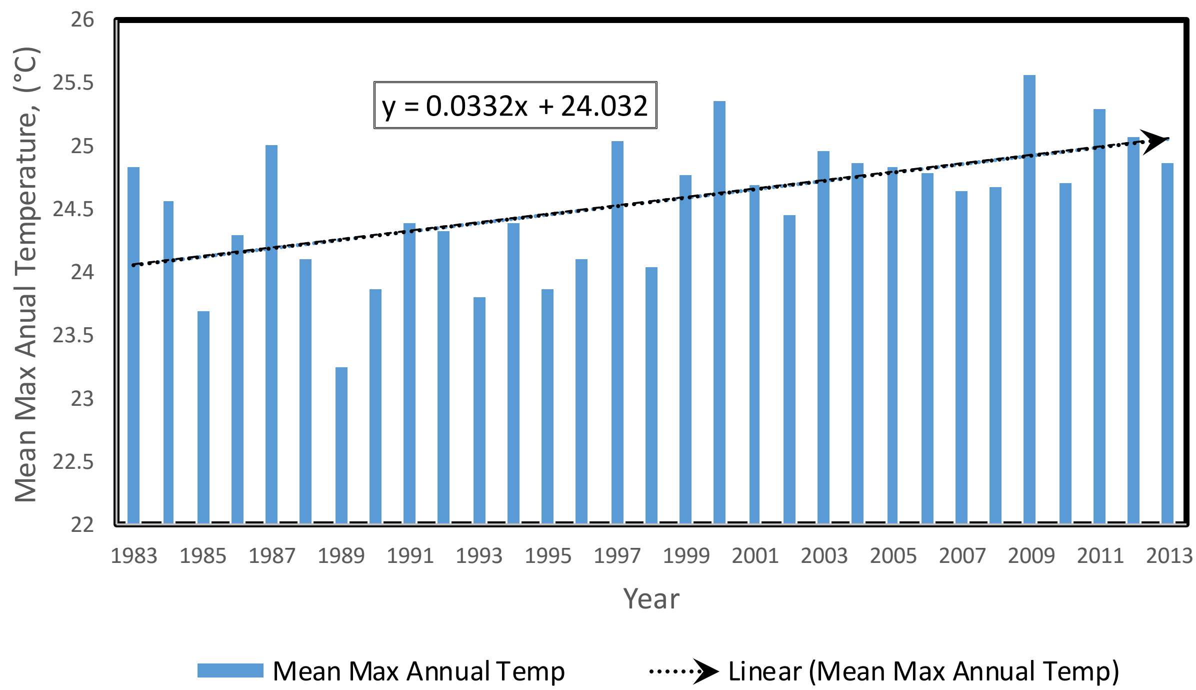

Figure 4. 2: Annual Mean Maximum Temperatures in Masinga Catchment

The temperature increase in Masinga catchment affects the reservoir inflows through increased evaporation, low precipitation, season shift, frequency of occurrence of extreme weather events like floods and droughts and biodiversity imbalance. Increasing catchment temperatures trend-lines conforms to global warming effects which occur as a result of climate change. Climate change results in increasingly unpredictable weather patterns, making hydropower plants ineffective due to reduced reservoir inflows to non-sustainable levels during dry seasons.

The dry period between January and March has recorded the highest mean maximum temperatures over the study period. (Fig. 4.3). Since this follows a wet season, it leads to rapid deletion of water resources thereby affecting Masinga reservoir levels and hydropower generation. Increased catchment temperatures lead to changes in the water balance. Increased temperatures will possibly lead to increases soil erosion in the catchment because the catchment area is likely to become barer because of the dry conditions brought about by the increasing temperatures. Increasing soil erosion rate will consequently result to higher reservoir sedimentation which will in effect affect hydropower generation by reducing the storage capacity of the dam.

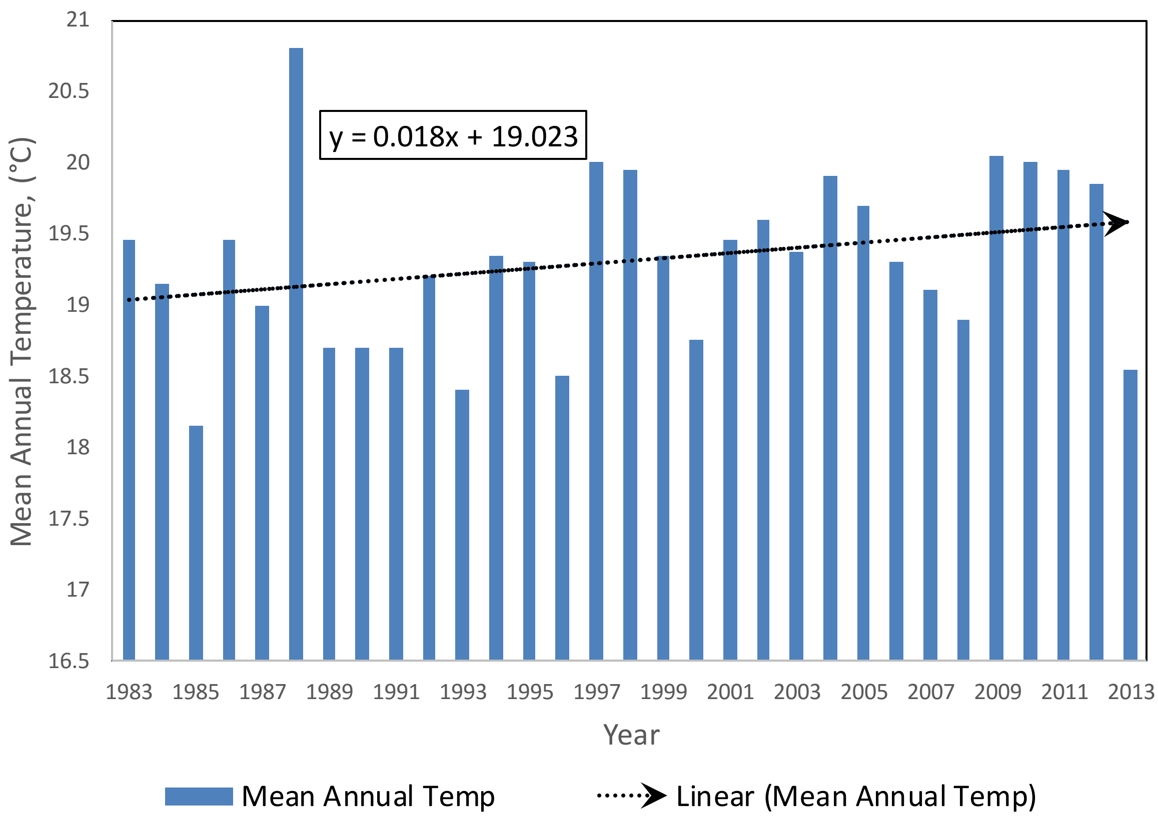

Figure 4. 3: Mean Annual Temperatures in Masinga Catchment

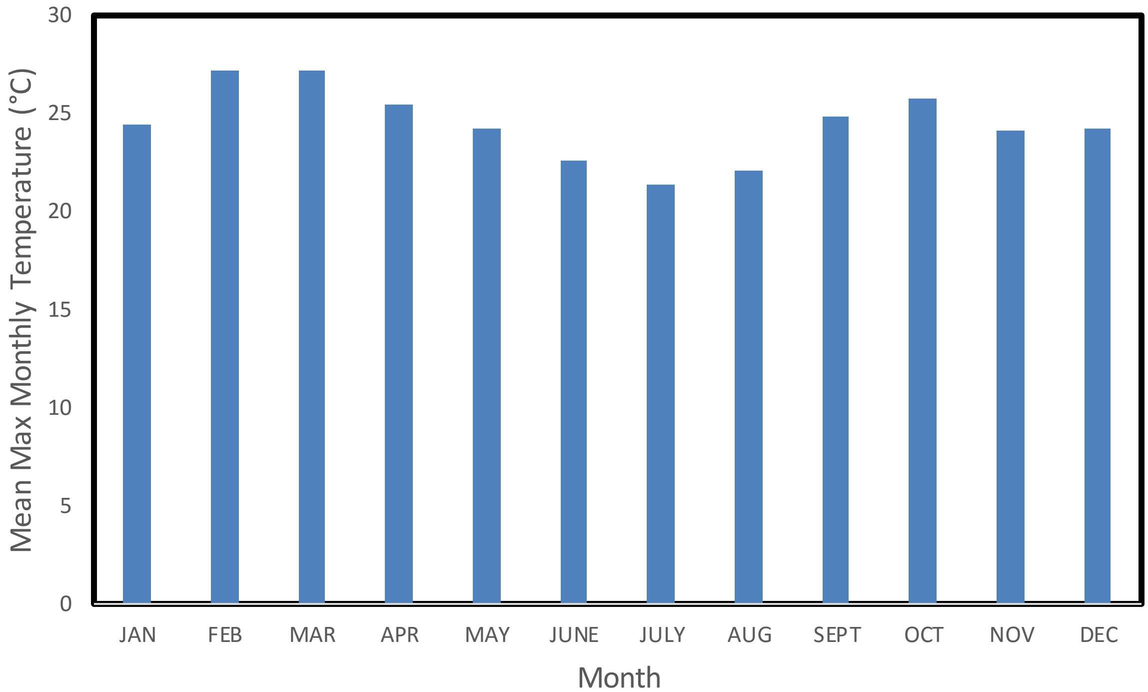

Figure 4. 4: Mean Monthly Temperatures in Masinga Catchment

4.1.2 Precipitation trends

Rainfall intensity and distribution is a key factor in determining the hydrology of a catchment. Masinga catchment annual average precipitation based on Embu and Nyeri weather stations shows that the amount of rainfall received between 1883 and 2013 is gradually and steadily decreasing as indicated by Figure 4.5. Decreasing Masinga catchment precipitation affects both the river flows and the Masinga reservoir levels and volume especially during the dry spells which occur between June and September and January to March. June is the driest month with average monthly precipitation levels of about 29.60mm while the coldest month is May with average monthly precipitation of around 187.30mm. The graphs trend line has a negative gradient of 0.45, this implies a decadal decrease of precipitation of about 4.5mm. Even though the catchment precipitation decline is gradual, highly invariable precipitation pattern endangers ability of catchment river flows to sustain economic and steady hydropower generation.

The precipitation in the upper tana catchment is sporadic in nature, the mean precipitation fluctuates from 587mm to 1622mm annually, this yields an annual catchment rainfall range of 1,035mm. This suggests that the catchment will be subjected to more frequent flash floods, which even though they fill the reservoirs more quickly, they don't provide sustainable water supply and leads to reservoir sedimentation.

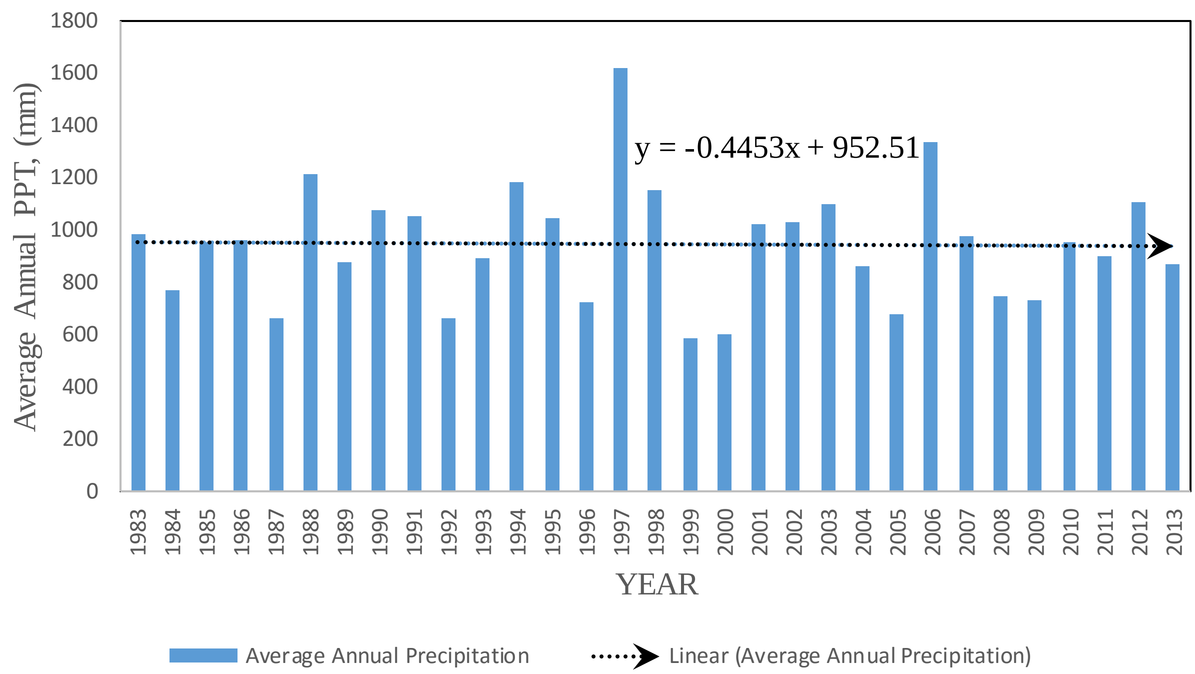

Figure 4. 5: Average annual rainfall intensity in the upper Tana catchment

The gradually decreasing precipitation coupled with the catchments rising temperatures presents the most intricate hydrological processes. The high temperatures have led to increased evapotranspiration rates, due to this, the dry spells are becoming drier which is causing even lower flows.

4.2 Upper Tana River Flow Regime

The stream flow response to rainfall depends on the catchment attributes that include the physiographic, underlying geology, vegetation cover and rainfall amount, intensity, and frequency. The interaction between these attributes and the nature of the response are variable in space and time and induce complexity, which cannot yet be predicted in hydrology (Berhanu et al., 2015). The complexity of stream flow response in a catchment can be addressed through the process of systematically organizing streams into groups that are most similar with respect to their flow characteristics.

The temporal pattern of river flow over a period is the river flow regime, which is a crucial factor sustaining the aquatic and riverine ecosystems. A river flow regime describes an average seasonal behaviour of flow and reflects the climatic and physiographic conditions in a basin. Differences in the regularity of the seasonal patterns reflect different dimensionality of the flow regimes, which can change subject to changes in climate conditions. For analysis of the river flow regime, flow observation period was divided into three classes according to years of flow record, the first class included flow data from 1983 to 1993, the second 1994 to 2003 and the last division was in the period of 2004 to 2013. River flow regime for those periods were analysed and any changes observed.

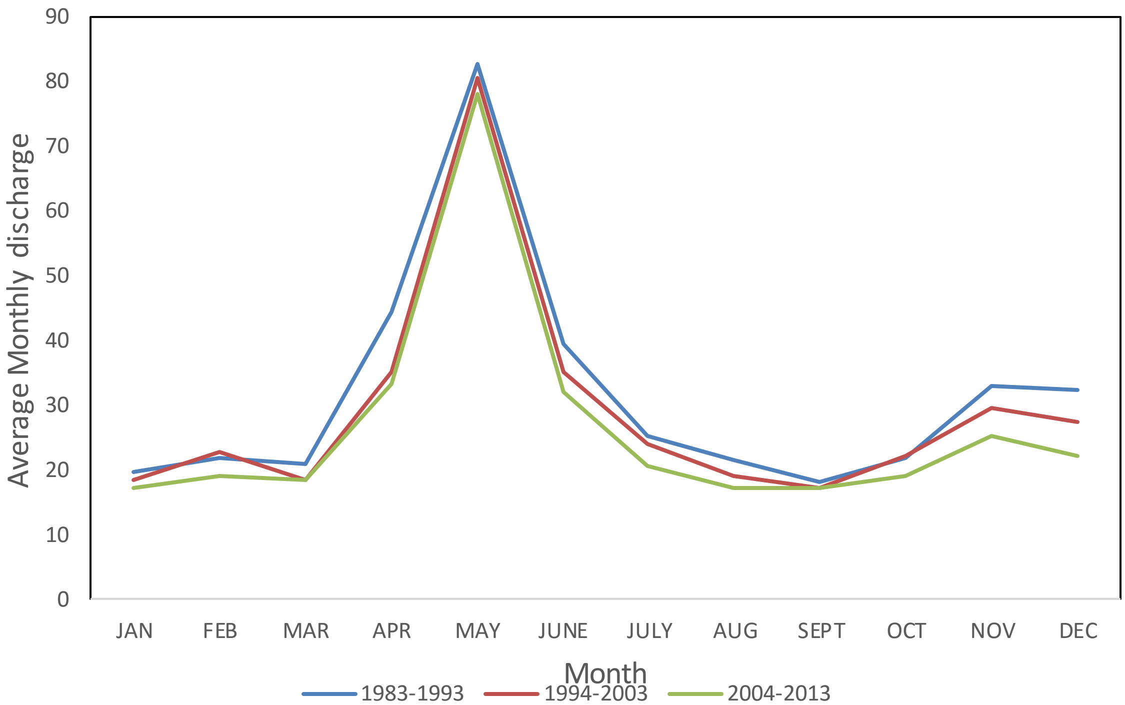

Figure 4. 6 Tana-Sagana river flow regime

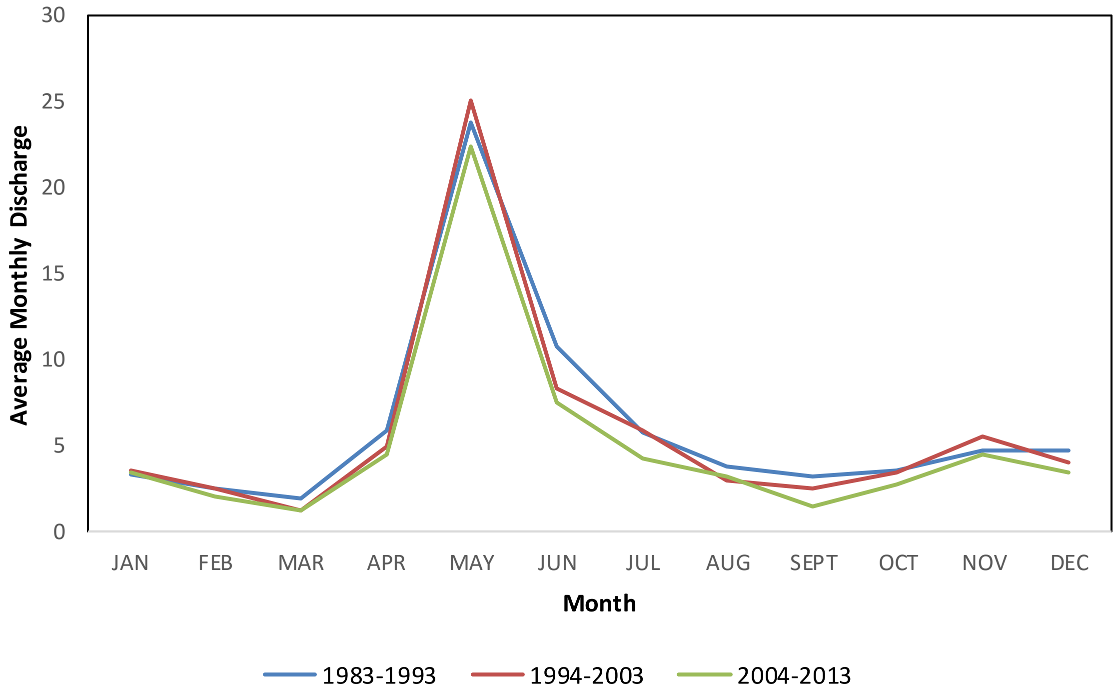

Figure 4. 7 River Thiba flow regime

There has been a gradual decrease in the river discharge over the 30-year study period as shown by the Figures 4.6 and 4.7. The highest peak discharge, which occurs in the month of May has shown a gradual decrease over the years, with the first decade registering a high peak flow of 82.74m^3/s in the Tana-sagana river followed by 80.65 m^3/s in the following decade and finally a high peak flow of 78.1m^3/s in the final decade ending in the year 2013.

The decline in the streamflow over the years is basically due to decline in the amount of water flowing through the river channels, the reduction in the river flow can be attributed to decreasing amounts of precipitation and also the gradually increasing temperatures from the year 1983 to 2013 as shown in Figure 4.5 and 4.3 respectively, which can be attributed to climate change.

4.3 Impact of River Flow Regime on Hydropower Generation

For efficient and sustainable hydropower generation, water availability is an essential component. Changes in the river flow regime in a catchment can affect the amount of water available in the hydropower generating reservoirs which can in turn have an impact on the hydropower plants operation and electricity generation.

4.3.1 Masinga reservoir inflow trends

The data of Masinga reservoir inflow was obtained from KENGEN, the data is based on the dam test flows in cubic meters per second. The inflow rates are determined based on daily dam levels. Based on the trend analysis, the dam inflow rates show a steady decline. (Figure 4.8)

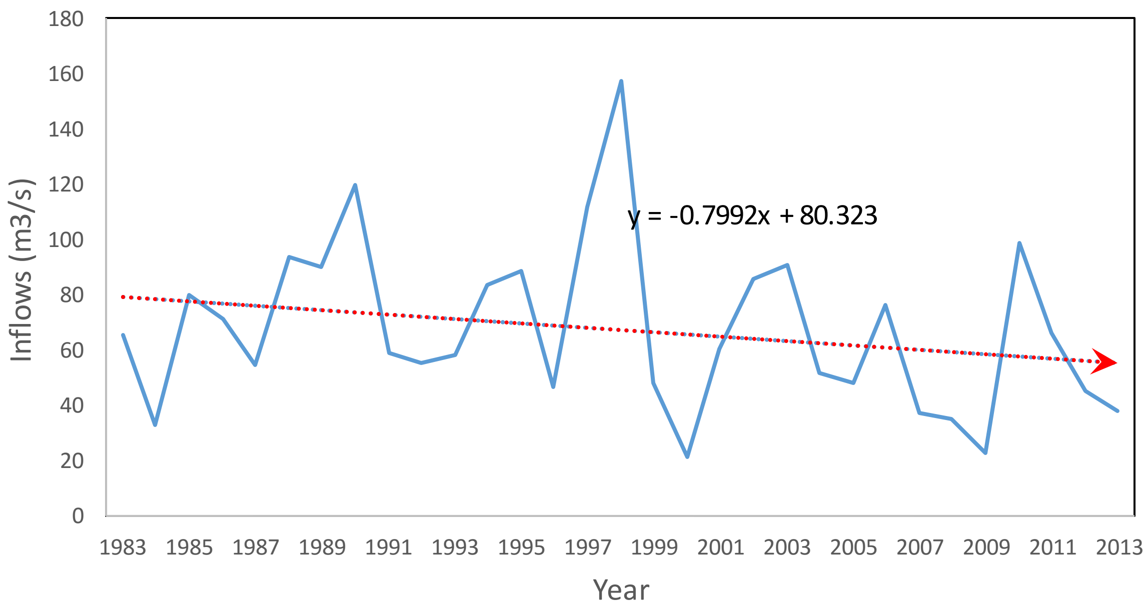

Figure 4. 8: Masinga reservoir inflows

Masinga is the largest reservoir of the seven forks project but has the least power output at 40 MW as indicated in table 3.1. The main purpose of the dam is to store water, regulate flow during dry season, and control downstream flooding of the Tana River system. Just like the catchments precipitation trends, the Masinga dam reservoir inflows indicate a declining trend. This declining trend can hugely be attributed to the decreasing stream flow in the streams contributing to the reservoir recharge. The annual average dam inflows are declining at the rate of 0.7992 annually based on the trend line equation $y=-0.7992x + 80.323$. This means that the reservoir inflow is declining by $0.7992m^3/s$ every year, in 30 years, the reservoir inflows have decreased by 23.98 cumecs. Based on figure 4.6, lowest inflow rates are on the increase with the year 2000 and 2009 recording the lowest inflows of $21.4m^3/s$ and $22.8m^3/s$ respectively. The highest inflow and the lowest inflow have occurred in the last two decades, in 1998 and 2009 respectively, this indicates an increase in extreme weather events like droughts and floods. During the 30-year period recording the lowest inflows on record at 22.8 cumecs (a year that Masinga plant operation was halted and the reservoir water levels declined to worrying levels). The major cause of variations in inflow is the alternating scarce and abundant rainfall pattern, high evapotranspiration rates and increasing catchment temperatures. Reduction in reservoir inflows unswervingly threatens the operation of the Seven Forks Project, because Masinga reservoir plays regulatory functions for subsequent dams and sediment trapping as a more recent function.

4.3.2 Masinga Dam Reservoir Levels

Daily dam reservoir levels were collected from the Kenya Power Generating company (KENGEN) for the period 1990 to 2013. From the obtained data, the mean annual reservoir levels are about 1054m a.s.l. At this level, the dam operates at its optimum capacity. The minimum water level required for power generation is 1035m a.s.l (Saenyi, 2002). In general, the reservoir levels fluctuate between 1057.56m a.s.l which is the highest level to 1035m a.s.l. The water level, however, dropped to its lowest value ever recorded, 1018.68m a.s.l. in 1999/2000 due to a severe drought.

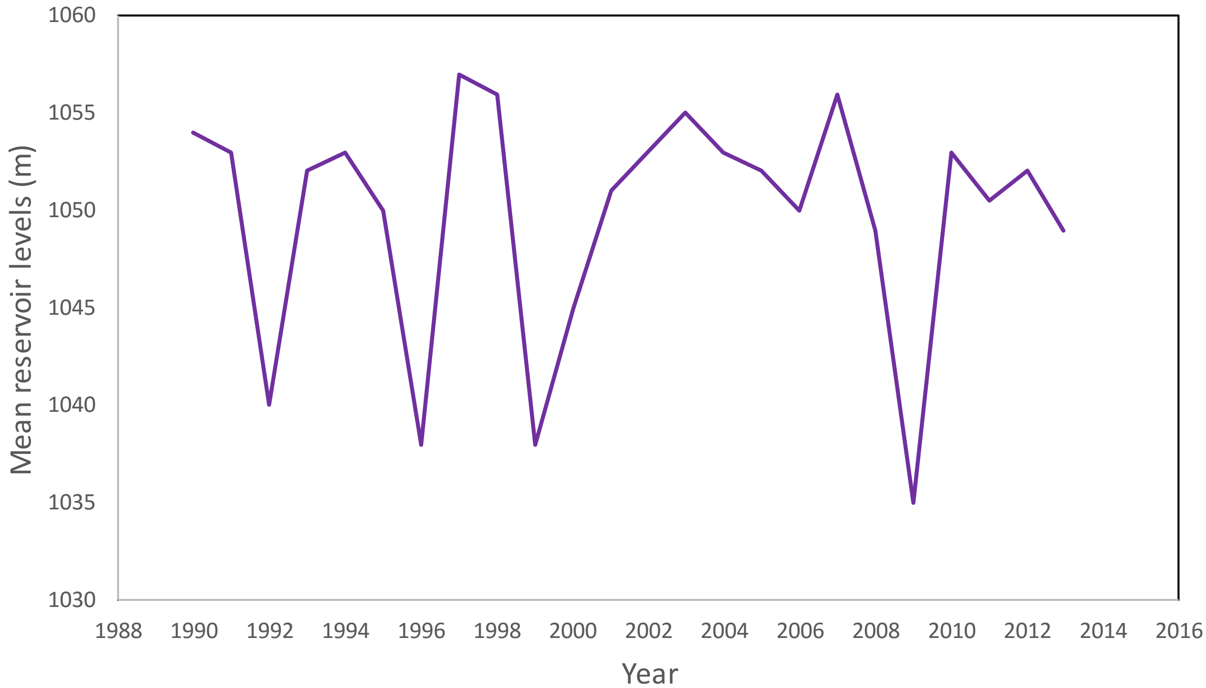

Figure 4. 9: Masinga dam reservoir levels

High dam levels result of higher dam head efficiency and therefore less water is required for generating a single unit of energy. The higher the dam levels the greater the reservoir's surface area and thus higher water storage capacity. Subsequently, any drop in the dam levels adversely affect power generation especially during dry seasons where inflows are minimal. A decline in stream flow in the Masinga catchment located in the upper Tana river catchment have resulted to reduced inflows into the Masinga dam reservoir over the 30-year study period which has subsequently led to reduced reservoir levels. As shown in figure 4.8, the years with the lowest dam inflows also exhibited lowest dam levels.

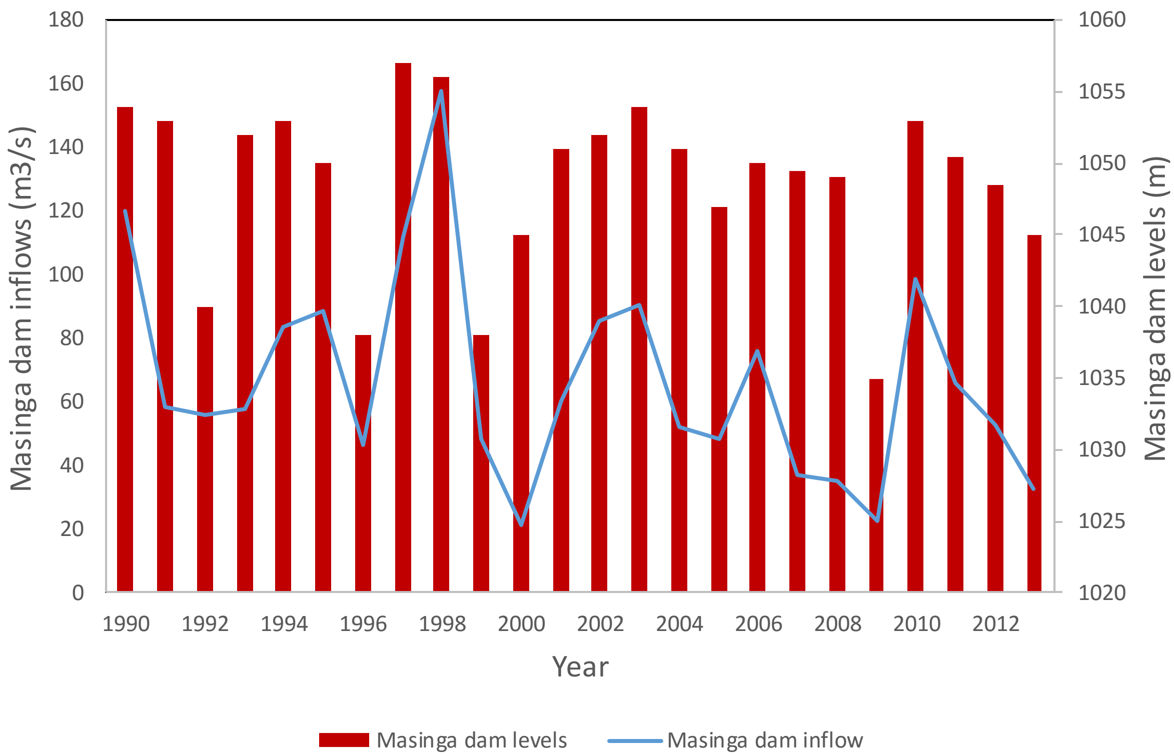

Figure 4. 10: Relationship between dam inflows and water levels

Water is essential for hydropower generation, therefore a decrease in dam water levels will directly have an impact on the power output. Masinga dam is important in the seven folks project because it acts as a regulator of water inflows into the other dams. A decrease of water levels in the Masinga dam will therefore be reflected on all the other hydropower generating dams downstream Tana river. Figure 4.9 illustrates the trend of hydropower generation from the seven folks scheme. There has been a decreasing trend in the amount of hydropower produced in the scheme from 1990 to 2010, as shown in the graph. The driest years, which were 1999-2000 and 2009 recorded the lowest levels of hydropower generation. The hydropower generation was even halted for some months in those years because the dam levels declined below the threshold values. The figure also depicts a clear correlation between stream flow, dam water levels and hydropower generation.

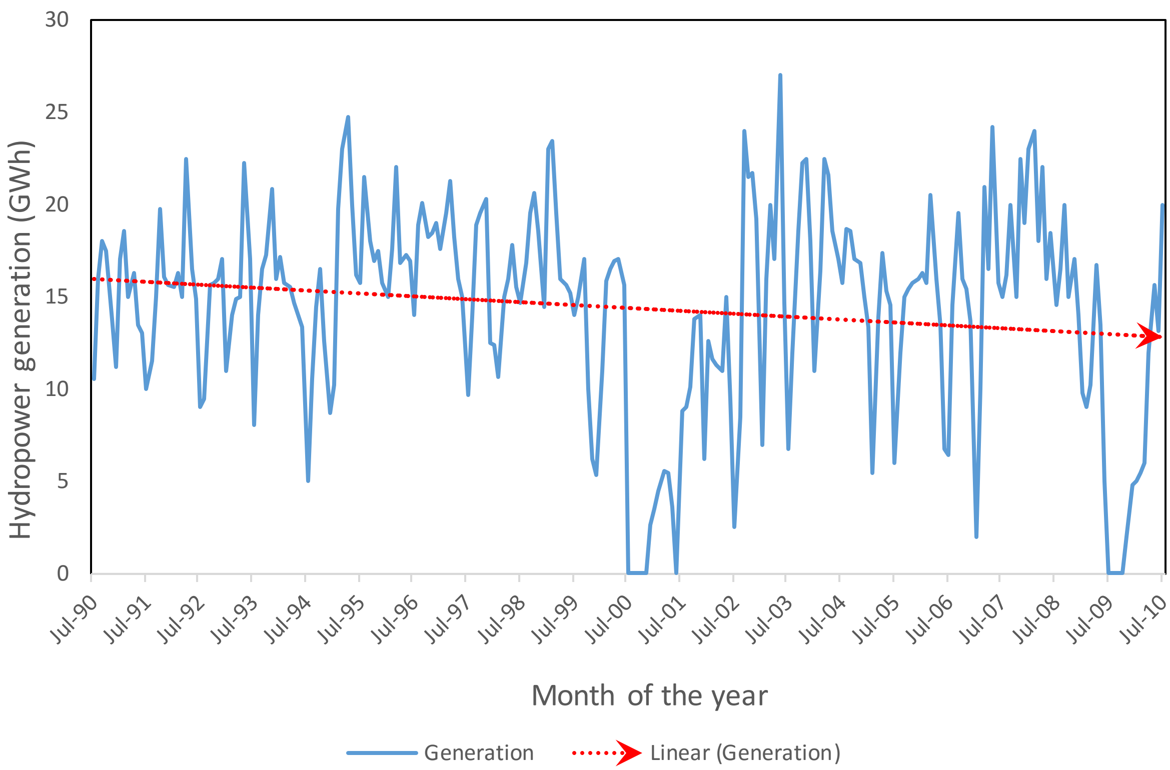

Figure 4. 11: Hydropower generation trend in the seven forks dams

Climate change effects on water resources and subsequently hydropower generation presents an intricate relationship which requires incised analysis to affirm the extent of climate change related events on sustainability of hydropower resources as a significantly reliable source of renewable energy in Kenya (Bunyasi, 2012). Decreasing amounts of precipitation and increasing temperatures have led to declining Masinga dam inflow rates as shown in Figure 4.8 which has led to decreasing hydropower generation over the years. Increasing temperatures will also stress the catchments floral biodiversity which may leave the soil bare and therefore susceptible to agents of erosion. Increased erosion rates in the catchment will lead to sediment deposition in the dams thereby reducing the reservoirs storage volume and also reducing overall dam operation efficiency.

Extreme climatic events like droughts and floods have also been experienced in the catchment with two major dry periods in 2000/2001 and 2009/2010. Occurrence of extreme climatic events threatens the sustainability and operation of hydropower generating structures.

Figure 4.11 shows the relationship between annual reservoir inflows in million cubic meters with the changes in the energy output in each year during the long rains in the months of April, May and June. There is a clear correlation between the amount of inflows into the dams, which can be linked to amounts of precipitation as shown above, and the changes in power generation. Although the observed reservoir inflows in 2002 and 2003 were comparatively high, the changes in energy output were not very significant. This is because these two years followed a very dry period on which the dam levels had reduced to critical levels and most of the inflow served to fill up the already depleted reservoir. This shows that occurrence of extreme climatic events, especially droughts is negatively impacting hydropower generation.

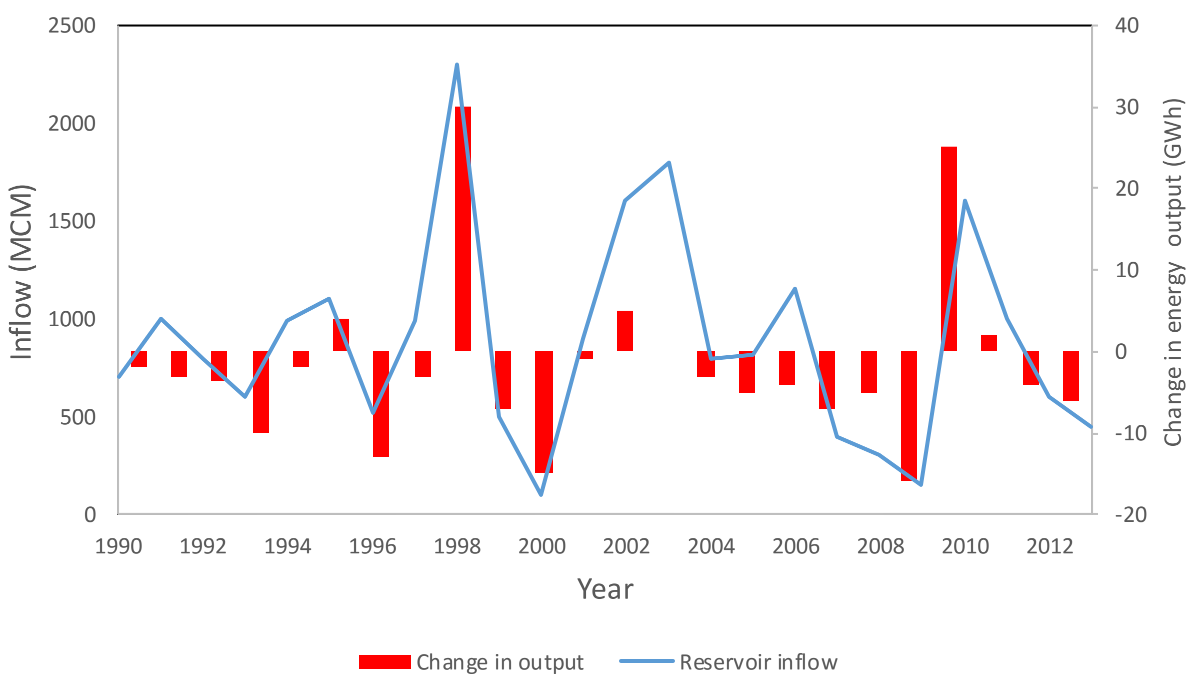

Figure 4. 12: Changes in energy output relative to Masinga dam reservoir inflows

4.4 Simulation of River flow using ArSWAT

4.4.1 Model Results

The model was run based on daily time step for the period 1/12007 to 31/12/2013. The model over predicted flow during certain periods but mostly under predicted stream flow while in some periods, the observed and simulated flows were in agreement. In general, the model under predicted high flows while simulating low flows fairly.

Comparisons based on daily time step are likely to be misleading due to the manner in which the model computes the daily flows which differs from that used in recording observed flows and this affects the values of peak flows (Obiero *et al.*, 2011). Obiero *et al.*, (2011) further argues that the observed flows are based on instantaneous readings taken at a certain time of day, for example 9.00 am in the morning while the simulated flows are based on the daily average. In cases when heavy rainfall occurs close to the time when the observation is about to be read say 7 am in the morning the resulting peak flow is likely to be reflected in the observed record. However, if the rainfall occurs much earlier e.g. the previous day, then it's is likely that the resulting runoff will have passed the catchment outlet before a reading is taken so the peak flow would not be reflected in the daily flow reading.

4.4.2 Parameter sensitivity analysis

In order to get the most sensitive parameters to discharge, global sensitivity analysis was carried out using the SWAT-CUP model. Since the program only reads the first for parameters, it is important to determine the most sensitive parameters in order to obtain optimum results. In this study, sensitivity analysis for eleven parameters has been conducted.

The t-stat and p-value values from the sensitivity analyses are shown in table 4.2

Table 4. 2: Global sensitivity analysis results

	Parameter	**Parameter description**	**p- value**	**t-value**
1	ALPHA_BNK.rte	Baseflow alpha factor for bank storage	0.007296424	0.994181329
2	SURLAG.bsn	Surface runoff lag time	-0.011904293	0.990506838
3	USLE_K(..).sol	USLE equation soil erodibility (K) factor.	0.476632566	0.633837136
4	GW_REVAP.gw	Groundwater "revap" coefficient.	0.525429139	0.599523551
5	ALPHA_BF.gw	Baseflow alpha factor (days).	-0.610638159	0.541723439
6	GWQMN.gw	Treshold depth of water in the shallow aquifer required for return flow to occur (mm).	1.389163824	0.165416496
7	GW_DELAY.gw	Groundwater delay (days)	-5.566938537	4.285139E-08
8	ESCO.hru	Soil evaporation compensation factor.	-6.485533138	2.171143E-10
9	SOL_AWC(..).sol	Available water capacity of the soil layer.	8.364491655	6.379499E-16
10	CN2.mgt	SCS runoff curve number f	-32.04224090	4.1295679E-12
11	CH_N2.rte	Manning's "n" value for the main channel.	54.672859040	3.2135860E-21

CH_N2.rte, CN2.mgt , SOL_AWC.sol and ESCO.hru were the four most sensitive parameters and hence they were adopted for the model calibration and validation. The other parameters had no significant effect on streamflow simulations and therefore changes in their values do not cause significant changes in the model output.

4.4.3 Model Calibration

The comparison between the observed and calibrated flow discharge values using SUFI-2 algorithms for seven years of SWAT simulations showed that there is a good agreement between the observed and simulated flows. The flow simulations together with the observed flow values were based on the outlet of the sub watershed 29. The values of coefficient of determination (R^2) and Nash Sutcliffe efficiency (NSE) were found to be 0.66 and 0.64 respectively after three iterations each with a run of 1000 simulations. SWAT model simulation can be judged as good if R^2 is greater than 0.6 and NSE is greater than 0.5 according to Setegn *et al.*, (2008). The calibration results agree reasonably well with the suggested values. The p-factor, which is the percentage of observations bracketed by the 95% prediction uncertainty (95PPU), brackets 39% of the observation and r-factor equals 0.79. An r-factor of 1 and p-factor o zero suggests a perfect model (Abbaspour, 2015). The results therefore can be deemed satisfactory.

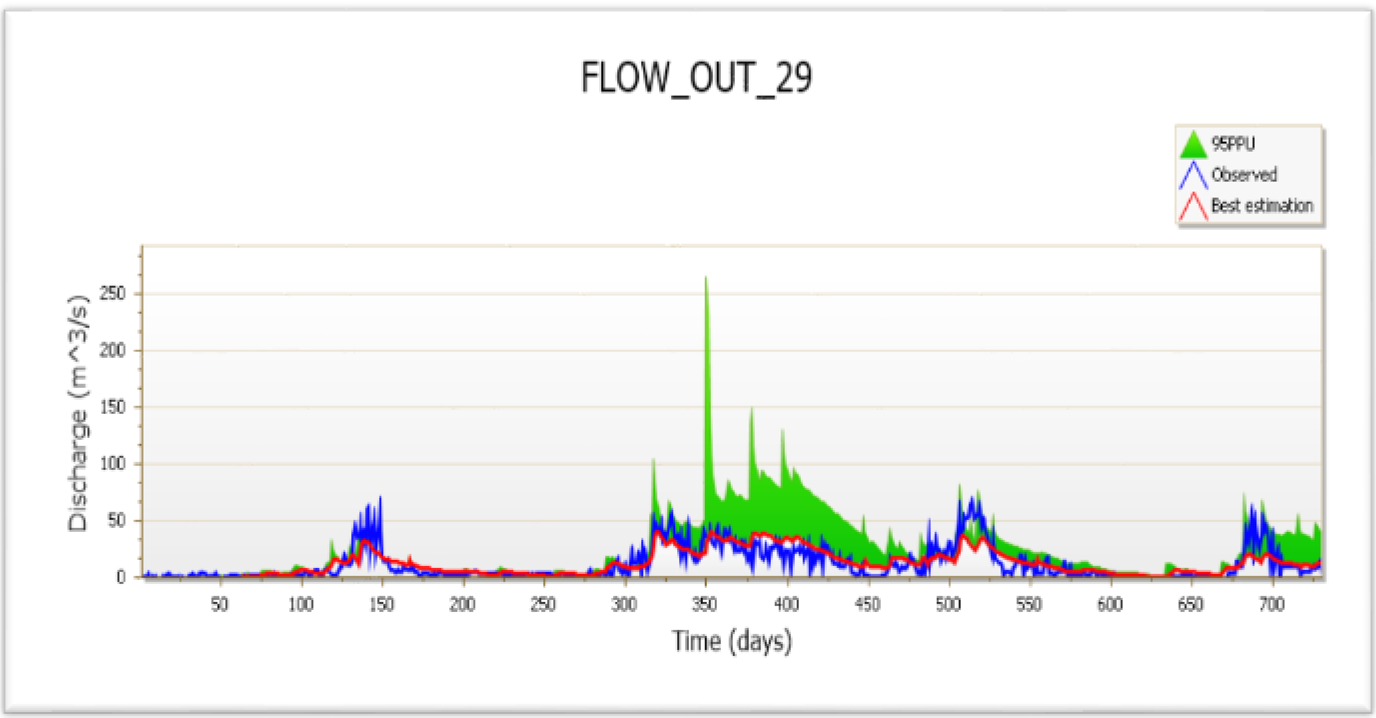

Figure 4. 13: Model calibration results

4.4.4 Model Validation

Based on the optimized parameters obtained during the calibration period, a further simulation was carried out to assess the model performance during the period 1/1/2011 to 31/12/2012 which is outside the period when the model was calibrated. The model validation returned good results with an R2 of 0.72 and NSE of 0.61. The observed and simulated stream flows showed a close fit as shown in figure 4.14.

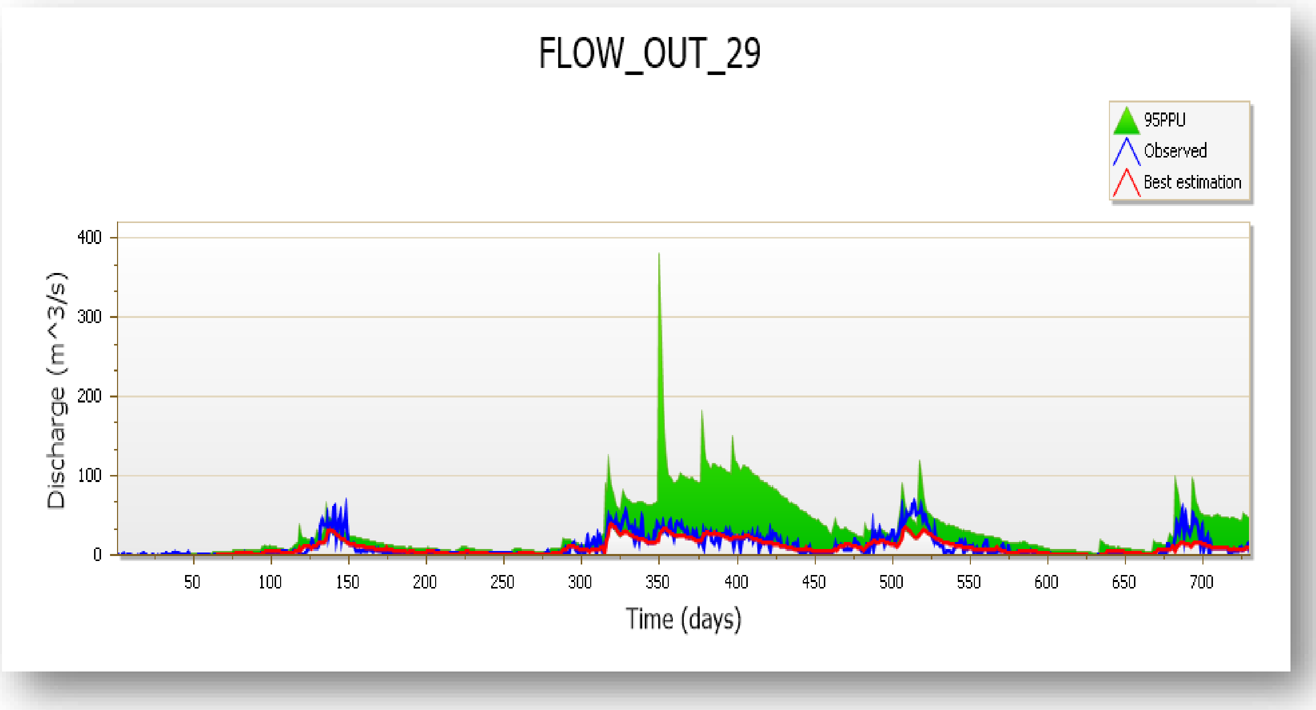

Figure 4. 14: Model validation results

Table 4. 3: Calibration and validation results

	First simulation	**Second simuulation**	**Third simulation**	**Final simulation**	**Validation**
Evaluation statistic	Daily	Daily	Daily	Daily	Daily
Nash-Sutcliffe efficiency (NSE)	0.53	0.57	0.57	0.64	0.61
Coefficient (r)Correlation	6.00	2.01	1.35	0.79	1.5
Coefficient of Determination (R2)	0.56	0.70	0.72	0.66	0.72
RSR	0.69	0.66	0.65	0.60	0.63
PBIAS	20.4	24.4	25.2	8.7	23.3

4.4.5 General Assessment of Model Performance

The NSE index ranged from good to satisfactory for the calibration period. The model was observed to have under estimated peak flows in this study, this is not unique as model applications across the world has yielded diverse results. An explanation for this could be due to inadequate description of rainfall input field due to the limited number of available meteorological stations and poor representation in higher areas due to orographic effects. Only one rainfall station was available to represent the rainfall near the higher elevations of Aberdare ranges.

4.4.6 Climate scenarios

The CMIP3 ensemble output for temperature and precipitation as done by Gosling *et al.,* 2011, for the A1B emission scenario, for Kenya and the surrounding region is shown in Figures 4.15 and 4.16.

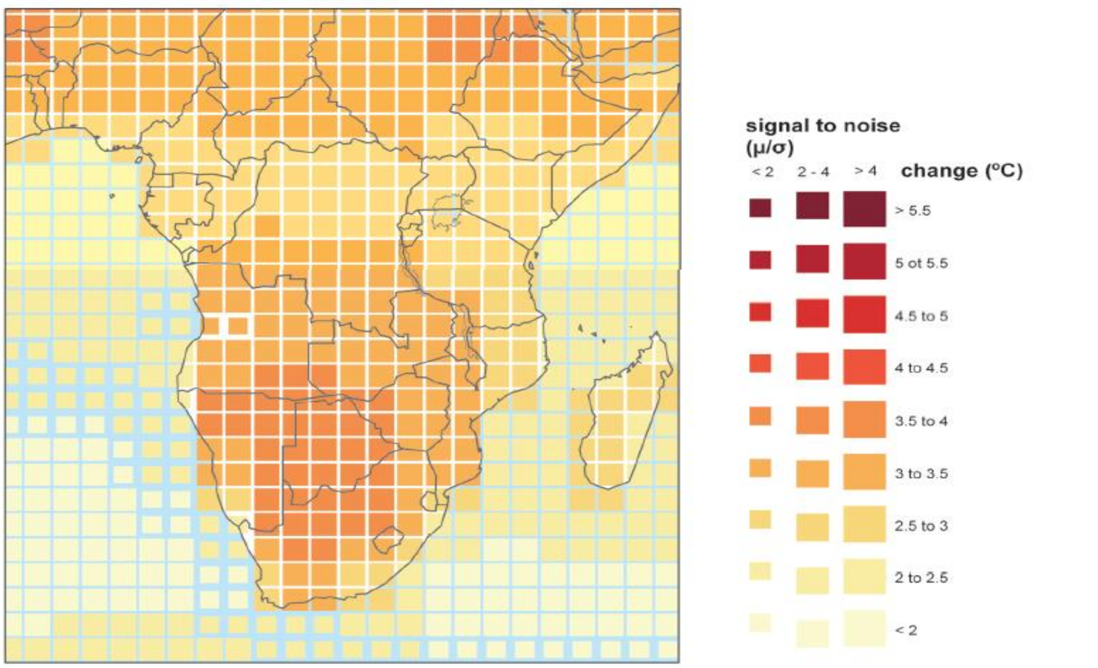

Figure 4. 15 Percentage change in average annual temperature by 2100 from 1960- 1990 baseline climate. Source: Gosling et al, 2011

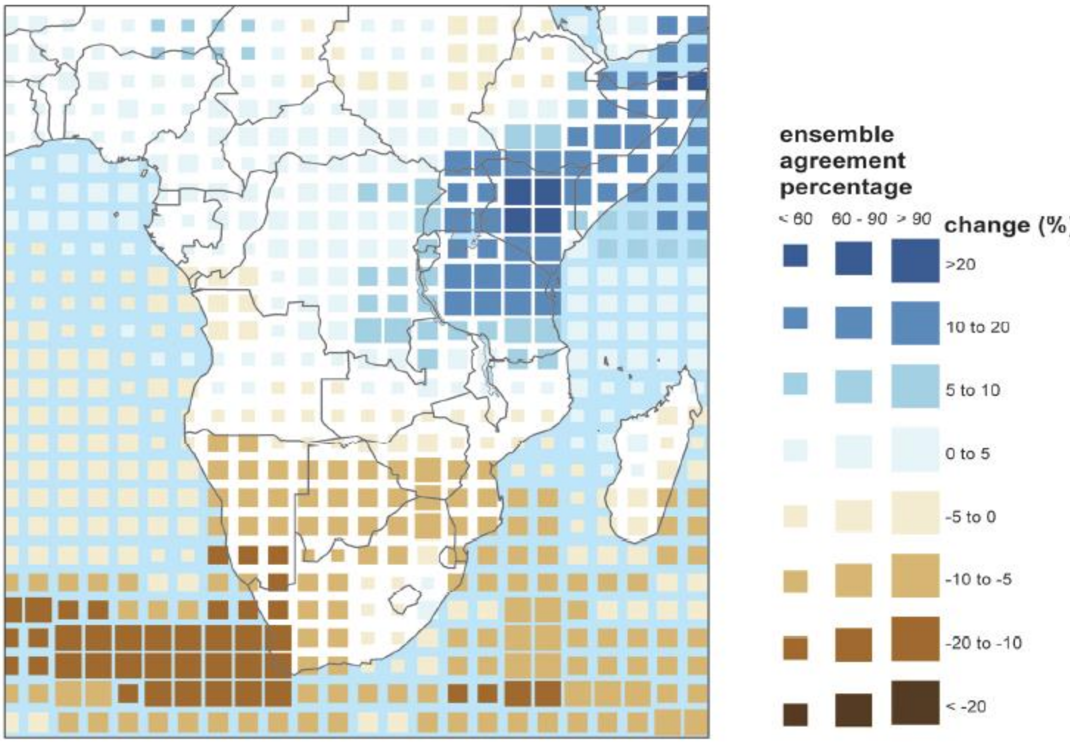

Figure 4. 16: Percentage change in average annual precipitation by 2100 from 1960- 1990 baseline climate. Source Gosling et al, 2011

Figure 4.15 shows the percentage change in average annual temperature by 2100 from 1960- 1990 baseline climate, averaged over 21 CMIP3 models. All of the models in the CMIP3 ensemble project increased temperatures in the future, but the size of each pixel indicates how well the models agree over the magnitude of the increase. Projections for temperature increases over Kenya, of up to around 3°C, show good agreement between the ensemble members.

Figure 4.16 shows the percentage change in average annual precipitation by 2100 from 1960- 1990 baseline climate, averaged over 21 CMIP3 models. Unlike for temperature, the models sometimes disagree over whether precipitation is increasing or decreasing over a region, so in this case the size of each pixel indicates the percentage of the models in the ensemble that agree on the sign of the change in precipitation.

The ArcSWAT model database was updated to represent the expected changes in temperature and precipitation as predicted by Gosling et al, 2011. The model was then run for the reported changes in temperature and precipitation. The figure below shows the model results for stream flow in the year 2100 compared to baseline period of 2010-2020.

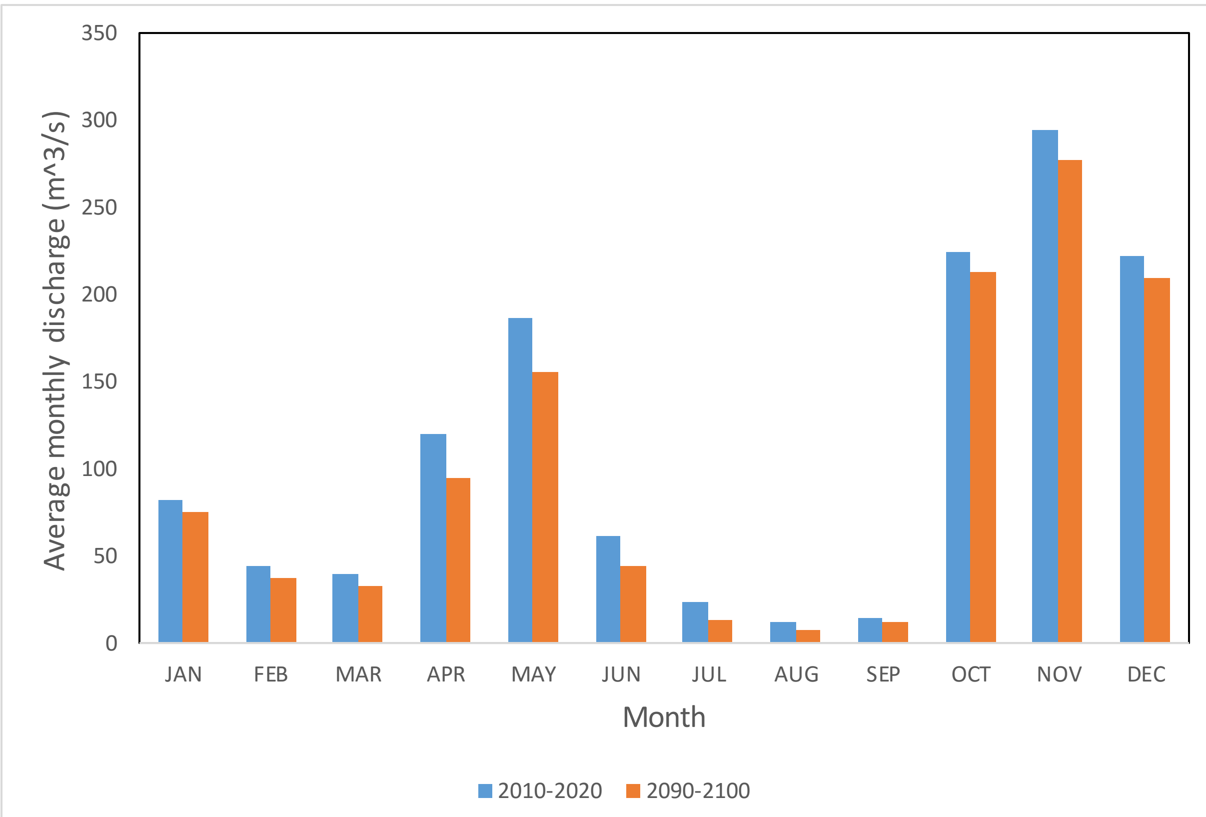

Figure 4. 17: Simulated streamflow in 2090-2100 compared to 2010-2020 baseline

From the Figure 4.17, a 3.5 decrease in temperature and precipitation will result in monthly stream flow reduction in every month of the year. The maximum flow reduction of 31.12m3/s was obtained in the month of May, with other wet months also recording major flow reductions. This shows that the climate change scenario will hugely affect the peak discharge of the Masinga dam catchment. The reduction of peak flow discharge can be attributed to reducing amounts of precipitation together with high evaporation rates due to high temperatures. High flow changes during the wet months can be directly linked to low amounts of precipitation received in the area.

The results above imply that in about a century's time, the mean monthly flow of the Masinga sub catchment will decrease by roughly 18 per cent, mostly as a result of temperature rise and changes in rainfall patterns and intensity. Reduction in stream flow directly affects the dam reservoir levels and hence hydropower generation. Hydropower generation basically relies on reservoir water level, which is directly affected by changes in streamflow upstream the dam.

With stream flow expected to continue declining in the future as a result of climate change, hydropower, one of Kenya's major supply of electricity is expected to be impacted by the declining flows. It is evident that hydropower generation from the seven forks dams has been decreasing over the years and that decrease is not expected to stop as future predictions show a further decrease in stream flow in the contributing basins. Climate change therefore remains a threat to the sustainability of hydropower generation in Kenya and in general a setback in sustainable development.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Climate change is a global phenomenon but the intensity varies on spatial temporal basis and therefore different catchment areas should tailor their own catchment management approaches and policies to cushion water resources and energy sector from the effect of climatic events like floods, droughts, precipitation, temperature variation and evaporation rates. Hydropower generation from the Upper Tana River basin is under threat of climate change specifically due to challenges relating to fluctuating river flows, high temperatures, decreasing and sporadic nature of precipitation and extreme evaporation rates.

There is a strong correlation between precipitation and temperature trends, stream flow, dam levels and hydropower generation from the seven forks dams. The efficient operation of the hydropower plants relies on the ability of the reservoirs to hold water, which depends on the stream flow and river discharge reaching the reservoirs. As the dam inflow rates decreases, the hydropower generation from the dams also decreases. Future simulations of stream flow shows that the downward trend is going to continue for the next century, this will put further strain to hydropower generation in the country.

The decreasing stream flow trend is however due to many factors including human activities upstream of the hydropower dams, precipitation and temperature changes, land use changes and changes in evaporation rates. Climate change impacts on the water resources of the upper Tana River basin can be mitigated by putting in structures and measures that will enhance environmental conservation and therefore safeguard the efficiency of hydropower generation from the dams.

5.2 Recommendations

Climate change is a global and complex phenomena, which is affecting both natural, and human resources across the world. Dealing with climate change therefore requires efforts from a wide range of stakeholders and policy makers working together towards climate change mitigation and building resilience on climatic conditions. This study has shown that climate change is negatively affecting the water resources of the Upper Tana River basin through reduction of Tana River stream flow and dam levels. Both of these factors have led to adverse impacts on the hydropower generation from the seven forks dams. This trend is expected to continue unless effective measures are taken to combat climate change and environmental degradation.

In light of the complexity of climate change, sound policies should be formulated by the authorities concerned with the Upper Tana River basin water resources and all the stakeholders to ensure a sustainable river water recharge and flow, environmental conservation, reduced sediment load, better land use practices, reliable weather patterns and the ability of the hydropower structures to withstand extreme climate events. Measures should be put to ensure compliance with the outlined policies.

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