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TITLE

Hydrological Modeling and Climate Change Impacts on River Kuja Basin Using HEC-HMS and HEC-GeoHMS Models

Defended on 02/09/2018 Before the Following Committee:

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Declaration

I, Vincent Ogembo, hereby declare that this thesis represents my personal work, realized to the best of my knowledge. I also declare that all information, material and results from other works presented here, have been fully cited and referenced in accordance with the academic rules and ethics.

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This thesis is the candidate's original work and has been prepared with my guidance and assistance. This thesis is therefore recommended for examination with my approval as official University Supervisors.

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Dedication

I dedicate this dissertation to my parents, Walter Obuya and Annah Aoko for their constant support and prayers, my entire family, who heartened me to work hard in order to accomplish the best.

Special thanks to my wife Wendy Amondi Ogembo for the prayers, encouragements and support during the research.

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Abstract

Climate change is real and the effects directly influence the general hydrology of a region. The assessment of these effects still remains an uncertainty owing to the fact that modeling of hydrological reactions is a factor of quality of the data and model limitations. This study sought to model the hydrology of River Kuja basin and the impacts of climate change on the river discharge. The research was carried out by determining the relationship between streamflow and rainfall variability using regression analysis. The HEC-GeoHMS and HEC-HMS models were used to model the impacts of climate change on the streamflow. Different streamflow scenarios were simulated and their effects and impacts on the downstream discharge assessed. The results of the study showed that there was a very significant decline in the streamflow in the drier months compared to the wetter months. Results from the regression analysis of streamflow against rainfall gave a coefficient of determination of 0.42 and correlation coefficient value of 0.65. This demonstrated a moderate but significant relationship between rainfall and streamflow. Both rainfall and streamflow trend analysis showed a decreasing trend for the period between 2000 to 2009. This analysis of the variability between streamflow and rainfall provided a moderately strong but significant relationship between the two variables. Results from the model calibration showed a satisfactory efficiency with an NSE value of 0.50. Simulations of three different future scenarios indicated that there would be a significant increase in the future streamflow as a result of increased rainfall during wet seasons due to climate change. The study therefore concluded that there will be high discharge in the future thus a risk in flash floods but consequently very low discharges during dry seasons. This study is useful to water professionals and managers in developing a robust integrated water and land management system. In addition, the findings from this study would inform policy makers to make informed decisions on river water resource management.

Key words: Hydrology, Climate Change, HEC-HMS, Modeling, GCM, River Kuja Basin.

Abstrait

Le changement climatique est réel et ses effets influencent directement l'hydrologie générale d'une région. L'évaluation de ces effets reste encore incertaine du fait que la modélisation des réactions hydrologiques est un facteur de qualité des données et des limitations du modèle. Cette étude visait à modéliser l'hydrologie du bassin de la rivière Kuja et les impacts du changement climatique sur le débit de la rivière. La recherche a été effectuée en déterminant la relation entre la variabilité des débits et des précipitations en utilisant une analyse de régression. Les modèles HEC-GeoHMS et HEC-HMS ont été utilisés pour modéliser les impacts du changement climatique sur le débit. Différents scénarios de débit ont été simulés et leurs effets et impacts sur la décharge en aval évalués. Les résultats de l'étude ont montré qu'il y avait eu une baisse très importante du débit au cours des mois les plus secs par rapport aux mois les plus humides. Les résultats de l'analyse de régression du débit par rapport à la pluie ont donné un coefficient de détermination de 0,42 et un coefficient de corrélation de 0,65. Cela a montré une relation modérée mais significative entre les précipitations et le débit. Les analyses de tendance des précipitations et des débits ont montré une tendance à la baisse pour la période 2000-2009. Cette analyse de la variabilité entre le débit et les précipitations a fourni une relation modérément forte mais significative entre les deux variables. Les résultats du calibrage du modèle ont montré une efficacité satisfaisante avec une valeur NSE de 0,50. Des simulations de trois scénarios futurs différents ont indiqué qu'il y aurait une augmentation significative des débits futurs due à l'augmentation des précipitations pendant les saisons humides en raison du changement climatique. L'étude a donc conclu qu'il y aurait des rejets importants à l'avenir, ce qui constituerait un risque en cas de crues éclair mais, par conséquent, de très faibles débits pendant les saisons sèches. Cette étude est utile pour les professionnels et les gestionnaires de l'eau dans la mise au point d'un système intégré solide de gestion de l'eau et des sols. En outre, les conclusions de cette étude informeraient les décideurs politiques pour qu'ils prennent des décisions éclairées sur la gestion des ressources en eau des rivières.

Mots clés: hydrologie, changement climatique, HEC-HMS, modélisation, GCM, bassin de la rivière Kuja.

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List of Abbreviations

CH_4 - Methane

CN - Curve Number

CO_2 - Carbon IV oxide

CORDEX - Coordinated Regional Climate Downscaling Experiment

DEM - Digital Elevation Model

DSS - Data Storage System

EIA - Environmental Impact Assessment

EPA - Environmental Protection Agency

FAO - Food and Agricultural Organization

GCM - Global Climate Model

GIS - Geographic Information System

GUI - Graphical User Interface

HEC-GeoHMS- Hydrologic Engineering Centre – Geospatial Hydrologic Modeling System

HEC-HMS - Hydrologic Engineering Centre – Hydrologic Modeling System

ILRI - International Livestock Research Institute

IPCC - Intergovernmental Panel on Climate Change

JICA - Japan International Cooperation Agency

KMD - Kenya Meteorological Department

KNBS - Kenya National Bureau of Statistics

LVSWSB	- Lake Victoria South Water Services Board
MW	- Mega Watts
NO_2	- Nitrous oxide
NSE	- Nash – Sutcliff Efficiency
O3	- Ozone
PAUWES	- Pan African University Institute of Water and Energy Sciences
RCPs	- Representative Concentrated Pathways
SCS	- SCS Soil Conservation Service
UNEP	- United Nations Environmental Program
USACE	- United States Army Corps of Engineers
USD	- United States Dollars
USGS	- United States Geological Survey
WCRP	- World Climate Research Program
WRMA	- Water Resources Management Authority
WRMA	- Water Resource Management Authority
WRUA	- Water Resources Users' Association

1.0 INTRODUCTION

1.1 Background Information

Climate change and variability patterns influences the availability and access to valuable natural resources ecosystems and human economy. Water resources are the most affected natural resource (IPCC, 2014). The main cause of the climatic variabilities is the high accumulation of greenhouse gases that contribute to global warming (Xu et al., 2011). The sub-Saharan Africa countries are more susceptible to climate change effects since a greater population draw their livelihoods from climate-sensitive sectors like agriculture, water resources and forestry (Xu et al., 2013).

According to Musau et al., 2015, water resources directly influence the socio-economic developments but consequently, its availability is threatened due to the rising population pressure. The world population has been increasing, causing general changes in the land-use systems and use of non-renewable energy. Industrialization has also shifted 50 times over the previous century, hence increased water demand (Karamouz et al., 2011).

The availability of water resources in different regions of the earth is dependent on human activities and climatic changes. Variability in rainfall and hydrological cycle affects the magnitude and timing of runoff and ecosystem patterns (Kingston & Taylor, 2010; IPCC, 2014). At local levels, the spatial distribution and extent of climatic changes defines how vulnerable the area water resources are. These impacts also make the communities livelihood be vulnerable (Kingston et al., 2011).

Kenya's major water towers include, Mt. Kenya, Aberdare Ranges, Mt. Elgon, Mau complex, and Cherangani hills. The hydrology of the country is solely dependent on these water towers. They have been affected by the increasing population pressure and uncontrolled exploitation to match agricultural and industrial demand. Climate change is a key threat to the sustainability of water resources in these ecosystems.

According to Kenyan Water Resource Management Authority, 2009, the per capita available water is about 650 m^3. This capacity is below the average global threshold of 1000 m^3. Kenya is therefore categorized as one of the water scarce countries in the world. The country's land surface area is approximately 586,367 km^2 with only 2% of this area covered with surface water resources (UNEP, 2015). Changes and variability of climatic conditions, population increase and land degradation prove to worsen the per capita water availability in the near future.

Figure 1. 1 Kenyan Water Catchment areas (Source: WRMA, 2002)

The Kuja river basin is an extensive basin spanning from Kiabonyoru highlands in Nyamira County downwards to Lake Victoria. The basin is averagely 2,000m above the sea level but

3,000m above the sea level at its source in Nyamira. River Kuja has a total length of 147km and a catchment area of 6,900 km^2.

The hydrology in this basin is likely to be affected by the climatic changes and variability. The massive irrigation water demand downstream, Gogo hydroelectric power station, structural developments, and both industrial and domestic water demands within the towns cause a need to project possible climate change impacts on the surface water resources. This study therefore sought to evaluate the probable climate change and variability impacts on hydrology and water yield for domestic, industrial and irrigation within Kuja river basin. To achieve this objective, HEC-HMS and GCM models were used with two different climate scenarios.

1.2 Statement of the Problem

Climate change is real and the effects directly influence the general hydrology of a region. The assessment of these effects still remains an uncertainty owing to the fact that modeling of hydrological reactions is a factor of quality of the data and model limitations (Bastola *et al*., 2009). Gucha-Kuja river basin contributes to the downstream flow volume of River Kuja. The surface water resource in this basin serves irrigated agriculture, Gogo hydropower station, rural and urban domestic water supply, livestock keeping, dams and Sony sugar company.

Future climate change may result into alteration in the hydrologic course in the basin. Such alterations may cause water scarcity, droughts, extensive floods and community vulnerability. Consequently, projection of the probable effects of climate change on water resources in Kuja river basin is crucial for disaster preparedness, river discharge modeling and community livelihood. This study seeks to assess the possible impacts of change of climate on water resources. The approach involves climate change model output used as input for the Hydrologic Engineering Centre – Hydrologic Modeling Systems (HEC-HMS) model.

1.3 Objectives

1.3.1 Overall

To evaluate the hydrological response and the climate change impacts on the surface water discharge of River Kuja basin under varying future climatic scenarios.

1.3.2 Specific

a) To delineate and process River Kuja Basin using ArcGIS software.
b) To model the hydrologic system of River Kuja basin using HEC-HMS and HEC-GeoHMS models.
c) To evaluate the River Kuja basin's future climate scenarios using GCM model.

1.4 Hypothesis

If temperature and rainfall amount which are the major climate variables, determine the surface water discharge of Kuja river basin, then any change in their pattern and quantities will alter hydrological yields in the catchment.

1.5 Justification of the Study

River Kuja basin is a very important water resource basin in Western Kenya under the Lake Victoria South basin. It is the source of water for human being and livestock livelihood in an area of about 6,900 km^2 and serves a population of over 2.5 million people. A long the course is Sony sugar factory, Gogo Hydroelectric power generation station of capacity 2MW-upscaling in progress, irrigation schemes, urban and rural water supply systems. The area is vegetative due to good rainfall distribution on the upper sub-catchments hence supporting biodiversity of various forms.

Change in climate is so far eminent globally. Extreme weather is likely to affect life in the near future. Poverty escalation and intensified food insecurity will soon expose the vulnerability of communities in area affected by climate change. Future climate change may result into alteration in the hydrologic course in the basin. Such alterations may cause water scarcity, droughts, extensive floods and community vulnerability. Projection of such probable effects of climate change on water resources in Kuja river basin is crucial for disaster preparedness, river discharge modeling and community livelihood. This study therefore sought to relate the future climatic scenarios to the hydrologic situation in River Kuja basin.

1.6 Scope of the Study

Kuja basin has an area of study of approximately 6,900 km^2. It is a sub basin to the larger Lake Victoria basin of East Africa. The data used included both the hydrological and geophysical that relates the hydrology and geographic features i.e rainfall (both historical and projected), river discharge, temperatures, geology, soil types and land use land cover systems. HEC-GeoHMS model is used to process an input data in ArcGIS software. HEC-HMS model uses the output from HEC-GeoHMS in modeling the hydrologic pattern of the Kuja basin under different conditions to determine surface water discharge. GCM model is applied to downscale climate change parameters and use the future climate data to model the basin hydrology. The study presents findings based on hydrology and impacts of climate change on River Kuja basin.

2.0 LITERATURE REVIEW

2.1 Hydrological Modeling

The basin hydrology is best simulated in a hydrologic modeling. Hydrologic modeling is a means of applying mathematical models and programs in enhancing the behavior of water movement in a catchment (Pechlivanidis et al., 2011). Such models are important in flood prediction, modeling of climate, planning for water resources etc. They transmute the precipitation in a catchment into surface flow runoff. Land use systems, topography and soil types are major determinants of the amount of surface runoff transformed from precipitation (Rwigi, 2014).

The various hydrological models used to simulate and predict future water resources scenarios under some projected conditions should reproduce accurately the observed streamflow through calibration (Wagener et al., 2007). However, modelling in poorly gauged or ungauged river basins and watersheds creates a major challenge. Thus, satellite data on hydrological and geophysical data can be used as an alternative in overcoming this challenge. Ungauged rivers are those with inadequate records in terms of both data quality and quantity (Sivapalan et al., 2003). Currently, Streamflow in ungauged and/or gauged watershed is generally forecasted using physically-based models, conceptually and semi-distributed model, and data-driven models. Some of the most commonly used hydrological models have been reviewed in the following sections. The choice of one model over the other depends on various factors which may vary from model and data availability to the complexity and expertise required by each model.

Kuja basin is one of the regions affected by floods. Both the upstream of Kisii and Nyamira counties and mid-stream of Homabay and Migori counties experience severe flash floods during rainy seasons which cause damages to farms and transport systems. The lower parts of the basin suffer from flash and riverine floods where the river undergo inundations that last for about three to four weeks (WARMA & JICA, 2014). Below is the map of vulnerable areas to floods within the basin.

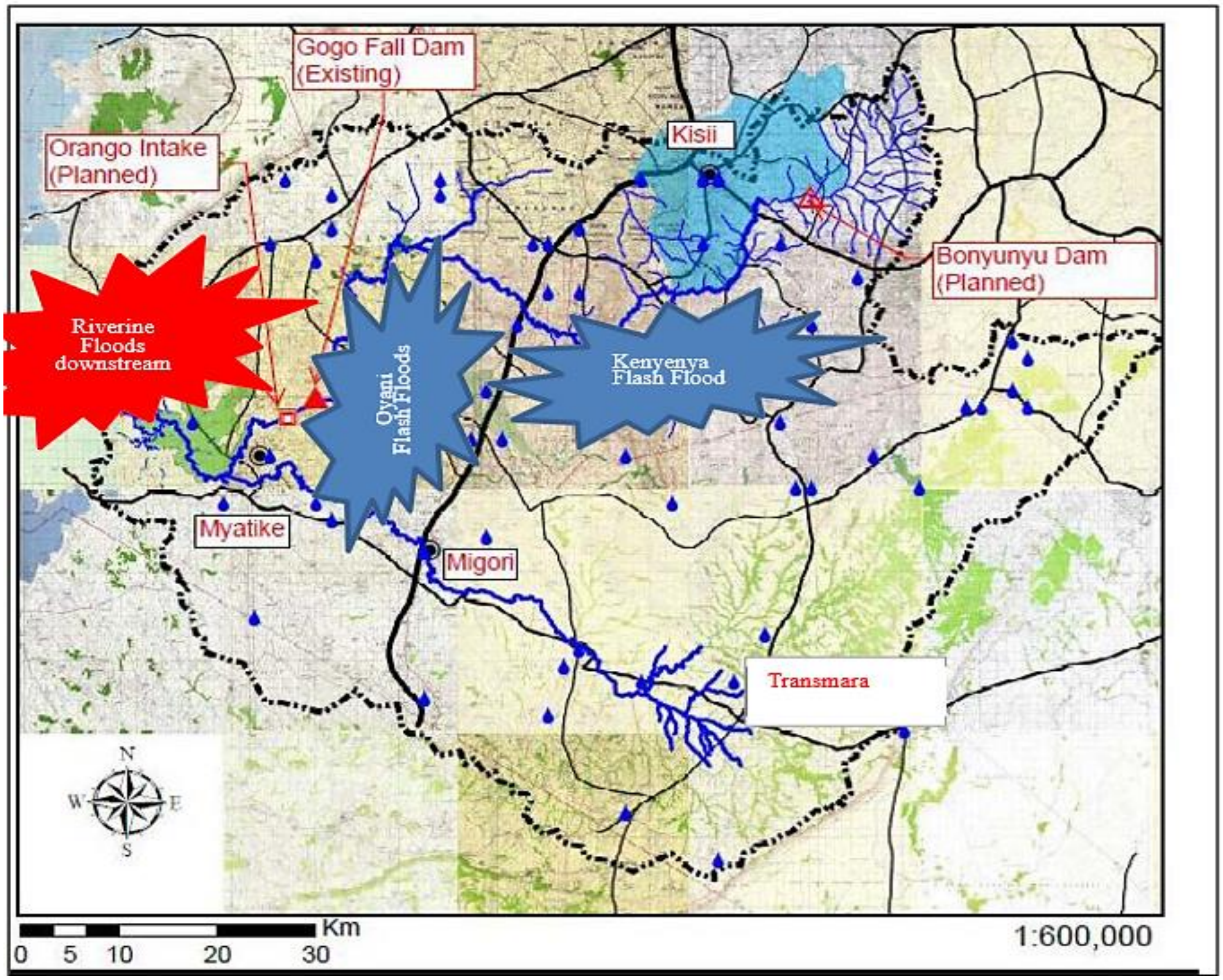

Figure 2. 1 Kuja River Basin floods occurrences (Source: Integrated Flood Management Plan by WARMA and JICA, 2014)

The lower parts of the basin experiences frequent perennial floods. Over the decades, the floods have damaged agricultural produce, infrastructure, land use and landcover systems, houses, lives and structures. This directly affects the economy in the area. The table below show the summary of the flooding situation in the basin both for the ordinary and extraordinary flooding scenarios (WARMA & JICA, 2014).

Table2.2 An overview of flooding records in River Kuja Basin

	Parameter	Ordinary year flood situation	Extreme flooding situations (year 1997, 2002 and 2006)
1.	Water Depth	1m	1.5m
2.	Area under flooding	25km^2	100 km^2
3.	Evacuee records	900	1800
4.	Evacuation Duration	1 month	3 months
5.	Yearly flood frequency	2	2

2.2 Climate Change

The magnitude of the effects of climate change to the environment, economy and general human being's livelihood has increased over the past decades. This change in climate conditions is brought about by the increasing concentrations of greenhouse gases mainly carbon dioxide gases. According to IPCC (2014), the change and variability of climatic conditions lead to alterations in the precipitation amounts and timing, extreme temperatures, and wind patterns and oceanic waves. The rainfall circulation patterns are influenced by availability of moisture in the atmosphere which are globally distributed at varying quantities.

According to (Trenberth & Shea, 2006), the change in climate is signified by the nature, frequency and the amount of precipitation in an area or region. Towards the Nothern hemisphere, the change causes increased precipitation while most parts of Africa, lower parts of Asia and the Mediterranean experiences reduced precipitations. Quite a number of research show that human activities cause emissions of Greenhouse gases which absorb heat and increase the temperatures within the atmosphere. These changes are state of variations in the atmospheric conditions due to inconsistency and fluctuations of weather patterns over long periods not less than three decades (IPCC, 2014).

2.2.1 Greenhouse Gases

The earth is full of human activities which contribute to the emission of greenhouse gases. The gases trap heat and other forms of energy within the atmosphere by forming a blanket cover near the earth's surface hence increasing the average global temperatures. The greenhouse gases include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (NO_2). Carbon dioxide (CO_2) is the major source of rising global temperatures. In 2014, 30% of the emissions was CO_2 generated from electricity generation, 26% from transportation sector, 21% from industries and 12% from households globally (Oluwatomiwa, 2014). The CO_2 levels in the atmosphere has risen by approximately 35% since the commencement of industrialization.

Methane CH_4 originates from coal, oil and natural gas. Its emission is enhanced during production and transportation of such hydrocarbons. Waste decay in livestock production and municipal solid waste management is another source of methane emission. NO_2 is majorly emitted from industries, combustion chambers and in agricultural sectors (IPCC, 2014). Ozone O_3, is another greenhouse gas generated due to explosive reactions between organic compounds and sunlight. Ozone gas has a short lifespan and is a major pollutant to respiratory organs in plants and animals.

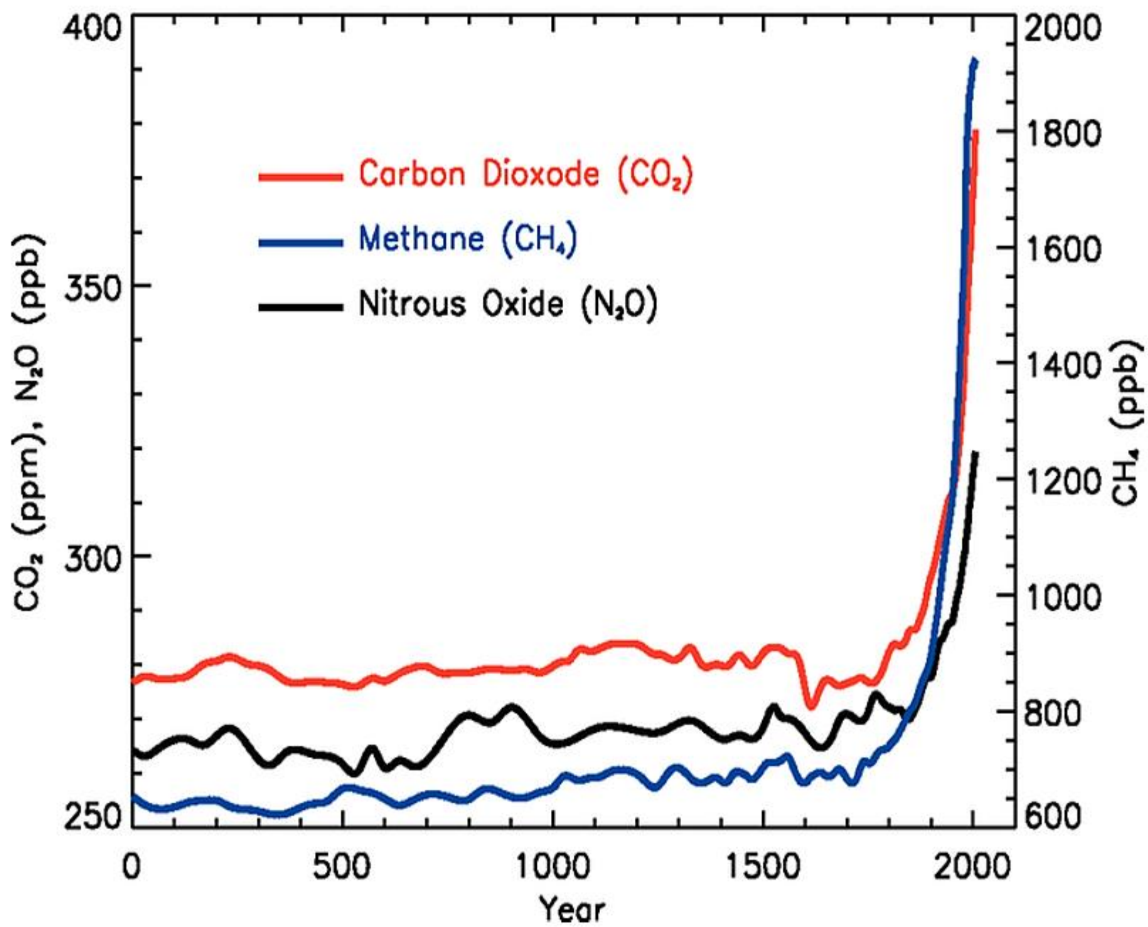

Figure 2. 2 Concentrations of Greenhouse Gases from 0 to 2005 (Source: IPCC, 2014)

2.2.2 Indicators for Climate Change

Climate change is a phenomenon that is experienced over a long period of time, over thirty years. Change in weather can be eminent within minutes or hours. Over centuries, there have been indicators for climate change, an assessment report by IPCC (2014). The conclusion is derived from the rise in the sea levels, melting of ice and snow in the Nothern hemispheres and steady increase in global temperatures.

According to Mach & Mastrandrea (2014) and Rothausen & Conway (2011), there has been gradual increase in global atmospheric temperatures of range 0.31- 0.51°F per decade. Wind patterns are also becoming unstable with fluctuating ocean currents. This has resulted into unpredictable precipitations with either increased or decreased precipitation levels in different regions (Funk & Brown, 2009).

2.3 Impacts of Climate Change

2.3.1 Water Quality

Water quality is a vital concern to human life and general ecosystem survival (Melillo et al., 2014). When there is increase in rainfall intensity due to climate change, the quality of water resources depreciates. This is caused by washing away of harmful wastes and substances by excess runoff. Water treatment plants and such facilities get overloaded by debris, sediments, pollutants, fertilizers, etc. hence reducing the efficiency in quality treatment and supply of water for both domestic and agricultural purposes (EPA, 2011).

Climate change has also resulted to rise in sea levels which increases the salinity of freshwater bodies and resources along the coastlines (Mach & Mastrandrea 2014). Availability of oxygen in water resources is the basis for aquatic life and self-purification of flowing waters. Increasing the temperatures of mass water reduces the oxygen solubility ratio hence reducing the content for aquatic biodiversity (Karl et al., 2009).

2.3.2 Water Quantity

Water is a natural resource and is essential for sustainable use by both flora and fauna. It is consumed by human beings, used in energy production, irrigation, navigation, recreation, manufacturing etc. (Melillo et al., 2014). Climate changes alters the hydrological cycles and general surface and groundwater flow. The alteration directly affect the water resources, forests, ecosystems, agriculture and the environment (Chien et al., 2013; Rwigi, 2014). Precipitation and temperature level are subject to climate change impacts, their increase lead to excess runoff and high evapotranspiration respectively.

According to IPCC (2014) and Melillo et al. (2014), water demand might increase while supply decreases due to climate change. Imbalance between extreme temperatures and precipitation causes severe drought and floods. Availability of water therefore remain varied over a long-time span hence affecting normal human activities. Water demand is likely to rise due to population increase and urban migration (Bates et al., 2008).

2.3.3 Agriculture and Environment

Agricultural sector has been greatly affected by the global variation and change in climate. According to Mach & Mastrandrea (2014), an average increase in temperature may quicken the growth of specific crops and contrarily decrease yields of some other plants. The crop growth requirements revolve around soil nutrients, availability of water, and optimum temperature. Increase in temperature tampers with these requirements hence alters general agriculture produce (Kauffman et al., 2014).

Farming in River Kuja basin solely rely on the rainfed agriculture. The effects of climate changes include extreme natural disasters like floods and droughts. These conditions damage crops and livestock livelihood in the basin hence food insecurity (Ouma, 2015). Heat waves caused by increase in global temperatures lead to vulnerability of human health and livestock. The vast area in the basin is under sugarcane plantations used to produce sugar in two different sugar processing factories. Floods and severe droughts have always lowered sugarcane productivity which affects the economic growth of the area (WRMA and JICA, 2014).

2.4 Global Climate Model, GCM

GCM is a climate model used in weather forecasting, predicting climatic scenarios. It involves mathematical models which exhibits the general planetary and oceans conditions. GCMs uses equations like Navier-Stokes within thermodynamic principles for different energy sources e.g. latent heat and radiation. While GCMs presents global spatial scales with complexity in the hemispheric systems, they are not able to downscale to local regions for specific climatic conditions (Schulze, 1997).

Downscaling process has enhanced relating global scale variables to local meteorological station data sets. Two major methods are used; statistical methods and dynamic methods. Statistical methods involve use of observed data in relation to identified system while dynamic methods focus on solving explicitly the physical dynamics of the whole process (Hewitson and Crane, 1996). Climate forecast depends on uncertainties in physical, chemical and social models with significant key icons as technology, industry and human population (IPCC, 2014).

2.5 Future Climatic Scenarios

According to IPCC (2014), the Representative Concentration Pathways (RCPs) define the four possible climatic scenarios in the near and far future. They consist of four greenhouse gases with new trajectories i.e. RCP2.6, RCP4.5, RCP6.0, and RCP8.5. The naming result from the different radiative forces of +2.6 W/m^2, +4.5 W/m^2, +6.0 W/m^2, and +8.5W/m^2 respectively (Van Vuuren et al., 2011). These pathways are important in climate modeling processes and comprise of remarkable changes in anthropogenic emissions of Greenhouse Gases.

Near future projections show that RCP2.6 will show peak emissions as from 2010 to 2020 thereafter a decline. The peak for RCP4.5 spans around 2040 and decline. RCP6.0 peaks in the year 2080 and declines thereafter while during late 21st Century, the emissions potentially rise throughout at RCP8.5. According to IPCC (2014), the table below indicate the mean temperatures and sea levels between 2046 to 2100.

Table2. 1 AR5 global warming projections (Source: IPCC, 2014)

Global Warming – rise in temperature projections		
	2045 - 2065	**2080 - 2100**
Scenario	**Possible projection range**	**Possible projection range**
RCP2.6	(0.4-1.6) Average 1.0°C	(0.3-1.7) Average 1.0°C
RCP4.5	(0.9-2.0) Average 1.4°C	(1.1-2.6) Average 1.8°C
RCP6.0	(0.8-1.8) Average 1.3°C	(1.4-3.1) Average 2.2°C
RCP8.5	(1.4-2.6) Average 2.0°C	(2.6-4.8) Average 3.7°C

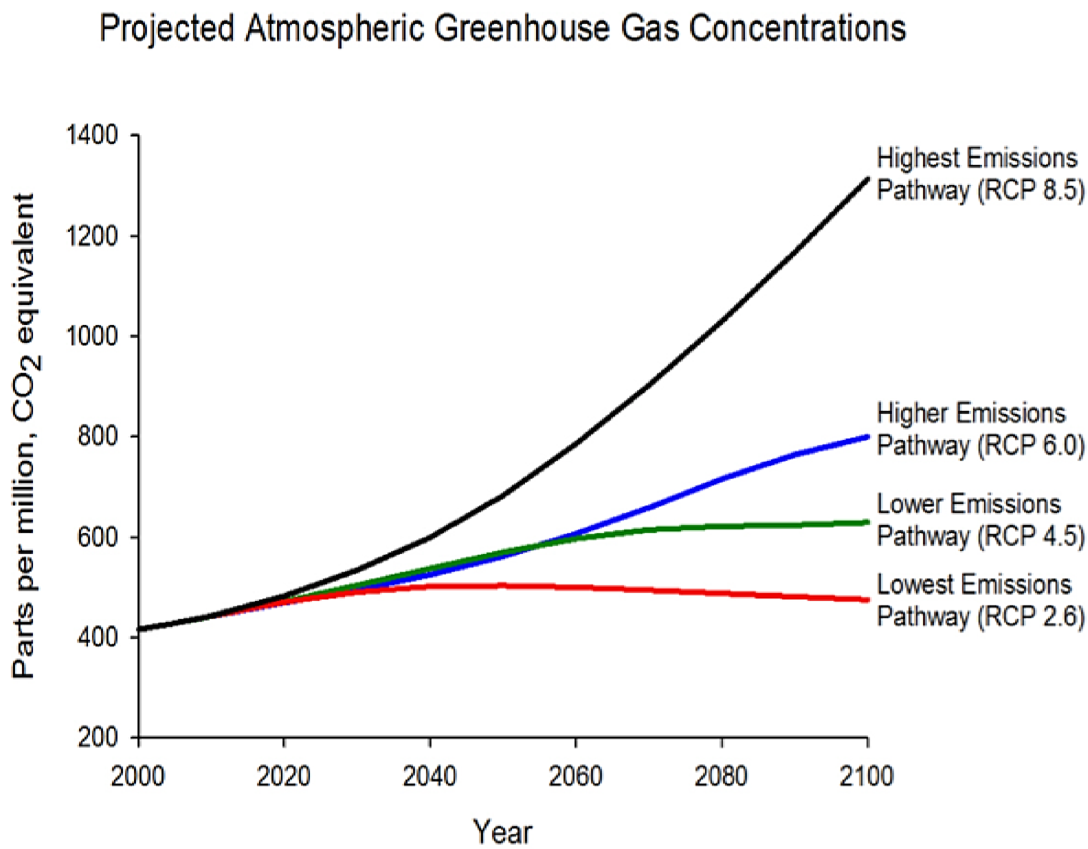

Figure 2. 3 Projected Atmospheric Greenhouse Gas Concentrations (Source: IPCC, 2014)

2.6 HEC-HMS Model

Description of HEC-HMS model The Hydrologic Modelling System HEC-HMS was designed in 1992 by the United States Hydrologic Engineering Centre to simulate precipitation runoff processes of dendritic watershed systems. This model was designed as a replacement of the HEC-1 model which was initially considered as the standard model for hydrological simulations (USACE, 2013). It was designed to be applied in large river basins water supply and also to solve flood hydrology problems. It can also be used in solving problems involving small urban and natural watershed systems. The hydrographs produced from this model can either be used directly or in conjunction with other models in studies involving water availability, flow forecasting, urban drainage, flood damage control, future impacts of urbanization, design of reservoir spillways and floodplain regulations among other hydrological uses. The model has the capability of representing various watershed systems at a given time.

The construction of the HEC-HMS model of a watershed system is done by separating the hydrological cycle into manageable pieces and dividing the watershed into smaller sub basins. The energy and mass flux balances within the cycle are then represented using mathematical equations. For simulating the precipitation runoff, the model consists of the following components: the precipitation specification option which describes the observed (historical) rainfall at a given location; the loss models which can estimate the runoff volume within the watershed given the precipitation and the watershed's characteristics; the direct runoff models which can account for the overland flow, storage and energy losses that take place as water runs off over the watershed and into the stream channels; the hydrologic routing models which account for storage and energy flux during the time water moves through the stream channels; models of naturally occurring confluences and bifurcations; and models of water control measures which include diversions and storage facilities. Additionally, the model contains a distributed runoff model which can be used with distributed precipitation data such as those obtained from the weather radar. The model also has a continuous soil moisture accounting model which is used for simulating the long-term response of the watershed to wetting and drying.

The HEC-HMS model contains eight hydrologic elements which include the sub basins, reach, junction, source, sink, reservoir and diversion. The sub basin is used to represent the physical outline of the watershed. For every sub basin, there should be a corresponding precipitation data. Using this precipitation data, the outflow from the sub basin element can be calculated through the subtraction of the precipitation losses. Additionally, calculation of the surface run off can be done and the base flow added. The reach element is used to convey streamflow to the basin model. The inflow into the reach is obtained from the upstream elements. This can be one or many upstream elements. In order to calculate the outflow from the reach, translation and attenuation must be accounted for. Additionally, channel losses can be included optionally in the routing. The junction element is used to combine streamflow from elements located upstream of the junction. Just like the reach, the inflow into the junction can be obtained from one or many upstream elements.

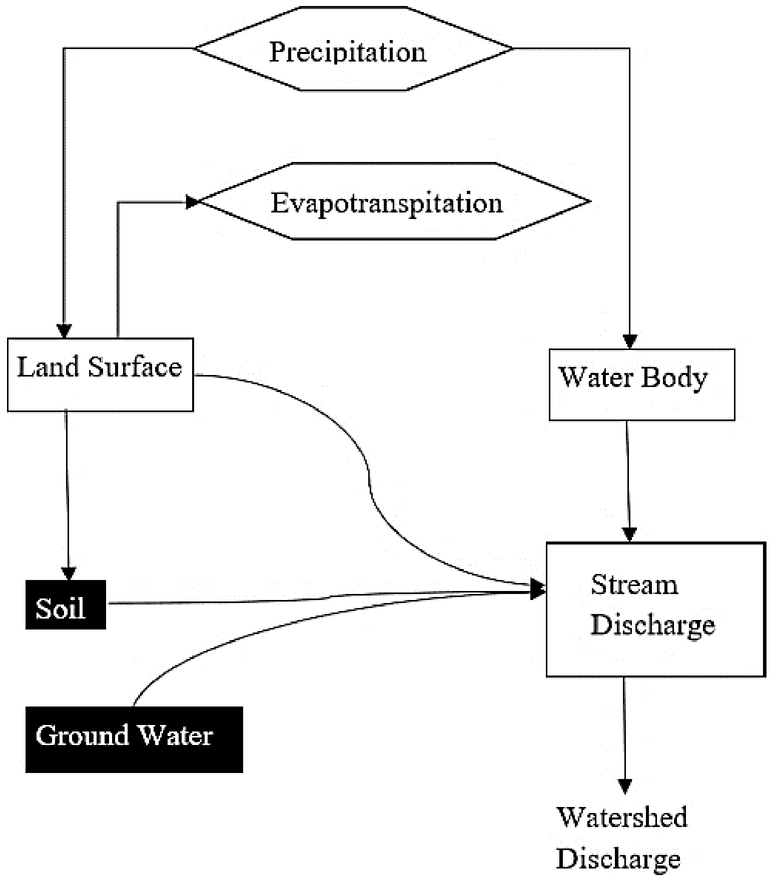

Figure 2. 4 Simplified Schematic Diagram of the Rainfall-Runoff Process in HEC-HMS

To obtain the outflow from the junction, all inflow into the junction must be summed up. The source element is generally used to introduce inflow into the basin model. The source element does not have any inflow however; its outflow may be defined by the user. The sink element is used to represent the outlet of the watershed. The sink element does not have any outflow however inflow into the sink might come from one or many upstream elements. The reservoir element is used to model the hydrograph detention and attenuation as a result of reservoir or detention pond. Calculation of the outflow from the reservoir can be carried out using any of the routing methods in HEC-HMS. The inflow however, can come from one or many upstream elements. The diversion element is used to model the streamflow leaving the main channel. Its inflow can be obtained from one or many upstream channels. However, the outflow from the diversion element mainly consists of diverted and non-diverted flows. The calculation of the diverted flow can be done using the user's input. The diverted and non-diverted can be connected to other hydrologic elements located downstream of the diversion element.

2.7 HEC-GeoHMS

The HEC-GeoHMS is a free public-domain hydrological modelling software package developed by US Army Corps of Engineers for use with ArcGIS. It utilizes ArcView and Spatial Analyst tool for development of various hydrological modelling inputs. It is a physically based, lumped, semi-distributed and geospatial hydrological tool that was developed by the Hydrologic Engineering Centre's Hydrologic Modelling Systems (HEC-HMS) to process geospatial data and create their input files in ArcGIS. It can be used to analyze terrain information, streams and sub-basin delineation, and preparation of hydrologic inputs using its Graphical User Interface (GUI) (USACE, 2013). HEC-GeoHMS is used to translate GIS spatial data into model files for HECHMS. ArcGIS is used for data formatting, processing and coordinate transformation. HEC-GeoHMS uses Digital Elevation Models (DEM) for catchment delineation and preparation of various hydrologic inputs.

HEC-GeoHMS extension is designed to extract drainage paths and the basin boundaries from the DEM so as to represent the hydrologic parameters that are used for simulating the catchment response to precipitation. In order to estimate the hydrologic parameters, tables containing physical characteristics of streams and sub-basins are generated. These physical characteristics of the catchment and the river are computed and used in estimation of the hydrologic parameters (Adnan et al., 2014). The results of the delineated catchment obtained from the HEC-GeoHMS is then imported to HEC-HMS where simulations are performed. The figure below adopted from USACE (2013) shows the relationship between GIS, HEC-GeoHMS, and HECHMS.

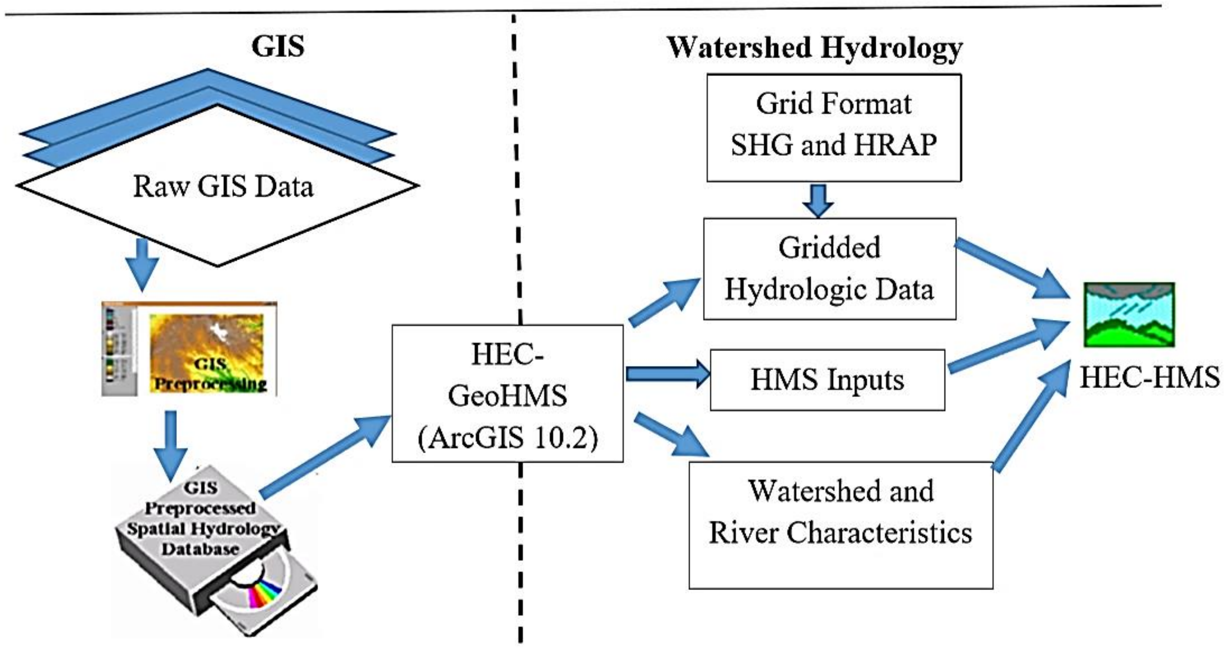

Figure 2. 5 Overview of the Relationship between GIS, HEC-GeoHMS and HEC-HMS

2.8 HEC-GeoHMS and HEC-HMS model applications

The HEC-HMS and HEC-GeoHMS have been applied successfully in various studies most of which involve flood assessment and evaluation of land use changes. For instance, in a study conducted by Kawasaki et al. (2010) using HEC-GeoHMS to evaluate the potential impacts of precipitation and land use on streamflow in Srepok basin, Vietnam, various scenarios were developed with regard to climate change, population and socio-economic development in a GIS platform, and each scenario was estimated for streamflow for 2025 and 2050. The results show that the water demand increases due to population growth, and land development which would have a greater impact on the streamflow change as compared to precipitation in the next 50 years. The study suggested policy adjustments in land development, however it pointed out that this was very difficult due to increased expansion of agricultural land and economic investments in the region.

In another study carried out by Knebl et al. (2005) using HEC-HMS, NEXRAD rainfall and GIS to study the regional scale flood modelling that is related to urban development in San Antonio River Basin, Texas, it was found that an increase in the level of development led to a reduction in infiltration capacity which increased the flooding risk. The HEC-HMS has also been used by

Emerson et al. (2005) in evaluating the effectiveness of the Valley Creek watershed's system of storm water detention basins in Pennsylvania. The study found out that the existing network of detention basins in Valley Creek watershed had very little, if any, impact on the storm water flow regime of the watershed. Significant peak flow reductions were simulated using HEC-HMS and HEC-GeoHMS by designing three different attenuated areas to detention basins. A study conducted by Hu et al. (2006) to determine future flood damages in the Red River, Minnesota, using HEC-GeoHMS it was suggested that in order to reduce the model's (HEC-HMS) uncertainties and improve its performance, better spatial and temporal precipitation representation was required. In a research to evaluate the impacts of land use change on streamflow in Northampton County by Lan (2012) using HEC-GeoHMS, investigations showed that further urban development in the basin would result into more runoff. The study also showed that there exists a relationship between residential development area and streamflow discharge which can also linked to the runoff volume.

HEC-GeoHMS and HEC-HMS models are thus important tools for decision support and day-today management. By being physically based, lumped and semi-distributed geospatial hydrologic models they can be adjusted to be applied in a number of hydrological studies with a high degree of certainty and accuracy.

3.0 METHODOLOGY

3.1 Study Area

3.1.1 River Kuja Basin

The Kuja river basin is an extensive basin spanning from Kiabonyoru highlands in Nyamira County downwards to Lake Victoria. The basin is averagely 2,000m above the sea level but 3,000m above the sea level at its source in Nyamira. It lies within coordinates 0.65ºS 43.97ºE (34.883110 -0.996036 Decimal Degrees) and has a total length of 147km.

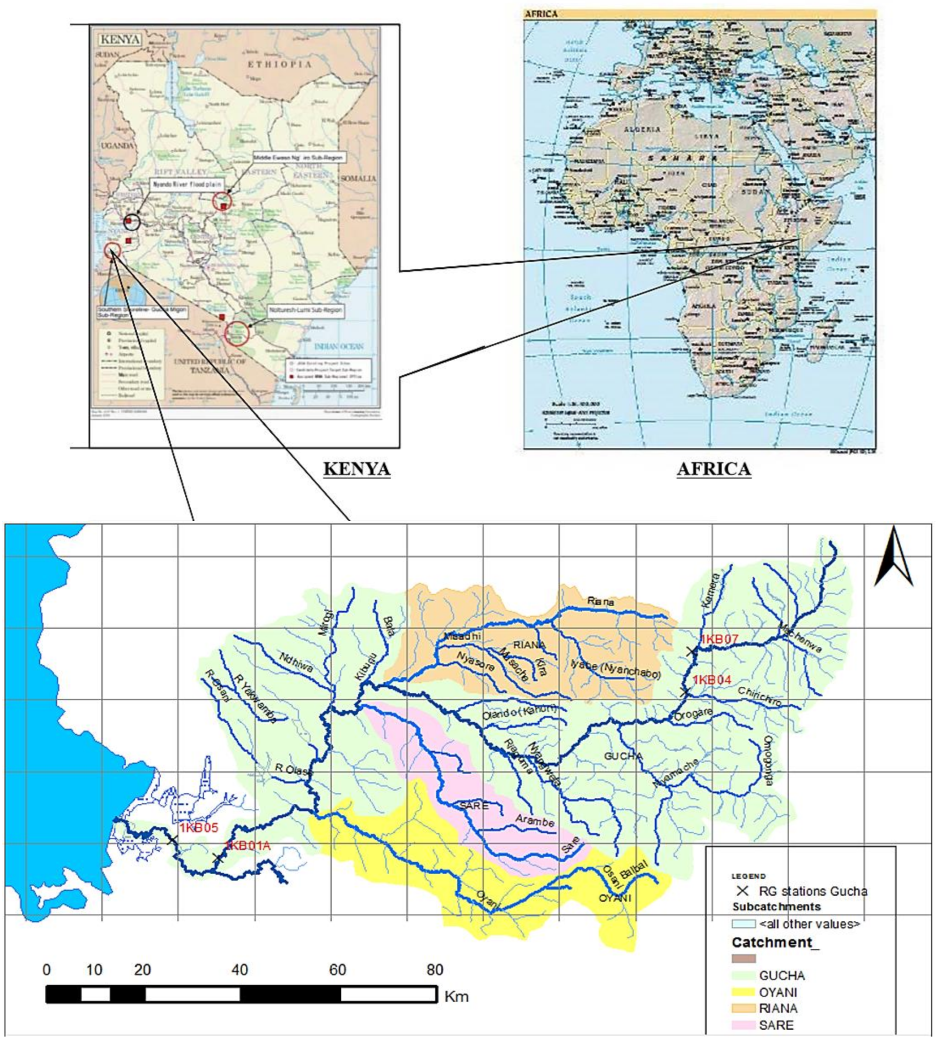

Figure 3. 1 Map of River Kuja Basin (*Source:Gucha-Migori basin IWRM Plan*)

The basin area is 6,900 km^2 (2,664 sq mi) with a population of approximately 2,584,313 people (Census, 2009). The river has an average discharge of 58 m^3/s (2,048 cu ft/s). The river runs across the Gucha land where it is commonly known as Gucha river. Part of it is referred to as River Mogonga, a name symbolizing the deadly effects of this river when it floods.

3.1.2 Hydrologic Characteristics

The basin cuts across five counties in Kenya; Nyamira, Kisii, Narok, Homabay and Migori counties. River Kuja drains into Lake Victoria downstream where it is joined by Migori River. In 2001-2002, the river changed its course and passed through the current channel Kabuto Nyora villages in lower parts of Kadem. It widens in some area like Sango where the river is 120m wide. The mean annual runoff near its outflow to Lake Victoria is estimated to be 1,884Mm^3/year.

The basin is densely fed by small tributaries that drain into River Kuja. The tributaries include, River Gucha at the source, Sare, Oyani, Onyinjo, Mirogi, Riana, Nyamache, Mugonga and Chirichiro Rivers among others. There are over 800 springs and 8 major dams within the basin. There are three major River Gauging Stations within the basin; KB01A, KB04 and KB07.

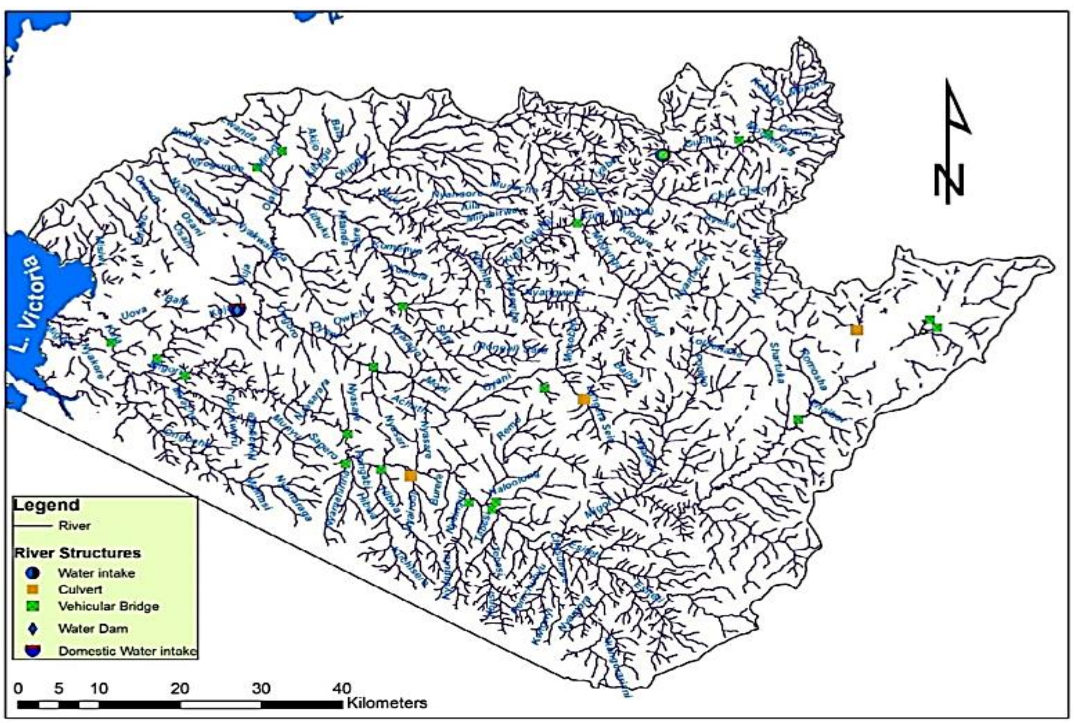

Figure 3. 2 Map of Kuja-Migori River Basin hydrologic patterns

3.1.3 Climate

The basin experiences two rainy seasons with the highest rainfall being between March and May. The average annual rainfall is approximately 1200 mm. Temperatures range from 15°C to 20 °C within the highlands of Nyamira, and 21°C to 30°C in the lowlands towards Lake Victoria. The average temperature of the basin is 25 °C.

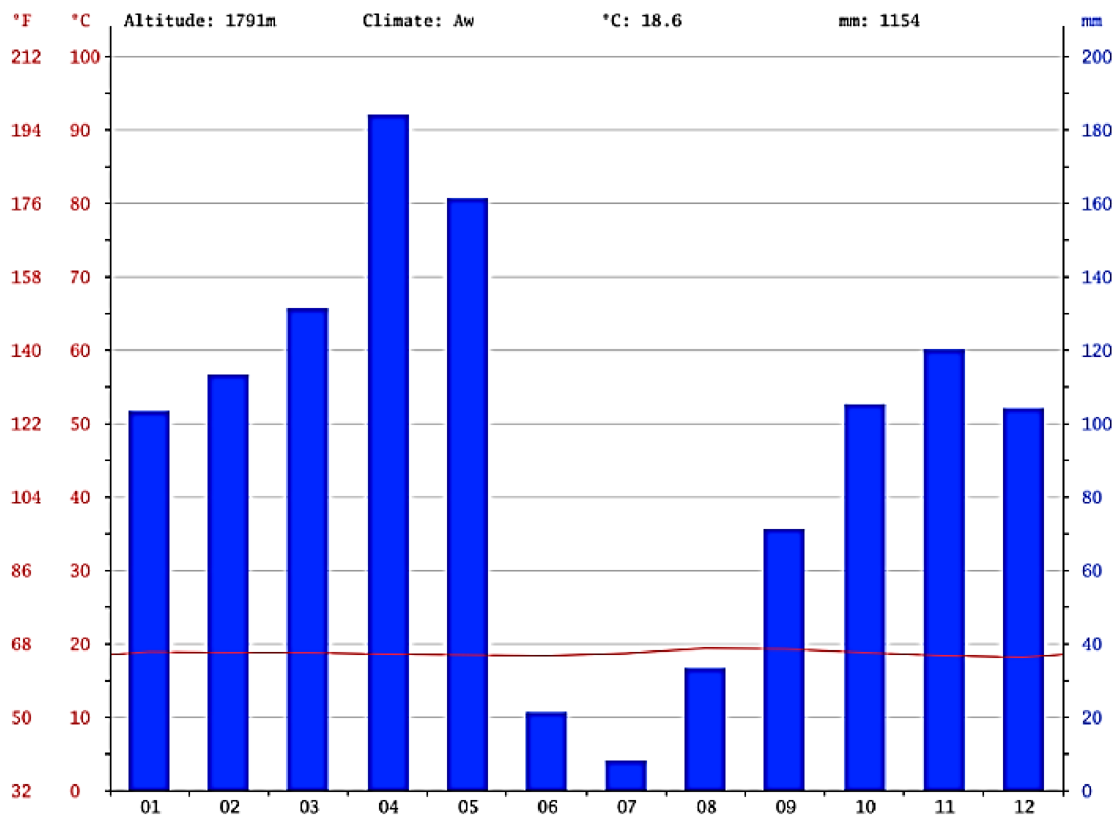

Figure 3. 3 Sample weather distribution of the basin (Source: World Climate 2018)

3.1.4 Economic Activities

The big population in this basin depends on subsistence agriculture with businesses in some of the urban centers and towns. Some economic activities include fishing around the lake, animal husbandry, sand harvesting, brick making, handicraft, carpentry, stone curving, small scale businesses, etc. There are quite a number of industrial factories within the basin which process agricultural products. They include; Sony sugar processing company in Awendo, Sugar factory in Transmara and also in Ndhiwa, Tea Factory in Nyamira and another Tea Factory in Kisii counties.

3.1.5 Topography and Geology

The basin is well vegetated in the highlands of Nyamira and Kisii counties where the altitude is 3,000 m above the sea level. Vegetation cover depreciates downslope towards Lake Victoria due to rise in temperatures in the areas surrounding the lake. Sloping system of the basin is divided into three major categories i.e. upstream slope system of 25% to over 40% slope, midstream slope system of 10% to 20% slope and downstream slope system of 0% to 10% slope.

The geology of the area is majorly of old Bukoban rocks that are Palaeozoic age in properties. This type of rock consists of acidic volcanics of quartzite and escarpments systems. In the sub catchments of Kisii, there is a thin belt of Kavirondian and Precambrian rock systems. The west near the Lake is characterized by quarzitic belt circumscribed by a wide belt of basalt. There exist large soapstone belts within mid sub-basin areas of Kisii. The soapstones originates from the basalt through hydrothermal activities. The South Nyanza parts of the basin is characterized by porphyritic and non-porphyritic andesite and felsite rocks.

3.1.6 Soils

Kisii and Nyamira highlands consist of reddish fertile volcanic loamy soils while the downstream of South Nyanza region consists of greyish fertile alluvial soils. Most of the low-lying areas are characterized by black cotton, clay and sandy soils.

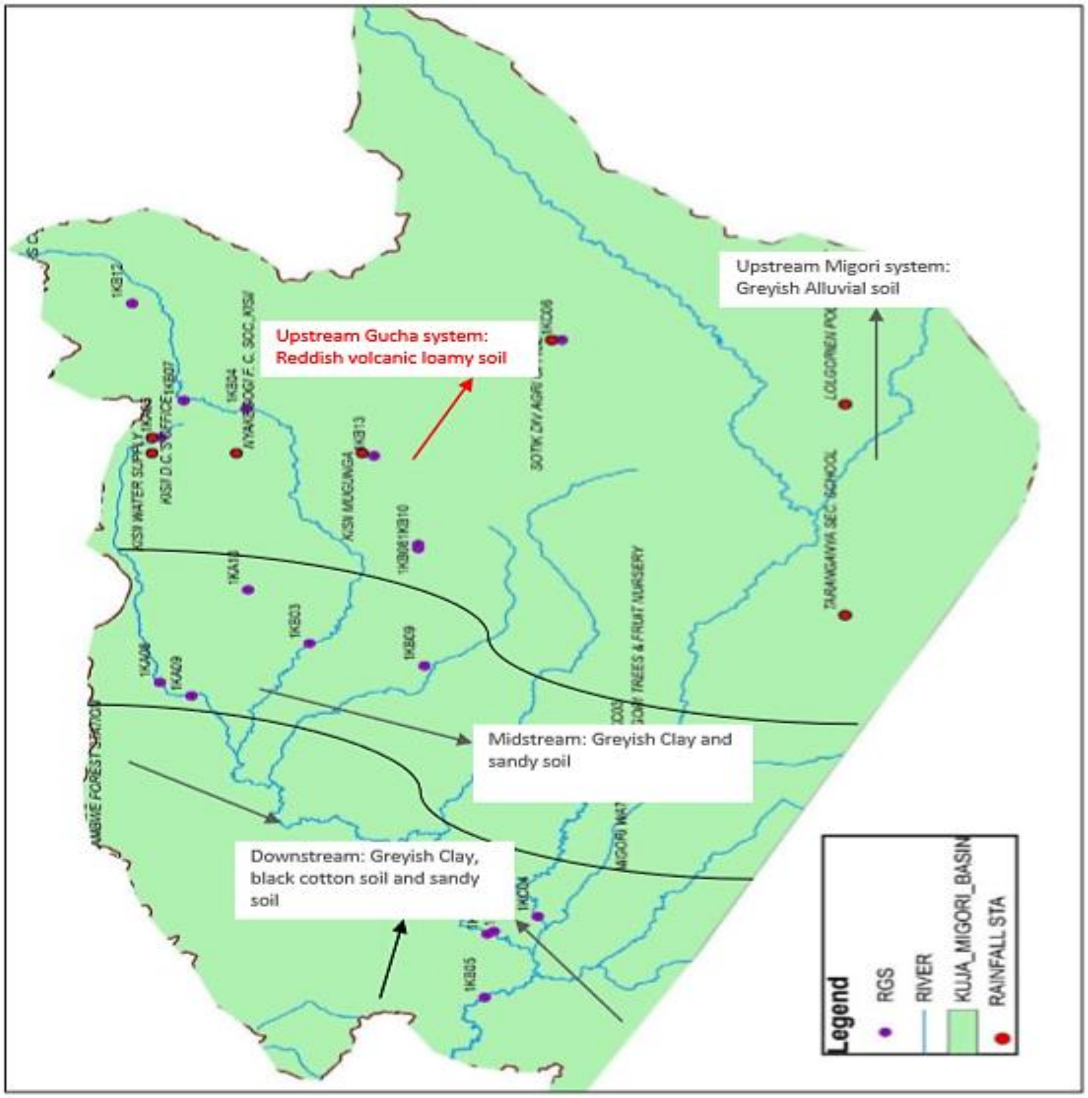

Figure 3. 4 Soil Distribution Map of Kuja River Basin

3.2 METHODS

This section presents the data types used and the methodology applied in achieving the objectives for the research. Data quality and correction methods are also discussed including missing data formulae and applications.

3.2.1 Data and Methodology

The data used in this research include historical and projected rainfall (precipitation), historical and projected temperature, Digital Elevation Model (DEM), historical river discharge and Kuja basin rivers shapefiles. The climatic projections were used for RCP4.5 and RCP8.5.

3.2.1.1 Digital Elevation Model (DEM)

The DEM used was downloaded from Shuttle Radar Topography Mission (SRTM)with a spatial resolution of 90m by 90m. It provided elevation and slopes of the tributaries networks within the basin. The spatial resolution of the DEM applied was 90m by 90m. The DEM described the terrain of the catchment and therefore it was very important for the watershed model. The DEM was processed using Arc Hydro and HEC-GeoHMS to obtain the stream path, watershed boundary and the basin slope. The basin was then divided into several sub-basins based on the terrain and flow path. The HEC-GeoHMS was then used to calculate the length of the stream segment and the areas of the sub-basins.

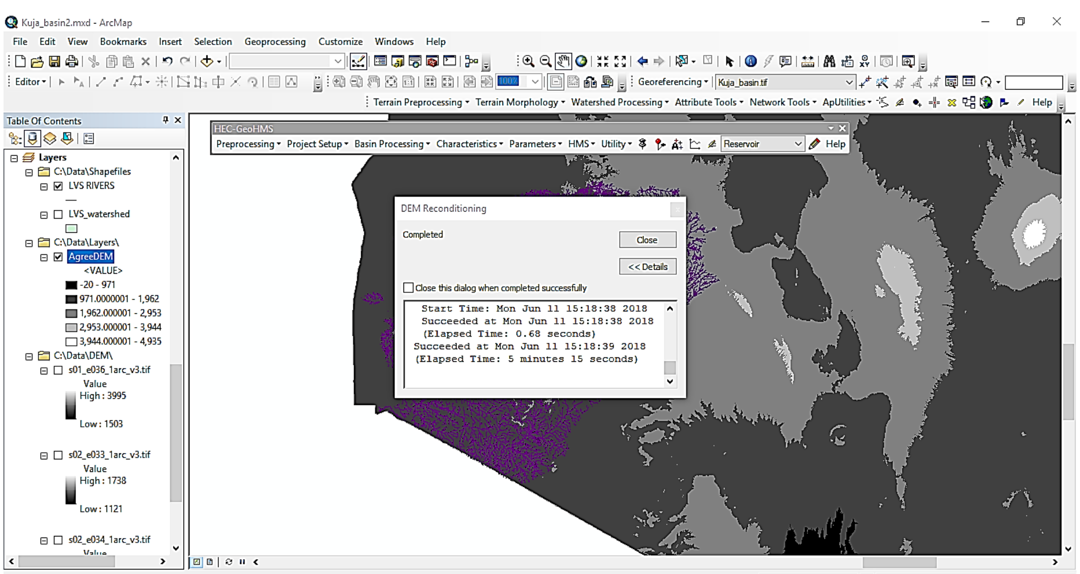

Figure 3. 5 DEM Reconditioning of Kuja basin in ArcMap 10.2.2

3.2.1.2 Climate Data

Stream flow and discharge data were obtained from the gaging stations downstream of River Kuja in Muhuru Bay for the period between 3/1/1969 at 9:00:00 AM to 11/30/2015 at 4:00:00 PM. The station data was availed by the regional office of the Kenya Water Resource Management Authority. Weather data i.e. rainfall and temperature were obtained from Kenya Meteorological Department (KMD) for the Lake Victoria South Water Services Board (LVSWSB). Rainfall data was for the period 2/1/1959 at 9:00:00AM to 4/3/2011 at 9:00:00AM, while temperatures from 1/2/1970 at 9:00:00 AM to 12/31/1990 4:00:00 PM

3.2.1.3 Projected Climate Data

The future projected weather conditions under climate change scenarios were initiated by World Climate Research Program (WCRP). The scenarios were therefore referred to as CORDEX RCPs runs. They have a 50km resolution for the African domain simulation pathways. The rainfall and temperature were simulated from CORDEX RCP4.5 for near future and CORDEX RCP8.5 for long-term modeling.

3.2.2 Establishment of the Rainfall and Streamflow Variability

Data from both the rainfall and streamflow were analyzed using regression analysis so as to establish the relationship in their variability. Regression analysis is the quantitative expression of the basic nature of the relationship between the dependent and independent variables (Fox, 1997). It was used to measure the direction of movement of the dependent (response) variable which is streamflow to its response to changes in the independent (explanatory) variable which is rainfall. In addition, it was used to reveal the amount by which the dependent variable (streamflow) would change given a one-unit change in the independent variable (rainfall). The regression model was calculated using the function:

$$y_i = \beta_0 + \beta_1 x_i + \varepsilon_i \qquad i = 1,2,3,\ldots,n \qquad \text{……………………(Eq. 3.1)}$$

Where:

- yi = the i^{th} observation of the response (dependent variable)

- x_i = the i^{th} observation of the explanatory (independent variable)
- $\beta 0$ = intercept
- $\beta 1$ = slope
- εi= the random error or residual for the i^{th} observation and
- n = sample size.

Fitting the model was done by finding values of $\beta 0$ and $\beta 1$ in such a manner that the sum of the squares of the vertical deviations was minimized. This process of minimizing is called least square regression, and was given:

$$(y_i - \hat{y}_i)^2 = (yi - \beta 0 - \beta 1xi)^2 \qquad i = 1,2,3,\ldots,n \quad \ldots\ldots(\text{Eq. } 3.2)$$

Where;

- $\hat{y}_i$ = forecasted data
- y_i = observed data

3.2.3 Justification for choosing HEC-GeoHMS and HEC-HMS models

The choice of HEC-GeoHMS is due to simplicity and easy approach in its application. It has the capability of analyzing watershed hydrology in both lumped and quasi-distributed forms (HECHMS (ModClark Method). The ModClark method allows spatially varying precipitation to be used in HEC-HMS (USACE, 2010a). In addition, the HEC-GeoHMS has a well-developed data management and visualization functions. Using the HEC-GeoHMS to perform spatial analysis when developing distributed hydrologic parameters not only saves time and costs but also helps in accuracy enhancement compared to ArcGIS alone (USACE, 2013).

The HEC-GeoHMS was designed by US Army Corps of Engineering to help and assist engineers, hydrologists or those with limited GIS experience to be able to visualize spatial information, perform spatial analysis functions, delineate catchments boundaries and streams, document watershed characteristics, prepare hydrological model inputs, and assist in preparation of hydrological reports (USACE, 2013). The main advantage of the HEC-HMS model is that it contains an automatic calibration package which can estimate certain model parameters and initial conditions when observed data of the hydro meteorological conditions are provided. The HECHMS model also links to a database management system known as Data Storage System (DSS) which can permit storage of data, their retrieval and connection with other analysis tools available from HEC such as HE-GeoHMS and other sources.

The limitation of the model is that when the SCS CN routing method is used, the infiltration rate will generally approach zero during a long duration storm instead of being constant as expected. Additionally, the initial abstraction of 0.2S does not depend on the storm characteristics or timing. The model sometimes underestimates the peak and low flows. This model was developed for application in mid-western US thus its application in other region is generally faced with lots of uncertainties (USCEA, 2013).

3.2.4 Hydrologic Model Development

In this study, HEC-GeoHMS 10.2 which is the ArcGIS 10.2 geo-processing extension and Arc Hydro tools were used to generate and process geospatial information of the Kuja River basin such as streamflow paths, sub-basins, catchment boundary, elevations, and soil type. The three main data sets that were used in this research so as to model the agricultural expansion impacts on streamflow included the Digital Elevation Map (DEM) which gave the topographic information and geologic characteristics of Kuja river basin, land use data, and hydrological data (rainfall, streamflow and evapotranspiration data). These data were then processed and computed using HEC-GeoHMS in ArcGIS 10.2 to generate the parameters that were required for the HEC-HMS model input that was used to generate runoff simulations.

3.2.5 Terrain processing using ArcGIS 10.2 and Arc Hydro

The downloaded DEM for the study area was used to delineate the watershed and generate its streams using ArcGIS 10.2. The boundary limit of the watershed was also developed and the resulting shape file used for clipping other GIS based raster data for the study area such as soil, land use and population density grid data. Arc Hydro tools were then used to perform the terrain processing using the DEM and stream files. The processes that were involved in the terrain processing.

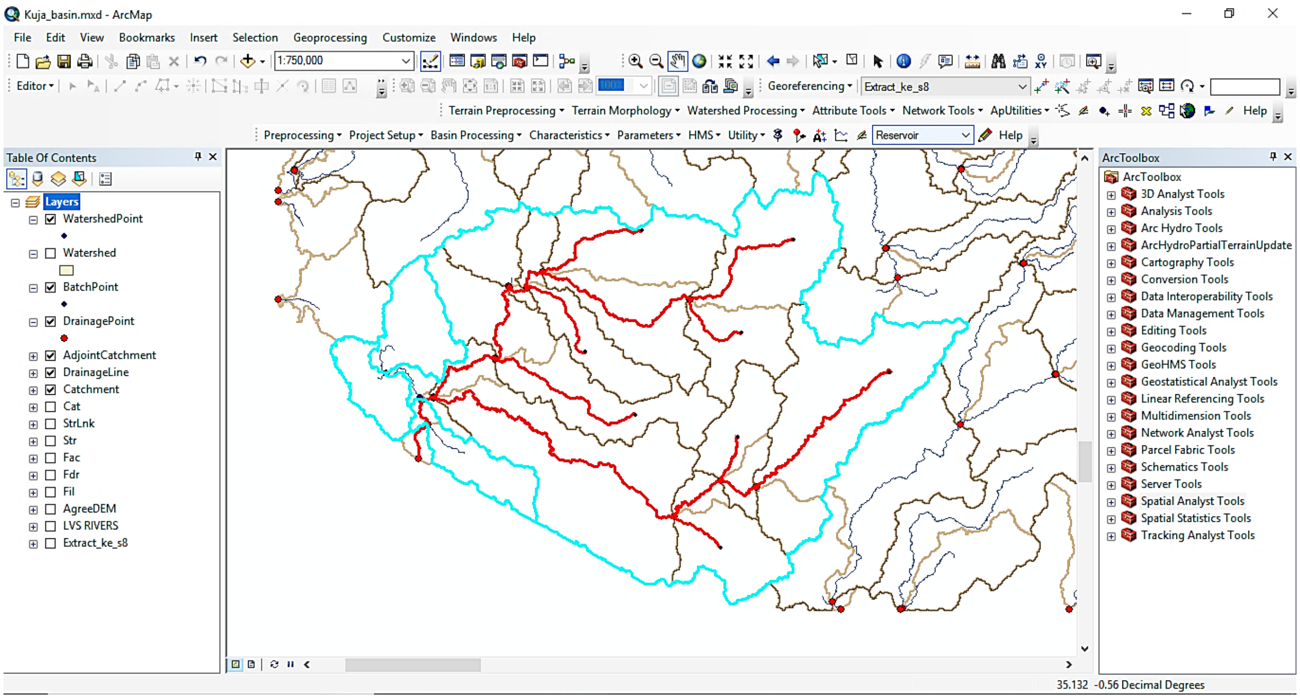

Figure 3. 6 Kuja basin terrain processing in ArcMap using ArcHydro and HEC-GeoHMS tools

The terrain processing tool was used to produce the hydro DEM, flow direction grid, flow accumulation grid, stream definition grid, stream segmentation grid, and catchment grid delineation. These processes were all performed in a sequential order before the watershed processing function could be used in HEC-GeoHMS. This process was preceded by DEM reconditioning and filling of the sinks. This was done to ensure the elevation data was consistent with the vector stream network. The terrain processing was concluded by generating the slope grid for the watershed. These files were then transferred to HEC-GeoHMS in order to delineate the watershed in such a way that it could be used in HEC-HMS model.

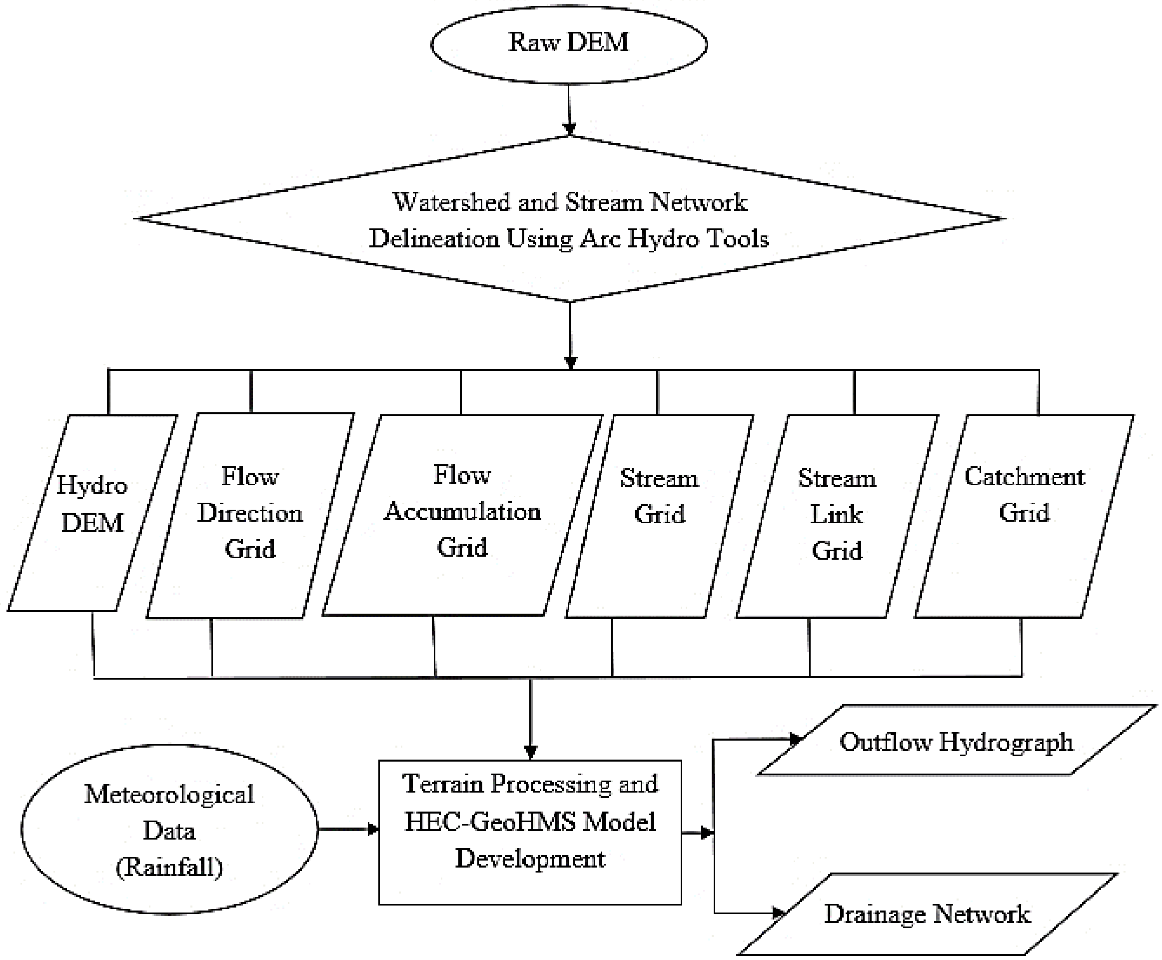

Figure 3. 7 Schematic layout of the terrain processing in Arc Hydro

3.2.6 Preparing HEC-HMS model inputs using HEC-GeoHMS

The input data for the HEC-GeoHMS model included both raster and vector data sets that had been prepared in Arc hydro. The raster data included the raw DEM of Kuja River basin, filled DEM, flow direction grid, flow accumulation grid, stream network grid, stream link grid, catchment grid and slope grid whereas the vector data were the catchment, drainage line and the adjoint catchment. The HEC-GeoHMS project for Kuja River Watershed was set-up and the outlet point of the watershed defined.

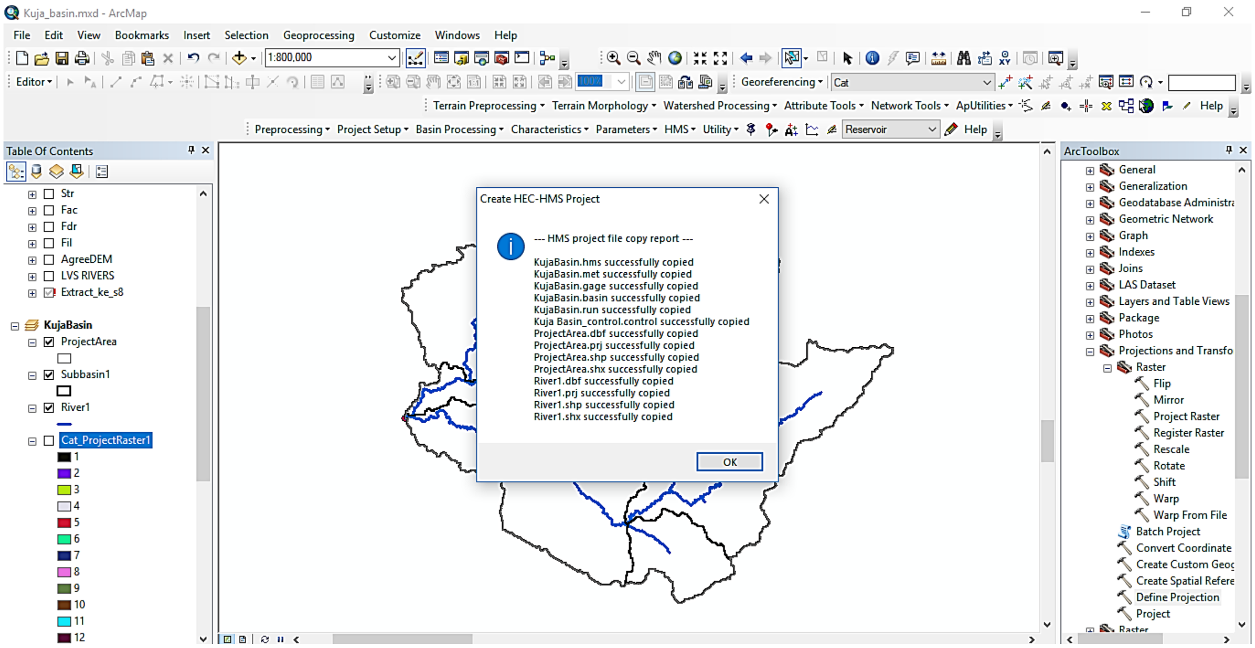

Figure 3. 8 Preparing HEC-HMS Model using HEC-GeoHMS in ArcMap

The project was started by processing the sub basins. This involved revising sub basin delineations through splitting the larger basins and merging extremely small basins so as to have sub basins of almost average areas. This was then followed by processing the river profile. In this process, the rivers could be split or merged in accordance with the newly formed sub basins. The river profile was then displayed which has a time of concentration of 5.31 hours. The basin and river characteristics that were calculated in this process included the river length, river slope, the longest flow path, basin slope, basin centroid, basin centroid elevation, and the centroidal longest flow path. The results of the delineated catchment obtained from the HEC-GeoHMS were then imported to HEC-HMS where simulations were performed.

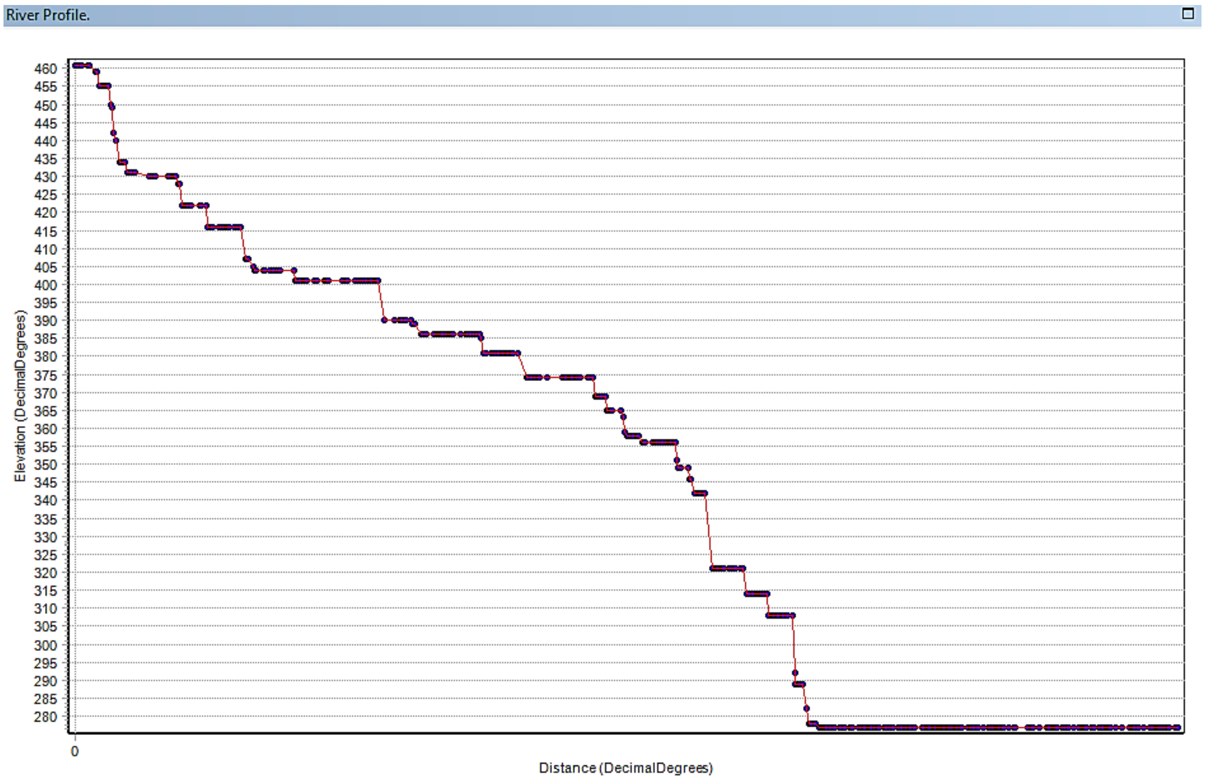

Figure 3. 9 River Kuja profile in HEC-HMS model

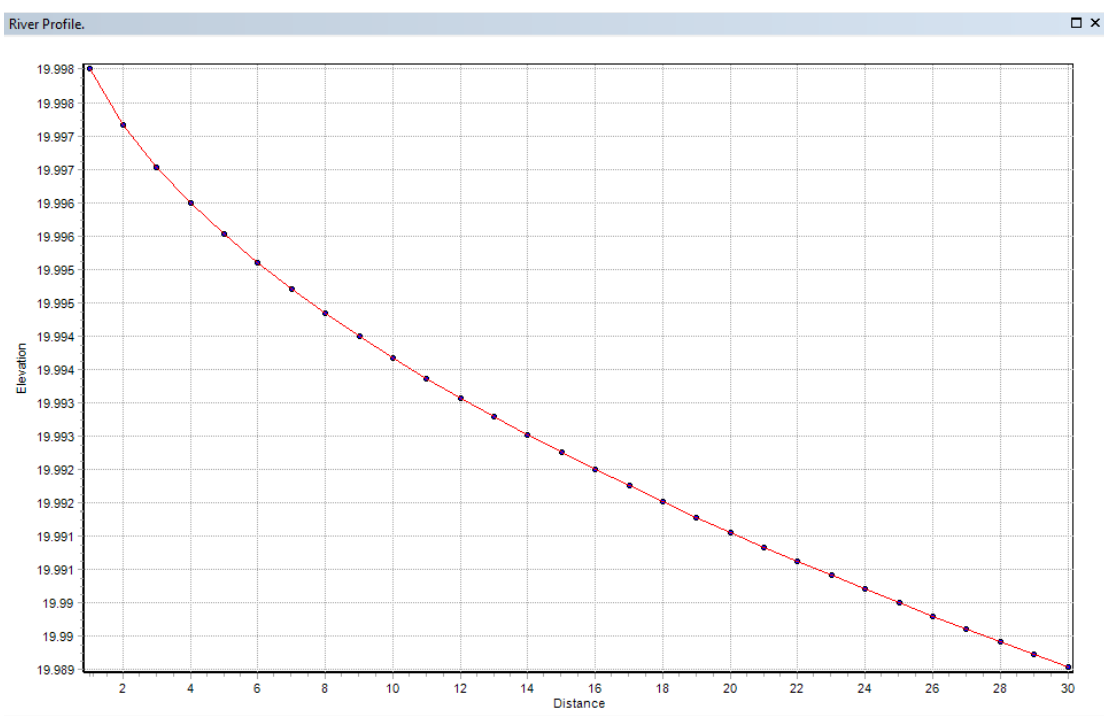

Figure 3. 10 Migori river profile in Kuja Basin in HEC-HMS model

3.2.7 HEC-HMS model parameters

The hydrologic parameters input for HEC-HMS model were also estimated using HEC-GeoHMS. Through the hydrologic parameter menu in HEC-GeoHMS, tools to assign and estimate various watershed and stream parameters for use in HEC-HMS were provided. These assisted in estimating the main parameters such as SCS curve number, the channel routing coefficients and the time of concentration among other parameters. For the channel routing, the Muskingum routing method was adopted in this study since it relates the amount of water stored in the river to both the inflow and outflow of the system. This Muskingum routing method was represented using the following equations:

$$S = K(xI + (1 - x)O) \qquad \text{……………………………(Eq. 3.3)}$$

$$O_2 = C_1I_2 + C_2I_1 + C_3I_1 \qquad \text{……………………………(Eq. 3.4)}$$

Where;

- S = storage,
- I = inflow,
- O = outflow,
- t = travel time, and
- K and x = Muskingum parameters (constants).

The value of x was assumed to be 0.2 whereas that of K was assumed to be same as the CN lag time.

$$C1 = 0.5\Delta t - Kx \;\; K - Kx + 0.5\Delta t \qquad \text{……………………………(Eq. 3.5)}$$

$$C2 = 0.5\Delta t + Kx \;\; K - Kx + 0.5\Delta t \qquad \text{……………………………(Eq. 3.6)}$$

$$C3 = K - KX - 0.5\Delta t \;\; K - Kx + 0.5\Delta t \qquad \text{……………………………(Eq. 3.7)}$$

$$C1 + C2 + C3 = 1 \qquad \text{……………………………(Eq. 3.8)}$$

Where; C1, C2 and C3 = Routing parameters which are obtained as using equations 3.5, 3.6, and 3.7 respectively, their sum was equal to 1 as shown in Equation 3.8. The other variables of K, x, and t remained as was defined in equation 3.5 and 3.6.

Land use was measured using the Soil Conservation Service (SCS) Curve Number (CN) which was the indicator of the potential of the land to generate surface runoff. The value of the CN ranges from 0 to 100 whereby a higher CN value would indicate low infiltration capacity and a lower CN would indicate a higher infiltration capacity of the soil. SCS CN was determined based on the percentage of imperviousness of the soil surface, land cover types, hydrological soil group type of the land, and the antecedent runoff conditions of the land. The SCS runoff was given by equation 3.9 (SCS, 1986).

$Q = (P-Ia)2/(P-Ia)+S$ ……………………………….(Eq. 3.9)

Where;

- Q = runoff (mm),
- P = rainfall (mm),
- S = potential maximum retention after runoff begins (mm),
- Ia= initial abstraction (mm).

The initial abstraction, Ia referred to all losses before runoff began. It was highly variable, however, for data from small agricultural watershed, it was approximated using equation 3.10.

$I_a = 0.2S$ …………………………(Eq. 3.10)

Through elimination of Ia as an independent parameter, this approximation allowed the use of S and P to produce some amount of runoff. Substituting equation 3.10 into equation 3.9, equation 3.11 was obtained.

$Q = (P-0.2S)2/(P+0.8S)$ …………………………(Eq. 3.11)

Where S was related to the soil and land use conditions of the sub-basin through the CN. The relation between S and CN was given by equation 3.12.

$S = 1000CN - 10$ ………………………….(Eq. 3.12)

The SCS unit hydrograph was used in this study for the unit hydrograph due to its simplicity since it only has two main parameters, that is, the watershed area, A, and the lag time, tL, as shown in equation 3.13 (Wurbs and James, 2002). The weighted time of concentration for each sub basin was computed using the CN lag method function in the HEC-GeoHMS. This function computed the basin lag time in hours as shown in equation 3.14. The CN lag value represented the time from the center mass of excess rainfall hydrograph to the peak of the hydrograph.

$Qp = 484A\ Tp$ ………………………….(Eq. 3.13)

$Tp = D\ 2 + tL$ ………………………….(Eq. 3.14)

Where;

- Qp= peak unit hydrograph (m3/hr.),
- A = catchment area (m2),
- Tp = flow to peak; it is estimated as a function of rainfall duration, D and lag time, tL (hrs.)
- D = rainfall duration (hrs.)
- tL = lag time (hrs.)

Once all the HEC-HMS parameters were prepared and calculated in HEC-GeoHMS, they were all converted to HMS units and then the data check function was run to verify that all input parameters and data sets were in order. A log file was then created and any errors that were present in the dataset identified and corrected before the data sets were exported to HEC-HMS for simulations. A HEC-HMS schematic was then created to provide a GIS representation of the hydrologic system using a network with basin elements such as nodes/links and junctions and their respective connectivity.

Geographic coordinates were then added to the HMSLink and HMSNode feature classes so to ensure the map was exported to the HMS model without losing its geospatial information. The watershed map file of hydrologic elements (nodes and links), their connectivity and geospatial information were exported with a text file of a .basin extension. Other files that contained meteorological data (rainfall and temperature) and discharge data were created as empty files which were later populated in the HEC-HMS model. The meteorological file was created using a .met extension whereas the discharge data input file was created using a gage file. A new HMS file was created where all these project files (.met, .map, gage file) were stored in one directory for ease of retrieval in the HEC-HMS model. The file created had a .hms extension. The created HMS file was then open in the HEC-HMS model where manipulation could be carried out without any interaction with GIS.

3.2.8 Streamflow simulations in HEC-HMS

The data processed in HEC-GeoHMS were then integrated into HEC-HMS. The HEC-HMS version 4.2 model was opened and the exported HMS files created in the HEC-GeoHMS were added to the program. The interface of the created project in HEC-HMS was as shown in Figure

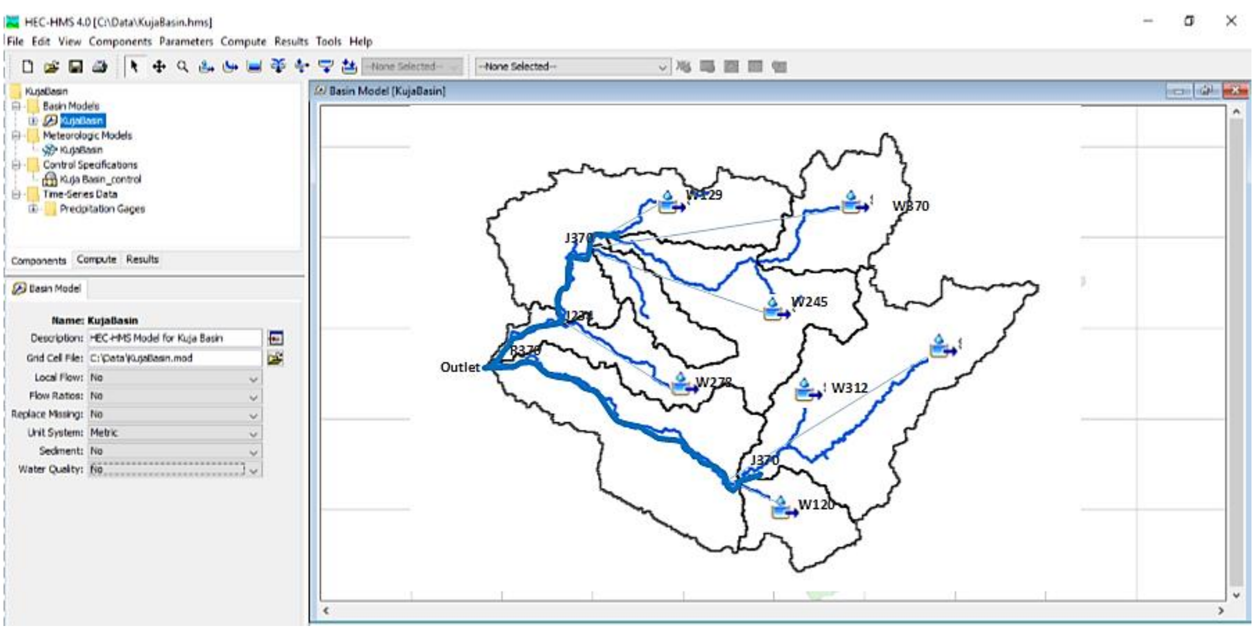

Figure 3. 11 Kuja Basin representation in HEC-HMS

The main component managers of the HEC-HMS model were the basin model manager, meteorological model manager, control specifications manager and time series data manager. The basin model manager contained the Kuja River basin map. This was the physical representation of the watershed. Initially, the map only contained the hydrologic elements which included junctions, reservoirs, reach, source, diversion and sinks after which the background map layers containing the boundaries of the watershed and its sub basins were added. The metrological manager was used to compute rainfall required by each sub basin element input the watershed. The metrological model used the watershed's average monthly evapotranspiration data to simulate the continuous hydrological response in the watershed. In order to obtain the storage-discharge relationship within the watershed, the SCS CN transformation method was applied. This method used the SCS CN by utilizing the CN grid to develop a routing method. The precipitation (rainfall) data and the Kuja River discharge data obtained at the outlet of the watershed (Muhuru Station 1KB01A) was input in the time series manager so as to simulate the flow within the watershed. Each sub basin that was created had its precipitation data. A total of 24 small sub basins were created in the HEC-GeoHMS. These sub basins were based on DEM characteristics, the slope of the watershed, the length of the stream and the number of the tributaries joining Kuja River. However, due to time constraints their parameters were merged and only the average values were used to represent the whole watershed. Each of the few sub basins had their own parameters but for this study their averages were used in the simulation process. Additionally, due to lack of sufficient rain gauge stations within the watershed, the average rainfall data for the three stations existing within Kuja River basin was used. Additionally, the discharge data at the outlet watershed was assumed to represent the whole study area. The study adopted the Muskingum routing method to model the stream routing. This method used the constants K and X to solve for flow rate numerically at each node. An assumed Muskingum X value of 0.2 was used which in general is usually used to indicate a small, natural stream. The Muskingum K value was assumed to be equivalent to the basin CN lag number for each sub basin in hours as defined by the HEC-HMS 4.2 user's manual. The reach value of 2 was assumed as the initial value for conveying the streamflow within the small sub basin. The method also utilized the channel characteristics such as width, length, slope and shape to provide the channel's physical properties which included the hydrograph diffusion and dispersion.

The hydrological processes for this study was represented using the SCS Curve Number method so that when estimating the future land cover changes as a result of agricultural expansion, the curve number change would be used to represent the changes. The initial abstraction, I_a, in the SCS method was assumed to be equivalent to 0.2S where S represented the potential maximum retention capacity for the normal antecedent moisture conditions. This retention was adjusted on a 5-day antecedent rainfall (Chow et al., 1988).

Once all the parameters were put in place various simulations were run to show the hydrologic response of the watershed using the provided meteorological data. The simulation runs applied meteorology conditions to the watershed's land surface to estimate the runoff. Each simulation run was composed of one basin model, one meteorology model and one control specification. The computed results of the simulation runs were displayed in form of hydrographs.

3.2.9 Model calibration

Calibration of the HEC-HMS model was done using the observed streamflow data at the outlet of the watershed located at 1KB01A Muhuru Bay. A medium sized rainfall event of two years was chosen. Rainfall and streamflow data for the year 2000 and 2001 were chosen in this study. The average precipitation from the three rainfall stations within the watershed and the discharge data at the outlet were used. The SCS loss parameters which included the initial abstraction, the percent imperviousness and the curve number for each sub basin was calculated using equation 3.10, 3.11 and 3.12 in HEC-GeoHMS as initial values. The time of concentration, Tc, was calculated by obtaining the longest flow path in HEC-GeoHMS (Hoblit and Curtis, 2001). The model calibration was done using the model optimization feature which would automatically adjust various parameters to obtain a minimum objective function value that matched the observed values (USACE, 2013).

The observed actual river flow discharges were input into the time series data manager after which the simulated flows were compared to these actual flows. Several iterations were made with each having 1000 runs until the best set of parameter values that had the highest Nash-Sutcliff Efficiency were obtained. The parameters that were calibrated included the loss functions such as the initial abstractions and curve number (CN), transform functions such as the SCS lag, and routing functions such as the Muskingum routing parameters. The SCS lag time and the Muskingum K value were the main parameters used for calibration. The curve number values based on the land use data for 2004 and 2014 were kept as they had been initially estimated in HEC-GeoHMS. The best set of the model parameters obtained after calibration were used to run the model for the land use scenarios in the Kuja River basin.

3.2.10 Model validation

The validation of the model performance was done by comparing the observed and simulated stream flows at River Gauging Station 1KB01A. The simulated stream flows were expected to produce a similar trend as the observed streamflows. In order to evaluate the hydrologic goodness of fit, a statistical criterion was applied on the observed (measured) streamflows and the predicted (simulated) streamflows. These results were compared using the Nash-Sutcliff Efficiency (NSE). NSE was used to indicate how well a plot of observed versus simulated values would fit the 1:1 line. According to Nash and Sutcliff (1970), the NSE represents a normalized statistic which determines the relative magnitude of the residual variance compared to the observed (measured) data variance. Its value ranges from $-\infty$ to 1, with an NSE = 1 being the optimal value. Values between 0 and 1 are generally regarded as acceptable levels of performance with values that are less than 0 being regarded as unacceptable performance levels.

3.2.11 Creating future precipitation scenarios

The input data or future prediction also required the precipitation data. In order to predict precipitation generally, the downscaled rainfall data from General Circulation Model (GCM) obtained from the IPCC were used (Kiem et al., 2008; Beyene et al., 2010). It must be noted that the GCM data are more reliable for temperature prediction than rainfall, wind and humidity prediction. However, the uncertainties could be reduced when ensemble approaches are adopted (Kundzewicz et al., 2007).

Projections also indicate future warming conditions within East African region whereby temperature will increase by 0.2°C (B1 - low scenario) to 0.5°C (A2 - higher scenario) per decade. Thus, in order to predict the future rainfall scenario for this study, a simple approach was adopted. According to IPCC reports, most global rainfall predictions indicate that there will be no change to 2.5% increase in rainfall within the next 25 years in the East African region. Similarly, in the next 50 years there will be no change to 5% increase in rainfall (Meehl et al., 2007). According to IPCC report, Kiem et al. (2008) also estimates that there will be a 6.3% to 10% increase in rainfall by 2100. Based on these estimates, this study adopted the 2.5% and 5% increase in the future rainfall for 2030 and 2060 respectively. These increases were applied uniformly to the 2009 average daily rainfall of Kuja River basin.

4.0 RESULTS AND DISCUSSION

4.1 Variation in Rainfall and Streamflow Results

The relationship between monthly stream discharge at the outlet of the Kuja River basin and average monthly rainfall was investigated to greater depth using regression analyses as shown in Figure 4.1. The results of the regression analysis gave an average but significant relationship between daily rainfall and daily streamflow. The value of R^2 which represents the coefficient of determination was 0.42. This showed that 42% of the variation between rainfall and streamflow was somehow related. This value represented a relationship that was moderately average, however the p-value was 0.008 which represents a rather significant relationship. The regression equation was given by the relation:

$$y = 1.2749x + 6.1419 \quad \text{……..(Eq.4.1)}$$

From the discharge trends within the basin represented in Figure 4.2, the river discharge analysis shows a decreasing trend from the year 2000 to 2009. This decrease is however minimal but it has in some way also affected the streamflow at the Kuja River basin's outlet. This declining rainfall in the region could be attributed to several factors among them climate change and land use changes that has seen mainly the forest land being converted to agricultural lands.

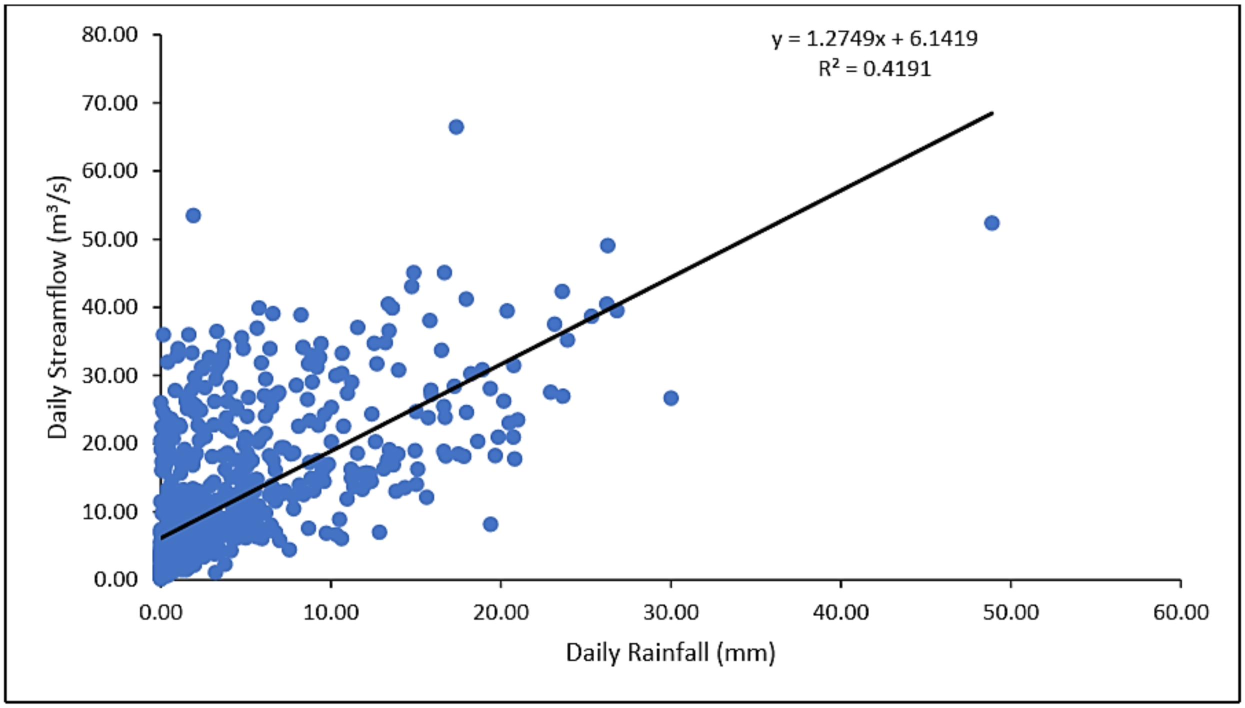

Figure 4. 1 Regression Analysis Plot between the Daily Stream flows and Average Daily Rainfall Data

Similarly, just as the rainfall trend analysis, the discharge trend analysis also exhibits a decreasing trend from 1990 to 2009. The regression relationship of the discharge trend is represented by the equation shown in Figure 4.1 using the relation:

$$y = -0.5542x + 30.995 \qquad \text{........(Eq.4.2)}$$

The decrease in discharge could be attributed to either decrease or increase in rainfall or increased land use systems that increase surface hydrology (flash floods) over a short time. However, it must be noted that despite the decreasing trend of the discharge, it also keeps on fluctuating from low to high, year to year, depending on the available rainfall for that particular year.

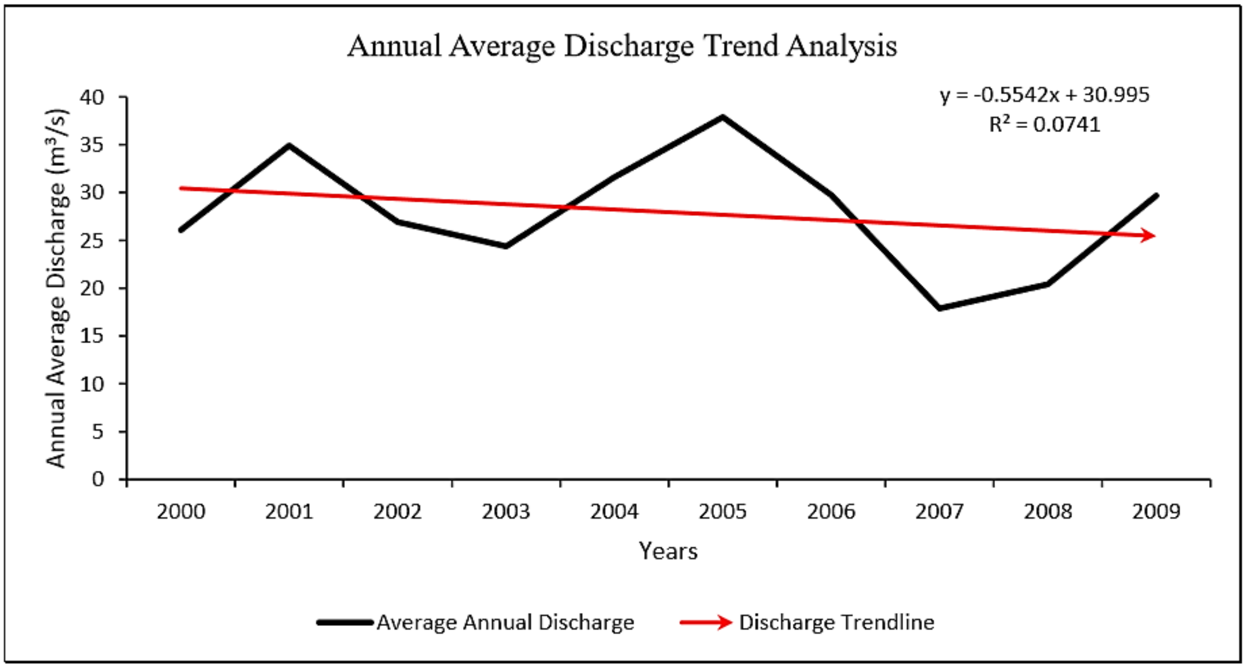

Figure 4. 2 Average Annual Discharge Trend Analysis for Kuja River basin

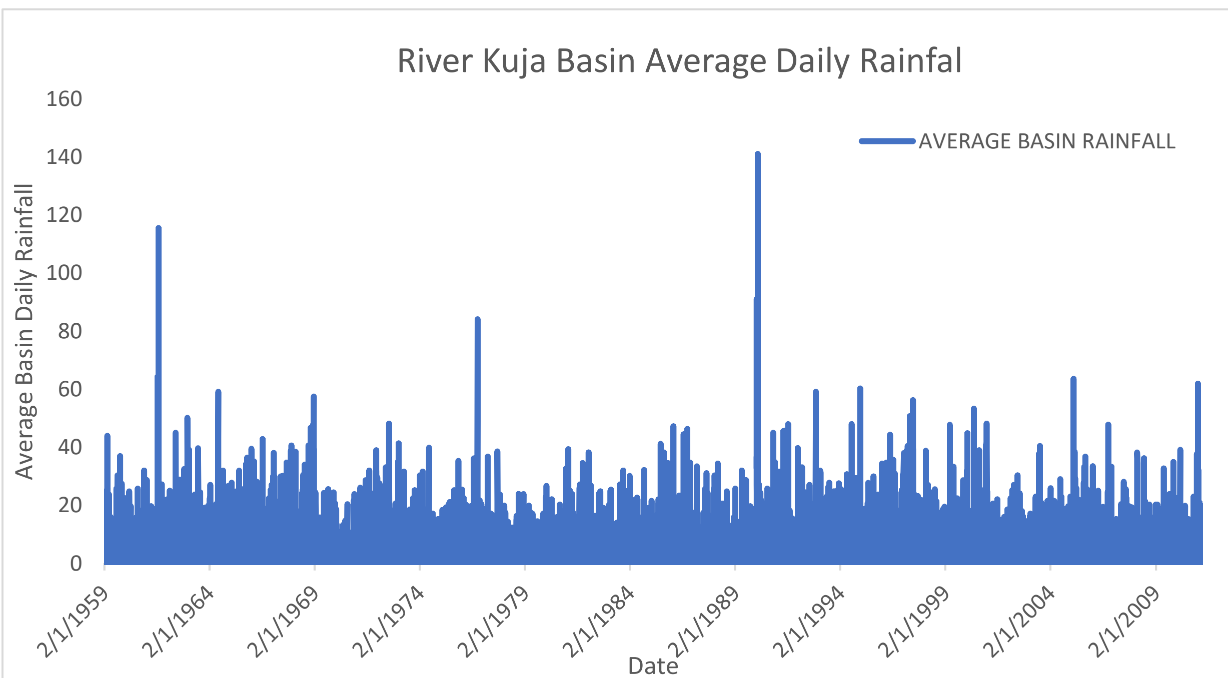

Figure 4. 3 River Kuja basin average daily rainfall at the Muhuru Bay Station

There is also a good agreement between observed rainfall and the simulated data that was later used in the modelling process. From the regression analyses carried out within the three station good correlation values were obtained which indicated that the data was best suited for the simulation processes. The comparison between the simulated and observed data for Sotik, Taranganya and Muhuru Bay gave correlation values of r as 0.74, 0.71, and 0.80 respectively. The result of the regression analysis for each of the three stations is provided below. The correlation values presented above were as a result of obtaining the square root of the R^2 value that was obtained during the process of carrying out regression analysis. Additionally, each of the three stations have the regression formulas that could be used to obtain future data.

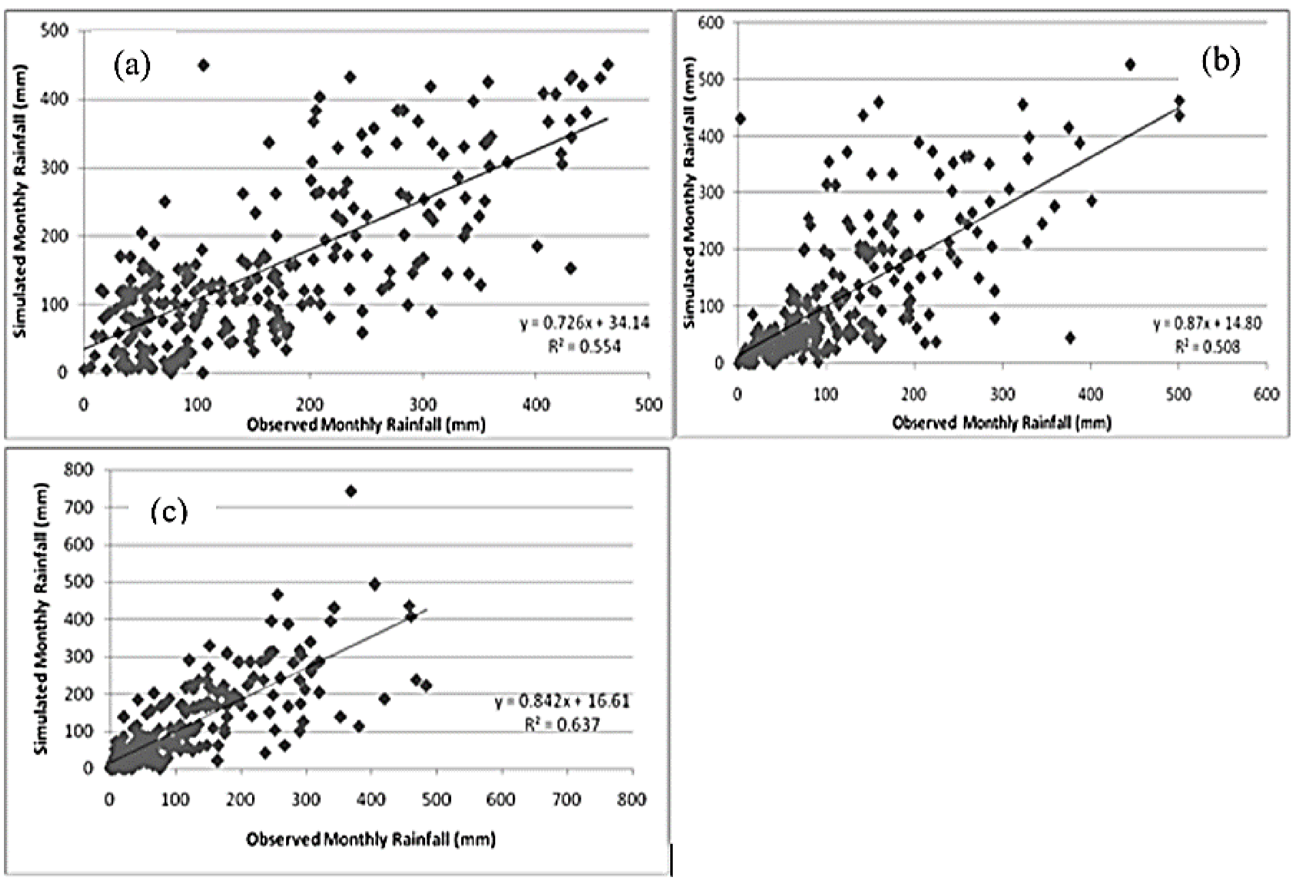

Figure 4. 4 Graph of Regression Analyses of Observed and Simulated Monthly Rainfall Data for a) Sotik, b) Taranganya and c) Muhuru Stations

4.2 Simulation of Kuja River Streamflow Using HEC-HMS

4.2.1 Model simulation results

The initial parameters that were obtained in the HEC-GeoHMS were as illustrated in Table 4.1. However, simulations carried out using these parameters did not provide a reasonable hydrograph that should have had its observed and simulated flows close to one another. This could be because of the merging of the sub basins and adopting their averages for the simulation process.

Table 4. 1 Initial Parameters from HEC-GeoHMS Used in the HEC-HMS Model

Parameter Name	***Initial Parameters***	***Optimized Parameters***
Curve Number (for Land Use)	67.10	35.00
SCS Lag Time	318.60 minutes	662.04
Muskingum X value	0.20	0.17
Muskingum K value	5.31 hours	26.77
Basin Reach	2.00	1.00
SCS CN - Curve Number Scale Factor	1.00	0.01

The model was run based on a daily time step for the period between 2000 to 2009. The parameters obtained from the model calibration and validation were used to run the simulations. The hydrograph comparison results of the observed discharges and simulated discharges for the simulation were presented as shown in Figures 4.5 and 4.6 below.

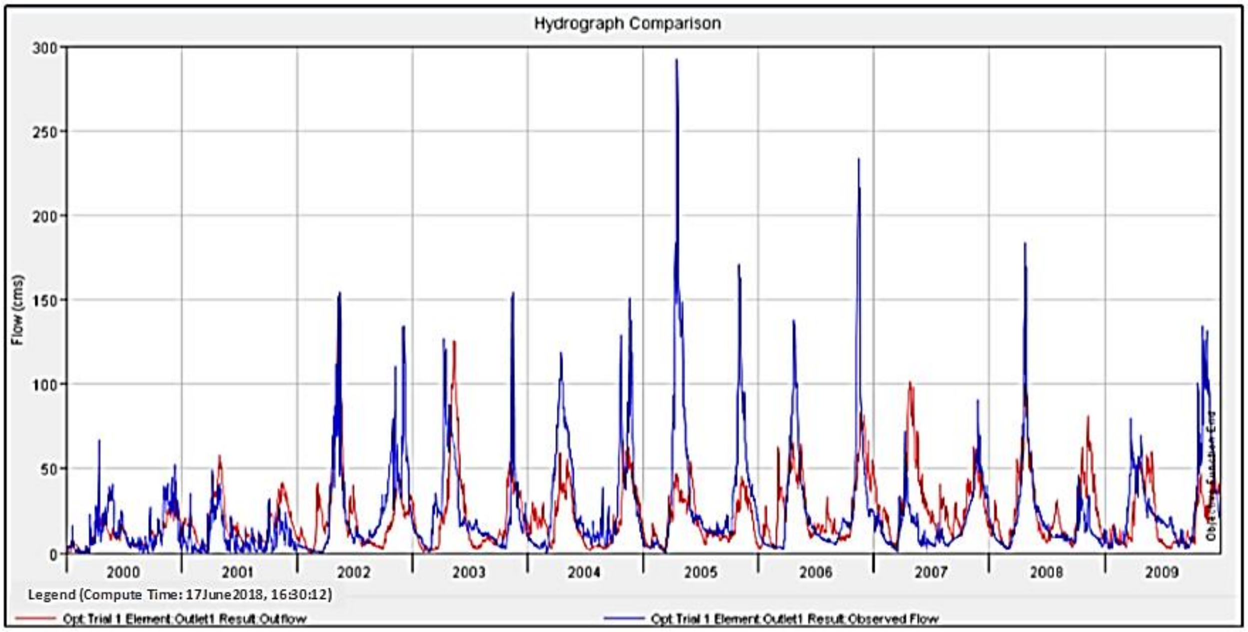

Figure 4. 5 Hydrograph Comparison Simulation of the basin from 2000 to 2009

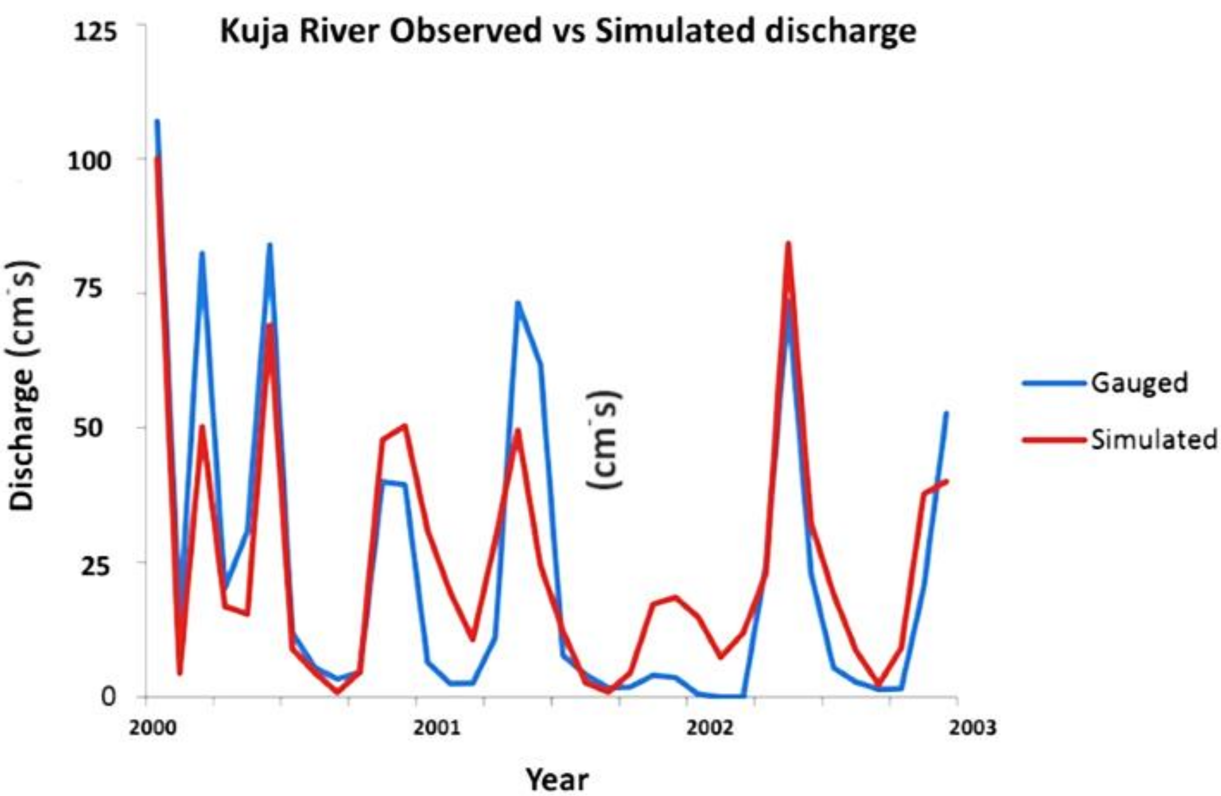

Figure 4. 6 Observed vs Simulated discharge for a three-year simulation

From the hydrographs, the observed values exceeded the simulated values by 8.1%. The observed discharge volume was 7058.28mm whereas the simulated discharge was 6525.38mm. This is a rather smaller margin and therefore the simulation was considered reasonable and acceptable. These results were within the permissible limits since the difference in the observed and simulated did not exceed the 10% which is acceptable. These results are close to those attained by Hashmi (2005) when studying rainfall – runoff modelling from Kaha hill torrent watershed in Pakistan where a difference of 8.2% was considered acceptable. However, as had been expected, the HE-CHMS model underestimated most of the peak flows and low flows as can be observed in Figure 4.5.

The HEC-HMS and HEC-GeoHMS modelling tools used for this study were very useful in analyzing the hydrologic modeling of the basin. There integration with ArcGIS provided a better platform to manipulate the various land use data for the study. The model proved to be very helpful in carrying out hydrological simulations and can thus be trusted for use in other sub-basins in the region.

4.3 Model calibration results

Firstly, the initial parameters shown in Table 4.1 were used to calibrate the model. These parameters produced unacceptable streamflow results with a very low NSE value of -42. The best calibration result that was obtained had an NSE value of 0.5 which was considered acceptable since it lied in the range of between 0 and 1. These results were similar to those obtained by Yassin et al. (2015), where they were modelling hill torrents in Pakistan using HEC-GeoHMS and HE-CHMS and found a calibration value of 0.54 and considered it as being acceptable. Errors in the calibration process could be as a result of the observed data containing several missing values which had to be filled before being used in the process. It could also be due the simplification that was done on the sub basins by merging all the sub basins and only using their averages. It was therefore concluded that the calibration results were acceptable since it fell within recommended range of NSE. The results of the calibration process were as shown in Figures 4.7 and 4.8.

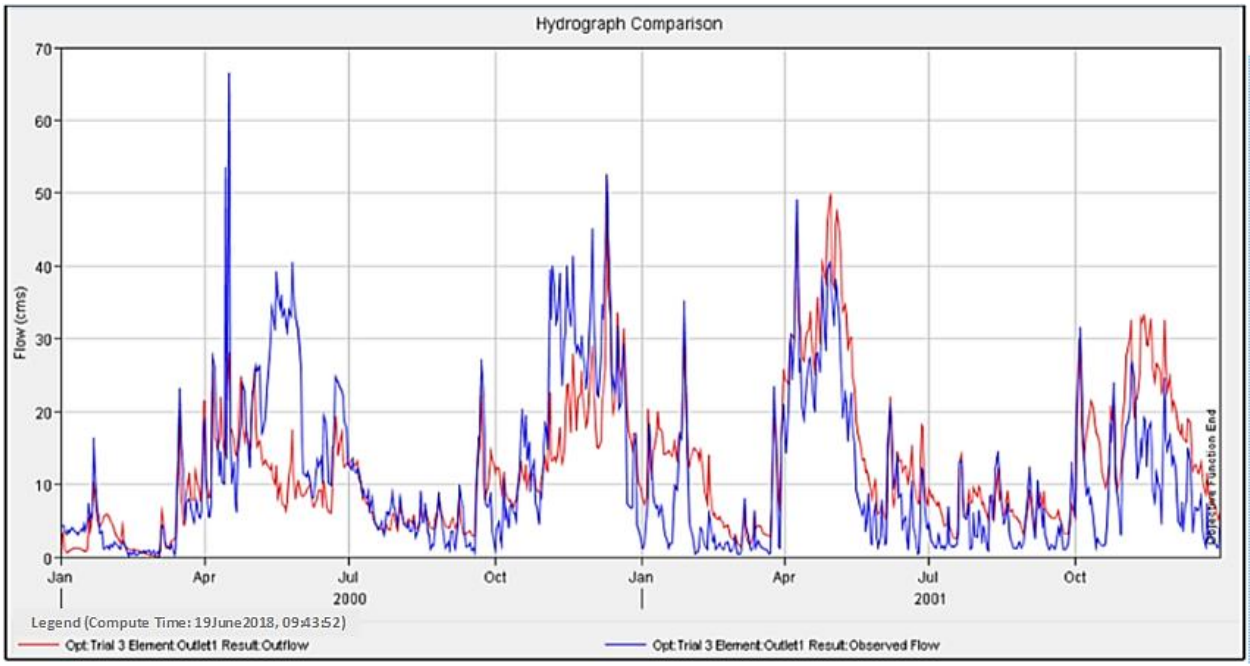

Figure 4. 7 Model Calibration Hydrograph for the Period between 2000 to 2001

Volume Units: MM 1000 M3

Measure	Simulated	Observed	Difference	Percent Difference
Volume (MM)	718.33	654.07	64.26	9.82
Peak Flow (M3/S)	52.6	66.5	-13.9	-20.9
Time of Peak	10Dec2000, 00:00	16Apr2000, 00:00		
Time of Center of Mass	16Feb2001, 23:29	19Dec2000, 07:01		

Figure 4. 8 Summary of the Objective Function Results for the Model Calibration

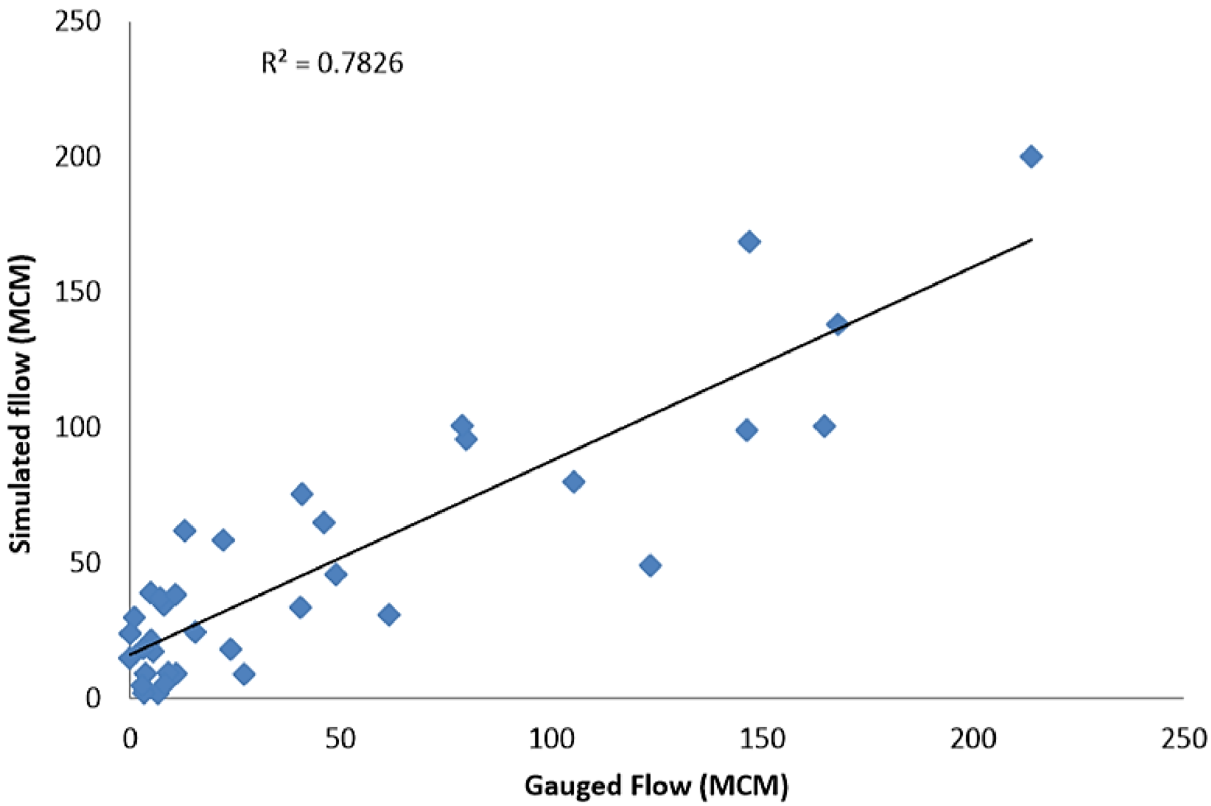

Figure 4. 9 Simulated river Kuja flow

4.4 Model validation results

The model validation process was carried out for the period between 1/1/2002 to 31/12/2003 which was outside the period when the model was calibrated. The optimized parameters shown in Table 4.1 were used to carry out further simulations to assess the model performance. The model validation showed a good NSE value of 0.31 which was also acceptable since it was between 0 and 1. In the research carried by Yassin et al. (2015) in Pakistan, the validation results were also less than the calibration results with an NSE value of 0.44. This they attributed to the fact that the rainfall data did not represent the entire watershed since there was only one station. They further recommended for the installation at least 4 to 5 rain gauge stations so as to meet international standards and improve on the modelling accuracy in future. The reduction in NSE value from 0.50 to 0.31 could have been as a result of errors in the rainfall and streamflow data due to several missing data. Another factor that could have led to this reduction could be as a result of merging the sub basins in order to simplify the simulation process. The results of the model validation process were as shown in Figures 4.10 and Figure 4.11.

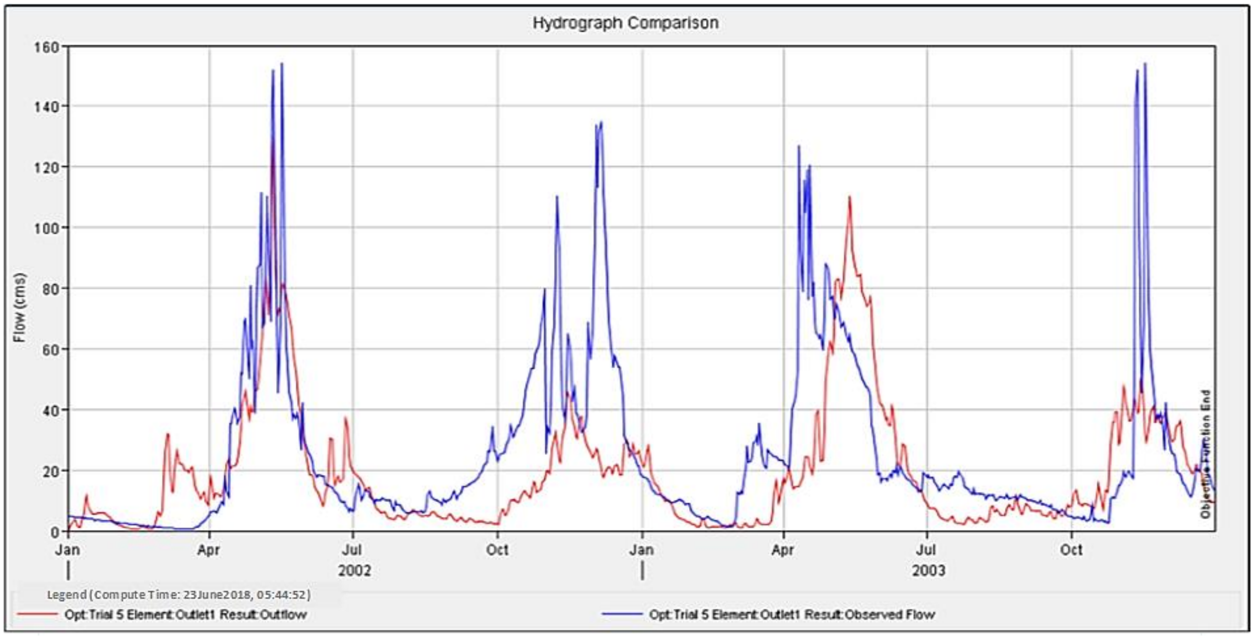

Figure 4. 10 Model Validation Hydrograph for the Period between 2002 to 2003

Volume Units: MM 1000 M3

Measure	Simulated	Observed	Difference	Percent Difference
Volume (MM)	1127.91	1501.63	-373.72	-24.89
Peak Flow (M3/S)	84.5	154.3	-69.8	-45.3
Time of Peak	13May2003, 00:00	17Nov2003, 00:00		
Time of Center of Mass	20Jan2004, 09:30	03Feb2004, 22:01		

Figure 4. 11 Objective Function Summary Results for the Model Validation

4.5 Impacts of Climate Change on the Hydrology of Kuja River Basin

When simulations were run using only the 2009 precipitation, there was a notable increase in the streamflow in those future years as was shown in Figure 4.12. The streamflows were projected to reduce by 5% in 2030 and up to 13% in 2060 as compared to the flows in 2009. However, due an increase in precipitation with no change in land use the scenario projected an increase in the flow of Kuja River. It projected a 3% and 6% increase in streamflow in 2030 and 2060 respectively.

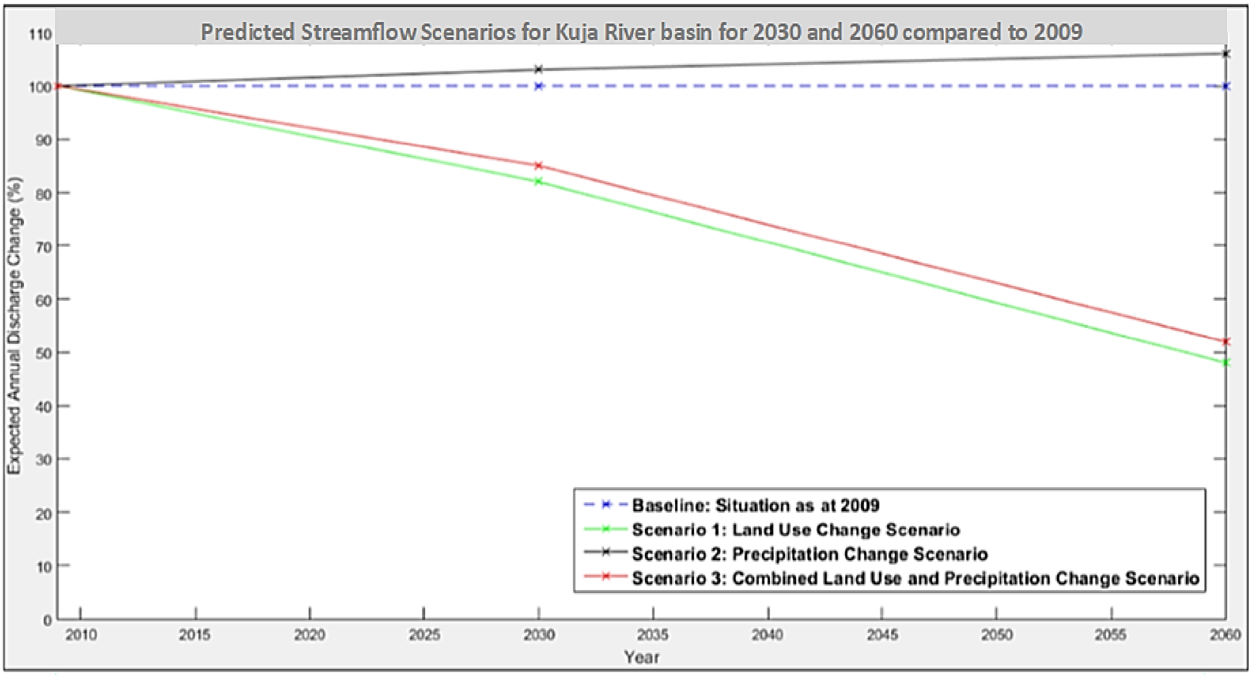

Figure 4. 12 Predicted Annual Streamflow Change in Kuja River basin for each Scenario in 2030 and 2060 compared to 2009

These results showed that as long as there is no change in land use and especially agricultural expansion, then the streamflows were likely to either remain the same or slightly increase due to precipitation increase. The final scenario combined both the future precipitation and the future land uses. This therefore demonstrated that the impacts of the increased precipitation are significant to the increased Kuja river discharge as shown in Figure 4.13 below.

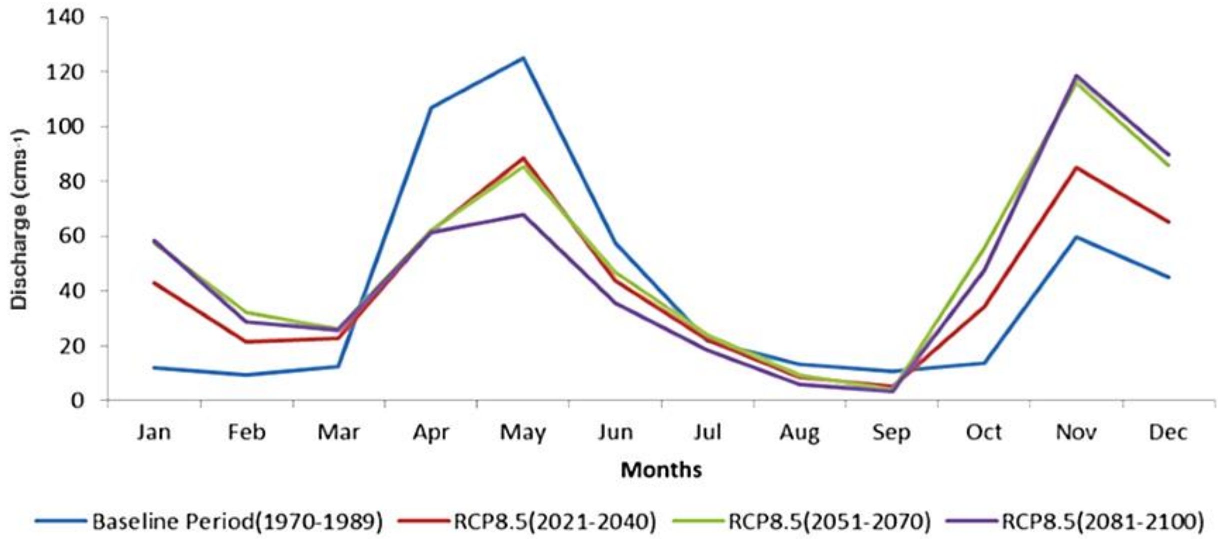

Figure 4. 13 Baseline and simulated mean monthly stream flow for RCP 8.5

According RCP8.5, there will be a reduced river discharge during March to June but a subsequently an overall increase in discharge during the other months as shown in Figure 4.13 above. Therefore, the basin shall experience prolonged wet months in the future. There is uniformity in rainfall distribution and discharge pattern in the periods 2040, 2070 and 2100. This is an indication that the effects of climate change are consistent regardless of the period, therefore, its impacts are assured.

Climate change is expected to exacerbate current stresses on water resources in the basin resulting from population growth, economic factors and land use changes, including urbanization. Runoff is projected with high confidence to increase by mid-century. There is also high confidence in the projection that the areas near Lake Victoria will suffer a reduction in water resources due to climate change.

5.0 CONLUSION AND RECOMMENDATIONS

5.1 Conclusion

Based on the three objectives of the research, the study found that;

Results from the regression analysis of streamflow against rainfall gave a coefficient of determination of 0.42 and correlation coefficient value of 0.65. This demonstrated a moderate but significant relationship between rainfall and streamflow. Both rainfall and streamflow trend analysis showed a decreasing trend for the period between 2000 to 2009.

The assessment of climate change impacts on river runoff prediction in Kuja river basin was studied based on future climate change scenarios from statistical downscaling driven by GCM. The Rainfall-Runoff model HEC-HMS was used to simulate hydrological processes in the Kuja river basin. The results reveal that future precipitation and river runoff regime is expected to be changed.

It can be concluded that a probability of flood happens to be higher due to increasing of rainfall intensity. The days with heavy precipitation will be expected to occur more frequently during the year. The changes in runoff values considering the control period will be expected according to the scenarios. Overall annual river runoff is predicted to increase in the region. It can be concluded that days with heavy precipitation will occur more frequently causing a higher frequency of high river flow events.

5.2 Recommendations

Based on this research the following recommendations were made:

Data availability was one of the major challenges in this study with several missing streamflow, rainfall and temperature data. It is therefore recommended that the Kenyan government agencies concerned with water resources utilization and management should come together to establish a central water resources database inventory. Modern data collection and storage techniques that could be easily accessed online by any one should be put in place.

It must be noted that increasing population requires additional lands and subsequently water to produce more foods for their sustainability. Additionally, most people are pushed by economic incentives thus expanding their agricultural lands so as to better their standards of living. There should be conserved agricultural practices to avoid massive surface flow (runoff) that increases river discharge over a short time hence flash floods. The Gogo falls hydro power plant should add more water storage infrastructures so as to avoid problems of low power production as a result of water shortages during the dry season.

There is need to carry out future research to understand the combined effect of climate change and land use changes on the flow of Kuja River as well as their impact on human livelihood within the basin. Future climatic predications are necessary to forecast on appropriate measures to be undertaken to prevent such effects. Therefore, there is need to carry out further and improved scenario simulations and optimization strategies that take into account upstream-downstream water users.

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7.0 APPENDIX

7.1 SIGNIFICANCE OF SPEARMAN'S RANK CORRELATION

Work out the 'degrees of freedom' you need to use. This is the number of pairs in your sample minus 2 (n-2).

• First plot the results of the obtained ρ on the table.

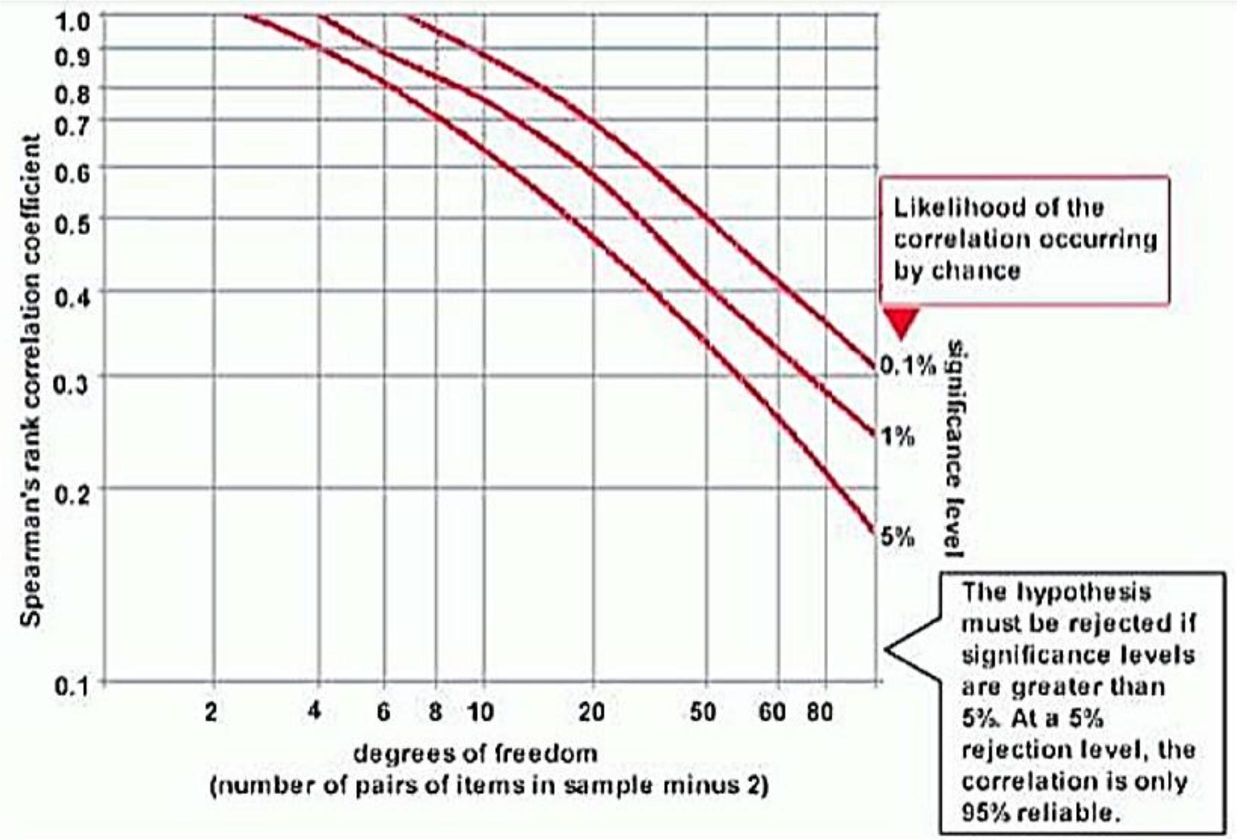
• If it is below the line marked 5%, then it is possible your result was the product of chance and you must reject the hypothesis.

• If it is above the 0.1% significance level, then we can be 99.9% confident the correlation has not occurred by chance.

• If it is above 1%, but below 0.1%, you can say you are 99% confident.

• If it is above 5%, but below 1%, you can say you are 95% confident (i.e. statistically there is a 5% likelihood the result occurred by chance.

Fig. 1: The significance of the Spearman's rank correlation coefficients and degrees of freedom


1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
Spearman's rank correlation coefficient
2
4
6
8
10
20
50
60
80
degrees of freedom
(number of pairs of items in sample minus 2)
Likelihood of the correlation occurring by chance
0.1%
1%
5%
significance level
The hypothesis must be rejected if significance levels are greater than 5%. At a 5% rejection level, the correlation is only 95% reliable.