UNIVERSITY OF NAIROBI

INTEGRATING CLIMATE CHANGE SCENARIOS IN THE HYDROLOGICAL STUDY OF THIKA RIVER, KENYA

BY

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A Thesis Submitted for Examination in Partial Fulfillment for the Requirements of the Award for the Degree of Master Science in Hydrology and Water Resources Management in the Department of Geography and Environmental Studies, University of Nairobi.

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DECLARATION

I declare that this thesis is my original work and has not been submitted elsewhere for examination, award of a degree or publication. Where other people's work or my own work has been used, this has properly been acknowledged and referenced in accordance with the University of Nairobi requirements.

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DEDICATION

This study is dedicated to Almighty God who gave me the will, power, knowledge and wisdom to undertake it. Without mention is, my daughter Viane and son Abel as well as my wife Violah and my dear parents; God bless you all.

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ABSTRACT

One of the most important factors influencing hydrological processes in a river basin is its weather/climate. The main objective of this study was to create a hydrological response model under changing rainfall and temperature conditions and specifically to determine climate and discharge trends and create a rainfall-runoff model for the Thika River. Data used were mainly from secondary sources. Time series analysis was used to determine climate and stream-flow trends. Thika Riverwatershed was delineated using Soil Water Assessment Tool (SWAT) with Digital Elevation Model (DEM) data, and simulated historical and projected streamflow using climate scenarios for RCP 4.5 and RCP 8.5. Double Mass Curves were used to test homogeneity and all the data used in the study depicted a straight line plot showing that they were good for the study. Results showed an increase in both minimum and maximum temperatures and decrease in annual and monthly rainfall in all stations except at Thika Agro Met Station. This was found out that Thika Agro Met station was located in a different agro climatological zone as the other stations. Mean annual streamflow analysis depicted a negative trend. However, rainfall projection under RCP 4.5 and RCP 8.5which represented medium and high emission scenarios respectively showed decrease in rainfall in the climate period 2021-2050. However, results from standardized rainfall anomalies for climate period of 2061-2080 showed an increase in rainfall in all the stations in the catchment area under all the emission scenarios except in Thika Agro Met where rainfall is expected to have a negative trend under RCP 8.5. Results from temperature projection showed that, the period 2020-2057 is expected to be cooler than average while climate period 2060-2100 temperature anomalies were found to be positive with the highest anomalies expected to be towards the end of 2100. Using SWAT model, water yields decreases in early 2020 and 2030s and increases in 2061-2080. There is an increase in water yields in early 2020 and 2030s in the catchment, decrease trend in early 2060s and an increase towards the end of 2070s during (2061-2080). The highest water yield in the catchment is expected to be in the year 2077 while the lowest water yield is expected to be in the year 2066. From this study it was concluded that changing climate could have an impact on water and the obtained results could be useful for water resources management and policy making so that climate change could be incorporated in the plans and management for sustainable water supply to local residents and other cities such as Nairobi and other satellite towns.

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LIST OF ACRONYMS AND ABBREVIATIONS

AMCOW	African Ministerial Council on Water
AR4	Fourth Assessment Report
AR5	Fifth Assessment Report
CFCs	Chlorofluorocarbons
CFSR	Climate Forecast System Reanalysis
CORDEX	Coordinated Regional Downscaling Experiment
DEM	Digital Elevation Model
DHI	Dutch Hydrological Institute
DJF	December January February
ET	Evapotranspiration
GHGs	Greenhouse Gases
GoK	Government of Kenya
HEC-HMS	Hydrological Engineering Centre-Hydrological modeling System
HRUs	Hydrological Response Units
IPCC	Intergovernmental Panel on Climate Change
ISRIC	International Soil Reference and Information Centre ()
ITCZ	Inter-Tropical Convergence Zone
IWRM	Integrated Water Resource Management
JJA	June July August
KENSOTER	Kenya Soil and Terrain
KFS	Kenya Forest Service
KMD	Kenya Meteorological Department

KNBS	Kenya National Bureau of Statistics
KSS	Kenya Soil Survey
LBC	Lateral Boundary Conditions
LLGHGs	Long Lived Greenhouse Gases
LR	Long Rain
LULC	Land Use Land Cover
MAM	March April May
MDGs	Millennium Development Goals
MoH	Ministry of Health
MWI	Ministry of Irrigation
NCCRS	National Climate Change Response Strategy
NWMP	National Water Management Plan
OND	October November December
RCM	Regional Climate Model
RCMRD	Regional Center for Mapping Resources for Development
RCPs	Representative Concentration Pathways
RGSs	River Gauging Stations
RMSE	Root Mean Square Error
SBC	Surface Boundary Conditions
SCS –CN	Soil Conservation Service- Curve Number
SDGs	Sustainable Development Goals
SEI	Stockholm Education Institute
SOTER	Soil and Terrain

SR	Short Rain
SRTM	Shuttle Radar Topographic Mission
SSTs	Seas Surface Temperatures
SWAT	Soil Water Assessment Tool
UNEP	United Environmental Programme
USDA-ARS	United States Department of Agriculture–Agricultural Research Service
USGS	United State Geological Survey
UTM	Universal Time Mercator
WEAP	Water Evaluation and Planning
WGS	World Geodetic State
WMO	World Meteorological Organization
WRA	Water Resources Authority

CHAPTER 1: INTRODUCTION

1.1: Background of the Study

Since 1950s the climate system has been warming leading to decrease in the amounts of snow and warming of oceans and sea level rise (IPCC, 2014). Therefore, water resources especially in the tropical region will be greatly affected by changing climate (Kishor, Gosain, Paul, & Khare, 2016). Human influence on the global climate system has resulted in the continuous emissions of greenhouse gases into the atmosphere exacerbating increase in global temperature at the present and in the future decades leading to changes in hydrological cycle due radiative forcing and cooling (IPCC, 2007).

In Africa, there is already an evidence of faster rise in warming as compared to global average, and this trend is likely to continue as most Sub Saharan countries are on the verge of industrialization. For example, the warming occurs for all seasons of the year although the trend is geographically varied. There have been few cold spells and more warm spell in western and southern Africa while in East Africa there has been fall in temperatures close to the Coasts and major inland (Conway, 2009).

1.2: Significance of the Study

Scientific studies in East Africa over the last few years concluded that the glaciers on Mt. Kenya and Mt. Kilimanjaro have drastically reduced in mass and extent leading to reduction of river discharge. In the case of Mt. Kenya the greatest extent was during the Little Ice Age in the 1950s (Odingo, 2006). Another study carried out in Nyando also concluded that water in most Kenya's rivers has decreased and it is mainly attributed to climate change (Immerzeel & Drooger, 2009) a fact too confirmed by (Rwigi, 2014).

Climate change and variability is therefore evident that it is an issue of global and regional impediment in the realization sixth Sustainable Development Goal (SDG) which ensures available and sustainability in the management of water and sanitation (Osborn & Cutter, 2015). A study by Pelling, (2003) found out that rise in the frequency and impact of climate related natural disasters, which is likely to continue since changing climate raises the danger of calamities including floods and droughts. In Sub-Sahara Africa a change in seasonal pattern, timing, distribution and intensity of rainfall is already being witnessed (CARE, 2012).

Kenya's climaticconditions have been changing in many parts of the country and rainfall is becoming more unpredictable every season and year (Makenzi, Omondi, & Wekesa, 2013). As a result of this, many regions of the world including Kenya are already facing a formidable freshwater management challenges (SEI, 2012). In Kenya some of these challenges include catchment degradation due to land use, climate change among others. Attempts have been made over time to address other challenges but climate change has proven to be one of the greatest challenge as it affects the spatial and temporal distribution of precipitation especially in most Kenya's catchments and thus water availability is expected to be variable (Marshall, 2011). The uncertainty of rainfall and uneven temporal and spatial distribution in Kenya is posing great management challenge to water resources of the Thika River. It is therefore anticipated that water availability would be extremely vulnerable under the projected climate change scenarios (Conway, 2009).

Kenya's total area is 582,646 km^2 with land cover constituting 581,679 km^2(99.8%) while water covers 11,230km^2 (1.2%). In addition Kenya's eighty percent (80%) of its land is classified as arid and semi-arid region while 20% is considered land of high and medium potential for agriculture (Nyanchaga, 2011). Central, South Western and western parts of the Kenya is densely populated where the water towers (Mount. Kenya, Aberdare, Mount. Elgon, Mau complex and Cherangani) are located and has consequently exerted pressure on water resources of most catchments resulting to changes in rainfall patterns leading to water scarcity in Kenya which is already a water deficit (GoK, 2009).

Potential impacts of changing climate in Kenya include extreme weather events, changes in the distribution and frequency of precipitation. In addition, changes in water supply for variety of uses for both human and wildlife use, drying up of rivers, melting of ice among others are also some of the impacts(Ozor & Madukwe, 2012). This study recognised the need for a reasearch on climate responses on runoff on a catchment. This is only achieved by use of historical and projected climate model output with a slightly higher resolution by recognising the fact that most studies on in the subject area have been approached on regional, country and continental scale without due consideration on a sub catchment catchment. In addition, from published literature most studies carried out in the study area have mainly addressed other water resource problems such as flooding, impacts of climate variability on hydropower generation sedimentation among others and therefore little has been done on climate impact on water. Thika River is a lifeline of Kenya's power generation and major water supply for industries, domestic and agricultural use and therefore this study was neccesary for water resources planning.

1.3: Statement of Research Problem

Water management challenges including siltation of dams, water pollution, floods, droughts, lack of water supply systems, and catchment degradation due to poor land management practices, increased deforestation especially in Aberdare forest, sedimentation, population growth and climate change have been a menace in Kenya. Problems such as forest degradation, poor management of water resources, and pollution from industrial and agricultural sources are potentially solvable, but the magnitude, intensity and severity of droughts and floods resulting from changing climate is likely to intensify in the foreseeable future (Marshall, 2011). In addition, increase in population exerts more pressure on water resources resulting to water rationing especially in urban centers such as Nairobi County (GoK, 2014) and consumption of polluted water has led to incidences of water borne diseases especially to the poor population who cannot afford good health care (GoK, 2014).

Dependency of Kenya's economy on agriculture has resulted into heavy losses in agricultural produce due to rainfall variability and increased evapotranspiration due to rise in temperatures. Furthermore, continued greenhouse gases at or above current rates would bring on additional warming that would undermine the advancement already made and become an impediment in the realization of the Sustainable Development Goals (SDGs) (UN, 2014).

The effects of climate change incorporate expanded recurrence and seriousness of dry seasons, surges and tempests, water stretch, decrease in agrarian efficiency and sustenance security, and further spread of water-related sicknesses, especially in tropical ranges (Oludhe, 2012).Kenya's Vision 2030 focuses on achieving mid-level income by 2030 will results to increased greenhouse gas emissions due to increase industrial activities. Greenhouse gases released into the atmosphere leads to changes rainfall in Thika River catchment resulting into water scarcity for agricultural activities, domestic, industrial and Nairobi City and other satellite towns as approximately 80% of water used in Nairobi City is dependent on water from Thika River.

Thika and Sasumua dams located along Thika River has had its levels fluctuate due to rainfall variability posing a challenge to water managers in Nairobi City Water and Sewerage Company (NCWSC) that has resultedinto frequent water rationing (Wambua, 2002). Extreme weather events within Thika River also results into low river volumes which might lead to power rationing and declining dam levels at Tana's Seven Folks Falls (Oludhe, 2012).

Enormous economic losses resulting from this extreme climatic events is a clear indication that there is need to carry out a study on how future climate is likely to change for planning, decision making and policy making in the water sector in Kenya. Most past studies in the study area have addressed other water related problems resources including siltation and sedimentation with little on climate related impacts on water (Nyandega, 2007, Gathenya, 2005, Oludhe, 2012). This study investigated impacts of changing climate on stream flow by use of climate model data on Soil Water Assessment Tool (SWAT) in future.

1.4: The Research Questions

The following questions guided in achieving the objectives of this study:

(i) What are the historical rainfall and temperature trends in Thika River catchment?
(ii) What is the trend in river discharge of Thika River?
(iii) What is the relationship between rainfall and river discharge in the Thika River Upstream?
(iv) What could the future climatic and river discharge conditions be in the Thika River catchment?

1.5: Objective of the Study

The main objective of this study was to create a hydrological response model under changing rainfall and temperature conditions in the Thika River catchment.

1.5.1 Specific Objectives

The specific objectives of the study were to:

(i) determine rainfall and temperature trends in Thika River

(ii) establish river discharge trends in Thika River

(iii) create rainfall-runoff model of the Thika River and

(iv) provide a simulation tool for assessing hydrological conditions under changing climate scenarios in the Thika River

1.6: Study Hypotheses

To guide in achieving the above objectives, the following hypotheses were used:

H_1**:** There is no long term change in the rainfall and temperature conditions in the Thika River catchment in the last 35 years.

H_2**:** There is no long term change in change in the river discharge conditions of Thika River

H_3**:** There is no significant change in discharge under changing climate in the Thika River Catchment

H_4**:** There is no significant relationship between the past and future climate conditions and discharge in Thika River Catchment.

1.7: Study Justification

Water having both social and economic importance, its availability is significant for sustaining life on earth (Snellen, 2004). In Kenya, most of the fresh water resources is in the form of river systems and tend to originate from the high rainfall areas which also happen to be high agricultural potential lands and therefore subject to high population density.

One of the most important river systems is the Thika River system which is part of the greater Tana Basin. Thika River originates from one of the key water tower Aberdares whose lower slopes and the associated plateaus are source of the intensely cultivated and densely populated lands in the world (GoK, 2009). This makes Thika River catchment to be so susceptible to changing climate conditions. It would therefore, be useful to consider integrating water resources of Thika River system in the climate change. The integration is necessary in making decisions in the use of limited water resources due to unlimited demand in the face of the changing climate.

A Study by (Ng'ang'a, 2006) showed variations in climate conditions in Kenya which affects rainfall especially in timing and distribution as well as temperature particularly the minimum conditions. This is due to the fact that increase in evaporation rates leads to reduced water availability. Therefore climate change could affect availablewater especially in countries located in the tropical region such as Kenya.The impacts of flood and drought events in Kenya has increased with the following events occurring since 1980; 1983/84, 1991/92, 1995/96, 1999/2001, 2004/05. El Niño related event of 1997/98 was the worst ever recorded in history since it cost the government US$ 70 billion and the most hit sector was water. In the target year 2030, water demand will increase in all Kenya's catchment areas and water balance expected to be tight in all areas and water deficits is predicted in most catchments including Tana Catchment area (GoK, 2013).

Land use within the Thika River upstream has altered the hydrology of the area resulting into reduction in river volume. Deforestation in Aberdares water tower has also resulted into flashfloods during heavy rainfall and increased soil erosion leading to siltation of Thika dam hence reducing its volume. These hydrological challenges are likely to worsen under climate change due to its ability to alter rainfall patterns in the Thika River catchment area. Most rivers within Upper Tana Catchment have an inadequate flow of water due to insufficient rainfall and therefore this insufficiency has been worsened by climate change. According to National Water Master Plan 2030 (GoK, 2012), climate change has been identified as the greatest challenge in Kenya and has resulted to increased frequencies of floods and drought.

In order to reduce vulnerability of changing climate in the Thika River, there was need to study and investigate climatic changes and its impact on water yields for management to ensure consistent water supply to Nairobi City County, local population and reliable power supply for Seven Folks Falls. Furthermore, this study will enable environmentalists and other stakeholders in the proper management strategies of the Thika River upstream catchment area. It is therefore, evident that the results from this research will be important in policy and management decisions in Thika River as well as other river systems in Kenya.

1.8: Operational Definitions

Climate Change scenario: Projecting greenhouse gases emissions to examine future vulnerability to climate change based on population growth, industrialization and economic growth.

Climate change: A statistical deviation of weather of a region by of its long term average and variation of weather parameters such as temperature and rainfall over a long period, typically 30 years.

Hazard: A situation that causes a threat to life, health property or environment

Hazard: Severity of climate change to environment to environment and ecosystems.

Hydrological Modeling: A conceptual representation of a part of the hydrological cycle for use in in hydrologic processes

Hydrology: The study of surface water including river runoff in the study area

Impact: Severity of climate change to environment to environment and ecosystems

Integration: Identifying climate risks and adjusting activities to reduce the risks.

Probability: The likelihood of something happening or being the case.

River Catchment: Extend of land where all surface water converges to a single point of a lower elevation.

River discharge: Volume of water flowing through a river channel.

Simulation: Mimicking operation of a world process or system over time.

Study Area: Thika River Catchment

Trends: Change in annual, seasonal or monthly climate and streamflow parameters

Water resources: Surface water draining in Thika River that is useful or potentially useful to agriculture, industrial, households, recreational and environmental activities

1.9: Scope and Limitations

Data availability is a general problem in hydro meteorological study due to a number of reasons (Rwigi, 2014) and this often result in lack of coverage in areas of interest. In the Thika River, there were few existing gauging stations for hydrometeorological measurements and this therefore necesitated the use of estimations techniques such as interpolation extrapolation and remote sensing amongst others. In this study, spatial representation of a number of climate elements (variables) were estimated using remote sensed data from Climate Forecast System Reanalysis (CFSR) generated for 36 (thirty six) years (1979-2014. Land use data for simulating hydrological responses were based on AFRICOVER data of year 2000 and therefore did not represent changes that could have occurred from then to present which were estimated using the change indices generated thereof.

CHAPTER 2: LITERATURE REVIEW

2.1: Introduction

The literature review was conducted topically on issues relevant to the study. The topics dealt with included; climate variability/change, climate change and water resources planning and management, hydrological cycle, climate modeling, and hydrological modeling.

2.2: Climate Change and Variability

According to IPPC (2007), climate is defined as describing weather elements by way of average and variation for duration from monthly to decades and century with thirty years being classical averaging period for most of its weather element to properly describe the climate of that particular region. While variation in climate is considered as deviations in average of climatic conditions of a place in both time and space past a single weather phenomena. It is often used to refer to variations of climatic conditions in duration of time (monthly and annual variations) in comparison to a length of period. In considering climate variations, anomalies of climate parameters are calculated by setting a deviation reference such as mean/median (Thuc, Hien, & Khiem, 2016).

Figure 1 which shows climate components, (atmosphere, biosphere, cryosphere etc.); interact to give a climate of a region, local or global (Miller & Yates, 2005). The intelligent reaction of the segments of the atmosphere framework to the outside vitality sources, for example, the sun based radiation and anthropogenic changes in any of the parts of atmosphere framework, decide the worldwide and additionally territorial foundation conditions that administer the world’s climate and atmosphere designs. Sun powered radiation is the fundamental wellspring of vitality that drives the atmosphere system (Al-kalbani, Price, Abahussain, Ahmed, & Higgins, 2014).

The energy goes through and interact with the air before coming to the earth’s surface and therefore any human changes to the environment and the area surface constitute another huge wellspring of energy to the climate framework since it modifies the energy parity between the approaching sun based and active physical radiation. Roughly $240WM^{-2}$ of sun oriented energy achieve the highest point of the earth's air from the sun (Treut, *et al.*, 2007). A third of the energy that reaches the earth surface is used for warming the earth’s surface while the rest is reflected back to space as long wave radiation. To adjust the approaching sun powered radiation, the earth must emanate the same measure of vitality back to space however in the long wave radiation band. Atmosphere has greenhouse gases allows shortwaves radiation but absorbs the long wave radiation from the ground and therefore results to warming of the earth surface.

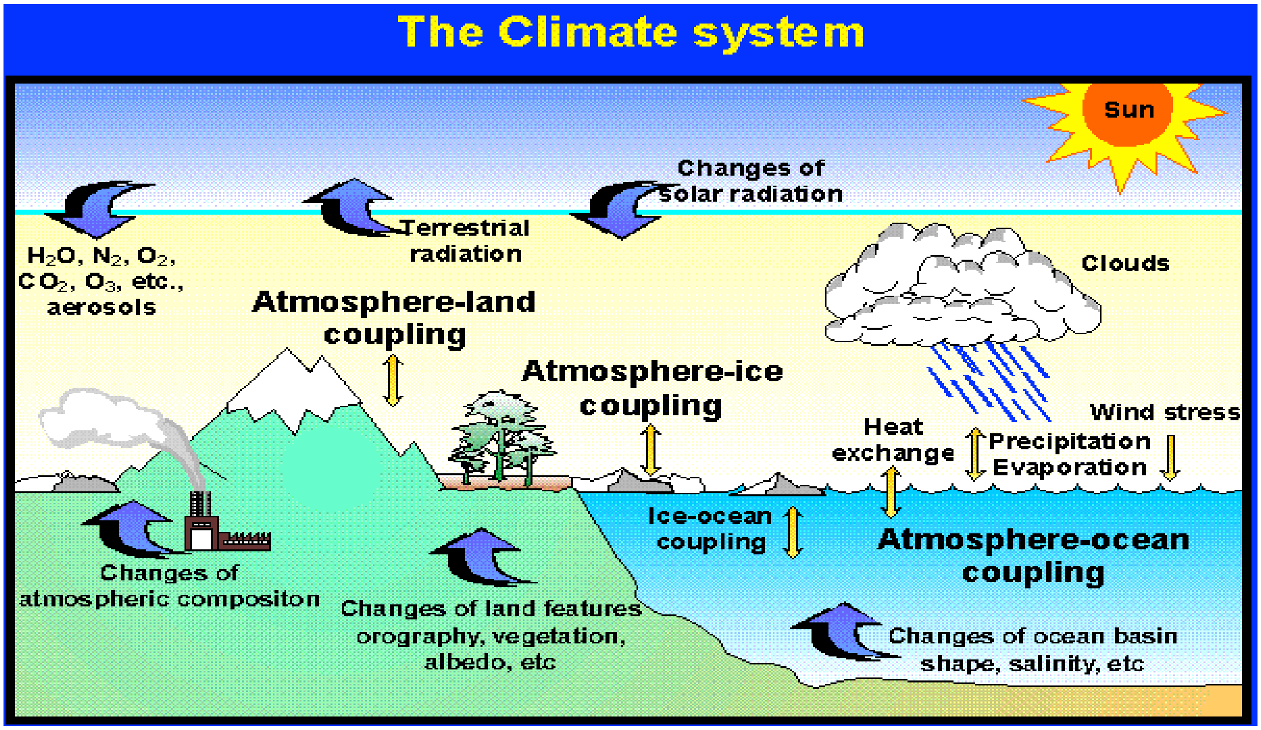


Figure 1: Climate System Components: Solar Radiation, Ocean, Atmosphere, Land, Snow/Ice, vegetation (Source: Met office, 2016).

All around us are now dedicated to future considerable environmental change throughout the following thirty years what's more, past. This change is liable to quicken over whatever remains of the 21st century (IPCC, 2007).

It is accordingly important that more point by point territorial environmental change forecasts frantic accessible so that financially savvy adjustment and suitable relief activities can be arranged. It is therefore evident that if no proper adaptation and mitigation measures are taken then changing climate is likely to impact on water availability due to changes in rainfall pattern.

This study focused on future climate projections on a sub catchment scale as most studies carried out have been done on a regional scale without due consideration on what happens at a river system.

Climate of Kenya is mainly associated with the latitudinal migration of Inter Tropical Convergence Zone (ITCZ). Varied country's topography also brings about considerable variations of climate throughout Kenya. The sun crosses the Kenyan territory twice in a year where it is overhead on March 21st on its way to the northern hemisphere and again on September 23rd on its way towards the southern hemisphere. The ITCZ is expected to be most active about a month after the sun is overhead. These periods correspond to the two main wet seasons; March-April-May (MAM) and September-October-November and December (SOND) seasons respectively (Mogaka, Gichere, Davis, & Hirji, 2006).

The climate of a region largely determines the volume of water supplied to the drainage basin through rainfall as well as the proportion of that rainfall that is returned to the atmosphere through evapotranspiration before it is converted into runoff, stream flow and ground water storage, the drying of the atmosphere and water supply into the catchment (Shope *et al*., 2014). Kenya's average rainfall is about 500 mm varying between 250 mm in the ASALs on the north and east of the country to over 2000 mm in the highlands and mountain ecosystems and generally follows the seasonal pattern of the ITCZ (Kiangi *et al.*, 1981; Omeny *et al.*, 2008).

Globally, changing climate is the most challenging phenomena in the recent and a near foreseeable future (GoK, 2010) and has affected the water availability by changes in time and space characteristics and variations of rainfall which will affect renewal of water availability. Increase in mean temperatures causes higher evaporation from open surfaces and soils, and increased transpiration by vegetation, potentially reducing water availability (UN-Water, 2015).

The negative impacts of climate change on freshwater systems will most likely outweigh its benefits. Current projections show that crucial changes in the temporal and spatial distribution of rainfall and the frequency and intensity of water-related disasters have risen significantly with increasing greenhouse gas emissions (UN-Water, 2015).

Impacts of climate change are sophisticated affecting the availability and demand for water Therefore, extreme weather events resulting from changing climate demands a sound water management strategies as a coping strategy(Cap-Net, 2009). Changing climate could have influence on Kenya's water in western parts of Kenya, which will have surplus of water as compared to the rest of the country (Immerzeel & Drooger, 2009). From the same study, results from model climate projections from different emission scenarios, it was concluded that there is a likelihood of increase in precipitation hence river discharge (36% in 2050 and 51% in 2090). However the limitation of this study was the use of climate models with coarse resolution and also it is from a basin that has water surplus and thus this study was carried out in a basin that has water deficit.

In a study conducted in Mau Forest Complex on influence of land changes and climate on water yields (Rwigi, 2014), it was found out that the days and nights have become warmer by about 0.5˚C and 0.4˚C respectively from 1961-1990 while on the other hand over the same period monthly rainfall patterns indicated a shifting tendency where the relatively dry DJF and SON seasons became relatively wetter by about 7.5% and 9.2% respectively by 1990s while the relatively wet MAM and JJA became relatively drier by about 2.2% and 4.5% respectively by 1990s.In the same period, annual rainfall indicated a slightly increasing trend.

It was also established from the observed land use patterns that indeed Mau forest complex experienced deforestation ranging from about 18% to 25% between 1973 and 2010 with peak deforestation rate witnessed in the early years of 2000s but the trend has since been reversed. It was therefore concluded from the results of the observed data that besides being deforested, the Mau forest catchments have become warmer and wetter during this period with stream flows showing decreasing trends. A projection of climate in 2010s and 2030s indicated an increasing trend in both temperatures and rainfall hence projecting a wetter catchment in future. This agreed with another study carried out in Nzoia River Basin by (Githui, Mutua, & Bauwens, 2010).

Changes in climatic conditions will make water availability to be scarce in South and North Africa and abundance in East and Western Africa due to increase in precipitation. Furthermore, frequency of extreme weather events in those areas with enhanced rainfall will increase (Schmitt, 2010).

Kenya's weather is tropical and the regular movements of tropical rain belts determine the rainfall patterns combined with the position of sub-tropical high pressure cells. Slight movements in the places of these rain belts may bring about vast nearby changes in rainfall. Changing Sea Surface Temperatures (SSTs) are likewise vital in controlling warm season precipitation inconstancy and patterns. For East Africa a temperature increment of 3.2 °C is anticipated for 2080-2099, a precipitation increment of 7% and an expansion in outrageous wet occasions by 30% in light of a 21 atmosphere show normal for the A1B situation (IPCC, 2007).

Water Resources in Kenya, are over exploited resulting to water pollution which are usually not enough to support many species and hence changes in climate will further decrease the water availability for human and wildlife (Schmitt, 2010). Investigating changes in climate over Thika River sub catchment, future climate change scenarios are necessary for policy and management issues of water resources.

2.3: Climate Change Scenarios

Situations are elective pictures of how the future may unfurl and are a fitting instrument with which to examine how main impetuses may impact future outflow results and to evaluate the related instabilities. They aid environmental change examination, including atmosphere displaying and the appraisal of effects, adjustment, and moderation (IPCC, 2000).

They are predictable arrangements of projections of just the segments of radiative driving (the adjustment to be determined amongst approaching and active radiation to the environment created essentially by changes in barometrical structure) that are intended to fill in as contribution for atmosphere demonstrating (Muthama *et al.,* 2014). Reasonably, the procedure starts with pathways of radiative constraining, not point by point financial accounts or situations. Key to the procedure is the idea that any single radiative compelling pathway can come about because of a differing scope of financial and innovative improvement situations. Four

Representative Concentration Pathways were chosen, characterized and named by their aggregate radiative constraining in 2100.

Climate modellers will carry out new atmosphere demonstrate tests utilizing the time arrangement of emanations and focuses related with the four RCPs, as a feature of the preliminary stage for the advancement of new situations for the IPCC's Fifth Assessment Report and future.

2.4: Representative Concentration Pathways

Most research studies have used the emission scenarios i.e. IS92 and SRES2007 while this study used the scenarios which were used to prepare Fifth Assessment Report(AR5) of IPCC released in 2015. The scenarios are based on selected modelers who work on models (climate modeling, and analysis of impacts). Table 1 shows each Representative Concentration Pathways and their descriptions.

Table 1: Representative Concentration Pathways

Representative concentration Pathway	**Description**
RCP 8.5	Rising radiative compelling pathway prompting 8.5 W/m² in 2100.
RCP 6	Adjustment without overshoot pathway to 6 W/m² at adjustment after 2100
RCP 4.5	Adjustment without overshoot pathway to 4.5 W/m² at adjustment after 2100
RCP 3-PD2	Crest in radiative constraining at ~ 3 W/m² before 2100 and decay

It is therefore necessary to establish possible future scenarios of emissions resulting from human activities so that the effects of changing climate and its response on water yield can be identified for proper mitigation measures on water resource policies, planning and management.

2.5: Climate Change and Water Resources

According to IPCC (2014), globally, a temperature prediction shows that an increase ranging 1.4°C to 5.8 °C is expected by the end of the year twenty one hundred (2100). Such increase in temperatures could exacerbate rainfall variability/levels, rising in sea levels changes in rainfall and storm intensities and sea/ocean dynamics. In addition, higher temperatures could decrease snow/ice and increased rates of evaporation which will eventually affect seasonal water availability globally and therefore climate change could increase the intensity of extreme weather events such as floods and drought (Yilmaz, 2015).

Availability of water and climate are closely connected and therefore climate system has an impact on water availability for development. The driving force of the hydrologic cycle, the lifeline of all the world's water resources, is the state of the climate. The hydrologic cycle, whose main components are evapotranspiration precipitation and runoff, is the main contributor of the climate system dynamics (Kundzewicz *et al*., 2017).

The character of precipitation is greatly influenced by temperature and other climatic elements(Bates *et al*, 2008.). Global mean temperatures will therefore result in regional changes rainfall, evapotranspiration, and soil water content. Rainfall, temperature and evaporative demand change, the most dominant climate drivers for water availability, will alter the flow regimes in streams and rivers as well as the ground water recharge rates and depths of ground water tables and consequently water quality and quantity will be altered (Akhtar *et al*. 2008; Wilby & Watts 2006). This will have an impact on the freshwater yields from the existing storage facilities such as the Aberdare water tower (IPCC, 2007; UNEP/IVM, 1998).

Timing and distribution of rainfall, changes in the rates of evaporation rates determines the volume of streamflow in rivers and lake levels as well as wetland areas due to changes in climate. Compared to the rest of the world, Africa has the least number of studies in relation to changes in climate to water availability since most them are mainly in the sub tropics including Asia, North and South America and Australia (Bates *et al*, 2008.)

Widespread increases in heavy rainfall events resulting from of warming of the globe, have been seen in area where rainfall amounts have reduced (IPCC, 2007). A change in the pattern of climate also affects the chances of some weather phenomena occurrence. Extreme weather events have become more frequent and intense while others become less frequent and mild. Depending on the condition of the other climatic parameters some regions will experience heavy precipitation events while others will experience less than average precipitation events. Both of these changes will impact on the freshwater yields from water catchment areas.

Increased evaporation resulting from warming of the globe will be the consequence of human activities. In addition the increase in the global air temperatures normally increases the capacity of the atmosphere to hold more water. Increase in water holding capacity of the atmosphere is expected by a percentage margin of seven percent (7%) by every increase of 1^0C temperature rise (IPCC, 2007. Modeling of the climate and researches indicates an evidence of warming of the global climate due to increase in the water content in the atmosphere leading to more rainfall despite reduction in total rainfall (IPCC, 2007).

According to Bates (2008), a trend in run off characteristics in basins globally indicates about 17% reduction. A projection of climate and data observations gives enough proof that fresh water is susceptible to environment and society. In African continent, the consequences are highly related to hydrology health food security and encroachments of deserts. Increase in human population and diminishing water resources are the main challenges to availability of water parts of Africa including Kenya.

One of Kenya's water vulnerability is the high variability with which annual rainfall occurs which is further exacerbated by the extensive degradation of the country's water resources such as the Mau Forest water tower as indicated in a study by Kinyanjui (2011). Alterations of the forest cover in Thika River have been altered in the catchment's response to rainfall, the ultimate source of water in a catchment area a situation that is likely to be increase due to changes in climate leading to increased erosion from degraded land surface leading to accelerated siltation, reduced recharge of groundwater and therefore loss of water storage capacity in Kenya's largest water tower (Mogaka *et al.*,2006).

2.6: Climate Modeling

Climate modeling involves the use of statistics in order to study the interactions of various systems of the climate (Figure 1). Climate models are important for studying the dynamism of system of the climate around the global and studies relating to the projections into the future. The shortwave and long wave radiation from the sun and earth surface is factored in the model simulations and any change in the temperature results into the changes in the average global temperatures. Modeling of the climate involves the representing the system of the climate by use of mathematical equations by use of computer codes to give a comprehensive and quantitative description of how weather parameters react to the heating of the atmosphere (IPCC 2007; (Mitchell *et al*., 2004).

Climate models also include numerical, mathematical computations using quantitative methods that describe how the greenhouse parameters of the atmosphere keep the stratosphere warmer than would ordinarily have been the case in controlling the loss of long wave radiation to the outer space. Climate models compute energy transfers through the atmosphere, influence of aerosols, and other dynamic process of the earth system (Seneviratne *et al*., 2013).

2.6.1Global Climate Models

A global climate model represents numerically the characteristics of the global climate system, how they interact and respond mechanism (Wilson *et al.,* 2009). They are used to examine the influence of increased concentrations of GHGs and aerosols in the atmosphere through simulation of the processes and interactions that define the global climate. The three-dimensional climate system is represented by equations that describe the movement of energy and momentum, conservation of mass and water vapor behavior (Wilby and Miller, 2009).Figure 2.

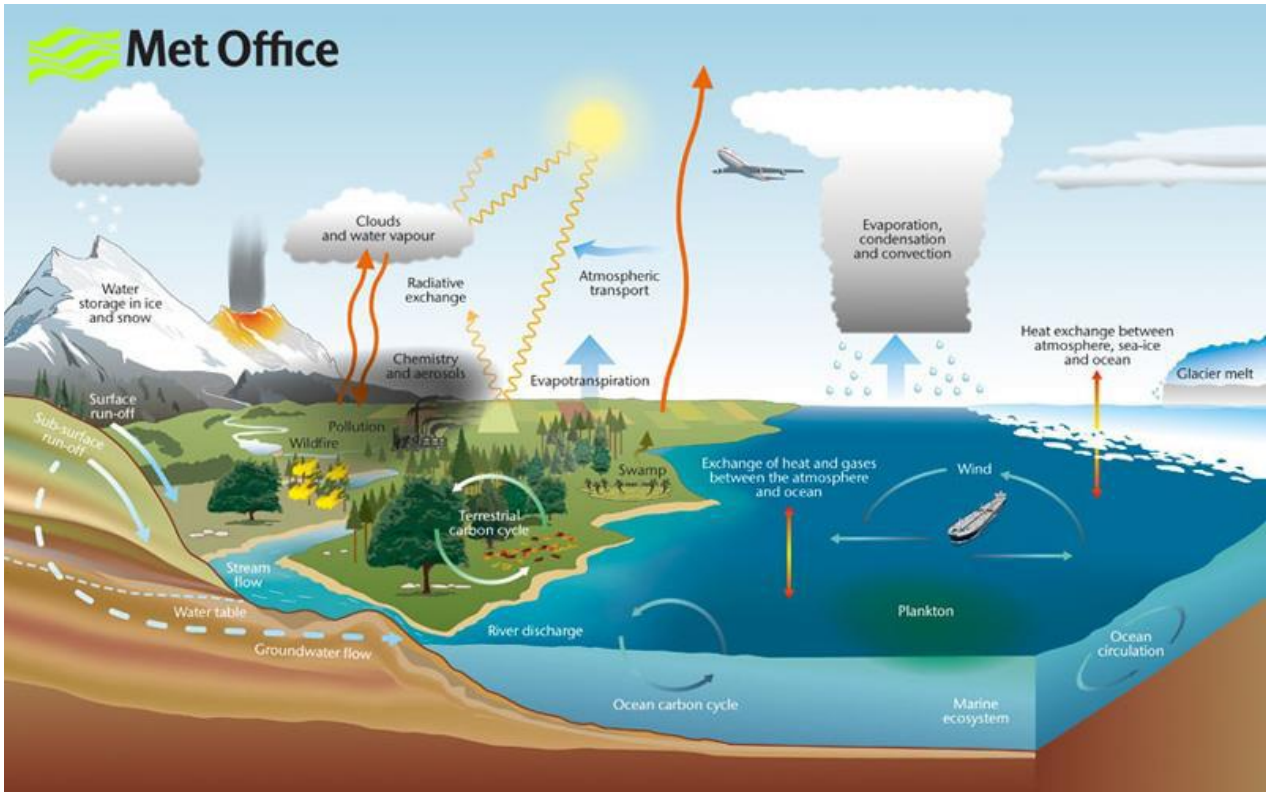


Figure 2: Model earth-Atmosphere system and the processes represented in GCM model (source: UK Met office 2016).

GCMs such as the Hadley Centre Third generation Coupled Model (HadCM3) are used to solve these equations at discrete grid-point across the surface of the Earth and between coupled layers in the atmosphere and ocean using concentration scenarios of GHGs as inputs to make climate projections (Wilson *et al*, 2009; Jones *et al*, 2004; UNEP/IVM, 1998).

Solving these equations for a large number of grid-points over the entire globe requires enormous computing resources such as the use of supercomputers. The task is usually made more manageable by using coarse horizontal resolutions of about 300 km (Rummukainen, 2010) with 20 levels in the vertical in order to decrease the number of grid points and computations. As a result of this, GCMs are unable to capture and resolve the local details of the mesoscale forcing that include orographic and other local climate drivers that influence regional climates which is what is required for this study (Jones *et al*, 2004).

Essentially, GCMs are used to study large scale phenomena such as global circulation of the atmosphere, land and ocean as well as at the continental scale of rainfall and temperature but cannot represent the fine scale details that characterize local climates in many regions of the world (Wilby and Miller, 2009; IPCC, 2007). One of the widely accepted methods of adding the finer details that are missed out by GCMs is the use of Regional Climate Models (RCMs) which are the subject of the next section.

2.6.2 Regional Climate Models

With the disadvantage of global models from capturing local information, the regional climate models provides a perfect opportunity in complementing the global models in studying hydrological related studies in a local scale (Met Office, 2016). Use of statistical techniques to downscale a coarse, GCM results to local detail is then done where assumption of relationship existing between global weather parameters and the true weather parameter measured at a point of observations which can be used then to make a future forecast by nesting a regional model in a global model (Met Office, 2016).

Regional Climate Models (RCMs) works by increasing the resolution of the GCM in a small, limited area of interest. Global Climate Models are used to study enormous change in greenhouse gases and eruptions resulting from volcanic matter on the climate of the world and the climate calculated by model as the input of the regional model for temperature and wind in addition to information such as orography and land cover/use (Met Office, 2016).

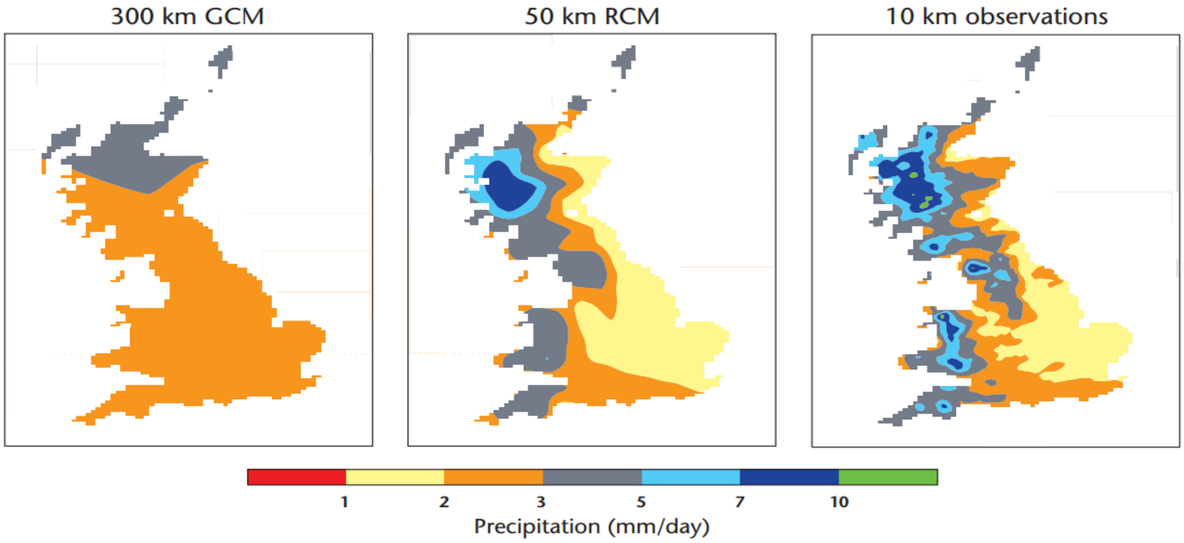


Figure 3: An illustration of Global model vs a Regional model (Source: Met office, 2016)

Assumptions in regional models are that the data used are drawn from global climate model over a limited area such as East Africa (IPCC, 2007). Such a limited regional domain allows for the use of a higher resolution than that of the global domain without necessarily resulting to prohibitive increases in the computational costs. The data driving the RCMs are supplied asinitial and set of Lateral BounderyConditions (LBC) data including weather parameters as well as the Surface Boundary Conditions (SBC) data that include: sea surface temperature and sea ice (Wilson *et al*, 2009).

Essentially, there is a teleconnections between the local climate and the global climate events such that the enormous global circulations interferes with domains such as the East African region, the boundary conditions of the RCMs consist of the information drawn from the GCM outputs. Since the two models have different resolutions, the RCM's domain should larger for it to accommodate the climatic event in relation to the orographic influence and other small atmospheric processes to grow and the domain should not be too large as to allow the flow to deviate too much in running model (Wilson *et al.*,2009; Jones *et al.*,2004). RCMs have some major limitations that include: the physics of the models, boundary data derived from the GCMs; and the relatively high computational facilities limiting the number of runs and computations (Jones *et al.*,2004).

In order to get regional climate model projections for purposes of impacts studies, regional climate model runs are normally done on time-slice modes (Christensen *et al*, 2007). This involves running the model for some recent past which may also be regarded as the present baseline period such as 1961-1990 and some future scenario period such as 2021-2050. Variations in the climate output are for analyses of changing climate in the 30-year means of seasonal or annual and variability of climate elements such as temperature and precipitation. Therefore, regional climate forecast are important in modeling influence on hydrological conditions of river basins and catchment worldwide (Rummukainen, 2010; IPCC, 2007), and thus Coordinated Regional climate Downscaling Experiment (CORDEX) climate data for the purpose of studies on climate change.

2.6.3: Coordinated Regional Climate Downscaling Experiment

This is a World Climate Research Program (WCRP) that intends to coordinate and provide regional climate forecasts in the world that will be useful for studies on impacts, adaption and mitigation of changing climate and for the preparation of IPCC 5th Assessment Report. In CORDEX, ensemble dynamical and statistical models are normally produced by looking at global models resulting from 5th Climate Intercomparison Project with an initial project being started in Africa since there are already other projects running.

Output from CORDEX, provides timely access to changes in climate scenarios which is vital to developing countries where economic stresses are likely to increase vulnerability to influence of climatic conditions especially on the hydrology of a river basin from a given rainfall event (Rwigi, 2014). CORDEX has special characteristics that make it adaptable for studies in Kenya that include a models having a high resolution of less than 50 Km grid hence provides good results for the study of the hydrology of Thika River.

Output from CORDEX have been used for impact studies especially over East Africa such as one carried out by (Ngaina, *et al.*, 2015). They found out that all the CORDEX models performed well in simulating rainfall over East Africa and predicted high variation minimum and maximum temperature for both RCP 4.5wm^{-2} and RCP 8.5wm^{-2}.

However, temperature increase was found to be higher during Long Rainy (LR) season while increase in rainfall was found to be higher during Short Rainy (SR) season. Variability in rainfall, maximum and minimum temperature indicated that there is an increase in the impact and of extreme weather phenomena in past and future climatic conditions.

A further study carried out in Southern Africa on extreme precipitation events and future climates, found out that the simulated climate output correlates well with station data observations of extreme rainfall events and hence the downscaling of the current climatic conditions depending on the units used (Christopher , *et al.*, 2015).

2.7: Hydrological Modeling

There are various definitions of a model depending on the field of study. A model represents the simple and complex processes in a system or a real world with its output being close to exactly what happens in the real system (Devi *et al.* 2015).

In this study a review of what a hydrological model is considered. Droogers *et al.,* (2006) consider hydrological modeling as involving simple, concept representing of part of the hydrological cycle to represent the physics that determines the formation of rainfall (input) to stream flow/runoff (output). Schulze (2000) define hydrological modeling as;

> "***quantifying expression of observation, analysis and prediction of the interactions of the various hydrological processes which vary in time and over space, i.e. rainfall, infiltration, evaporation or stream flow***."

Hydrological modeling involves the application of mathematical equations to model the physical responses of a watershed to meteorological events in a catchment area(Rwigi, 2014). For purposes of hydrological modeling, the river basin is the most appropriate scale to focus on for analyses of water management issues using hydrological models. Stream flow and runoff are interplays of many physical processes that include: the hydrological, meteorological, topographical, human activities cover, and soil characteristics. Hydrological models relate stream flow and these parameters and are primarily used for hydrologic predictions as well as for understanding the hydrologic processes in a catchment area (Mutua, 1986).

Hydrological model uses mathematical estimations of streamflow as a function of basin characteristics with rainfall and drainage area being the most important input elements. In addition soil characteristics, tree cover and topography of the watershed soil water content, availability of an aquifer and therefore hydrological models are vital and necessary for water and environment management. (Devi *et al.* 2015).

Modeling provides a good knowledge of the hydrological dynamics in a system and can be used to predict possible outcomes of present and future scenarios, hence assist in developing solutions to real world problems with a detail unattainable with conventional pen and paper analysis. In addition, it is essential in hydrology because it is difficult and impractical to ascertain physically the above-mentioned interactions at a sufficiently representative number of points in the catchment. Furthermore, any possible modifications to the hydrological system, for example, due to human activities need to be determined much earlier so that mitigation measures can be put into place in appropriate time. Therefore, modeling is the only way to ‘peek’ into the future and determine what will happen if present conditions remain constant, improve or worsen. The next subsection therefore presents a brief description of types and classification of hydrological models.

2.8: Soil Water Assessment Tool

The Soil and Water Assessment Tool (SWAT) is a physical hydrological model developed by United States Department of Agriculture–Agricultural Research Service (USDA–ARS) to study the influence of land use on hydrology, sedimentation, and chemical yields from agriculture in watersheds with distinct physiographic parameters and management conditions over a period of time. Currently the model is being used to estimate impacts of climate change and land use management on water resources (Hunink & Droogers, 2015).In SWAT a catchment is divided into sub basins based on type of soil, land use/cover and slope for simulating runoff. Complete functionalities of SWAT model is presented in chapter 4.

This study reviewed some of the empirical studies on the use of SWAT model in various watersheds in the world, Africa, East Africa, Kenya and specifically Tana basin. SWAT model has been used widely in the world to study various aspects of hydrological processes but specific application on climate change was reviewed on this study.

(Zhang *et al*, 2016) studied impacts of changing climate and variability on the Headwater River in China. Separate and combined human activities on land and changes in climatic conditions were studied and it was concluded that SWAT model simulated well historical and future land use and changes in climate change. However this study was carried out in sub tropics with different climatic conditions as the tropical region.

(Kim *et al*, 2015) studied global climate changes on water projects and streamflow behavior in Geum River basin by use of SWAT hydrological model. In this study output from regional model were used to provide projected climatic data and daily streamflow by SWAT model. The model simulated well runoff during two future periods compared to baseline period. In South Africa, (Dabrowski, 2014) utilized SWAT hydrological model to study ortho-phosphate loads and trophic status in some reservoirs in, South Africa. From the research it was concluded that SWAT model provided good estimates of ortho-phosphate concentrations in the four dams of varying sizes.

In Ethiopia, (Dile, Berndtsson, & Setegn, 2013), used SWAT to study response of climate to the hydrology of Gilgel Abay River, in the Lake Tana Basin - Upper Blue Nile Basin of Ethiopia. (Rwigi, 2014) used SWAT hydrological model to determine of impacts of changing climate and deforestation in Mau Forest Complex Catchment in Kenya on water yields and found out that SWAT hydrologic model has a potential in modeling water yields in the study area under different climate and forest cover scenarios. However the study used PRECIS climate output which has a coarse resolution and its susceptibility to errors during downscaling of GCM model data.

(Musau, Sang, Gathenya, & Luedeling, 2015) used SWAT model to investigate responses of hydrology due to changes in the climate of the watershed in the Mt. Elgon and found out that SWAT model efficiently captured the past hydrological characteristics in the upper Nzoia Basin based on the meteorological observations and concluded that the model can be used to know the water balance dynamics in a watershed. In Nzoia Basin Kenya, (Muiruri, 2012), investigated land use change and changes in climate using SWAT and concluded that the model fairly well in estimating historical climates and future after calibration.

In Thika River, Kenya (Gathenya & Home, 2005), conducted a research on sedimentation and resulting from land use influence and its impact on the hydrology of Thika river catchment Kenya, using SWAT model.

2.9: Summary of Literature Review

From the literature review of hydrological modeling it was found out that no studies by use of SWAT model in Tana Basin and specifically Thika River have been carried out and therefore this study provides an opportunity to perform rainfall-runoff modeling with the intention of addressing future impacts of climate change using SWAT hydrological model.

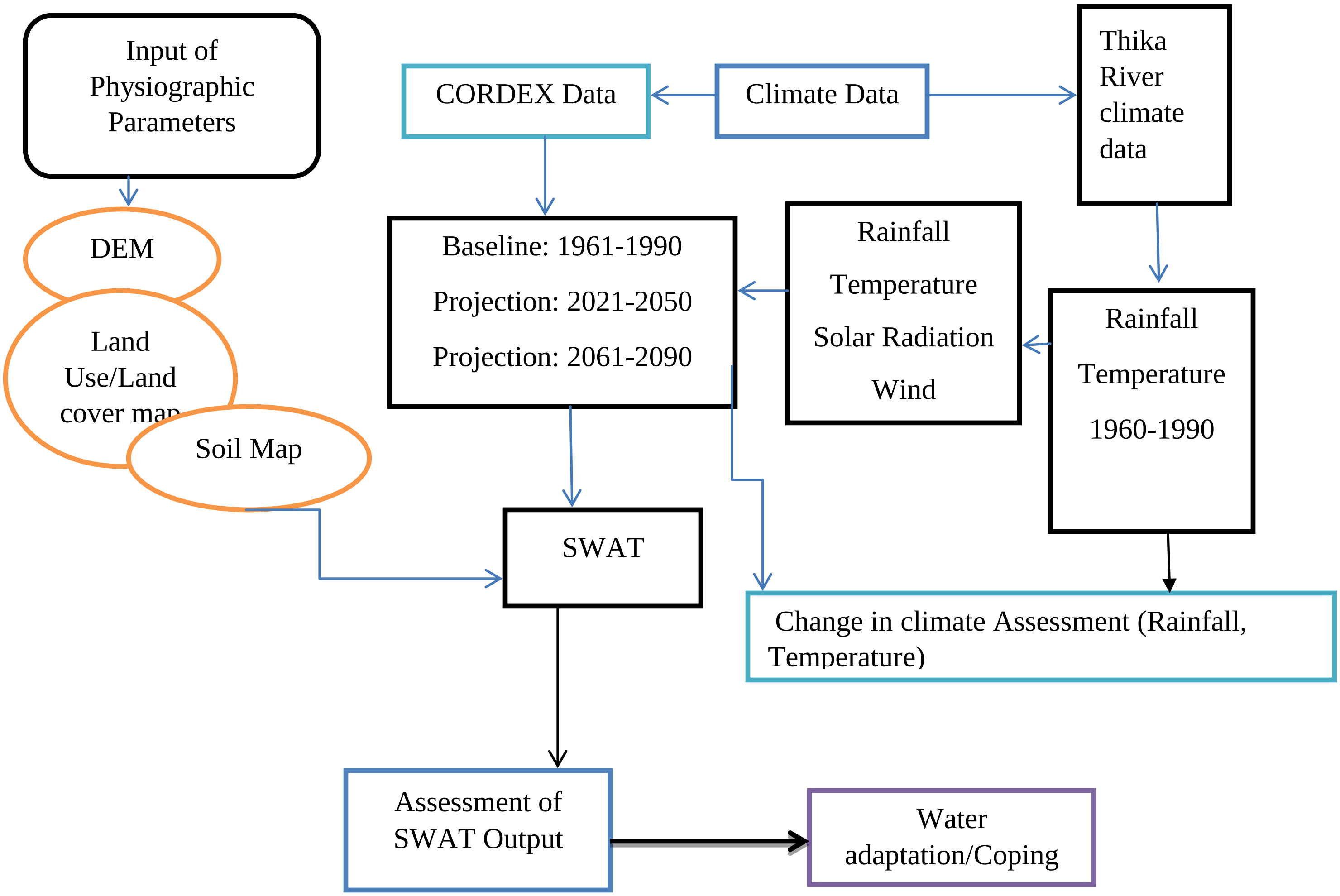


Figure 3: Conceptual model of the study (Modified from Kishor *et al*., 2016).

CHAPTER 3: STUDY AREA

3.1: Location and Size

The study area lies within Tana Basin centered at about $0^\circ 54' S, 37^\circ 39' E$ and $0^\circ 43' S, 36^\circ 37'$E bordering Kiambu to the South West, Machakos to the South, Embu to the South East and Nyandarua Counties to the North. Thika River is located 80 kilometers north of Nairobi with an approximate length of 165 Km from upstream to downstream as it joins Seven Folks Falls. The source of Thika River is Aberdare Forest and is the main source of water to Seven Folks Falls, Sasumua and Thika dams that supply to Nairobi residents (Figure 4).

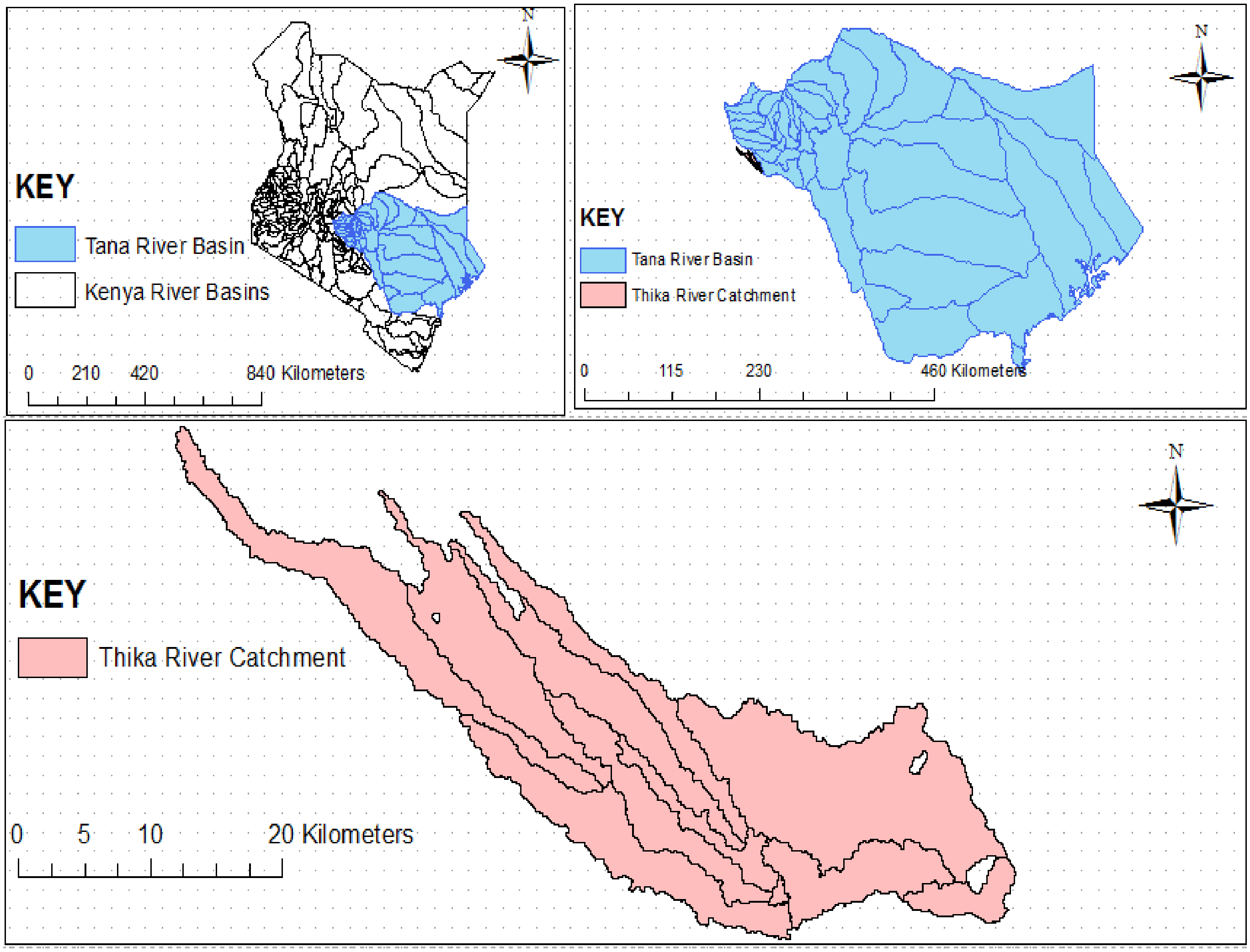


Figure 4: Study Area in Kenyan Map

3.2: Characteristics of Thika River Catchment

The four primary basin characteristics that govern water yields into a river network include those that affect runoff response time (topography and size), those that affect subsurface base flow (geology and soils), those that affect hydrologic abstraction and runoff volumes (land use/land cover), and those that affect the amount of rain water arriving in the basin (climate) (Arnold *et al*,1998). These characteristics affect different aspects of stream flow hydrograph and briefly in the next sub section.

3.2.1. Topography and Physiographic Features

The topography of the study area varies from 1320-2522m above sea level (Figure 5). The land rises from the southeastern part of the catchment as it rises towards the southwestern part of the catchment. Aberdare forest is a tourist attraction and one of major water towers and home to varied wildlife.It also supplies 55% of the water to Nairobi City County through Sasumua and Ndakaini Dams and a major source of water for hydropower production. Rivers system forms a dendritic drainage pattern as it slopes down south of Thika River.

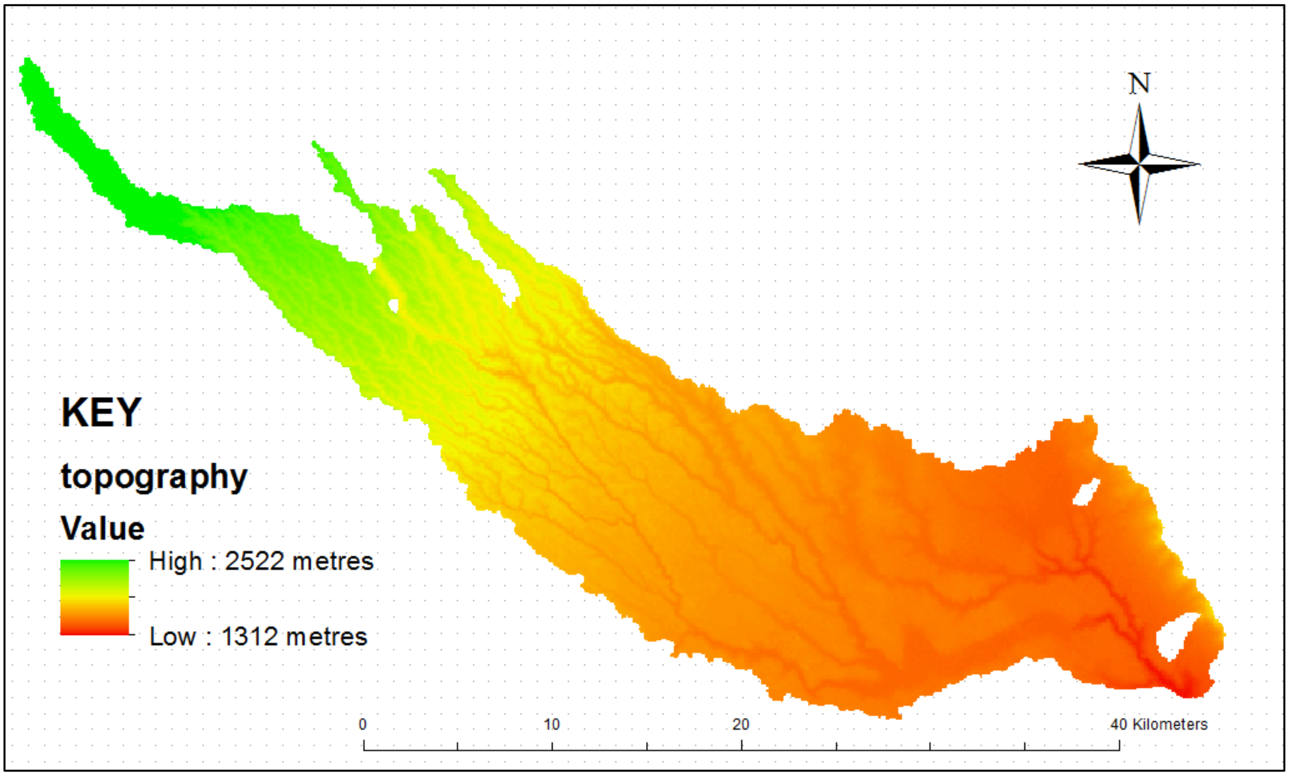


Figure 5: Topography and Elevation of Thika River Catchment.

3.2.2. Soils

The study area has a high deforestation rates which has weakened the soil making it be prone to landslides. Although it has a high fertility it was evident from various field visits that Thika River has many geomorphologic problems in Thika River which is susceptible to soil erosion and normally leads to siltation of Thika, Sasumua dams and Seven Folks Falls. Soils Classification in the study area is as shown in Figure 6.

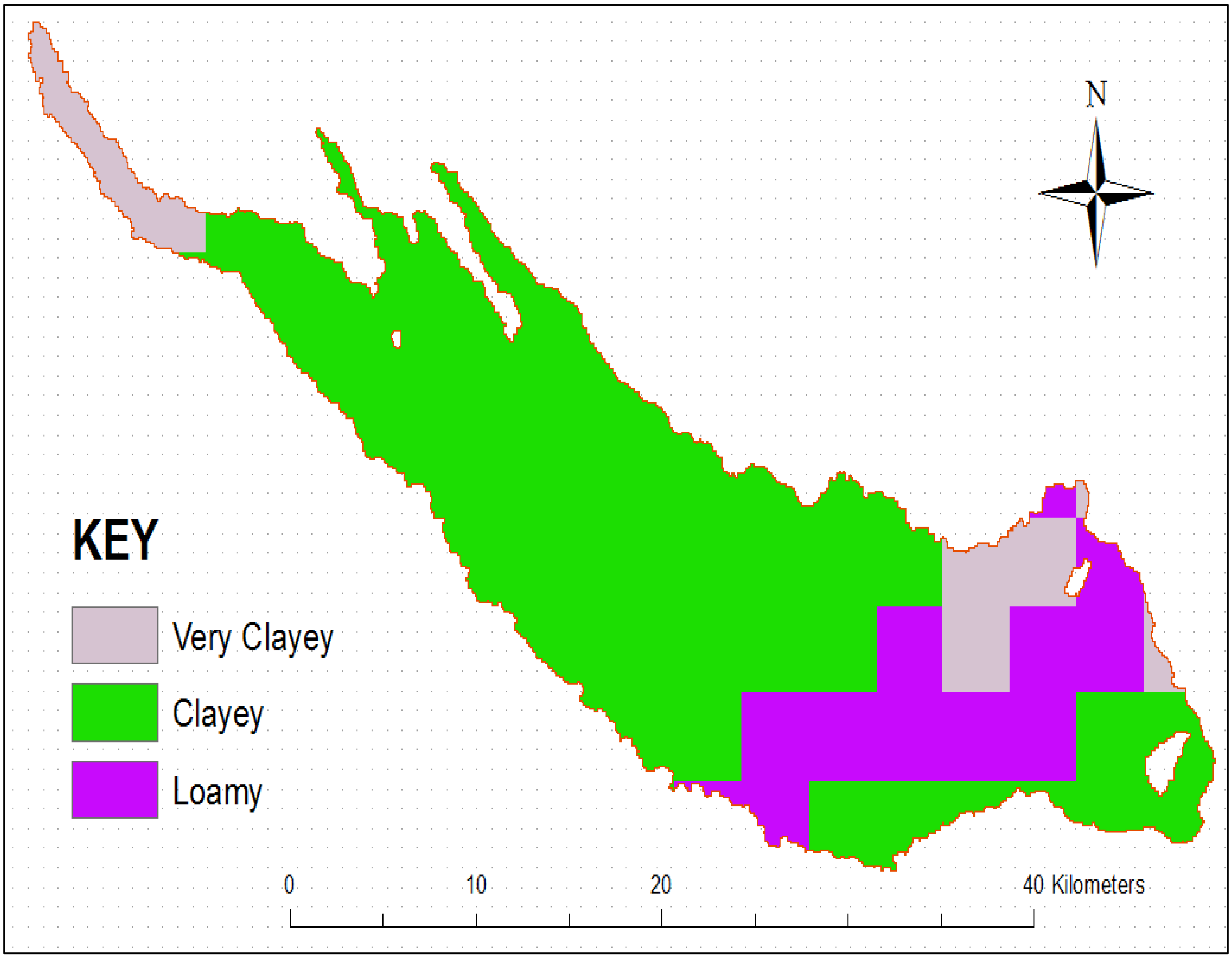


Figure 6: Soils Classification in the Study area

3.2.3Land Use and Cover

Kenya's economy is dependent on land as a major factor of production and therefore has a bearing on water yields. Poor land use has resulted to deforestation leading to increased surface runoff, reduced infiltration rates, increased soil erosion and siltation of water structures such as dams(Thika and Sasumua Dams). In addition the land use in most Kenya's catchments has reduction and changes in the runoff trends characterized by flashfloods resulting from clearing of forests and inappropriate land use practices. However, the level of changes in streamflow and infiltration is not fully understood due to scanty availability of monitoring information. Within Thika River catchment, there are records of catchment degradation from cultivation of steep sloping grounds having poor soil management practices resulting into increased sediments of river systems (GoK, 2009). The area around the northern part of the study area has very high agricultural potential due to the fertile soils and reliable rainfall which is in contrast with the extreme southern part which has an arid and semi-arid climate that is not conducive for farming (GoK, 2009).Figure 7

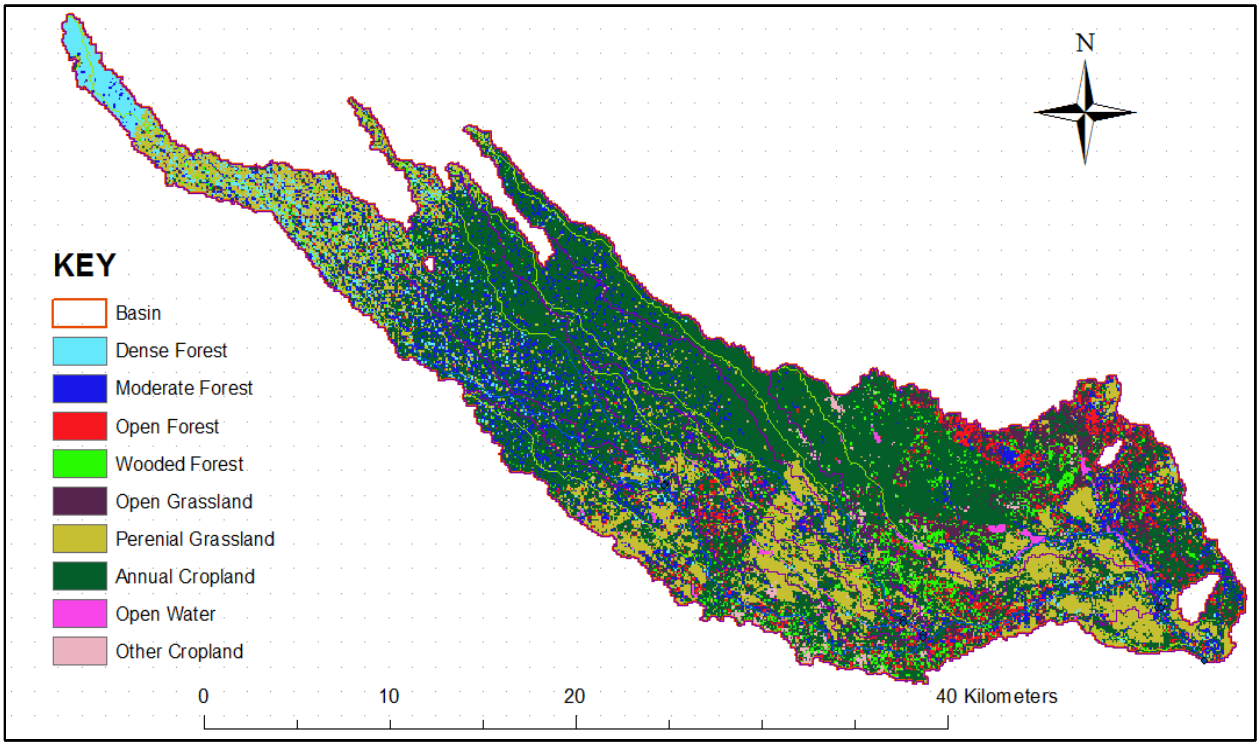


Figure 7: Land use/Cover in Thika River Catchment

3.2.4Climate

Rainfall distribution in Thika River catchment is determined by inter-tropical convergence zone (ITCZ) of air masses of both hemispheres and modified by local orography, to Congo Air mass Basin and Indian Ocean monsoon. The ITCZ is a zone characterized by low and medium level convergence. It is marked by a line of thunderstorms and showers in most areas and marks the boundary between the two inter-hemispheric monsoon wind systems over the region. This is the main synoptic scale system that affects the intensity, distribution and migration of seasonal rainfall over the Eastern Africa region (Omeny, 2008).

Generally, airstreams from the northern and the southern hemisphere converge over the ITCZ.

However, over Africa, this generality is broken since the ITCZ breaks into two spatial components over the central parts of Africa to form the zonal and the meridional components. The division into the two components has been attributed to the geography of the Rift Valley and the mountain chains of the East African region (Okoola, 1996).

The zonal component of the ITCZ is a zone of convergence between the NE and SW monsoons while the meridional component is observed as a quasi-permanent low over the Central African region. The latitudinal arm of ITCZ fluctuates from zonally while the zonal arm of the ITCZ migrates longitudinal of the equator following the seasonal match of the sun with a time lag of about one month. It traverses the Thika River catchment area twice a year bringing with it the long rains during the months of March, April and-May and the short rains during the months of September, October and November (Okoola, 1996).

The Atlantic and Indian Oceans are the major sources of moisture for the East African region greatly influences the regional climate through interactions associated with Oceanic and atmospheric circulations (Nyakwanda, 2009). The above normal rainfall over the region is associated with the low level circulation patterns dominated by easterly inflows from the East African Coast, Congo air mass with intensification of pressures in St. Helena (South Atlantic).

Unlike in the higher latitudes where climatic patterns are marked by a high seasonal variability of temperature and other climatic parameters, the climatic parameter with the highest variability within the tropics is rainfall. Being in the tropical zone, seasonal temperature changes are small in relation to the rainfall due to the insignificant seasonal changes in the solar radiation. The warmest month is normally February and July the coldest with an average range of about 10˚C between the warmest and the coldest months (Ahrens, 2009).

The temporal distribution of rainfall within the Thika River catchment exhibits a bi-modal distribution in the months of March, April and May (Long rains); September, October and November (Short rains) with average annual rainfall in the catchment ranges between 2000 to 2500 mm/year.

3.2.4.1: Temperature

Figure 8 shows the annual cycle of mean monthly temperature for Thika Agro Meteorological Station located in the study area. The temperature ranges between 12^0C in July being the coldest as a result of enhanced East Africa Low Level Jet during Southern Winter and warmest during Southern summer 27^0C in February. The average maximum temperature is 25.6^0C and minimum temperature is 12^0C

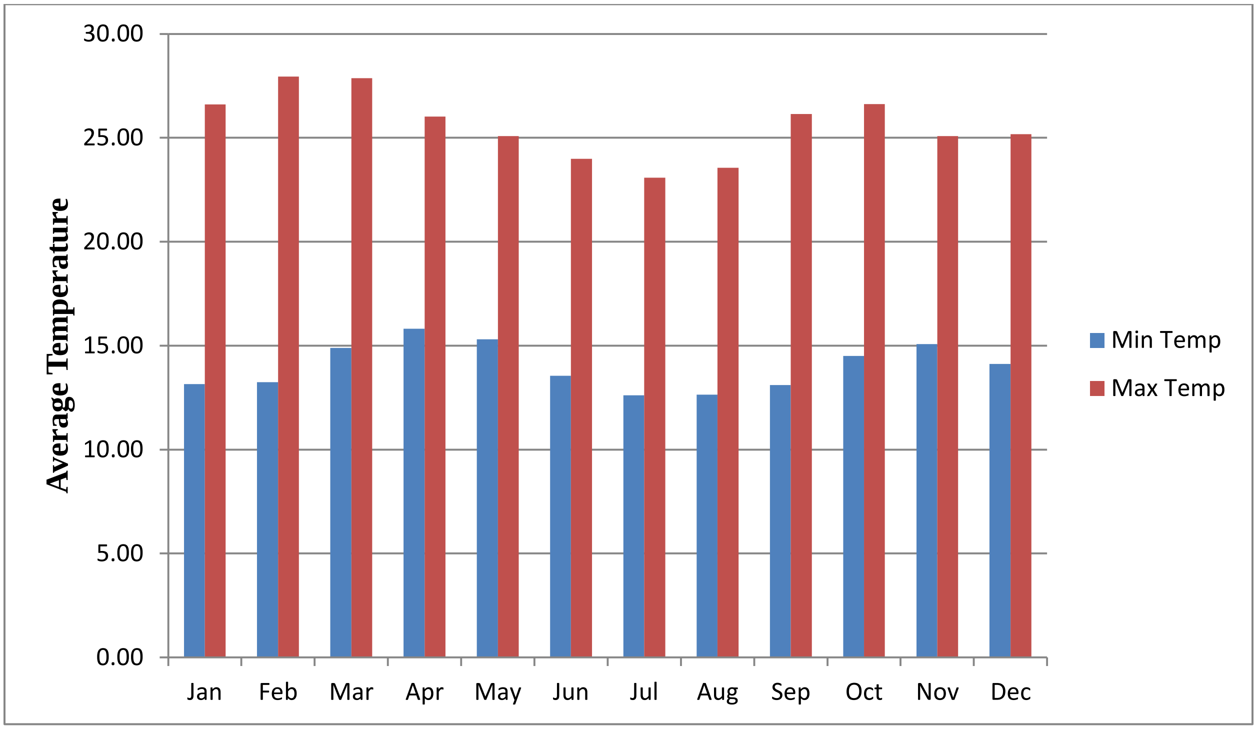


Figure 8: Average Monthly Maximum and Minimum Temperature

3.2.4.2 Rainfall

Figure 9 shows the annual cycle of average monthly rainfall for the period 1959-2010 at Gethumbwini station. The figure shows that rainfall patterns in the area follows a bimodal pattern with the main rainfall season in March, April May (MAM) and short rains in the months of October November and December with mean rainfall ranging from about 12mm in July and 250.6mm in April.

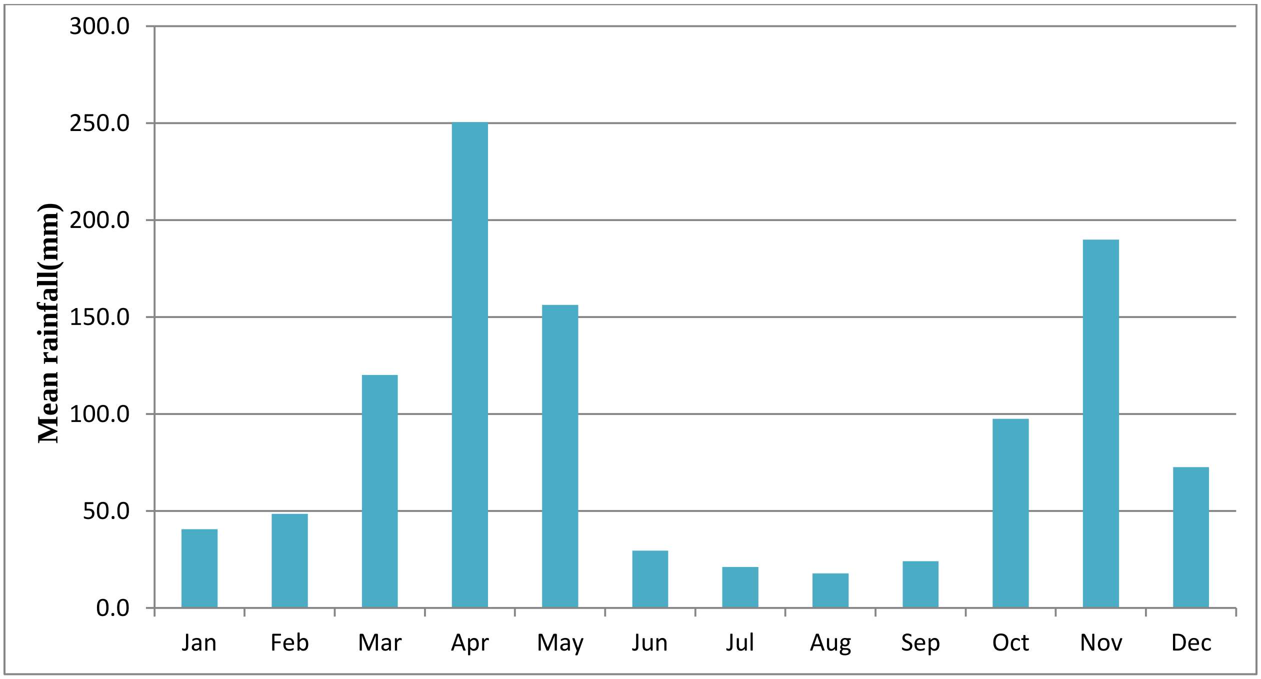


Figure 9: Mean monthly rainfall characteristics over the Thika River catchment (1960-1990).

The average monthly rainfall totals exceeds 12mm in all the months with a mean annual total of more than 1200mm, which is a close threshold values for tropical wet type climate (Ahrens, 2009) therefore the study area can be described as under being a tropical wet type climate.

3.2.5 Hydrology

There is presence of permanent and seasonal rivers in the catchment area having a dendritic drainage pattern originating from Aberdare water tower (Figure 10). To the southern part there is Chania River flowing almost parallel to the Thika River.

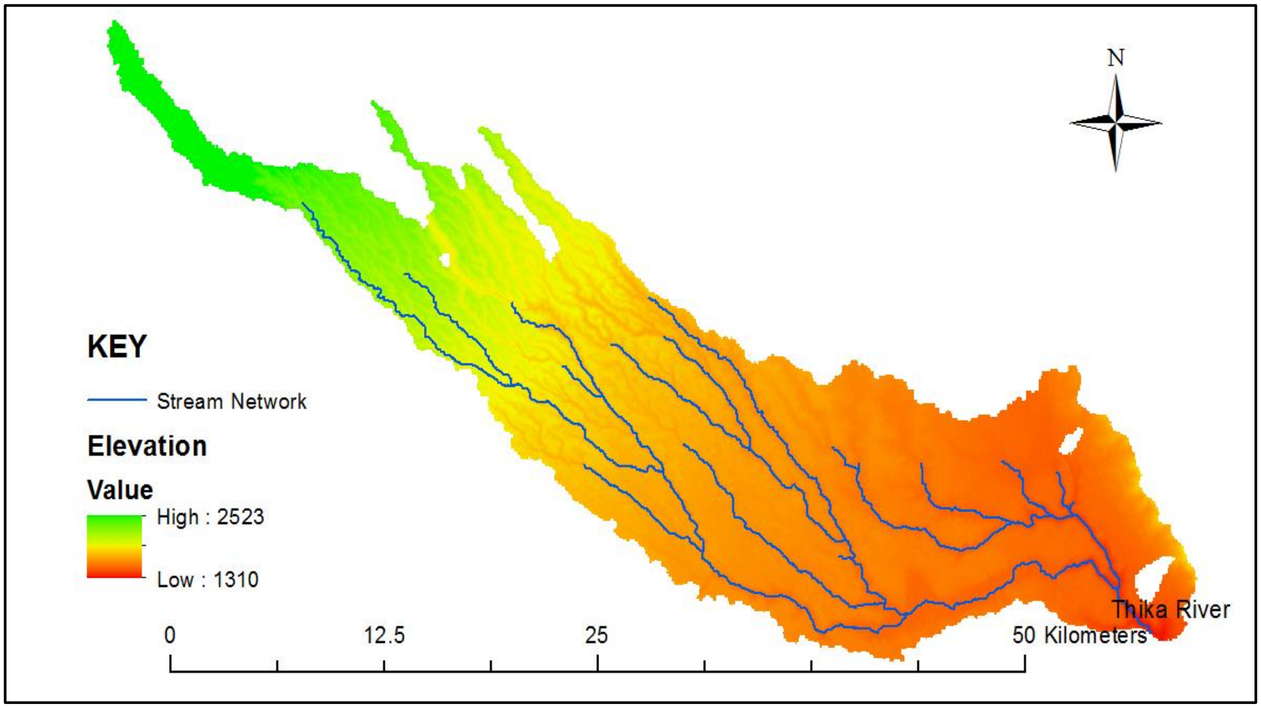


Figure 10: Drainage pattern and River network in Thika River Sub Catchment

Figure 11 shows the hydrographs of observed mean monthly discharge at two of the River Gauging Stations (RGSs) showing the annual cycle discharge distribution in Thika River. From figure 11 it is evident that July has the lowest discharges in the area while May and November have the highest. Therefore the hydrological year in the Thika River starts in April peaks in May declines in June to the lowest in July and starts peaking up in September to December before declining towards February.

The peaks and low flows follow the general rainfall pattern in the area quite closely but generally lag by one month in all the River Gauging Stations. This can be attributed to the time the soils take to reach infiltration capacity in the catchment before the excess rainfall is converted into effective runoff.

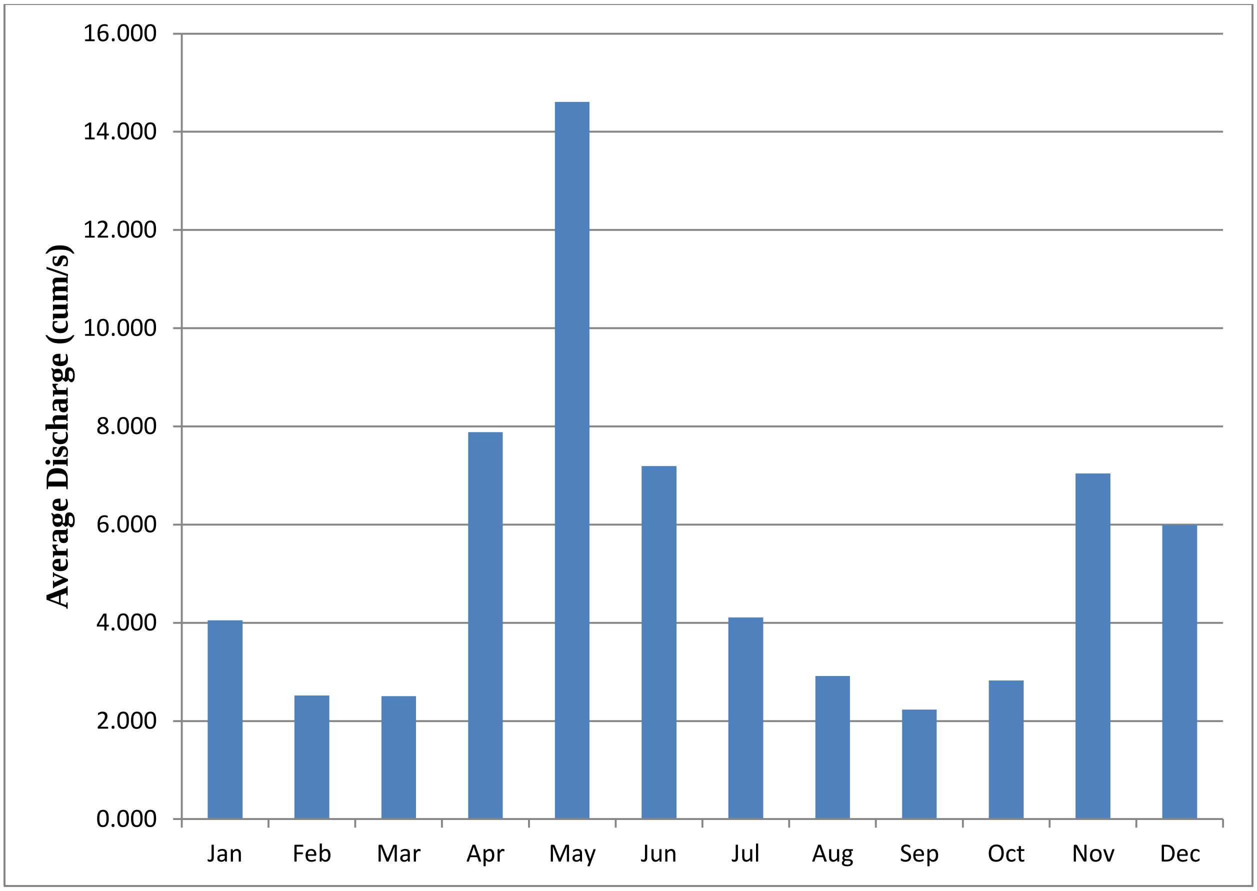


Figure 11: Mean annual Cycle characteristics of Stream flow of Thika River

CHAPTER 4: METHODOLOGY

4.1:Study design

This study was a sample survey design which captured hydrological and meteorological information on the Thika River catchment required in the determination of trends in hydrological and climatic conditions. The survey was purposeful since it targeted only datasets that had representation of rainfall and temperature in the input output response of the Thika River catchment hydrological response characterization.

To estimate hydrological responses in the catchment using rainfall and temperature as the input variables, the study required information on topographic characteristics and this was represented by Digital Elevation Model (DEM) data. The inputs and topographic interface was represented by land use which was considered an intervention variable affecting amount and time of response within Thika River catchment. The intervention variables affected evapotranspiration, albedo, percolation and surface runoff which together provided the hydrological water balance in the catchment.

For climate and hydrological trend analysis, the study used monthly rainfall, temperature and streamflow data for the years 1959-2014. Simulation of river discharges from different hydrological response units in the Thika River catchment was based on slope, flow accumulation and flow direction estimation using spatial elevation model together with soil; land use/cover, rainfall and temperature data in the Arc SWAT environment (Figure 4).

4.2: Data Types and Sources

Data used in this study were varied in types and sources and were mainly secondary (Table 2). Monthly climate (rainfall and temperature) data were sourced from Kenya Meteorological Service (KMS) while daily river discharge data were from the Ministry of Water and Irrigation. Regional climate model data from Coordinated Regional Downscaling Experiment (CORDEX) site (2016) were downloaded via the download node (https://esgf-data.dkrz.de/search/cordex-dkrz). The climate model data included simulated historical and projected temperature and rainfall data(1951-2005 and 2006-2100) for RCP4.5 and RCP8.5. Spatial data that included

DEM data downloaded from the Shuttle Radar Topography Mission (SRTM) 90 m by 90 m resolution generated by the United States Geological Survey (USGS) EarthExlorer site (2016).

Table 2: Data sources and types used in the study.

Data Type	**Period**	**Category**	**Data sources**
Rainfall	(1961-2014)	Secondary	Kenya Meteorological Department
Temperature	(1974-2007)	Secondary	Kenya Meteorological Department
Streamflow	(1945-2010)	Secondary	Ministry of Water & Irrigation
DEM	2016	Secondary	United States Geological Survey
Soil	2009	Secondary	Kenya Soil Survey Maps
Land Cover	2014	Secondary	(RCMRD)
Climate scenarios	(2006-2100)	Secondary	(https://esgf-data.dkrz.de/search/cordex-dkrz

DEM which is a three dimensional representation of the continuously varying topographic surface of the earth consisting of a number of elevations for a number of ground positions at equal intervals (Rwigi, 2014) was used to represent elevations in three-dimensional form of any point in the study area. DEM data provided good terrain representation and was applied in hydrological modeling to derive flow and stream networks as well as define watershed boundaries by use ArcGIS software.

SWAT model used DEM data for catchment and drainage network delineation, routing analysis, and Hydrological Response Units (HRUs) definition. DEM therefore formed one of the primary SWAT input datasets for hydrological modeling and was used to define the topography and to delineate Thika River.

Soil data was obtained in digital map format from the Kenya Soil and Terrain (KENSOTER) database compiled by the Kenya Soil Survey (KSS) in conjunction with the International Soil Reference and Information Centre (ISRIC) according to the Soil and Terrain methodology (www.isric.org/data/soil-and-terrain-database-kenya-primary-data, August, 2016.)

Land use data were obtained from the Regional Centre for Mapping of Resources for Development (RCMRD) which carries out a number of surveys aimed at providing LULC data by use of sample aerial photography and processing of satellite images. The LULC data, which are a result of classifying raw satellite data into LULC categories based on the return value of the satellite image, were then processed to obtain LULC maps.

4.2.1Pilot Survey

A preliminary survey in the area of the study was conducted to identify the target population, and determine the sample size given data availability. The survey indicated that the spatial data required for SWAT analysis would include the global Digital Elevation Model data for which the Kenya terrain data constituted the target population; the land use data of which the AFRICOVER data for Kenya was the target population and; the Kenya soil data constituted the soil target population.

The climate data required for trend analysis were found to be available from twenty nine(29) weather stations in the catchment of which only those stations that had records of at least thirty (30) years and had relatively consistent observations constituted the target population. River discharge data were found to be available from seven (7) stations of which only those stations with at least 30 years of record and relatively consistent observations constituted discharge target population.

For climate scenario simulation, there was need to check if there were simulated data that were downscaled enough to represent the Thika River Catchment and this was found to be available as CORDEX data for the period 1951-2005 as historical and 2006-2100 as projection data. The CORDEX data were found to be useful in modeling rainfall run off and water yields within a river catchment.

4.3: Target Population and Sample Size

Climate data obtained from Kenya Meteorological Service (KMS) headquarters for four synoptic stations within the study area were sampled and chosen. Selection and choice of the stations was based on stations that had the least amount of missing data, length of data availability and with good quality of data. Initially a total of twenty nine (29) rainfall stations within the catchment were selected but due to unavailability of the data and their closeness to each other a number of them were excluded in this research. All the four stations had datasets of at least thirty years (30 years) monthly data with less than 10% of missing data. Thika Agro Met-meteorological station had the longest period of data availability for 55 years (1959-2014) of rainfall data while Chania Dam had the shortest period of data availability of 28 years (1968-1996).

For the whole study area to be representative and research to be dependable the four rain gauge stations were generally distributed across Thika River catchment area. World Meteorological Organization (WMO) recommended density of rain gauge network within the study area was also factored in the selection of the rain gauge stations. The other criterion for selecting the rain gauge stations was their location relative to the stream gauging station. (WMO, 2008), recommends that the location of rain gauges be coordinated with the location of the stream flow gauges so that basin rainfall can be estimated for each stream gauging station. Such locations are generally on the upstream side of the River Gauging Stations (RGS). For the rainfall stations chosen for this study, Thika Agro Met station (ID 9137048) had a complete data for maximum and minimum temperature for a period of 40 years (1974-2014).
Table 3 shows a list of meteorological stations that were used in the study.

Table 3: weather station and data availability data

No	**Station Identification**		**Station Location**			**Data Availability**			**Missing Data (%)**
	Name	Code	Lat	Lon	Alt.(m)	From	To	(years)	
1.	Gethumbwini	9037005	-0.86	37.03	1524	1959	2011	52	6
2.	Karamaini	9136029	-1.05	36.98	1554	1959	2009	50	5
3.	Thika Agromet	9137048	-1.01	37.1	1463	1959	2009	50	3
4.	Chania	9036286	-0.81	36.76	2192	1968	1996	28	8

Stream flow for hydrological analysis, discharge data were daily records obtained from a network of seven selected river gauging stations (RGSs) which are manned by the Ministry of Water and Irrigation(MWI) under supervision of Water Resources Authority. Choice of the network of RGSs, the minimum recommended density of $1875 km^2$/station (WMO, 2008) was adhered to. The selected network covers about 188 square kilometers per station, which is well above the WMO recommended minimum threshold density.

Streamflow is an important water cycle parameter since it combines all the processes occurring in a watershed and also provides an output variable that can readily be determined besides serving as an indicator for climate change and variability by reflecting changes in rainfall and evapotranspiration (WMO, 2009). Table 4 shows the RGS stations that were used in the analysis of stream flow in the study area.

Table 4: River Gauging Stations used in the study

No	Station Identification		RGS Location		Data Availability			Missing data (%)
	Name	Code	Latitude	Longitude	From	to	Period (years)	
1.	Thika	4CB04	-1.021	37.066	1945	2011	66	10
2.	Thika	4CB05	-0.808	36.817	1950	2003	53	8
3.	Thika	4CB07	-0.743	36.749	1982	2013	29	9

4.4: Data Analysis

Spatial data used in this study were Digital Elevation Model (DEM), soil types, and land use which existed in various spatial formats thus requiring format transformations. The main format transformation involved fitting the source data to the Thika River catchment area through geo-processing clip procedure. The clipped datasets were of geographic projections (longitude and latitude) which could not be used in SWAT hydrological model and therefore required projection transformation from geographic World Geodetic State (WGS) 1984 format to UTM zone 37S WGS 1984. Each of projected dataset was stored separately as a layer for SWAT Hydrologic Response Unit (HRUs) definitions.

For Digital Elevation Model data was downloaded from the USGS public domain website in geographic coordinate system. In order to apply the DEM in the SWAT model, it was projected to the World Geodetic System of 1984 (WGS84) zone 37S of the Universal Transverse Mercator (UTM) set of coordinate system since this is the UTM zone containing the area of study. To limit the analysis to the area of study, a predefined map of Thika River sub catchment basin was used to mask out the area of interest.

The soil data was provided as a polygon layer projected to WGS84 Zone 36N. It was therefore re-projected to the World Geodetic System of 1984 (WGS84) zone 37S of the Universal Transverse Mercator (UTM) set of coordinate system since this is the UTM zone containing the area of study so that it could overlay with the DEM layer and therefore make it possible to analyze the two together using SWAT model. The map of Thika River sub catchment basin was used to clip the data to the area of interest.

Land cover data collected from Regional Centre for Mapping (RCMRD) was provided as a raster layer in geographic coordinate system Universal Transfer Mercator Zone 37S and it was re-projected to World Geodetic System of 1984 (WGS84) zone 37S of (UTM) set of coordinate system since this is the UTM zone containing Thika River.

4.5: Data Limitations

Before the observation data for both climate and discharge were used for analysis, quality control was carried out to get rid of errors in the results. This is because consistency of data is an indispensable prerequisite in any analysis. Inadequate data of climate and discharge data may trade off the uprightness of results got from the data. Incomplete records of hydro meteorological data sometimes occur possibly due to operator error or equipment malfunction. Like many parts of the developing world, Kenya has a problem in sustaining operational equipment for stream flow and rainfall measurements. Further, the personnel to take readings are either too few or unreliable (Opere, 1991).

Estimation of the missing records of climate and discharge datasets was essential since they were utilized to drive and adjust the SWAT model that requires consistent data records. A few techniques are available for estimating missing records both climate and discharge data. They include; spatial relationship, weighted arithmetic mean, double mass curve, isohyetal, Thiesen Polygon Method, Normal Ratio Method and Inverse distance method others. More methods of estimation have been discussed by in (Rwigi, 2014). In such cases, it was necessary to fill in the missing records using estimated values and the next subsection presents a brief description of methods that were used to estimate missing climate and discharge data.

4.5.1Estimation of Missing Rainfall Data

Missing rainfall data was estimated using cross correlation between the observations over the stations and the ratio of the climatological values of rainfall over the stations (Wambua, 2010) .

The cross correlation between the rainfall (r_{xy}) is given by:

$$\boldsymbol{r_{xy}}=\frac{\frac{1}{n}\sum_{i=1}^{n}[(x_i-\bar{x})(Y_i-\bar{y})]}{[\frac{1}{n}\sum_{i=1}^{n}(x_{i-\bar{x})}{}^{2}\frac{1}{n}\sum_{i=0}^{n}(y_i-\bar{y})^{2}]^{\frac{1}{2}}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (1)$$

Where;

$\boldsymbol{r_{xy}}$= correlation co efficient

n =number of observations

x_i= Observation in station *x*

y_i= Observation in station *y*

$\bar{x}$= Mean Observations in station *x*

$\bar{y}$= Mean Observations in station *y*

To compute the correlations between the stations, a block of the data was taken over a sub-period where most of the data was available. If station Y_i has a missing value at a certain year, and the station is best positively correlated with station X which has available dataX_a, the formula used to estimate Y_i was given by:

$$\boldsymbol{Y_i}=\boldsymbol{X_a}\frac{\overline{\boldsymbol{Y_a}}}{\overline{\boldsymbol{X_a}}}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

Where;

Y_i =the missing data

X_a=the available data of the station with the highest correlation with station whose data is missing.

$\overline{X_a}$= the mean value for the station with complete data.

$\overline{Y_a}$=the mean value for the station with missing data.

4.5.2 Estimation of Missing Discharge Data

The linear relationship is used as a predictive model of a missing record using the corresponding available record in another station. Regression of data from significantly correlated RGSs was performed to obtain the slope coefficient for the relationship which was then tested for significance before the model could be applied to estimate the missing values.

$$\hat{\boldsymbol{Y}}=\mathrm{a}+\mathrm{b}\boldsymbol{x_i}+\acute{\varepsilon} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

$\hat{Y}$ = the estimated value of the variable of the missing series.

x_i = the available random variable corresponding to the missing record,

a= the *y*-interception of the regression equation

b= the gradient of the equation

The values of *a* and *b* are obtained by minimizing the least squares equation

$$\boldsymbol{\sum_{i=1}^{n}(y_i-\hat{y}_i)^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

The significance of the slope was tested at α=0.05 by use of student *t*-test given by:

$$t_{call}=\frac{b}{s(b)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

Where:

t_{call}= computed t-statistic

b =the gradient of the equation

$s(b)$= the standard deviation of the gradient.

t_{call}, was then compared with the tabulated critical value t_{tab} and slope was considered significant whenever $t_{call}>t_{tab}$ this equation was also used to determine the significance of the trend in both observed and simulated values.

4.5.3 Homogeneity Test

Homogeneity test was necessary for detection of errors in the data and ensured that the data sets were free from errors. Data inconsistency arises due to relocation of instruments, changes in instruments, or changes in observation practices changes in the environment of the observation site such as urbanization (Rwigi, 2014).

The double mass curve technique was used and involved accumulating observed annual discharge and rainfall records for two stations and plotting against each other. A single straight line indicates a homogeneous record and hence originates from the same population whereas deviation from a straight line indicates heterogeneous data sets (Wambua, 2010).

4.5.4 Time Series Analysis

For trend analysis, time series which is an important tool in hydrological and meteorological analysis was used. Its main applications included constructing models to produce hydrologic data, forecasting hydrological phenomena, detecting trends and shifts, cycles and seasonality in hydrological data, and filling in missing records including extension of short hydrologic records where necessary. Time series analysis was used in this study to examine the past, current and future trends of hydro meteorological data. This subsection presents the methods used to determine the mean, variance and trend sample statistics.

4.5.5 Overall Sample Statistics

The means ($\bar{X}$) and the variance (S^2) for hydro meteorological parameters (rainfall and temperatures) were determined for monthly and annual time series over Thika River. For a time series denoted by Y_t the mean ($\bar{Y}$) and variance (S^2) were determined.

$$\overline{Y} = \left(\frac{1}{n}\right)\sum_{t=1}^{N} Y_t \qquad (6)$$

$$\boldsymbol{S^2 = \frac{1}{n-1}\sum_{t=1}^{n}(Y_t - \bar{Y})^2} \qquad (7)$$

Where;

$\bar{Y}$= the sample mean

S^2=the sample variance

N= Sample size

Y_t =time series variable.

These statistics were therefore used to detect trends in observed and model data sets.

4.6: Trend Analysis using Regression Analysis

Trends in hydrologic data could be due to extended periods in changing climate or in the case of discharge due to changes in a watershed's response to effective rainfall as a result of land use change that leads to the deforestation of the watershed. Due to its robustness in detecting trend, the linear regression analysis which assumes normal in errors, constant variance was chosen for this study (equation 8).

$$Y_t=b_o+b_1 t \quad (8)$$

Where;

Y_t = the time series variable

b_o= initial value of the time series variable.

b_1=the trend of the time series variable

t =the time at which Y_t parameter was observed

This equation was used to determine trends in observed and simulated time series and the significance of the trend was tested at α=0.05 level of significance using student t-statistic given by:

$$t=\frac{\bar{X}_1-\bar{X}_2}{\sigma\sqrt{1/N_1+1/N_2}} \quad (9)$$

Where,

$$\sigma=\sqrt{\frac{N_1 S_1{}^2+N_2 S_2{}^2}{N_1+N_2+2}} \quad (10)$$

4.7: Determination of Observed Discharge Trends in Thika River Catchment

To determine discharge trends, data from four river gauging stations were used. This included calculation of decadal means ($\bar{X}$) and Variance (S^2) from 1950s-2000. Time series plot were plotted for visual graphical representation of the trend.

For the purpose of this study Mann Kendall statistic which is a non-parametric test of hypothesis was used to assess if there was a monotonic upward or downward trend of discharge over the study period. A monotonic upward trend meant that the discharge was increasing while a monotonic downward trend meant that the discharge was decreasing over time within the catchment.

Mann-Kendall tested whether to reject the null hypothesis (H_o) and accept the alternative hypothesis (H_a) where;

H_o: No monotonic trend of discharge

H_a: There is a monotonic trend of discharge.

The initial assumption of the Mann-Kendall test is that the null hypothesis (H_o)is true and that the data must be convincing beyond a reasonable doubt before null hypothesis (H_o) is rejected and alternative hypothesis (H_a)is accepted.

The procedure for conducting Mann-Kendall statistic involved the following procedure:

The discharge data were arranged in the order in which they were collected over time,x_1,x_2,x_3…..x_n; which denoted the measurements obtained at times 1, 2, 3… n respectively.

The sign of all the $\frac{n(n-1)}{2}$ possible differences $x_j - x_k$were determined where j>k.

These differences where;$x_2 - x_2$, $x_3 - x_1$,…,$x_n - x_1$, $x_3 - x_2$,$x_4 - x_2$,$x_n - x_{n-2}$, $x_n - x_{n-1}$

sgn ($x_j - x_k$) was let to be an indicator of a function that takes the values 1,0 or -1 according to the sign of $x_j - x_k$. i.e.

sgn ($x_j - x_k$) =1 if $x_j - x_k$>0

=0 if $x_j - x_k$=0

or if the sign of $x_j - x_k$ cannot be determined due to non-detects

=-1 if $x_j - x_k$<0

S=$\sum_{k-1}^{n-1}\sum_{j-k+1}^{n} Sgn(x_j - x_k)$) was computed which represented the number of positive differences and the number of negative differences.

Variance of S was computed using;

Var(S) = $\frac{1}{18}$[n (n-1) (2n+5)-$\sum_{p-1}^{g} t_p(t_p$-1) ($2t_p + 5$)]………………………………….……..… (11)

Where,

$g$is the number of tied groups and

$t_p$is the number of observations in thep^{th} group.

Mann Kendall test statistic was computed as follows;

Z_{MK}= $\frac{S-1}{\sqrt{VAR(S)}}$ if S>0…………………..………………..……………………………….……… (12)

$=$ 0 if S=0…………………………………………………………...……..…………………..… (13)

$=\frac{S+1}{\sqrt{VAR(S)}}$ If S<0………………………………......……..……………….. ....……..… (14)

4.8: Spatial Data Analysis

SWAT model was used in delineation of Thika River Watershed. In SWAT, the basin was divided into various sub basins, which were then detailed into hydrological response units according to distinct soil and land use properties. SWAT uses Equation (14) in a soil water balance equation in the soil profile:

$\boldsymbol{SW_t}$=$\boldsymbol{SW_o}$+$\sum_{\boldsymbol{i=1}}^{\boldsymbol{t}}(\boldsymbol{R - Q_{surf} - ET_i - T_i - Q_{gw}})$...…………….…………………………….. (15)

Where;

SW_t = soil water held in the soil at time t (mm),

SW_o= the soil water held in the soil at the start on day i (mm)
$R_, =$ daily amounts (mm)of precipitation

Q_{surf}= runoff

, ET_i= evapotranspiration

T_i= percolation

Q_{gw}= return flow

These parameters were used to compute water balance at each water balance at the Hydrological Response unit. Stream flow generated is added in all hydrologic response units. SWAT model calculates and produces hydrological components.

In SWAT model, stream flow in all the HRUs is simulated by use of two methods; Green & Ampt infiltration method and Soil Conservation (SCS) Curve Number (CN) procedure(Arnold *et al*., 2012). In this study, Soil Conservation Curve number method which incorporates soil, land use and management information was used to calculate runoff. Figure 12 describes the framework that was used to calculate runoff fusing SCS-CN method.

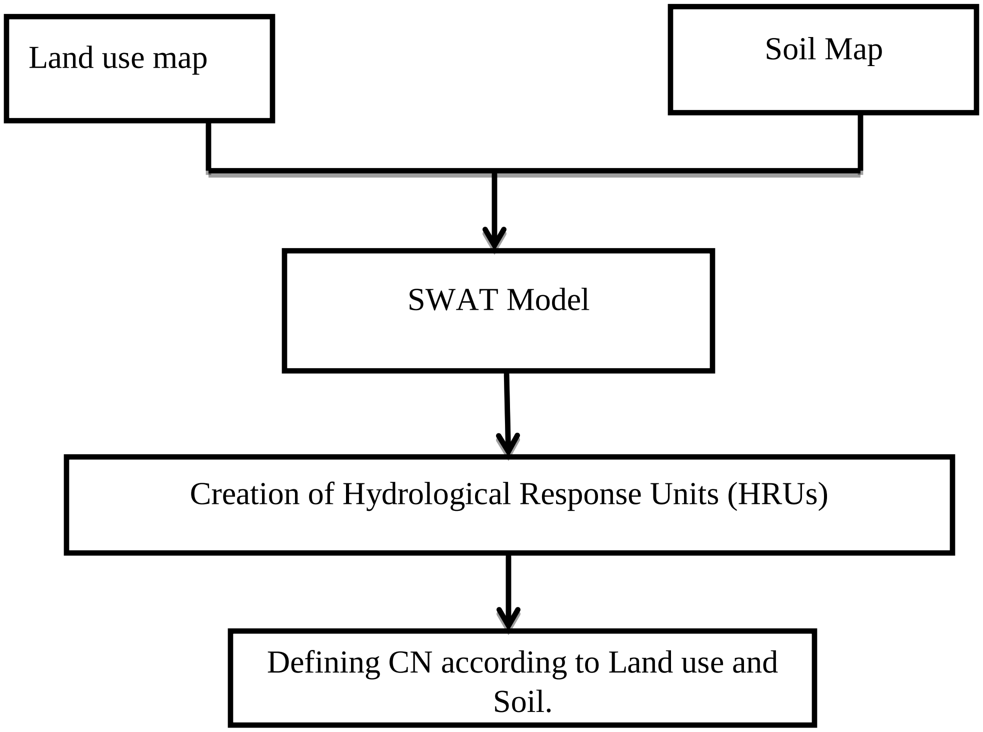


Figure 12: Framework for SWAT model; modified from (Singh 2009).

In SWAT model there is variety of methods of estimating evapotranspiration. This study however adopted Penman-Monteith since it takes into account the influence of carbon dioxide in calculating transpiration. For river channel routing, Muskingum technique was used to calculate and simulate river flows via the soil layers in the root zone(Pervez & Henebry, 2015).

4.8.1 Watershed Delineation

The watershed boundaries of the area of study were obtained from the global Shuttle Radar Topographical Mission (SRTM) 90 m by 90 m DEM using automated procedures within the watershed delineator ArcSWAT; a GIS extension within SWAT2012. The key procedures followed in the delineation process included: loading the DEM that was used to calculate sub-basin and reach parameters; Specifying the critical source area which was used to determine the network of streams and sub basins in the Thika River catchment; Reviewing and editing the stream network outlet points so as to achieve the maximum number of sub-basins and calculating the sub-basin parameters.

The next step after was to input LULC and soil data thematic maps. The thematic maps were input, overlaid, and the characterization of each sub-basin was automatically performed using the ArcSWAT interface. Having done this, areas with unique soil land use- slope combination were differentiated within each sub-basin. These distinct areas, referred to as hydrological response units was used as the basis of the water balance calculations (Abbaspour *et al.*, 2009; Schuol *et al.,* 2008).

4.8.2 Sub- Basin Parameters

Spatially, the model was parameterized by subdivision of the Thika River Catchment into eleven (11) sub basins based on the surface orography so that the entire catchment drains through the outlet at southeast of the catchment. Each sub-basin was again subdivided into a number of hydrological response units according to distinct soil, land use, and slope properties.

4.8.3 Hydrological Response Units

Spatial characterization for the main catchment area and for each of the respective sub-basins was performed using ArcSWAT interface where the land use and soil data sets were imported and linked to the SWAT databases. Slope classification was performed based on the DEM. Multiple class slopes option was chosen on account of the wide range of slopes in the Thika River catchment area. Spatial datasets were used to define at least one HRU for every sub-basin. Land use data were defined and reclassified into SWAT land cover types.

Since the area of study was outside the United States (US)., a text file containing the locations of the weather stations was created and editing of the default LULC database in order to reflect the local conditions. The soil dataset was also defined and reclassified. Soil map obtained from the Kenya Soil Survey (KSS), the various categories of soils found within the Thika River catchment area were linked to the SWAT soil database.

After land use and soil datasets were successfully reclassified and the slope class chosen, the spatial datasets of various thematic layers were overlain to the catchment. These layers were used to automatically define the HRUs for each of the 11 sub-basins using preset threshold levels of: 5% land use, 10% soil, and15% slope.

4.8.4 Climate Data

Climatic parameters that determine hydrologic water balance are: rainfall, temperature, sun radiation, wind speed and atmospheric humidity (Arnold *et al.,* 1998). Where available, observed daily rainfall, temperatures can be input directly; however, the model can simulate them using a weather generator. In addition, the model can internally generate solar radiation, wind, humidity

In this study, the weather data used in the catchment simulation of stream flow were imported into the SWAT databases. Weather stations; Karamaini, Gethumbwini Coffee Estate, and Thika Agro Met loaded to the model and used to define the Weather generator datasets which were used to generate various weather parameters for the model. SWAT model weather generator database was created by first creating a location table to give the station location of the stations within the Thika River watershed (Winchell *et al.,* 2010). Table 5 shows the local weather stations used to provide the weather generator data sets for the area of study.

Table 5: Weather stations used in SWAT model

No	**Station ID**	**Station Name**	**Latitude**	**Longitude**	**Elevation(m)**
1.	9037005	Gethumbwini Coffee Estate	-0.967	37.033	1524
2.	9136029	Karamaini Thika	-1.05	36.083	1554
3	9137048	Thika Agromet	-1.01	37.100	1463

CHAPTER 5: RESULTS AND DISCUSSION

5.1: Introduction

In this chapter, the results obtained from the various methods and analysis used in the study are presented which includes; data quality control, trends of observed rainfall and temperature, trends in observed discharge, rainfall -runoff modeling of the catchment and simulation of future hydrological conditions of the catchment under different climate change scenarios.

5.2: Estimation of Missing Data

Estimation of the missing records formed an integral part of this study. Results obtained from the estimation of missing rainfall, temperature and discharge are presented in the next section.

5.2.1 Estimation of Missing Rainfall Data

Before attempting to fill in any missing rainfall data, there was need to first determine the relations between rainfall and river gauging stations. This was done by calculation of linear correlation coefficients $r_{x,y}$ between the stations that were selected for the study. Equation (3) was used to compute the inter stations linear correlation coefficients; $r_{x,y}$ The purpose of generating these values was to find out whether data from a certain weather station were related to data from other stations. Results of the correlation coefficients are presented in Table 6 and Table 7.

The results in Table 6 indicate that most rainfall stations used in the study were linearly correlated to each other since $r_{x,y}$ ≥0.5 for most of the stations. This threshold was taken on the basis that the values beyond 0.5 are close to 1, which is the value that signifies a perfect relationship.

Values below 0.5 were considered close to zero hence poor relationship. For the purpose of this study, values beyond 0.5 were considered to be significant while those below 0.5 were considered insignificant and therefore used for the estimation of missing data in the study.

Except for Chania Dam (9036286), whose $r_{x,y}$ values range from -0.222 to 0.156108, all other stations exhibited values of linear correlation with $r_{x,y} \geq 0.5$. The low values of $r_{x,y}$for Chania Dam indicate lack of a reasonable relationship with other stations and data. This station was found to be located at the upstream of the catchment and it always receives the largest amount of rainfall as compared to other stations located downstream hence it was located in a different climatic zone.

Table 6: Correlation coefficients between rainfall stations

	Chania	**Karamaini**	**Thika Agromet**	**Gethumbwini**
Chania Dam	1			
Karamaini	0.088161	1		
Thika Agromet	0.156108	0.823575	1	
Gethumbwini	-0.0222	0.526843	0.644296	1

5.2.2 Estimation of Missing Discharge Data using Simple Linear Regression

In estimating missing discharge data in the study area, correlation coefficients ($r_{x,y}$) between the RGSs were computed and results presented in Table 7. Results for $r_{x,y}$ obtained by calculation of discharge data indicated that, of the five River gauging Stations selected for the study, 4CB05-Thika RGS negatively correlated with other stations and therefore was excluded for estimating of missing data for other RGSs. On the other hand all the other four stations positively correlated where 4CA02 and 4CB04 having the highest correlation coefficient of +0.99. Using same method of estimation of missing rainfall data, each two RGSs stations with high correlation was used to estimate missing data in the corresponding station having missing data.

Table 7: The computed correlation coefficients of river gauging stations

	4CB04	**4CB07**	**4CA02**	**4DA01**	**4CB05**
4CB04	1				
4CB07	0.959872	1			
4CA02	0.998695	0.95544	1		
4DA01	0.95507	0.97013	0.9473786	1	
4CB05	-0.041454	-0.1001	-0.046938	-0.106643	1

5.2.3 Homogeneity Test

Once the problem of estimating missing data was done, test for homogeneity for rainfall and discharge data was performed to test for data consistency. As discussed in section 4.5.3, results of double mass curve are presented in this section (Figures 13-21).From the results it was found out that all the dicharge and rainfall data from the selected stations were homogeneous and therefore fit to use for further analysis. However homogeneity test results for rainfall measurements from Chania Dam showed some heterogeneity when double mass curves were plotted with other stations (Figure13, Figure 14 and Figure 15). This was also the case when correlation coeffiecients were computed relative to other rainfall stations and therefore it was exluded for further analysis.

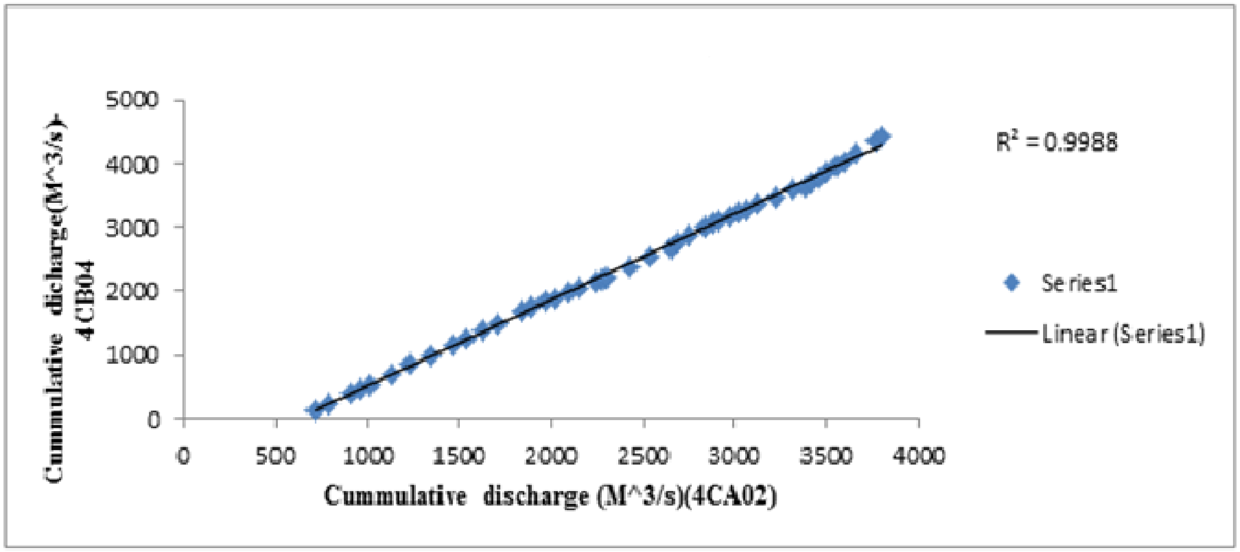


Figure 13: Double Mass curve showing cumulative discharge of 4CA02 and 4CB04 RGSs

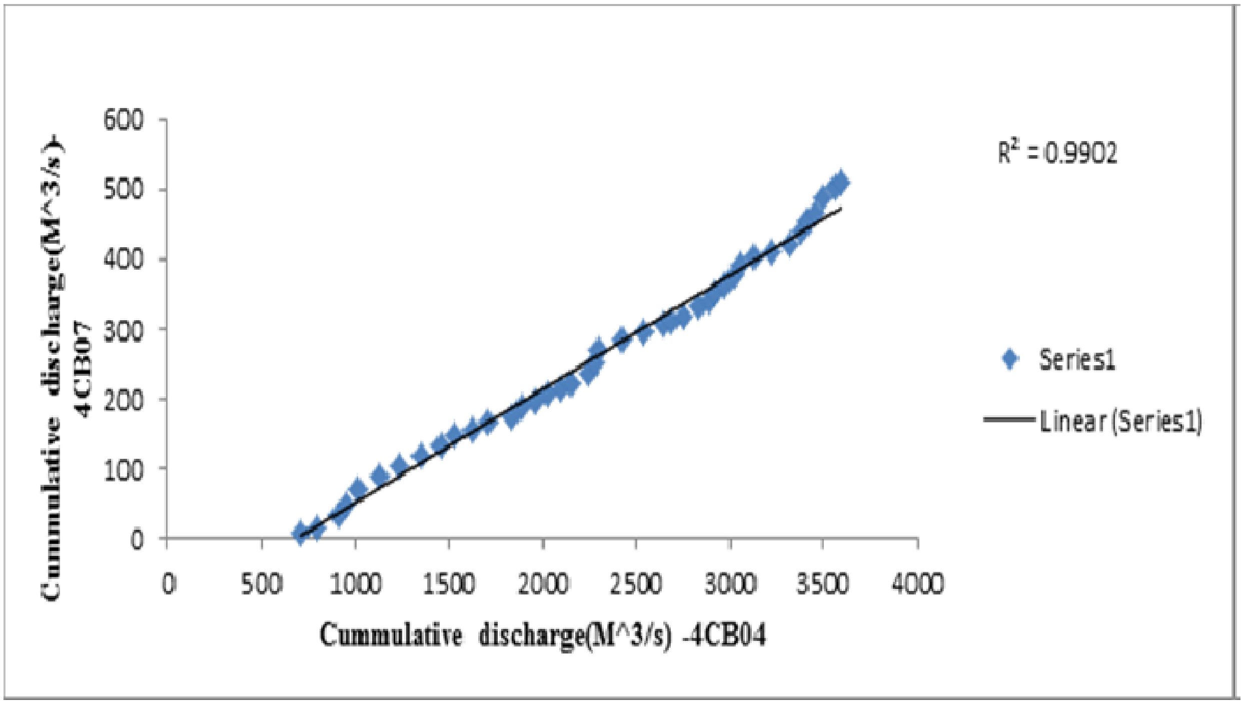


Figure 14: Double Mass curve cumulative discharge of 4CB07 and 4CB04 RGSs

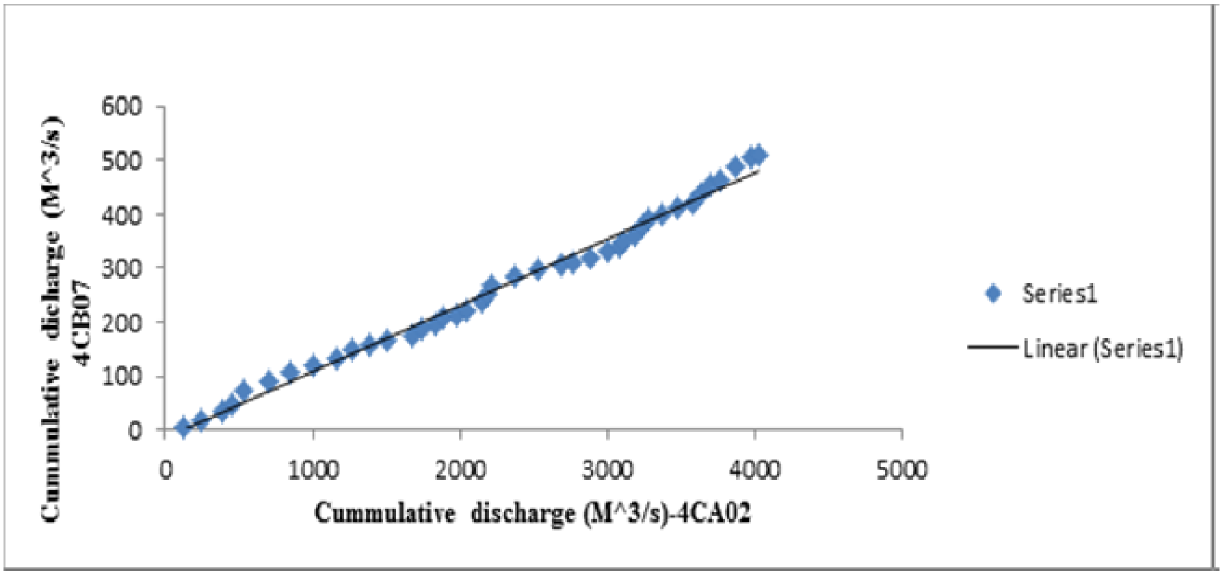


Figure 15: Double Mass curve of cumulative discharge of 4CB07 and 4CA02 RGGs

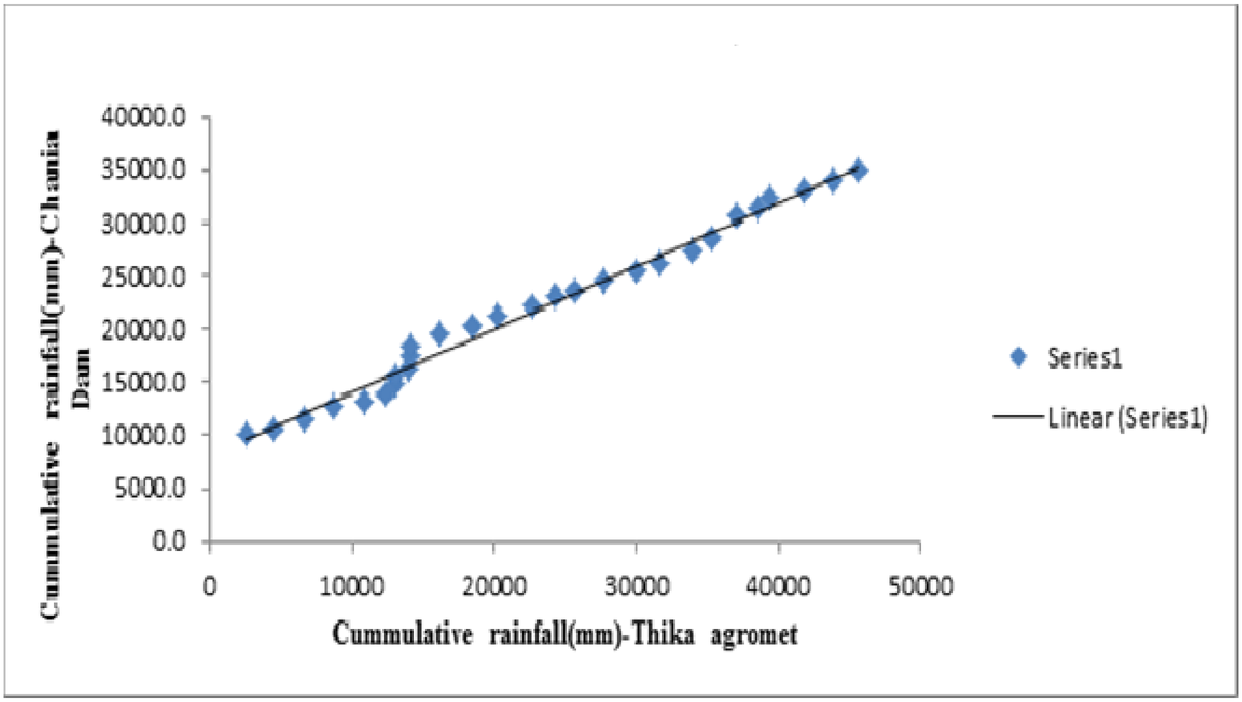


Figure 16: Double Mass Curve showing cumulative rainfall between Thika Agro Met and Chania Dam

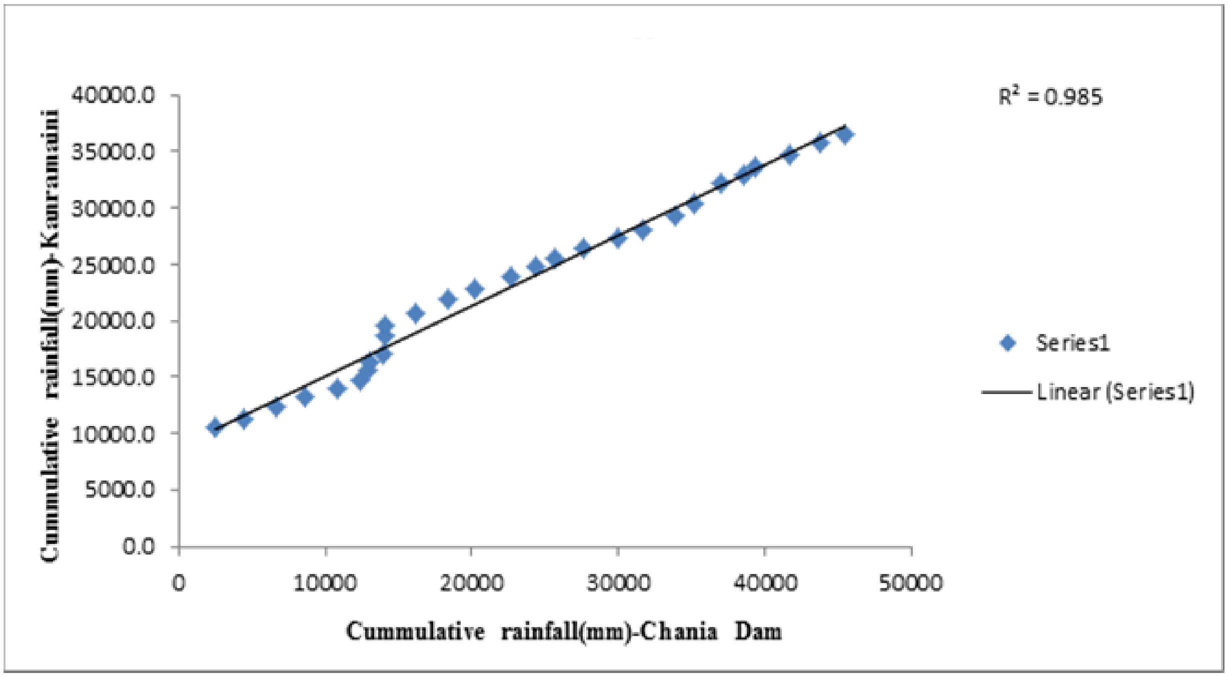


Figure 17: Double Mass Curve showing cumulative rainfall between Karamaini and Chania Dam

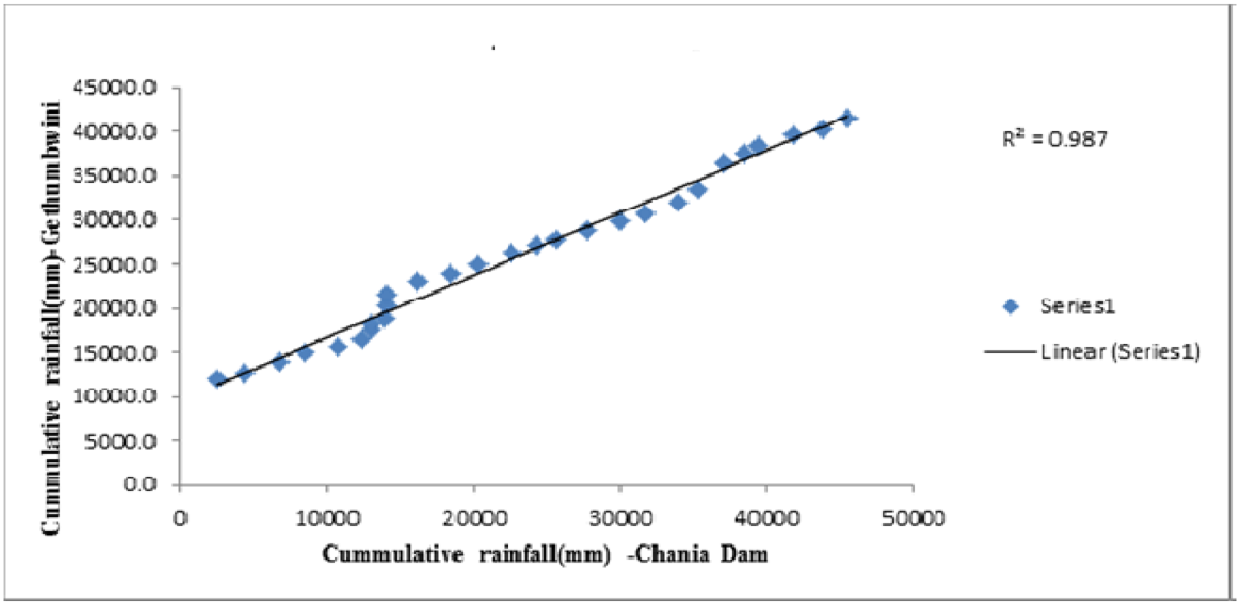


Figure 18: Double Mass Curve showing cumulative rainfall between Gethumbwini and Chania Dam

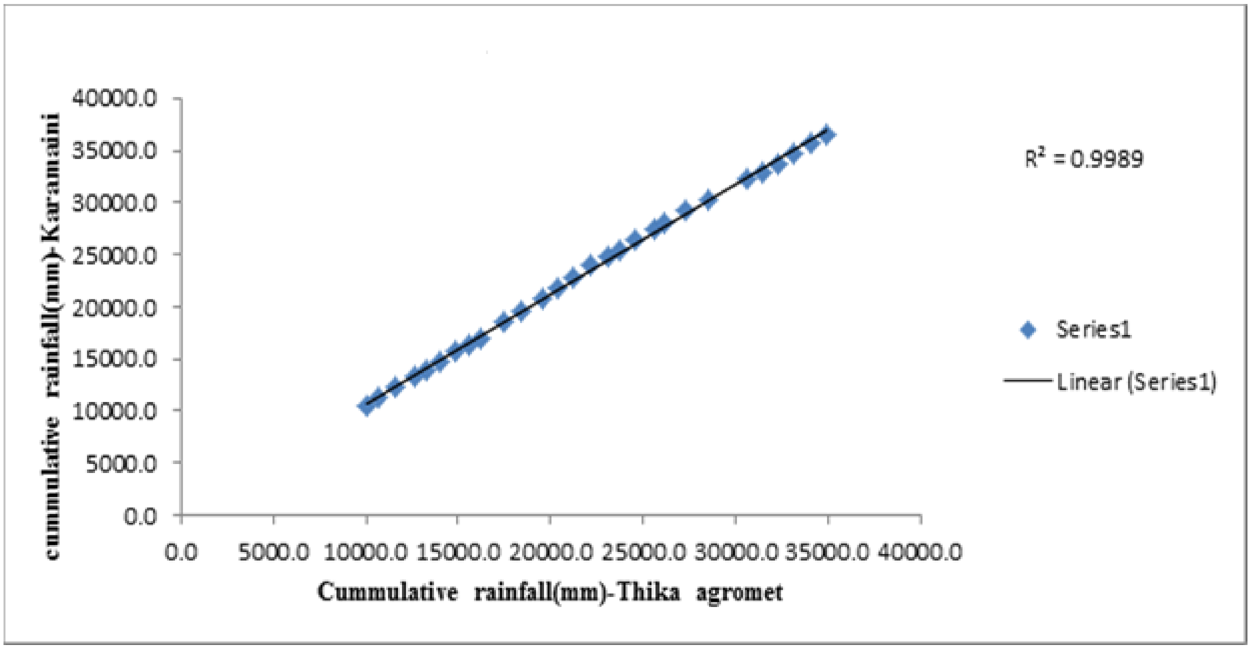


Figure 19: Double Mass Curve showing cumulative values between Thika Agro Met and Karamaini

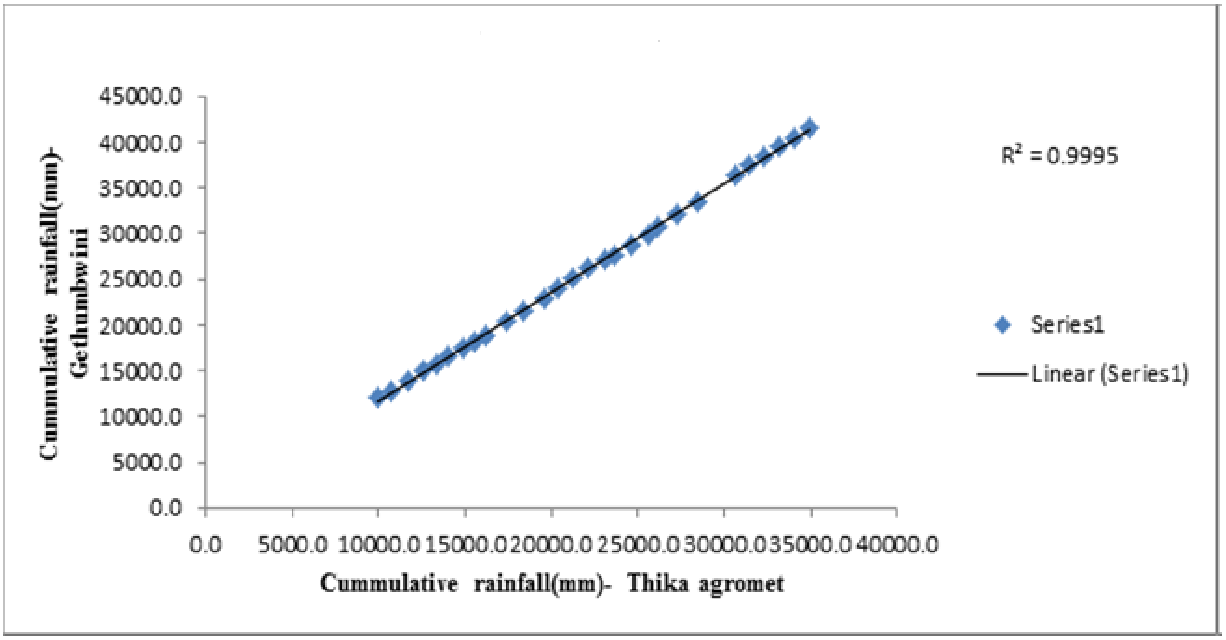


Figure 20: Double Mass Curve showing cumulative values between Thika Agro Met and Gethumbwini

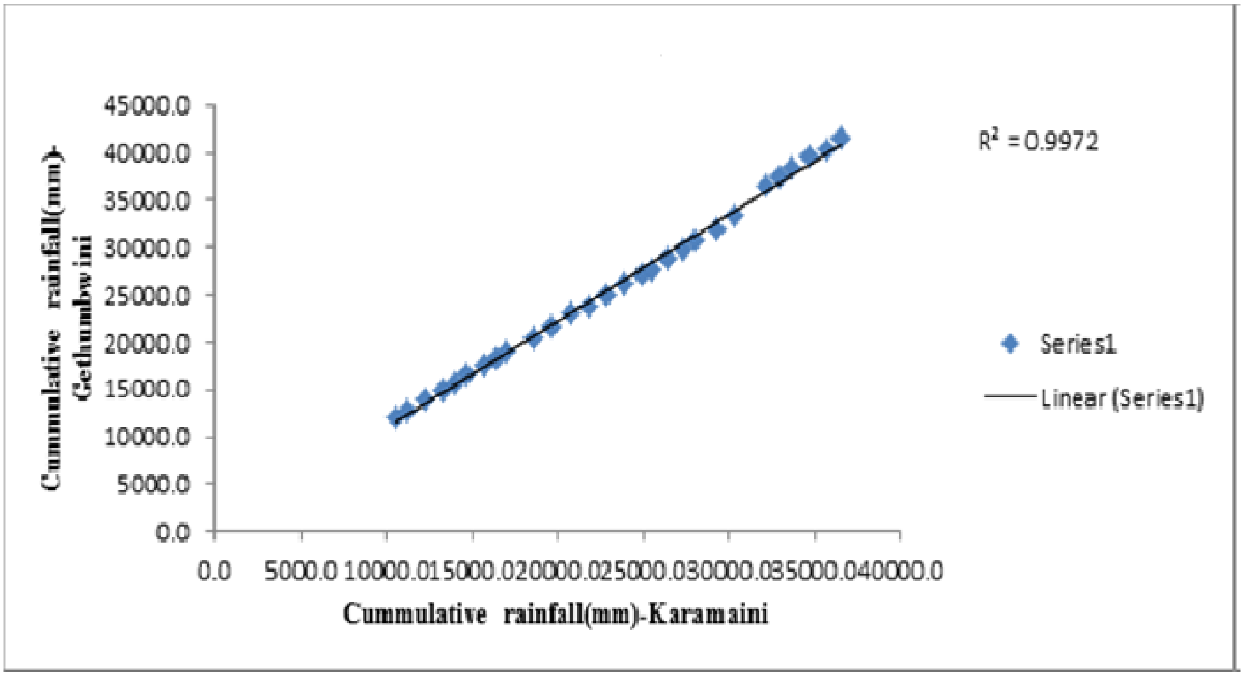


Figure 21: Double Mass Curve showing cumulative values between Gethumbwini and Karamaini.

5.3: Ensemble Climate Model output Validation

Using monthly ensemble model simulated data from CORDEX and corresponding observation data for rainfall, maximum and minimum temperature at Karamaini, Gethumbwini and Thika Agro Met, regression parameters were used to validate the model and results presented in Table 8.

Table 8: Regression parameters for rainfall used to validate CORDEX model Output

Station	**Rainfall**			
	a_{rf}	b_{rf}	R^2	r_{os}
Karamaini	0.8129	26.89	0.52	0.72
Thika Agro Met	1.1408	19.73	0.65	0.81
Gethumbwini	1.358	18.06	0.75	0.86

Correlation coefficients of simulated and observed range from 0.72 to 0.86 were tested for significance using student t-test at α=0.05 level of significance and results is as shown in Table 9. In all the calculations, the computed values of $t(t_{cal}$) for correlation coefficient were found to be greater than tabulated value ($t_{\alpha=0.05}$ =3.17) which showed that the multi model output from CORDEX and observed station values were significant.

Table 9: Results for test of significance of correlation coefficients

Station	r_{os}	*n-2*	t_{cal}	($t_{\alpha=0.05}$	Comments
Karamaini	0.72	10	3.82	3.17	Significant
Thika Agro Met	0.81	10	4.36	3.17	Significant
Gethumbwini	0.86	10	5.32	3.17	Significant

Plots of observed and ensemble model output average was done and the results showed a fairly perfect relationship. It was also noted that model output under forecasted during March April May season and fairly good during June July August and September, October November December seasons (Figures 22-24).

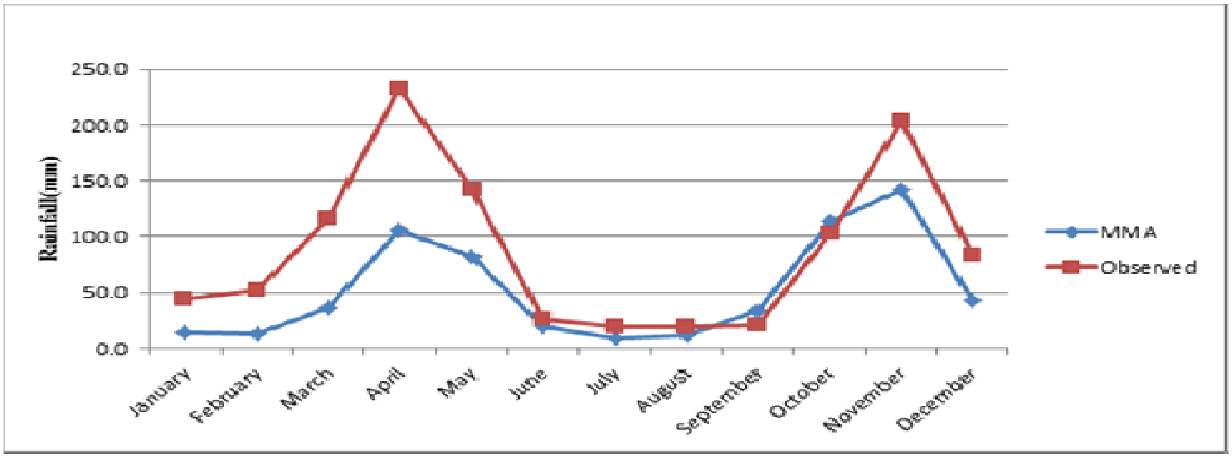


Figure 22: Monthly variations for both observed and Ensemble Model output (CORDEX)-Gethumbwini

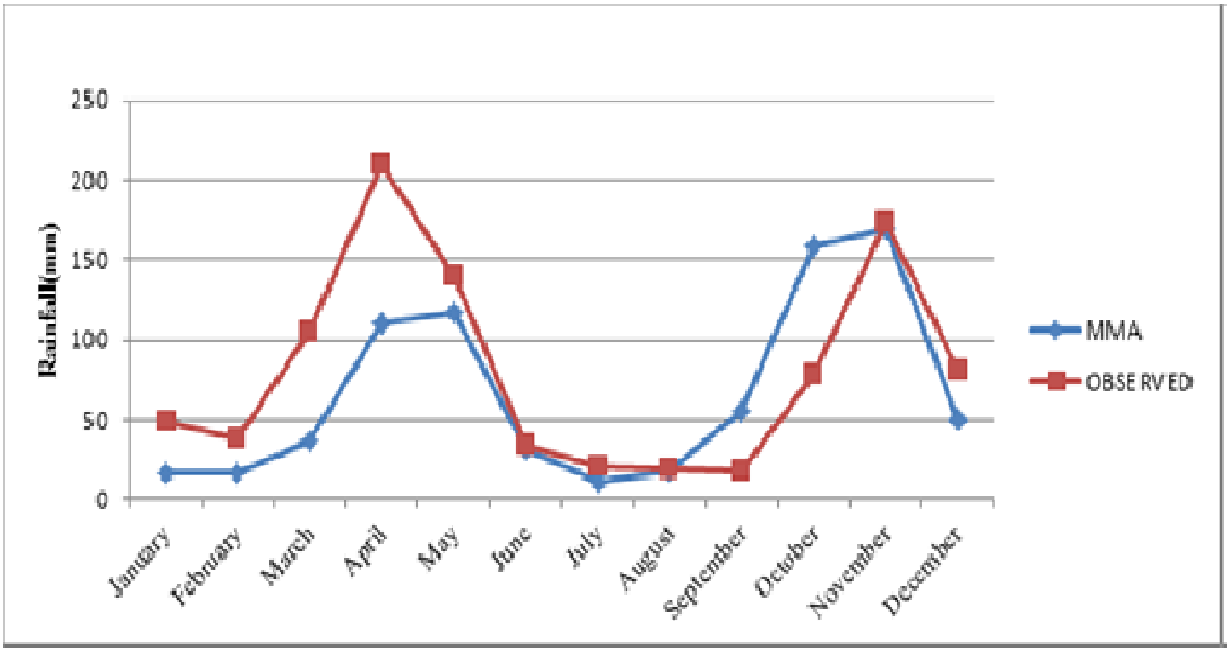


Figure 23: Monthly variations for both observed and Ensemble Model Output (CORDEX)-Karamaini

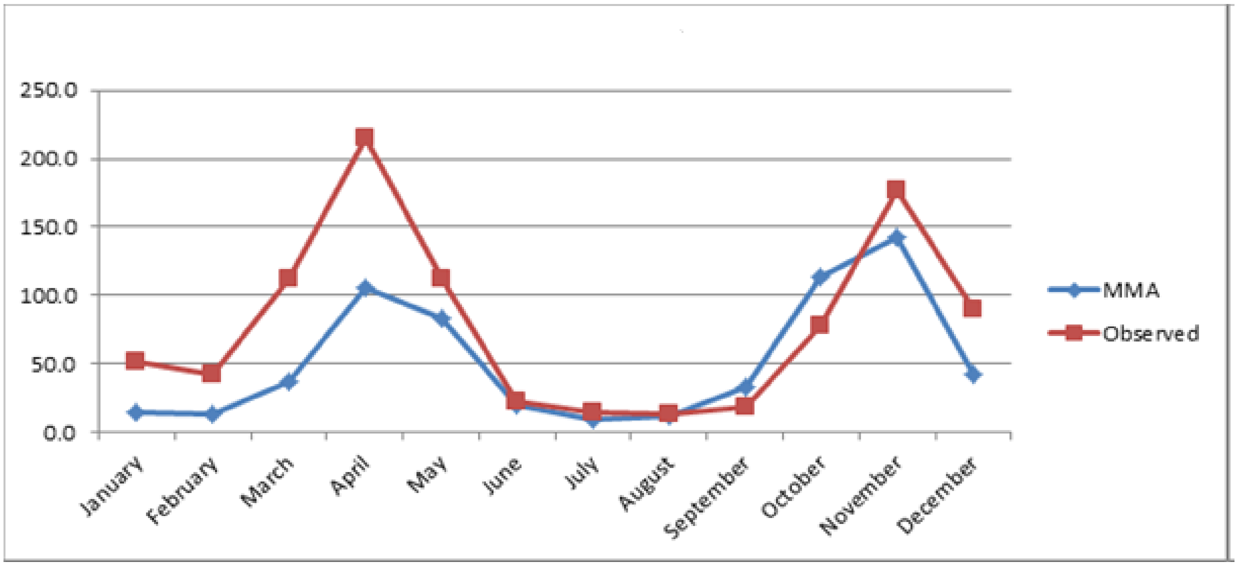


Figure 24: Monthly variations for both observed and Ensemble Model Output (CORDEX)-Thika Agro Met

5.4: Results for Observed and Projected Climate Trends

This section presents results for historical trends of rainfall and temperature in the study area as well as results for climate projection from CORDEX model output in order to achieve the first objective of the study.

5.4.1 Observed Annual Rainfall Trend Characteristics

Plots of standardized rainfall anomalies fitted with a trend line are as shown in Figures 25 - 27. From the time series plots of standardized rainfall, it was noted that there has been a decreasing trend of annual rainfall at Gethumbwini Coffee Estate and Karamaini Thika. However, it was found out that at Thika Agro Met station there has been an increasing annual trend of rainfall (Figure 27).

In order to determine significance of trends of rainfall at the three meteorological stations Mann-Kendall statistic was used. Results for the test of significance in trend using Mann-Kendall showed that the computed p-value was greater than the significance level α=0.05, and therefore the null hypothesis was not rejected (Table 9).

It was thus concluded that although there was trend in rainfall in the study area it was not significant. However small changes in rainfall can bring about significant changes in the river runoff in the sub catchment.

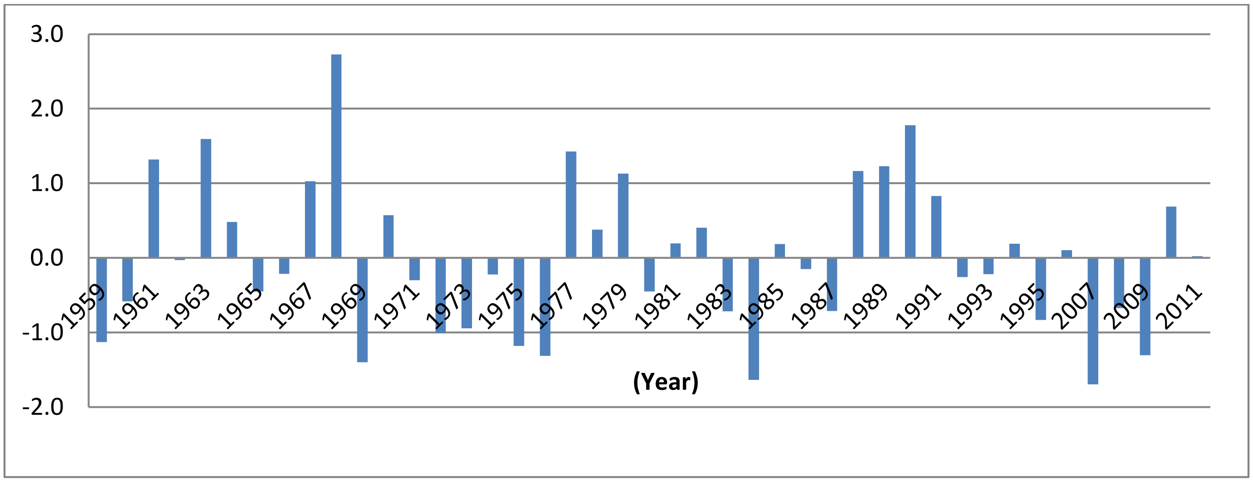


Figure 25: Observed standardized rainfall anomalies at Gethumbwini Coffee Estate

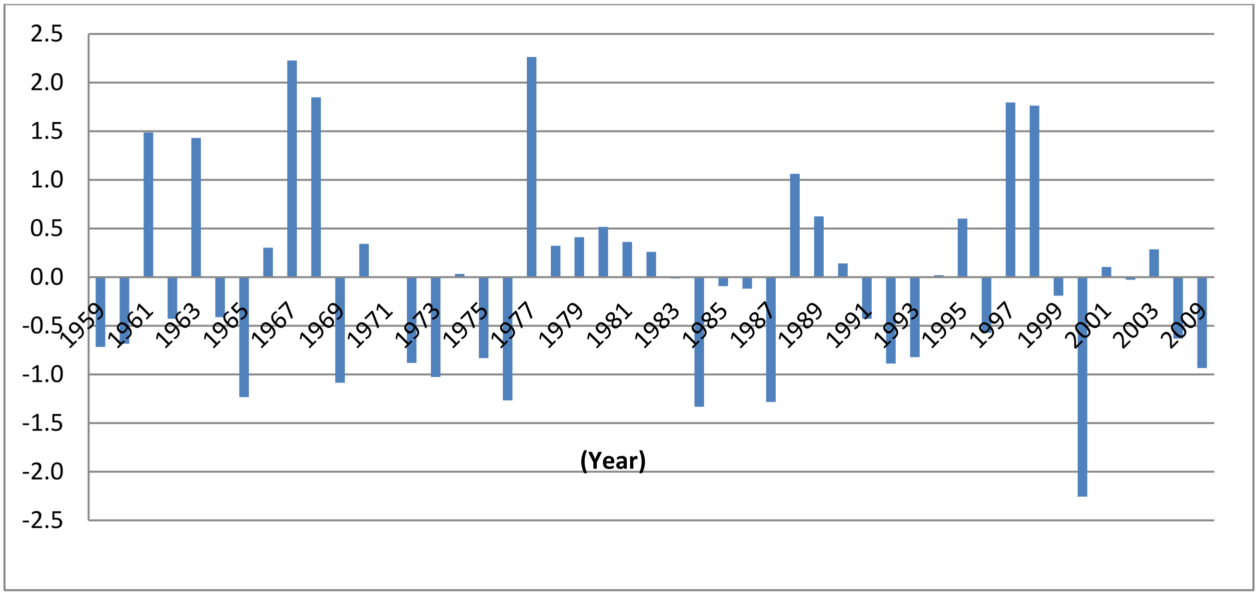


Figure 26: Observed standardized rainfall anomalies at Karamaini Thika

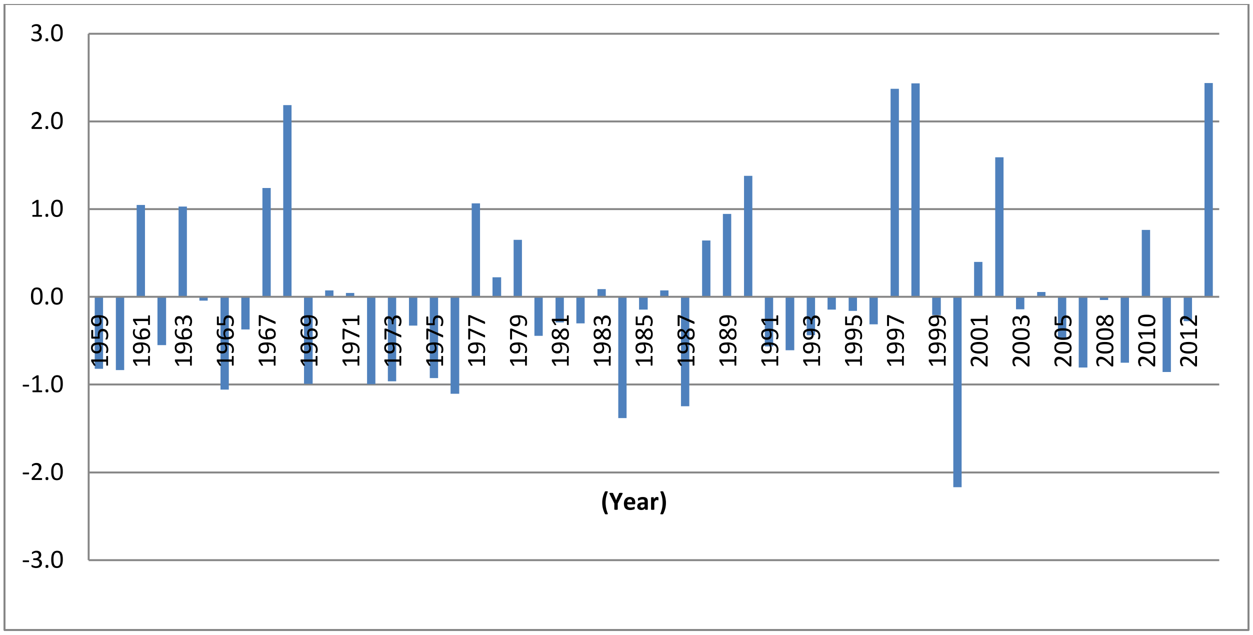


Figure 27: Observed standardized rainfall anomalies at Thika Agro Met

Table 10: Results for test of significance of annual rainfall trends using Mann-Kendall at Gethumbwini Coffee Estate, Karamaini Thika and Thika Agro Met

	Gethumbwini Coffee Estate	Karamaini Thika	Thika Agromet
Kendall’s tau	-0.092	-0.074	0.059
S	-79	-77	85
Var(S)	0.00	0.00	17967
p-value(two-tailed)	0.40	0.47	0.531
Alpha(α)	0.05	0.05	0.05
Remarks	Not significant	Not significant	Not significant

5.4.2 Observed Monthly Rainfall Trend Characteristics

This section presents results for annual cycle of mean monthly rainfall and seasonal variations for three climate periods (30 years) updated after 10 year period for 1961-1990, 1970-2000 and

1980-2010 to represent climates in 1970s, 1980s and 1990s respectively at Karamaini Thika, Thika Agro Met and Gethumbwini Coffee Estate (Figures 28 - 33).

From the results it can be shown that the study area has two rainy seasons depicting a bimodal rainfall pattern with the highest peak of rainfall received during April (Long rains) and a moderate peak during November (Short rains). The bimodal pattern of rainfall is influenced by inter-tropical convergence zone (ITCZ) of air masses of both hemispheres and modified by local orography, to Congo Air mass Basin and Indian Ocean monsoon (Okoola, 1996). The result of this study further confirms that ITCZ is the main synoptic scale system that affects the intensity, distribution and migration of seasonal rainfall over the Eastern Africa region (Omeny, 2008). It was further noted from the results that dry season occurs during the months of December, January and February (DJF) and June, June, July and August (JJA) with JJA season being the driest.

Using 1961-1990 as the baseline climate period, percentage change in rainfall in the three meteorological stations in 1980s and 1990s relative to the baseline climate were calculated and results was as presented in Figures 29, 31 and 33. The Results for observed rainfall change (%) shows that there is a seasonal shift in wet season where October, November, December and January(ONDJ) season is becoming wetter with the highest change in rainfall as compared to the reference years of (1961-1990). The percentage increase in rainfall during ONDJ ranged between 1%-33% and 6%-70% in 1990s and 1980s respectively (Figures 29, 31 and 33).

It was further noted that that there has been a decreasing trend in rainfall in the seasons of March, April and May (MAM) and June July and August (JJA) as compared to the baseline period (1961-1990) in all the stations with the change ranging between 5%-19% in 1990s and 7%-19% in 1980s. Karamaini Thika station recorded the highest decrease in rainfall in the months of August and September with a decrease of 18% in 1980s and 34% in 1990s.

Therefore, from the analysis of results of seasonal rainfall pattern from the three climate periods it can be shown that there is a seasonal shift in wet season where MAM has become less wet and more wet ONDJ season as compared to baseline period of 1961-1990 which might have an impact on water resources in Thika River sub catchment area.

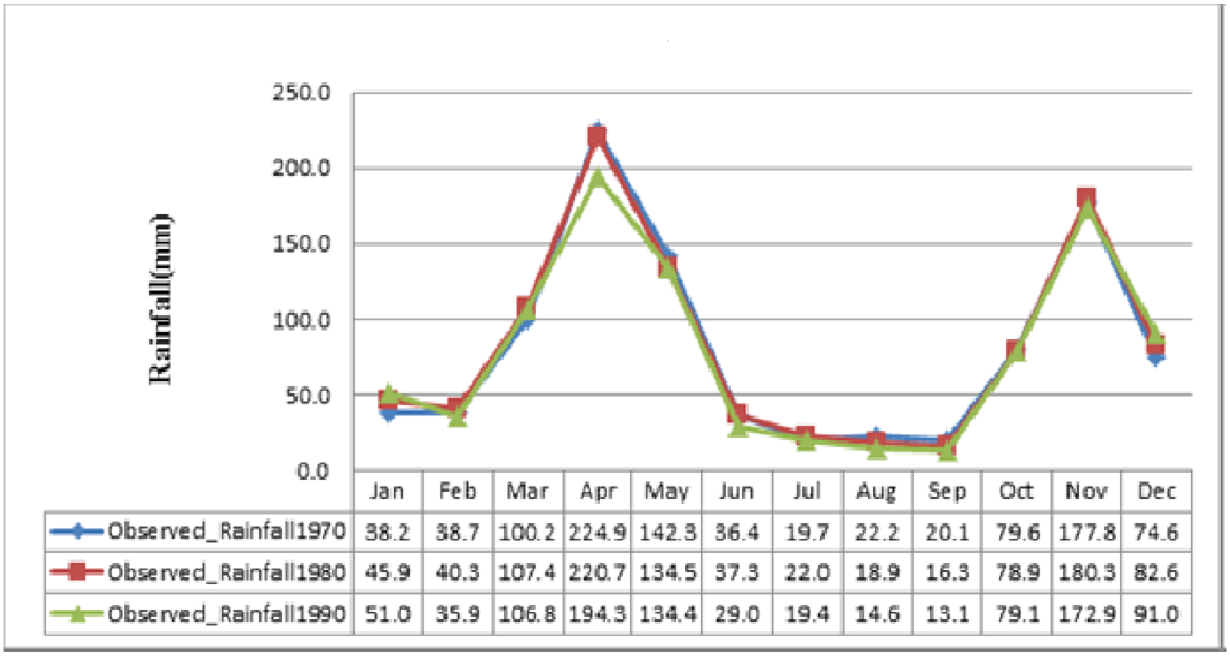


Figure 28: Observed monthly rainfall climatology of 1970s, 1980s, 1990s at Karamaini

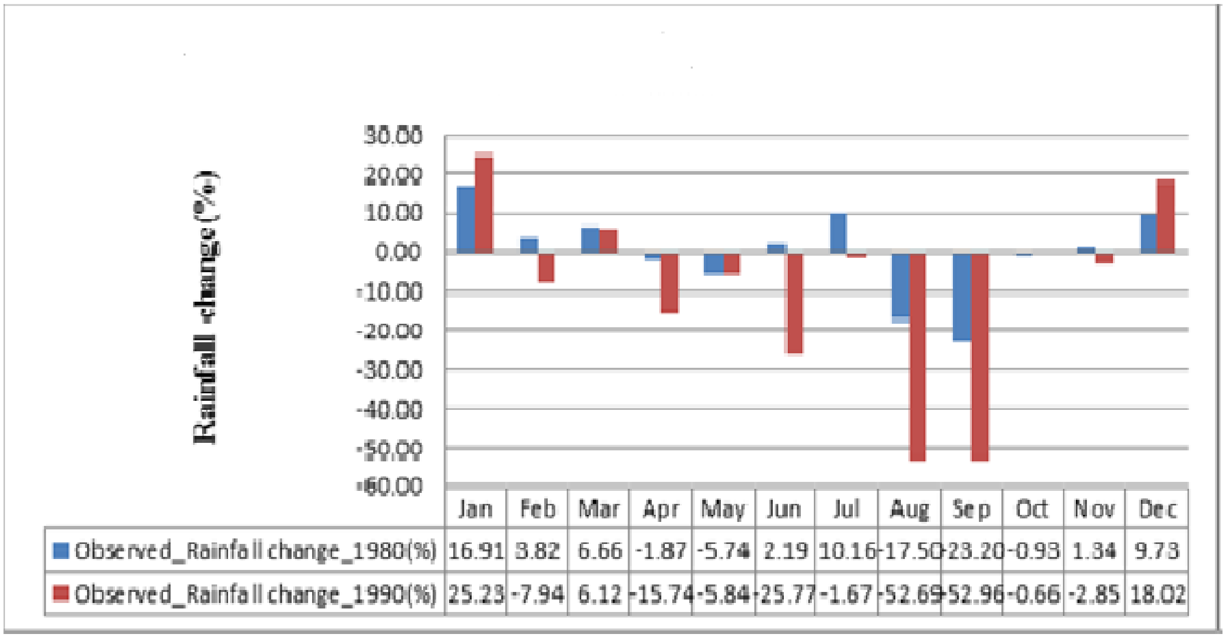


Figure 29: Observed change (%) in rainfall at Karamaini 1980s and, 1990, relative to base period (1960s)

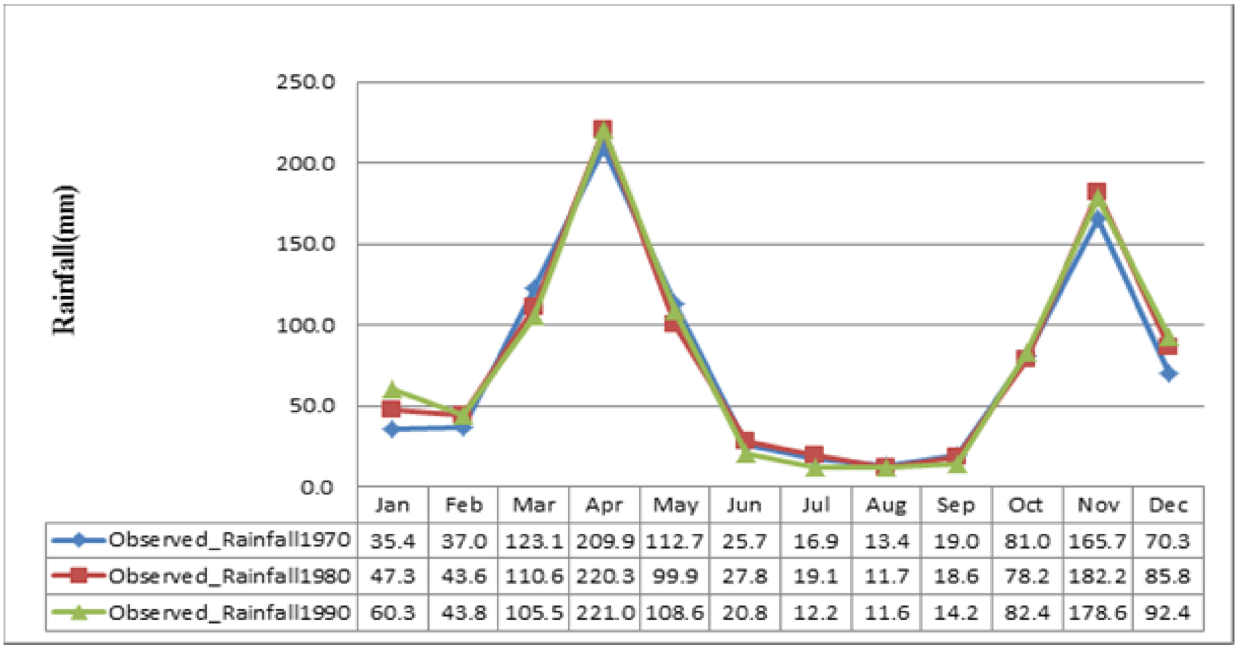


Figure 30: Observed monthly rainfall climatology of 1960s, 1970s, 1980s, 1990s and 2000s at Thika Agro Met

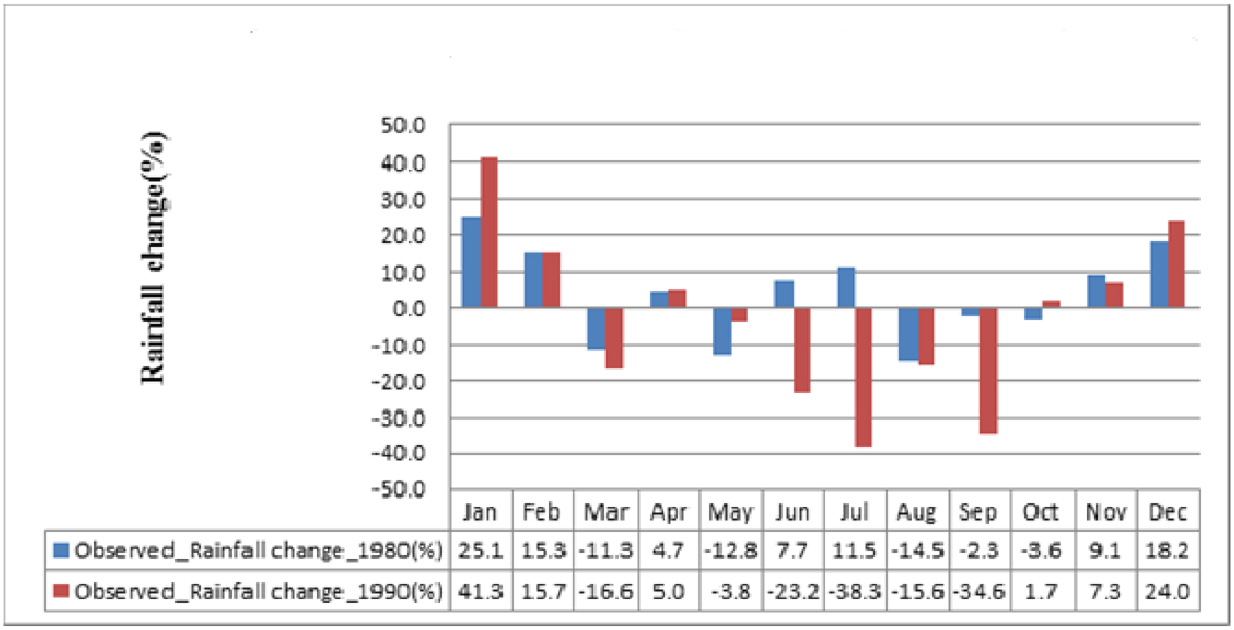


Figure 31: Observed monthly change (%) in rainfall at Thika Agro Met 1980s and, 1990, relative to baseline period (1960s)

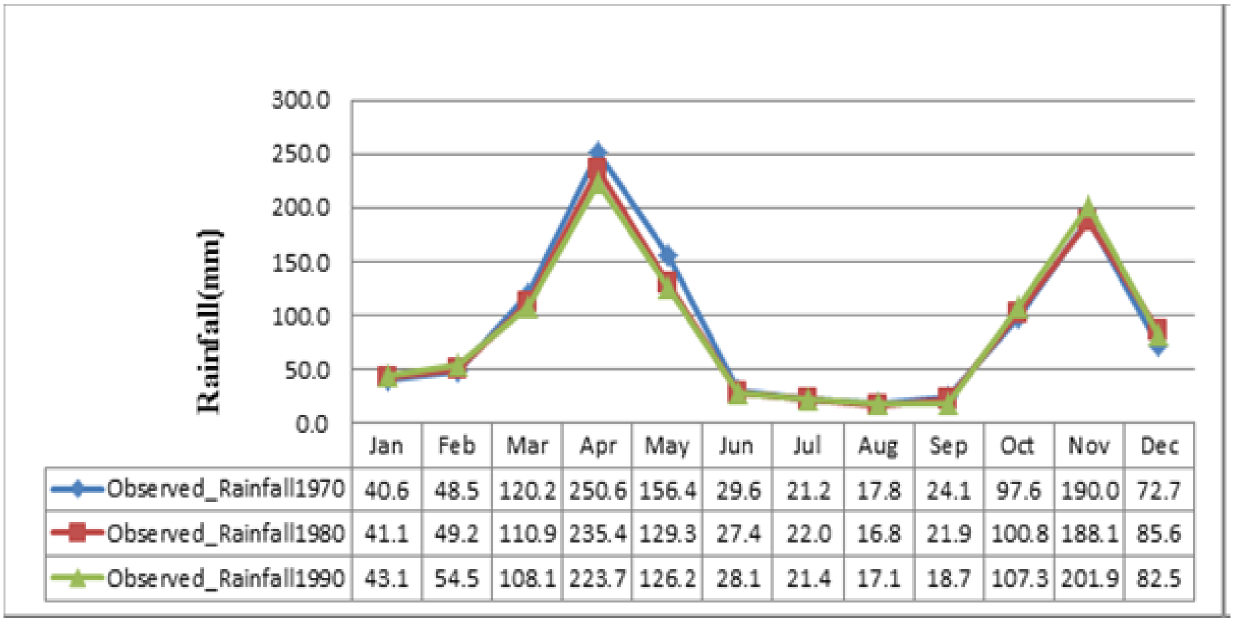


Figure 32: Observed monthly rainfall climatology of 1970s, 1980s, 1990s at Gethumbwini Coffee Estate

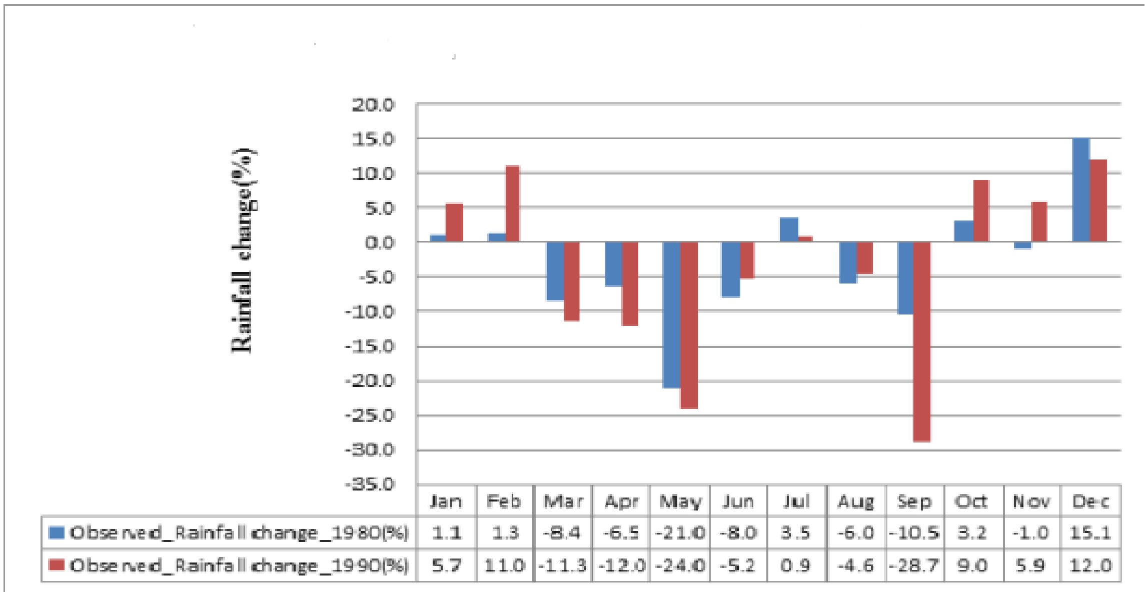


Figure 33: Observed monthly change (%) in rainfall at Gethumbwini Coffee Estate 1980s and, 1990, relative to base period (1960s).

Using Student *t* test at $\propto$=0.05 level of significance, a hypothesis that differences in means is zero for monthly rainfall within Thika River catchment area was done and it was found out that in all the weather stations used, the computed value is greater than the significance level α=0.05, one cannot reject the null hypothesis H_o (Table 11).

Table 11: Results for test of significance for maximum and minimum temperatures using Mann-Kendal trend at Thika Agro Met.

Station	t_{cal}	t_{cr}	**Comments**
Karamaini Thika	-11.025	2.003	H_o**not rejected**
Gethumbwini Coffee Estate	-9.442	2.003	H_o**not rejected**
Thika Agro Met	-17.593	2.003	H_o**not rejected**

5.4.3 Historical Maximum and Minimum Temperature Trends Characteristics

This subsection discusses results for analysis of historical trends of temperature in Thika River sub catchment from annual, seasonal and long term monthly trends and finally tests of significance of long term mean and test trends by use of student t-test at $\propto=0.05$ level of significance.

Annual time series plot and standardized anomalies of annual averages for both maximum and minimum temperature shows an increasing trend (Figures 34-37). From the results of annual time series, it was found out that the highest temperatures of $27.4^{o}C$ were recorded in the year 2001 which was also found out that it was a La Niña Year while the lowest maximum temperatures of $24^{o}C$ were recorded in 1984. The lowest minimum temperatures of $13^{o}C$ were recorded in 1994 and highest temperatures were recorded in the year 2001 (Figure 36).

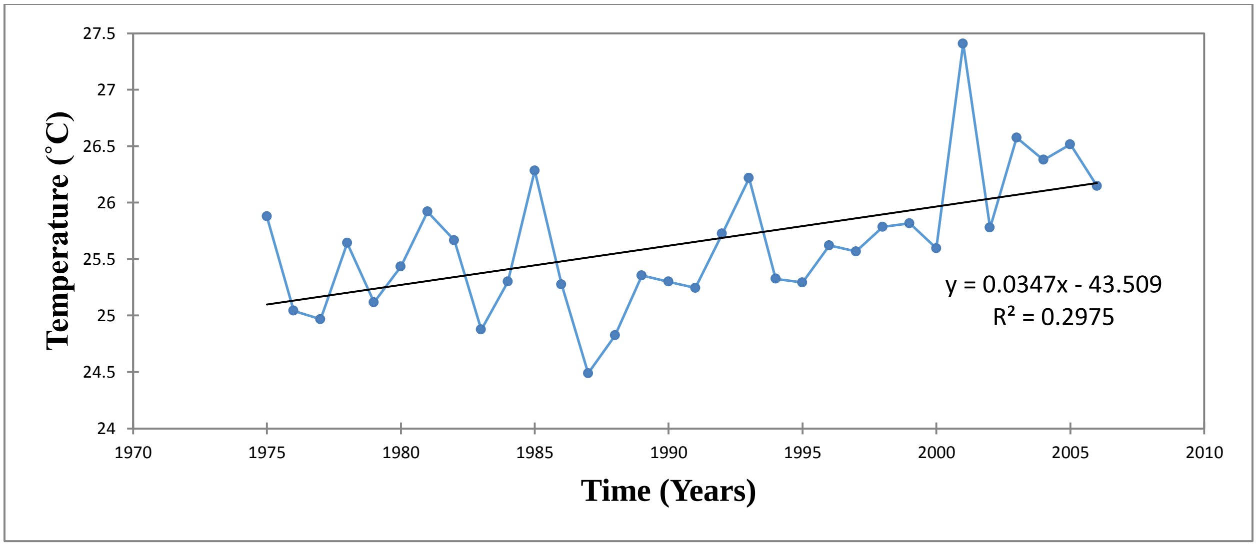


Figure 34: Observed annual Maximum temperature trend at Thika Agro Met

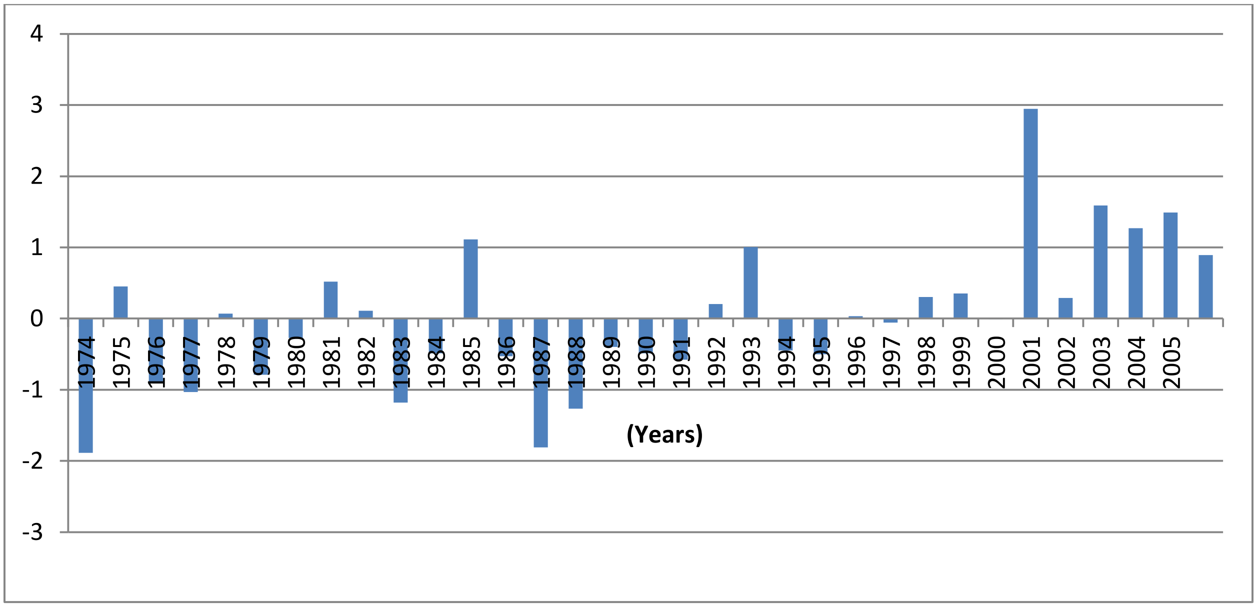


Figure 35: Maximum temperature standardized anomalies at Thika Agro Met station

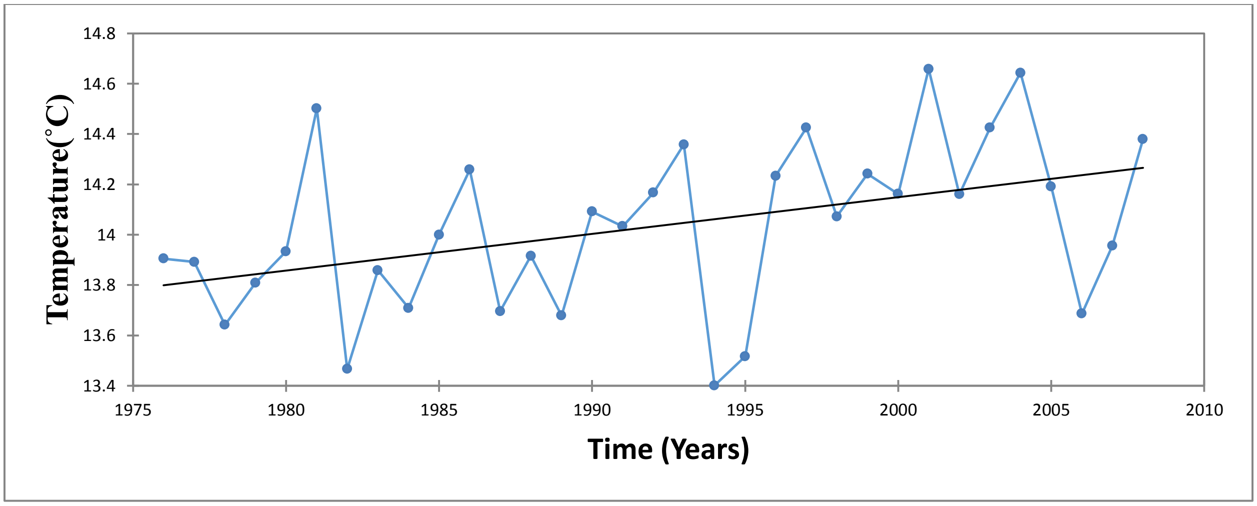


Figure 36: Observed annual Minimum temperature trends at Thika Agro Met

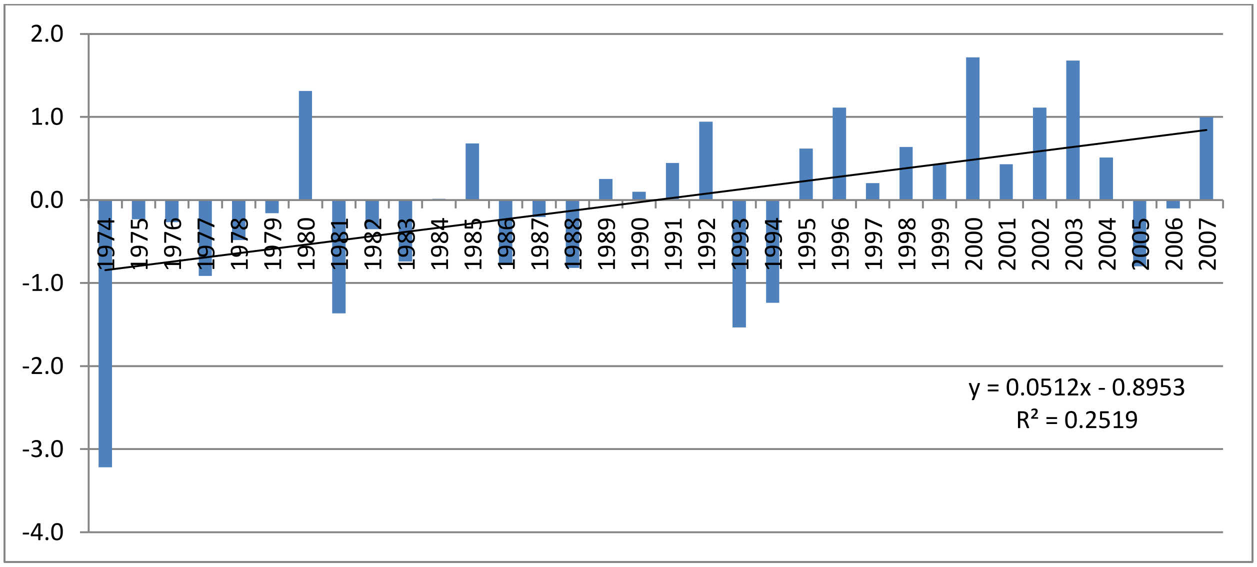
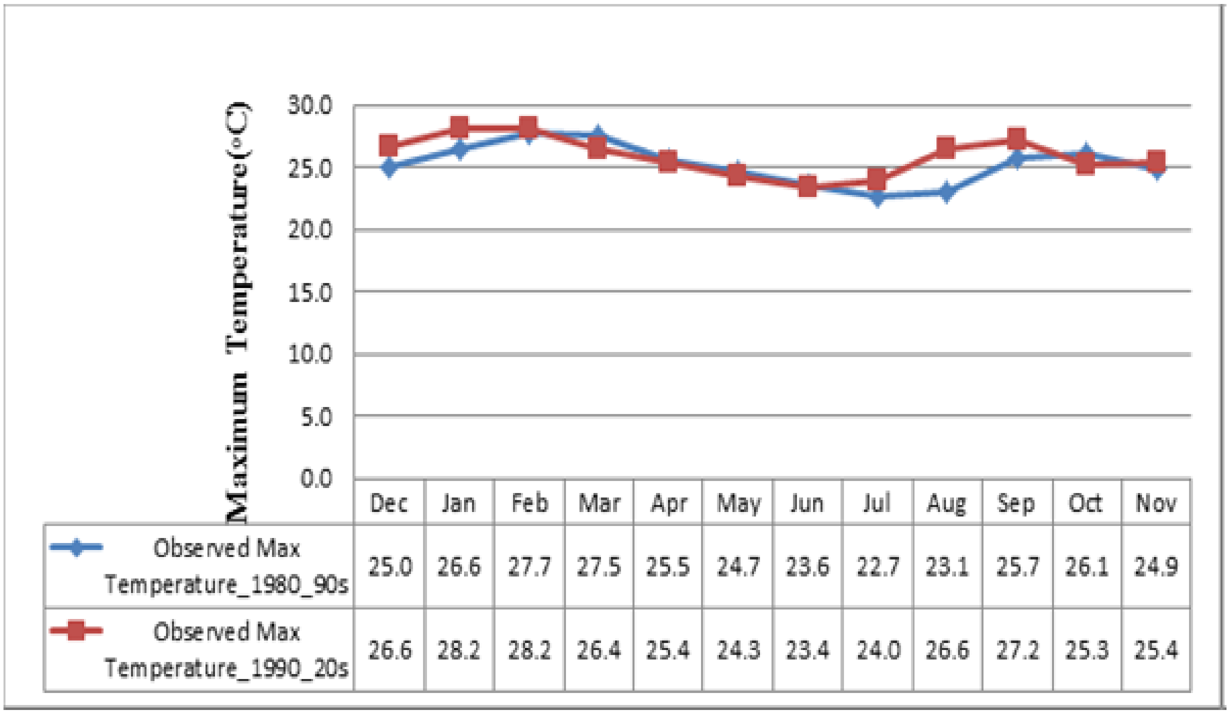


Figure 37: Minimum temperatures standardized anomalies at Thika Agro Met station

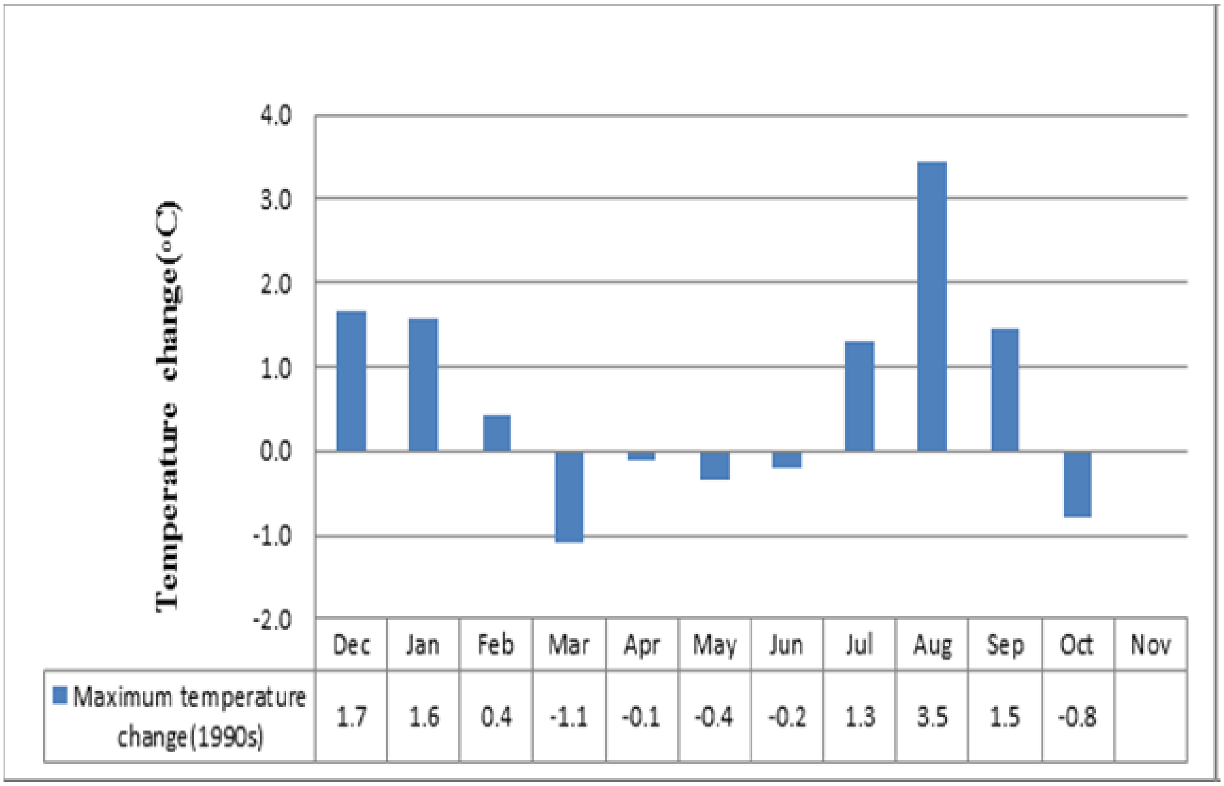
Results of monthly and seasonal variations of temperature showed that there was general increase in average maximum and minimum temperatures in 1990s as compared to observed monthly temperatures in 1980s (Figures 38 and 41).

A comparison of monthly changes in maximum temperature in 1980s and 1990s showed that the months of July, August, September, December, January and February were becoming warmer with temperature range of $0.4^{o}C$in February and $3.5^{o}C$ in September. On the other hand the months of April, May, June, July and October were found out to have had a decrease in monthly temperatures with the month of March recording the largest change in temperature of $1.1^{o}C$ and April the lowest range of $0.4^{o}C$ (Figure 39). Likewise for minimum temperature all the months except February, March and July recorded an increase ranging from $0.2^{o}C$ in August and $0.6^{o}C$ in November. The months of February, March and July recorded a negative trends of temperature ranging from -0.1 in February and July to -0.4 in March (Figure 39).



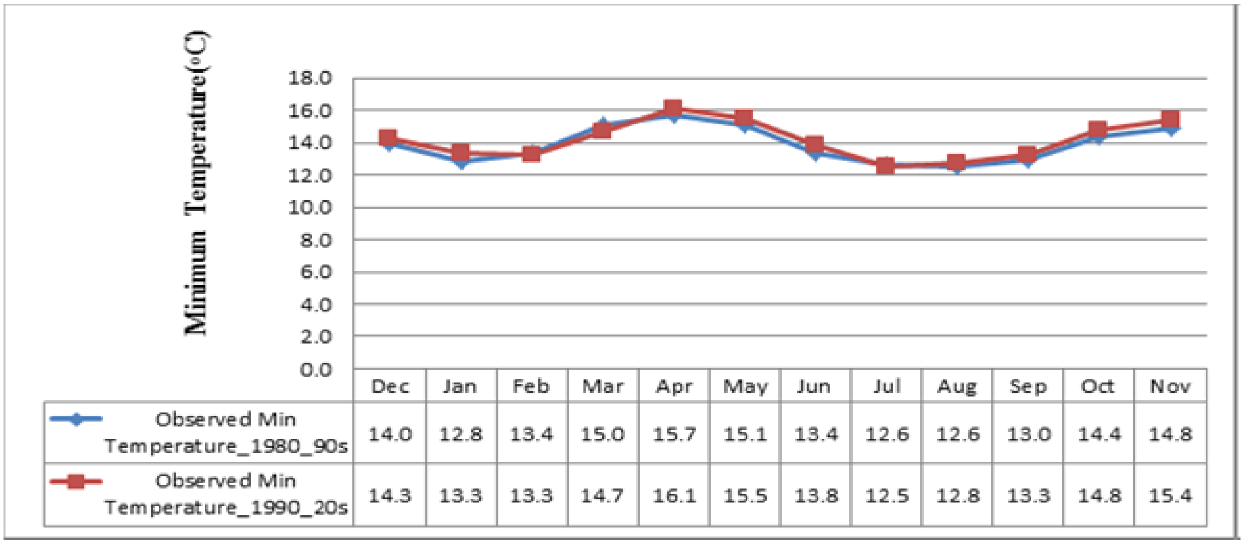
	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Observed Max Temperature_1980_90s	25.0	26.6	27.7	27.5	25.5	24.7	23.6	22.7	23.1	25.7	26.1	24.9
Observed Max Temperature_1990_20s	26.6	28.2	28.2	26.4	25.4	24.3	23.4	24.0	26.6	27.2	25.3	25.4

Figure 38: Annual cycle of minimum temperatures at Thika Agro Met station in 1980s and 1990s



	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
■ Maximum temperature change(1990s)	1.7	1.6	0.4	-1.1	-0.1	-0.4	-0.2	1.3	3.5	1.5	-0.8	

Figure 39: Observed change in Maximum temperature at Thika Agro Met in 1990s relative to base period (1980s)



	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
◆ Observed Min Temperature_1980_90s	14.0	12.8	13.4	15.0	15.7	15.1	13.4	12.6	12.6	13.0	14.4	14.8
■ Observed Min Temperature_1990_20s	14.3	13.3	13.3	14.7	16.1	15.5	13.8	12.5	12.8	13.3	14.8	15.4

Figure 40: Observed monthly minimum temperature climatology of 1980s, and 1990s, at Thika Agro Met

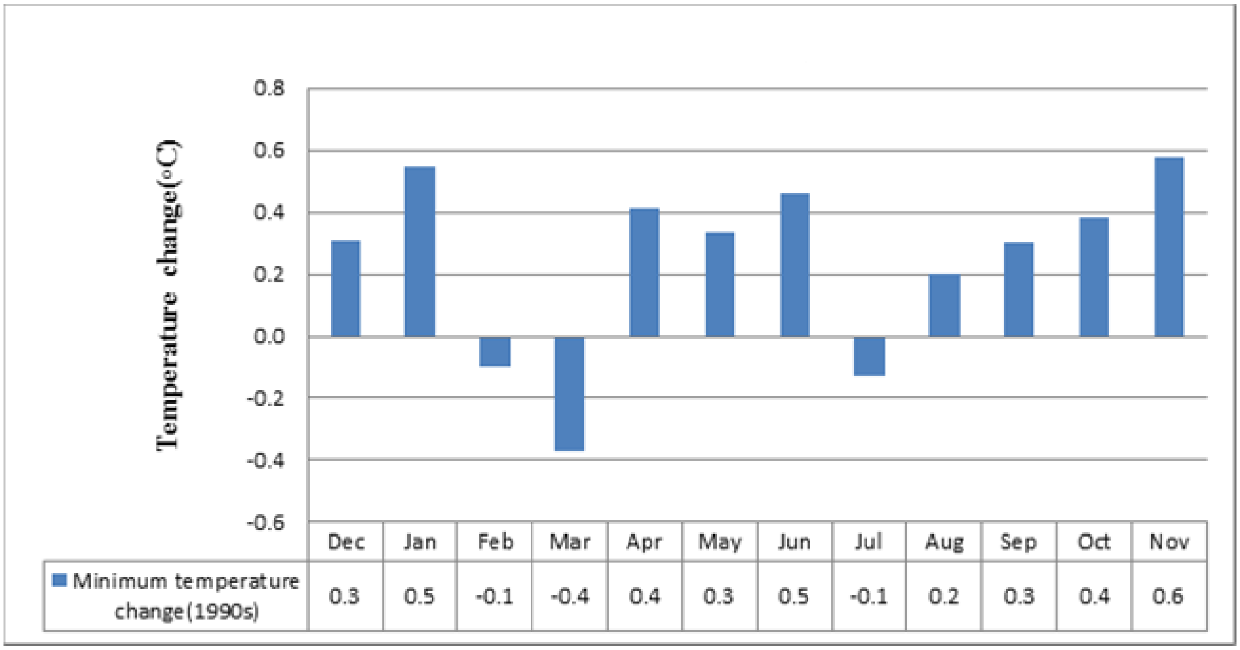


Figure 41: Observed change in Minimum temperature at Thika Agro Met in 1990s relative to base period (1980s).

Trends in maximum and minimum temperatures at Thika Agro Met were tested for significance against the hypothesis that they are not significantly different from zero $H_o: b_1 = 0$by use of Mann-Kendall statistic at α=0.05 level of significance. The results show that the computed p-value was lower than the significance level α=0.05 in for both maximum and minimum temperatures in the area of study and since the trend in temperatures is statistically significant, null hypothesis $H_o$was rejected and alternative hypothesis H_a accepted (Table 12).

Table 12: Results for test of significance for maximum and minimum temperatures using Mann-Kendal trend at Thika Agro Met.

Parameter	**Kendall's tau**	**p-value**	**$\propto$ (alpha)**	**Comments**
Max. Temperature	0.381	0.002	0.05	H_o rejected
Min. Temperature	0.317	0.01	0.05	H_o rejected

5.4.4 Projected Rainfall Trends (2021-2050) and (2061-2090)

This subsection discusses and presents results for rainfall characteristics for two climate periods 2021-2050 and 2061-2090 under emission scenarios of Representative Concentration Pathways (RCPs) RCP 4.5 and RCP 8.5 in relation to rainfall characteristics of historical climate period of 1960-1990 for Thika Agro Met, Gethumbwini Coffee Estate and Karamaini Thika meteorological stations.

From the results of analysis of standardized rainfall anomalies for climate period of 2021-2050 a general decrease in rainfall in all the stations under the emission scenarios of RCP 4.5 and RCP 8.5 was found out within the catchment (Figure 42, 44 and 46). However, a wet decade in early 2020s is expected in all stations with the highest anomaly of +1.5 at Thika Agro Met station under the RCP 8.5. However, rainfall in Thika Agro Met and Karamaini Thika is expected to decrease under RCP 4.5 with the highest anomaly of -0.8 in the year 2022 in both stations. From late 2020-2040 except years 2032 and 2034 rainfall is expected to have negative anomalies of rainfall in Gethumbwini under all the RCPs. The decade of 2040-2050 in Gethumbwini Coffee Estate is expected to receive more of rainfall in all the years except 2042 and 2048. The highest anomaly is expected in Thika Agro Met towards the end of the climate period 2021-2050 where under RCP 8.5 the catchment area is expected to receive below normal rainfall while under RCP 4.5 the catchment area is expected to receive above normal rainfall.

However, results from standardized rainfall anomalies for projected climate period of 2061-2090 showed an increase in rainfall in all the stations in the catchment area under all the emission scenarios except in Thika Agro Met where rainfall is expected to have a negative trend under RCP 8.5 (Figure 43, 45 and 47).

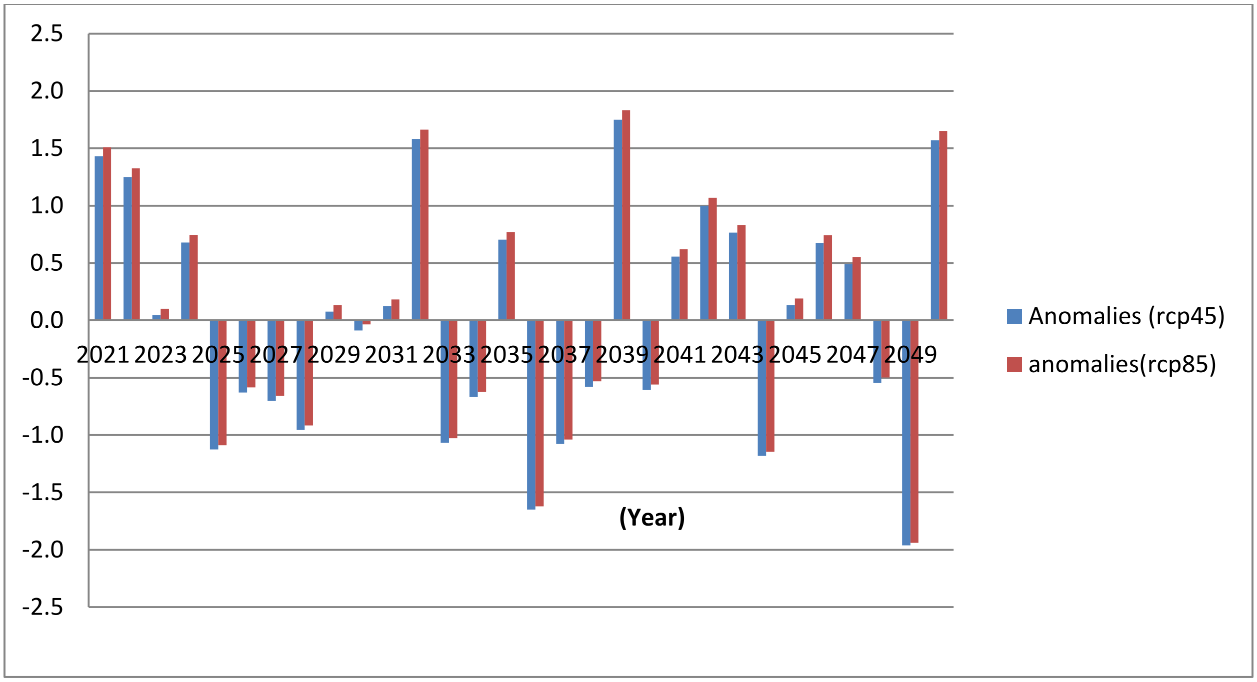


Figure 42: Standardized anomalies of projected rainfall at Gethumbwini Coffee Estate for RCP 4.5 and RCP 8.5 (2021-2050)

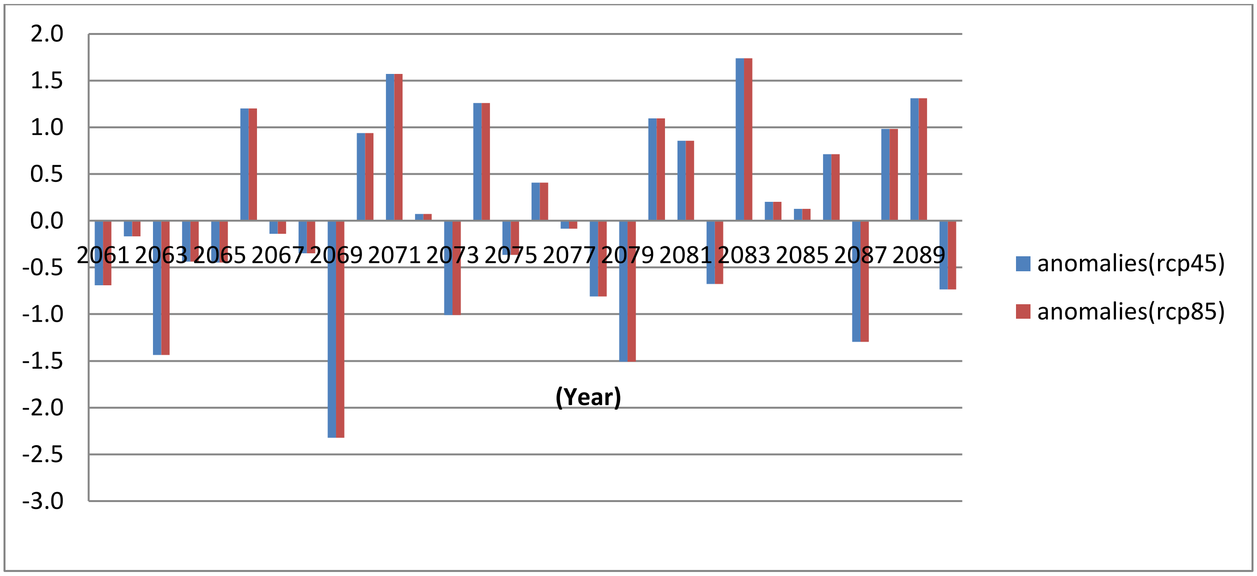


Figure 43: Standardized anomalies of projected rainfall at Gethumbwini Coffee Estate for RCP 4.5 and RCP 8.5 (2061-2090)

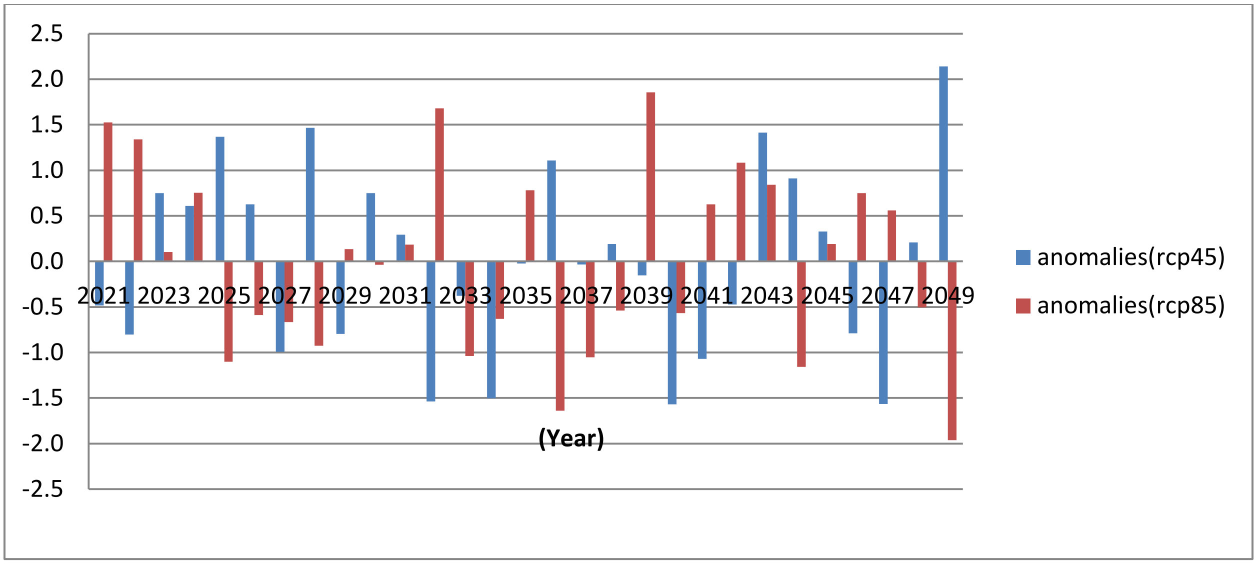


Figure 44: Standardized anomalies of projected rainfall at Thika Agro Met for RCP 4.5 and RCP 8.5 (2021-2050)

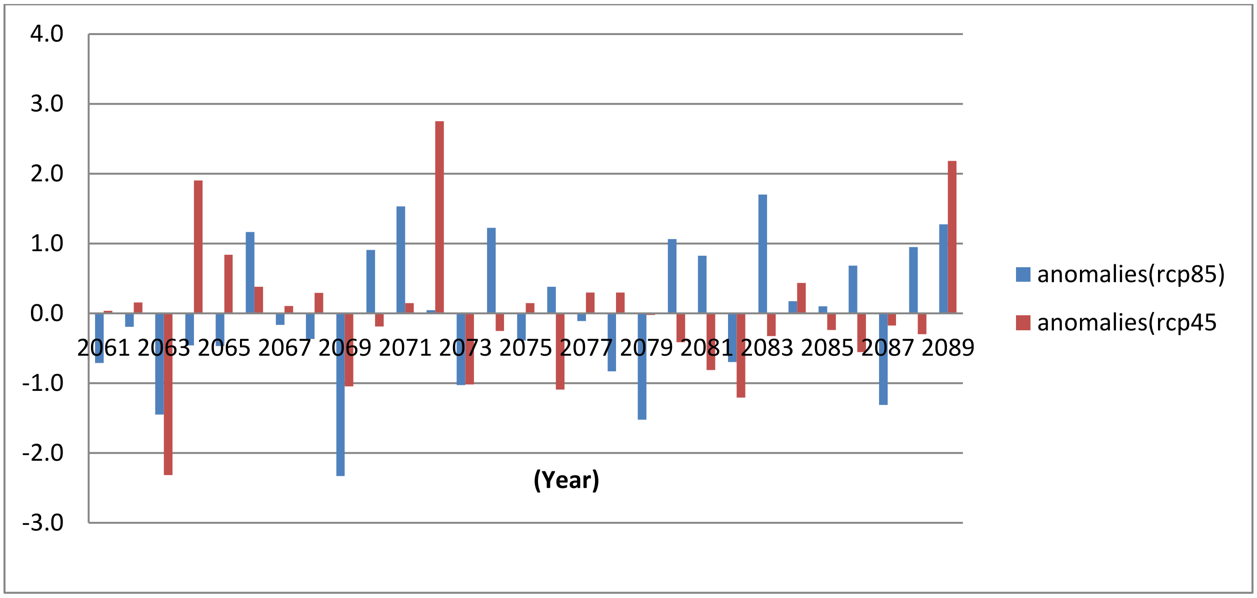


Figure 45: Standardized anomalies of projected rainfall at Thika Agro Met for RCP 4.5 and RCP 8.5 (2061-2090)

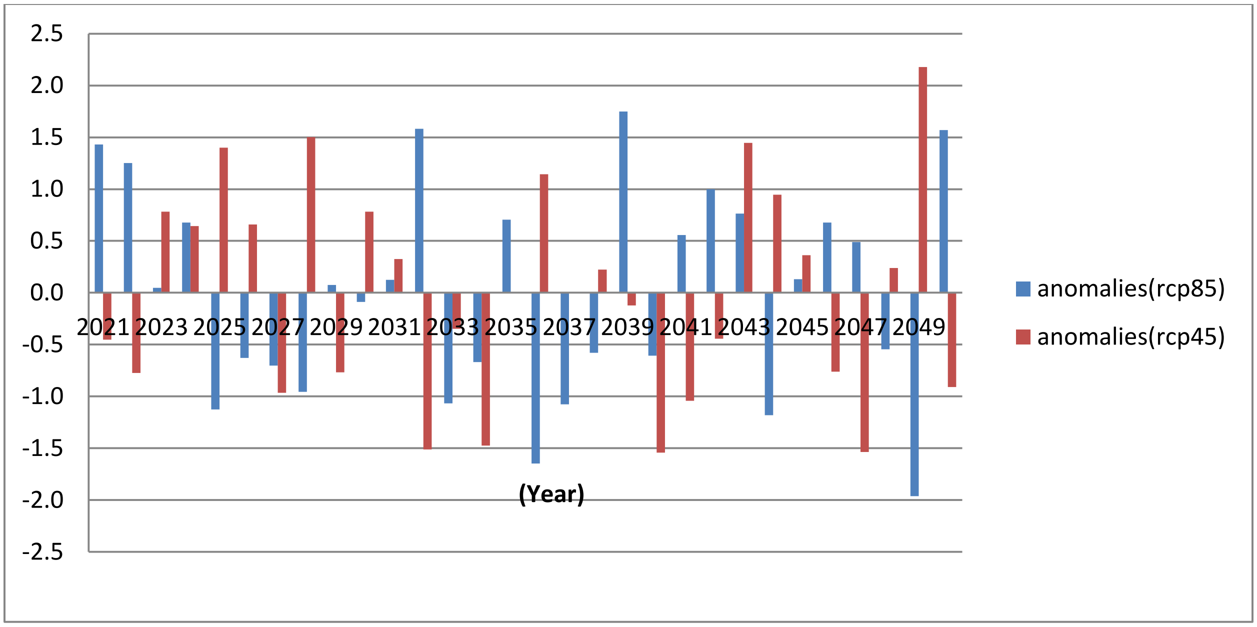


Figure 46: Standardized anomalies of projected rainfall at Karamaini Thika for RCP 4.5 and RCP 8.5 (2021-2050)

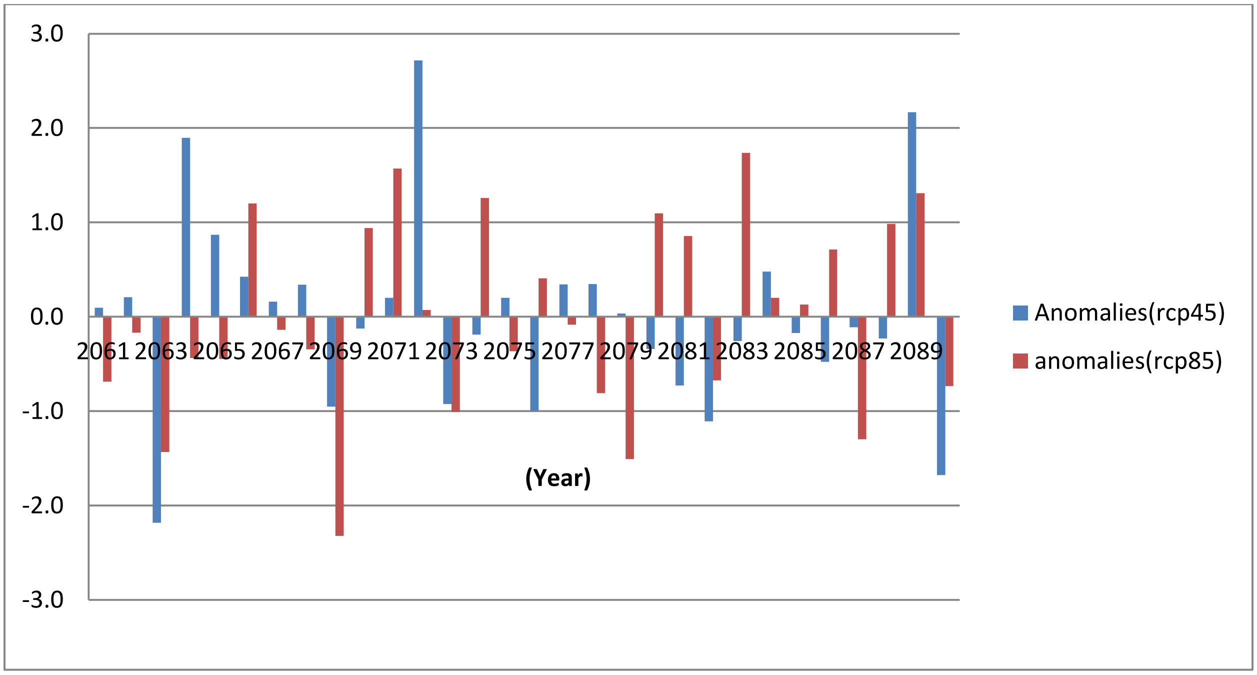
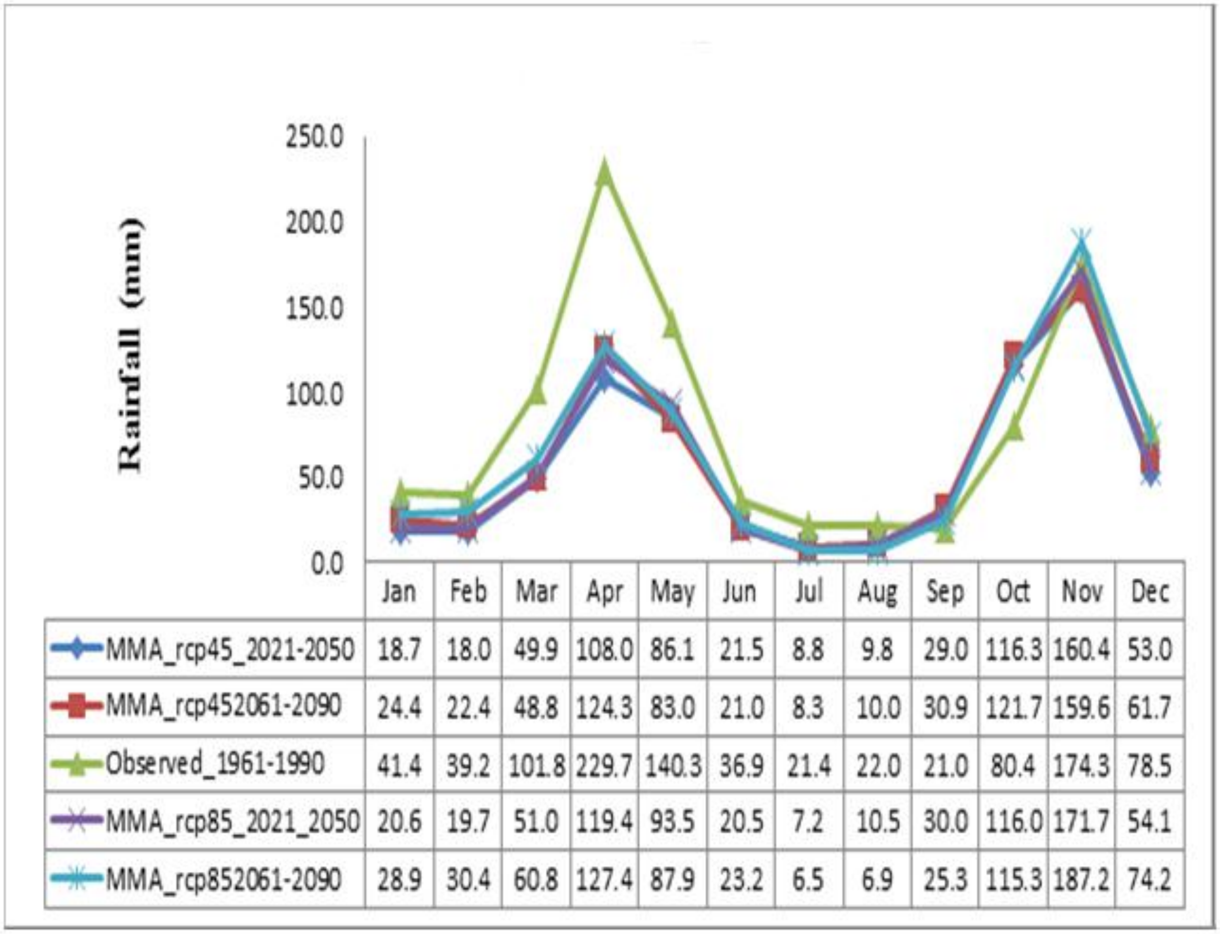


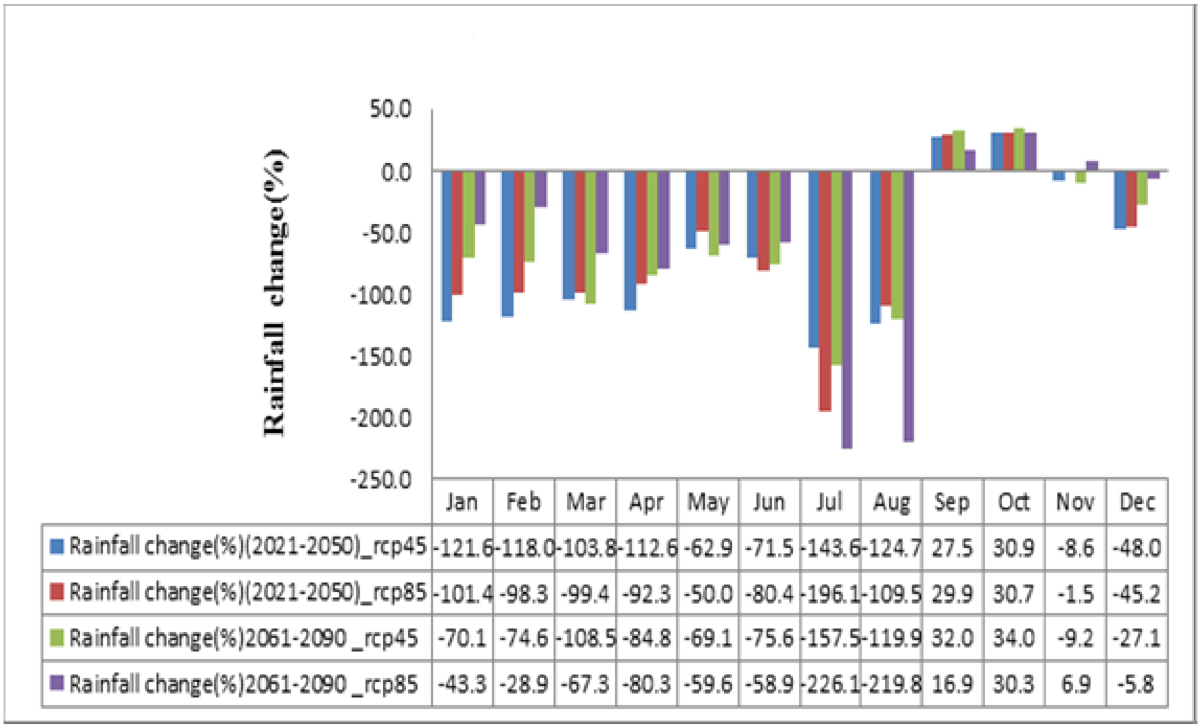
Figure 47: Standardized anomalies of projected rainfall at Karamaini Thika for RCP 4.5 and RCP 8.5 (2061-2090)

Comparison of average monthly rainfall for historical climate of 1961-1990 with projected climate periods of 2021-2050 was made and results showed that all the stations will have a decrease in rainfall in all the months except the months of September and October were rainfall is expected to increase (Figure48, 50 and 52).The results showed a highest decrease of 429% and 416% in the month of March at Gethumbwini Coffee Estate and Thika Agro Met respectively (Figure 51 and Figure 53) under emission scenario of RCP 8.5.



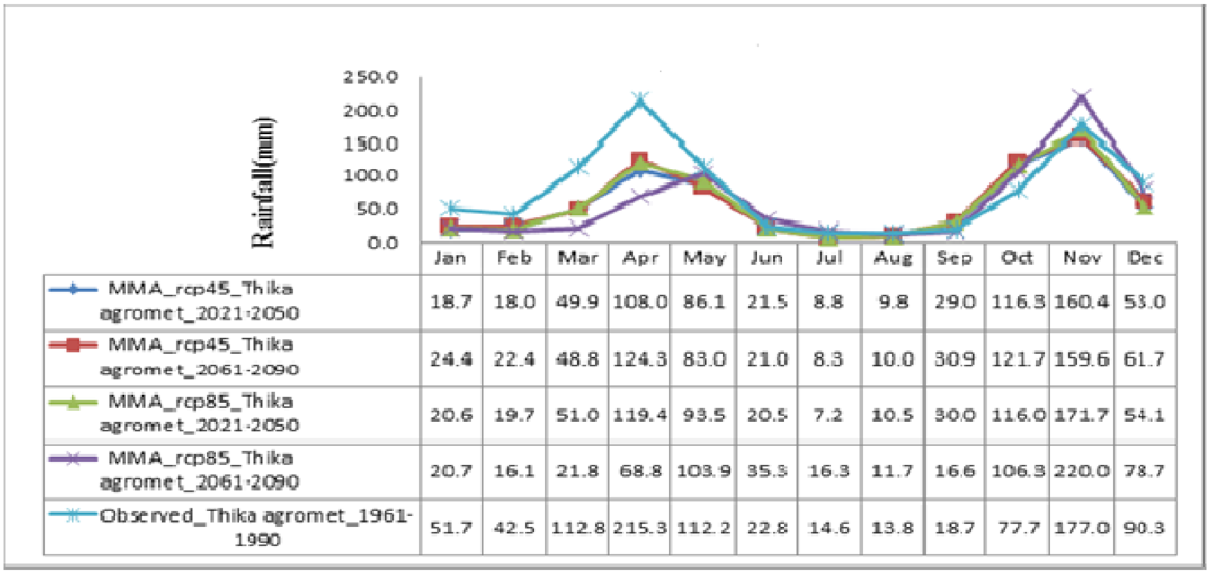
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
MMA_rcp45_2021-2050	18.7	18.0	49.9	108.0	86.1	21.5	8.8	9.8	29.0	116.3	160.4	53.0
MMA_rcp452061-2090	24.4	22.4	48.8	124.3	83.0	21.0	8.3	10.0	30.9	121.7	159.6	61.7
Observed_1961-1990	41.4	39.2	101.8	229.7	140.3	36.9	21.4	22.0	21.0	80.4	174.3	78.5
MMA_rcp85_2021_2050	20.6	19.7	51.0	119.4	93.5	20.5	7.2	10.5	30.0	116.0	171.7	54.1
MMA_rcp852061-2090	28.9	30.4	60.8	127.4	87.9	23.2	6.5	6.9	25.3	115.3	187.2	74.2

Figure 48: Monthly average of historical rainfall in 1961-1990, projected rainfall in 2021-2050 and 2061-2090 under emission scenarios RCP 4.5 and RCP 8.5 at Karamaini Thika.



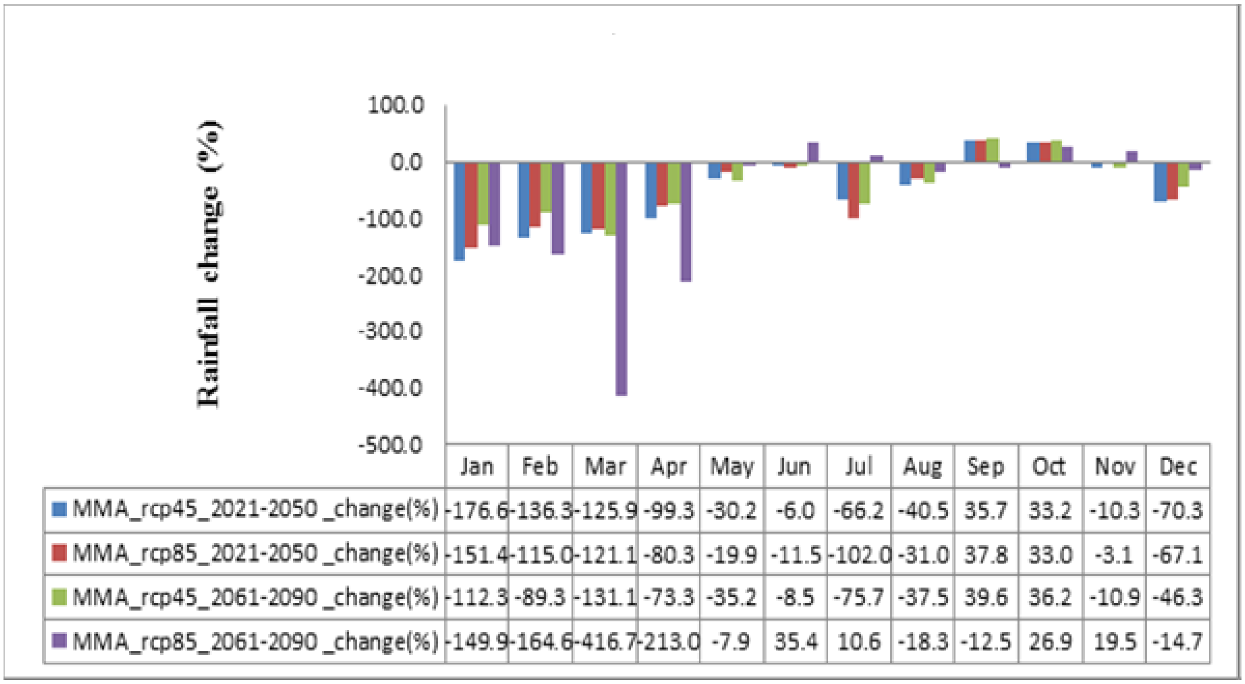
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
🟦 Rainfall change(%)(2021-2050)_rcp45	-121.6	-118.0	-103.8	-112.6	-62.9	-71.5	-143.6	-124.7	27.5	30.9	-8.6	-48.0
🟥 Rainfall change(%)(2021-2050)_rcp85	-101.4	-98.3	-99.4	-92.3	-50.0	-80.4	-196.1	-109.5	29.9	30.7	-1.5	-45.2
🟩 Rainfall change(%)2061-2090 _rcp45	-70.1	-74.6	-108.5	-84.8	-69.1	-75.6	-157.5	-119.9	32.0	34.0	-9.2	-27.1
🟪 Rainfall change(%)2061-2090 _rcp85	-43.3	-28.9	-67.3	-80.3	-59.6	-58.9	-226.1	-219.8	16.9	30.3	6.9	-5.8

Figure 49: Projected rainfall change (%) at Karamaini for 2021-2050 and 2061-2090 relative to base period (1960s) for RCP 4.5 and RCP 8.5



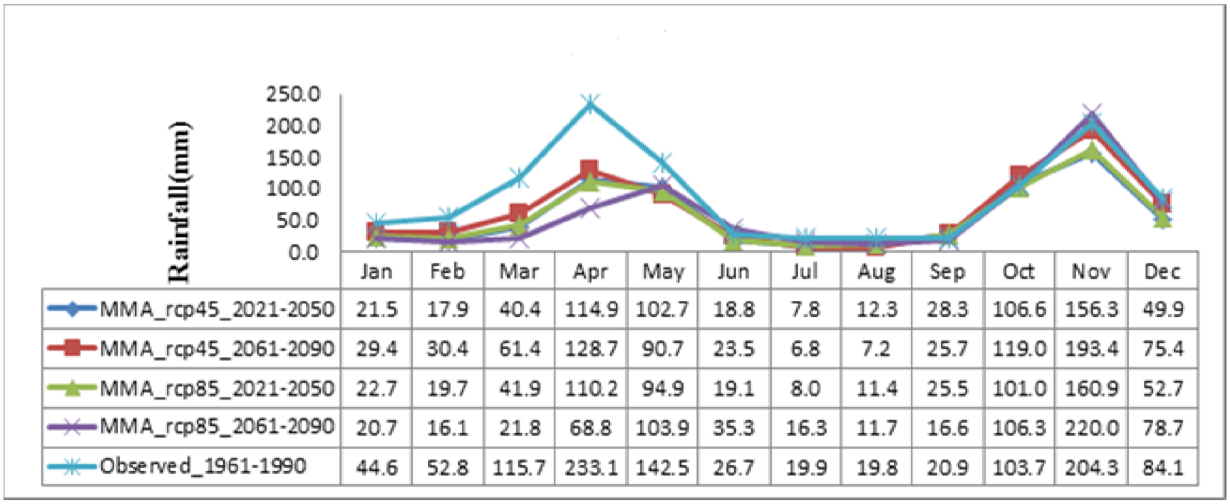
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
MMA_rcp45_Thika agromet_2021-2050	18.7	18.0	49.9	108.0	86.1	21.5	8.8	9.8	29.0	116.3	160.4	53.0
MMA_rcp45_Thika agromet_2061-2090	24.4	22.4	48.8	124.3	83.0	21.0	8.3	10.0	30.9	121.7	159.6	61.7
MMA_rcp85_Thika agromet_2021-2050	20.6	19.7	51.0	119.4	93.5	20.5	7.2	10.5	30.0	116.0	171.7	54.1
MMA_rcp85_Thika agromet_2061-2090	20.7	16.1	21.8	68.8	103.9	35.3	16.3	11.7	16.6	106.3	220.0	78.7
Observed_Thika agromet_1961-1990	51.7	42.5	112.8	215.3	112.2	22.8	14.6	13.8	18.7	77.7	177.0	90.3

Figure 50: Monthly average of historical rainfall in 1961-1990, projected rainfall in 2021-2051 and 2061-2090 under emission scenarios RCP 4.5 and RCP 8.5 at Thika Agro Met



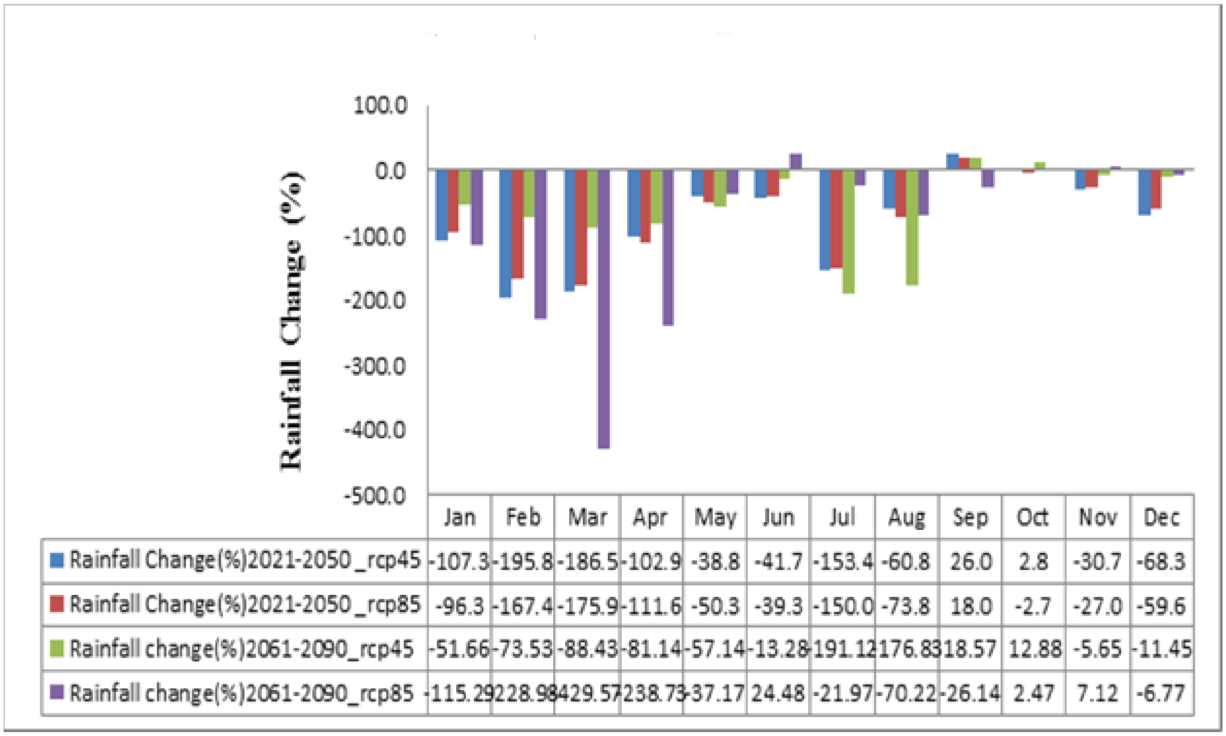
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
🟦 MMA_rcp45_2021-2050 _change(%)	-176.6	-136.3	-125.9	-99.3	-30.2	-6.0	-66.2	-40.5	35.7	33.2	-10.3	-70.3
🟥 MMA_rcp85_2021-2050 _change(%)	-151.4	-115.0	-121.1	-80.3	-19.9	-11.5	-102.0	-31.0	37.8	33.0	-3.1	-67.1
🟩 MMA_rcp45_2061-2090 _change(%)	-112.3	-89.3	-131.1	-73.3	-35.2	-8.5	-75.7	-37.5	39.6	36.2	-10.9	-46.3
🟪 MMA_rcp85_2061-2090 _change(%)	-149.9	-164.6	-416.7	-213.0	-7.9	35.4	10.6	-18.3	-12.5	26.9	19.5	-14.7

Figure 51: Projected rainfall change (%) at Thika Agro Met for 2021-2050 and 2061-2090 relative to base period (1960s) for RCP 4.5 and RCP 8.5



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
MMA_rcp45_2021-2050	21.5	17.9	40.4	114.9	102.7	18.8	7.8	12.3	28.3	106.6	156.3	49.9
MMA_rcp45_2061-2090	29.4	30.4	61.4	128.7	90.7	23.5	6.8	7.2	25.7	119.0	193.4	75.4
MMA_rcp85_2021-2050	22.7	19.7	41.9	110.2	94.9	19.1	8.0	11.4	25.5	101.0	160.9	52.7
MMA_rcp85_2061-2090	20.7	16.1	21.8	68.8	103.9	35.3	16.3	11.7	16.6	106.3	220.0	78.7
Observed_1961-1990	44.6	52.8	115.7	233.1	142.5	26.7	19.9	19.8	20.9	103.7	204.3	84.1

Figure 52: Monthly average of historical rainfall in 1961-1990, projected rainfall in 2021-2051 and 2061-2090 under emission scenarios RCP 4.5 and RCP 8.5 at Gethumbwini Coffee Estate



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
🟦 Rainfall Change(%)2021-2050_rcp45	-107.3	-195.8	-186.5	-102.9	-38.8	-41.7	-153.4	-60.8	26.0	2.8	-30.7	-68.3
🟥 Rainfall Change(%)2021-2050_rcp85	-96.3	-167.4	-175.9	-111.6	-50.3	-39.3	-150.0	-73.8	18.0	-2.7	-27.0	-59.6
🟩 Rainfall change(%)2061-2090_rcp45	-51.66	-73.53	-88.43	-81.14	-57.14	-13.28	191.12	176.83	18.57	12.88	-5.65	-11.45
🟪 Rainfall change(%)2061-2090_rcp85	-115.29	228.98	429.57	238.73	-37.17	24.48	-21.97	-70.22	-26.14	2.47	7.12	-6.77

Figure 53: Projected rainfall change (%) at Gethumbwini Coffee Estate for 2021-2050 and 2061-2090 relative to base period (1960s) for RCP 4.5 and RCP 8.5

Test of significance using student t-test at α=0.05 of differences in means was performed and under the hypothesis that there no difference in means of historical and projected rainfall in both climate periods of 2021-2050 and 2061-2090 under emission RCP 4.5 and RCP 8.5. The results showed that the computed p-value is lower than the significance level α=0.05 in all the stations and therefore null hypothesis H_o was rejected that there is no difference in means hence alternative hypothesis H_a was accepted (Table 13). Therefore it was concluded that the rainfall patterns of the Thika River Catchment will undergo significant changes in future climate under emission scenarios of RCP 4.5 and RCP 8.5 in climate periods of 2021-2050 and 2061-2090 which will increase/decrease water yields in the catchment area.

Table 13: Results for test of significance of change in rainfall using student t-test at in Thika River Catchment

Station Name	**Climate Period**	**RCP**	t_{cr}	t_{cal}	**∝(alpha)**	**Comments**
Karamaini Thika	2021-2050	4.5	2.003	28.021	<0.001	H_o rejected
		8.5	2.003	30.000	<0.001	H_o rejected
	2061-2090	4.5	2.003	24.857	<0.001	H_o rejected
		8.5	2.003	22.226	<0.001	H_o rejected
Gethumbwini Coffee Estate	2021-2051	4.5	2.003	-39.016	<0.001	H_o rejected
		8.5	2.003	40.120	<0.001	H_o rejected
	2061-2090	4.5	2.003	39.016	<0.001	H_o rejected
		8.5	2.003	39.016	<0.001	H_o rejected
Thika Agro Met	2021-2051	4.5	2.003	22.605	<0.001	H_o rejected
		8.5	2.003	25.493	<0.001	H_o rejected
	2061-2090	4.5	2.003	19.798	<0.001	H_o rejected
		8.5	2.003	16.893	<0.001	H_o rejected

5.4.5 Projected Temperature Trend Characteristics 2021-2050 and 2061-2090

This section presents results for projected temperatures for emission scenarios RCP 4.5 and RCP 8.5 from suite of regional climate models output. Annual trend was analyzed by plotting a time series of standardized temperatures from 2020 -2100 and a trend line fitted to examine the trend characteristics. From the results for both the emission scenarios, the period 2020-2057 is expected to be cooler than average as it was found out that both maximum minimum temperatures anomalies are below average. However, climate period 2060-2100 temperature anomalies were found to be positive with the highest anomalies expected to be towards the end of century and therefore temperatures are expected to increase (Figure 54 and 55) which is likely to affect evaporation rates in the study area and therefore affect availability of water resources.

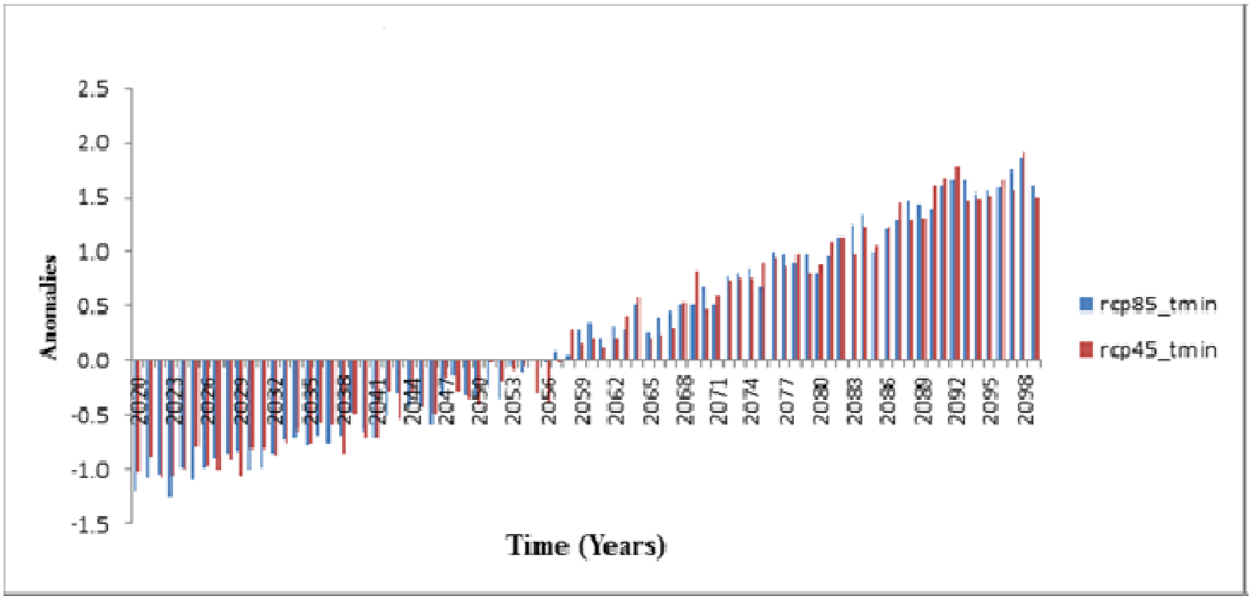


Figure 54: Projected annual average minimum temperature anomalies at Thika Agro Met

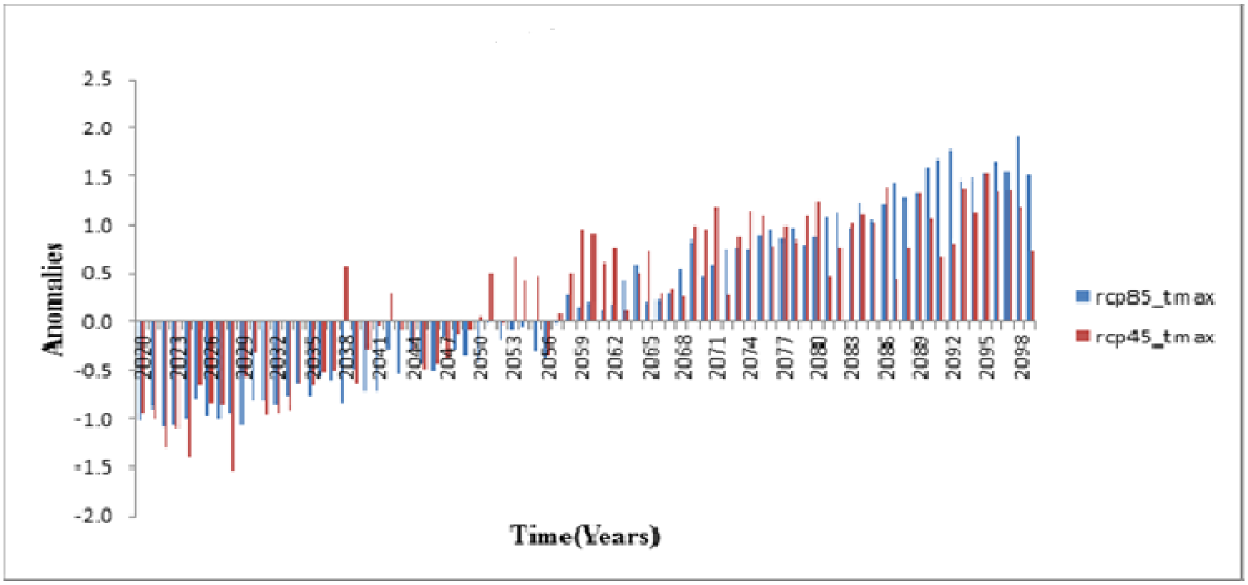


Figure 55: Projected annual average maximum temperature anomalies at Thika Agro Met

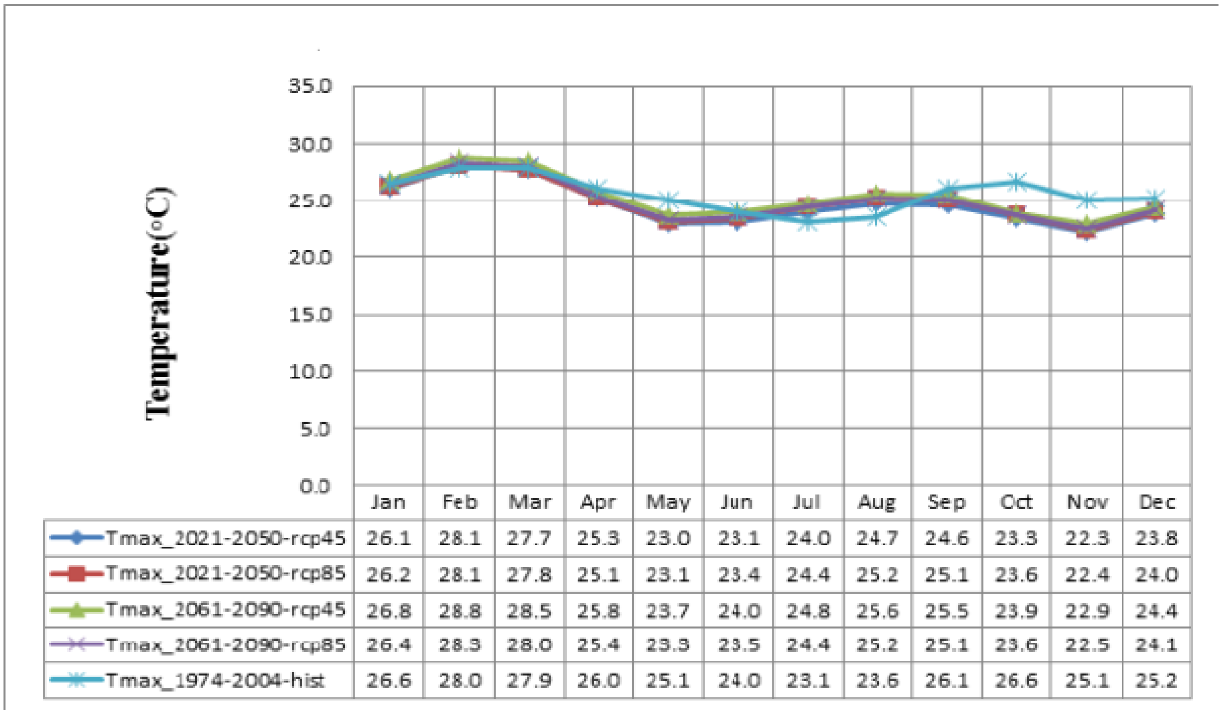
Using Mann-Kendall statistic at α=0.05 under the hypothesis that there is no significant trend in both maximum and minimum temperature, results showed that in all the emission scenarios the p-value was less than the α=0.05 and therefore null hypothesis was rejected and alternative hypothesis accepted that there is trend in the temperature series in Thika River sub catchment up to 2100 (Table 14).

Table 14: Results for Mann-Kendall test of significance of projected maximum and minimum temperature trend (2020-2100)

Parameter	**Kendall's tau**	**p-value**	**$\propto$ (alpha)**	**Comments**
Max. Temperature	0.779	0.002	0.05	H_o rejected
Min. Temperature	0.289	0.003	0.05	H_o rejected

Projected monthly mean averages of temperatures in Thika Agro Met station in the climate periods of historical (1974-2003), projected 2021-2051 and 2061-2090 under emission scenarios of RCP 4.5 and RCP 8.5 is presented in Figure 56 and Figure 57.

From the results of maximum temperatures, it was noted that the months of January, April, May, June, October, November and December is generally projected to be cooler as compared to the baseline period in both climate periods of 2021-2050 and 2061-2090 with cooling ranging from -0.1^0C in the month of March in the climate period 2021-2050 to -3.3^0C in the month of October in the climate period 2021-2050 under emission scenario RCP 4.5. However, the months of February, March, July and August is projected to experience a daytime warming ranging from $+0.1^0C$ in the month of February during the climate period 2021-2050 under RCP 8.5 and $+2.1^0$ in the month of August in future climate period of 2061-2090 under RCP 8.5 (Figure 56 and Figure 57).



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Tmax_2021-2050-rcp45	26.1	28.1	27.7	25.3	23.0	23.1	24.0	24.7	24.6	23.3	22.3	23.8
Tmax_2021-2050-rcp85	26.2	28.1	27.8	25.1	23.1	23.4	24.4	25.2	25.1	23.6	22.4	24.0
Tmax_2061-2090-rcp45	26.8	28.8	28.5	25.8	23.7	24.0	24.8	25.6	25.5	23.9	22.9	24.4
Tmax_2061-2090-rcp85	26.4	28.3	28.0	25.4	23.3	23.5	24.4	25.2	25.1	23.6	22.5	24.1
Tmax_1974-2004-hist	26.6	28.0	27.9	26.0	25.1	24.0	23.1	23.6	26.1	26.6	25.1	25.2

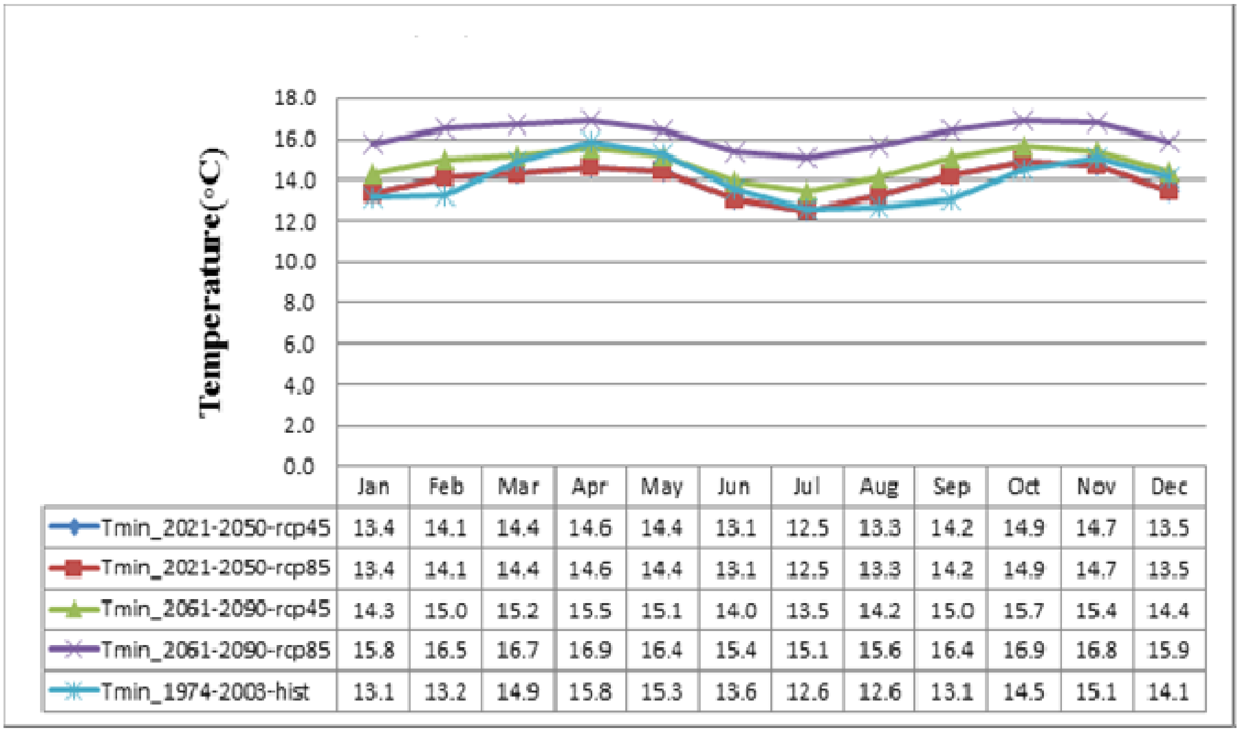
Figure 56: Historical and projected monthly mean maximum temperatures in 2021-2050 and 2061-2090 at Thika Agro Met

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Tmax change_2021-2050-rcp45	-0.5	0.2	-0.1	-0.8	-2.1	-0.9	0.9	1.1	-1.5	-3.3	-2.8	-1.3
Tmax change_2021-2050-rcp85	-0.4	0.1	-0.1	-0.9	-1.9	-0.6	1.3	1.7	-1.0	-3.0	-2.7	-1.2
Tmax change_2061-2090-rcp45	0.2	0.8	0.7	-0.2	-1.3	0.0	1.7	2.1	-0.7	-2.7	-2.1	-0.7
Tmax change_2061-2090-rcp85	-0.2	0.4	0.1	-0.6	-1.8	-0.5	1.3	1.6	-1.1	-3.0	-2.6	-1.1

Figure 57: Change in maximum temperature in 2021-2050 and 2061-2090 relative to baseline period 1974-2004 in Thika Agro Met

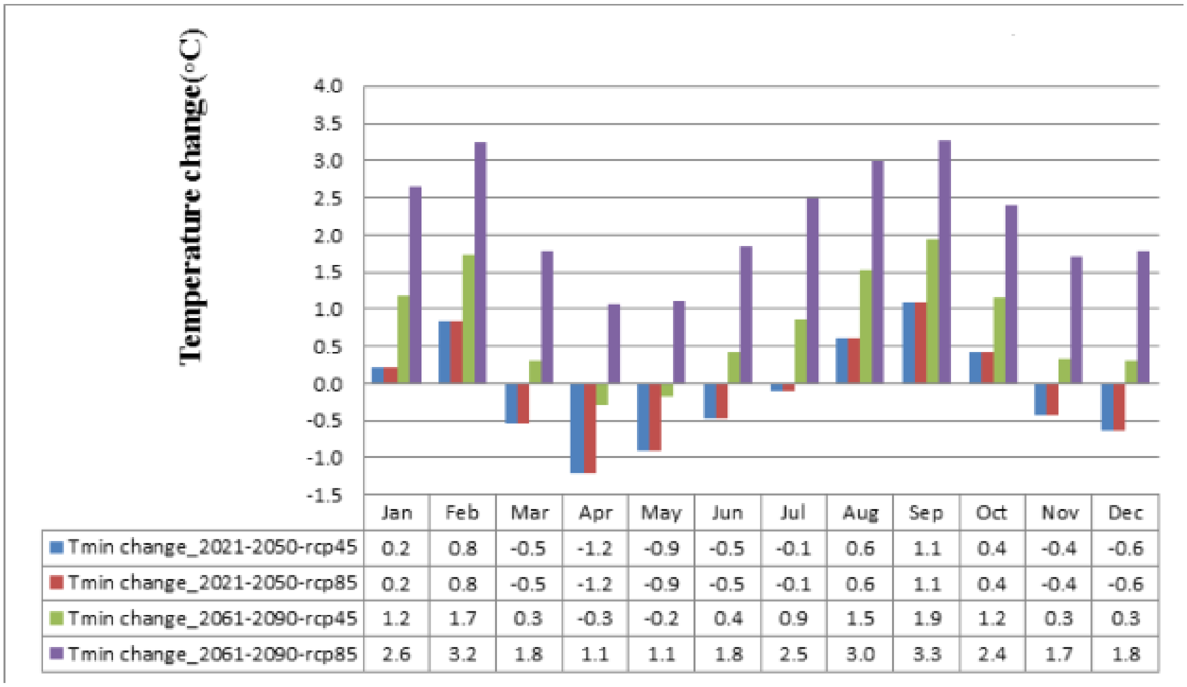
Figure 57 and Figure 58 shows projected minimum temperature and change in minimum temperature relative to the baseline period (1974-2004) respectively. From the results of minimum temperature projections it was noted the climate period of 2061-2090 is projected to increase under all the emission scenarios of RCP 4.5 and RCP 8.5 with the highest increase being under RCP 8.5. However during the same climate period, minimum temperatures are expected to fall during the months of April (0.3^{0}C) and May (0.2^0C) under emission scenario of RCP 8.5.

During the climate period of 2021-2050 minimum temperatures is expected to increase in the months of January, February, August, September and October in all the emission scenarios with the increase ranging from 0.1^0C in January to 1.1^0C in September. However, the months of March, April, May, June, July, November and December is projected to have a decrease in minimum temperatures in all the emission scenarios with the decrease ranging from 0.1^0C in July and 1.2^0C in April (Figure 59).



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Tmin_2021-2050-rcp45	13.4	14.1	14.4	14.6	14.4	13.1	12.5	13.3	14.2	14.9	14.7	13.5
Tmin_2021-2050-rcp85	13.4	14.1	14.4	14.6	14.4	13.1	12.5	13.3	14.2	14.9	14.7	13.5
Tmin_2061-2090-rcp45	14.3	15.0	15.2	15.5	15.1	14.0	13.5	14.2	15.0	15.7	15.4	14.4
Tmin_2061-2090-rcp85	15.8	16.5	16.7	16.9	16.4	15.4	15.1	15.6	16.4	16.9	16.8	15.9
Tmin_1974-2003-hist	13.1	13.2	14.9	15.8	15.3	13.6	12.6	12.6	13.1	14.5	15.1	14.1

Figure 58: Historical and projected mean monthly minimum temperatures in 2021-2050 and 2061-2090 at Thika Agromet.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Tmin change_2021-2050-rcp45	0.2	0.8	-0.5	-1.2	-0.9	-0.5	-0.1	0.6	1.1	0.4	-0.4	-0.6
Tmin change_2021-2050-rcp85	0.2	0.8	-0.5	-1.2	-0.9	-0.5	-0.1	0.6	1.1	0.4	-0.4	-0.6
Tmin change_2061-2090-rcp45	1.2	1.7	0.3	-0.3	-0.2	0.4	0.9	1.5	1.9	1.2	0.3	0.3
Tmin change_2061-2090-rcp85	2.6	3.2	1.8	1.1	1.1	1.8	2.5	3.0	3.3	2.4	1.7	1.8

Figure 59: Historical and projected mean monthly minimum temperatures in 2021-2050 and 2061-2090 at Thika Agromet.

Results of test of significance using student t-test at α=0.05 level of significance, shows that the change in mean in temperature is significant in the period 2021-2050. Since the t-computed t_{cal} was greater than the t-critical t_{cr} (2.003) null hypothesis that the differences in mean are zero was rejected and alternative hypothesis that the difference in means is different from zero was accepted. However this was not the case when hypothesis testing by use of student *t* test for minimum temperature emission scenario RCP 4.5for climate period of 2021-2050 as compared to the baseline period of 1974-2003 were the t-calculated t_{cal} was found to be less than the t-critical value t_{cr} (2.003) and therefore null hypothesis was failed to be rejected and therefore no significant change in minimum temperature in the climate period 2021-2050 under the emission scenario RCP 4.5.

Finally from the analysis of both maximum and minimum temperatures in the two projected climate periods, it can be concluded that there is a seasonal shift of warm period in July and August and cooler months in April, to, June and September, to December which could have an influence of water resources in Thika River Catchment.

5.5: Historical Trends in River Discharge in Thika River Catchment

This section presents results for the analysis of historical trends of river runoff from data obtained from RGSs in the study area to achieve the second objective of the study. Results from standardized anomalies plotted against time showed that all the RGSs stations had a negative trend. However, standardized anomalies of discharge at 4CC07-Thika RGS showed a general positive trend in discharge.

Analysis of ten year period trend of discharge anomalies indicated that most stations had positive anomalies in the years 1960-1969 with the highest anomaly of +2.0 in 1968 at RGS 4CB04-Thika (Figure 60).However, negative trend anomalies were 1960, 1961, 1969 in all the gauging stations with the highest anomaly of -1.3 recorded in station 4CB07-Thika in the year 1960 (Figure 60).

Analysis of Stream flow anomalies in 1970s showed that most of the stations recorded above normal discharge in the years 1977, 1978 and 1979 with the highest anomaly of +2.1 at 4CB07-Thika in 1977. However, below normal discharge were recorded most of the years in 1970s recorded a negative anomalies of discharge with the highest anomaly of -1.6 in 1976 at 4CA02-Chania. Positive anomalies of discharge were noted in the years, 1981, 1982 and 1989 (4CA02-Chania), 1980, 1981, 1984 and 1988 and 1989 (4CB04-Thika), and 1980, 1981, 1982, 1983 and 1984 (4CB07-Thika) in most of the RGSs with the highest anomaly of +1.2 at 4CB07 in 1980. Negative anomalies of discharge were noted in the years 1983, 1984, 1985, 1986, 1987 and 1988 (4CA02-Chania), 1982, 1984, 1985, 1986, and 1987 (4CB04), and from 1985-1989 both 4CB07-Thika and 4CC07-Thika recorded negative anomalies of discharge.

Analysis of anomalies in 1990s positive anomalies were noted in 1990, 1994, 1995, 1997 and 1998 (4CA02-Chania), 1990, 1991, 1995, 1996 and 1998 (4CB07-Thika), 1992, 1994, 1996 and 1998 (4CC07-Thika) and 1998(4CB04-Thika). All the stations used in the study showed that 1998 had the highest positive anomaly and it was also found out that this is an El Nino year.

Finally analysis for anomalies in 2000s at 4CC07-Thika showed a positive anomaly in 2008-2012 which showed that there was an increase in discharge.

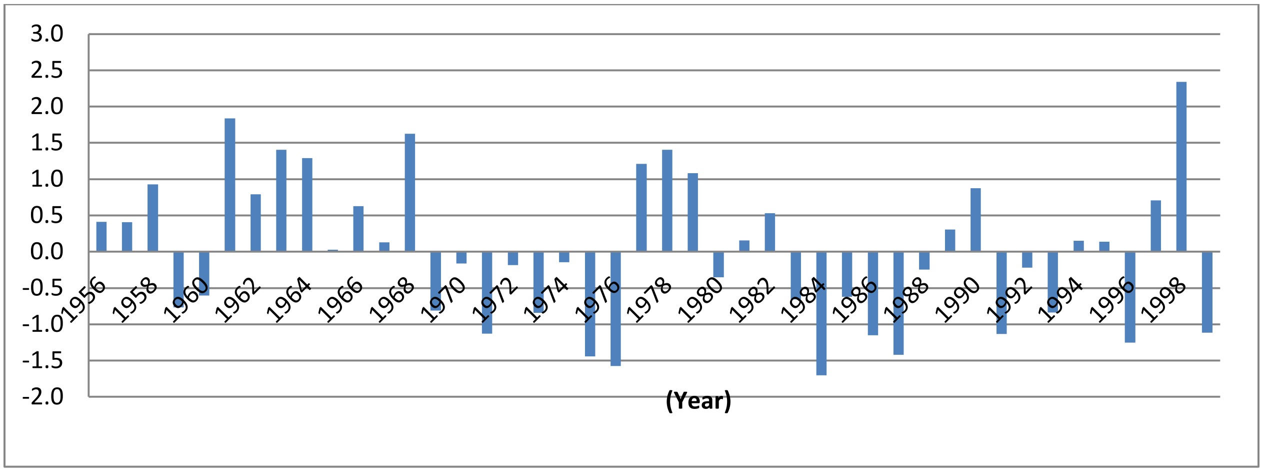


Figure 60: Observed discharge anomalies at 4CA02-Chania

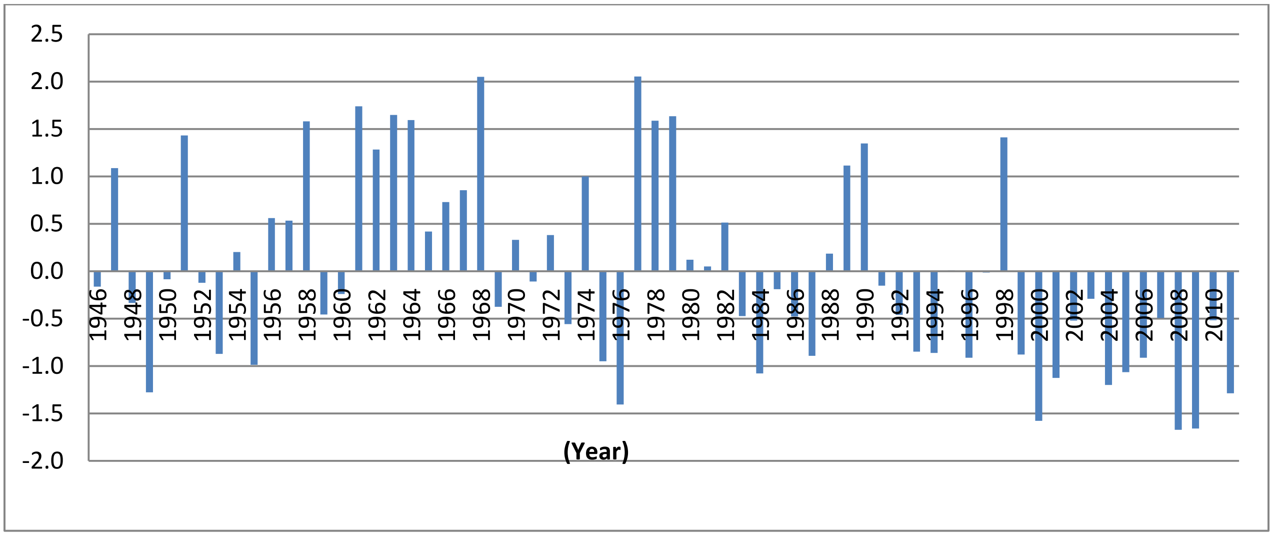


Figure 61: Observed discharge anomalies at 4CB04-Thika

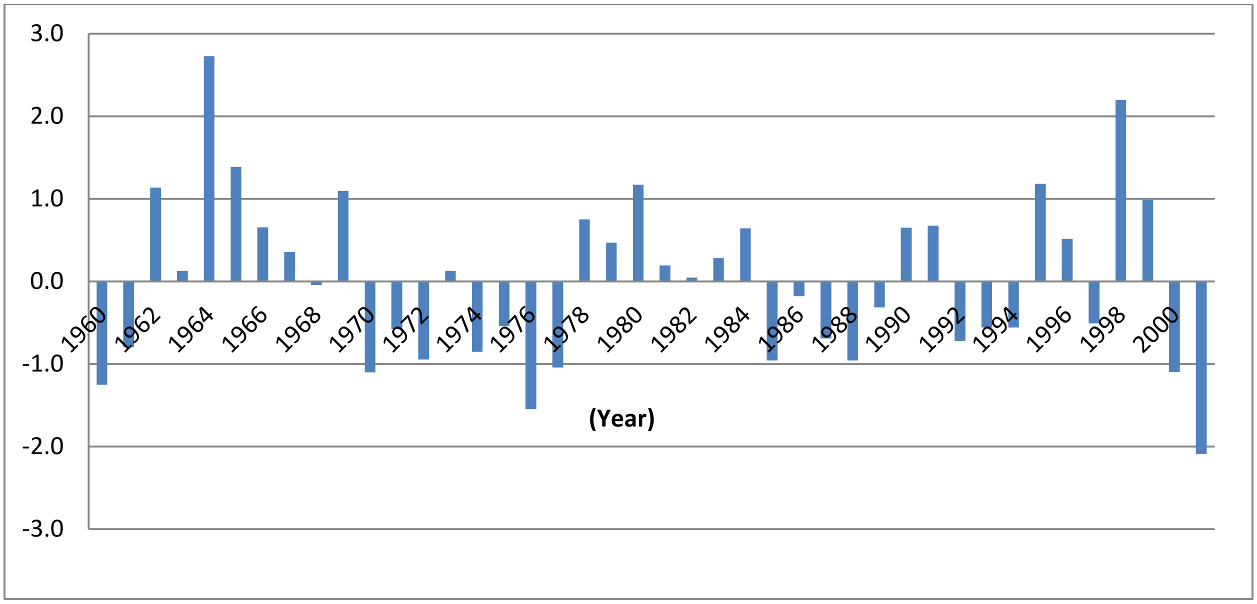


Figure 62: Observed discharge anomalies at 4CB07-Thika

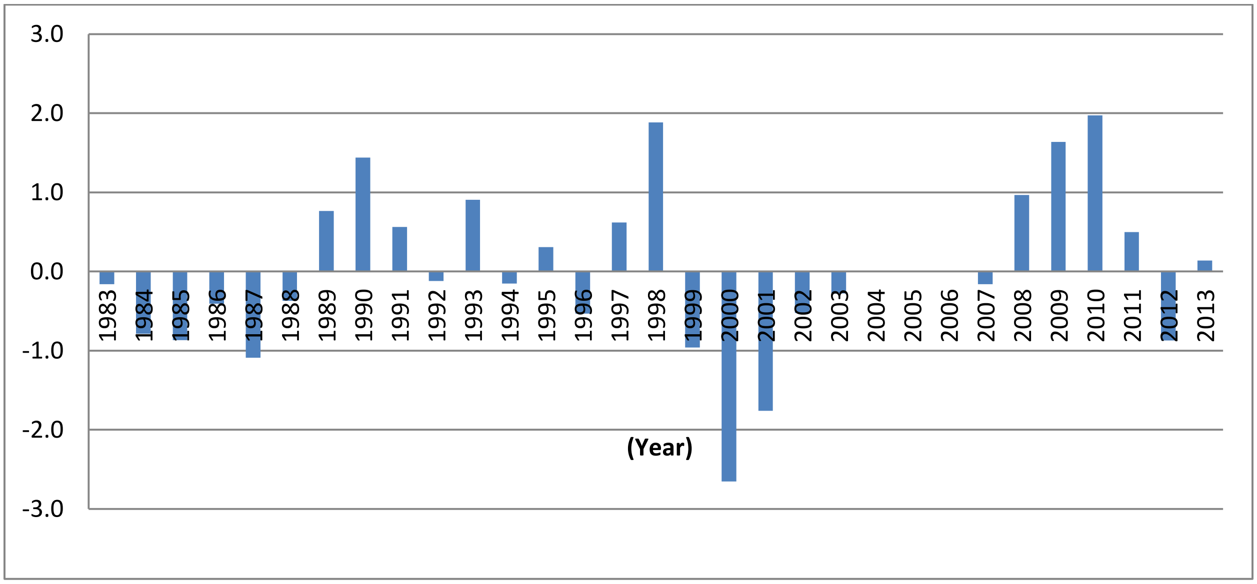


Figure 63: Observed discharge anomalies at 4CC07-Thika

Table 15 shows results for test of significance in trend using Mann-Kendal statistic at α=0.05 level of significance against null hypothesis (H_0) that there is no significant trend in discharge and alternative hypothesis that there is trend in the discharge. Results shows that although there is a negative trend in anomalies of discharge in discharge, it was not significant all the stations except 4CB07-Thika which had a significant trend.

Table 155: Results for Mann-Kendall test of significance of projected maximum and minimum temperature trend (2020-2100)

	4CB04-Thika	4CBO7-Thika	4CA02-Chania	4CC07-Thika
Kendal’s tau	-0.325	-0.115	-0.178	0.18
S	-676	0.90	-161	78
Var(S)	31200	0	0	3138
p-value (two-tailed)	0.00	0.32	0.94	0.16
Alpha(α)	0.05	0.05	0.05	0.05
Remarks	Significant	Significant	Significant	Significant

5.6: Thika River Catchment Delineation

Using Arc SWAT, Thika River Catchment was delineated using Digital Elevation Model data and topographic report generated. From a total area of 63,253 hectares, 11 sub basins were generated by taking an outlet at the South eastern part of the catchment. From the 11 sub basins 49 hydrological Response Units were further generated depending on distinct soil, land and slope types. Figure 64 shows the delineated Catchment of Thika River and Table 16 shows the topographical report of the Catchment. From the topographic report, also found out that the elevation of the catchment ranges between 1320m -2522m and the mean elevation was found out to be 1585m.

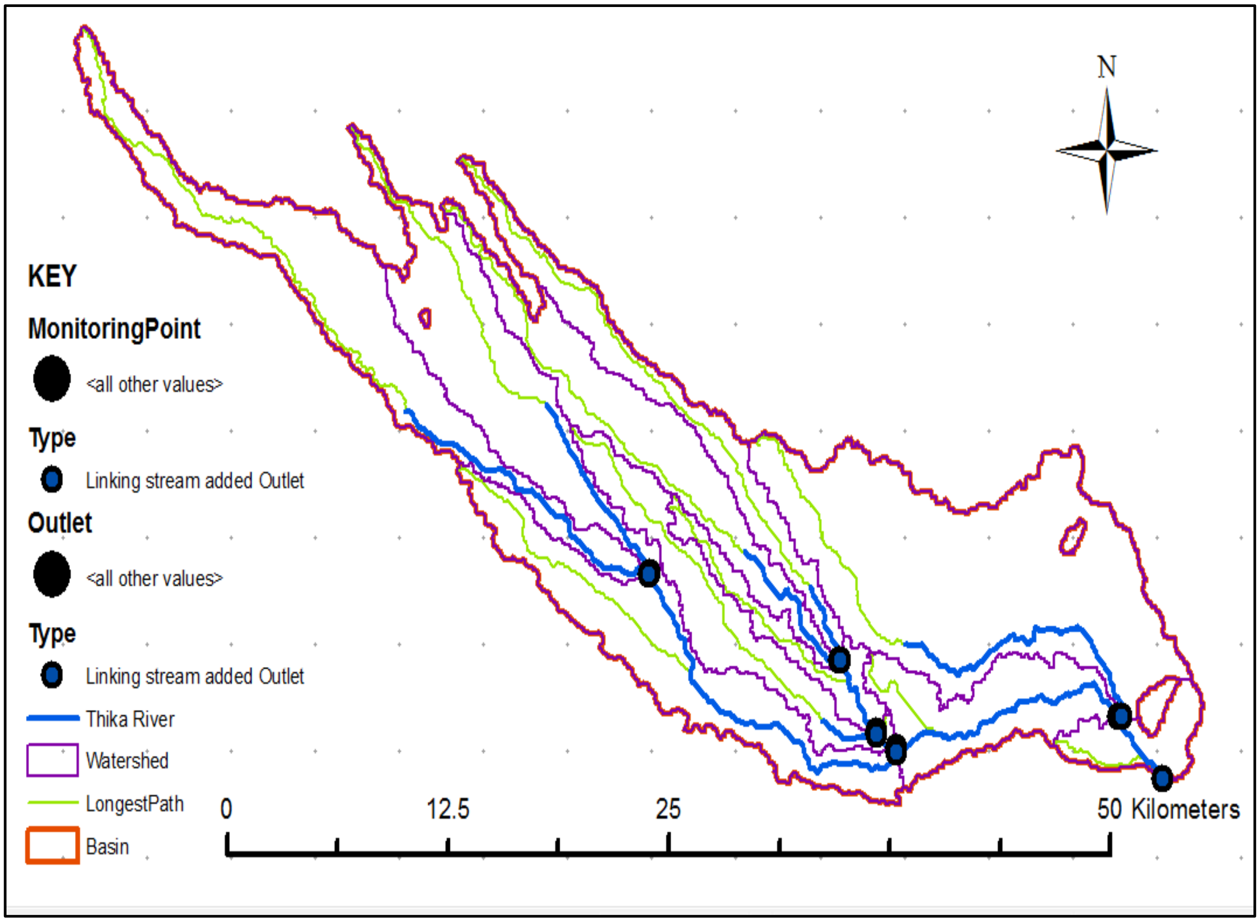


Figure 64: Delineated Watershed Thika River Catchment

Table 16: Topographical Report for Delineated Thika River Watershed

Sub Basin	**Maximum Elevation**	**Minimum Elevation**	**Mean Elevation**
1.	2522	1507	1917
2.	2029	1506	1719
3.	1897	1446	1591
4.	1882	1446	1596
5.	1650	1342	1456
6.	1568	1429	1496
7.	1651	1428	1526
8.	1478	1427	1444
9.	1489	1342	1489
10.	1729	1427	1528
11.	1639	1320	1407

5.6.1Hydrologic Response Units

In hydrological analysis section in SWAT model, land use and soil data were loaded into the model, reclassified and slope defined overlaid was done and hydrological definition tab was used to create11 Hydrological Response Units (HRUs). Figures 65, 66 and 67 shows slope definition, SWAT Soil and SWAT Land use Classification that was derived in this study.

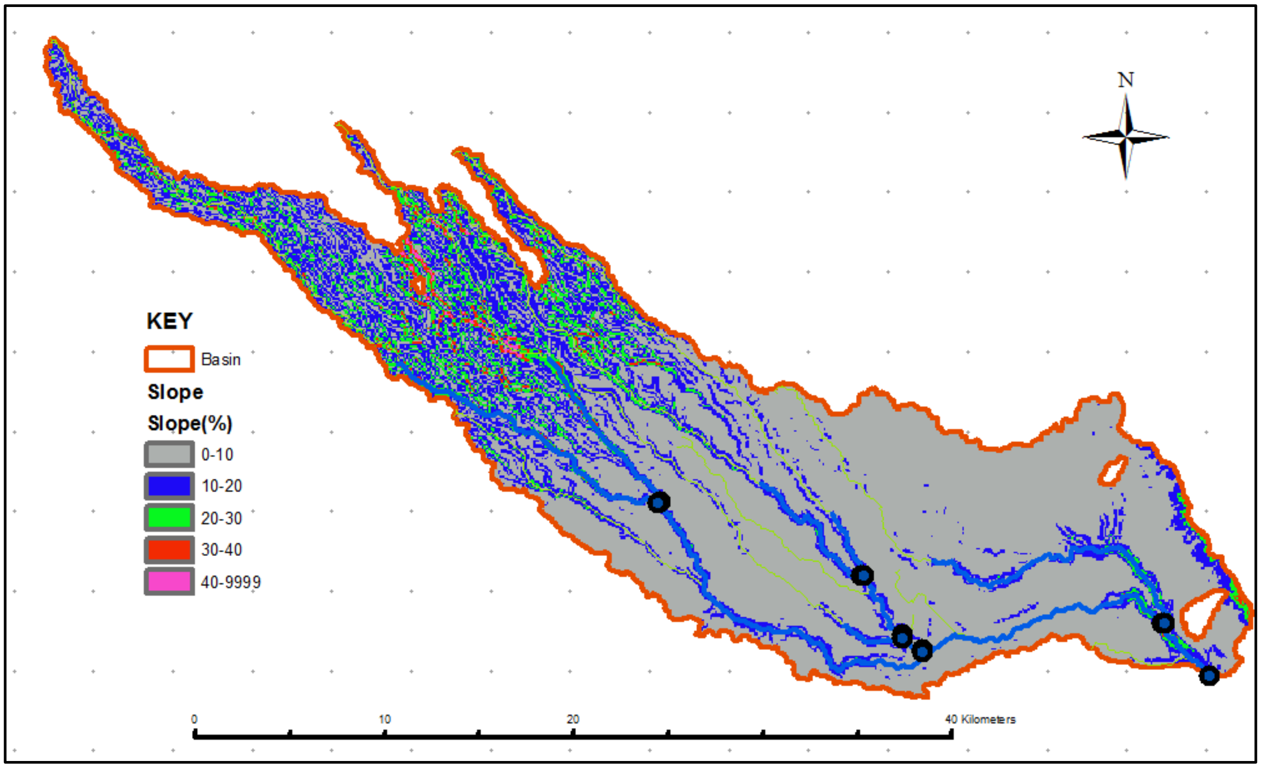


Figure 65: Thika River Catchment Slope Classifications

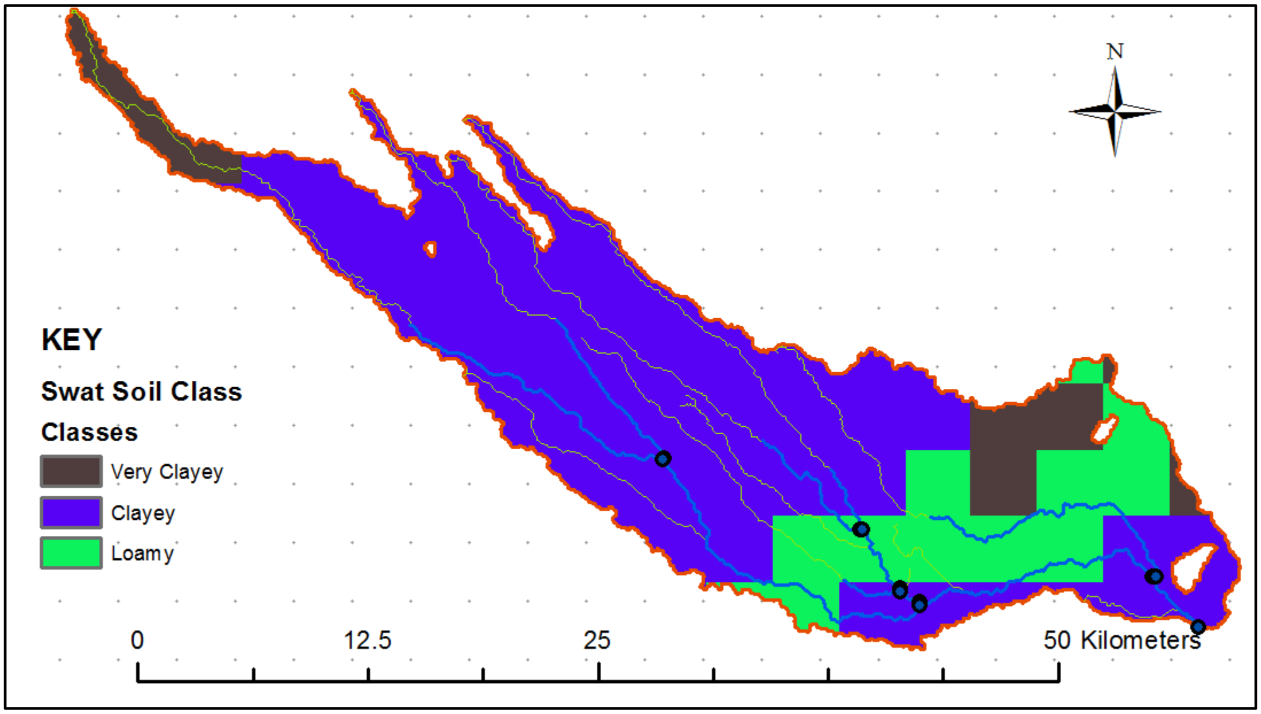


Figure 66: Thika River Catchment SWAT Soil Classification

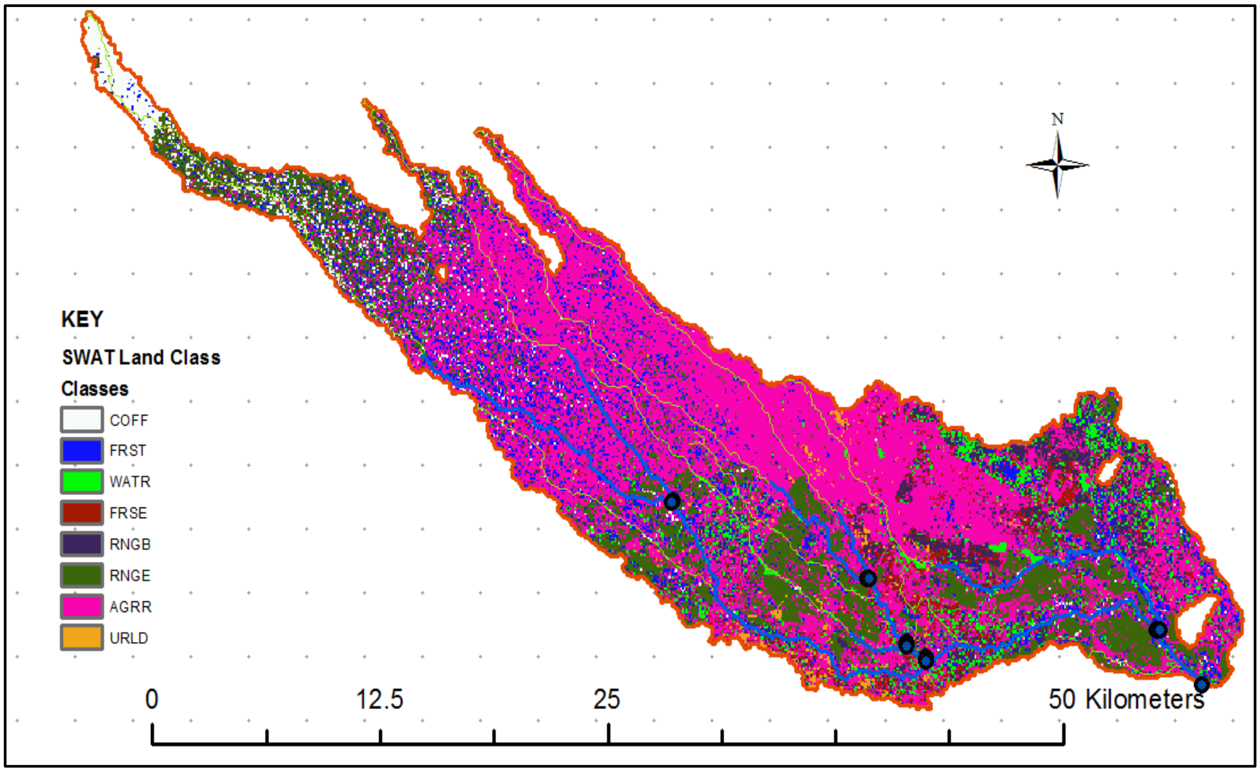


Figure 67: Thika River Catchment SWAT Land Use Classes

5.7: Water yields Simulation under Climate Change Scenarios (2021-2040) and 2061-2080 using SWAT Model.

Results from simulated Stream flow using climate change data to drive SWAT model are presented in Figure 68 and 69. Standardized mean annual analysis showed an increase in water yields in early 2020 and 2030s. However a decrease in Stream flow is expected 2023 being the highest in the first decade and 2034 in the second decade (Figure 68).

Water yields in the years 2061-2080 shows a decrease trend in early 2060s and an increase towards the end of 2070s. The highest water yield in the catchment is expected to be in the year 2077 while the lowest water yield is expected to be in the year 2066 (Figure 69).

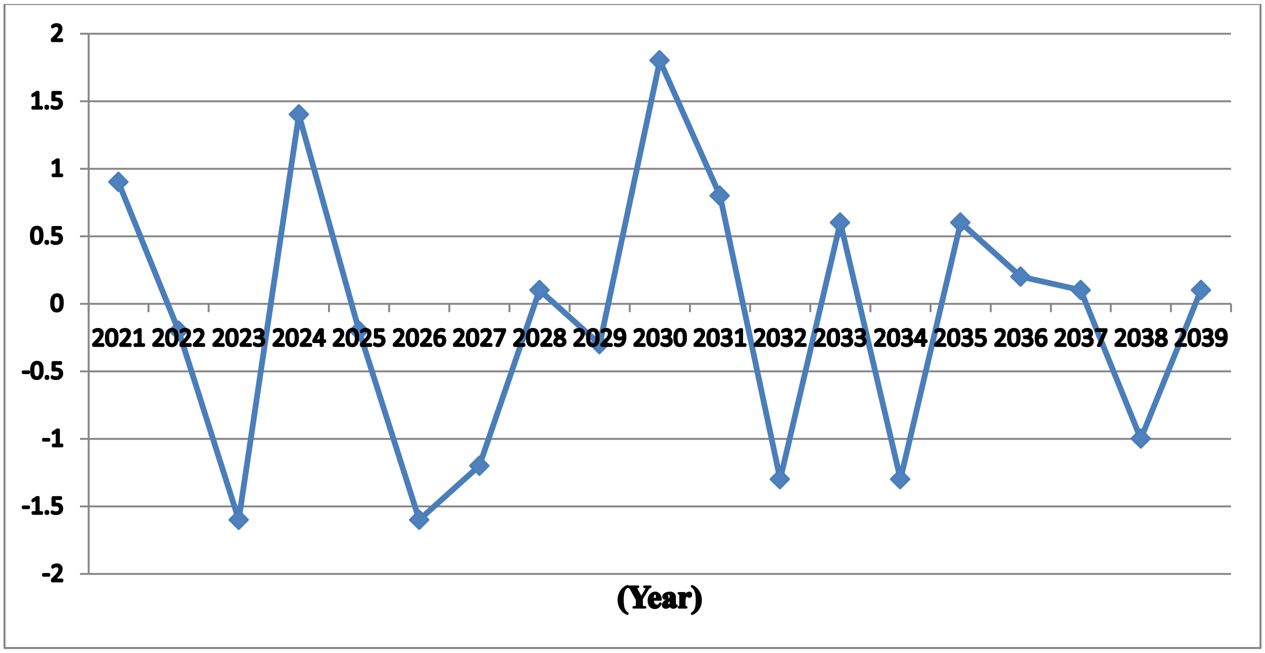


Figure 68: Simulated Stream flow (2021-2040) Thika River Catchment

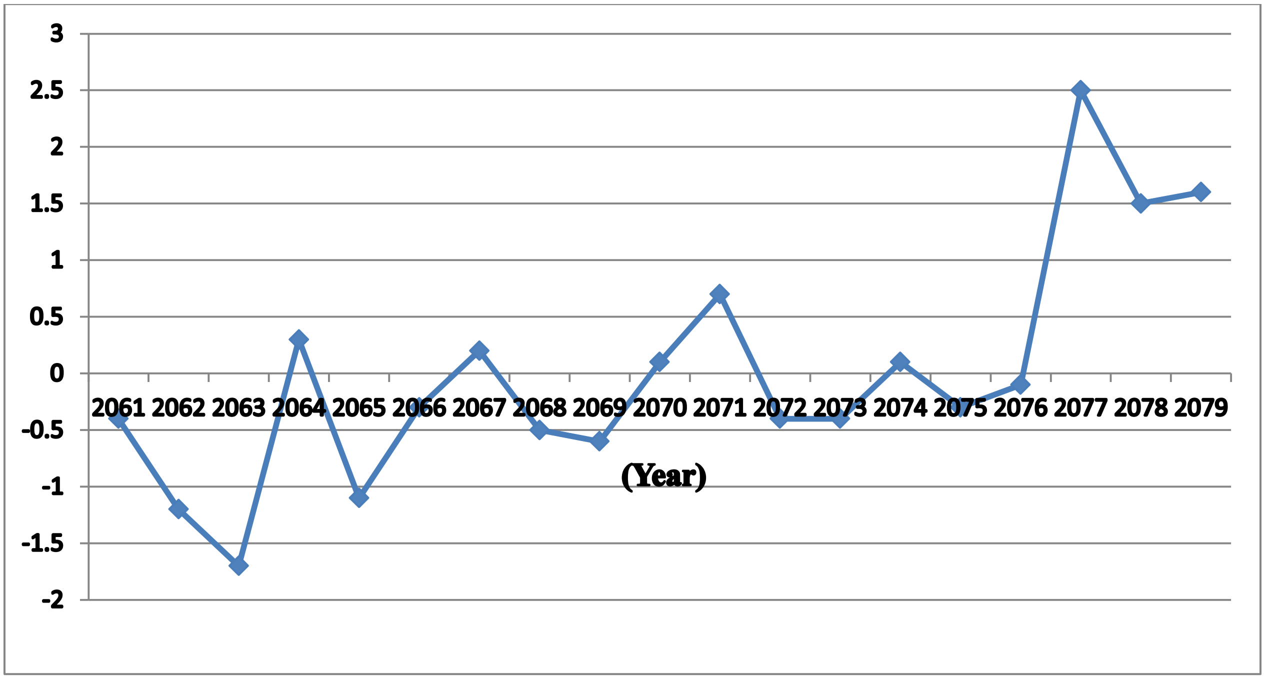


Figure 69: Simulated Stream flow (2061-2080) Thika River Catchment

5.8: Projected Annual Stream flow in Relative to Base period (1961-1990).

Analysis of monthly and seasonal variation of water yield due to climate change in Thika River Catchment was carried out and the results are presented in this sub section. Figure 58 shows that an increase in water yield is expected in the catchment in both periods of 2021-2040 and 2061-2080 in January, February, March and September in comparison to observed Stream flow in the catchment. However, a decrease in water yields is expected in April, November and December.

From the results, it was further noted that during the years 2021-2040, lower water yields is expected during the months May, June, July and August relative to the baseline period. However, during the period 2061-2080 water yields is likely to increase in the months of May, June July and August. In addition, the results showed that there will be a shift of water yields in Thika River (Figure 70).

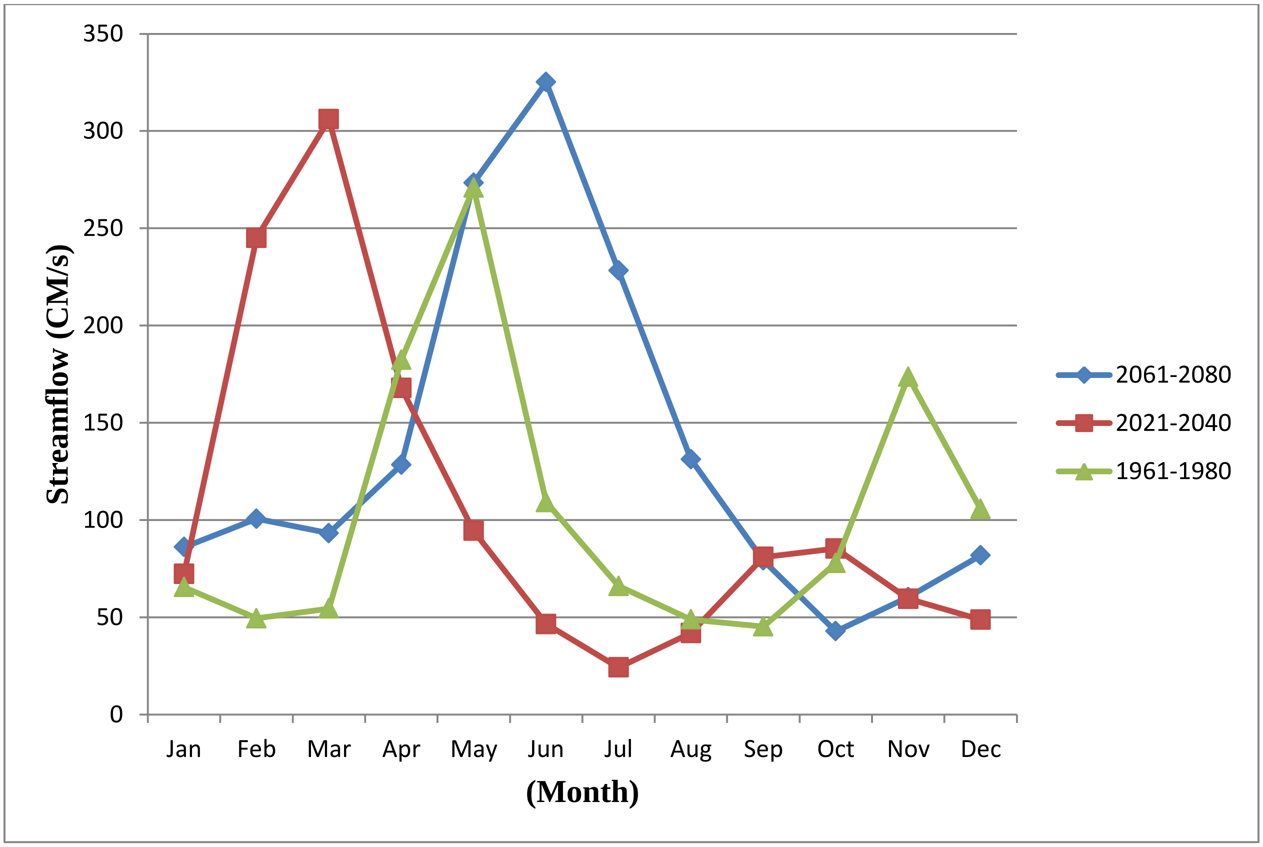


Figure 70: : Monthly Variation of Stream flow in 2021-2040 and 2061-2080 relative to 1979-2009 period in Thika River Catchment.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1: Conclusions

From the results of the study, the climate of the study area has been changing since 1961-1990. Annual rainfall trends in Gethumbwini and Karamaini have been decreasing while an increasing rainfall was observed at Thika Agro Met over the same period. Results from test of hypothesis using Mann Kendall statistic at $\alpha=0.05$ showed that although there was change in rainfall the change was not significant.

Analysis of annual cycle of rainfall showed a seasonal shift of rainfall where October, November and December is becoming relatively wetter as compared to baseline climate (1960-1990).The percentage change increase in rainfall during ONDJ ranged between 1%-33% and 6%-70% in 1990s and 1980s respectively. It was also noted that that there has been a decreasing trend in rainfall in the seasons of March, to May (MAM) and June to August (JJA) as compared to the baseline period (1961-1990) in all the stations with the change ranging between 5%-19% in 1990s and 7%-19% in 1980s. Karamaini Thika station recorded the highest reduction in amount of rainfall in August and September with a decrease of 18% in 1980s and 34% in 1990s.

Analysis of annual temperature trends in the study area showed that the area has been experiencing rise in temperatures. Increase in temperatures has an impact of increasing evaporation within the catchment and therefore affect water yield within Thika Sub Catchment.

Results for projected rainfall in the catchment for Emission Scenarios RCP4.5 and RCP 8.5 showed a drier climate period of 2021-2051 and wetter climate period of 2061-2090. This variation of rainfall could have an impact on water yield from the Thika Sub Catchment.

In addition, analysis of projected temperature shows a warmer future climate in Thika Sub Catchment with the highest increase for RCP 8.5 at the end of 2100 which is likely to affect future water availability.

Results for Stream flow showed that all the River Gauging Stations recorded a reduction of discharge. However, standardized anomalies of discharge at 4CC07-Thika RGS showed a general positive trend in discharge.

Results for simulated Stream flow by use of SWAT model showed decrease in water yields from Thika Sub Catchment during climate periods of 2021-2040 and an increase in 2061-2080. Monthly variation on the hydrology resulting from changes in climate indicated an increase in water yields is likely in January, February, March and September. On the other hand a decrease in water yield is also likely in April, November and December. Simulated Stream flow was compared with rainfall projection under climate change and it was found out that a decrease/increase in rainfall will lead to reduction/increase in water yield. Therefore this study concluded that a change in climatic conditions variables would have an influence on hydrological responses in the study area.

6.2: Recommendations

Results from this study has provided an insight on how hydrological responses under changing climatic conditions would impact water resource availability in this area of study and therefore this information will be useful to water resources managers and other policy makers.

SWAT hydrological model has shown to be a robust tool in modeling impacts of climate change within the catchment area and therefore future researchers should utilize it more in research especially in water sector.

The greatest limitation of this study was unavailability of hydro meteorological data and therefore it was recommended that a good network of stations should be established to enhance research on water resources.

This research was done by only climate change response to water yields but in a catchment there are other factors that impact water yield as land use/cover and therefore future research should be done by incorporating them.

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APPENDIX I: Scripts used to extract CORDEX Climate model data forRainfall, maximum and Minimum Temperature.

```
** For Focus downscaling tasminojections at Stations
**   For use with other Stations change lon-lat locations
**===================================================================
** The script reads CORDEX RCM Historical and rcp 4.5 and 8.5 .nc
** Data and extracts area average for thestationlat and lon
** The parameters are: tasminecipitation (tasmin)
**                    mean temperature (tas)
**                    Maximum temperature (tasmin)
**                    Minimum temperature (tasmin)
**Change the station name folder
**Change the station latlon
**
*****************************************************************
'reinit'
'set display color white'
'c'
**===>we read files for Historical data
** To generate time series file
'Sdfopen C: /Kiptum/CCCMA/hist/pr_1951-2005_rg.nc'
```

```
*'sdfopen C: /Kiptum/Kiptum/CNRM/Hist/tasmin_1951-2005_rg.nc'
*'sdfopen C: /Kiptum/Kiptum/MIROC/Hist/tasmin_1951-2005_rg.nc'
*'sdfopen C: /Kiptum/Kiptum/MOHC/Hist/tasmin_1951-2005_rg.nc'
** Define latlon of station of interest
**==> define area minus to plus 0.5 in both longitude & latitude
lon1 = 37.100
lon2 = 37.109
lat1 = -1.033
lat2 = -1.042
** Set t range to read whole file extracting the monthly model values...
'sett 1 660'
**These steps extract the data into the stdout (standard output) and
**writes the timeseries values to a file
'set x 1'
'set y 1'
'setgxout print'
'define print= tloop (aave(pr.1,lon='lon1',lon='lon2',lat='lat1',lat='lat2')*84600*30)'
fname='C:\Kiptum\thikado\Thikawatersupply\pr_hist_1951-2005\CCCMA_pr_hist_1951-2005.txt'
'fprintf print 'fname' %8.3f 12 1'
'reinit'
'c'
'reinit'
```

```
'set display color white'

'c'

**===>We read files for Historical data

** To generate time series file

'sdfopen C:/Kiptum/CNRM/hist/pr_1951-2005_rg.nc'

*'sdfopen C:/Kiptum/Kiptum/CNRM/Hist/tasmin_1951-2005_rg.nc'

*'sdfopen C:/Kiptum/Kiptum/MIROC/Hist/tasmin_1951-2005_rg.nc'

*'sdfopen C:/Kiptum/Kiptum/MOHC/Hist/tasmin_1951-2005_rg.nc'

** Define latlon of station of interest

**==> define area minus to plus 0.5 in both longitude & latitude

lon1 = 37.100

lon2 = 37.109

lat1 = -1.033

lat2 = -1.042

** Set t range to read whole file extracting the monthly model values...

'sett 1 660'

**These steps extract the data into the stdout (standard output) and

**writes the timeseries values to a file

'set x 1'

'set y 1'

'setgxout print'

'define print= tloop(aave(pr.1,lon='lon1',lon='lon2',lat='lat1',lat='lat2')*84600*30)'

fname='C:\Kiptum\thikado\Thikawatersupply\pr_hist_1951-2005\CNRM_pr_hist_1951-2005.txt'
```

```
'fprintf print 'fname' %8.3f 12 1'
'reinit'
'c'
'sdfopen C:/Kiptum/ERAINT/hist/pr_1951-2005_rg.nc'
*'sdfopen C:/Kiptum/Kiptum/CNRM/Hist/tasmin_1951-2005_rg.nc'
*'sdfopen C: /Kiptum/Kiptum/MIROC/Hist/tasmin_1951-2005_rg.nc'
*'sdfopen C: /Kiptum/Kiptum/MOHC/Hist/tasmin_1951-2005_rg.nc'
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*'set y 1'
*'set gxout print'
*'define print= tloop(aave(pr.1,lon='lon1',lon='lon2',lat='lat1',lat='lat2')*84600*30)'
fname='C:\Kiptum\thikado\Thikawatersupply\pr_hist_1951-2005\ERAINT_pr_hist_1951-2005.txt'
```

```
*'fprintf print 'fname' %8.3f 12 1'
'reinit'
'c'
'Sdfopen C: /Kiptum/MIROC/hist/pr_1951-2005_rg.nc'
*'sdfopen C:/Kiptum/Kiptum/CNRM/Hist/tasmin_1951-2005_rg.nc'
*'sdfopen C:/Kiptum/Kiptum/MIROC/Hist/tasmin_1951-2005_rg.nc'
*'sdfopen C:/Kiptum/Kiptum/MOHC/Hist/tasmin_1951-2005_rg.nc'
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'set y 1'
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'define print= tloop(aave(pr.1,lon='lon1',lon='lon2',lat='lat1',lat='lat2')*84600*30)'
fname='C:\Kiptum\thikado\Thikawatersupply\pr_hist_1951-2005\MIROC_pr_hist_1951-2005.txt'
```

```
'fprintf print 'fname' %8.3f 12 1'
'reinit'
'c'
'sdfopen C:/Kiptum/MOHC/hist/pr_1951-2005_rg.nc'
*'sdfopen C:/Kiptum/Kiptum/CNRM/Hist/tasmin_1951-2005_rg.nc'
*'sdfopen C:/Kiptum/Kiptum/MIROC/Hist/tasmin_1951-2005_rg.nc'
*'sdfopen C:/Kiptum/Kiptum/MOHC/Hist/tasmin_1951-2005_rg.nc'
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'set y 1'
'setgxout print'
'define print= tloop(aave(pr.1,lon='lon1',lon='lon2',lat='lat1',lat='lat2')*84600*30)'
fname='C:\Kiptum\thikado\Thikawatersupply\pr_hist_1951-2005\MOHC_pr_hist_1951-2005.txt'
```

```
'fprintf print 'fname' %8.3f 12 1'
'reinit'
'c'
'sdfopen C:/Kiptum/MPI/hist/pr_1951-2005_rg.nc'
*'sdfopen C:/Kiptum/Kiptum/CNRM/Hist/tasmin_1951-2005_rg.nc'
*'sdfopen C:/Kiptum/Kiptum/MIROC/Hist/tasmin_1951-2005_rg.nc'
*'sdfopen C:/Kiptum/Kiptum/MOHC/Hist/tasmin_1951-2005_rg.nc'
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lon2 = 37.109
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lat2 = -1.042
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'set y 1'
'setgxout print'
'define print= tloop(aave(pr.1,lon='lon1',lon='lon2',lat='lat1',lat='lat2')*84600*30)'
fname='C:\Kiptum\thikado\Thikawatersupply\pr_hist_1951-2005\MPI_pr_hist_1951-2005.txt'
'fprintf print 'fname' %8.3f 12 1'
```

```
'reinit'
'c'
'sdfopen C:/Kiptum/NCC/hist/pr_1951-2005_rg.nc'
*'sdfopen C:/Kiptum/Kiptum/CNRM/Hist/tasmin_1951-2005_rg.nc'
*'sdfopen C:/Kiptum/Kiptum/MIROC/Hist/tasmin_1951-2005_rg.nc'
*'sdfopen C:/Kiptum/Kiptum/MOHC/Hist/tasmin_1951-2005_rg.nc'
** Define latlon of station of interest
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fname='C:\Kiptum\thikado\Thikawatersupply\pr_hist_1951-2005\NCC_pr_hist_1951-2005.txt'
'fprintf print 'fname' %8.3f 12 1'
'reinit'
```

```
'c'
'sdfopen C:/Kiptum/NOAA/hist/pr_1951-2005_rg.nc'
*'sdfopen C:/Kiptum/Kiptum/CNRM/Hist/tasmin_1951-2005_rg.nc'
*'sdfopen C:/Kiptum/Kiptum/MIROC/Hist/tasmin_1951-2005_rg.nc'
*'sdfopen C:/Kiptum/Kiptum/MOHC/Hist/tasmin_1951-2005_rg.nc'
** Define latlon of station of interest
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lon1 = 37.100
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'setgxout print'
'define print= tloop(aave(pr.1,lon='lon1',lon='lon2',lat='lat1',lat='lat2')*84600*30)'
fname='C:\Kiptum\thikado\Thikawatersupply\pr_hist_1951-2005\NOAA_pr_hist_1951-2005.txt'
'fprintf print 'fname' %8.3f 12 1'
'reinit'
'c'
```

APPENDIX II: Someimagesfrom the study area.

Plate 1: Thika/Ndakaini Dam.

Plate 2: Kindaruma hydropower station, Tana

Plate 3: Pineapple Plantation in Thika.

Plate 4: Land use in Thika River Catchment.