ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

SCHOOL OF GRADUATE STUDY

EVALUATION OF CLIMATE CHANGE IMPACT ON EXTREME HYDROLOGICAL EVENT

Case study: Addis Ababa and surrounding catchment

Submitted in partial fulfillment for the degree of Masters of science in Civil Engineering

(Major in Hydraulic Engineering)

By Abayneh Alemu
Addis Ababa
May 2011

Declaration and Copyright

I, Abayneh Alemu, do hereby declare to the Senate of Addis Ababa University that this thesis is entirely original work and all other materials are duly acknowledged. This work has not been submitted for any academic degree award at any University.

Declaration

Abstract

The global climate may have serious impact on the frequency, magnitude, location and durations of hydrological extremes. Change in hydrological extremes will have implications on the design of future hydraulic structures, flood- plain development and water resource management .This study assesses the potential impact of climate change on extreme hydrological events in Akaki River catchment in and around Addis Ababa area. Projection of the future climate variables is done by using General Circulation Model (GCM) which is considered as the most advanced tool for estimating the future climatic condition. The climate projection analysis was done by dividing the coming 90 years into two time periods. The 1990-1999 was taken as baseline period against which comparison was made. A hydrological model, HEC-HMS was utilized to simulate Runoff in the study area. The performance of the model was assessed through calibration and validation process and resulted R^2=0.78 during calibration and R^2=0.81 during validation.

For the coming 90 years, the mean monthly precipitation may both increase and decrease. The decrease in mean monthly precipitation may be up to 51% in 2030s and the increase may reach up to 131% in 2090s. The maximum and minimum temperature indicated an increasing trend. The simulated result shows that the maximum river flows in the study area will be high and more variable in terms of magnitude, and irregular of occurrence, than they are at present. It is observed that climate change has negligible effect on the low flow condition of the Akaki River flow. According to the evaluated scenarios, climate change has impact on the distributions of hydrological extremes in the study area. The impact of climate change may also cause a decrease in monthly mean flow up to 41% in the 2030s and increase up to 126% in the 2090s. Seasonal mean flow may show increase up to 13% and 15% in Kiremt (JJAS) season for 2030s and 2090s time periods respectively. The increasing of seasonal mean flow in Kermit (JJAS) has its own contribution for occurrence of flooding in Addis Ababa city. The increase in Bega (ONDJ) season flow will have a paramount importance for water harvesting in dam of water supply to Addis Ababa city. It is observed that there may be a net annual increase in mean annual flow volume in Akaki River due to climate change.

Key words: Climate change; GCM, SDSM, flood; low flow; HEC-HMS; Addis Ababa

Acknowledgments

First of all I would like to thank the almighty God for giving me the strength to walk unpaved way to reach this point in life.

I would like to express my sincere gratitude to my supervisor Dr. Semu Ayalew for giving me valuable guidance and for his continuous support from the inception of this work to the end. I would like also to thank him for providing me GCM data.

I would also like to thank International Water Management Institute (IWMI) for their financial support .I am also grateful to the Hydrology Department of MOWE and NMA of Ethiopia for providing me data free of charge.

I would like to thank my Classmate Abdurhman B., Ahmed M., Bogale T., Daniel A. and others for their encouragement, moral support and true friendship.

At last but not least, I would like to extend my deepest gratitude to my family, without your encouragement and care this would not have happened.

DEDICATED

To

Kiyya

TABLES OF CONTENTS

List of Figures

List of Tables

Abbreviations

AAU	**Addis Ababa University**
AAWSA	Addis Ababa water Sewerage Authority
a.s.l	above Sea Level
AU	African union
CN	Curve number
DEM	Digital Elevation Model
FAO	Food and Agriculture Organization
G CM	General Circulation Model
GIS	Geographical Information System
HEC	Hydrological engineering center
HEC HMS	Hydrological Engineering Center hydrological Modeling system
HEC-DSSVue	Hydrologic Engineering Center Data Storage System Visual Utility Engine
HMS	Hydrological Modeling System
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Inter Tropical Convergence Zone
IDF	Intensity duration frequency
JICA	Japan International Cooperation Agency
NMSA	National Meteorological Service Agency
SCS	Soil Conservation Services
SI	International Unit system
TR-50	Technical Release number 50
UNDP	United Nation Development Program
USACE	United states Army Corps of Engineers
USDA	United States Department of Agriculture
MoWE	Ministry of Water and Energy

RCM	Regional Circulation Model
SDSM	Statistical down Scaling Method

CHAPTER ONE

1.0 Introduction

The difference between weather and climate is a measure of time. Weather is what conditions of the atmosphere are over a short period of time, and climate is how the atmosphere "behaves" over relatively long periods of time. When we talk about climate change, we talk about changes in long-term averages of daily weather. Weather consists of the short-term (minutes to months) changes in the atmosphere. In short, climate is the description of the long-term pattern of weather in a particular area. Climate change and global warming is the most significant threat to the living beings in this planet at the twenty-first century. It is distressing that it has already begun when we have just passed the doorstep of the new millennium. Extremities in weather conditions cause droughts and floods when we look at the phenomenon from a water resources perspective. When increasing populations, growing urban and industrial areas are taken into account, it is obvious that the above water related problems will be of utmost significance throughout the next decades. Extensive care should be given to the operation and management of river basins and dam reservoirs (no matter are they used for water supply or flood control or both) to be able to overcome the water related problems. Akaki Basin is selected as the study area in this research and basin parameters (infiltration and base flow) are calibrated using the rainfall-runoff data of the basin that are collected by 5 rainfall Stations and one stream flow stations for 1997-2004 period.

The environment has been influenced by human beings for centuries. However, it is only since the beginning of the industrial revolution that the impact of human activities has begun to extend to a global scale (Baede *et al.* 2001).Today, environmental issue becomes the biggest concern of mankind as a consequence of scientific evidence about the increasing concentration of greenhouse gases in the atmosphere and the changing climate of the Earth. Globally, temperature is increasing and the amount and distribution of rainfall is being altered (Cubasch *et al.* 2001).According to the International Panel on Climate Change (IPCC) Scientific Assessment Report, global average temperature would rise between 1.4 and 5.8°C by 2100 with the doubling of the CO_2 concentration in the atmosphere. Local climate conditions are expected to occur as a consequence of rising global temperature (Cubasch *et al.* 2001). This is expected to have a potential impact on level rise, change in precipitation pattern (up to ±20%), and change in other different socio-economic sectors; accordingly the report of Intergovernmental Panel on Climate Change (IPCC, 2001). Scientists have made estimates of the potential direct impacts on various socio-economic sectors, but in reality the full consequences would be more complicated as impacts on different sectors are indirectly interrelated to one another (UNEP, 2005).

Being one of the very sensitive sectors, climate change can cause significant impacts on water resources by resulting changes in the hydrological cycle. The change on temperature and precipitation components of the cycle can have a direct consequence on the quantity of evapotranspiration component, and on both quality and quantity of the runoff component. Consequently, the spatial and temporal water resource availability, or in general the water balance, can be significantly affected, which clearly amplifies its impact on sectors like agriculture, industry and urban development (Hailemariam 1999).

Although climate change is expected to have adverse impacts on socio economic development globally, the degree of the impact will vary across nations. The IPCC findings indicate that developing countries, such as Ethiopia, will be more vulnerable to climate change. It may have far reaching implications to Ethiopia for various reasons, mainly as its economy largely depends on agriculture. A large part of the country is arid and semiarid, and is highly prone to desertification and drought. Climate change and its impacts are, therefore, a case for concern to Ethiopia. Hence, assessing vulnerability to climate change and preparing adaptation options as part of the entire program is very crucial for the country (NMSA, 2001).

Despite the fact that the impact of different climate change scenarios is forecasted at a global scale, the exact type and magnitude of the impact at a small watershed scale remains untouched in most parts of the world. Hence, identifying local impact of climate change at a watershed level is quite important. This gives an opportunity to define the degree of vulnerability of local water resources and plan appropriate adaptation measures that must be taken ahead of time. Therefore, this study focuses on evaluation of climate change impact on extreme hydrological event in and around Addis Ababa area.

1.2 Description of the Study area

The project area lies within the Awash River basin, which has a total drainage area of 110,000 square kilometers (Tesfaye Chernet, 1993).The surface water divides between Awash basin and the Abay (Blue Nile) basin, lies on the top of Entoto ridge, immediate north of the project boundary.

The total catchment area of the Akaki river catchment, includes Addis Ababa, is divided into two sub-catchment areas by approximately north-south running surface water divide. These are the Big Akaki river (Eastern) sub-catchment and the Little Akaki River (Western) sub-catchment. Addis Ababa is located at the geographical center of the country and lies between 8°55” north and 9° 05” north latitude and 38° 40” east and 38° 50” east longitude. Addis Ababa being at an altitude 2300-2500 meter (AAWSA, AAU, 2003).The topography is undulating and form plateau in the northern, western and southwestern parts of the city, while gentle morphology and flat land areas characterize the southern and southeastern parts of the city (JICA and Region 14 Administration, 1998).The watershed of the study area was defined as covering about 1462km^2, encompassing the water flow contributing area of the watershed that flows from Oromia region.

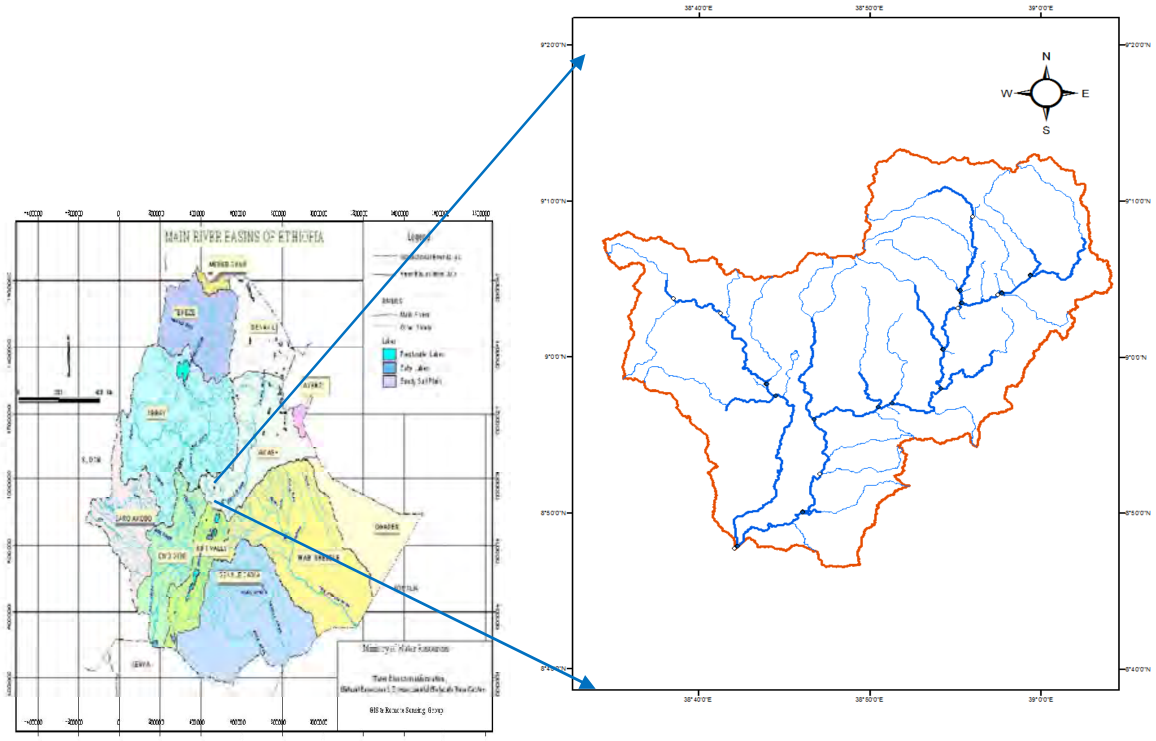


Figure: 1.1 Study Areas

1.3 Problem Statement

One of the most important consequences of climate change will be alterations in major climate variables, such as temperature, precipitation, and evapotranspiration. This in turn will lead to changes in the hydrological cycle, influencing the components of water balance of drainage basins in several ways such as the availability and distribution of water resources in space and time, stream flow, frequency of extreme events etc**.**

The potential impacts of climate change on water availability and the regime of hydrologic extremes have received considerable attention from hydrologists during the last several years. Changes in the frequency and timing of extreme events may be one of the most significant consequences of climate change. Moreover, the flooding problem affects the whole of Addis Ababa drainage network according to a report (JICA and Region 14 Administration, 1998).Therefore assessing the possible impact of climate change on the extreme hydrological event is essential for future development as well as for managing the current water resource development projects in adaptive way in Addis Ababa and surround area.

1.4 Impact of climate change in water Availability

Findings of the IPCC 2001, strongly suggests that water resource respond to global warning in ways that will negatively impacted the water availability and water supplies. The climate change has also the potential to deteriorate the surface water quality due to increased evapotranspiration, lower flows and rivers becoming warmer, making the management of water treatment works (and subsequent compliance with the drinking water quality regulations) more challenging. The reduction in the runoff volume will lead to the decrease in the inflow to the reservoirs consequently; longer period might be required to fill the reservoir. As result of the increase in temperature the rate of evaporation from the reservoir open water surface may increase and this may create the reservoir to fail to supply at least the required amount of demand because of its depletion or decrease in the active storage volume.

1.5 Impact of Climate change on Extreme Hydrological Events

Changes in global climate will have significant impacts on local hydrological regimes, which will consequently have ramification on ecological as well as social and economic systems. Some of these effects include changes in stream flows which support aquatic ecosystems, navigation, hydropower, irrigation systems, etc. There may also be a significant change in the frequency and severity of floods and droughts.

The projected global climate change in the coming century may have both beneficial and adverse environmental impact, but the larger the changes and the rate of change in climate, the more adverse effect predominate (IPCC, 2001). The effects of climate changes on the frequency and intensity of floods and droughts is expected to increase the challenges for water and flood management in the 21st century. Therefore, the potential impacts of such variations in the future climate need to be taken into consideration by policy and decision makers when managing water resources and making plans for the future (Mehdi et al., 2002).

1.6 Impact of Climate Change on Urban context

In urban areas the most obvious increased risk comes from the likely increase in the number and intensity of extreme events. Of course, there are large differentials in the scale of such risks between urban in each nation. Urban areas are vulnerable to many damages to the larger systems on which they depend because of climate change for instance flooding, water supply and treatment, transport and electricity and thus everything that depends on electricity, including lighting, pumping and communications (Wilbanks et al., 2007).

1.6.1. Flooding

Urban areas always present some risk of flooding when rainfall occurs. Buildings, roads, infrastructure and other paved areas prevent rainfall from infiltrating into the soil and so produce more runoff. Heavy and/or prolonged rainfall produces very large volumes of surface water in any city, which can easily over flow drainage systems. Floods are already having very large impacts on cities and smaller urban centers in many African nations for instance the floods in Mozambique in 2000 which included heavy floods in Maputo, the floods in Algiers in 2001 (with around 900 people killed, and 45,000 affected); heavy rains in East Africa in 2002 that brought floods and mudslides forcing tens of thousands to leave their homes in Rwanda and the very serious floods in Port Harcourt and in Addis Ababa in 2006 (UN- Habitat 2007, Douglas et al., 2008). The flood problems are common in most parts of the country. Large scale flooding is rare and limited to the lowland areas where major rivers cross to neighboring countries. However, intense rainfall in the highlands causes flooding of settlements close to any stretch of river courses. The most serious flood problems are found in the abovementioned Awash River basin. Irrigation development in this basin is quite advanced and is located in the flood plains on either side of the river, with close to 70% of the country s large-scale irrigated agriculture; thus, high economic damage occurs during flooding. It is estimated that in the Awash Valley almost all of the area delineated for irrigation development is subject to floods; this amounts to an inundated surface of some 200,000-250,000 ha during high flows. The other rivers where significant floods occur are the Wabi-Shebelle River in southeastern Ethiopia near the Somali border and Baro-Akobo/Sobat River in western Ethiopia, near the Sudanese border. In the Baro-Akobo Plain an area of about 300,000-350,000 ha is prone to annual flooding and in the Wabi-Shebelle Basin some 100,000 ha may be inundated. Flooding in urban settlements, especially in Addis Ababa, annually causes damages to property along streams coming down from the nearby hills (Kefyalew, 2001).

1.6.2 Constraints on water supplies and other key natural resources

IPCC Working Group II noted that, in Africa, by 2020, between 75 million and 250 million people are projected to be exposed to an increase of water stress due to climate change (Adger, Aggarwal, Agrawala et al., 2007).

Any reduction in the availability of freshwater resources caused by climate change will be particularly problematic for those who live in areas already suffering water scarcity or water stress with poorer groups likely to be most affected (Romero Lankao, 2006). Many cities and their water catchments will get less precipitation (and have more constrained fresh water sources) which is particularly problematic for growing cities and large cities already facing serious problems obtaining sufficient fresh water supplies (Anton, 1993; UN Habitat, 2006). At least 14 African nations are already facing water stress or water scarcity and many more are likely to join this list in the next 10 to 20 years (Muller 2007).There is already a failure to manage water resources well in much of this region, independent of climate change where around half the urban population already lacks adequate provision for water and sanitation, although this is linked far more too inadequate governance than to water shortages (UN-Habitat, 2003).

1.6.3 Health risks related to climate change

Climate change is also likely to bring an increased burden of diarrheal disease and altered spatial distribution of some infectious disease vectors; for instance as warmer average temperatures permit an expansion of the area in which many “tropical” diseases can occur. Expansion is likely in the area in which the mosquitoes that spread malaria can survive and breed (Adger, Aggarwal, Agrawala et al., 2007; WHO, 1992).Populations with poor sanitation infrastructure and high burdens of infectious disease often experience increased rates of diarrheal diseases, cholera and typhoid fever after flood events. The transmission of enteric pathogens is generally higher during the rainy season (Nchito et al 1998; Kang et al., 2001).

1.7 Objective

The objective of this study is to evaluate the impact of climate change on extreme hydrological event for different climate scenarios in time scale up 2100 at in Akaki watershed using HEC-HMS rainfall runoff modeling. The Specific Objective includes:

- To quantify the possible impact of climate change on extreme hydrological events and the water availability of Akaki catchment for different future time periods.

1.8 Climate

In order to understand the environment and the possible impact of human activity on it a basic knowledge of weather and climate is required. The former is the physical condition of the atmosphere at a specific time and place with regard to wind, temperature, cloud cover, fog, and precipitation. Weather is highly variable and somewhat unpredictable. As a result, a longer-term view of the weather pattern of a particular locality is frequently more useful as an environmental tool (Andrew et al, 1996).National Atlas of Ethiopia (1981) defined five traditional climatic zones: "Kur" (Alpine), 3000m and above; "Dega" (temperate), 2300m to about 3000m; "Weina Dega" (Sub tropical),1500 to about 2300m; "Kolla" (Tropical), 800m to about 1500m and "Bereha" (Desert), less than 800m.

The variation in the seasonal distribution of rain fall in Ethiopia can be attributed by the reference to the position of the Inter-Tropical Convergence Zone (ITCZ), the relationship of between upper and lower air circulation, the effects of topography and the role of local convection currents and the amount of rainfall (Kebede, 1964; Gizaw, 1965; Suzuki, 1967; in Daniel, 1977). Regarding the type of precipitation in Ethiopia, Hadwen (1975) stated that there are very few areas in the country where snow is an important type of precipitation, but hailstorms are quite common in the rainy season, especially in areas above 2,000m a.s.l. According to Daniel (1977) classification of Ethiopia's rainfall region, Addis Ababa is located in the region where the rainy months are contiguously distributed (***Regime IE***). In this region there are about seven rainy months from March to September/and the small rains occur from March to May. The big rains are from June to September. High concentration of rainfall occurs in July and very high concentration in August.

There are three recognized seasons. The main rainy season (kiremt) lasts generally from June to September during which south-west winds bring rains from the Atlantic Ocean. About 70-90 percent of total rainfall occurs during this season which is also typified by minimum levels of sunshine, low variation in daily temperatures and high relative humidity. A dry season (Bega) lasts from October to January during which clear skies are associated with maximum sunshine, high daily temperature variation, and low relative humidity. Minor rainy season (Belg) lasts from February to May during which south-east winds bring the small rains from the Indian Ocean and temperatures are at their highest (Daniel, 1977).

1.9 Topography and Land Use

The study area found at the southern flank of Entoto ridge (3199m a.s.l.) and expanded in all directions. This ridge marks the northern boundary of the city following the east-west trending major fault (Ambo-Kassam). Other prominent volcanic features surrounding the city are Mt. Wochacha in the west (3385m a.s.l.), Mt. Furi (2839m a.s.l.) in the southwest and Mt. Yerer (3100 a.s.l.) in the southeast. (AAWSA, AAU, 2003).

The topography is undulating and form plateau in the northern, western and southwestern parts of the city, while gentle morphology and flat land areas characterize the southern and southeastern parts of the city (JICA and Region 14 Administration, 1998).

The center of the city lies on an undulating topography with some flat land areas. The topography is undulating and form plateau in the northern, western and southwestern parts of the city, while gentle morphology and flat land areas characterize the southern and southeastern parts of the city. In the surrounding of the urban parts of Addis Ababa, cereal crops like wheat, teff, barely and maize are cultivated seasonally. Vegetable farms on small plots of land on the terraces of the valleys are a common practice in different parts of the city. Besides, household plantations of different species (garden parks, road side vegetations etc.) and eucalyptus trees cover large parts of the city.

The foundation and expansion of Addis Ababa was associated with the rapid conversion of land from rural to urban uses more than anywhere else in the country. For the last more than one hundred years it has been noticed that there is an intensive conversion of rural land to urban development like buildings, transportation networks and facilities (airports and highways), recreation areas, reservoirs and other manmade structures. The introduction of eucalyptus tree in the beginning of the century was partly due to the shortage of timber for residential houses at the time. At present eucalyptus tree covers most parts of the city and it is the main sources of firewood. The less controlled urbanization that includes construction of residential houses, commercial centers, and transport infrastructure, various types of industry, parks, and recreational areas covered most proportion in the urban parts of Addis Ababa (AAWSA, AAU, 2003).

1.10 Hydrology

1.10.1 Streams and Rivers

The total catchment area of the Akaki river basin, including Addis Ababa, is divided into two sub-catchment areas by approximately north-south running surface water divide. These are the Big Akaki river (Eastern) sub-catchment and the Little Akaki River (Western) sub- catchment. In the project area the stream drains towards south from the Entoto ridge; southeast direction from Mt. Wechecha and Mt. Furi; and towards southwest direction on from Mt. Yerer and other elevated areas of the eastern outskirts of the city. The perennial streams in the city are Little Akaki, Bantyiktu, Kurtume, Kebena, Ginfile, and Big Akaki. Other streams are intermittent in nature. On the top of the mountain streams are dense forming radial drainage pattern, whereas on the slope and most parts of the city core they form dendrite drainage pattern. Towards the south almost all streams /or big tributaries crossing the city in different direction join either Little Akaki or Big Akaki river. The two rivers flow on either side of Addis Ababa Debrezeit road (which is the surface water divide at this part of the city) and complete their courses entering Lake Abba Samuel. Figure1.1 indicates daily flood recorded at the rivers stream gage used for calibration and verification for each study area.

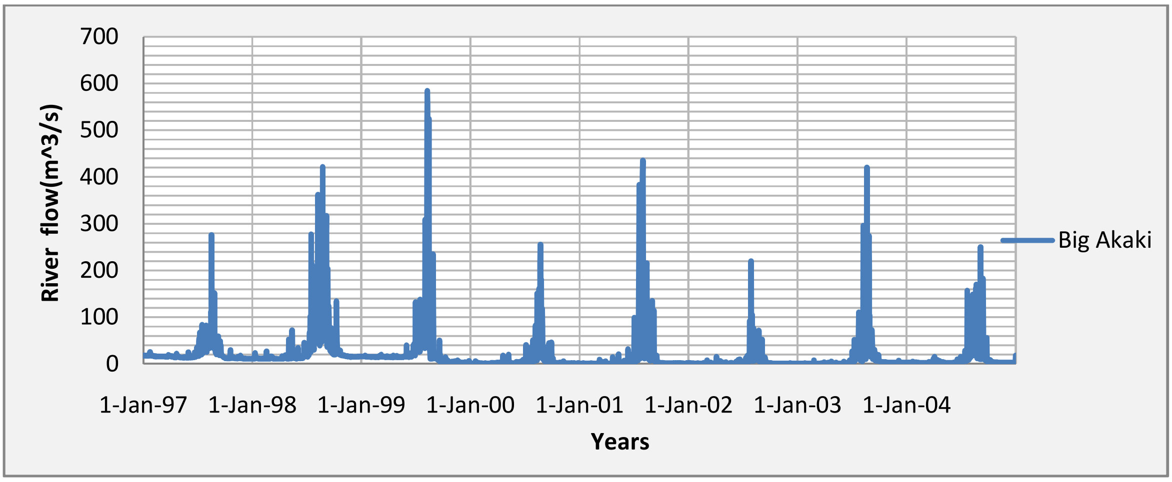


Figure 1.1: *Daily time series of big -Akaki river at Akaki Bridge*

1.10.2 Water reservoirs

In the outskirts of the city four water reservoirs were built for two main purposes. Gefersa, Legadadi, and Dire dam were built for public water supply, while Abba Samuel dam was built for hydroelectric power generation. As a consequence, Lake Gefersa in the northwest, Lake Dire and Legedadi in the northeast and Lake Abba Samuel in the southern outskirts of the city were formed at different times.Gefersa was the first dam built in 1944 about 18 kms west of Addis Ababa. At present the dam has a reservoir capacity of 6.5 million cubic meters and the maximum capacity of the treatment plant is 30,000 m^3 of water per day. Due to rapid growth of the population and expansion of the city from year to year, there is a serious shortage of water in different parts of Addis Ababa. To alleviate the problem Legedadi and Dire dams were built in 1970 and 1999 at about 33 kms east of Addis Ababa. In 1940 Abba Samuel dam was built on the Akaki River, 30 kms south of Addis Ababa. The dam has a storage capacity of 65 million cubic meters and an annual output of 23 million kilowatt- hr (Berhane, 1982). However, due to siltation and pollution it is not functional at present.

1.11 Limitation of the study

In this study the impact of climate change was assessed by assuming the land cover will remain the same at future time horizons. However, in real world the land covers change.

1.12 Thesis outline

This thesis contains six chapters organized as follows. Chapter one gives a general introduction to the study with its background, objective, problem and a brief description of the study area. Chapter two describes the reviewed literature related to the study. Chapter three deals with the material used and methodology adopted for the study; as well as how the models are setup and data are analyzed. Chapter four concerned with the availability data and analysis part. Chapter five discussed the result of the study and lastly chapter six ends with the conclusions and recommendations by the study.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Weather / climate definition

In common languages, the notions of “Weather” and “Climate” are loosely defined. “Weather” is the fluctuating state of the atmosphere around us, characterized by the temperature, wind, precipitation, clouds and other weather elements. This weather is the result of rapidly developing and decaying weather systems such as mid-latitude low and high pressure systems with their associated frontal zones, showers and tropical cyclones. Weather has only limited predictability. Mesoscale convective systems are predictable over a period of hours only; synoptic scale cyclones may be predictable over a period of several days to a week .Beyond a week or two, individual weather systems are unpredictable.

“**Climate**” refers to the average weather in terms of the mean and its variability over a certain time-span in a certain area. Classical climatology provides classifications and descriptions of the various climate regimes found on earth. Climate varies from place to place, depending on latitude, distance to the sea, vegetation, presence or absence of mountains and other geographical factors. Climate varies also in time; from season to season, year to year, decade to decade or on much longer time-scales, such as the Ice ages. Statistically, significant variations of the mean state of the climate or of its variability are referred to as climate change (IPCC, TAR 2001).

Climate variations and changes, caused by external forcing, may be partly predictable, particularly on the larger continental and global spatial scales. Because human activities, such as the emission of greenhouse gases or land-use change, do result in external forcing, it is believed that the large-scale aspects of human-induced climate change are also partly predictable.

2.2 Climate change

Climate change is the most serious problem that the whole world is facing today. It is now widely accepted that climate change is already happening and further change is inevitable; Over the last century (between 1906 and 2005), the average global temperature rose by about 0.74^{o}C. This has occurred in two phases, from 1910s to 1940s and more strongly from the 1970s to the present (IPCC, 2007a). Many studies into the detection and attribution of climate change have found that most of the increase in average global surface temperature over the last 50 years is attributable to human activities (IPCC, 2001a).

It is estimated that, for the 20th Century, the total global mean sea level has risen 12-22 cm, this rise has been caused by the melting of snow cover and mountain glaciers (both of which have declined in both hemispheres)(IPCC, 2007a).

The IPCC also notes that observations over the past century shows, changes are occurring in the amount, intensity, frequency and types of precipitation globally (IPCC, 2007a).

At this point it is worth mentioning the role and remit of the Intergovernmental Panel on Climate Change (IPCC).The IPCC was established in 1988 by the World Meteorological Organization and the United Nations Environment Programme, and its role is to assess on a comprehensive, objective, open and transparent basis the scientific, technical and socio-economic information relevant to understanding the scientific basis of risk of human-induced climate change, its potential impacts and options for adaptation and mitigation. Among the different assessment that are carried out by the IPCC, the most recent one that was published in 2007, states the projected global surface warming lies within the range 0.6 to 4.0^{o}C, whilst the projected see level rise lies within the range 0.18 to 0.59 m at the end of next century (IPCC, 2007a).

2.3 Modelling Climate Change

In order to estimate the impacts of anthropogenic emissions on climate, a mathematical model called a Global Circulation Model (GCM) has to be constructed of the complete climate system, which must include the atmosphere, oceans, land and cryosphere (glaciers and ice sheets). This model is a mathematical description of the earth's climate system, firstly broken down into layers (both above and below sea level) and then each grid is broken down into boxes or cells. A number of research centers around the world have developed their own versions of GCMs, but all predictions contain uncertainties. For example, because future emissions of greenhouse gases are unknown, numerous emissions scenarios have been developed; therefore, different scenarios will obviously produce different results. However, the largest uncertainty arises from the models themselves. Even if each of the different GCMs uses the same emissions scenario, they will give quite different predictions due to the different ways they represent aspects of the climate system (Robert K and Colin H, 2007).

2.4 Climate change in Ethiopia

According to the Ethiopian National Meteorological Services Agency (NMSA, 2001) study for 42 meteorological stations, the country has experienced both dry and wet years over the last 50 years. Trend analysis of the annual rainfall showed there was a declining trend in the northern half of the country and southern Ethiopia while there is an increasing trend in the central part of the country. However, the overall trend in the entire country is more or less constant. Figure 2.1 shows the year to year variation of rainfall over the country expressed in terms of normalized rain fall anomaly averaged over 42 stations

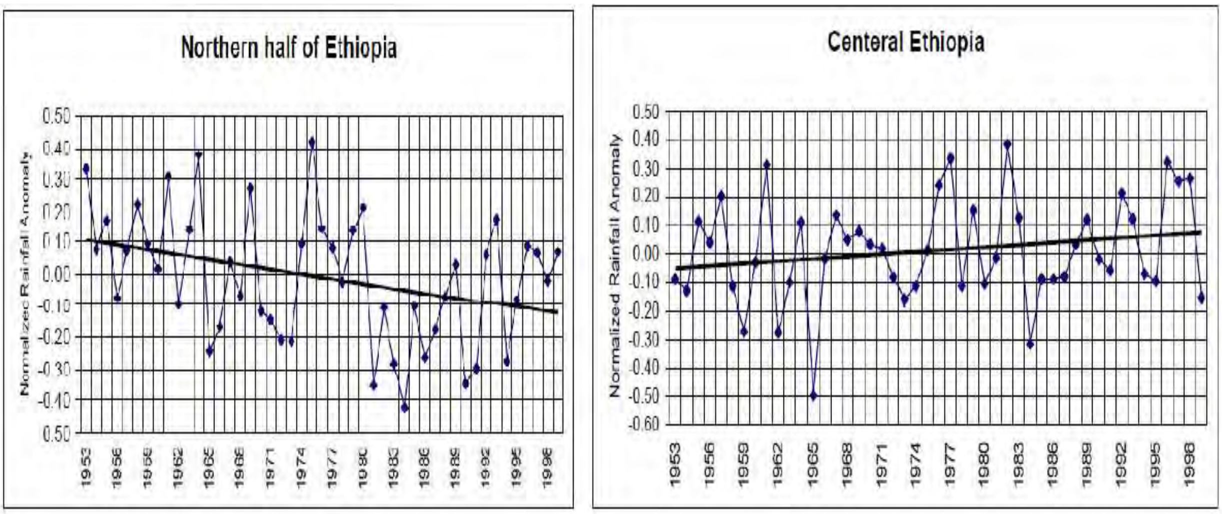
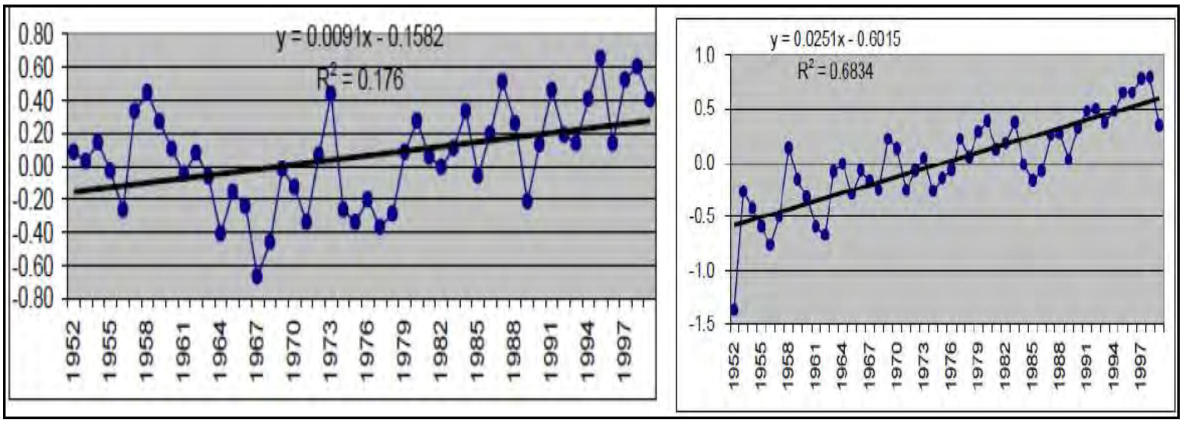


Figure 2.1: Annual variability of rainfall over Northern half (left side) and Central (right) Ethiopia expressed in normalized deviation (NMSA, 2001)

The study of NMSA at the same year for 40 stations showed that there have been very warm and very cold years. However, the general trend showed there was an increase in temperature over the last 50 years. The study also noted that the minimum temperature is increasing at a higher rate than the maximum temperature. Figure 2.2 shows the year to year variation of annual maximum and minimum temperatures expressed in terms of normalized temperature anomalies averaged over 40 stations.



(a) (b)

Figure 2.2 (a) Annual mean maximum and (b) minimum temperatures variability and trend over Ethiopia

Associated with rainfall and temperature change and variability, there was a recurrent draught and flood events in the country. There was also observation of water level rise and dry up of lakes in some parts of the country depending on the general trend of the temperature and rainfall pattern of the country.

2.5 Climate of study area

In order to understand the environment and the possible impact of human activity on it a basic knowledge of weather and climate is required. The former is the physical condition of the atmosphere at a specific time and place with regard to wind, temperature, cloud cover, fog, and precipitation. Weather is highly variable and somewhat unpredictable. As a result, a longer-term view of the weather pattern of a particular locality is frequently more useful as an environmental tool (Andrew et al, 1996).National Atlas of Ethiopia (1981) defined five traditional climatic zones: "Kur" (Alpine), 3000m and above; "Dega" (temperate), 2300m to about 3000m; "Weina Dega" (Sub tropical),1500 to about 2300m; "Kolla" (Tropical), 800m to about 1500m and "Bereha" (Desert), less than 800m.

The variation in the seasonal distribution of rain fall in Ethiopia can be attributed by the reference to the position of the Inter-Tropical Convergence Zone (ITCZ), the relationship of between upper and lower air circulation, the effects of topography and the role of local convection currents and the amount of rainfall (Kebede, 1964; Gizaw, 1965; Suzuki, 1967; in Daniel, 1977). Regarding the type of precipitation in Ethiopia, Hadwen (1975) stated that there are very few areas in the country where snow is an important type of precipitation, but hailstorms are quite common in the rainy season, especially in areas above 2,000m a.s.l. According to Daniel (1977) classification of Ethiopia's rainfall region, Addis Ababa is located in the region where the rainy months are contiguously distributed (***Regime IE***). In this region there are about seven rainy months from March to September/and the small rains occur from March to May. The big rains are from June to September. High concentration of rainfall occurs in July and very high concentration in August.

There are three recognized seasons. The main rainy season (kiremt) lasts generally from June to September during which south-west winds bring rains from the Atlantic Ocean. About 70-90 percent of total rainfall occurs during this season which is also typified by minimum levels of sunshine, low variation in daily temperatures and high relative humidity. A dry season (Bega) lasts from October to January during which clear skies are associated with maximum sunshine, high daily temperature variation, and low relative humidity. Minor rainy season (Belg) lasts from February to May during which south-east winds bring the small rains from the Indian Ocean and temperatures are at their highest (Daniel, 1977).

2.6 Climate change uncertainty

One of the major challenges both for climate modellers and users of climate change information is how to deal with uncertainty. Sources of uncertainty, which are not exclusive to climate change, are numerous, such as lack of information or knowledge, natural variability and processes that are essentially unpredictable. In climate change, rather than adopting a best or worst case scenario or an average of scenarios, it is commonly preferred to use a set of alternative scenarios and also from different GCMs. This helps to explore a whole range of plausible scenarios, thus addressing the uncertainty of climate change and its impacts in a more effective way. Accurate predictions will never be achieved given the complexity of the earth-ocean- atmosphere processes coupled to greenhouse gas emissions, land surface modifications and some feedback mechanisms which cannot be adequately modelled.

2.7 Climate change scenarios

Hydrologic models have been used to investigate the relationship between climate and water resources (Dvorak et al., 1997, Pao-Shan Yu et al., 2002, Miller et al., 2003, among many others). GCMs and regional climate models (RCMs) are important tools and are preferred for use in the assessment of impacts of climate change. The RCMs have a higher resolution than GCMs and are constructed for limited areas. Local climate change is influenced greatly by local features such as mountains, which are not well represented in GCMs because of their coarse resolution. Thus, RCMs may provide more credible information on climate change than GCMs, especially in regions with very heterogeneous terrain, but would still contain the uncertainties inherent in GCMs. This is because they are constrained by boundary conditions of GCMs in which they are nested. In the developing countries, regional climate data from RCMs is not readily available and is only at the early stages of development. One of the methods used for scenario generation is to estimate average annual changes in precipitation and temperature using one or more GCMs, and then use these estimates to adjust the observed time series of precipitation and temperature. Hypothetical scenarios using personal estimates or historical measurements of change, instead of GCM results, can also be generated using this procedure. One difficulty in this approach is that of maintaining consistency in adjusting variable by variable or a combination of variables. The other disadvantage of this approach is that it accounts only for changes in the mean of the time series and that it does not provide for a change in the variance. Changes in variability are important in determining the frequency of extreme climate events (Katz and Brown, 1992). Precipitation and temperature change fields imposed on the historical time series is one of the approaches used by IPCC for impact assessment (IPCC, 2001). Incremental changes as well as changes in variance of the time series have been implemented in some hydrologic assessments by varying precipitation and temperature changes on a monthly basis (Gleick, (1987), Bultot et al. (1988), Arnell, (1992), McCabe and Hay (1995), Chiew et al. (1995), Avila et al. (1996), Arnell and Reynard (1996), Singh and Kumar (1997), Müller et al. (2000), Middelkoop et al. (2001), Miller et al. (2003), among many others. Other methods of creating climate change scenarios use techniques of downscaling GCM outputs, such as regression methods (Kim et al., 1984; von Storch et al., 1993); weather pattern-based approaches (Wilby, 1995); and stochastic weather generators (Wilks, 1992; Katz, 1996, Semenov and Barrow, 1997). Downscaling of climate information from GCMs is an important exercise for hydrologic modeling which requires input data at high spatial and temporal resolutions. Besides, use of outputs from RCMs nested within GCM is also preferred because its resolution is much closer to that of landscape-scale hydrology.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 MATERIALS

The objective of the study is to carry out the rainfall runoff generating for Akaki catchments to evaluate climate change impact on extreme hydrological event for different scenarios. The methods used include desk study of the previous study on different basins, data collection from institutions such as Ministry of water resource, national meteorological agency and etc. After collecting the necessary data for the research delineation of the study areas, determination of basin characteristics, and analysis of rainfall and stream flow data have been made. The basin data is pre-processed by ARC-GIS 9.3 Arc- hydro and HEC-GeoHMS and exported to HEC-HMS for generation of rainfall-runoff model.

The materials used for this research are:-

- ARC-GIS to obtain hydrological and physical parameters and spatial information of the catchments of the study area.
- HEC-GeoHMS to sub-divide the basin to more manageable form and determine basin characteristics for future use in HEC-HMS for modeling.
- DEM data is used as an input data for ARC-GIS software for catchment delineation and estimation of catchment characteristic.
- Hydrological data and meteorological data and etc.

3.2. Discussions of Models

A number of hydrologic models have been developed which estimate the peak discharges and the runoff hydrograph for a given rainfall distribution. The applicability and performance of these hydrological models depends on factors such as mathematical representation of processes occurring, structural complexity of the model, and reliability of the model predictions for the available data, geographic location, climatic conditions, and area of interest, physiographic characteristics, computational skill level, Cost and others. These hydrological Models with different approaches are used nowadays for different water resource development works.

The choice of methods of estimation of peak discharge clearly depends on the data requirements and data availability. Among the different approaches, GIS based hydrological model systems are increasingly becoming major hydrological modeling tools because of its capability to handle the spatial variation of hydrological and physiographic inputs of the watershed. Several models, which either are embedded in the GIS environment or have capability of importing the GIS derived spatial and temporal attributes, have been developed. One of which is the United States Army Corps of Engineers HEC-HMS (the Hydrologic Engineering centers Hydrological Modeling System).The program simulates precipitation-runoff and routing processes, both natural and controlled (USACE, 2000). This study currently focused on application of watershed model (HEC-HMS) for Akaki catchments to establish rainfall-runoff modeling for the determination of important hydrologic parameter runoff volume and peak value in order to use them for climate change impact quantification and for further water resource development works. The figure 3.1 shows one of the processes in HEC-HMS model in converting rainfall to runoff.

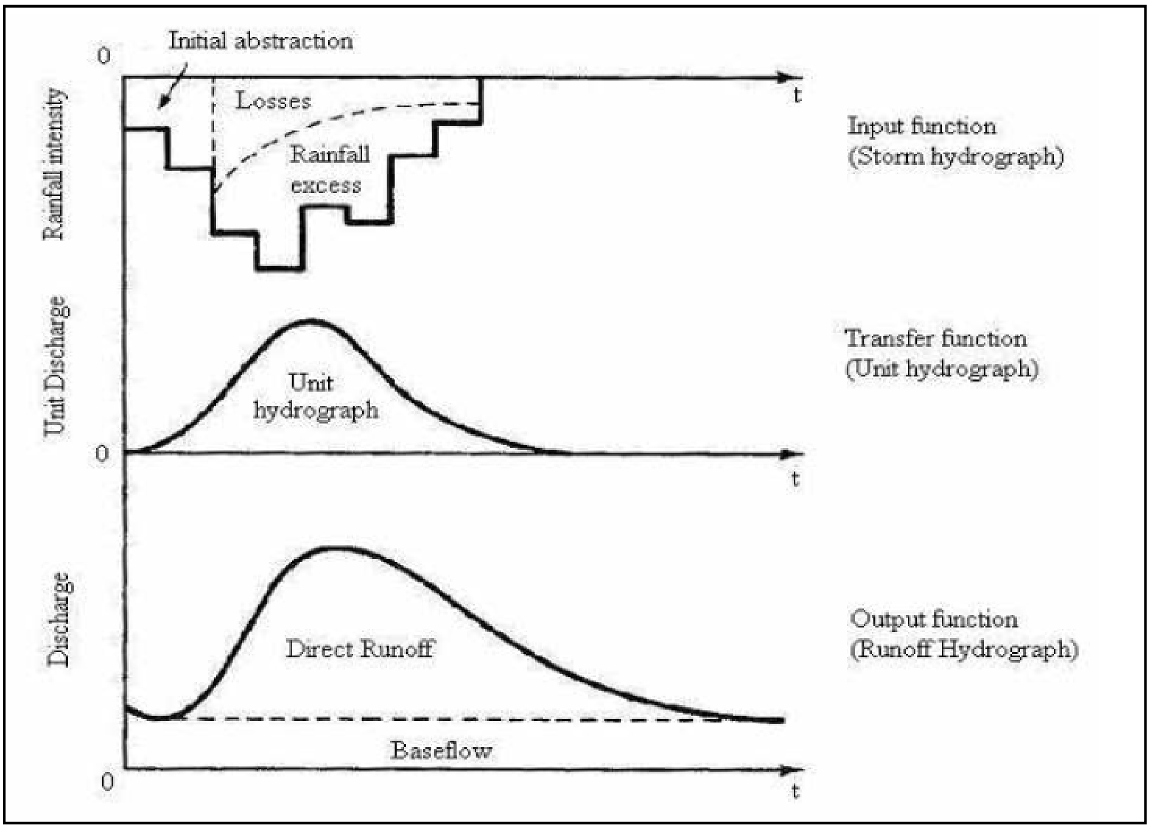


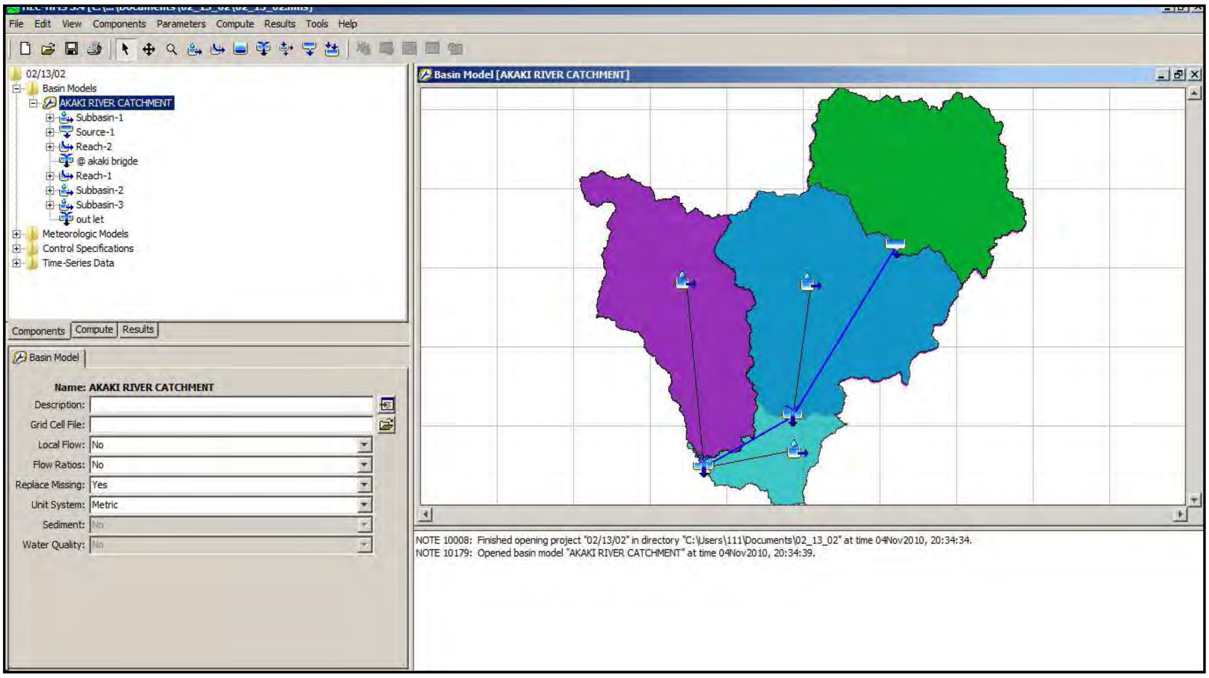
Figure 3.1: Conceptual Model Depicting Rainfall Runoff Process (McCuen, 1998)

3.2.1. HEC-GeoHMS

Hydrologic modeling has evolved to represent the sub-basin in more detail than the traditional lumped approach where hydrologic parameters are averaged over the sub-basin. With availability of rainfall and spatial data, hydrologic modeling on a grid level has introduced a more detailed representation of the basin. To meet the need of both the traditional lumped and distributed basin approaches, HEC-GeoHMS can create HMS input files that are compatible with both approaches. HEC-GeoHMS creates background map files, lumped basin model, a grid-cell parameter file, and a distributed basin model, which can be used by HMS to develop a hydrologic model. To assist with estimating hydrologic parameters, GeoHMS can generate tables containing physical characteristics of streams and watersheds. Starting from terrain preprocessing which comprises filling of sink, determination of flow direction, flow accumulation, stream definition, stream segmentation, watershed delineation, watershed polygon processing, stream segment processing, watershed aggregation, in GeoHMS basin processing, estimation of watershed characteristics, and hydrologic parameter estimation are performed. The basin is aggregated to workable sub-basins by merging small sub catchments which drain to common point and finally the result is exported to HEC-HMS for modeling the hydrologic system.

3.2.2. HEC-HMS Hydrological Model

HEC-HMS is a comprehensive hydrologic model developed by Hydrologic Engineering Center (HEC) of United States Army Corps of Engineers (USACE). It is designed to simulate the precipitation-runoff processes of dendrite watershed systems. It is also designed to be applicable in a wide range of geographic areas for solving the widest possible range of problems. This includes large river basin water supply and flood hydrology, and small urban or natural watershed runoff. Hydrographs produced by the program are used directly or in conjunction with other software for studies of water availability, urban drainage, flow forecasting, future urbanization impact, reservoir spillway design, flood damage reduction, floodplain regulation, wetlands hydrology (HEC, 2006b). HEC-HMS model components are used to simulate the hydrologic response in watershed. HMS model components include basin models, meteorological models, control specifications, and input data. A simulation calculates the precipitation-runoff response in the basin model given input from the meteorological model. The control specifications define the time period and time step of the simulation run. Input data components, such as time-series data, paired data, and gridded data are often required as parameter or boundary conditions in basin and meteorological models. The following figure shows the main component of the model to be used in this particular study.



Name: AKAKI RIVER CATCHMENT
Description:
Grid Cell File:
Local Flow: No
Flow Ratios: No
Replace Missing: Yes
Unit System: Metric
Sediment: No
Water Quality: No

```
NOTE 10008:  Finished opening project "02/13/02" in directory "C:\Users\111\Documents\02_13_02" at time 04Nov2010, 20:34:34.
NOTE 10179:  Opened basin model "AKAKI RIVER CATCHMENT" at time 04Nov2010, 20:34:39.
```

Figure 3. 2: Basic HEC-HMS Model Components

The main reasons for the selection of HEC-HMS hydrological model is that the model is physically based, spatially distributed and it belongs to public domain. It has been used in wide geographical area including climate change studies. Bashar and Zaki (2005) have applied this model for the whole Upper Blue Nile Basin and they have found good performance. The current version of HEC-HMS (3.4.0) is a highly flexible package. It includes different methods to simulate infiltration losses, transforming excess precipitation, base flow estimation and channel routing. The user can choose a suitable combination of models depending on the availability of data; the purpose of modeling and the required spatial and temporal scales. The following tables show some components of the model. For this particular study, Deficit and constant, Clark Unit Hydrograph Transformation, and Lag methods were used for loss rate, transform and Routing methods respectively. Details are given in subsequent sections:

3.2.3.1. Deficit and Constant

The deficit and constant rate loss method uses a single soil layer to account for continuous changes in moisture content. The maximum storage specifies the amount of water the soil layer can hold, specified as a depth. An upper bound would be the depth of the active soil layer m multiplied by the porosity. However, in most cases such an estimate will have to be reduced by the permanent wilting point and for other conditions that reduce the holding capacity of the soil. The constant rate defines the infiltration rate when the soil layer is saturated. A good approximation is to use the saturated hydraulic conductivity. The percentage of the sub-basin which is directly connected to impervious area can be specified. No loss calculations are carried out on the impervious area; all precipitation on that portion of the sub-basin becomes excess precipitation and subject to direct runoff. This study makes use of the deficit and constant loss rate model because it is designed to simulate the long-term relationship between rainfall, runoff, storage, Evapotranspiration, and soil losses.

3.2.3.2 Clark Unit Hydrograph Transform

Clark unit hydrograph technique was used to transform the excess rainfall to direct runoff. In this method, the processes of translation and attenuation of excess rainfall dominate the movement of flow through a watershed. Translation is the movement of flow down gradient through the watershed in response to gravity whereas attenuation is a reduction of the magnitude of the discharge as the excess is stored throughout the watershed. The time area curve built in the model develops the translation hydrograph resulting from a burst of precipitation, and the resulting translation hydrograph is routed through a linear reservoir for accounting storage attenuation affects across the sub basins. Time of concentration and storage coefficient are the two important parameters in Clark unit hydrograph transforming excess rainfall in to runoff. The time of concentration is used in the development of the translation hydrograph where as storage coefficient is used in the linear reservoir that accounts for storage changes. In this study due to lack of cross section and other morphological data to use other transformation model the Clark unit hydrograph method that requires only two input data, time of concentration and storage coefficient is employed.

3.2.3.3 Lag Model

The Lag routing method only represents the transformation of flood waves. It is best suited to short stream segment with predictable travel time that doesn't vary with depth of flow. The parameter is the lag time in minutes. Inflow to the reach is delayed in time by an amount equal to the specified lag, and then becomes outflow .The lag time for flood transformation in stream need to be determined through calibration. The routing models included in HEC-HMS are: Lag; Muskingum; Modified Puls (storage routing), Kinematic-wave; and Muskingham Cunge. Lag method is used in this study because of data limitation.

3.2.3.4 Modelling Base Flow with HEC-HMS

The Base flow models simulate the slow subsurface drainage of water. This base flow is the sustained runoff from precipitation that was stored temporarily in the watershed, plus the delayed subsurface runoff from the current storm. The base flow is added to the direct runoff (obtained with the transformation model) to obtain the total flow, which is routed through the stream reach to the outlet. To model the base flow, HEC-HMS offers alternative models, which can be combined with other loss, and direct runoff models. These are: the constant monthly varying base flow method, the Exponential recession model and the linear reservoir model. In this study, the mean monthly constant is adapted for base flow calculation methods.

3.3 HEC-HMS Model setup

HEC-HMS has four main model components: basin model, meteorologic model, control specifications and input data (time series, paired data and gridded data). The Basin Model, for instance, contains information relevant to the physical attributes of the model, such as basin areas, river reach connectivity, or reservoir data. Likewise, the Meteorological Model holds rainfall data. The Control Specifications section contains information pertinent to the timing of the model such as when a storm occurred and what type of time interval is to be used in the model, etc. Finally, the input data component stores parameters and boundary conditions for basin and meteorological models (HEC, 2006b). Each of the sections is explored below individually.

3.3.1 Basin Model

The Basin model contains the hydrologic element and their connectivity that represents the movement of water through the drainage system. Its main purpose is to convert the atmospheric conditions in to stream flow at specific locations in the watershed (HEC, 2006b). HEC-GeoHMS, an Arc view extension developed by the U.S.Army Corps of Engineers (USACE) was employed to create the basin model background map file and to delineate the sub catchments from the Digital Elevation Model (DEM).The background maps provide a spatial context for the hydrologic elements composing basin model. The maps are not actually used in the computational process, but they can be very helpful in showing the spatial relationship between the elements. They are commonly used for showing the boundaries of a watershed or the location of streams. Terrain preprocessing, Basin processing and HMS model support are the main functionalities of HEC-GeoHMS. In the terrain preprocessing DEM is used as input and a series of steps consisting of computing the flow direction, flow accumulation, stream definition, stream delineation, watershed delineation, and watershed aggregation were performed step by step to derive the drainage networks. The basin processing step gives capability of merging, editing and subdividing of basins and rivers whereas the HMS model support produces a number of hydrologic inputs that are used directly in HMS. With this the basin model and background map files are included and imported in to HMS the setup is then completed with meteorologic and control specification.

3.3.2 Meteorological Model

The meteorologic component is the first computational element by means of which precipitation input is spatially and temporally distributed over the river basin. The spatio-temporal precipitation distribution is accomplished by the gauge weight method. The Thiessen’s polygon technique was used to determine the gauge weights. The Meteorologic model uses monthly evapotranspiartion as input for continuous hydrological simulation which is the case for this model. For this particular study potential evapotranspiartion computation were carried out using FAO Penman- Monteith method in Cropwat model. FAO Penman-Monteith Method is recommended as a sole standard method for the definition and computation of the reference evapotranpspiartion (ETo) (Allen et al., 1990).

3.3.3 Control specification and HEC-DSSvue

Control specifications are one of the main components of a project, and principally used to control simulation runs. They control when a simulation starts and stops, and what time interval is used in the simulation. A simulation run is created by combining a basin model, meteorological model, and control specifications. The data input to HEC-HMS is possible through two ways. The first and simplest method is manual data input. Here the time series data is copied from Excel or any compatible format and pasted in HEC-HMS time series table for any time series data (either precipitation or discharge).The second and relatively complex is saving the data in HEC-DSS and retrieving from it during analysis. For this study manual data input method is used because this method is simple one.

3.3.4 Model Calibration, Verification and Sensitivity Analysis

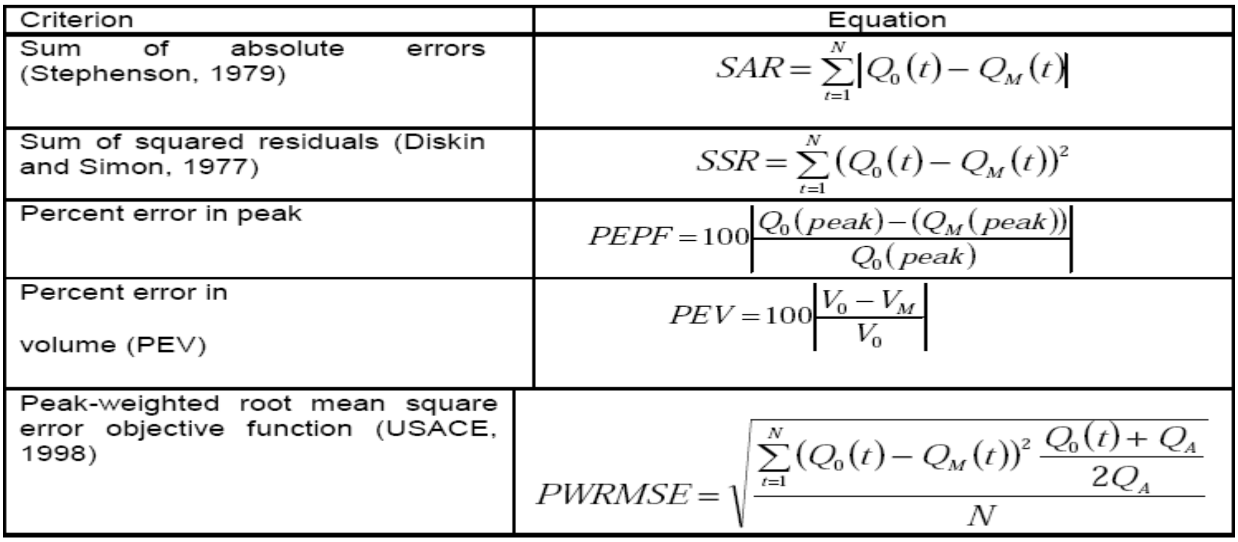
Rainfall and runoff observations must be from the same storm. The runoff time series should represent all runoff due to the selected rainfall time series. The rainfall data must provide adequate spatial coverage of the watershed. The volume of the runoff hydrograph should approximately equal the volume of the rainfall hyetograph. If the runoff volume is slightly less, water is being lost to infiltration, as expected. But if the runoff volume is significantly less, this may indicate that flow is stored in natural or engineered ponds, or that water is diverted out of the stream. Similarly, if the runoff volume is slightly greater, base flow is contributing to the total flow, as expected.

However, if the runoff volume is much greater, this may indicate that flow is entering the system from other sources, or that the rainfall was not measured accurately. The duration of the rainfall should exceed the time of concentration of the watershed to ensure that the entire watershed upstream of the concentration point is contributing to the observed runoff.

3.3.4.1 Calibration

HEC-HMS has the capabilities to process automated calibration in order to minimize a specific objective function, such as sum of the absolute error, sum of the squared error, percent error in peak, and peak-weighted root mean square error. However in this case, the resulted automated parameters are not reasonable and practical. Therefore manual calibration method was adopted to determine a practical range of the parameter values preserving the hydrograph shape, minimum error in peak discharges and volumes. To compare a computed hydrograph to an observed hydrograph, the program computes an index of the goodness-of-fit. Algorithms included in program search for the model parameters that yield best value of an index, also known as objective function. Model calibration is a systematic process of adjusting model parameter values until model results match acceptably the observed data. The quantitative measure of the match is described by the objective function. In the precipitation-runoff models, this function measures the degree of variation between the observed and the computed hydrographs. The calibration process finds the optimal parameter values that minimize the objective function. Further, the calibration estimates some model parameters that cannot be estimated by observation or measurement, or have no direct physical meaning. Calibration can be either manual or automated (optimization). Manual calibration relies on user's knowledge of basin physical properties and expertise in hydrologic modeling. In the automated calibration model parameters are iteratively adjusted until the value of the selected objective function is minimized (CFCAS, 2004). The latest version of HEC-HMS model includes optimization manager that allows automated model calibration. There are five objective functions available in the optimization manager as shown in Table 3.3 (CFCAS, 2004). However, the PWRMSE was used for this study, because this paper is concern on the peak flow (extreme flow).

Table: 3. 3 Objective function determination method available in HEC HMS model



Criterion	Equation
Sum of absolute errors (Stephenson, 1979)	$SAR = \sum_{t=1}^{N} \left\| Q_0(t) - Q_M(t) \right\|$
Sum of squared residuals (Diskin and Simon, 1977)	$SSR = \sum_{t=1}^{N} (Q_0(t) - Q_M(t))^2$
Percent error in peak	$PEPF = 100 \left\| \frac{Q_0(peak) - (Q_M(peak))}{Q_0(peak)} \right\|$
Percent error in volume (PEV)	$PEV = 100 \left\| \frac{V_0 - V_M}{V_0} \right\|$
Peak-weighted root mean square error objective function (USACE, 1998)	$PWRMSE = \sqrt{\frac{\sum_{t=1}^{N} (Q_0(t) - Q_M(t))^2 \frac{Q_0(t) + Q_A}{2Q_A}}{N}}$

Source: HEC-HMS Technical Reference manual

Note:

[1]Q0 (QM) is the observed (modeled) flow at time t1 and QA is the average observed flow. V0 (VM) is the volume of the observed (modeled) hydrograph

- ❖ Peak-weighted root mean square error (PWRMSE). Using a weighting factor, the PWRMSE measure gives greater overall weight to error near the peak discharge:

$$PWRMSE = \sqrt{\frac{\sum_{t=1}^{N} (Q_0(t) - Q_M(t))^2 \frac{Q_0(t) + Q_A}{2Q_A}}{N}};$$

$$Q_A = \frac{1}{N} \sum_{t=1}^{N} Q_0(t)$$

……………………………… [3.1]

Where : Q0 (QM) is the observed (modeled) flow at time t1 and QA is the average Observed flow.

3.3.4. 2 Verification

Model verification is the process of testing model capability to simulate observed data other than used for the calibration, with acceptable accuracy. During this process, calibrated model parameters are not subject to change, their values are kept constant. The quantitative measure of the match is again the degree of variation between computed and observed hydrographs.

3.3.4.3 Sensitivity analysis

Search method estimate optimal parameter values but do not indicate which parameters have the greatest impact on the solution. At the conclusion of the optimization, the sensitivity of each parameter with respect to the objective function is estimated. Values of the objective function are computed for parameter values 0.995 and 1.005 times the optimal values using the following equation:

$$S = \frac{(0.995X-1.005X}{(X)} \qquad \text{..} \; [3.\ 2]$$

Where S is the sensitivity measure and X is the final parameter value at the end of optimization. The sensitivity measure is the percent change in the value of the objective function resulting from a 1% increase in the value of the parameter. If a parameter value obtained by multiplying by 0.995 or 1.005 exceeds a hard constraint, the constraint value is used to calculate the sensitivity measure. All other parameter values are held at their solution to compute the sensitivity for an individual parameter (USACE, 2001).

3.3.4. Model Efficiency Criteria

The performance of a model must be judged on the context to which, it satisfies its practical objectives, the achieved level of accuracy persists through different samples of data, and it can sustain the achieved level of accuracy when subjected to diverse applications and tests other than those used for calibrating the model. Model efficiency criteria have to be applied to explore the level at which the required performance of the model is achieved. The most widely accepted model efficiency criterion is the one suggested by Nash and Sutcliffe (1970). In this criterion, the efficiency **R^2** is defined analogous to the coefficient of determination used in linear regression. It denotes the proportion of the initial variance accounted for by the model and is given by:

$$R^2 = \frac{F - F_o}{F_o} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots [3.\ 3]$$

In which

$$\boxed{\begin{aligned} F_0 &= \sum_{t=1} (Q_{t,obs} - \overline{Q}_{obs})^2 \\ F &= \sum_{t=1}^{n} (Q_{t,obs} - Q_{t,sim})^2 \end{aligned}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots [3.\ 4]$$

Where, $F_{o=}$ *the initial (no model) variance, and*

F=the residual model variance

3.4 Model simulation corresponding to future climate change scenarios

After calibrating the hydrological model the next step is simulation of flows corresponding to future climate conditions by using the downscaled precipitation and temperature data for each emission scenarios discussed in the previous sections. This will help to identify any specific trend in the mean flows in the Akaki River corresponding to future time horizon considered in this study. The future simulation is done with the downscaled precipitation and temperature data from GCM. The downscaled precipitation data were divided in to two (2030s and 2090s) data periods and the hydrologic model is re-run for each case. One of the main limitations of this study is that, except temperature and rainfall all the other climate variables such as wind speed, sunshine hours, and relative humidity were assumed to be constant which is not possible in actual case. Since climate is a complex process and it involves many complex feedbacks this assumption doesn’t hold but the main objective of this study is to provide an indicative possible effect of climate change on the stream flow assuming changes only in the two main drivers (Temperature and precipitation).

3.5 Flood frequency analysis

Flood frequency analysis is determination of the magnitude of flood flows at deferent frequencies or recurrence intervals. Due to its large economical and environmental impact, such analysis remains a subject of great importance in catchment infrastructures design and management .Flood frequency analyses are usually based on annual flood series. The standard procedure to determine probabilities of flood flows consists of fitting the observed stream flow recorded to specific probability distribution. Assuming independence and stationary, a statically distribution is fitted to the data using a given estimation method ,and flood with pre-specified exceedance probability can then be inferred from this distribution .There are a number of two- and three-parameter distributions described in literature exceedance (Cunnane,1987) such as Gumbel, General Extreme value ,Generalized Logistic ,Log-Normal, Gama and Log-Pearson

III. However, the Log-Pearson III method is generally recommended for analysis of annual flood series (Klemes, 1993).

The result will show the possible trend in the frequency of flooding in Akaki rive corresponding to the climate change scenario. The US army Corps of Engineers flood frequency analysis software known as HEC-SSP is used in this study. HEC-SSP is used to compute flood frequency analysis in accordance with “Guidelines for Determination flood Flow frequencies”Bulletin17B of the U.S Water Resources Council(USWR); March1982.This guideline is designed for computing flood frequency curves where systematic stream gauging records of sufficient length(at least 10 years) to warrant statistical analysis are available as basis of determination .

When developing flood flow frequency curve, the analyst should consider all available information; which could be either observed flood discharge data or flood discharge estimated from climate data (rainfall). Once the discharge data is made available, flood events can be analyzed using annual series. The annual flood series is based on the maximum flood peak for each year. The analysis in this section based on annual flood series and the Pearson Type III distribution with log transformation of the flood data (log-Pearson Type III) is recommended as the basic distribution for defining annual flood series and is implemented in HEC-SSP. The method of moments is used to determine the statistical parameters of the distribution from station data.

CHAPTER FOUR

4.0 DATA COLLECTION AND ANALYSIS

4 .1 General

One of the problems in hydrology especially in developing countries is hydrological data both in quantity (length of record) and quality (standard of scientific approach). The output of any research depends highly on data input. The Advances in scientific hydrology and in the practice of engineering hydrology are dependent on good, reliable and continuous measurements of the hydrological variables. The measurements are recorded by a wide range of methods, from the simple writing down of a number by a single observer to the invisible marking of electronic impulses on magnetic tape. Although the most advanced techniques are used in the developed countries, many emerging nations of the third world employ only direct manual methods (Shaw, 2004). In this sub topic data from different institutes are assembled and analyzed giving more emphasis on hydro-metrological and basin variables.

4.2 Meteorological Data

Meteorological data is needed by the HEC-HMS model to simulate the hydrological conditions of the study area of catchment .The metrological data required for this study were collected from the Ethiopia National Metrological Services Agency (NMSA). There are around five meteorological stations in Akaki catchment. Two of these stations are first classes, which measure all meteorological variables such as rainfall, temperature, sunshine hour, relative humidity, pan evaporation, wind speed and directions. The locations of the meteorological stations in the location are shown figure 4.1. In this study, Daily rainfall records of fives stations for the year between1997-2004 is used to analyze current flow in catchment and to determinate parameter of the study area for further hydrological simulation in different scenarios. The mean monthly rainfall of stations at Addis Ababa Bole, Addis Ababa Observatory, Intoto, Sendafa and Akaki Mission are shown in Figure 4.2. The five stations are located at different latitude and longitudes as shown in table 4.1.below. Daily time series rainfall recorded of all the meteorological stations in catchment in is also provided in appendix: D.

The mean monthly and annual mean rainfall of National Meteorological Services Agency (NMSA) stations at Addis Ababa Bole, Addis Ababa Observatory, Intoto, Sendafa and Akaki Mission are shown in table 4.2.

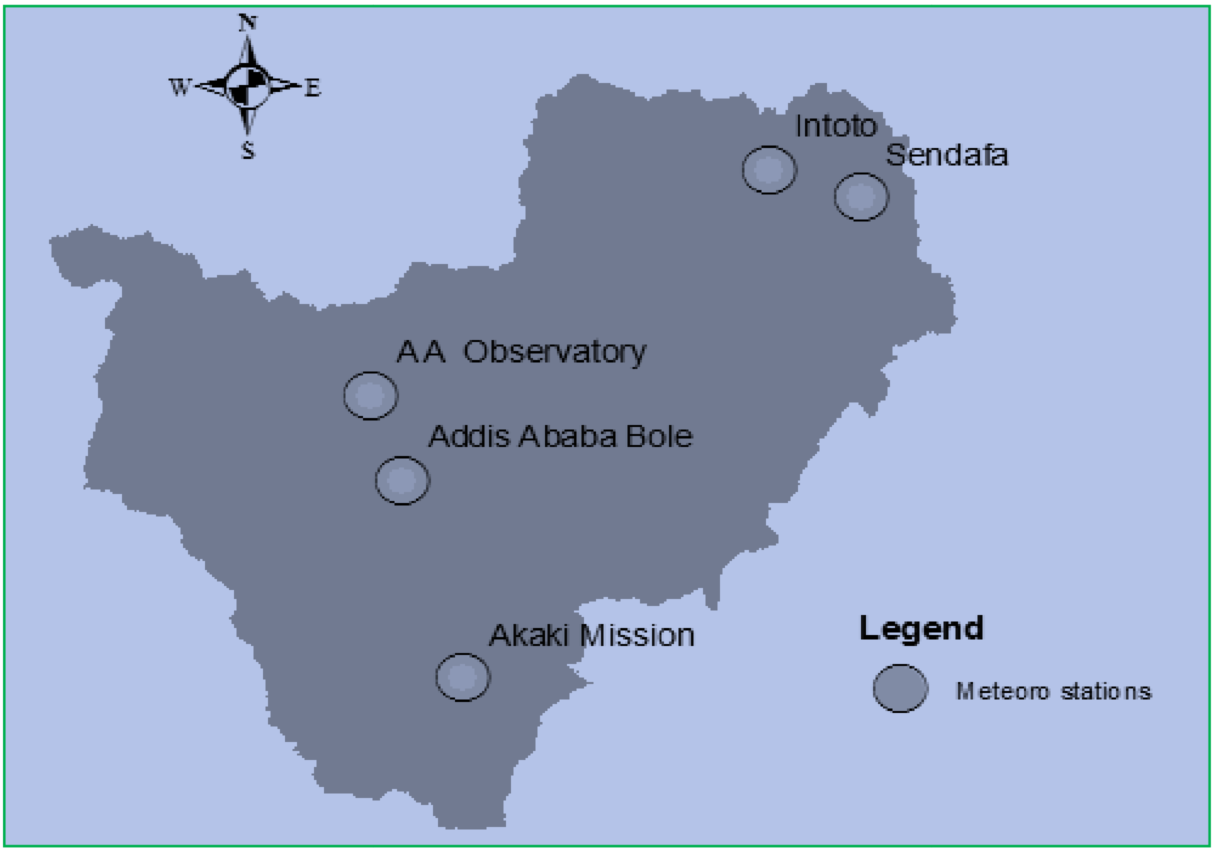


Figure 4.1: Metrological stations in Akaki catchment area

Table 4.1: Climatic Stations in Akaki River Catchment Areas.

No	Location	Longitude	Latitude	Elevation (a.s.l.)
1	A.A Bole Airport	38^0-45'	09^0-02	2324
2	A.A Observatory	38^0-43'	09^0-02'	2408
3	Sendafa	39^0-01'	09^0-09'	2560
4	Akaki Mission	38^0-25'	08^0-56'	2120
5	Entoto	38^0-80'	09^0-03'	2900

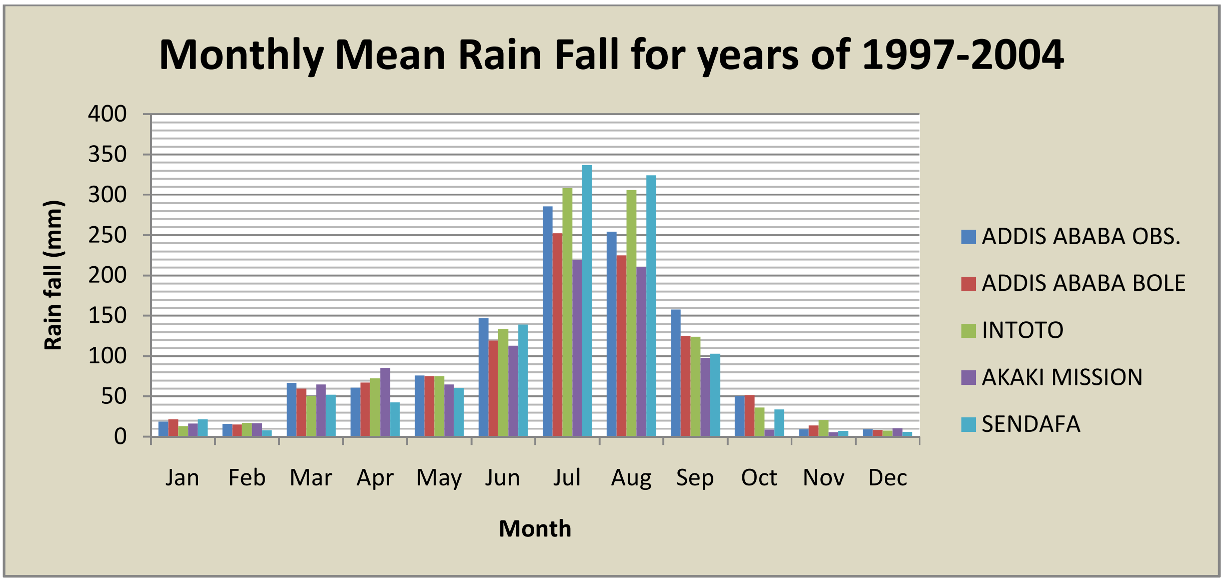


Figure 4.2: Monthly mean rainfall of stations in study area

Table 4.2 Mean monthly rainfall of five stations in the study area

Stations	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual mean**
A.A OBS. (mm)	18	16	67	61	76	147	286	254	158	50	9	9	**1151**
A.A BOLE (mm)	21	15	59	67.4	74.9	119	252.4	224.9	125	51.3	13.9	8.26	**1033.2**
INTOTO (mm)	13.3	16.9	50.3	72.5	75.2	133	308.2	306.1	124	36	20.4	7.38	**1163.4**
AKAKI (mm)	16.1	16.7	64.4	85.6	64.5	113	218.9	210.4	98	8.91	5.25	10.5	**912.1**
SENDAFA (mm)	21.3	7.9	51.7	42.4	60.2	139	337	324	103	33.8	6.83	5.89	**1132.4**

4.3 Hydrological Data

The hydrological data is required for performance sensitivity analysis, calibration and validation of the model. The hydrological data was also collected from the Ethiopian MoWE (Ministry of Water and Energy) hydrological section. The hydrological data collected was daily flow which used for modeling and climate change impact analysis. There is only one stream flow gauging station in the study area which was gauged near Akaki town on Addis Ababa - Debrezeit road. The gauged part of the catchment is about 61% of the total catchment area (Figure 4.3). Flow data for study area at Akaki Bridge (884 km2) from 1997 to 2004 was collected from Ministry of Water and Energy, department of hydrology. Time series plots of flow data is provided in Appendix: C and the mean monthly discharges of Big Akaki River shown in the figure 4.4.

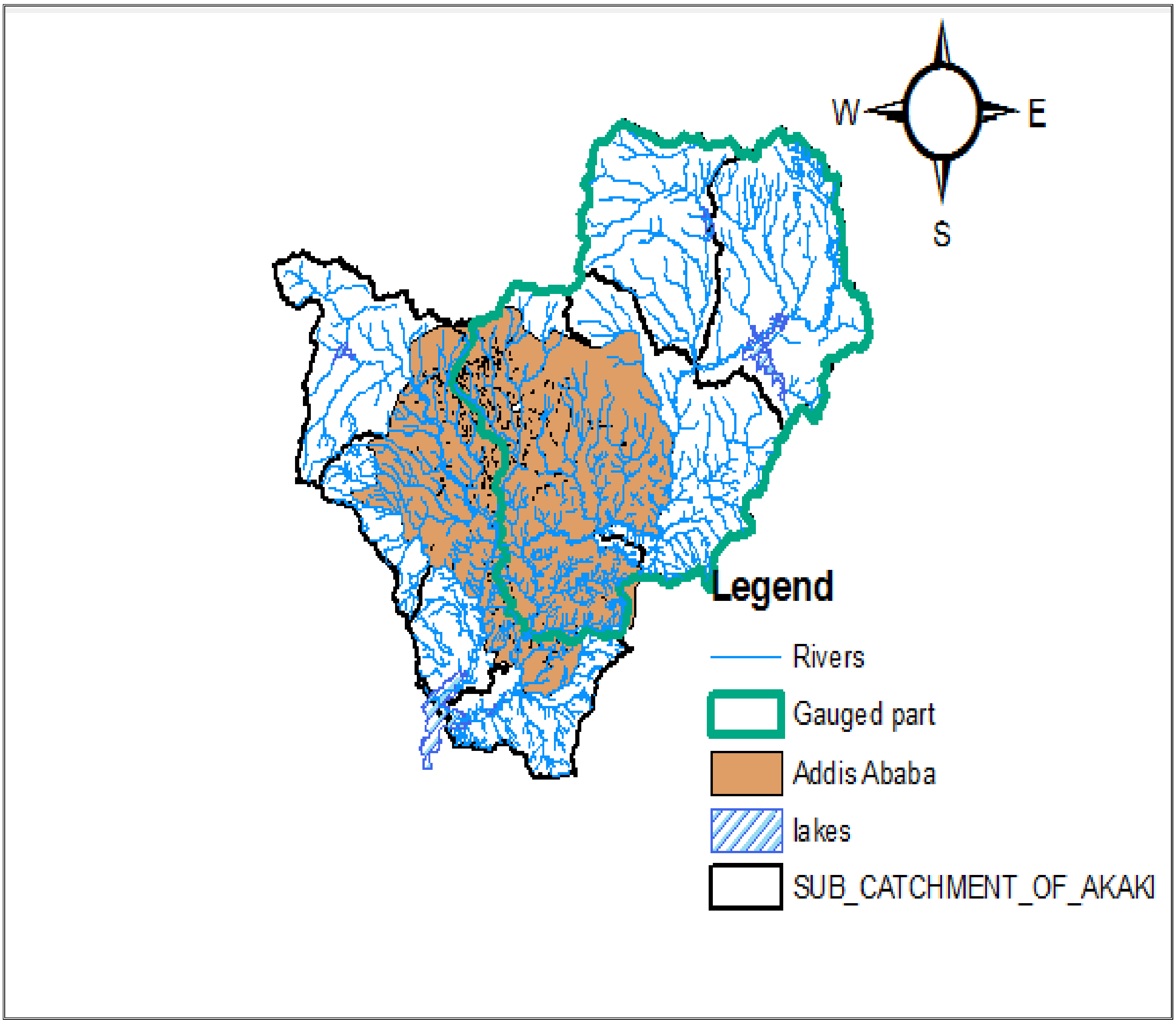


Figure 4.3: The gauged part of study area

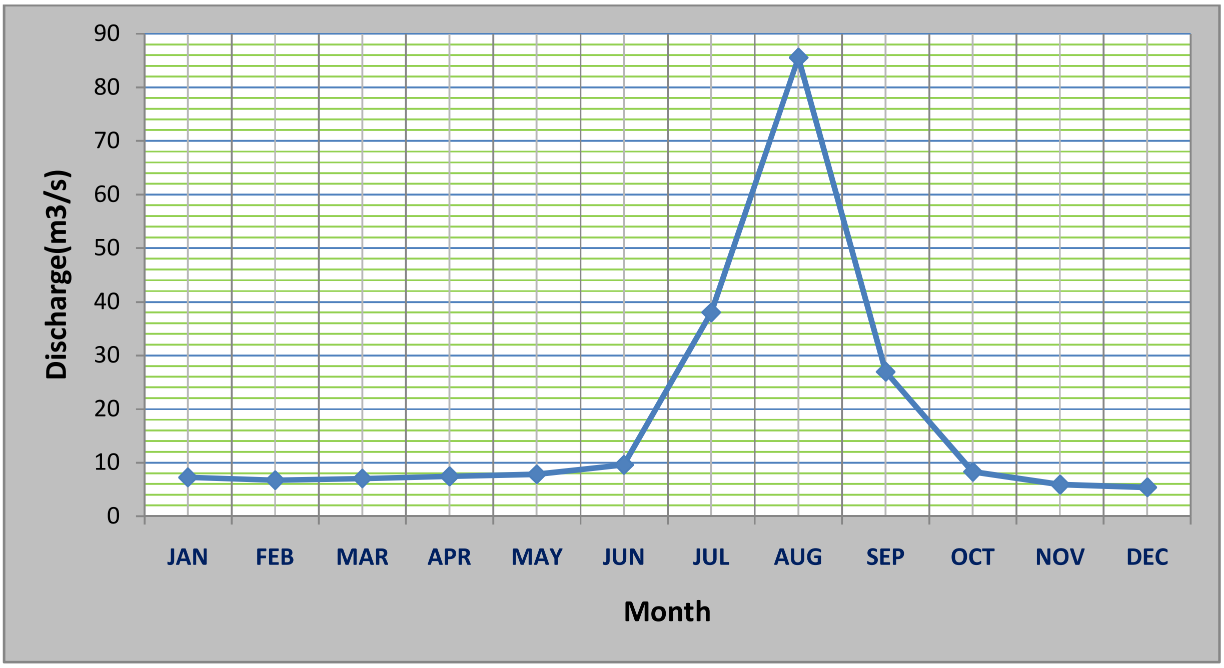


Figure 4.4: Mean monthly Discharge of Big Akaki River

4.4 Digital Elevation Model (DEM)

The DEM 90 by 90 Ethiopia from Ministry of Water and Energy was used to delineate the study area. The DEM was processed according to the location of the study area. The process of DEM is described in methodology.

CHAPTER FIVE

5.0 RESULT AND DISCUSSIONS

5.1 Analysis of Climate Change Scenario

5.1.1 Precipitation

The precipitation projection exhibited an increase in annual mean precipitation in the 2030s and 2090s time periods. As it can be seen in figures 5.1 and 5.2 precipitation increase would be expected during rainy season (Kirmet) where as Belg consisting of February, March, April and May (FMAM) precipitation shows an increase in 2030s time period and a decrease for 2090s. Precipitation is also expected to increase in Bega season consisting of October, November, December and January (ONDJ) months. But these changes are not as pronounced as we can see from the figures, because the absolute precipitation values are small in Bega (ONDJ). As it can be shown on figure 5.2 for example in 2090s in the month of October precipitation change from 75mm/month to 174mm/month shows 132 % precipitation increases.

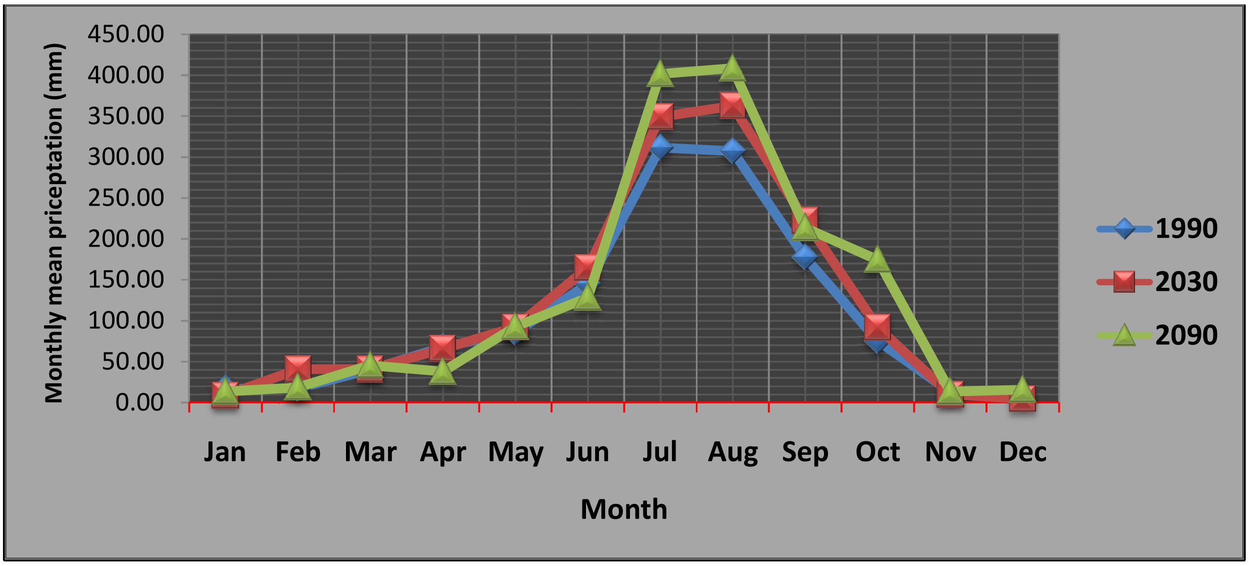


Figure 5.1: *Monthly mean precipitation for different time periods*

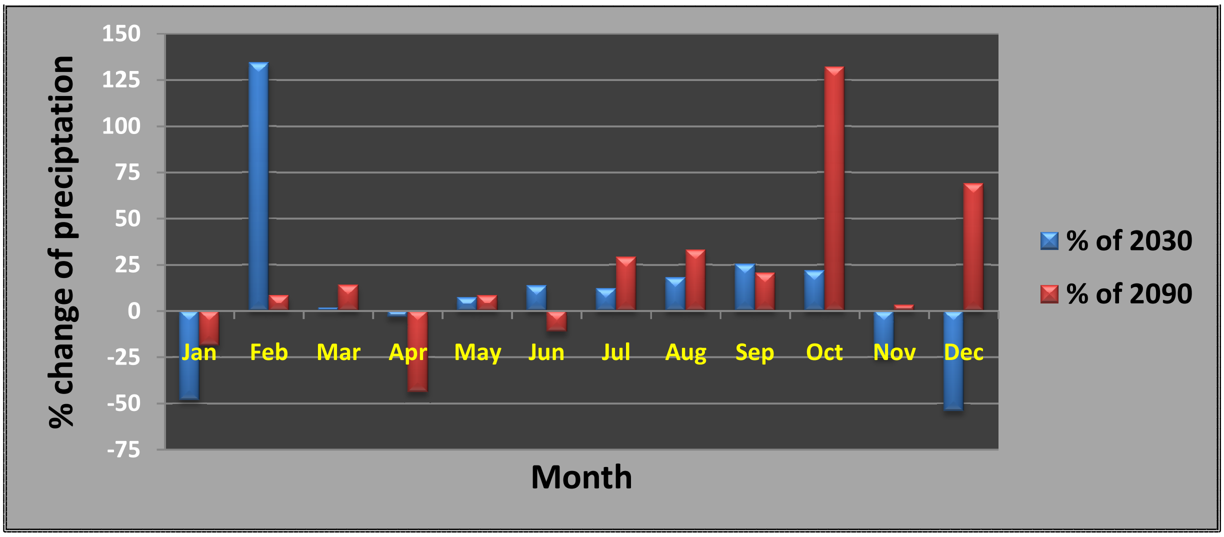


Figure 5.2: precipitation increase/ decrease in percentage for study area

5.1.2 Max Temperature

The maximum temperature scenario generation showed that there may be an increase in mean maximum temperature in all the months in the 2030s and 2090s. As it shown in figures 5.3 below seasonally, a pronounced increase in mean maximum temperature is observed in the Bega (dry season) and Kiremt (rainy season).

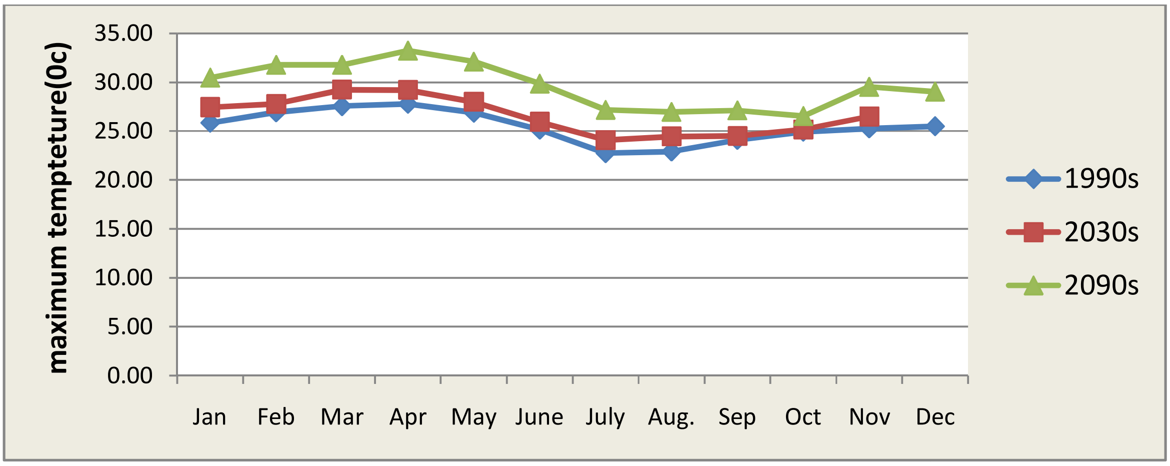


Figure5.3: Monthly mean maximum temperature

5.1.3 Minimum Temperature

Like the maximum temperature there is a general increasing trend minimum temperature.

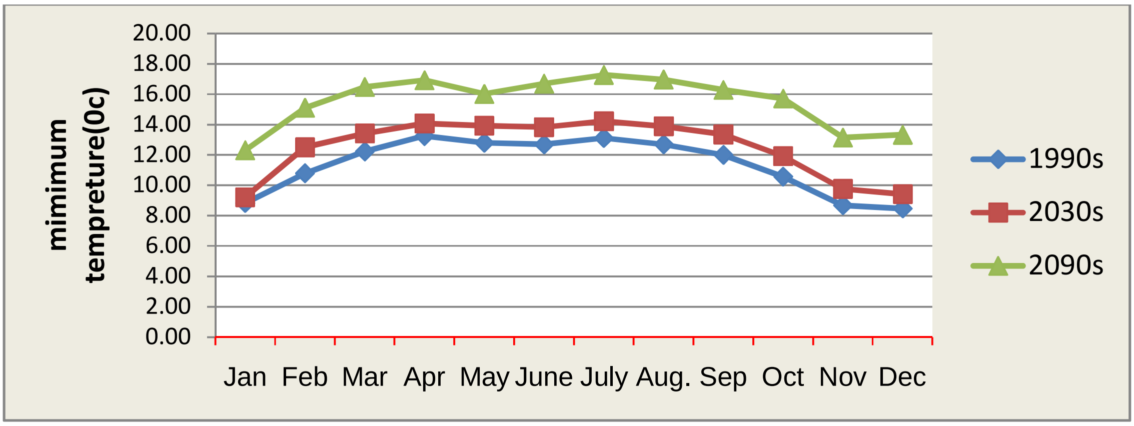


Figure5.4: Monthly mean minimum tempera

5.2 Descriptive statistics results for simulated flow

Statistics is a set of procedures for gathering, measuring, classifying, computing, describing, analyzing, and interpreting systematically acquired quantitative data. Descriptive Statistics gives numerical and graphic procedures to summarize a collection of data in a clear and understandable way. Descriptive statistics help us to simplify large amounts of data in a sensible way. Each descriptive statistic reduces lots of data into a simpler summary. There are two basic methods: numerical and graphical. Using the numerical approach one might compute statistics such as minimum value; maximum value; mean; standard deviation, coefficient of variance; skewness of deferent time periods for the Akaki River catchment. These statistics convey information about the average. Graphical methods are better suited than numerical methods for identifying patterns in the data. Numerical approaches are more precise. Since the numerical and graphical approaches complement each other, it is wise to use both. Table 5.1 shows that the coefficient of variance for 1990s, 2030s and 2090s time periods. This figure shows there is variability related to climate change but the variability is no clear due to the variability is different from month to month. The detail monthly simulated flow result for each time periods: 1990s, 2030s and 2090s are attached in appendix G.

Table 5.1: Descriptive statistics results of simulated flow for 1990s, 2030s and 2090s time periods.

Time perio	Statistic	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1990s	Mean	6.6	9.2	15.3	22.9	25.2	45.8	118	165.4	71.4	21	20.6	4.5	43.7
	Max	23.1	26.5	37.5	39.8	40.1	58.2	177	263.4	98.2	31	31.4	15	53.3
	Min	2.1	2.2	2.2	5.7	14.1	32.9	74.5	97.7	43.7	6.5	6.5	2.3	31.9
	S.dev	6.3	7.9	12.7	11.7	7	9.3	27.9	55.6	16.7	9.3	9.3	3.8	7.4
	C_s	2.3	1.3	1.1	0	0.9	-0.1	0.7	0.3	0.3	-0	-0.3	2.9	-0.1
	C_v	1	0.9	0.8	0.5	0.3	0.2	0.2	0.3	0.2	0.5	0.5	0.8	0.2
2030s	Mean	5.2	8.9	16.1	15.7	27.9	42.2	145	195.7	81.9	47	6.3	6.2	49.8
	Max	16.7	16.3	37.4	22.9	40.5	64.5	188	274.9	105.6	99	20.3	26	59.3
	Min	1.9	2.2	5.8	7.5	19.1	24.9	109	161.7	63	13	2.6	2	43.2
	S.dev	4.5	5.4	9	5.3	8.4	12.9	21.3	37	12.6	25	5.7	7.4	6
	C_s	2.2	0.1	1.6	0.2	0.3	0.3	0.5	1.2	0.4	1	2	2.4	0.5
	C_v	0.9	0.6	0.6	0.3	0.3	0.3	0.1	0.2	0.2	0.5	0.9	1.2	0.1
2090s	Mean	5.2	8.9	16.1	15.7	27.9	42.2	145	195.7	81.9	47	6.3	6.2	49.8
	Max	16.7	16.3	37.4	22.9	40.5	64.5	188	274.9	105.6	99	20.3	26	59.3
	Min	1.9	2.2	5.8	7.5	19.1	24.9	109	161.7	63	13	2.6	2	43.2
	S. dev	4.5	5.4	9	5.3	8.4	12.9	21.3	37	12.6	25	5.7	7.4	6
	C_s	2.2	0.1	1.6	0.2	0.3	0.3	0.5	1.2	0.4	1	2	2.4	0.5
	C_v	0.9	0.6	0.6	0.3	0.3	0.3	0.1	0.2	0.2	0.5	0.9	1.2	0.1

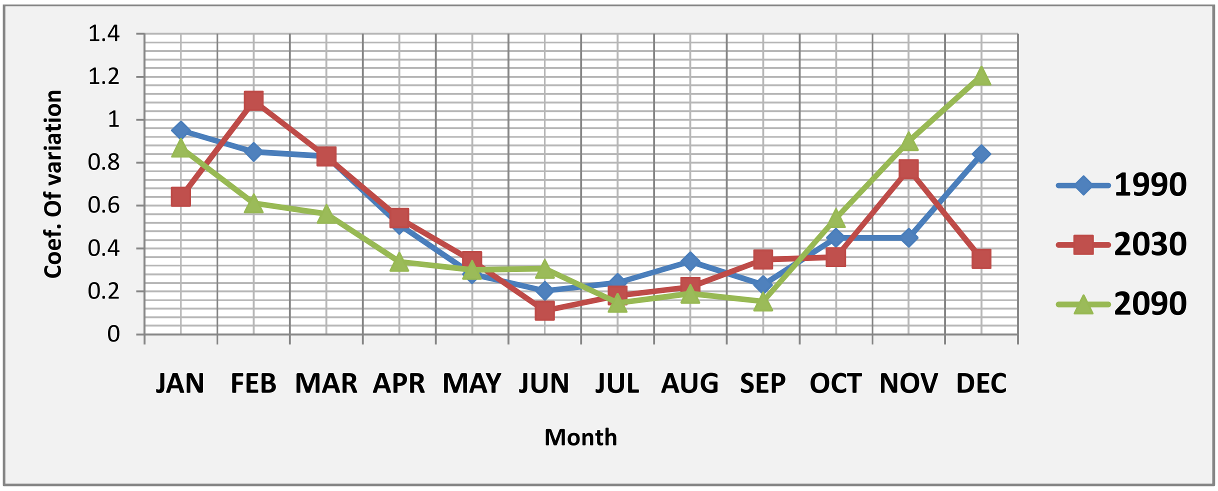


Figure 5.5: Coefficient of variations for deferent time period horizon.

5.3 HEC-HMS Hydrological Model Results

5.3.1 Calibration

The calibration of HEC-HMS for this particular study area was carried out using five years from 2000 to 2004 daily rainfall and daily stream flow data of Big Akaki River. Table 5.2 shows the optimal parameters found in calibration. The coefficient of determination (R^2) during calibration was found to be 0.864 (Figure 5.8). The stochastic nature of precipitation effect on the simulated hydrograph was handled by stochastic calibration. In the stochastic calibration observed and simulated discharge time series were arranged in descending order and the objective function, $\mathbf{\sum(Q_{ob}-Q_{sim})^2}$ was minimized by observing the plot of observed and simulated discharge. As it can be seen in (Figure 5.6, 5.8, 5.9 and 5.11) the observed and simulated hydrograph coincides very well for peak discharge for calibration and verification respectively. Therefore we can conclude that the model can reasonably be used for the intended purpose.

Table 5.2: optimal model calibration parameters

Parameters	**Minimum**	**Maximum**	**Optimal parameters**		
	Loss parameters				
Constant Rate (mm/hr)	0.001	500			**2**
Initial Deficit (mm)	0.001	500			**20**
Maximum Deficit(mm)	0.001	500			**117**
Recovery Factory	0.1	5			**5**
	Transform				
Storage Coefficient(Hr)	0.01	1000			**13.6**
Time of concentration (Hr)	1	1000			**25.14**
	Routing				
Lag time (Min)	0	1000		**165**	

Deficit and constant loss method is adopted together with constant base flow and Clack unit hydrograph transformation. The parameters needed for each adopted methods were taken into consideration in this simulation. The above tables 5.2 indicates parameters used with their minimum and maximum limits. Time of concentration, Clark storage component as well as base flow parameters had significant influence on the simulated flow discharges. The remaining parameters were adjusted to match the simulated and observed peak flows, volumes and hydrograph shape. Optimized parameters are also shown in this table 5.2. As it can be seen in the figure 5.6 the observed and simulated hydrograph coincides very well.

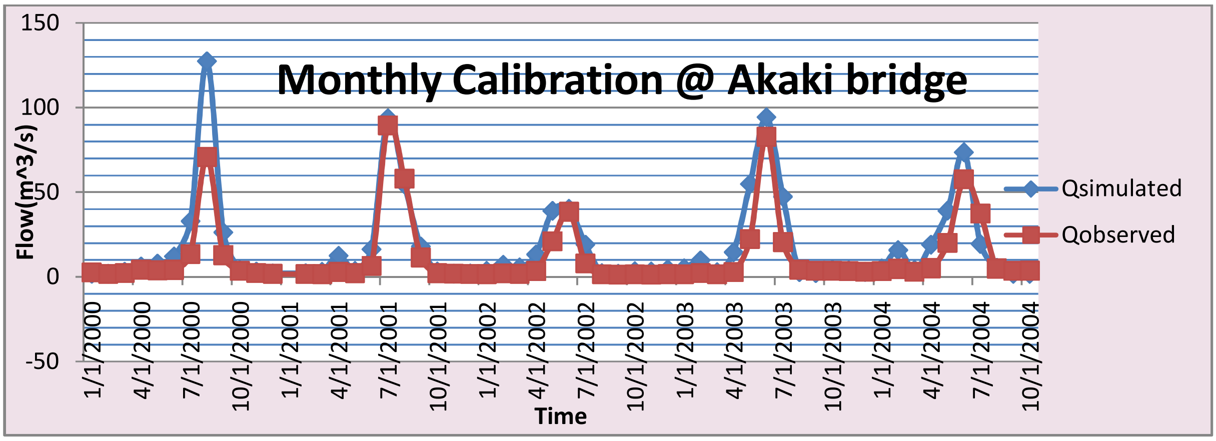


Figure5.6: Simulated and observed flow hydrographs

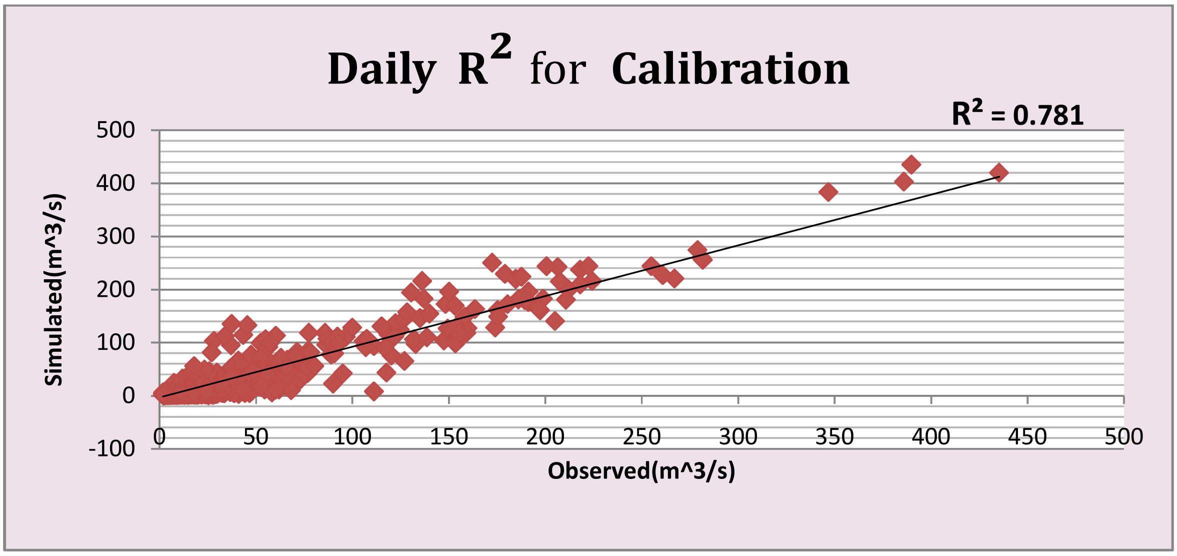


Figure 5.7: Observed vs. simulated (calibration)

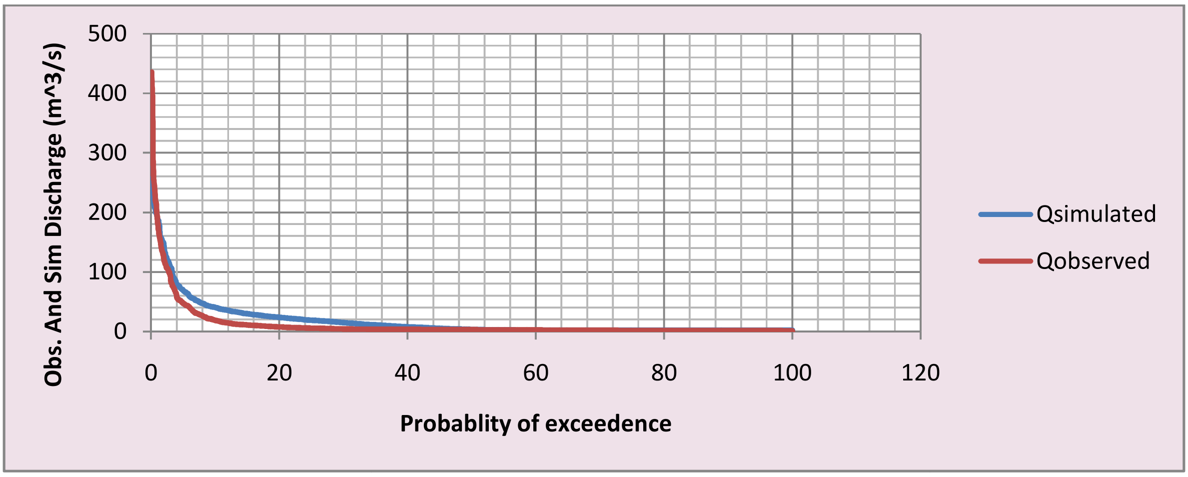


Figure5.8: Simulated and observed flow in model calibration (stochastic calibration)

5.4.2 Validation

Model validation was carried out over the period of 1997-1999. As it can be seen in (Figure 5.11) the model performance is improved, the coefficient of determination in this case is found to be 0.806 (Figure 5.12). The observed and simulated flow hydrograph show well agreement except in peak flow in year 1999. In general the model performed reasonably in simulating flows for periods outside of the calibration period, based on adjusted parameters during calibration.

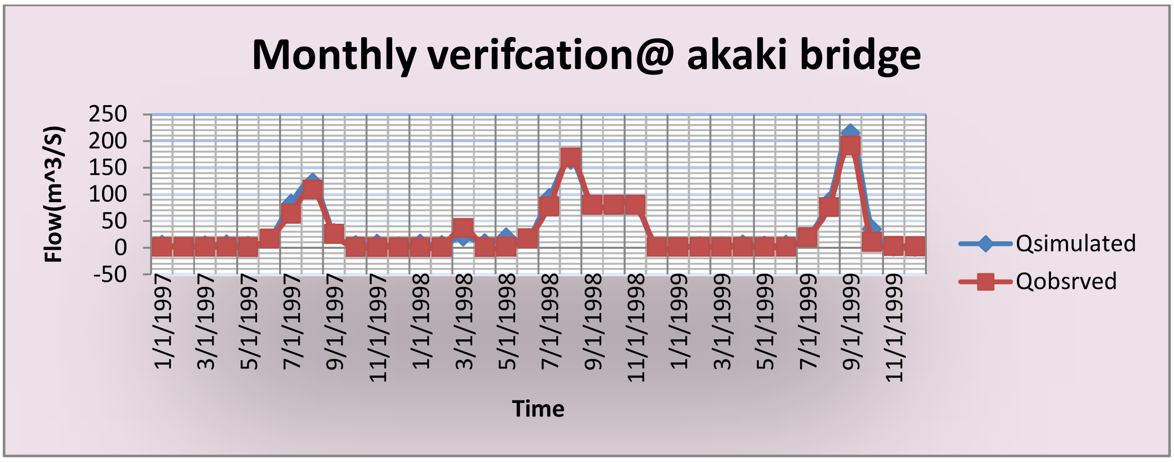


Figure5.9: Simulated and observed flow hydrographs

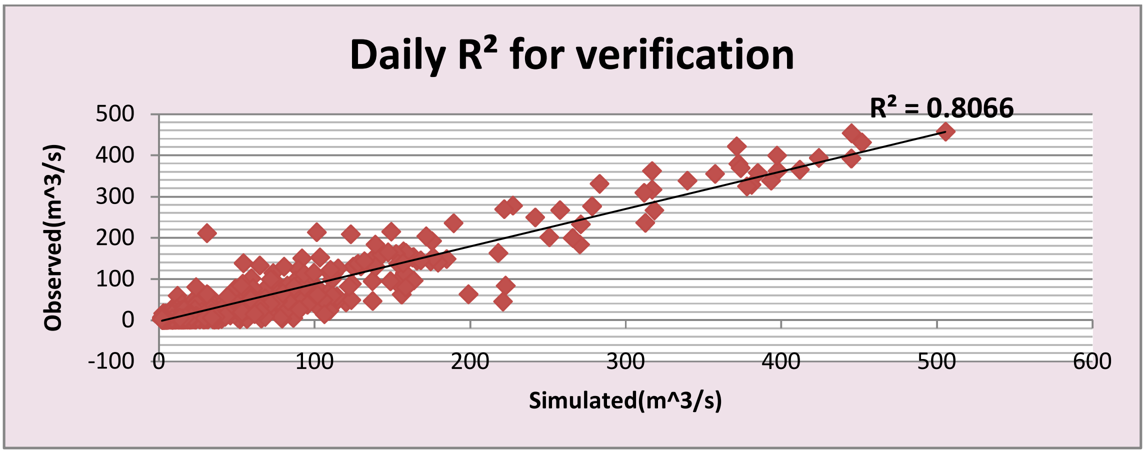


Figure5.10: Observed vs. simulated

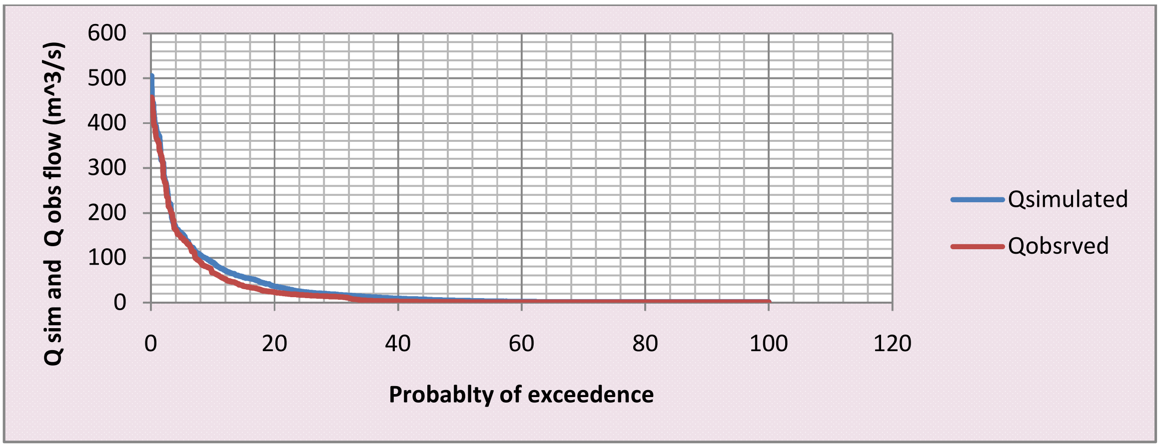


Figure5.11: Simulated and observed flow in model Verification (stochastic calibration)

5.4 Model simulation output corresponding to future climate change scenarios

Such simulation helps to identify the possible trend in mean flow as well as low and peak flow values corresponding to the climate change scenario. Simulation is done with HEC-HMS model as described in the previous sections. Inputs data to the hydrological model consists of future precipitation and temperature data. The simulation results corresponding to each of downscaling scenario time period (1990s, 2030s and 2090s) are analyzed for all days of each year. Monthly mean and high flows are calculated for each year and then averaged over the number of years in each scenario period. The simulation results corresponding to each period for Akaki catchment at Abba Samuel is summarized in Table 5.2.The figure11 shows simulated changes in monthly mean flows between the current and 2030s, 2090s time period corresponding to precipitation and temperature downscaled with GCM downscaling method. The impact of climate change on flow was analyzed on a monthly, seasonal and annual basis. The effect of climate change on low flow was also analyzed. The results for the analysis were discussed in the following sections.

5.4.1 Impact on monthly mean flow

The impact of climate change was analyzed taking the 1990-2000 river flow as the baseline flow against which the future flows for the 2030s and 2090s compared. Precipitation, minimum and maximum temperature were the climate change drivers considered for the impact assessment. The inputs for the change in precipitation, maximum and minimum temperature are discussed in section 5.1.The monthly percentage change in mean flow for the period 2030s, and 2090s are presented in Figure 5.12. In the 2030s for the monthly mean flow may show a increase for all the months except January, April and December. In this period a decrease up to 41% and an increase up to 90% in monthly mean flow may be expected. Increase in mean flow may be observed in months which showed an increase in monthly precipitation.

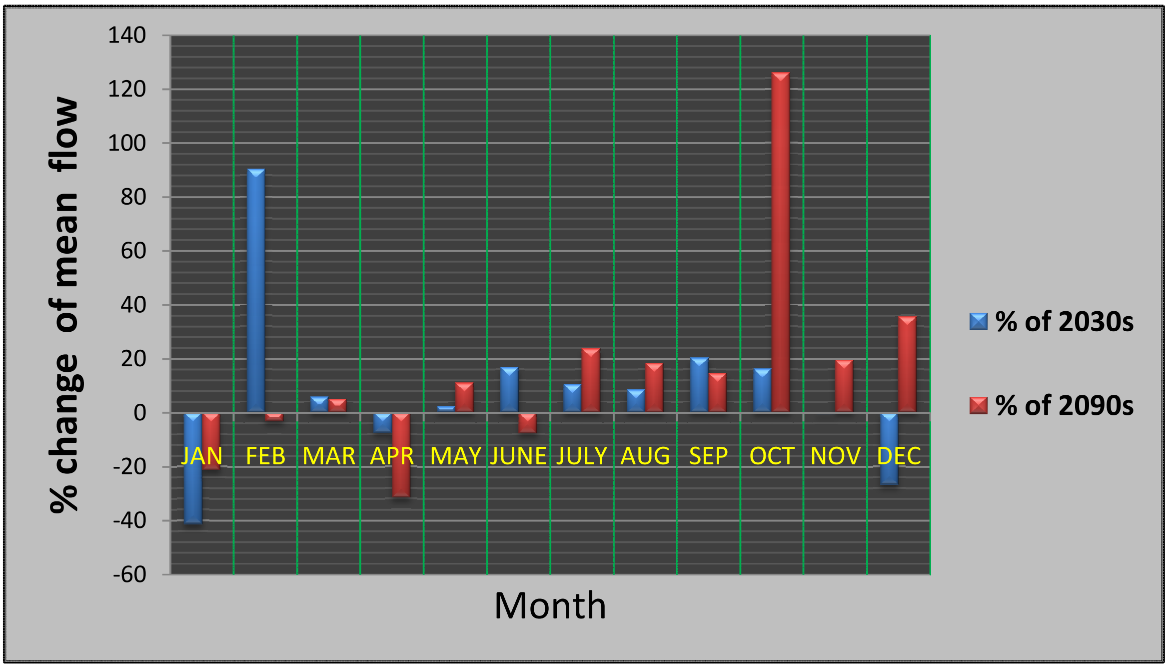


Figure5.12: Monthly percentage change in mean flow for the periods 2030s and 2090s against the baseline.

In 2090s an increase in monthly mean flow in all months except January and April may be observed. The increase in monthly mean flow may reach up to 126% in October. But In this period monthly mean flow decrease up to 32% in April.

5.4.2 Impact on Seasonal and Annual Flow Volume

In this section, the impacts of climate change on the seasonal and annual mean flow are presented so as to foresee its consequence on the socio-economic condition of the area. As discussed in the section 2.5, there are three seasons in the study area: Kiremt (rainy and cropping season), Belg (small rain season) and Bega (dry season). Figure 5.13 exhibit the implication of climate change on the river flow in these seasons.

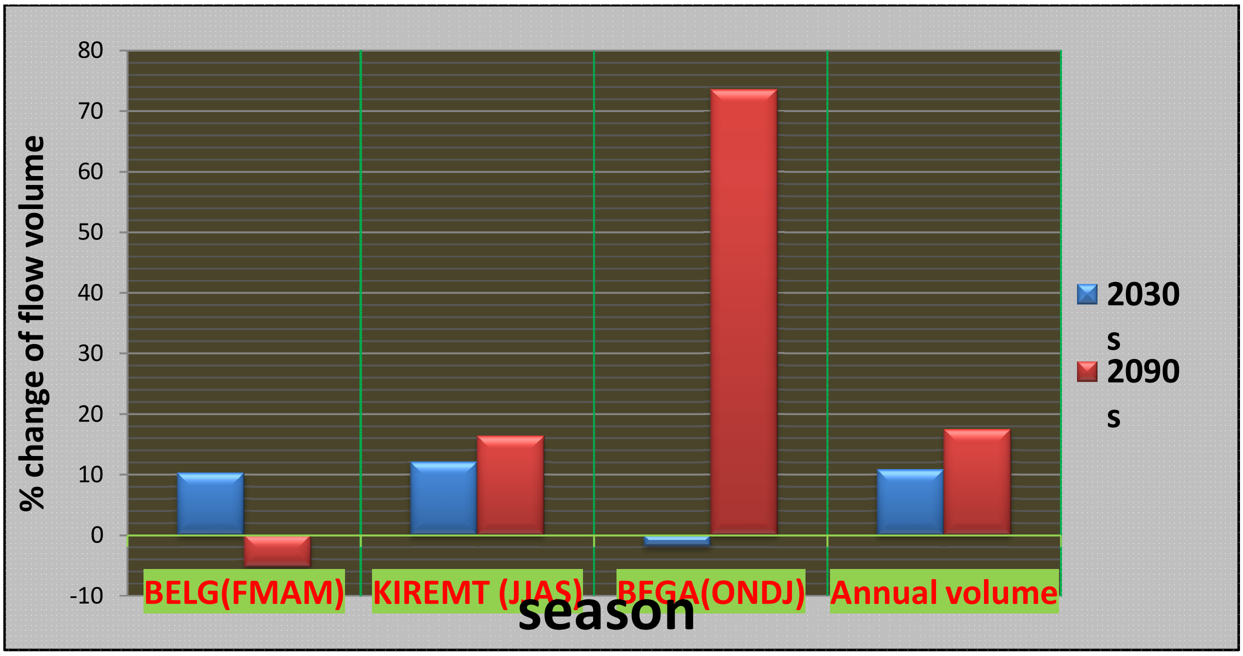


Figure5.13: Percentage change in seasonal and mean annual flow in respect to baseline climate for 2030s and 2090s time period.

As can be seen from Figure 5.13 there may be an increase in mean annual flow for the next 90 years. The annual volume increase may reach up to 13% in 2030s and 15% in 2090s. Kiremt season is expected to have the larger share in increased annual flow volume; because the absolute precipitation values are small in Bega (ONDJ) and the changes are not as pronounced as we can see from the figures. In 2030s, in both Belg and Kiremt season there might be increase in flow volume by 10% and 12% respectively. However, the Bega season shows that there might be a decrease in flow volume by 2%. In 2090s flow volume increase up to 72% in Bega season and also there might descent increase in Kiremt up to 17%. But, the flow volume may decrease up to 6% in Belg season.

5.4.3 Low Flow Analysis

Analyzing low flow statistics is important for water quality and aquatic habitat needs (e.g. water supply). Climate change affects both the high flows and low flows owing to variability in the precipitation and temperature. In this study a 95 percent exceedance probability was considered to characterize low flow conditions in the stream. It is found that there may be no significant effect in the low flows at this probability of exceedance.

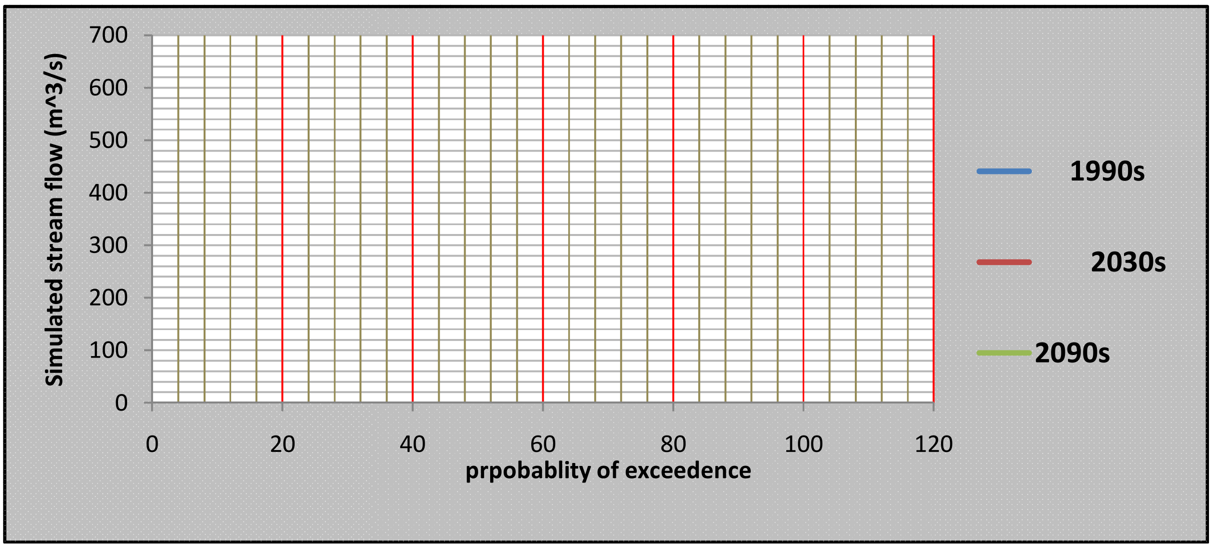


Figure 5.14**:** Flow duration curve for different time periods.

5.5 Flood frequency analysis of the flow simulation outputs

The flood frequency analysis of Akaki River may give different outcomes based on the time scale of the future climate scenario. Flood frequency analysis of the simulated flows in Akaki River in akaki catchment for current (base climate) and different time periods are presented in Appendix E (a, b and c). All the result are also summarized in figure 5.15 and Table 5.3 which present the percentage increase in peak flow (from the current period) of Akaki river corresponding to different return periods (5,10,20, 50 and 100) by the 2030s and 2090s. These results indicate on average increase in flood events. Moreover, the analysis indicates that the overall increasing trend in frequency of flood event is not linear. This can be witnessed from the graph where frequency curve corresponding to the1990s is over the one for 2030s.

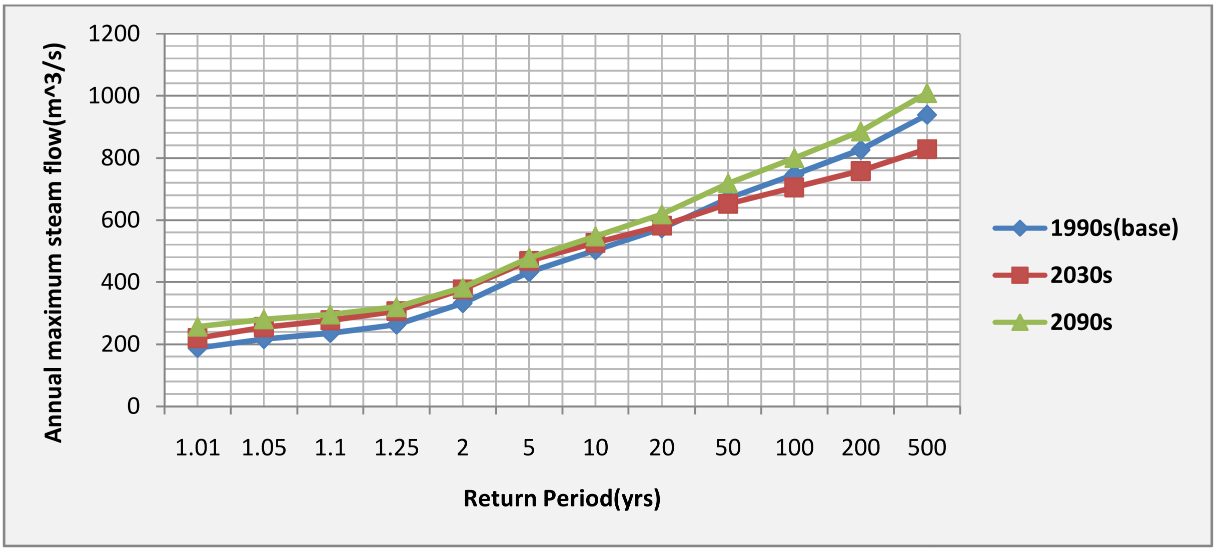


Figure5.15. Flood frequency curves for Akaki River at Abba Samuel based on future scenario simulations

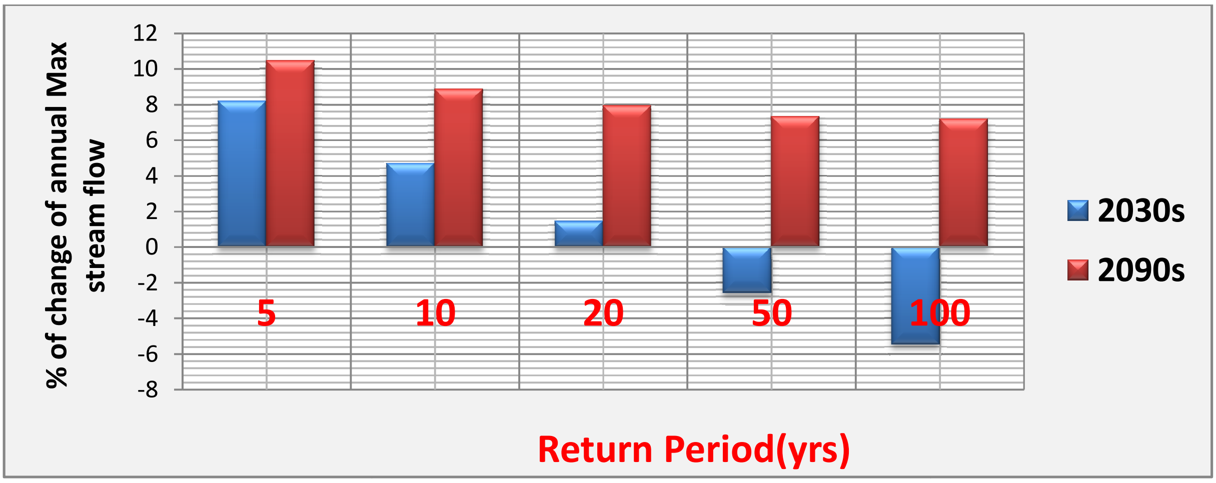


Figure 5.16 Changes in flood magnitudes between the current and the 2030s, 2090s the time period corresponding to the return period

Table 5.3: Changes in flood magnitudes between the current; and the 2030s and 2090s time periods.

			% change			
Return Period		***5***	***10***	***20***	***50***	***100***
Periods	**2030s**	8.2	4.7	1.5	-2.6	-5.5
	2090s	10.5	8.9	8	7.3	7.2

5.6 Uncertainties related to study

There may existed various sources of uncertainties related to this study staring from the quality of the data, uncertainty related to model assumptions itself and uncertainties arise from the level of understanding the atmospheric chemistry. The climate change impact on extreme hydrological event of Akaki catchment is evaluated only by considering the change in precipitation, maximum and minimum. However, in real situation other climatic variables and land use; because of expansion of Addis Ababa city will also change. Such and other similar characteristics will certainly reduce the reliability of the result.

CHAPTER SIX

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary and Conclusions

This study addresses climate change impact assessment on the hydrological extremes in Akaki catchment. The IPCC mentioned with high confidence, in the Fourth Assessment report, that warming observed during the last 50 years is attributable to human activities.

Moreover, changes in the frequency and intensity of extreme events are surely having more impacts on environment and human activities than changes in the mean climate. Losses of life and very high economic damages have been experienced during recent flooding events in the last decade at some area in Ethiopia like Addis Ababa city. A vital question for Addis Ababa city is, therefore, whether such events will occur stronger and more frequently in the future.

A methodology for assessing climate change impacts on hydrological extremes in Akaki catchment (Addis Ababa and its surrounding catchment) were therefore set and applied to high peak flow, mean month and low flow river discharges of Akaki River at Abba Samuel. For hydrological simulation the HEC-HMS model is selected. The HEC-HMS model which is calibrated and validated in daily and monthly time step, simulate the observed discharge in reasonably well manner with the model performance criteria of Nash and Sutcliffe value R^2 =0.78 for calibration and R^2= 0.81 for validation. Hence, it is concluded that the HEC- HMS is an acceptable hydrological model for this study, in order generate the stream flow and simulate the stream flows in the catchment under future climatic condition.

According to HEC-HMS simulations in the coming 90 years, a decrease in monthly mean flow up to 41% and an increase up to126% may be expected. There may be a significant increase in flow volume in Bega (ONDJ) season up to 72% and there may also be a descent increase in flow volume in Kermit (JJAS) season up to 15%. The increase in Bega season flow may have paramount importance for raw water harvesting in dam for water supply. It is generally observed that the increase in precipitation will be accompanied by a corresponding increase in mean flow and vice versa.

This study showed that there may be a net annual flow increase in Akaki River due to climate change. This may have a positive as well has a negative implication to the socio-economic condition of the region. The increase in flow will help to harness a significant amount of water for the new dam projects in Akaki river catchment either for water supply or other purpose. However, it may also aggravate the recurrent flooding problems in Addis Ababa and its surrounding area.

The high flow peaks and flood risk have potential tendency to increase up to 10%, or decrease to -5.5% depending on the different time periods corresponding with similar return period. However, from low flow analysis low flows show no reduction for deferent climate change scenarios.

In this study, the hydrological model parameters were assumed to remain valid under changing climatic conditions, and the same sets used both for current and future simulations. However, these assumptions may not be held in the future under changing land use and hydrological processes.

6.2 Recommendation

For the coming 90 years, the discharge values (floods) of the same return period may be more relatively the current climate condition; and more likely urban flooding (street flooding) due to increased rain fall may occur. Therefore, there is a need to modify urban infrastructure design criteria (for example take in to account the climate change impact for design of culvert in the city).

This study involved a number of models and model outputs where each possessed a certain level of uncertainty. Hence, the results of this study should be taken with care and be considered as indicative of the likely future rather than accurate predictions. Meanwhile, this study should not be extended by considering changes in land use, soil and other climate variables in addition to the changes in precipitation and temperature.

The model simulation consider only the climate variable by assuming all other thing constant. But change in land use and soil management activities will also contribute great impact on rain fall runoff process of the watershed. Therefore future research should be focus on land use land cover change including climate change.

Future research should also include adaptation option to climate change.

References

AAWSA, AAU (2003) Ground water vulnerability mapping of the Addis Ababa Water supply aquifers, Ethiopia. Report to UNEP/UNESCO/ UNHABITAT/ECA.

AAWSA, BCEOM (2000) Seureca-space in association with tropics Engineers: Akaki Ground water model report: Report V.I-IV.

Aggarwal, D. and M. Lal (2001), Vulnerability of Indian Coastline to Sea Level Rise, Centre for Atmospheric Sciences, Indian Institute of Technology, New Delhi.

Arc Hydro Tools Overview (2002) Version 1.0 beta 2

E-MAIL info@esri.com .WEB www.esri.com

Baede, A. (2001) The Climate System, an Overview. In: Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J.T., Y. Ding, D.J. Griggs, M. Noguer, P.J. vander Linden, X. Dai, K. Maskell, and C.A. Johnson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881pp.

Cunderlik, M. (2003) Hydrologic model selection fort the CFCAS project: Assessment of Water Resources Risk and Vulnerability to Changing Climatic Conditions, Project Report I, 40pp.

Cunnane, C (1987) Review of Statistical Methods for flood frequency Estimation, in Hydrologic Frequency Modeling.

Daniel, G (1977). Aspects of Climate and Water Budget in Ethiopia. A Technical Monograph Published for Addis Ababa University. Addis Ababa University.

Getahun, Y. G. E. (2007) Constructing a homogeneous Rainfall dataset to study Climate of Ethiopia, the University of Reading.

Gleick, P. H. (1997) Water Planning and Management under climate change. Journal of the American Water Works Association.

Hailemariam, K. (1999) Impact of Climate Change on the Water Resources of Awash River Basin Ethiopia. CLIMATE Research.

HEC (2006a) HEC-DSSVue, HEC Data Storage System Visual Utility Engine, User's Manual.

HEC (2006b) Hydrological Modeling system (HEC-HMS) User's Manual, US Army Corp Of Engineers

IPCC, 2001: Climate Change 2001. The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J.T.,Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden,X. Dai, K.Maskell, And C.A. Johnson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881pp.

IPCC-TGICA, 2007: General Guidelines on the Use of Scenario Data for Climate Impact and Adaptation Assessment. Version 2. Prepared by T.R. Carter on behalf of the Intergovernmental Panel on Climate Change, Task Group on Data and Scenario Support for Impact and Climate Assessment, 66 pp.

JICA and Region 14 Administration (1998) Addis Ababa flood control project Volume I

Kim, U. (2007) Regional Impacts of Climate Change on Water Resources of the Upper Blue Nile River Basin, Ethiopia, Utah State University.

Klemes, V (1993) Probability of Extreme Hydro metrological Event of Different approach, in Extreme Hydrological Events: Precipitation, Flood and Droughts.

Lenhart, T., K. Eckhardt, N. Fohrer, H.-G. Frede, 2002. Comparison of two Different Approaches of sensitivity analysis, Physics and Chemistry

Of the Earth 27 (2002), Elsevier Science Ltd., 645–654pp.

Lijalem, Z. A. (2006) Climate Change Impact on Lake Ziway Watershed Water Availability, Ethiopia, University of Applied Sciences Cologne, Germany.

Miller, K. A., and Yates, D. (2004) Climate Change and Water Resources. National Center for Atmospheric Research.

Tesfaye, C. (1993) Hydrogeology of Ethiopia and Water Resources Development. Ethiopian Institute of Geological Survey. Addis Ababa.

Romero Lankao, P. (2006), "Climate change risk: A mitigation and adaptation agenda for Indian cities," Environment and Urbanization, Vol. 19, No. 2.

Shaw, (2004) Hydrology in practice, Abingdon, Oxon, Ox144RN

UN-Habitat (2003), Water and Sanitation in the World s Cities: Local Action for Global Goals, Earthscan, London.

UN Habitat (2006), Meeting Development Goals in Small Urban Centres; Water and Sanitation in the World's Cities 2006, Earthscan, London.

UN Habitat (2007), Enhancing Urban Safety and Security; Global Report on Human Settlements 2007, Earthscan Publications, London, 480 pages.

Warwick, Hugh and Vicky Cann (2007), Going Public: Southern Solutions to the Global Water Crisis, World Development Movement, London, 72 pages.

Wilby, R. L., and Harris, I. (2006) A framework for assessing uncertainties in Climate Changes impacts: Low-flow scenarios for the River Thames, UK. WATER RESOURCES RESEARCH.

.

ANNEXES

APPENDIX

Appendix A.1: Monthly Rain fall data of Addis Ababa station

STATIONS		MONTHS											
	YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
	1997	30.1	0	25.1	66.8	49.8	128	264	160.7	103.7	58.6	26.3	0
Addis Ababa Bole	1998	67.6	40	46.8	99.8	203	112	278	236.8	182.4	139	11	0
	1999	5.4	0	38	17.8	35.5	105	301	270.5	71.8	127	11	0
	2000	1	0	20.6	87.8	100	102	200	221.9	166.5	19.6	18.5	0
	2001	1	10.3	177	14.8	122	166	296	207.3	122.3	10.6	11	0
	2002	31.6	25.9	82.4	36.6	54.6	116	221	233.6	81.6	0.5	11	32.8
	2003	5.8	34.1	51.9	112	23	111	211	238.4	139.2	4.6	11	33.3
	2004	27.1	11.7	35.4	104	12	115	248	230.1	131.1	50	11.6	0
	SUM	169.6	122	478	539	600	953	2019	1799	998.6	410	111	66.1
	AVERAGE	21.2	15.3	59.7	67.4	74.9	119	252	224.9	124.8	51.3	13.9	8.26

Appendix A.2: ***Monthly rain fall data of Addis Ababa Observatory station***

STATIONS		MONTHS											
	YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
	1997	39.2	0	24.5	51.3	38.5	104	273	194.3	113.8	62.4	50.3	1.5
Observatory station	1998	55.2	20.5	49	48.5	154	124	285	260	213.6	127	0	0
	1999	2.9	0.3	28.8	16.3	23.8	120	269	305.3	88.4	75.4	0	0
	2000	0	0	17.6	49.9	110	145	245	306.2	250.6	46.4	21.1	0
	2001	0	12.2	211	25	168	216	428	246.4	131.7	13.7	0	0
	2002	14.7	21	90.2	56.3	63.1	173	257	215.9	108.8	0.2	0	16.5
	2003	10.5	53.3	62.6	99.3	20.2	152	292	233.3	193.3	0.8	1.5	54.9
	2004	24.8	20.3	49.5	140	30.1	142	239	272.6	164	76.9	0	0
	SUM	147.3	128	533	487	608	1175	2287	2034	1264	403	72.9	72.9
	AVERAGE	**18.41**	**16**	**66.6**	**60.8**	**76**	**147**	**286**	**254.3**	**158**	**50.3**	**9.11**	**9.11**

Appendix A.3: Monthly Rain fall data of Intoto station

STATIONS		MONTHS											
	YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
	1997	21.2	0	18.6	77.3	27.4	77.2	256	240.8	89.3	88.3	90	0.2
Intoto station	1998	25.3	25.3	45.2	47	150	149	369	376.3	204.8	44.5	0	0
	1999	15.8	6.3	34.9	25.4	37	128	283	280.3	105	58	0.2	0
	2000	0	0	5.2	108	91.4	111	304	359.1	132.8	17.2	33.5	1.7
	2001	0	0	5.2	108	91.4	111	304	359.1	132.8	17.2	33.5	1.7
	2002	20.6	5.5	148	29.8	142	164	286	321.4	92.5	52.4	0	1.8
	2003	17.9	50.4	88.8	67.4	49.2	139	293	262.9	92.1	10.7	0	28
	2004	5.2	47.7	57.1	117	13.9	188	371	248.9	141.1	0	6.3	25.6
	SUM	106	135	403	580	602	1067	2466	2449	990.4	288	164	59
	AVERAGE	**13.25**	**16.9**	**50.3**	**72.5**	**75.2**	**133**	**308**	**306.1**	**123.8**	**36**	**20.4**	**7.38**

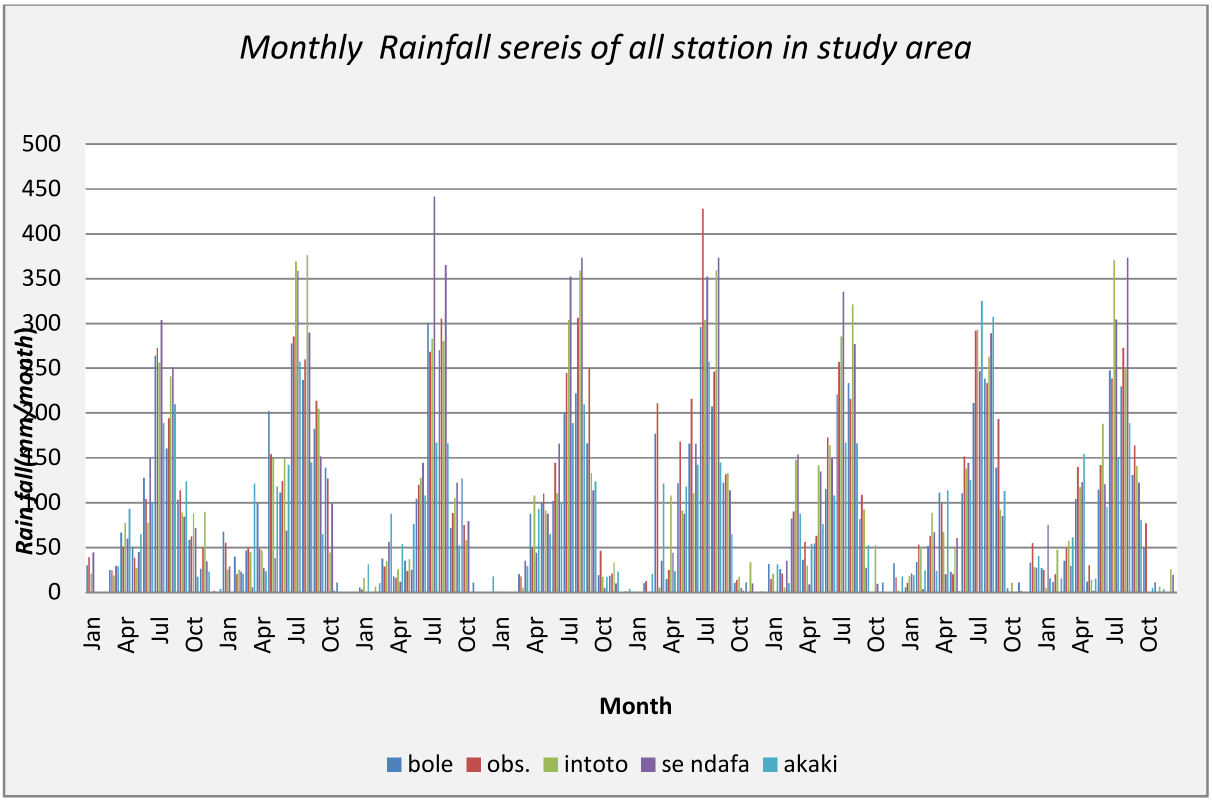
Appendix A.4: Monthly Rain fall data of Sendafa station

STATIONS		MONTHS											
	YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
	1997	44.5	0	29.4	60	44.8	150	303.8	251.1	84.7	72	34.6	0
Sendafa	1998	28.9	23.3	5.8	27	38.2	68.8	359.1	289.7	152	98.9	0	0
	1999	0	1.2	56.3	11.8	25.4	145	441.6	365.2	122.4	79.6	0	0
	2000	0	0	35.5	44	87.9	166	352.2	373.4	113.9	5	10	0
	2001	0	0	35.5	44	87.9	166	352.2	373.4	113.9	5	10	0
	2002	0	35.3	154.1	9.2	135	150	335.5	276.8	27.4	9.8	0	0
	2003	21.2	3.4	67.2	20.6	60.9	144	246.8	289.1	85.4	0	0	27.4
	2004	75.5	0	29.7	123	1.7	121	304.4	373.4	122.4	0	0	19.7
	SUM	170.1	63.2	413.5	340	482	1110	2696	2592	822.1	270	54.6	47.1
	AVERAGE	**21.26**	**7.9**	**51.69**	**42.4**	**60.2**	**139**	**337**	**324**	**102.8**	**33.8**	**6.83**	**5.89**

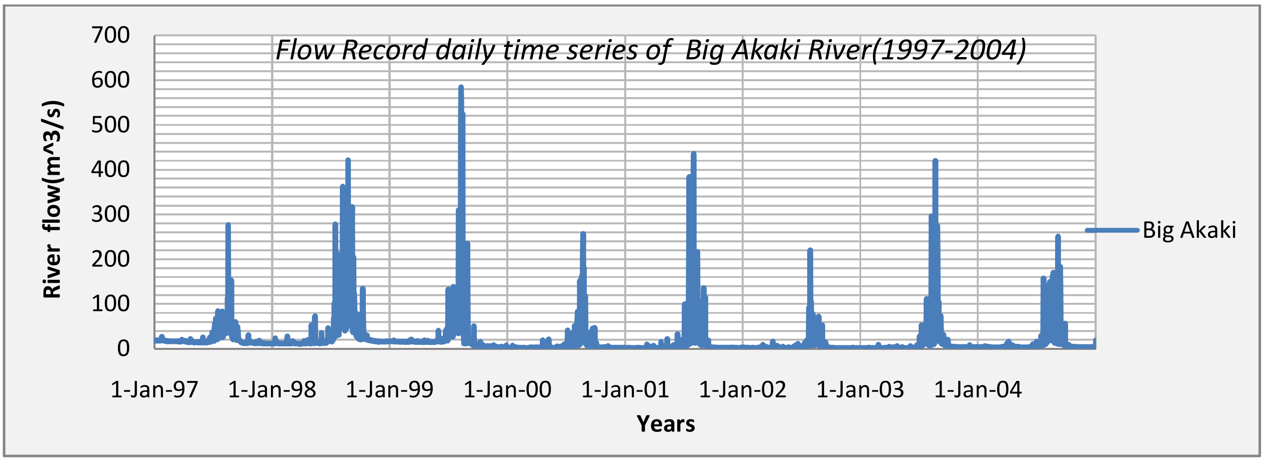
Appendix A.5: Monthly Rain fall data of Akaki Mission station

STATIONS		MONTHS											
	YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
	1997	2.6	44.2	56.3	79.7	22	84.3	276.4	267.6	143.1	38	0	3.2
Akaki Mission	1998	0	20.7	121.2	23.6	118	143	257.5	145	64.9	2.2	0	0
	1999	31.1	10.5	87.8	53.9	76.6	108	167.1	166.3	52.3	0	0	17.7
	2000	0	0	29.1	93	64.9	100	188.9	210	124.1	17.2	23.4	3.8
	2001	28.8	7.3	47.9	112	141	140	218.7	231.4	152.7	9.1	15.2	0
	2002	31.1	10.5	87.8	53.9	76.6	108	167.1	166.3	52.3	0	0	17.7
	2003	19.6	24.8	23.9	114	1.4	125	325.1	307.4	113.4	0	0	40.8
	2004	15.6	15.8	61.4	155	15.4	95.2	150.3	189.1	80.9	4.8	3.4	0.7
	SUM	128.8	134	515.4	685	516	904	1751	1683	783.7	71.3	42	83.9
	AVERAGE	**16.1**	**16.7**	**64.43**	**85.6**	**64.5**	**113**	**218.9**	**210.4**	**97.96**	**8.91**	**5.25**	**10.5**

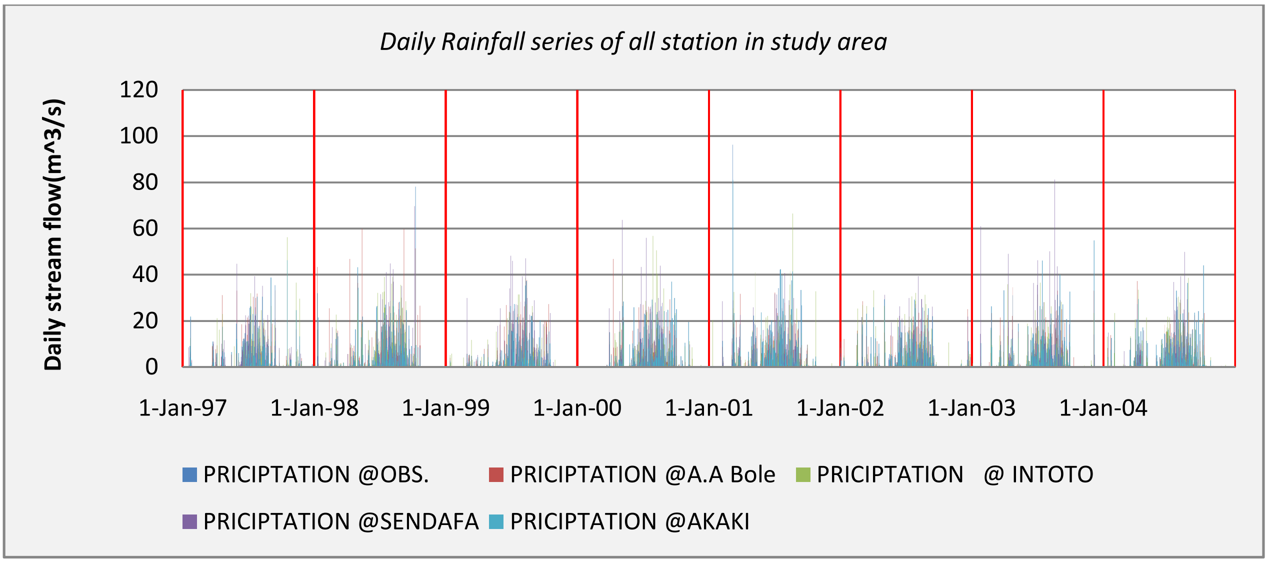
Appendix B: Monthly rainfall series of all station in the study area



Appendix C: Daily time series of big akaki river @Akaki Bridge



Appendix D: Daily rainfall series of all atation in the study area



Appendix E: Grahgs for simulated and observed for((a):- calibration and (b):-verification)

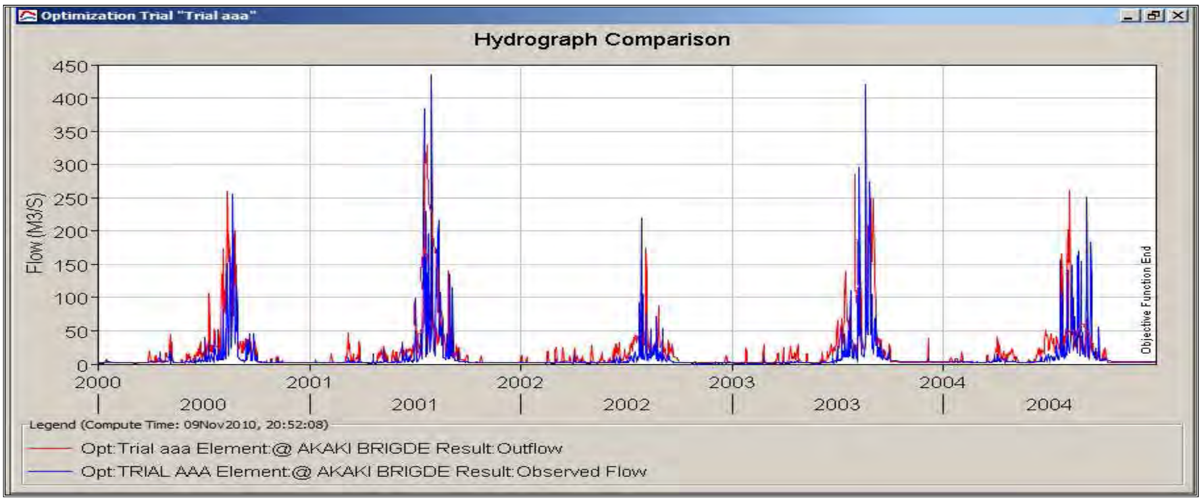
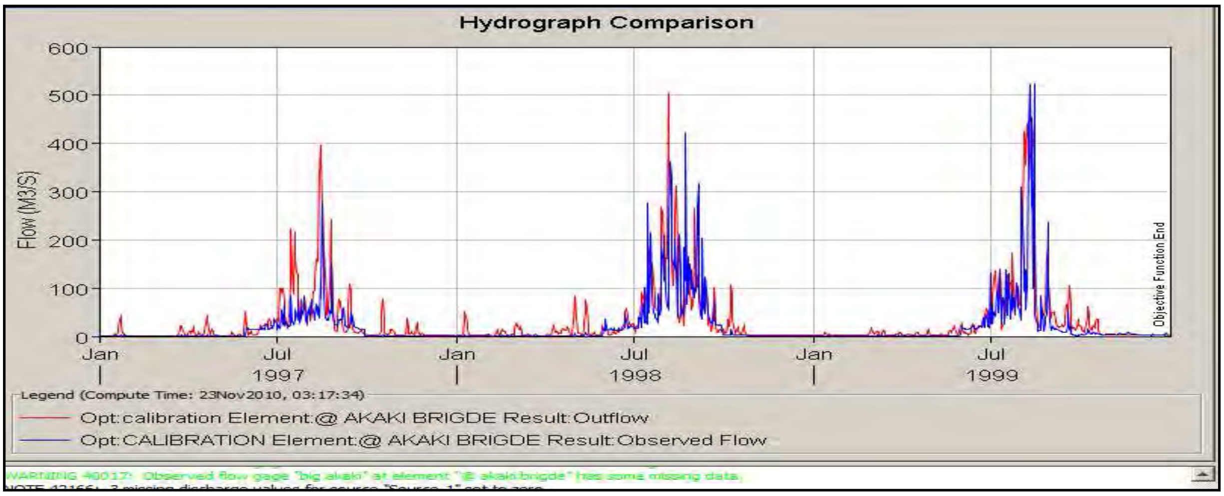


Figure5.6: Calibration result of HEC- HMS for the study area.

(a)***:-calibration***

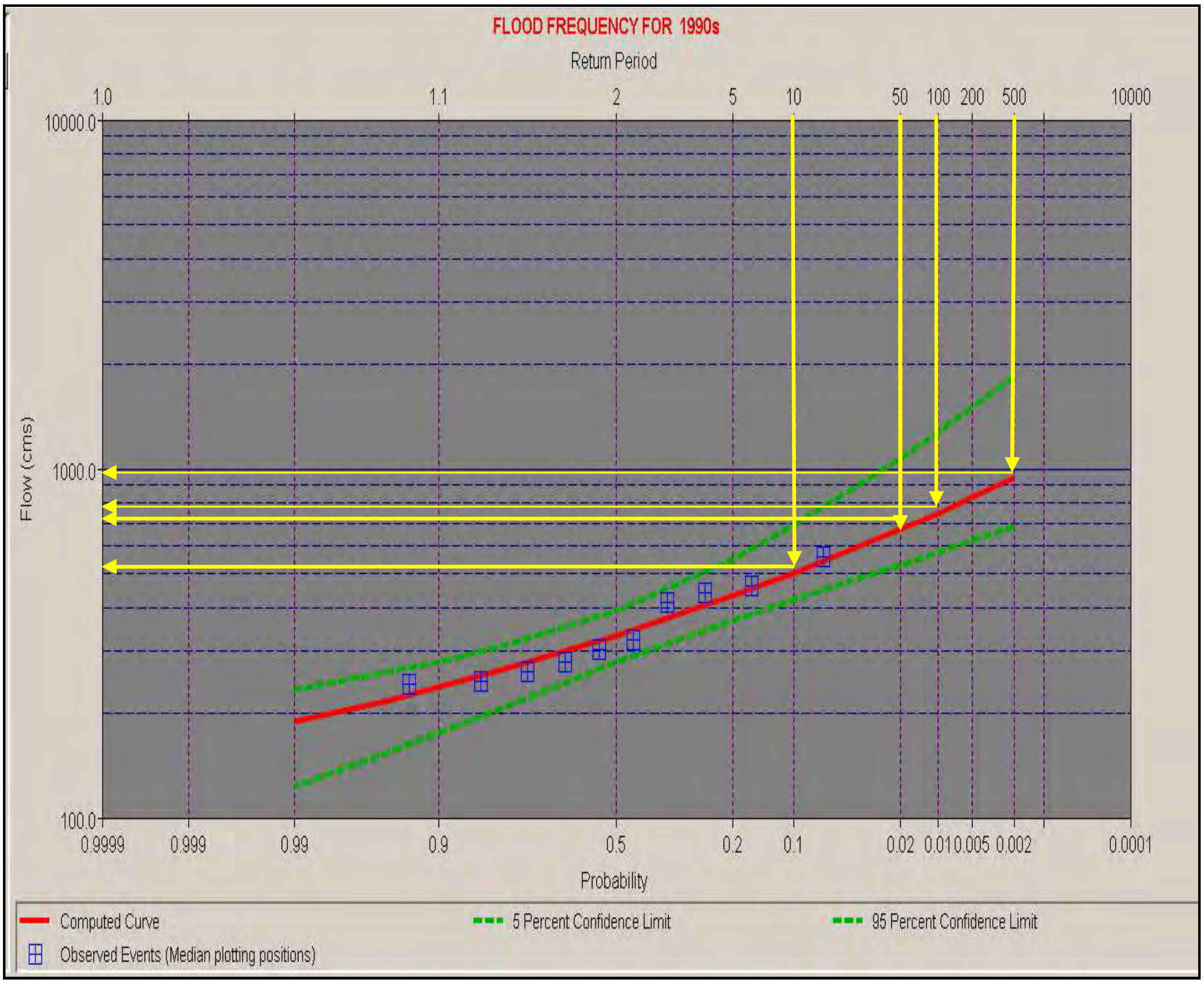


WARNING 40017: Observed flow gage "big akaki" at element "@ akaki brigde" has some missing data.

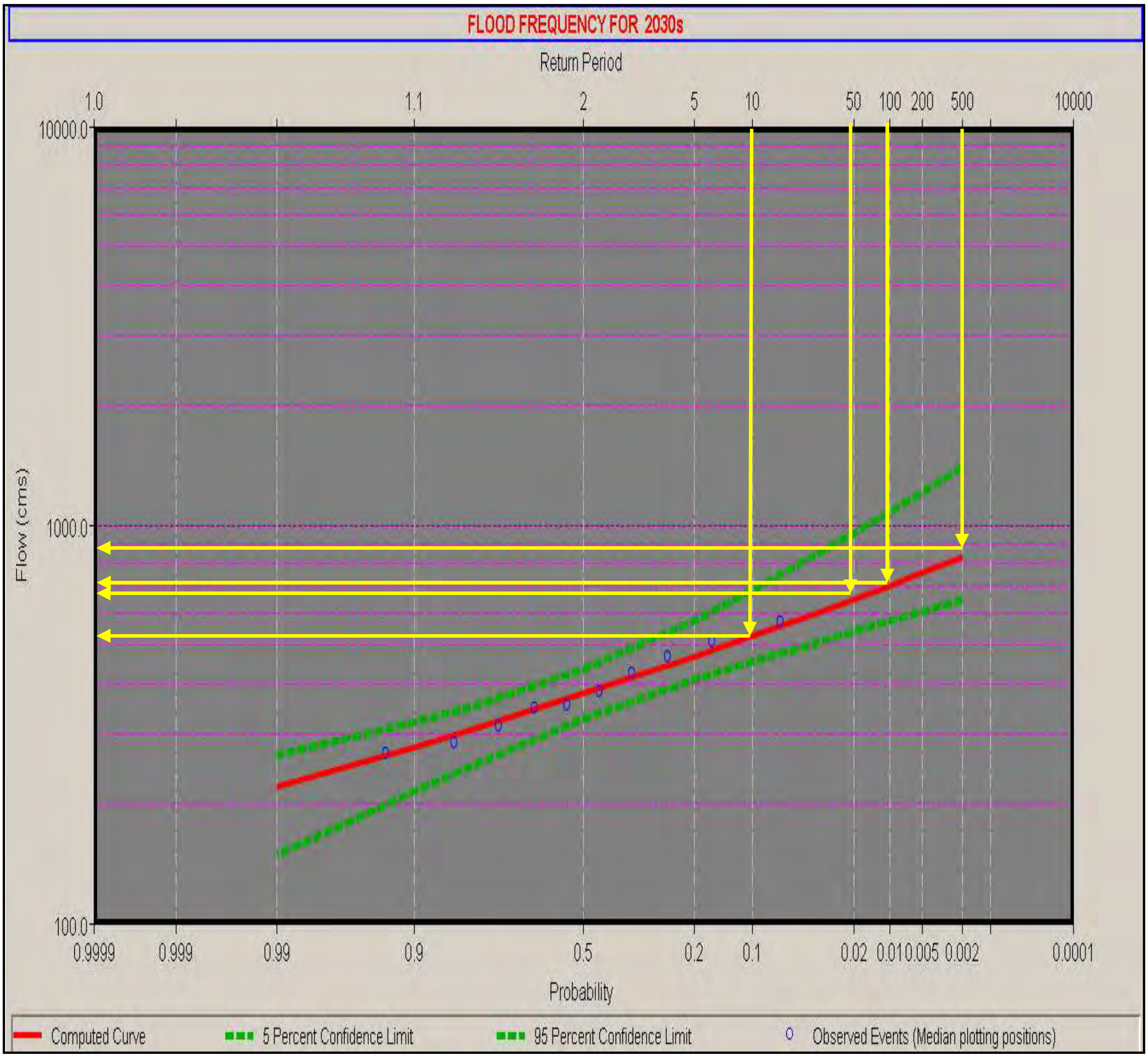
Figure5.10: Verification result of HEC -HMS for the study area

(b)***:-verification***

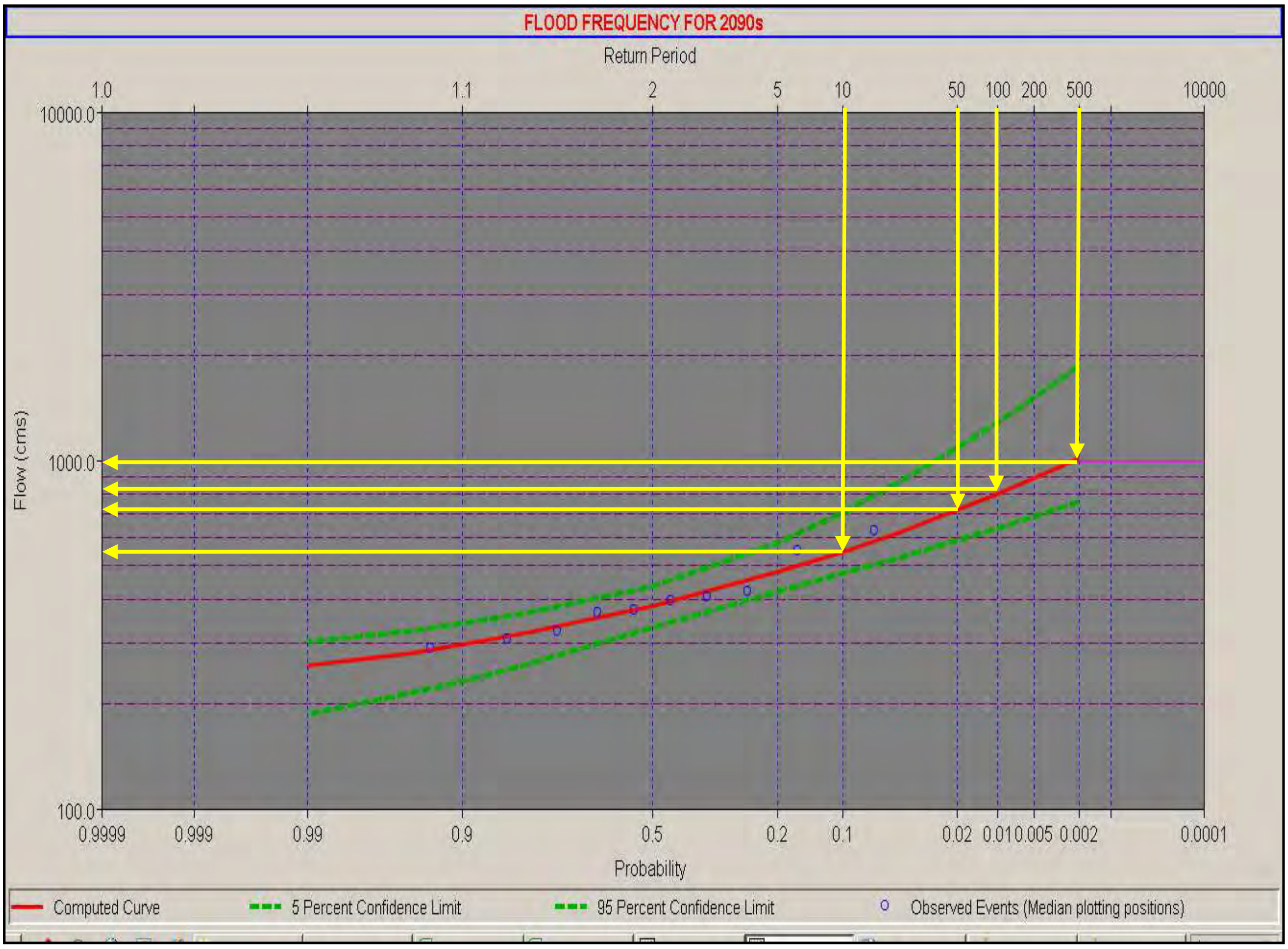
Appendix F: Flow frequency analysis graphs for different time periods:



(a) HEC- SSP output of Flood frequency for 1990s (base time)



(b)HEC- SSP output of Flood frequency for 2030s



(c) HEC-SSP output of Flood frequency for 2090s

Appendix G: Monthly Simulated results of each time periods: (a) 1990s, (b) 2030s and 2090s at Abba Samuel.

Table (a): Monthly simulated and its statics result for 1990s period of Akaki catchment at Abba Samuel.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	**Annual**
1990	4.961	6.5	37.5	5.67	40.07	36.93	90.68	140.1	69.4	16.9	16.9	4.33	39.17213
1991	4.616	13.89	2.223	8.497	32.79	49.06	74.47	97.69	64.4	16.2	16.2	2.69	31.88788
1992	23.14	9.854	14.48	39.83	20.31	33.32	136.4	200.1	96.3	31.4	31.4	3.12	53.30467
1993	9.426	17.39	8.323	32.72	24.55	32.88	176.9	218.9	98.2	6.5	6.5	3.1	52.94964
1994	2.135	2.282	6.987	17.75	26.74	42.95	116.7	263.4	73.5	26.7	26.7	15.1	51.74854
1995	8.81	4.75	8.765	18.47	22.78	49.65	95.8	196.9	58	13.9	13.9	4.76	41.37027
1996	2.713	4.629	21.23	35.72	24.24	53.11	115.3	98.83	43.7	8.55	8.55	3.13	34.97322
1997	4.568	4.018	36.83	33.32	14.06	43.91	124.3	111.6	62	30.1	30.1	2.59	41.45031
1998	2.252	2.239	12.18	18.15	23.38	57.53	122.6	181.2	79.7	29.1	29.1	2.34	46.64335
1999	3.561	26.47	4.339	19.2	22.72	58.15	121.5	145.3	69	26.4	26.4	4.29	43.939
Mean	**6.618**	**9.202**	**15.29**	**22.93**	**25.16**	**45.75**	**117.5**	**165.4**	**71.4**	**20.6**	**20.6**	**4.54**	**43.743**
Max	**23.14**	**26.47**	**37.5**	**39.83**	**40.07**	**58.15**	**176.9**	**263.4**	**98.2**	**31.4**	**31.4**	**15.1**	**53.3**
Min	**2.13**	**2.23**	**2.22**	**5.67**	**14**	**32.8**	**74.4**	**97.6**	**44**	**6.5**	**6.5**	**2.3**	**31.88**
St.dev	**6.33**	**7.88**	**12.7**	**11.7**	**7.03**	**9.32**	**27.9**	**55.6**	**16**	**9.2**	**9.2**	**3.8**	**7.438**
Cs	**2.33**	**1.34**	**1.11**	**0.035**	**0.89**	**-0.12**	**0.69**	**0.31**	**0.3**	**-0.3**	**-0.3**	**2.9**	**-0.09**
Cv	**0.95**	**0.85**	**0.83**	**0.51**	**0.28**	**0.2**	**0.24**	**0.34**	**0.23**	**0.45**	**0.45**	**0.84**	**0.17**

Table (b): Monthly simulated and its statics result for 2030s period of Akaki catchment at Abba Samuel

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	**Annual**
2030	4.626	18.07	15.28	29.2	14.98	58	116	194.9	58.8	19.2	2.72	3.64	44.62214
2031	3.042	2.043	7.784	10.51	29.97	60.27	131.7	144.7	100	28.6	2.63	5.57	43.93385
2032	2.194	5.896	5.181	18.35	44.09	54.09	144.7	185.5	72.3	26.3	7.19	3.01	47.40545
2033	3.006	55.04	31.65	22.61	23.95	56.01	154	212.1	141	10.7	2.71	3.16	59.65652
2034	9.381	9.968	27.13	15.43	19.8	59.7	110.6	254.2	120	18.5	3.81	2.47	54.21187
2035	1.935	44.07	5.055	16.89	41.67	47.91	141.5	200.3	54	19.2	3.44	2.59	48.21431
2036	2.342	2.15	2.939	10.16	23.72	52.58	119.2	144.8	67.1	25.9	3.38	2.29	38.04349
2037	2.045	26.75	9.571	10.55	20.88	44.69	89.89	116.6	58.1	29.7	4.09	5.22	34.83613
2038	3.165	4.521	14.22	44.85	24.36	56.76	120.2	180.3	110	42	15.8	2.78	51.55218
2039	7.09	4.868	42.94	33.42	28.84	44.62	170	160.7	78.5	19.1	6.96	2.48	49.96394
Mean	**3.883**	**17.34**	**16.18**	**21.2**	**27.23**	**53.46**	**129.8**	**179.4**	**86**	**23.9**	**5.27**	**3.32**	**47.24399**
Max	**9.381**	**55.04**	**42.94**	**44.85**	**44.09**	**60.27**	**170**	**254.2**	**141**	**42**	**15.8**	**5.57**	**59.65652**
Min	**1.935**	**2.043**	**2.939**	**10.16**	**14.98**	**44.62**	**89.89**	**116.6**	**54**	**10.7**	**2.63**	**2.29**	**34.83613**
St.dev	**2.482**	**18.84**	**13.39**	**11.47**	**9.307**	**5.872**	**23.39**	**39.55**	**29.9**	**8.59**	**4.05**	**1.17**	**7.348348**
Cs	**1.598**	**1.257**	**1.057**	**1.059**	**0.901**	**-0.57**	**0.099**	**0.289**	**0.71**	**0.75**	**2.31**	**1.35**	**-0.13709**
Cv	**0.64**	**1.08**	**0.82**	**0.541**	**0.34**	**0.11**	**0.18**	**0.22**	**0.3**	**0.3**	**0.7**	**0.3**	**0.15554**

Table (c): Monthly simulated and its statics result for 2090s period of Akaki catchment at Abba Samuel

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	**Annual**
2090	8.097	13.04	11.88	12.67	39.82	42.07	130.2	189.3	76.8	31.8	4.19	25.5	48.78048
2091	16.69	11.19	10.25	22.89	19.11	32.75	108.5	161.7	75.1	74.8	4	11.2	45.67657
2092	**3.14**	**5.37**	**5.77**	**22.12**	**19.1**	**46.7**	**144**	**212**	**63**	**27**	**2.78**	**6.78**	**46.444**
2093	2.519	14.21	23.07	17.49	29.56	32.41	188.2	211	106	38.9	3.19	4.51	55.88245
2094	7.203	4.111	12.7	14.57	28.78	64.53	147.5	274.9	83.9	58	11.8	3.08	59.25652
2095	1.906	14.34	37.39	11.53	33.84	56.25	168.3	232.8	84.1	32.1	3.6	2.36	56.54106
2096	3.568	3.979	21.21	22	40.53	27.2	143	162.2	68.8	43.4	2.55	2.14	45.0456
2097	2.981	3.979	13.53	14.74	19.16	24.92	135.8	170.3	76.7	46.6	8.03	2.05	43.22036
2098	2.587	2.2	11.88	7.463	20.03	45	146.6	177.8	92.8	13.1	3	2	43.7033
2099	3.413	16.31	12.93	11.24	29.45	50	141.2	165.2	92.4	99.4	20.3	1.97	53.65382
Mean	**5.211**	**8.871**	**16.06**	**15.67**	**27.94**	**42.18**	**145.3**	**195.7**	**81.9**	**46.5**	**6.35**	**6.16**	**49.82042**
Max	**16.69**	**16.31**	**37.39**	**22.89**	**40.53**	**64.53**	**188.2**	**274.9**	**106**	**99.4**	**20.3**	**25.5**	**59.25652**
Min	**1.906**	**2.2**	**5.768**	**7.463**	**19.11**	**24.92**	**108.5**	**161.7**	**63**	**13.1**	**2.55**	**1.97**	**43.22036**
St.dev	**4.526**	**5.413**	**9.022**	**5.295**	**8.404**	**12.88**	**21.27**	**37.04**	**12.6**	**25.2**	**5.71**	**7.42**	**5.954286**
Cs	**2.16**	**0.113**	**1.638**	**0.153**	**0.314**	**0.278**	**0.528**	**1.17**	**0.42**	**1.05**	**1.99**	**2.39**	**0.45187**
Cv	**0.869**	**0.61**	**0.562**	**0.338**	**0.301**	**0.305**	**0.146**	**0.189**	**0.15**	**0.54**	**0.9**	**1.2**	**0.119515**

Appendix H: Annual daily maximum simulated flow for deferent time periods: 1990s, 2030s and 2090s.

1990(current)		2030s(1930-1939)		2090s(2090-2099)	
1990	**279.4**	*2030*	**312.1**	2090	**288.6**
1991	**246.5**	*2031*	**283.6**	2091	**306.3**
1992	**440**	*2032*	**423**	2092	**407**
1993	**561.8**	*2033*	**570.4**	2093	**628.3**
1994	**463.6**	*2034*	**506.7**	2094	**549.3**
1995	**414.1**	*2035*	**382**	2095	**372.4**
1996	**262.4**	*2036*	**352.8**	2096	**421.6**
1997	**241.9**	*2037*	**265.7**	2097	**322.8**
1998	**324**	*2038*	**346.8**	2098	**365.6**
1999	**304.6**	*2039*	**465.3**	2099	**393.6**
S.dev	**109.4**		**99.48**		**107.37**
C_s	**0.77**		**0.56**		**1.21**
C_v	**0.31**		**0.25**		**0.26**