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ADDIS ABABA UNIVERSITY

COLLEGE OF NATURAL AND COMPUTATIONAL SCIENCES

SCHOOL OF EARTH SCIENCES

ASSESSING THE IMPACT OF CLIMATE CHANGE ON GROUNDWATER
RECHARGE: A CASE STUDY OF AKAKI CATCHMENT, CENTRAL ETHIOPIA

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A THESIS SUBMITTED TO

SCHOOL OF EARTH SCIENCES OF ADDIS ABABA UNIVERSITY IN PARTIAL
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SCIENCE IN HYDROGEOLOGY.

ADDIS ABABA, ETHIOPIA

Jan, 2021



Addis Ababa University
College of Natural and Computational Sciences
School of Earth Sciences

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Abstract

This study was conducted in the Akaki catchment to assess climate change and its impacts on groundwater recharge with a total area of (1470 km²). To analyze the possible impacts of future climate change on the groundwater recharge, climate projections for rainfall and temperature data have been carried out using downscaled GCM (MIROC5) model output which in turn was used as input to the WetSpass model to simulate future groundwater recharge and other hydrological components based on RCP 4.5 and RCP 8.5 scenarios. The linear scaling bias correction method was applied to adjust the bias for both temperature and rainfall projections. The bias corrected MIROC5 has shown that near perfect match with observation in each meteorological station. The change in mean annual precipitation during 2050s is expected to decrease by 2% in RCP4.5 but, increased by 3% in RCP8.5. During 2080s it expected to increase by 1% and 3% in RCP4.5 and RCP8.5 respectively. The rainfall shows an increasing trend under RCP8.5, but it is decreasing under RCP4.5 respect the baseline. In the period 2050s, the change in mean annual temperature expected to increase by 1.5°C and 1.8°C in RCP4.5 and RCP8.5 respectively. During 2080s is also expected to increase by 2.1°C and 3.5°C in RCP4.5 and RCP8.5 respectively. The change in temperature is expected to increase in the two projected periods. The simulated results from the WetSpass model showed that the annual average precipitation (1131) mm is distributed as 42% of mean annual evapotranspiration (469mm), 35% of runoff (396 mm), 23% of groundwater recharge (266mm) in the baseline. In 2050s, mean annual groundwater recharge is expected to be 257 mm and 269 mm under RCP4.5 and RCP 8.5 respectively. This shows decrease by 3 % in RCP4.5, but an increase by 2% in RCP 8.5. In 2080s this is expected to be 268 mm for RCP4.5 and 270 mm for RCP 8.5. It expected increase by 1% and 2 % under RCP 4.5 and RCP 8.5 respectively. Based on the results of the model, the groundwater recharge shows an increasing trend in all scenarios, except in the period 2050s under RCP4.5. But, this result considered only future precipitation, maximum and minimum temperatures scenarios by assuming other parameters are constant. The rapid population growth in the catchment area, higher demand for water resources is inevitable. As a result, sound and effective groundwater management is compulsory.

Keywords: *Groundwater recharge, WetSpass model, Bias correction, Akaki Catchment*

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Addis Ababa University, School of Earth Sciences

This is to certify that the thesis prepared by Worknesh Jemberie entitled: **Assessing the Impact of Climate Change on Groundwater Recharge: Case Study of Akaki Catchment, Central Ethiopia** submitted in partial fulfillment of the requirements for the Degree of Master of Science in Hydrogeology complies with the regulations of the university and meets the accepted standard with respect to originality and quality.

Approval by Board of Examiners

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Chairman (Department graduate committee)	Signature	Date
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External Examiner	Signature	Date

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List of Abbreviations

AET	Actual Evapotranspiration
AR5	Fifth Assessment Report
CMIP5	Coupled Model Inter Comparison Project Five
DEM	Digital Elevation Model
GCM	Global Climate Model
GHG	Green House Gas
IPCC	Inter- Governmental Panel for Climate change
MIROC5	Model for Interdisciplinary Research on Climate
MoWIE	Ministry of water Irrigation and Energy
NMA	Ethiopian Metrological Agency
NSE	Nash Sutcliff Efficiency
PBIAS	Percent Bias
PET	Potential Evapotranspiration
R ²	Coefficient of Determination
RCM	Regional Climate Model
RCP 4.5	Representative Concentration Pathway 4.5 Wm ⁻²
RCP 8.5	Representative Concentration Pathway 8.5 Wm ⁻²
WetSpass	Water and Energy Transfer between Soil, Plants and Atmosphere at quasi-Steady State

Chapter One

Introduction

1.1 Background

Nowadays, more than two billion people worldwide rely on groundwater resources for irrigation, industrial and domestic purposes. Fresh groundwater is normally originated from precipitation, either by direct infiltration of rainfall or indirectly from rivers, lakes, and canals. Groundwater constitutes about two-thirds of the liquid freshwater resources of in the world (Chapman, 1996). But rapid population growth combined with climate change and inadequate groundwater recharge lead to declining groundwater levels. In addition, the direct consequence of reduction in groundwater level brought about either by excess extraction or lowering recharge (Pgeo, 2009).

Groundwater recharge is the addition of any water to an aquifer system. Groundwater recharge is a complex hydrological process (Jasechko et al., 2014). It depends on lots of factors such as amount, distribution and frequency of rainfall, land use and land cover, soil, vegetation type, soil type and properties. It also mainly depends on the accessibility of high-quality hydrogeologic and climatic data (Kumar, 2013). Accurately estimate and forecast groundwater recharge is very essential for water resource investigation. Groundwater recharge mainly occurs in the summer months from late June to early September (Molla Demlie et al., 2006). However, Climatic factors can affect its amount and distribution. Moreover, Tamiru Alemayehu (2006) explains that the groundwater recharge system is variable, due to the uneven distribution rainfall of in the country of Ethiopia.

Climate change is defined as a mean of alteration of the climate of the world that humans are causing, through deforestation, burning fossil fuel and other practices that increase the greenhouse gases concentrations in the atmosphere. It mainly occurs mainly related to human activities, particularly the emission of greenhouse gases (GHG) into the atmosphere due to an increase in the concentration of carbon dioxide (CO₂). An increasing trend of CO₂ significantly changes the global and local climate system as well as temperature and

precipitation. These changes may occur in regional temperature and precipitation has important implications on the hydrologic cycle and groundwater recharge (Kumar, 2012). On the other hand, climate variability may be happening due to natural internal processes within the climate system due to variations in natural or anthropogenic factors (Aizebeokhai, 2011).

The expansion of urbanization, climate change impact and land-use change have a negative influence on groundwater resources due to change in climate-driven variables such as temperature, rainfall, evapotranspiration, humidity etc. So it is an important understanding of the impact of climate change on groundwater recharge for groundwater management. The aim of this study is to estimate the level of climate change impact on groundwater recharge at the catchment level. Hydro-metrological data and climate modeling output of the Model for Interdisciplinary Research on Climate (MIROC5) is used for impact assessments. To evaluate the bias correction methods, the linear scaling method was applied for temperature and precipitation projections. Therefore, bias-corrected precipitation and temperature are used as input to the hydrologic model to simulate future water balance changes based on Representative Concentration Pathways (RCP4.5 and RCP 8.5) scenarios. To understand the effects of spatial and temporal variation of groundwater recharge, the physically distributed water balance model (WetSpass) was applied. WetSpass model is a quasi-state physically distributed seasonal-water balance model, which requires soil, land use, slope, groundwater depth, and hydro-climatologically distributed maps with associated parameter tables for estimating groundwater recharge and other parameters (Woldeamlak et al., 2007).

1.2 Problem Statement

Climate change has a negative impact on groundwater quality, quantity, availability, and also sustainable yields. The quantity and quality of the water available for Addis Ababa city supply have been significantly affected by climate change (Hailu Worku, 2017). The volume and the quality of the groundwater directly depend on its recharge. The supplied water quantity per capita from Surface sources in Addis Ababa and surrounding areas has been reduced (Daniel Elala, 2011). This leads to an imbalance between the water demand and supply, due to the challenges posed by climate change and poor management activities. It is also expected that Addis Ababa city will experience water supply stress as a result of a complex interaction of

urbanization and climate change (Bisrat Kifle et al., 2018). In addition to climate change, urbanization activity, and low land use management practice, in Addis Ababa will continue (Getnet Feyissa et al., 2018). Rapid urbanization has a great challenge in Addis Ababa similar to those in other African cities (Wafa et al., 2017). This leads to increasing the water demand in the city. So, it requires a detailed assessment of the available groundwater resource to balance both the water supply and demand within the catchment area to promote sustainable socio-economic development.

Climate changes have a direct influence on the availability of adequate water resource potential. It can alter the major climate-driven variables such as temperature, precipitation, and evapotranspiration (Zheng et al., 2016). The variation in climate variables can have a direct consequence on the quantity of groundwater recharge, evapotranspiration, and surface runoff (Dragoni and Sukhija, 2019). This in turn will lead to changes in the hydrological cycle and influencing the water balance components of the area. Several studies have been conducted in and around the catchment area: the impact of climate change on the water resources of Awash river basin (Kinfu Hailemariam, 1999; Meron Teferi et al., 2018); climate forecast system reanalysis weather data in upper Awash basin, (Mesfin Benti et al., 2018) ; in addition, studies in Addis Ababa were:- climate change and population growth impacts on surface water supply and demand (Bisrat Kifle, 2017); vulnerability assessment of surface water supply systems due to climate change and other impacts (Daniel Elala, 2011); flooding regime change, and its effect on adaptation to climate change (Semu Ayalew et al., 2019); and climate change and its adaptation (Herslund et al., 2015). However, no attention has been given to the impact of climate change on groundwater resource and groundwater recharge in the catchment. Therefore, the current research aims to quantify the distribution of groundwater recharge under climate change scenarios in the Akaki catchment. To see the groundwater recharge variations, the WetSpa model was applied.

1.3 Basic Research Questions

- ✓ Is the WetSpa model applicable for the estimation of groundwater recharge in the Akaki catchment?

- ✓ Is there climate change in the Akaki catchment?
- ✓ If there is climate change, what is its impact on groundwater recharge?

1.4 Objective of the Research

1.4.1 General Objectives

The major objective of this research is to assess the existing and future impacts of climate change on groundwater recharge from baseline (1981-2005) and two projected periods 2050s and 2080s and estimate its impact on groundwater recharge using the WetSpass model in the Akaki catchment.

1.4.2 Specific Objectives

- ✓ To evaluate distributed annual and seasonal groundwater recharge from the baseline (1981-2005) and the projected periods of the 2050s (2036-2050) and 2080s (2066-2080) using the WetSpass model.
- ✓ To evaluate climate change impacts on groundwater recharge and estimate the magnitude of the change using MIROC5 under two future climate scenarios of RCP 4.5 and RCP 8.5.

1.5 Scope of the Research

This research is focusing on the Akaki catchment, which the main water supply of Addis Ababa city and the surrounding areas depend on. It utilized and reviewed different research articles studied by various authors relevant to the topic of the research and conducted the analysis using relevant secondary data as input for the model. It mainly focused on the effect of climate change on groundwater recharge using the WetSpass model.

1.6 Research Importance

This research is expected to provide a better understanding of the impact of climate change on groundwater recharge. The water demand is increasing as a result of population and economic growth as well as intensive urbanization particularly within and around the study area. Therefore, this research has value to add to the topic of the study by generating relevant

information about the spatial distribution of groundwater recharge under a change in climatic conditions, which contributes to managing the groundwater resources. Also, it increases awareness about the current and future application design, implementation, and collaborations among different sectors, organizations, institutions, and individuals. Moreover, it helps to add relevant information to fill the gaps for decision-makers and researchers for further studies.

1.7 Thesis Outline

This research contains seven chapters. Chapter one is an introduction to the study area, objective, problem, and its importance. Chapter two reports on a literature review about the subject matter. Chapter three indicates a basic description of the study area, Chapter four explains the general methodology, materials, and types of data used in this research. Chapter five explains and shows WetSpass model inputs. Chapter six discussed the result of the study. Finally, chapter seven deals with the conclusions and recommendations of the study.

Chapter Two

Literature Review

A review of literature on climate change, water resources, and groundwater recharge at the catchment level provides the conceptual framework for this chapter. Also, the literature on climate and hydrological modeling which, gives an overview of its effect on recharge is presented in this chapter.

2.1 Climate change and its impacts

Weather and climate have an intense influence on life on Earth. The “weather”, refers the fluctuating state of the atmosphere around us and “Climate” refers to the average weather in terms of the mean and its variability over a certain time-span and a certain area (IPCC, 2001). Climate varies from one place to the other place, depending on latitude, vegetation, presence or absence of mountains or other geographical factors. Climate change refers to the change in the state of the climate due to changes in the mean value or the changeability of its properties and typically it extends a decade or more (IPCC, 2007). It exhibits itself in the form of extreme events such as drought and heat waves including shortage in rainfall, and conversely increases in rainfall causing floods (IPCC, 2013).

Now a day, changes in climate have serious impacts on both natural and human systems on all continents and across the oceans. This is due to observed climate change, irrespective of its cause, indicating the sensitivity of natural and human systems to changing climate (IPCC, 2014). The impact of solar variations on the climate provides an example of human induced climate variations. But even without changes in man activities, the climate may vary naturally (IPCC, 2001). To understand, detect and eventually predict the human influence on climate, needs to understand the system that determines the climate of the Earth and of the processes that lead to climate change.

Climate change is caused by the global increase in atmospheric concentrations of greenhouse gasses (GHGs). These gasses include methane (CH₄), carbon dioxide (CO₂) and oxides of nitrous (NO_x) (IPCC, 2001). The continued Greenhouse gases will cause further warming and

long-lasting changes in all components of the climate system, increasing the likelihood of severe, pervasive and irreversible impacts for people and ecosystems (IPCC, 2014). The figure (2.1) shows, global mean surface temperature increase as a function of cumulative total global carbon dioxide (CO₂) emissions. Cumulative emissions of CO₂ largely determine global mean surface warming by the late 21st century and beyond (IPCC, 2014).

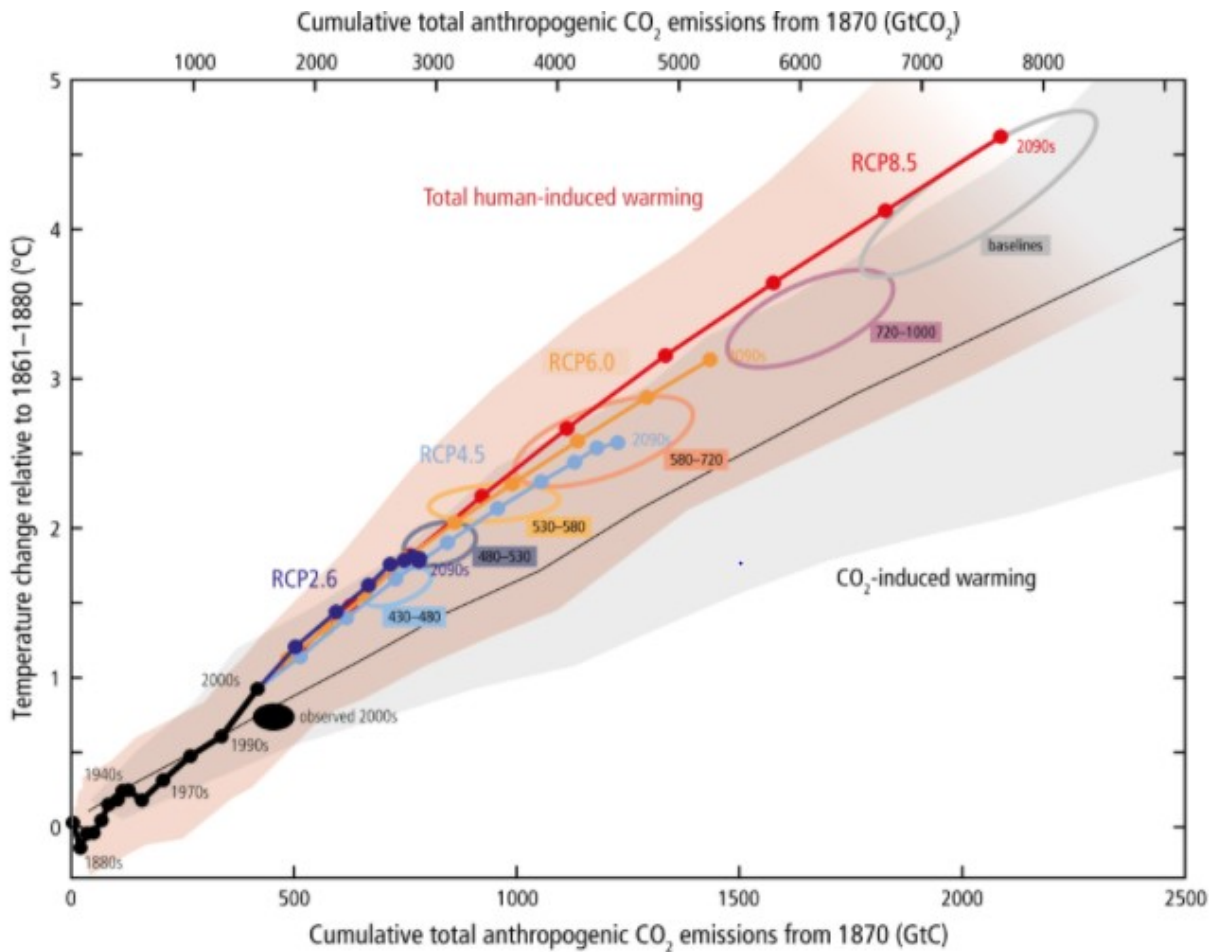


Figure 2.1: Anthropogenic warming in 2100 versus cumulative CO₂ emissions 1870 to 2100 (IPCC, 2014)

2.1.1 Climate change in Ethiopia

Ethiopia's vulnerability to climate change risks has its root in various factors, including its geographic location and social and economic structure (UNDP, 2011). High rainfall and

temperature variability on both temporal and spatial scales are typical characteristic for climate in Ethiopia (NMA, 2007). This is due to variation in latitude, altitude, wind, and humidity. According to (Echeverría and Terton, 2016) temperature increase of 1.3°C between 1960 and 2006 has been observed in Ethiopia, representing an average change of 0.28°C per decade. In the same period, the period of July to September had the fastest warming rate of 0.32°C per decade but for precipitation, there is no statistically significant trend in mean rainfall in any season due to the large interannual and interdecadal variability in Ethiopia's rainfall.

According to First Assessment Report of Ethiopian Panel on Climate Change (EPCC, 2015), between 1963 and 2012 two areas in central Ethiopia received much higher than average rainfall in the 1970s, but lower than average in the 1980s and 1990s. Rainfall in dry season over central Rif Valley and the nearby highlands areas have decreased whereas rainfall over southern Rif Valley areas has increase. And the southeastern part of the country has also experienced warming trend (0.4°C/decade) in both dry and rainy seasons.

Table 2. 1: Observed and projected climate change in Ethiopia (Echeverría and Terton, 2016)

Periods	Temperature	Rainfall
historical Trend	Mean temperature increase of 1.3°C from 1960 to 2006	Highly variable from year to year, season to season, and decade to decade. And no significant trend
2050s	+1.2°C (0.7°C to 2.3°C)	+0.4%
2090s	+3.3°C (1.5°C to 5.1°C)	Wetter conditions

2.1.2 Climate change in the study area

The historical trend of climate observation and analysis is presented of the longest record from 1898 to 2002 (Conway et al., 2004). During the period (1898 to 2002) the minimum and maximum temperature records show evidence of statistically significant inhomogeneities. But homogeneity tests on the full rainfall record show it is reliable, with minor statistically significant breaks in the record before establishment of the Addis Ababa Observatory (AAO). Minimum and maximum temperatures show increasing trends from 1951 to 2002 of 0.4 °C/decade and 0.2 °C/decade respectively (Conway et al., 2004).

Recently the frequency and magnitude of different climate variables have shown an increasing trend due to the growing urbanization has been occurring in Addis Ababa city in the past decades (semu Ayalew et al., 2019). The environmental problems and extreme events (high temperature and rainfall), results in flooding in Addis Ababa which, the main signals of climate change. Such Extreme events and climate change impacts on the already existing challenges in catchment area (Daniel Elala, 2011). Many studies have been conducted on the impacts of climate change on groundwater recharge in global scale (Meixner et al., 2016). But the global studies lack the specificity to inform decision making, while the local studies do may clarify potential changes than global scale.

2.1.3 Regional Climate Model (RCM)

Climate models are tools for studying local, regional or global climate behavior and its variability over changing conditions on the earth (Green et al., 2011). The Regional Climate Model (RCM) is a numerical climate prediction model used for downscaling coarse-scale. Global Climate Models (GCMs) to provide richer regional spatial information for climate assessments and impact and adaptation studies (wu et al., 2019). Furthermore, RCMs are models that developed with a higher spatial resolution to evaluate climate change at the regional level (Gebrekidan worku et al., 2018). GCMs are used to predict a change in climate from increase of GHGs like CO₂ and other atmospheric gases (Crosbie, 2010). RCMs simulated data are used as input to hydrological models to quantify the effects of a changing climate on water resources and recharges (Tootoonchi, 2019).

2.2 Impacts of climate change on water resources and hydrological cycle

The increase irrigation practices, industries, urbanization, and population within the Awash basin which, resulted increase water demands (Meron Teferi, 2018). Due to increasing the water demand coupled with climate change, showed reduction in the groundwater resources. This needs setting appropriate adaptation options to mitigate its consequences, may help to manage, allocate and evaluate the groundwater resource (Claudia Sadoff and Mike Muller, 2009). More over global climate are expected to impacts the hydrological processes (Treidel, 2012). There for it needs to modifying the patterns of rainfall and evaporation in the given river or basins. Knowing the future likely consequences climate changes on groundwater systems and hydrological cycle is important (Kumar, 2013). Hydrologic cycle is the movement of water within the atmosphere, earth's surface and rocks and vice versa. The hydrologic cycle is highly sensitive to climate change because the components of the hydrologic cycle are vulnerable to changing climate. Hydrologic cycle also varies due to increase extreme weather events like: droughts and floods.

2.2.1 Climate change on Groundwater Resources

Groundwater is defined as all subsurface water like soil water, deeper vadose zone water, and unconfined and confined aquifer waters (Green et al., 2011). In many countries of the world the use of groundwater resources for public water supply constitutes important potable water. The impacts of climate change on water resources are well known in worldwide and have influence on water resources (Aizebeokhai, 2011). But, establishing or demonstrating its impact on groundwater resources is complicated (Moseki, 2017). In addition to climate change, improper utilization and uncontrolled exploitation may also result in reduction and contamination of groundwater resources.

The direct effect of climate change on groundwater resources mainly depends on the change in the quantity and distribution of groundwater recharge (Thampi and Raneesh, 2011). Groundwater suppliers are mainly directly related to surface water and rainfall, with groundwater recharging through soil-infiltration (Melese Gezie, 2019). When rainfall rains, a

quantity of water percolates into the ground by the means of infiltration (Oyanyan and Toko, 2018). Large urban areas have often a micro-climate which may alter rainfall patterns and evapotranspiration rates (Lerner, 1990). The influence of climate change on global groundwater resources needs multi-disciplinary study. However, it has limited consideration in the scientific researches (Stoll et al., 2011; Kumar, 2012; Kumar, 2013; Kolusu et al., 2019; Aizebeokhai, 2011). Therefore, groundwater is a vital water resource and awareness needs to be raised on its vulnerability to overexploitation, pollution and most importantly, climate change.

2.2.2 Climate change on Groundwater Recharge

Groundwater recharge is one of the most significant factors for determine the groundwater development potential (Mohan, 2018). However, climate change can affect its quantity and distribution. In humid regions characterized high groundwater recharge compared to arid or semi-arid regions, due to the higher quantity of water to recharge (Mohan, 2018). Groundwater recharge may vary from one place to place due to variation in rainfall, temperature, evapotranspiration and surface runoff. Groundwater recharge is depends on physical state, amount and intensity of rainfall, topography, water table level, geology, soil type, vegetation characteristics, and climatology (Jasechko et al., 2014). The Groundwater recharge has direct relationships with rainfall, the high rainfall rains the high water infiltrates the soil to the groundwater and thus the high recharged water stored in the water table.

Many studies have been conducted on the impacts of climate change on groundwater recharge (Meixner et al., 2016; Holman, 2006; Bouraoui et al., 1999; Taye Alemayehu et al., 2016). Most of the studies have been carried out about the impacts of climate change on groundwater recharge global scale. But the global studies may lack the specificity to notify decision making, while the local studies do may clarify potential changes.

2.3 Estimation of Groundwater Recharge

Recharge is an important factor in evaluating groundwater resources but it is often difficult to quantify (Batelaan and De Smedt, 2007). Estimate the groundwater recharge a critical issue in

hydrogeological study for sustainable groundwater management (Rwanga and Ndambuki, 2017). Recharge estimation based on availability and quality of data (Walker et al., 2018).

Several researchers (Smith and Wikramaratna, 2009; Salem et al., 2019; Kuisi and Naqa, 2013; Pantoja and Hiscock, 2008; Crosbie, 2010; Kuruppath et al., 2018) have used different methods to estimate groundwater recharge and other water balance components. However, each method has its own limitations on available data, space and timescales, and range and reliability to estimate recharge (Zhu, 2000) cited in (Hydar Ebrahimi et al., 2016). Now a day's different hydrological models are available for quantify groundwater recharge. Hydrological models are designed to work based on spatiotemporal distributions of the complex hydrological systems (Gebremedhin Gebremeskel and Asfaw Kebede, 2017).

2.4 Groundwater Recharge Models

Groundwater modeling provides for investigation of groundwater recharge and other hydrological components. Hydrological models are mainly used for predicting system, behavior and understanding various hydrological processes (Devi et al., 2015). It is designed to work based on spatiotemporal distributions of the complex systems of groundwater recharge. Different hydrological models are used for estimate ground recharge and other hydrological process such as Soil and water Assessment Tool (SWAT), Water and Energy Transfer between Soil, Plants and Atmosphere at quasi-Steady State (WetSpass). Water Evaluation and Planning system (WEAP), and Soil Moisture Accounting model (HEC-HMS). Now a day, those models are a very important and necessary tool for water and environmental resource management issues. In this study, the groundwater recharge was estimated through the WetSpass hydrologic model.

2.4.1 WetSpass Model

WetSpass is a spatially distributed simulation model for water and energy transfer between soil, plants, and atmosphere under a quasi-steady-state (Batelaan and De Smedt, 2001). For inputs the WetSpass model, the grid maps, and parameter tables which, are prepared with the help of Arc GIS software. The WetSpass model inputs are long-term mean hydrometeorological data and physical characteristics such as land use/land cover, soil type,

topography, groundwater level, and slope (Teklebirhan Arefaine et al., 2012). These parameters, such as land-use and related soil type, are connected to the model as attribute tables of the land-use and soil raster maps (Rwanga, 2013). The WetSpass model results include several monthly hydrologic outputs such as digital maps of monthly groundwater recharge, surface runoff, actual evapotranspiration, and interception (Zarei et al., 2016).

2.4.2 Application of WetSpass Model

WetSpass model is used to estimate the spatial distribution of actual evapotranspiration, surface runoff, and groundwater recharge (Ali Salem et al., 2019). This model can be used to assess the groundwater recharge from precipitation (Armanuosa and Negm, 2016). Increase precipitation may increase the groundwater recharge. Several studies have been carried out the WetSpass model in worldwide to simulate the long-term seasonal and annual runoff, evapotranspiration, and groundwater recharges, and other related water balance parameters. It was applied in Belgium (Batelaan and De Smedt, 2001); determining conditions governing recharge of shallow groundwater in the Poznań Upland, Poland (Graf and Przybyłek, 2018); in the Jafr basin, Jordan (Kuisi and Naqa,2013); in the Gaza Strip, Palestine (Aish, 2014); in Nile Delta aquifer, Egypt (Armanuos, Negm, Yoshimura, and Valeriano, 2016); in Northeast Iran (Zarei et al., 2016); in the Drava Basin, Hungary (Salem et al.,2019). Moreover, studies have been in Ethiopia: in Upper Bilate Catchment, Southern Ethiopia (Bitsiet Dereje and Dessie Nedaw, 2019); in the Ilala Catchment, Northern Ethiopia (Teklebirhan Arefaine et al., 2012); in the Werii watershed of the Tekeze River Basin, Ethiopia (Gebremedhin Gebremeskel and Asfaw Kebede, 2017). WetSpass model is suitable for studying the long-term effects of and climate changes on the water balance components in a given catchment. Its set-up is extremely flexible and easily compatible and integrated with Arc GIS software during the simulation Process. This is the reason why the WetSpass model is selected to this research for evaluate the impacts of climate change on recharge.

Chapter Three

General Description of Study Area

3.1 Location

Akaki catchment is located along the western margin of the Ethiopian Main Rift. The catchment area is geographically bounded between 8°50'- 9°10'N latitude and 38°40'- 39°02'E longitude. The total area of the catchment is 1470 km². The catchment is divided into two sub-catchment areas. These are the big Akaki River found along the eastern part of the catchment and the little Akaki River along the western part of the catchment. Both groundwater and surface water sources are the main water supply for Addis Ababa city and the surrounding areas. The groundwater sources in the study and surrounding areas, supply from Akaki wells, spring, and other drilled water wells. The main surface water supply dams in the catchment area are Legedadi, Gefersa, Dire and Abasamuel (Fig 3.1).

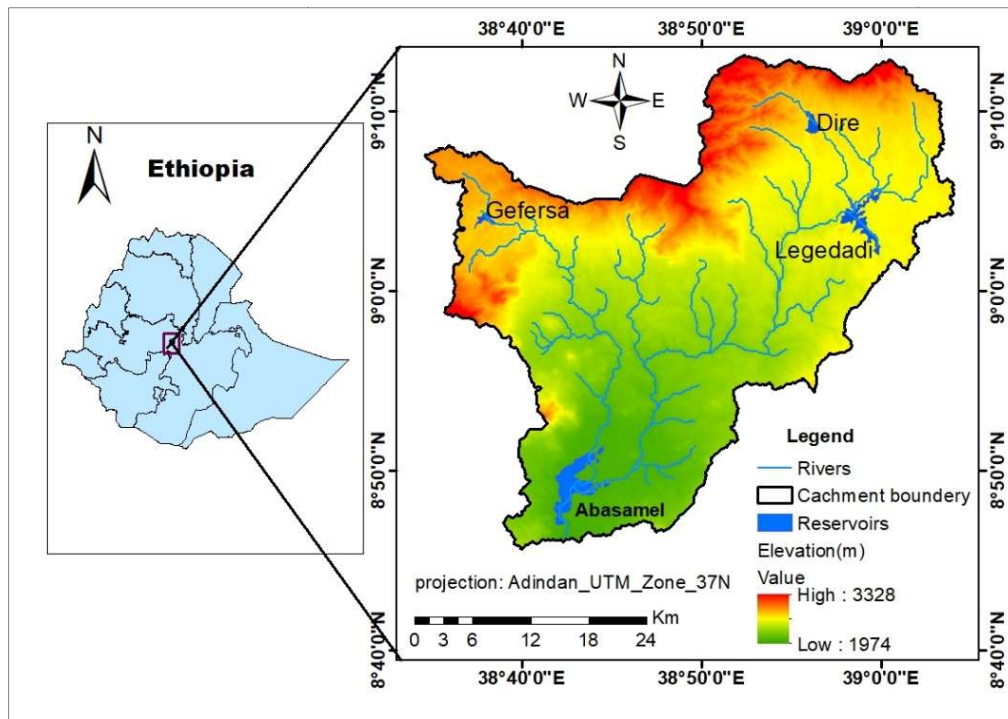


Figure 3.1: Location map of the study area

3.2 Topography

The main physiographic regions in Ethiopia are western plateau, southeastern plateau, the Main Ethiopian Rift and Afar Depression. The study area is located partly within the Central Ethiopian plateau and partly within the northern Main Ethiopian Rift System. The topography of the catchment area is characterized by steep slope at upstream part (Entoto, Sendafa) and gentle slope along the downstream part (Akaki). It also bounded by mountainous along different directions. Entoto along the northern, Bilbilo and Guji along the southern, Menagesha and Wechecha along the western, Yerer volcanic centre along eastern, Furi along the southwestern, and Gara Bushu hills along southeastern. The elevation ranges of the study area from the highest peak of Entoto to the lower part of Akaki plain (1972-3,333) meter above sea level (Fig 3.2).

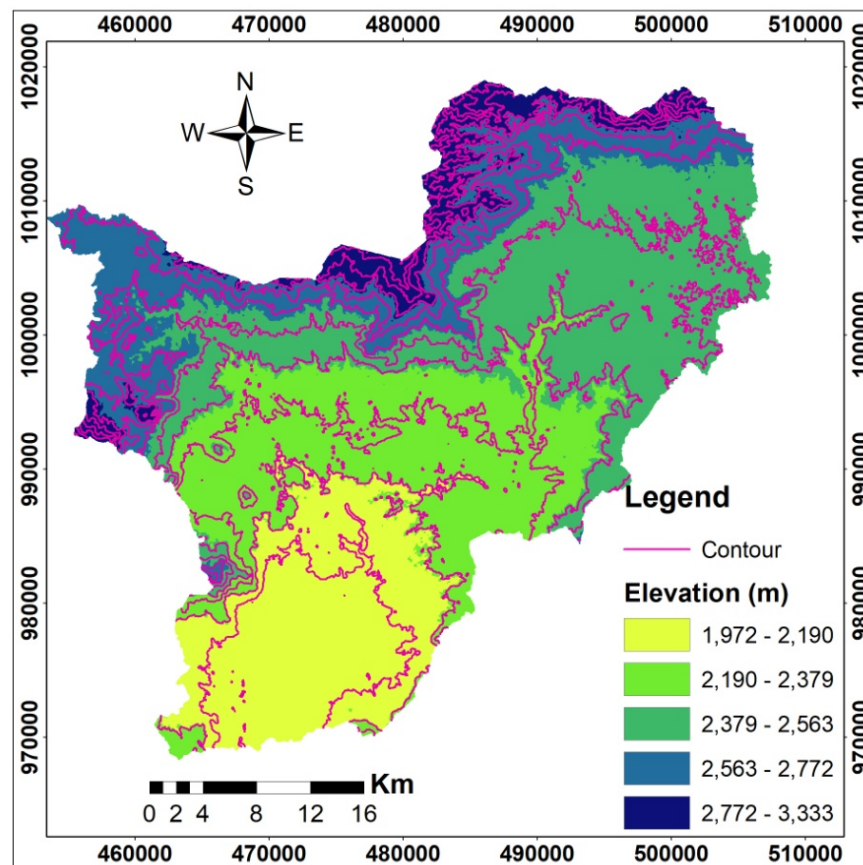


Figure 3.2: Physiographic map of the study area

3.3 Climate

Ethiopia lies within the tropics and near the equator. The climate of the country is greatly varies due to the complex topography. Ethiopian topography mainly consists of high, rugged plateaus and the minor lowlands. The highland areas characterized by a high amount of rainfall with a low rate of evapotranspiration leads to moisture surplus. But, lowlands areas are characterized by the low amount of rainfall with a high rate of evapotranspiration results to moisture deficit. The Ethiopian plateau is mainly found in northern, western, central, and southern parts of the country and its climate is cool. According to (NMA, 2001), Ethiopia has a diversified climate ranging from hot and semi-desert to mild and humid topographic elements.

Table 3. 1: Traditional classifications of climatic zones in Ethiopia (NMA, 2001)

Climate zone	Altitude (meter)	average annual rainfall(mm)	Average annual temperature (°C)	Climate condition
wurch (upper highland)	>3000	>2000	<10	Cold
Dega (highland)	2500-3000	1000-2000	10-16	Cool to cold
Woina Dega (midland)	1500-2500	1200-2400	16-20	Warm to cool
kolla(lowland)	500-1500	Around 600	20-28	Warm to hot
Bereha (desert)	<500	<400	28-34	hot

3.3.1 Rainfall pattern

The Akaki catchment is characterized by mild climatic zones with warm to cool climates. The Intertropical Convergence Zone (ITCZ) influences the rainfall distribution over the catchment area. The main seasonal variation of rainfall occurs due to the movement of ITCZ and also altitudinal variation. There are five metrological stations within the catchment area and their mean annual rainfall ranges from 996mm (Akaki) to 1245mm (Intoto). In all stations, high amount of average monthly rainfall was recorded in July and August whereas the lowest value was observed in December and November (Fig 3.3) corresponding to Table 3.2. Entoto station

shows the highest mean annual monthly rainfall as results of the highest elevation; while the minimum Mean annual monthly rainfall was recorded in Akaki station.

Table 3. 2: Mean monthly rainfall of the study area (1981-2005)

Stations	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
AA.Bole	13.9	32.8	69.3	92.6	75.5	121.5	231.7	238.0	132.8	33.1	3.6	4.9
AA.Obs	13.8	40.0	71.0	94.4	88.5	135.2	263.2	283.8	169.9	35.4	6.0	8.3
Akaki	9.4	29.0	59.2	90.0	68.9	109.4	245.8	241.6	117.6	17.8	3.0	5.4
Intoto	15.2	38.8	60.3	87.9	66.7	138.1	306.0	341.2	151.2	15.2	15.2	9.1

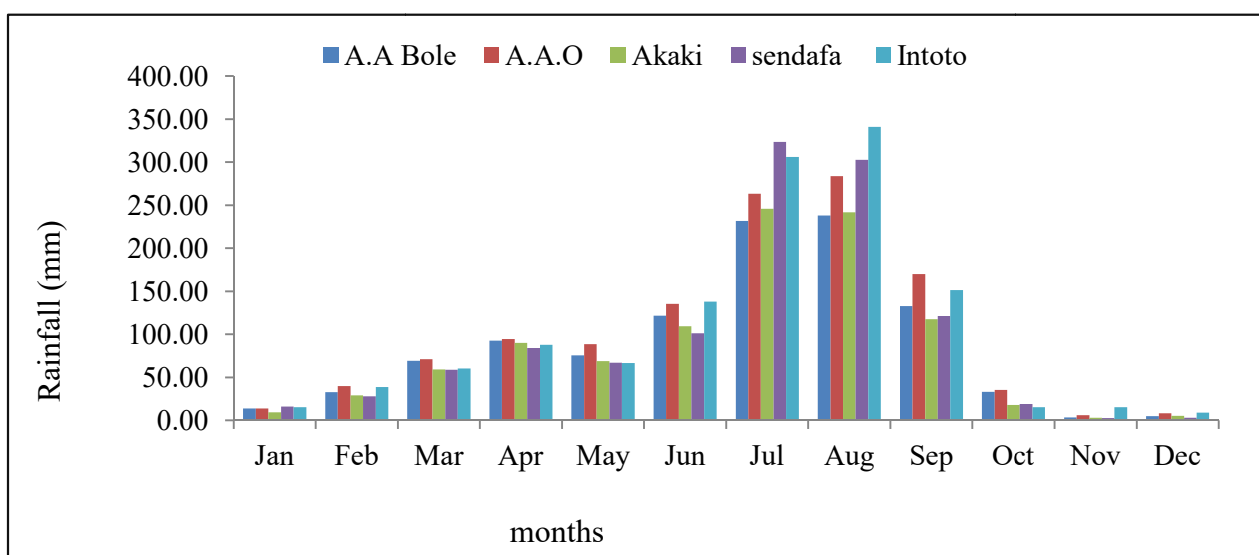


Figure 3.3: Mean monthly rainfall values of the five metrological stations (1981-2005)

3.3.2 Temperature

Temperature, which is another element of climatic parameters, is also highly dependent on elevation. It varies significantly in the catchment. Thus, the temperature decreases as elevation increases. Temperature data in the study area was obtained from National Metrological Agency in the year (1981-2005). These data are available from three metrological stations (Addis Ababa bole, Addis Ababa observatory, and Entoto). The mean annual maximum temperature of the study area varies from 19.2°C to 23.8°C; while the mean minimum

temperature varies from 7.7°C to 11.4°C. The mean annual temperature of the area also varies from 14.7°C to 16.4°C see Table 3.3 corresponding to Fig 3.4.

Table 3. 3: Maximum and minimum averages temperature of the study area

Temp	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Max.	22.3	23.5	23.8	23.3	23.5	21.7	19.5	19.2	20.1	21.5	21.7	21.8
Min.	8.4	9.4	10.6	11.2	11.4	10.6	10.4	10.4	10.3	9.3	8.0	7.7
mean	15.4	16.4	17.2	17.2	17.4	16.2	14.9	14.8	15.2	15.4	14.9	14.7

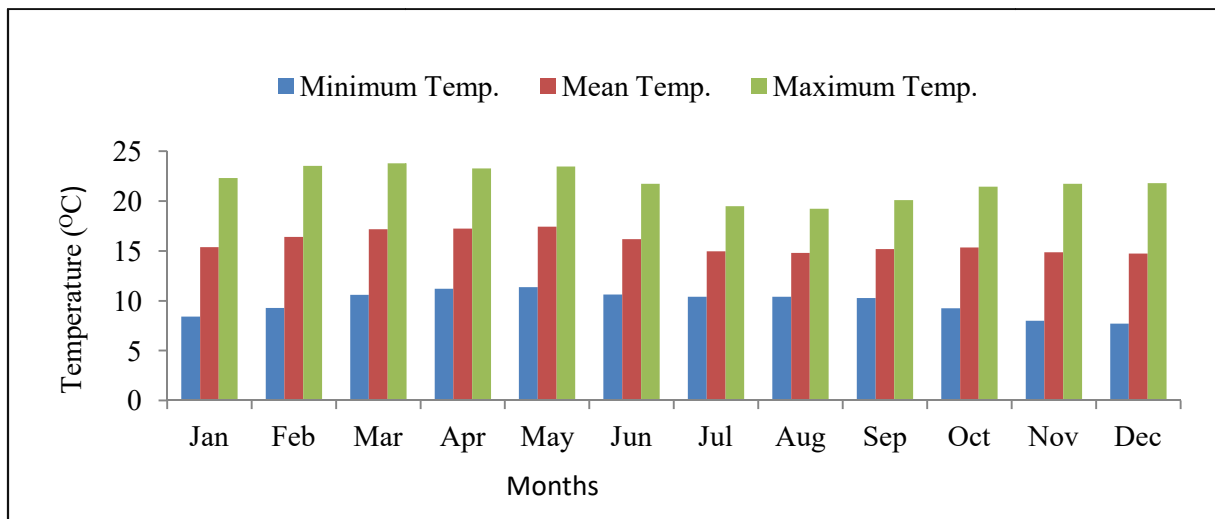


Figure 3.4: Average monthly temperature of the study area (NMA)

3.3.3 Wind speed

Wind speed data in the study area is analyzed from Addis Ababa observatory Station from (1985-2005). The maximum wind speed is recorded in the months of October, November, December and February and minimum values in the months of July and August. The mean annual wind speed is 0.6 (see Fig 3.5)

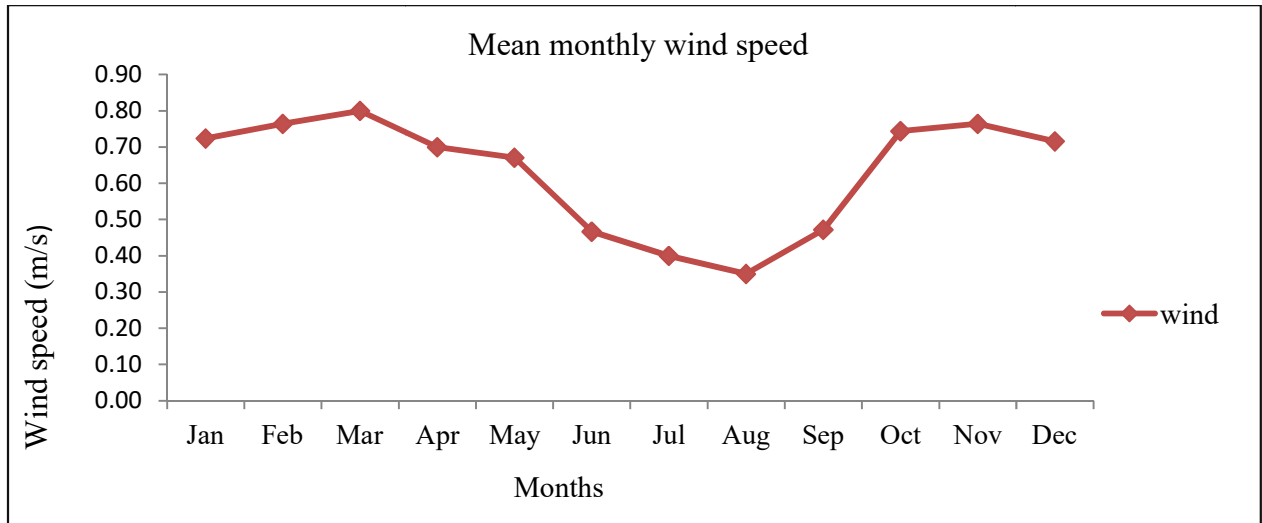


Figure 3.5: Wind speed of the study area (NMA)

3.3.4 Sunshine hour

Sunshine hour of the Akaki catchment area is characterized by data obtained from Bole and Addis Ababa observatory stations. In both stations the maximum sunshine hour is recorded in the months of October, November, December and February. While minimum values observed in the months of July and August (Fig 3.6). The mean monthly of sunshine hours is 6.9hr.

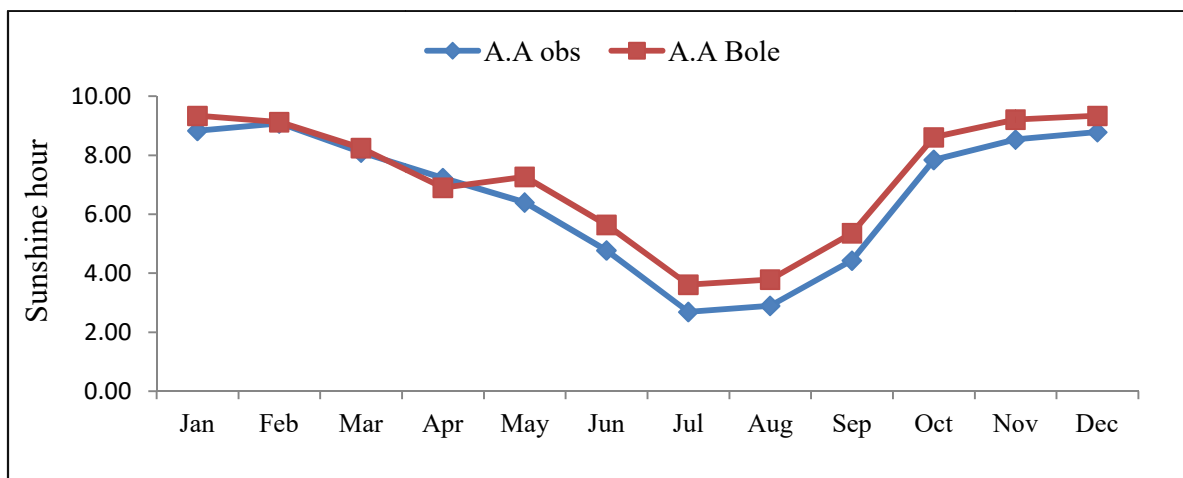


Figure 3.6: Sunshine hour of the study area (NMA)

3.3.5 Relative humidity

The Relative humidity data is analyzed from Addis Ababa Bole and Addis Ababa observatory stations (1981-2005). Relative humidity is the relative measure of the moisture content in the air. The value of relative humidity is expressed in percent (%). It mainly depends on amount of temperature and rainfall within an area. In both stations have a maximum mean relative humidity value recorded in the month of August. While a minimum relative humidity value recorded in the month February (Fig 3.7).

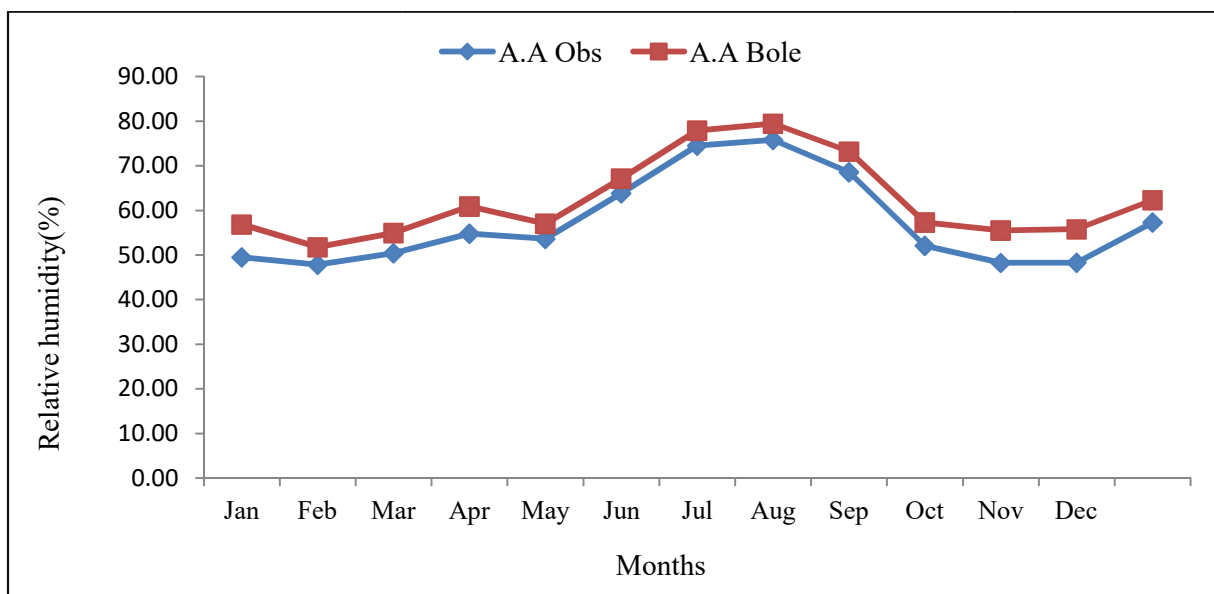


Figure 3.7: Monthly relative humidity of the study area

Table 3. 4: Average monthly Wind speed, Sunshine hours and Relative humidity

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wind speed	0.7	0.8	0.8	0.7	0.7	0.5	0.4	0.4	0.5	0.7	0.8	0.7
Sunshine hours	9.1	9.1	8.2	7.1	6.8	5.2	3.2	3.4	4.9	8.2	8.9	9.1
Relative humidity	53.2	49.8	52.7	57.8	55.3	65.5	76.2	77.6	70.9	54.7	51.8	52.1

3.4 Drainage network

The major perennial rivers originate from the northern part of the study area and drain to southern part. The rivers in the catchment consist of two main branches, joining together at the Abasamuel reservoir. The western branch of the river, the little Akaki, rises north-west of Addis Ababa along the side of Wechacha Mountain. The eastern branch of the river, the big Akaki, rises north-east of Addis Ababa and flows into Abasamuel reservoir. Big Akaki, little Akaki and Kebena rivers are drain through the city of Addis Ababa. The drainage pattern of the study area is dominantly dendritic pattern as shown (Fig 3.8).

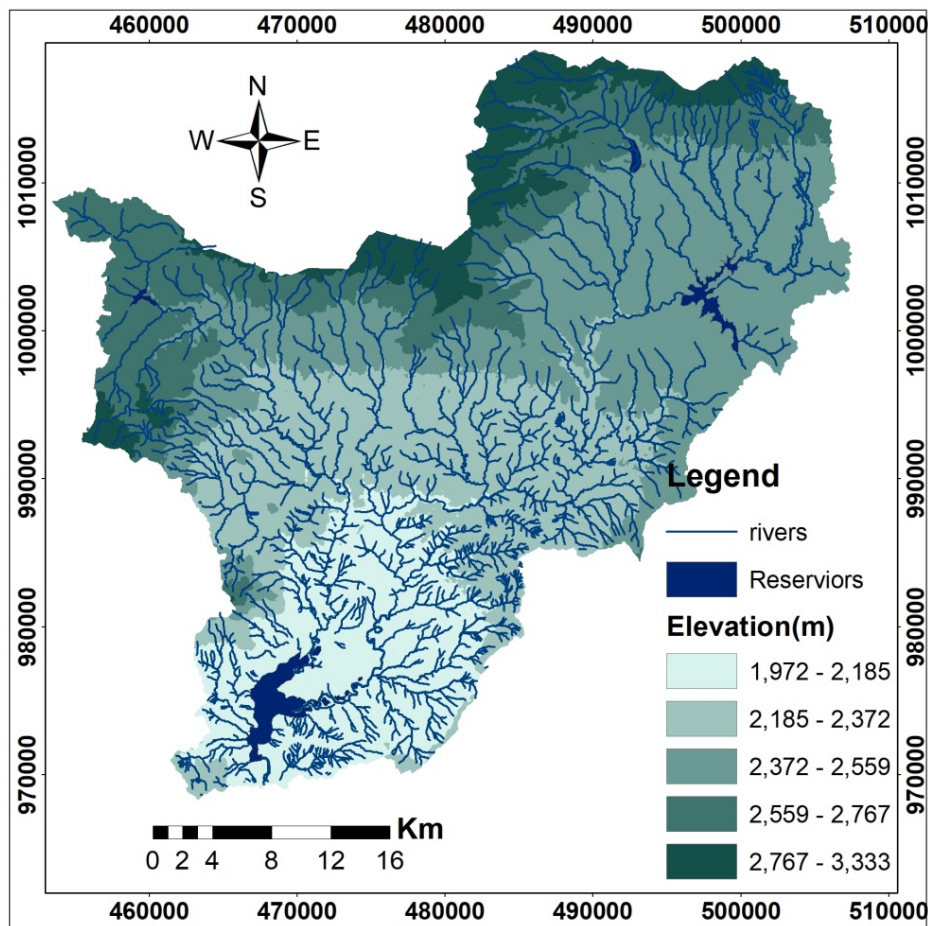


Figure 3.8: Drainage pattern of the study area

3.5 Land-use/land cover

Land-use/land cover has direct impacts on water balance components. The land use map of the catchment area was prepared from sentinel satellite images with supervised classification method. The sentinel satellite images of the years 2019 of the study area was obtained from Ethiopian Mapping Agency (EMA). The land use map of the study area was classified in to five main classes. These are cultivated land, forest, urban settlement, grass land and water body. The dominant land uses in the catchment are urban settlement (38%) and cultivated land (36%). While others are covers small portion (Table 3.5). The land use land cover map of the study area is shown in (Fig 3.9).

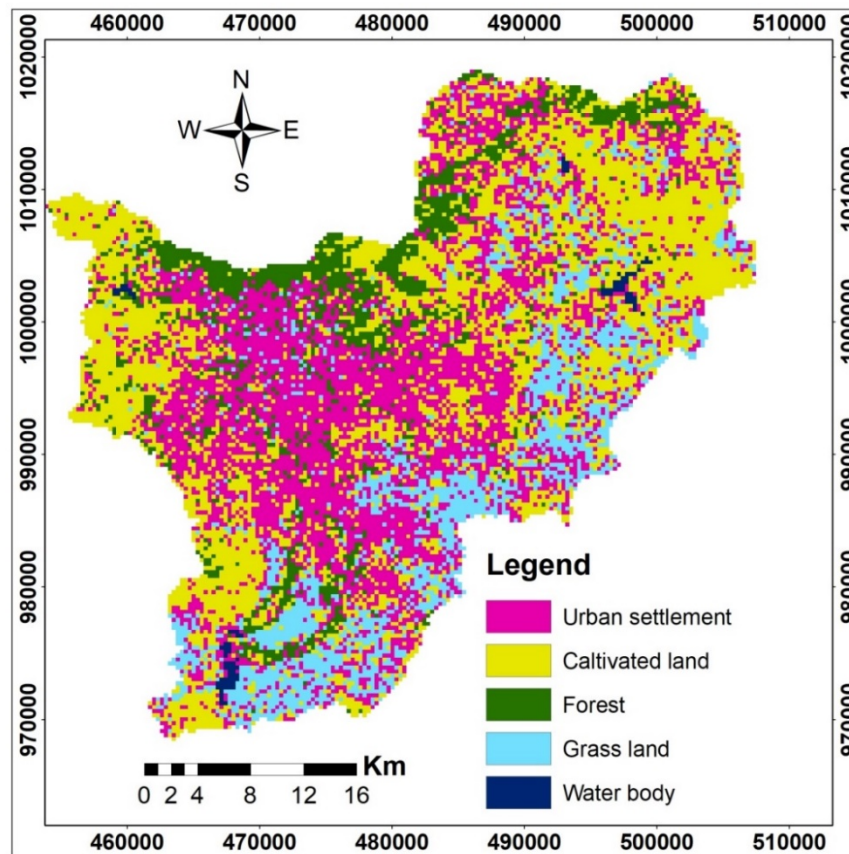


Figure 3.9: Land use land cover map of the area

Table 3. 5: Land use/cover Classes of the study area

Land use class name	Area coverage (km ²)	Area in percent (%)
Forest land	163	11
Water body	9	1
urban settlement	557	38
Grass land	212	14
Cultivated land	528	36
Total	1471	100

3.6 Soil

According to Ministry of Water Resources, Electricity and Irrigation, four major soils types were identified for the study area. These are: - clay, clay loam, silty and sand clay (Fig 3.10). Clay soils cover large portion of the catchment in areas with flat to moderately undulating slopes. It covers 77.8% of the total area. It has characteristically fine textures and low permeability with very low percolation rate. While, clay loam has the intermediate textures relative to clay. The Clay loam is found in northern part of the area and it covers smaller area (0.4%). Silt is found the northern parts and it covers 0.8% of the total area of the study. Sandy clay mainly found in northern part of the area around Entoto and Wechecha mountainous. It covers 21% of the total area. The soil code system used in WetSpas modeling is based on the soil texture. The soil texture is the most important descriptions of a soil and it tells the relative proportions of clay, slit, loam and sand.

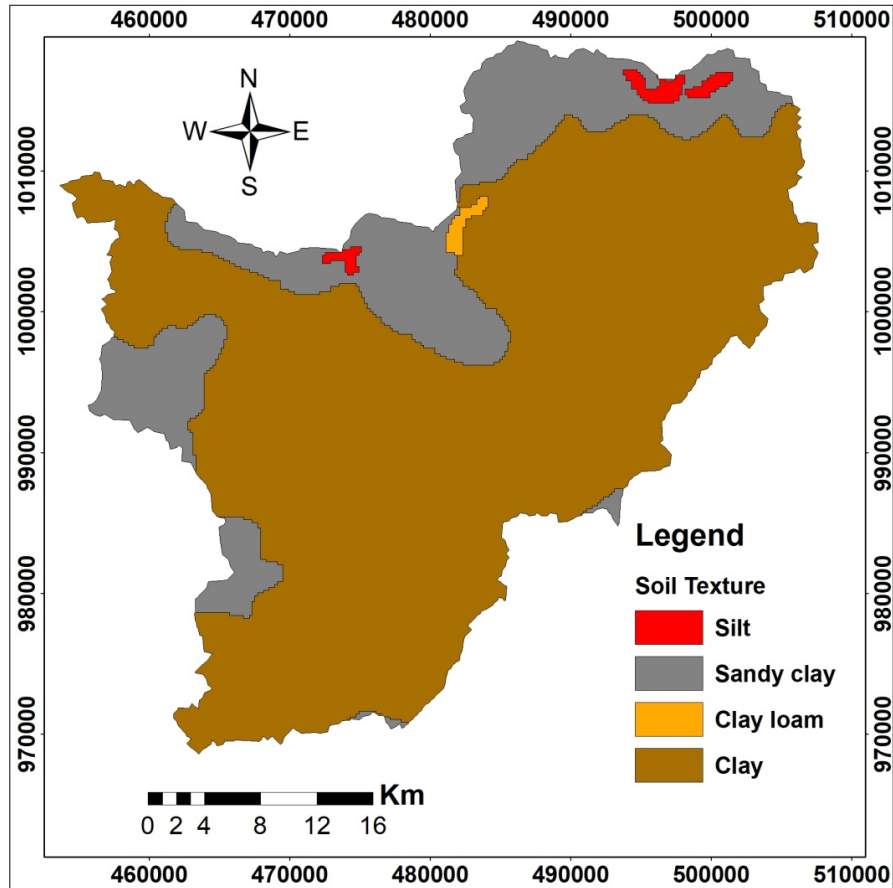


Figure 3.10: Soil map of the study area

3.7 Geology

3.7.1 Regional Geology

Neogene and Quaternary volcanic and sedimentary rocks are exposed along the main Ethiopian plateau. It mostly found in wide variety from liquid basalt rocks to highly viscose acidic rhyolite representing a fissured and central type of volcanism. The Neogene and Quaternary volcanic units include: - the Blue Nile basalts, Aiba basalt, Alaji rhyolites, Tarmaber basalt, and Rift volcanic. The Main Ethiopian Rift (MER) is the northern boundary of the East African Rift system. MER links the afar triple junction and the Kenya Rift regions. It characterized by different structural pattern (faults, graben, and lineaments) that composed of southern, central, and northern segments. It also characterized by active extensional tectonics accommodating the $\sim 6-7$ mm/yr relative movement between the African and

Somalian plates (Chu and Gordon, 1999). The Neogene up to recent volcanic rocks are mainly exposed along the Main Ethiopian Rift floor. Mostly quaternary volcanic and minor fluvio-lacustrine sediments are exposed in the MER (Tsegaye Abebe et al., 2010).

3.7.2 Local Geology

The Lithological units of the study area, the data mainly obtained from the geological survey reports at a scale of 1:250,000. The rock units including:-tertiary volcanic rocks, quaternary volcanic rock and quaternary surficial deposits (sediments). Most parts of catchment covered with volcanic rocks. The main lithological units in the study area are:-

Intoto trachyte (Tt1) This unit is the oldest rock units in the study area and exposed along northern part. It makes up about 6km² of the map area and covers 0.4% of the total area. It is a coarse grained porphyritic and highly weathered rock. It has a light pink to white color. It also characterized by minor fracturing is developed in the unit which also has EW and SE-NE trending joints. These joints are filled with dark brown clay (Assiged getahun, 2007).

Intoto mixed volcanic rocks (Ti1) Entoto mixed volcanic rocks are overlying with the Entoto trachyte. This rock unit covers 95km² and 7% of the total area of the study. It is found in northern parts of the study area and it is a mixed rock contains trachyte, ignimbrites, pyroclastic rocks and other sediments. The trachyte forms variegated color of weathering mainly pink, yellow, white and gray. It has also porphyritic texture at some places. The pyroclastic rocks form light green and reddish brown and contain trachyte and rhyolite. The rhyolite is vasicular and amygdaloidal with filling secondary material by malachite (Assiged getahun, 2007).

Foota basalt (Tb1) this rock unit is found in northern parts of the study. It covers 17km² and 1% of the total area of the study. This rock unit forms ridges. It is dark grey color and shows vesicular basalt with porphyitic basalt or aphanic basalt (Assiged getahun, 2007).

Cheleka basalt (Tb2) this rock unit is found in northern and southern parts of the study area. It covers 255km² and 18% of the total area of the study. It is mainly characterized by high degree of fracturing, and penetrated by deep weathering with a gray appearance. It forms

different layers which are aphanitic basalts agglomerate and pyroclastic rocks and some layers of the basalts are more scoriaceous (Assiged getahun, 2007).

Repi trachy basalt and basalt (Tb3) this lithological unit mainly found along the central and the western portion of study area. It covers 135km² and 9% of the total area of the study. This rock unit is overlain by Wechecha-Furi-Yere ignimbrite to the center and Wechecha-Furi-Yere trachyte to western. Repi basalt mainly greenish grey to dark gray color and porphyritic to aphanitic texture (Assiged Getahun, 2007). It mainly found at flat topography except some place forms Ridges.

Lower ignimbrite (Ti2) The Lower ignimbrite is found along the central and southern portion of the catchment area. It overlies cheleka basalt unit and covers 38km² and 3% of the total area of the study. This unit is mainly intercalation of ignimbrite, ash and tuff. This rock unit is medium to fine grain sanidine phenocrysts (Assiged getahun, 2007).

Wechecha-Furi-Yere Trachytes and trachy basalt (Tt2) this lithological unit mainly found along the western and southern portion of the catchment area. It is overlying with Repi basalt and Wechecha-Furi-Yere ignimbrite. This rock unit covers 163km² and 11% of the total area of the study. It mainly composed of trachyte and pyroclastic material. Wechecha-Furi-Yere Trachytes and trachy basalt mostly forms big mountains such as Furi-Yere and Wechecha. It is a coarse-grained, light gray, brown-grey to dark-grey in fresh rock whereas pinkish yellow to reddish brown in weathered parts (Assiged Getahun, 2007).

Wechecha-Furi-Yere ignimbrite (Ti3) Wechecha -Furi-Yere ignimbrite is dominant part and found in the central and northeast parts of the study area. It covers 447km² and 31% of the total area of the study. It overlain by Repi basalt to the center and it overlain by Entoto mixed rock and cheleka basalt to the northeast. It is grey, which contain rock unit contains rock fragments of ignimbrite, rhyolite and pumice. This rock unit is fine to medium texture (Assiged Getahun, 2007).

Tertiary sediments (Ts) this unit is exposed in the southern parts of the study and it overlain by the young quaternary basalt. It covers 25km² and 2% of the total area of the study. It is yellowish and yellowish pink. This unit forms gentle slope and lower topography. The

deposits (sediments) are mainly a well sorted conglomeratic sandstone to fine sandstone (Assiged Getahun, 2007).

Quaternary basalt (Qb) this is exposed in the north and southern parts of the study. It covers 218 km² and 16% of the total area of the study. It is dominantly olivine basalt with a characteristic grey color on fresh outcrops, whilst it becomes reddish brown when weathered. This rock unit is found in boulder form and vesicles are filled by zeolite and quartz (Assiged Getahun, 2007).

Quaternary sediments (Qs) These deposits are exposed small position of the study, which found along the southern and northern parts. It covers 37km² and 2% of the total area of the study. It forms flat-lying topography and marshy areas. It consists of loose, brown to grey color sand, silt and clay bearing clasts. These clasts are including boulders of basalt, rhyolite and scoria (Assiged Getahun, 2007).

Quaternary scoria cones (Qsc) Quaternary scoria cones are found in the Southern parts of the study. It covers 0.07% of the total area of the study. it is found either cones or simple domes. it is layered but some times contain vesicular basalt domes(Assiged Getahun, 2007) and mainly cut by basaltic dikes. It has a dark brown, reddish grey colour, vesicular coarse grained rock (Efreem Beshawered, 2010). Fig 3.11 shows the main litological units of the catchment area.

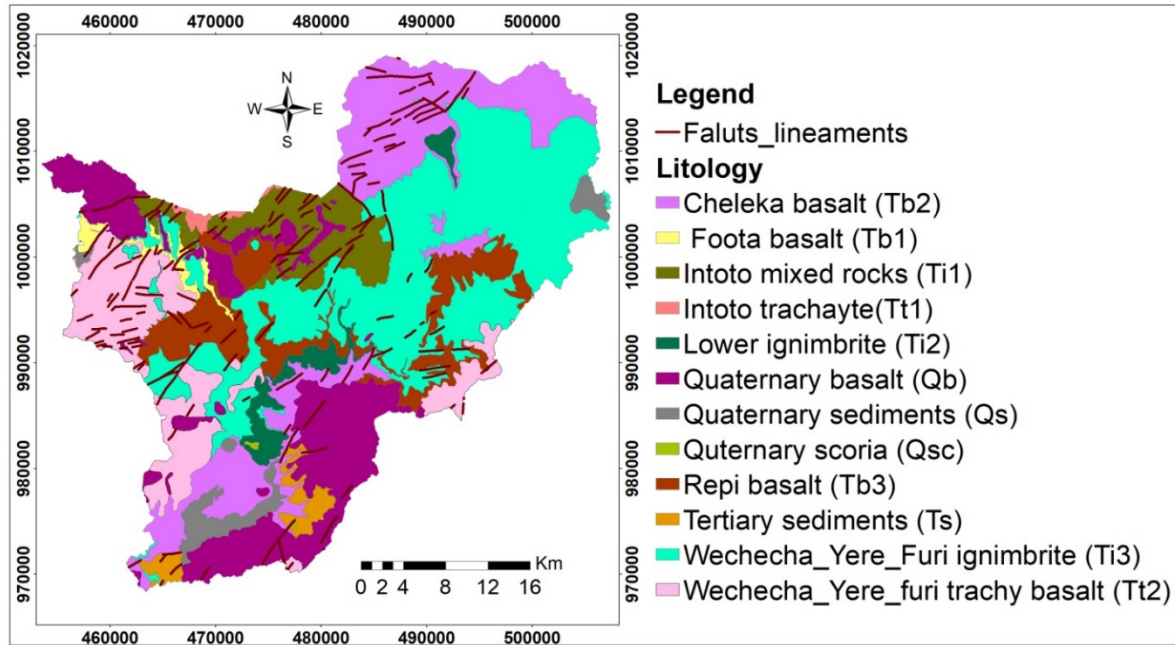


Figure 3.11: Geological map of Akaki catchment

3.7.3 Geological Structures

The Main Ethiopian Rift is enclosed by discontinuous boundary faults that give rise to major fault escarpments separating the rift depression from the Somalian and Ethiopian Plateaus (Tsegaye Abebe et al., 2010). The study area is characterized by highly tectonic activities and has a complex geological structure due to its vicinity to the Main Ethiopia Rift margin. The main geological structures found in the area are lineaments and faults. The major lineaments characterized by four distinct sets of linear features trending in a NE-SW, NW-SE, N-S and rarely E-W directions (Efreem Beshawered, 2010). The most faults in this study aliened NE-SE trending and theses faults are mainly normal. In addition to these, several subordinate jointing and fracturing are common in the catchment.

3.8 Hydrogeology

The hydrogeological map of the area (Fig 3.12) is modified from geological survey reports at a scale of 1:250,000. According to Bereket Fentaw and Leta (2011) the hydrological units of the study classified as high productive aquifer, moderate productive aquifer, Low productive aquifer and minor aquifers.

Extensive and high productive aquifer:-This aquifers type is exposed on the central southern parts of the study area the groundwater is accumulated in and flow through the pours of unconsolidated material. It consists of Quaternary scoria (Qsc), Tertiary sediments (Ts), quaternary sediments (Qs) and Quaternary basalts (Qb). This aquifer system covers 21% of the total area the study.

Extensive and Moderate Productive Aquifer: -This aquifer system is mainly exposed in the central and northeastern parts of the study area. It covers large portion (44%) of the total area the study. In this aquifer, the groundwater is stored in and flow through the fractured and weathered parts of volcanic rocks. Mostly Volcanic lava flows may have high porosity, but in order to have a good permeability the combination of primary and secondary structure should be an integrated. It also depends on the intensity, degree, depth and extent of fractures and joints. However, in some cases the presence of secondary infilling material decreases the permeability of such structures. It consists of foota basalt (Tb1), Repi basalt (Tb3) and lower ignimbrite (Ti2) and Wechecha- Furi - Yerer ignimbrite (Ti3).

Extensive and Low Productive aquifer:-This hydrostratigraphic unit is exposed in eastern and western parts of the study and covers smaller portion (12%) of the total area of the study. Wechecha-Furi and Yerer Trachytes is categorized under this aquifer class.

Minor aquifers with local and limited groundwater resources:-This aquifer system is exposed in the northeastern, central, southwestern parts of the study area. It covers 22% of the total area of the study. The fresh massive and very limited fractured, rhyolitic and trachytic lava domes give in a very low Permeability and limited groundwater occurrence. Minor aquifer in the study includes: Entoto trachyte (Tt1), Entoto mixed rocks (Ti1), cheleka basalt (Tb2). The discharge (Q) and Transmissivity(T) of the aquifer system are shown in Table 3.6.

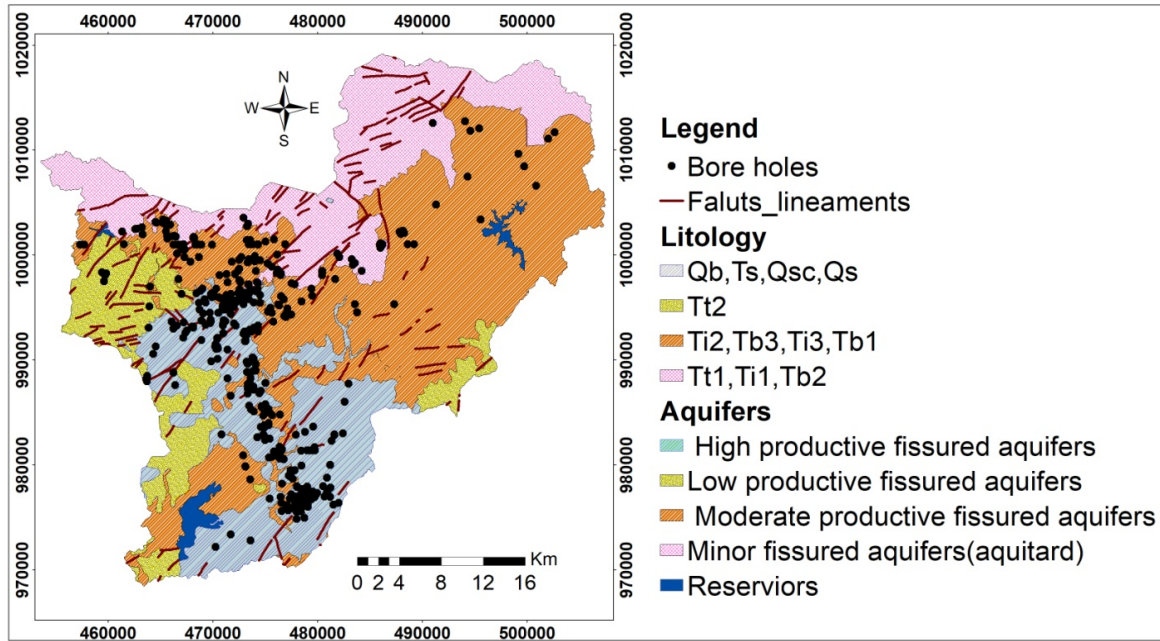


Figure 3.12: Hydrogeological map of the Akaki catchment

Table 3. 6: summary of aquifer system in the study area

Classification of Aquifers	Q (l/s)	T (m ² /d)	Area (km ²)	Area (%)
High productive fissured aquifers	5-25	100-500	303	21
Moderately productive fissured aquifers	2-5	50-100	633	44
Low productive Aquifers	0.05-0.5	1-10	166	12
Minor fissured aquifers (aquitard)	<0.05	<1	318	22

Chapter Four

Materials and Methods

4.1 Materials and software used

The materials used for this research were Arc GIS 10.3 for conversion of data, displaying mapping, Grid data preparation, and spatial data analysis, interpolation of point data and interpretation of the simulated results. DEM used as an input data for Arc-GIS software for prepare the elevation and slop map. WetSpass1.2 was used for simulating groundwater recharge, AET, surface runoff and other hydrologic parameters.

4.2 Methods and Data used

The methodology involved with two major steps.

Firstly, the boundary of the catchment area was delineated by using ArcGIS software. Based on the catchment boundary, the data were collected from different sources and organizations. The collected data includes: - meteorological data, climate simulated data, topographical data, soil data and land use data. The meteorological data were collected from National Metrological Agency Ethiopian (NMA). It includes: - precipitation, minimum and maximum temperature, wind speed, sunshine hours and relative humidity based on the meteorological stations found within the catchment area. The Metrological stations (Addis Ababa Bole, and Addis Ababa observatory, Akaki mission, Intoto and Sendafa) provided data for analysis of the climate on baseline and the projected scenarios (Fig 4.1).

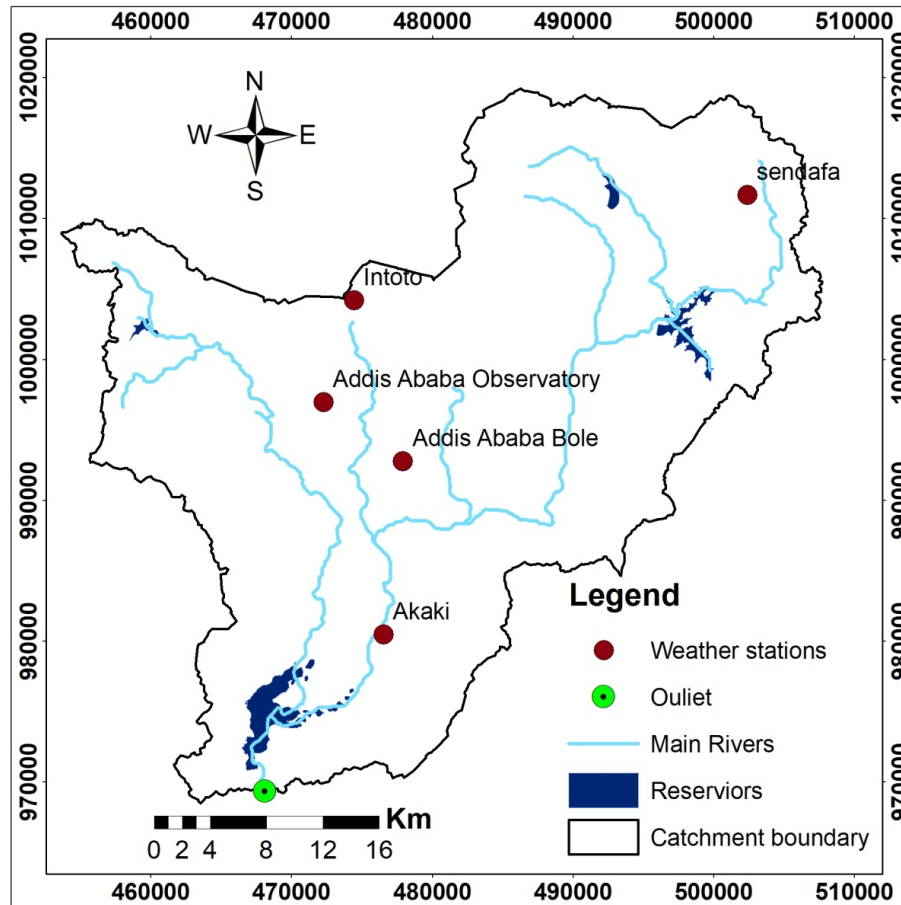


Figure 4.1: Metrological stations in the catchment area

Secondly, the collected data were organized and prepared as input for WetSpss modeling to calculate the annual and seasonal recharge map and other water balance components such as surface water runoff and Actual evapotranspiration. Two types of inputs were used to run the WetSpss model. These are:-grid map and parameter tables. Grid maps (wind speed, elevation, slope, land use, soil, potential evapotranspiration, and rainfall and groundwater depth) were prepared with the same number of column, rows and cell size 1081, 1015 and 50 respectively. The topographic and the slope grid maps were prepared by extracting Digital Elevation Model (DEM) of the study area using ArcGIS10.3 software. In addition to grid maps, the parameter tables of land use, soil texture and runoff coefficient also required for the model inputs.

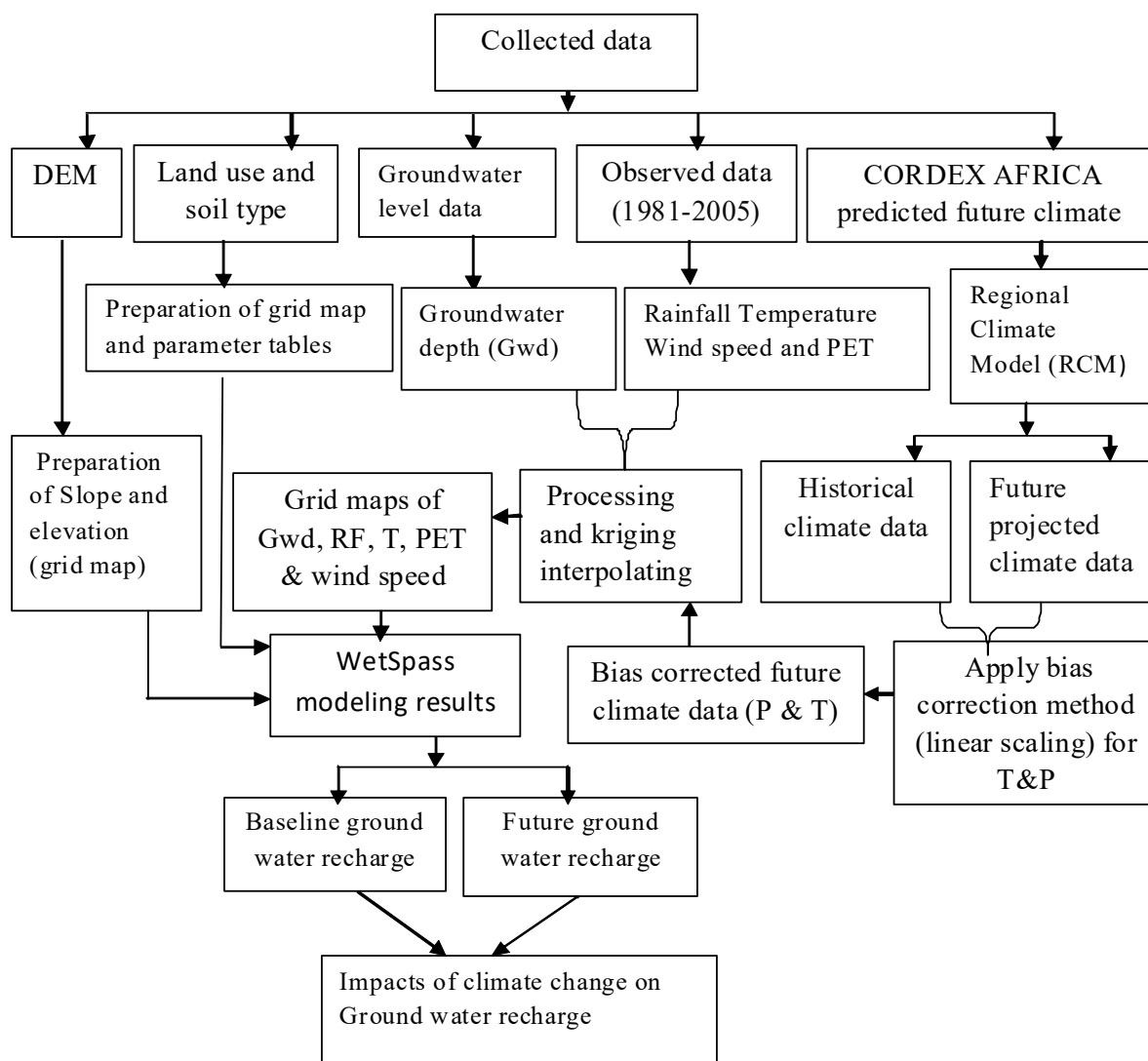


Figure 4.2 : Methodological flow chart

4.2.1 Observed climate data

The observed monthly climate data for the year (1981-2005) was obtained from the Ethiopian Meteorological National Agency (EMA). It includes monthly minimum temperature, maximum temperature, rainfall, humidity, sunshine hours, and wind speed. The observed climate data are available in five stations in the study area with minimum missing data values. The missed data is obtained by computing the arithmetic average of the data values. The accuracy of the missed data was confirmed by the relation of mean annual value of

metrological data with elevation of each station. This filed observed data have been used for bias correction of temperature and precipitation of the RCM.

For processing the WetSpass model, the period 1981-2005 was chosen with an average value for each seasonal and annual time step. The mean annual and seasonal meteorological parameters were prepared from the available meteorological data. The seasonal periods classified into dry and rainy seasons. The month includes June, July, August and September (JJAS) are considered as rainy season and the remaining eight months are considered as dry season. The grid maps of seasonal and annual (precipitation, wind speed, potential evaporation and temperature) were prepared by spatial interpolation of the values observed in the metrological stations, using the Kriging interpolation module of ArcGIS10.3. The observed monthly climate data are used as reference period (1981-2005) for evaluated upcoming impacts of climate change and to obtained quantitative values for expected change in climate.

4.2.2 Regional Climate model data

In the study, the historical RCM simulation (1981-2005) and future projected climate data outputs of midterm (2036-2050) and long term (2066-2080) were driven by Climate Modeling Intercomparison Project Phase 5 (CMIP5) GCMs. Climate refers to the average weather experienced over a long period of time, typically 30 years. And most of the downscaling studies perform time series simulate typically two periods of 30 years intervals. In this study time interval of periods a 30-year gap was between the baseline, midterm (2050s), and long-term (2080s). The data were downloaded from the African CORDEX data <https://esgf-node.llnl.gov/projects/esgf-llnl/>. The Model for Interdisciplinary Research on Climate (MIROC5) model output was daily large-scale RCM data with 50km by 50 km or (approximately $0.44^{\circ} \times 0.44^{\circ}$) spatial resolutions. MIROC5 data output was selected based on comparing the observation metrological data and the historical GCMs with two Representative Concentration Pathways (RCP). MIROC5 is developed jointly at the Center for Climate System Research (CCSR), University of Tokyo, National Institute for Environmental Studies (NIES) and Japan Agency for Marine-Earth Science and Technology (Masahiro Watanabe et al., 2010).

There are four types RCP pathways: RCP 8.5, RCP 6.0, RCP 4.5 and RCP 2.6. In total, a set of four pathways were produced that lead to radiative forcing levels of 8.5, 6.0, 4.5 and 2.6 W/m². In this research, the analysis of future climate projections of 2050s and 2080s from MIROC5 simulation outputs based on two scenarios RCP4.5 and RCP8.5. The two selected RCPs were considered to be representative of medium stabilization scenario (RCP4.5) and very high baseline emission scenario (RCP8.5). The RCP8.5 is a highly energy-intensive scenario as a result of high population growth and lower income with a lower rate of technology development (Riahi, 2011).

4.2.3 Bias Correction Method

Climate simulated data was extracted and bias corrected based on five metrological stations in the study. To carry out the bias correction of precipitation and temperature, the linear scaling (LS) method was applied. The precipitation, minimum and maximum temperature change were evaluated comparatively between the baseline (1981-2005) and two future periods the midterm (2036-2050) and long term (2066-2080). Precipitation is typically adjusted with a multiplier of raw of RCM simulated data while, the temperature data with an additive terms in monthly basis (Fang et al., 2015). Mathematically:-

$$P_{hst,m,d}^{cor} = P_{hst,m,d} \times \mu (P_{obs, m,d} / \mu (P_{hst,m,d})) \quad \text{Eq (4.1)}$$

$$T_{hst,m,d}^{cor} = T_{hst,m,d} + \mu (T_{obs,m,d}) - \mu (T_{hst,m,d}) \quad \text{Eq (4.2)}$$

Where $P_{hst,m,d}^{cor}$ and $T_{hst,m,d}^{cor}$ are represents corrected precipitation and temperature on the **d-th** day of the **m-th** month respectively. $P_{hst,m,d}$ and $T_{hst,m,d}$ are represents precipitation and temperature from obtained from RCM outputs; the subscripts **d** and **m** are specific days and months, respectively. μ represents the mean value of the historical and observed data.

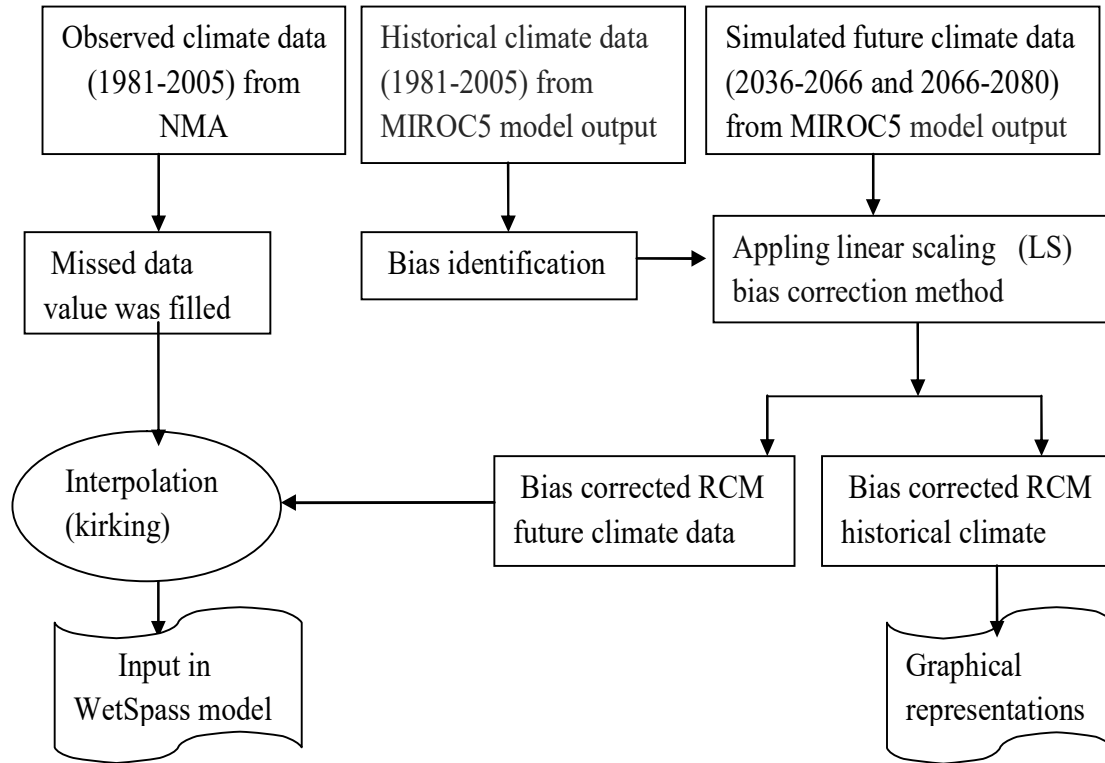


Figure 4.3: Bias correction flow chart

4.2.4 WetSpass Model

There are various methods to estimate groundwater recharge. In this study the groundwater recharge is estimated using WetSpass model. It is a physically based model used for simulate long-term average spatial patterns of groundwater recharge, surface runoff and evapotranspiration (Batelaan and Woldeamlak, 2003). Its inputs are soil, land-use, slope, groundwater depth, and hydro-climatologically distributed grid maps with associated parameter tables for estimating the annual and seasonal groundwater recharge and other hydrologic parameters.

$$R = P - S - AET \quad \text{Eq (4.3)}$$

Where, R, P, S and AET are express groundwater recharge, precipitation, surface runoff and actual evapotranspiration respectively. All parameters are expressed in millimeter units. The surface runoff (S) depends on the land-use, soil, and slope and precipitation intensity in

relation to infiltration capacity of the soil. Surface runoff (S) calculated using the classical rational formula:

$$S = C_{\text{HOR}}C(P - I) \quad \text{Eq (4.4)}$$

Where, C_{HOR} is a coefficient that parameterizes the part of the seasonal precipitation that actually contributes to runoff, C is a runoff coefficient based on the rational formula and I expressed the interception (mm). The actual evapotranspiration (AET) is sum of transpiration, evaporation and interception.

$$\text{AET}_{\text{tot}} = I + T_v + E_s \quad \text{Eq (4.5)}$$

Where, AET_{tot} is the total actual evapotranspiration, ' I ' is evaporation of water intercepted by vegetation, T_v is transpiration of vegetation cover, and E_s is evaporation from the bare soil between the vegetation.

Chapter Five

WetSpass Model Input Analysis

5.1 Parameter Tables

Two types of inputs are required to run the WetSpass model. These are parameter tables and grid maps. The parameter tables contain average values pertinent to soil, land use, vegetation and runoff coefficient. Parameter tables are prepared an appropriate format for the effective model running process.

5.2 Grid Maps

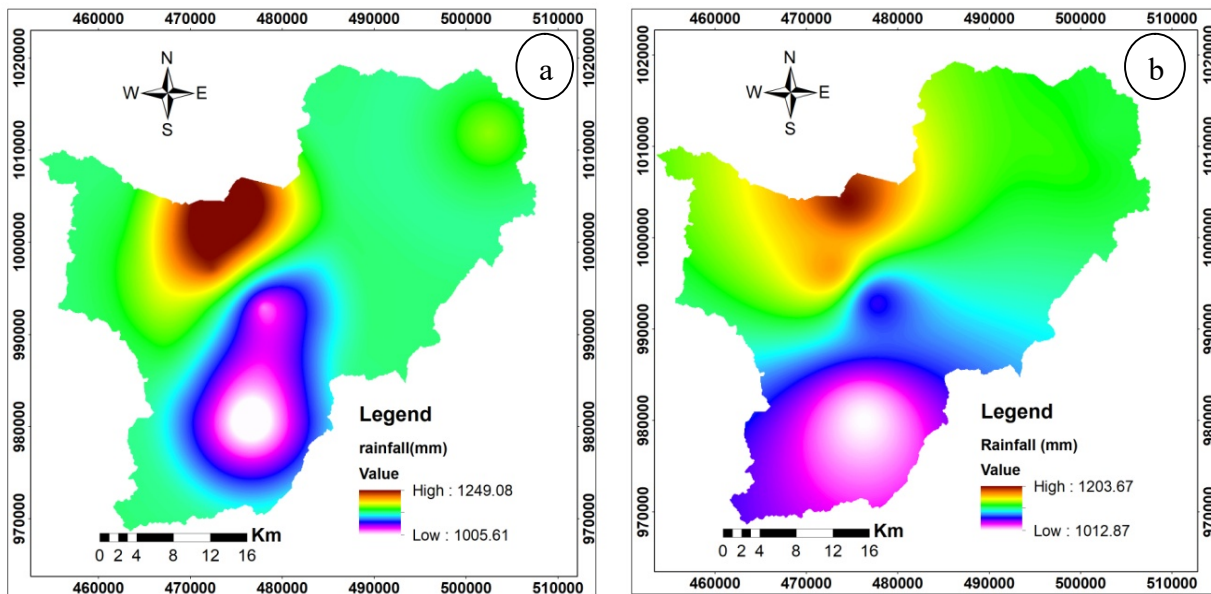
In addition to parameter tables, physical and meteorological grid maps are used for WetSpass model inputs. The physical maps such as Elevation and slope maps are extracted from DEM of boundary of the study area. Meteorological Grid maps (precipitation, PET, wind speed and temperature) and groundwater depth were prepared in grid map by kriging interpolation method. Precipitation, temperature, potential evapotranspiration, wind speed and groundwater depth and land use vary seasonally or annually. That is why the data were prepared separately in two seasons and annual time steps. Topography (Elevation), slope and soil type grid maps were constant and prepared without seasonal basis. All grid maps were prepared with same number of columns rows and cell size. The grid maps were prepared in grid format of 50m cell size with 1081 and 1015 number of row and columns respectively. PET and Precipitation are given the sum of all values in each month, while others are prepared in the monthly averaged values. In this study, all maps are prepared in to seasonal and annual periods. The annual grid maps are illustrated bellow.

5.2.1 Precipitation

Rainfall data from five meteorological stations within the catchment is analyzed to produce the rainfall grid map. For processing the WetSpass model, the rainfall data was chosen baseline (1981-2005) and the two future projected periods 2050s and 2080s rainfall grid maps

was prepared by Kriging interpolation method. The simulation period for rainfall was classified into seasonal and annual time steps.

Seasonal grid map values of rainfall for the WetSpass model inputs are shown (Table 5.1). The model inputs were an average annual precipitation extends 1005.6mm to 1249.1mm for the baseline period. The projection under RCP 4.5, the annual average precipitation ranges from 1012.9 to 1218.7mm during 2050s. And in the period 2080s, the annual precipitation extends from 1087.8 to 1249.8mm corresponding to minimum and maximum respectively. The projection under RCP 8.5, the annual average precipitation ranges from 1057.0 to 1235.9mm during 2050s and ranges from 1075.9 to 125.3 mm during 2080s. The increase in precipitation is more pronounced under RCP 8.5 than RCP 4.5. Except during 2050s under RCP 4.5, all projection is expected to increase annual precipitation compared to baseline period. The input grid maps of rainfall are shown in (Fig 5.1a-e).



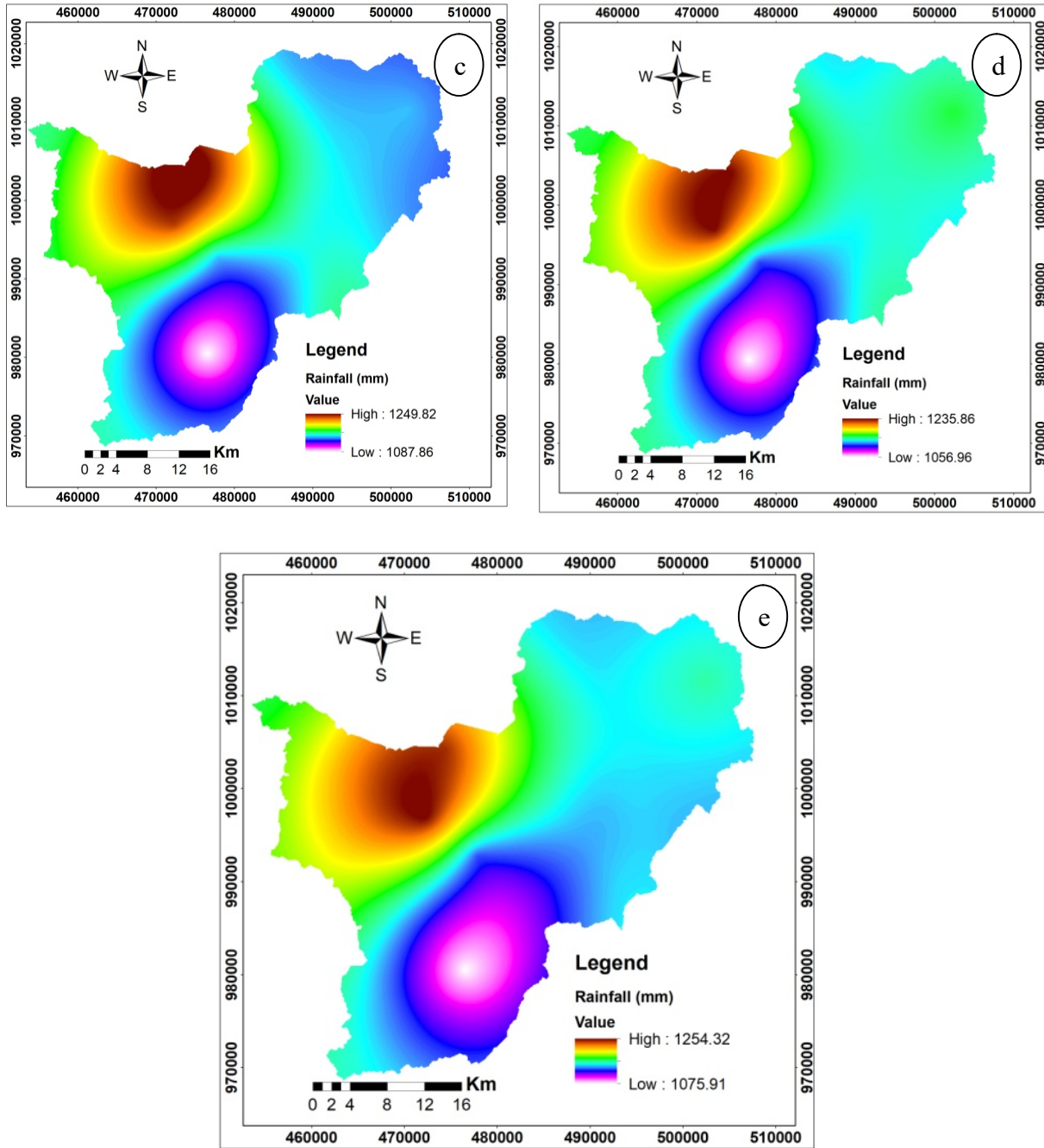
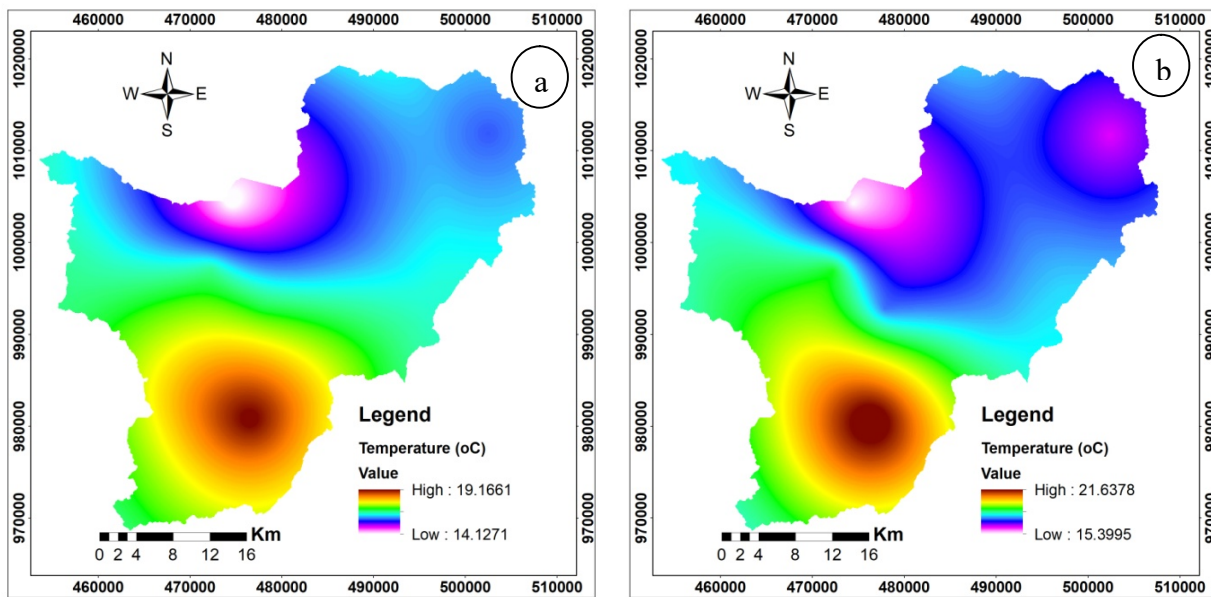


Figure 5.1: Mean annual precipitation grid maps: baseline (a) and the projected periods: 2050s RCP 4.5 (b), 2050s RCP 8.5(c), 2080s RCP 4.5 (d), 2080s RCP 8.5 (e)

5.2.2 Temperature

Similarly, with precipitation data, the simulation time for temperature was divided into two periods. The annual and seasonal temperature of grid maps was prepared by kriging interpolation method. The inputs in the dry and rainy season average temperature are shown in (Table 5.1). In the baseline (1981-2005), the average annual temperature was ranges from 14.1°C to 19.2°C with a mean of 16.7°C. The future climate projection under RCP 4.5, the annual average temperature ranges from 15.4°C to 21.6°C during 2050s and ranges from 15.7°C to 22.2°C with a mean of 18.0°C in the period 2080s. Under RCP 8.5, the annual average temperature ranges from minimum 15.4°C to 18.7°C with the mean of 18.3°C during 2050s and ranges from 17.0 to 23.7°C with the mean of 20.0°C during the period 2080s. In all cases, the average seasonal and annual temperature of the projected periods shows an increasing trend compared to the baseline period. The annual average temperature for the model inputs is shown in (Fig 5.2a-e).



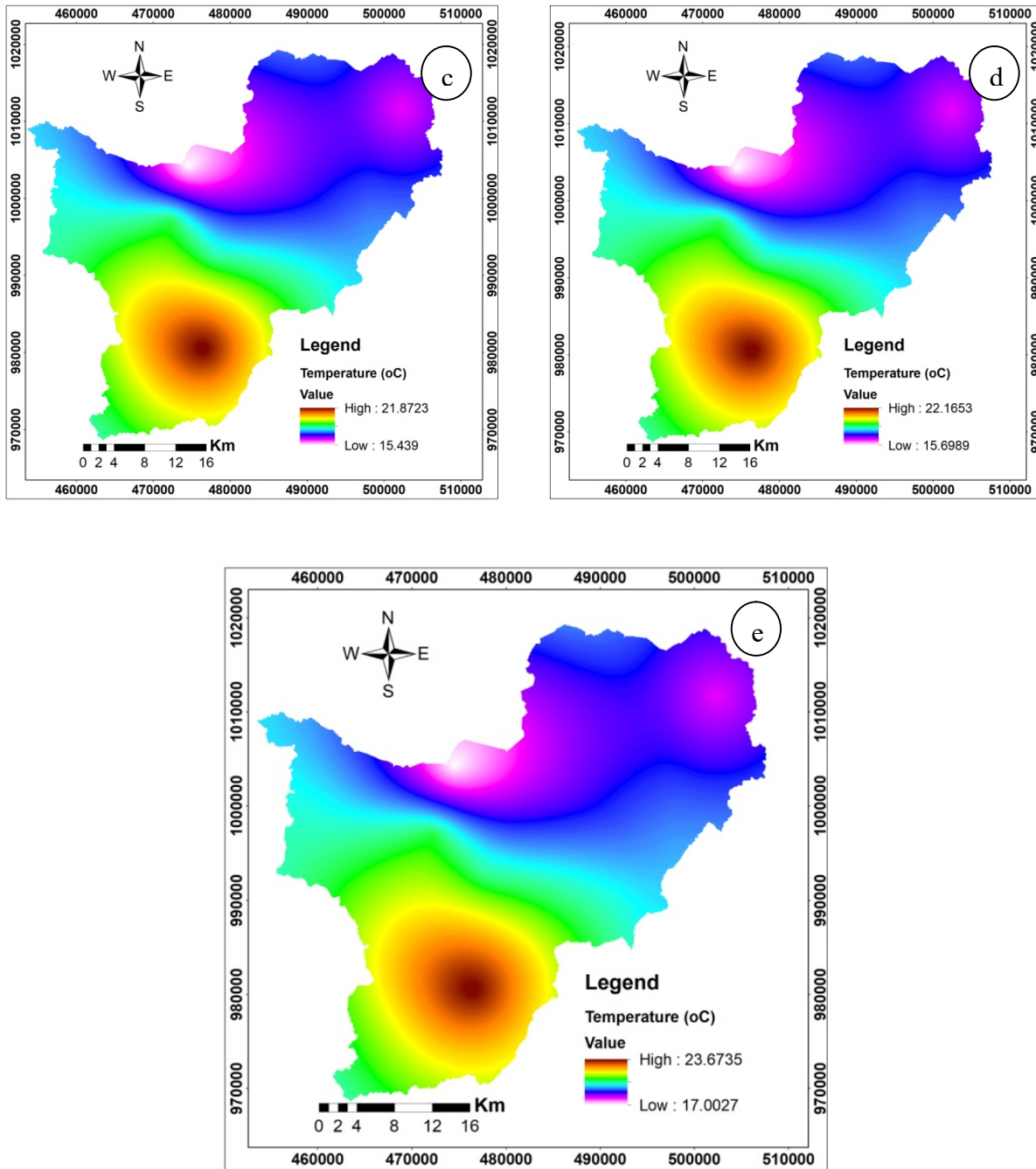


Figure 5.2: Mean annual temperature grid maps: baseline (a) and the projected periods: 2050s RCP 4.5 (b), 2050s RCP 8.5(c), 2080s RCP 4.5 (d), 2080s RCP 8.5 (e).

5.2.3 Potential Evapotranspiration (PET)

Evaporation is Process of liquid water passes directly in to the gas phase. Whereas, transpiration is a process in which water passes from liquid to vapor through plant metabolism. Potential evapotranspiration is the water lose, which will occur if at no time there is a deficiency of water in the soil for the use of vegetation. Like temperature and precipitation, PET also varies with elevation and locations. In the study the PET was calculated using thornthwaite method. It was done based on the following equations.

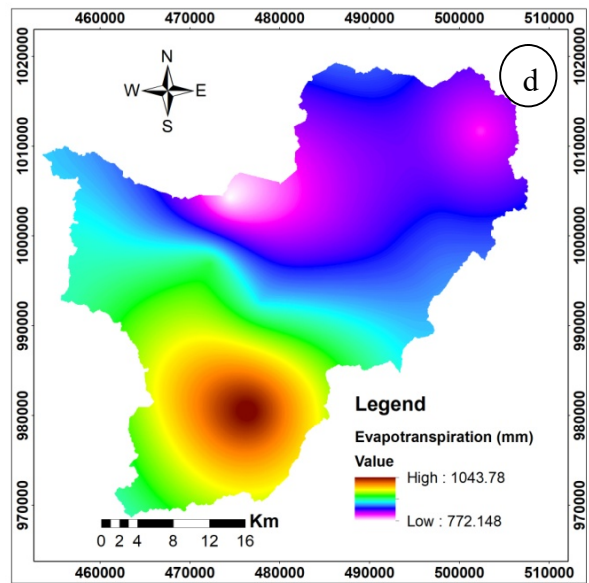
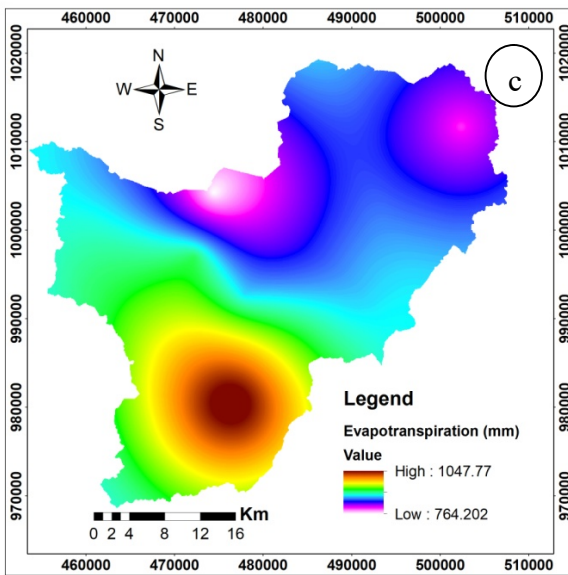
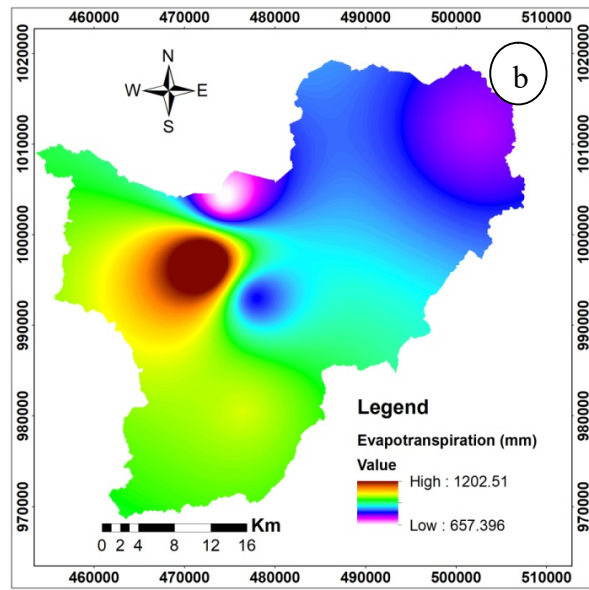
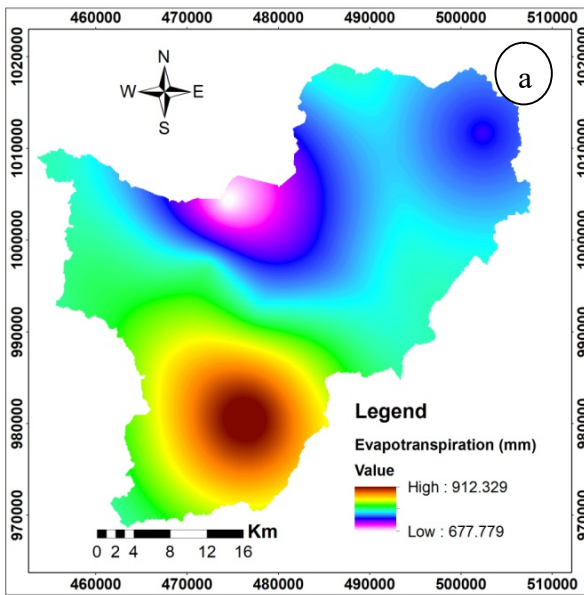
$$PET = 16Nm (10t/I)a \quad \text{Eq (5.1)}$$

$$I = \sum im = \sum (t/5)^{1.514} \quad \text{Eq (5.1a)}$$

$$a = 6.75*10^{-7}*I^3 - 7.71*10^{-5}*I^2 + 0.017921*I + 0.49239 \quad \text{Eq (5.1b)}$$

Where, **m** is the number of months in year (1, 2, 3.....12), **Nm** is the monthly adjustment factor of hours in daylight and dividing it by 12, **t** is the mean monthly temperature ($^{\circ}\text{C}$) and **I** is annual heat index obtained by adding 12 months heat indices.

Finally, the calculated monthly PET results are categories into dry and rainy seasons then converted to spatially distributed grid maps by kriging interpolation method. The seasonal value of grid maps of PET for the WetSpss model inputs are shown (Table 5.1). The average annual PET grid maps are shown (Fig 5.3a-e). In the baseline period, the average annual PET was a minimum ranges from 677.8 to 912.3 mm with a mean of 786.1 mm. Likewise temperature, the PET of future climate projection in both RCP4.5 and RCP8.5 shows increasing trend relative to the baseline periods. The inputs in future climate projection under RCP 4.5, the annual average PET ranges from 657 to 1202.5mm with a mean of 870.1mm during 2050s and ranges from 764.2mm to 1047.8mm with a mean of 882.42mm during 2080s. Under RCP 8.5, the annual average PET ranges from 771.1 to 1043.8mm with the mean of 886.6 during 2050s and ranges from 907.4 to 957.2 mm with the mean of 931.1mm during 2080s.



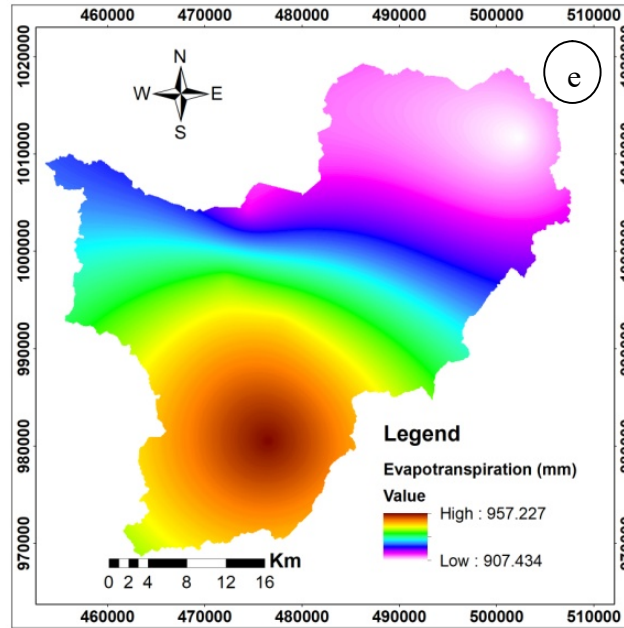


Figure 5.3: PET annual grid maps: baseline (a) and the projected periods: 2050s RCP 4.5 (b), 2050s RCP 8.5(c), 2080s RCP 4.5 (d), 2080s RCP 8.5 (e).

Table 5. 1: Mean value of seasonal and annual precipitation, temperature and PET inputs for WetSpss modeling

Climate parameters	Seasons	Baseline	2036-2050		2066-2080	
			RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Precipitation	dry season	318.1	293.8	326.0	319.2	293.9
	rainy season	812.9	814.3	834.1	827.9	867.9
	annual	1131.0	1108.1	1160.0	1147.1	1161.8
Temperature	dry season	17.0	18.5	19.0	19.2	20.7
	rainy season	16.4	17.4	17.6	17.9	19.3
	annual	16.7	17.9	18.3	18.5	20.0
Potential evapotranspiration	dry season	527.1	610.8	608.4	608.2	641.2
	rainy season	259.0	259.3	274.1	278.5	289.2
	annual	786.1	870.1	882.5	886.6	930.4

5.2.4 Wind speed

Like the other climate parameters (temperature, rainfall, potential evapotranspiration), the simulation time for wind speed also is prepared into two periods, a dry season extends from October to May and a wet season from June to September. The minimum and maximum wind speeds for the winter season are 0.7 m/s and 1.5 m/s with the of mean 1.0 m/s while for the summer season are 0.6 and 0.7 with a mean of 0.7 m/s. The input grid maps of the wind speed are shown (Fig 5.4).

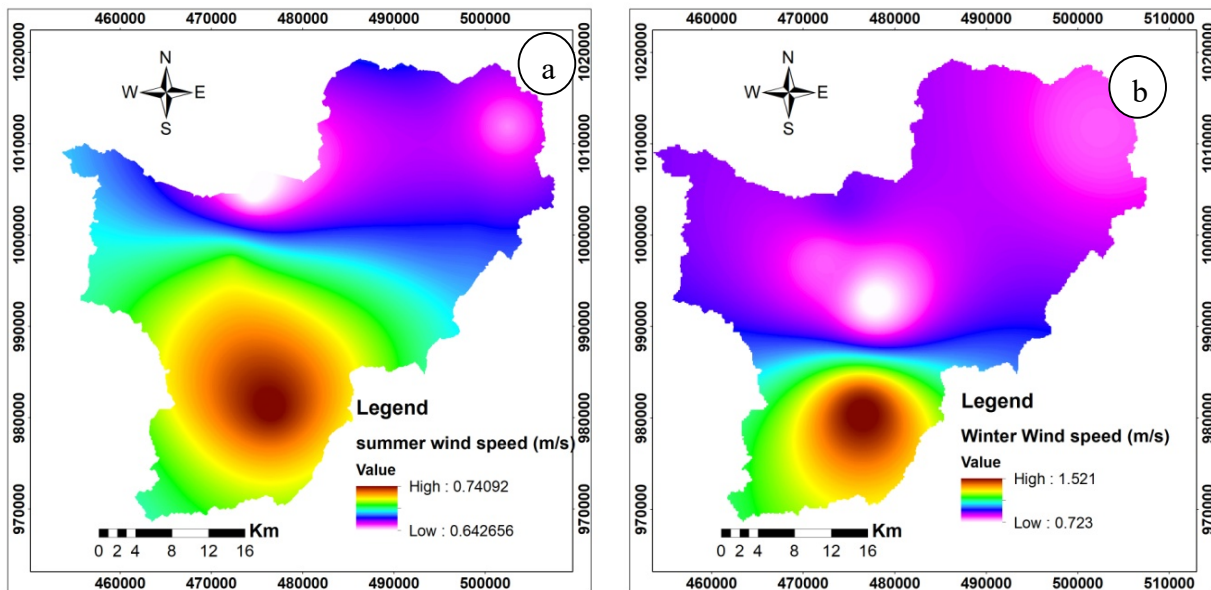


Figure 5.4: Wind speed grid maps: summer (a) and winter (b)

5.2.5 Elevation and Slope

The elevation map and slope map are used for an input for WetSpss modeling. These maps extracted from Digital Elevation Model (DEM) of the study area with a cell size of 30x30 m. The lowest elevation point in the catchment is 1994 m in the southern part while, the highest is 3,273 m in the northern part (Fig 5.5a). The mean elevation of Akaki catchment is 2,435m. The slope map of the catchment is directly derived from the topography map. The slope ranges from 0 to 49 % with a mean 6% (Fig 5.5b).

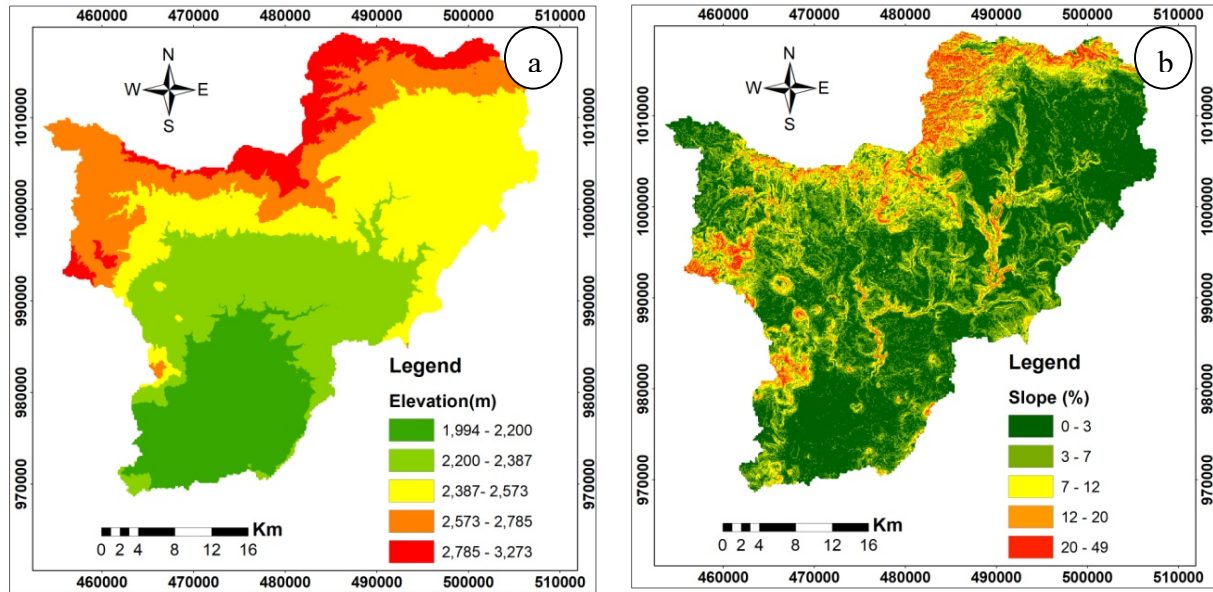


Figure 5.5: Elevation (a) and slope map (b)

5.2.6 Land-use/ Land-cover

Land-use map is used as an input for WetSpss modeling. The model requires dry and rainy land-use/land-cover maps. But, for this research was done with same land use /land cover for both seasons. Even though it is definite that in the future land use changes will also take place, this was also assumed to be constant as this study to investigate results with respect to the change in the climate variables keeping all other factors constant. The land use of the study area was briefly discussed in chapter three (see Fig 3.11). It classified in to five main classes:- cultivated land, forest, urban settlement, and grass land and water body. The dominant land uses in the catchment are urban settlement (38%) and cultivated land (37%). While the rest are grass land, forest land and water body 14%, 11% and 1% respectively.

5.2.7 Soil

Four major soils types were identified for the study area. These are: - clay, clay loam, silty and sand clay. The area dominantly covered by clay and sandy clay soil, which accounts 77.8% and 20.9% respectively. And others cover in small portion, Clay loam (0.4%). Silt (0.8%) The soil code system used in WetSpss modeling is based on the soil texture. The soil texture is the

most important descriptions of a soil and it tells the relative proportions of clay, slit, loam and sand. The soil map of the study area is presented in chapter three (see Fig 3.12).

5.2.8 Groundwater Depth

The groundwater depth data of the study area was obtained from Ministry of Water Resources, Electricity and Irrigation. The groundwater depth was calculated by subtracting the measured static water level from the elevation of the well to produce the groundwater depth grid map. The ground water depth map in grid format is required as input to run WetSpass modeling. The elevation of groundwater depth extends from 1965 to 2668 m (Fig 5.6).

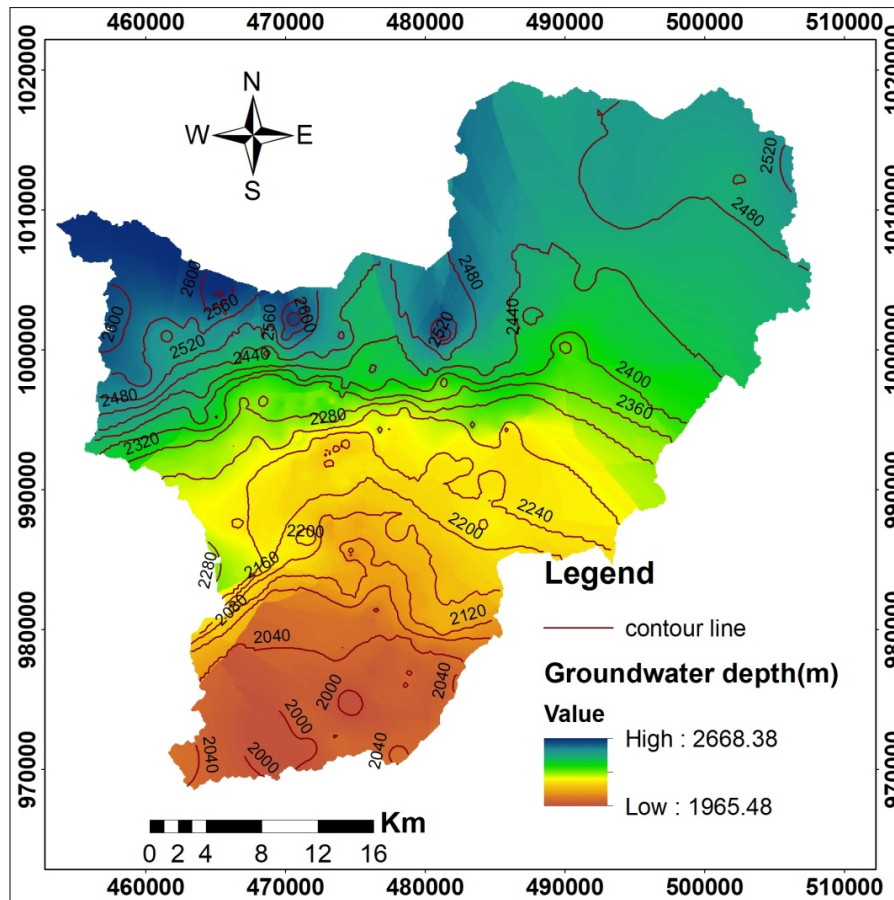


Figure 5.6: Groundwater depth map of the study area

Chapter Six

Result and Discussion

In this chapter, the discussion mainly focused on the possible climate change over future projected based on MIRCO5 model output and the WetSpass model results of main water balance components such as groundwater recharge, surface runoff and Actual evapotranspiration (AET).

6.1 Bias correction

The output of Global Climate Model (GCM) is not directly used for climate change impact on water resource assessments. Evaluation of uncertainties associated with GCMs is a critical concept for assessing future climate scenarios (Ali Ahmadalipour et al., 2015). In this study, the bias adjustment was carried by linear scaling method. It is simple techniques of bias correction, more approachable and sufficient for hydrological analysis at monthly data sets (Shrestha et al., 2016). The bias correction was applied to correct the projected monthly MIRCO5 simulation output, using the differences in the mean between historical MIROC5 output and observations based on the reference period. From the historical observations, the bias corrected of the future climate data of (precipitation, maximum and minimum temperate) was obtained.

6.1.1 Bias correction of precipitation

The correction was done with the mean monthly observed precipitation data and historical MIROC5 model simulated outputs in the period (1981-2005). The correction was done with the five stations in the catchment area. The projected changes in climate will vary from one place. Precipitation is more complex and has some latitude dependent features. High latitude areas experienced higher precipitation compared to lower latitude areas. Before bias correction, the model overestimated in Addis Ababa observatory, Entoto and Sendafa station. Because those stations have higher latitude and the precipitation value showed overestimated.

While underestimated in Addis Ababa bole and Akaki stations. After bias correction, the comparison shows near perfect agreements between the baseline and bias corrected data.

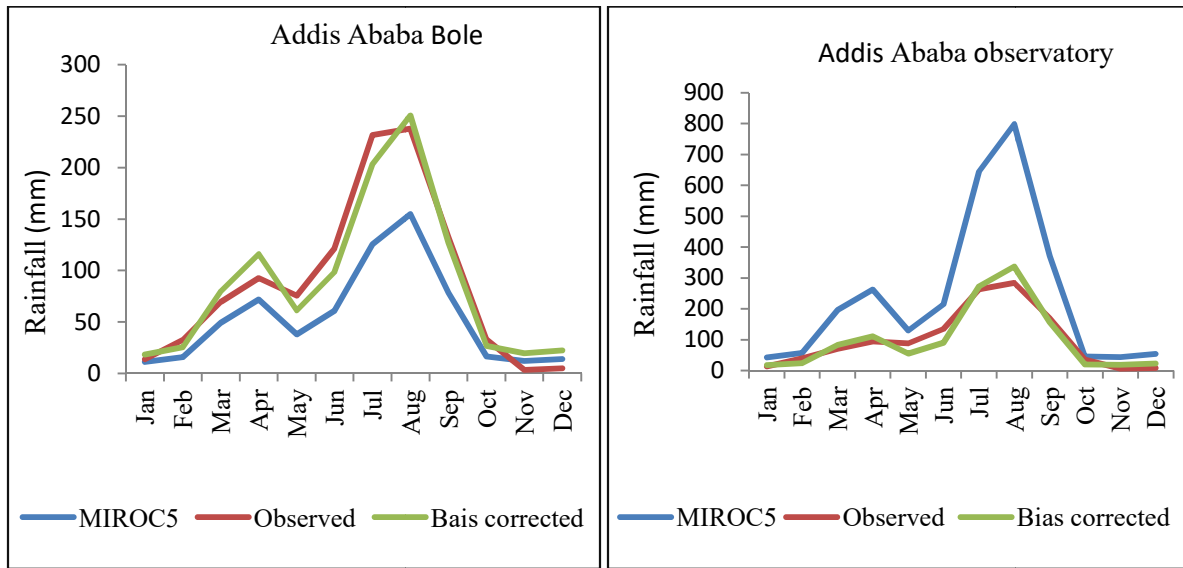


Figure 6.1: Bias correction of mean monthly precipitation for Addis Ababa Bole and Addis Ababa observatory (See others at an appendix C.1)

6.1.2 Bias correction of maximum and minimum Temperature

Like precipitation, the bias correction of maximum and minimum temperature was done with the mean monthly observed maximum and minimum temperature data (1981-2005) with historical MIROC5 model simulated outputs in same period. The comparison shows near perfect agreements between the baseline and bias corrected data of maximum and minimum temperature. Before bias correction, the maximum temperature at Addis Ababa Bole station was underestimated in dry season and Addis Ababa observatory station underestimated in all months. After bias correction, the variation was minimized and near perfect agreements with the observed data (Fig 6.2). Before bias correction, the minimum temperature at Addis Ababa Bole was overestimated in mainly in wet season and Addis Ababa observatory underestimated in dry seasons. And after bias correction, it shows near perfect agreements with the observed data (Fig 6.3). Similarly, the maximum and minimum temperature to the Akaki, Intoto and sendafa stations the bias correction were applied (see appendix C.2 & C.3) respectively.

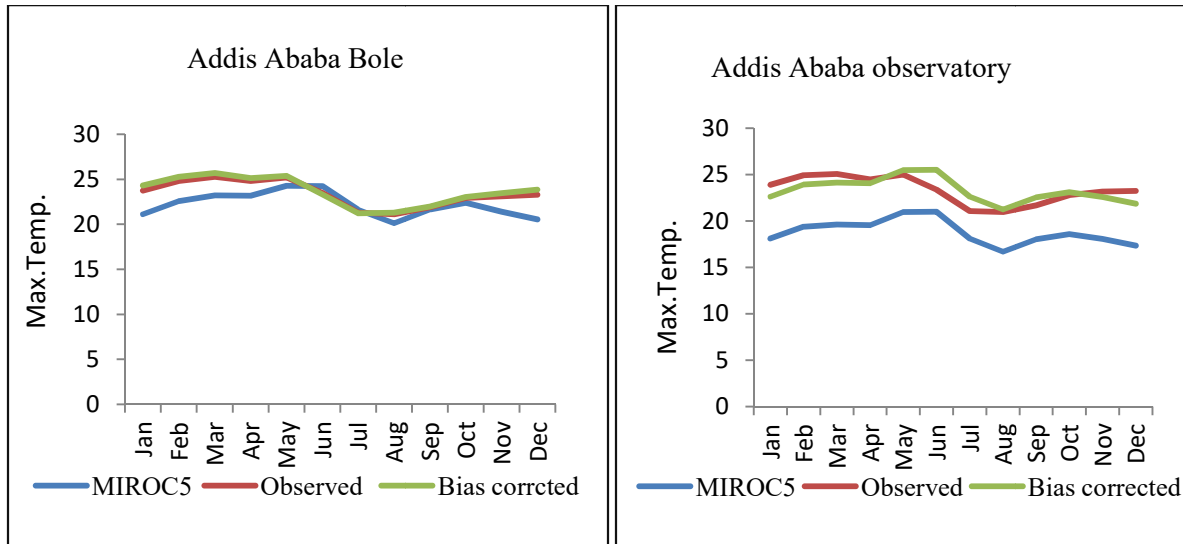


Figure 6.2: Comparison of mean monthly maximum temperature (see others stations appendix C.2)

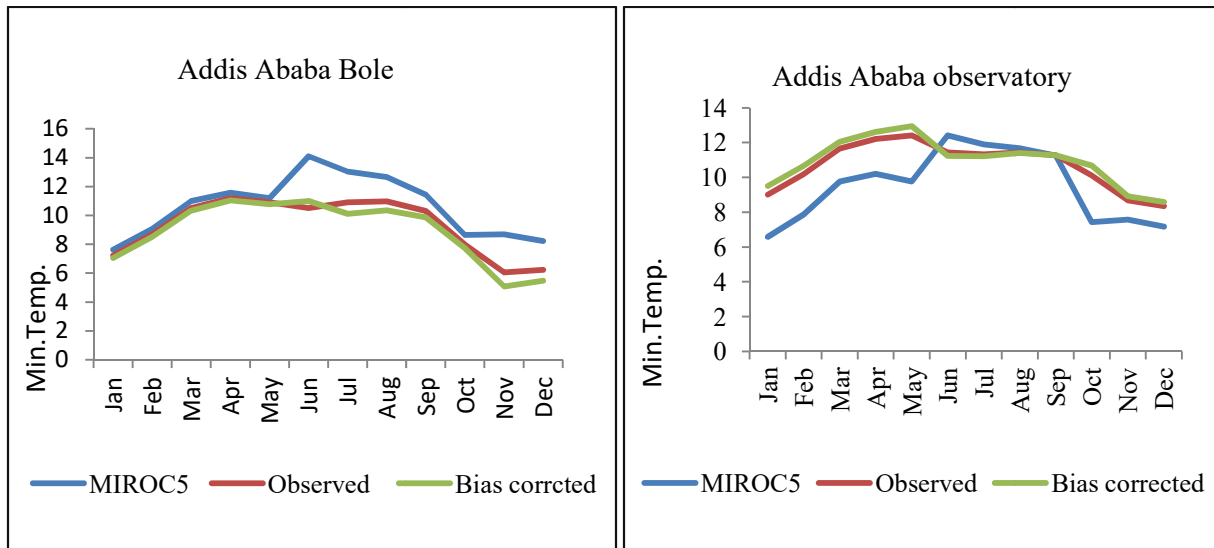


Figure 6.3: Comparison of mean monthly minimum temperature (see other stations at appendix C.3)

6.2 Performance evaluation of RCM outputs

The performance evaluation of RCM was done as per the statistical measure with the corrected RCM data time series against observed data. In this study, the evaluation was done with the following statistical parameters.

Correlation coefficient of determination (R^2): It was applied for describing the degree of collinearity between MIROC5 simulated output and observed data series. R^2 ranges from 0 to 1, with higher values indicating less error variance. Typically R^2 Values greater than 0.5 are considered acceptable (Moriassi et al., 2007). As shown in (Fig 6.4) corresponding to Table 6.1, the R^2 values indicate less error variance. Thus, the value of all meteorological stations is greater than 0.5 and the evaluation is acceptable.

Nash-Sutcliffe efficiency (NSE): it is stabilized statistic to determine the relative magnitude of the residual variance. It ranges between $-\infty$ and 1.0 (1 is inclusive). When $NSE=1$ is the optimal value. The value between 0.0 and 1.0 are acceptable. Whereas values <0.0 are considered to mean observed value is a better predictor than the simulated value and it is unacceptable performance. In this study, the result of NSE obtained from the five meteorological stations range from 0.92 to 0.95. Therefore, the performance evaluation is acceptable level (see Table 6.1).

Percent bias (PBIAS): It measures the difference between the simulated and observed value and the optimum value is 0. A positive value of the model is considered underestimation. While a negative value represents an overestimation of the model (Shrestha et al., 2017). The Percent bias Addis Ababa bole station showed a positive value and it closed to zero (0.001). The optimum of value PBIAS observed in Akaki station. While other stations showed a negative value but it close to zero (see Table 6.1). Therefore model performed well overall as indicated by the good results of R^2 , NSE, and PBAIS (%). It is also true for maximum and minimum temperature.

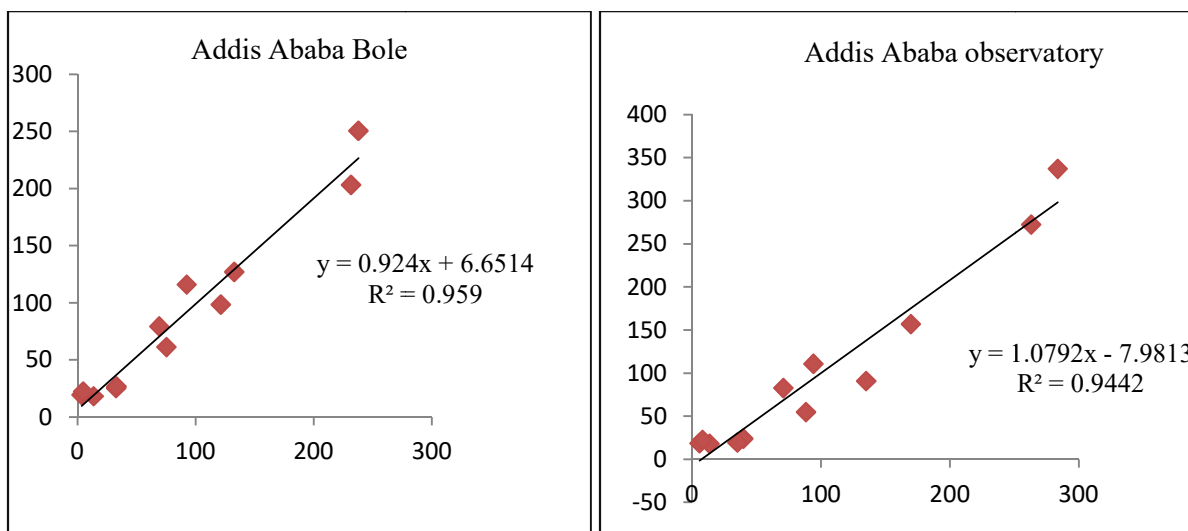


Figure 6.4: R^2 between observed and bias corrected rainfall data (see other station appendix C.4)

Table 6. 1: Summary of performance evaluation of the rainfall data

Metrological stations	R^2	NSE	PBAIS (%)
Addis Ababa Bole	0.95	0.95	0.001
Addis Ababa observatory	0.94	0.92	-0.0008
Akaki	0.95	0.94	0.0
Entoto	0.96	0.94	-0.0003
Sendafa	0.94	0.93	-0.0009

6.3 Analysis of climate change of the projected periods

The change in rainfall, the maximum and minimum temperature in the catchment area was determined for the selected future periods 2050s and 2080s compared with the baseline (1981-2005). The projected period was analyzed based on RCP 4.5 and RCP 8.5 scenarios in a monthly basis.

6.3.1 Changes of the projected Precipitation

The average monthly rainfall in the catchment area for the projected periods 2050s and 2080s has been evaluated under RCP 4.5 and RCP 8.5 climate scenarios. In the period 2050s under RCP 4.5 scenario, the maximum change of monthly average rainfall shows an increment of 33

mm (3%) in August. Whereas the change minimum value of mean monthly rainfall shows 2mm (1%) in February. Under RCP8.5, the change in average monthly rainfall shows an increment of 39 mm (4%) in July and the minimum is -0.08 mm (-0.01%) in January (Fig 6.5). In the period 2080s under RCP 4.5 scenario, the maximum change of monthly average rainfall shows a maximum of 40 mm (4%) in May and the minimum change is -4mm (-0.4%) in January while under RCP8.5, an average monthly rainfall shows an increment of 53 mm (5%) in August and the minimum change is -5 mm (-0.4%) in November (Fig 6.6). Relative to the baseline period, the monthly precipitation shows insignificant change (Table 6.2).

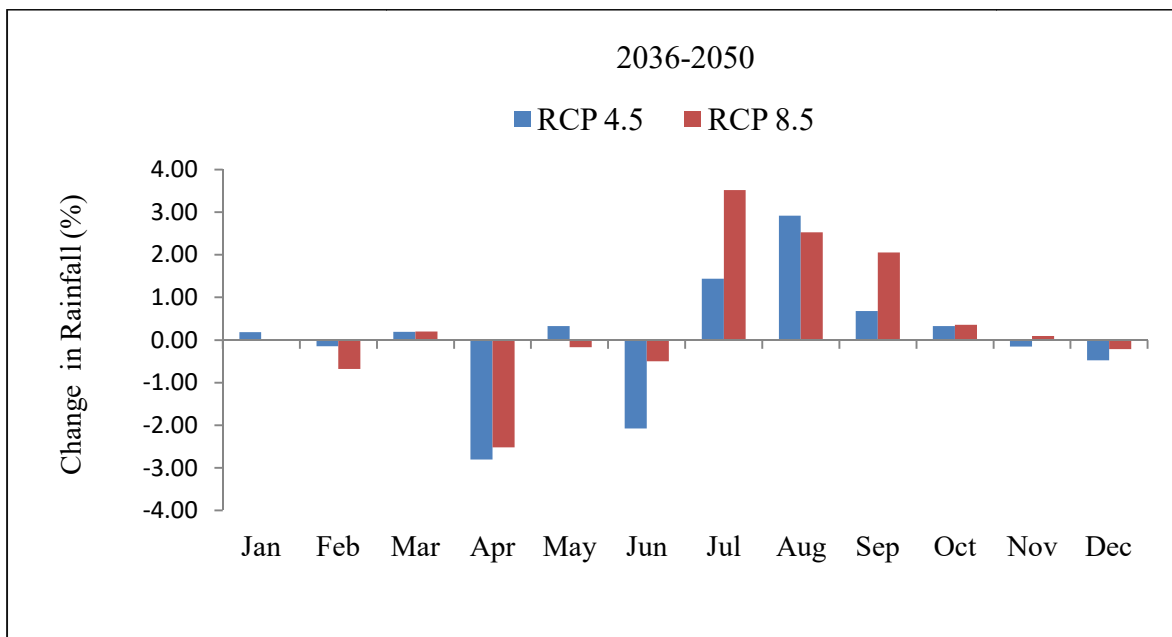


Figure 6.5: The change in rainfall of 2050s under: a) RCP4.5 and b) RCP 8.5 scenario compared to the baseline (1981–2005).

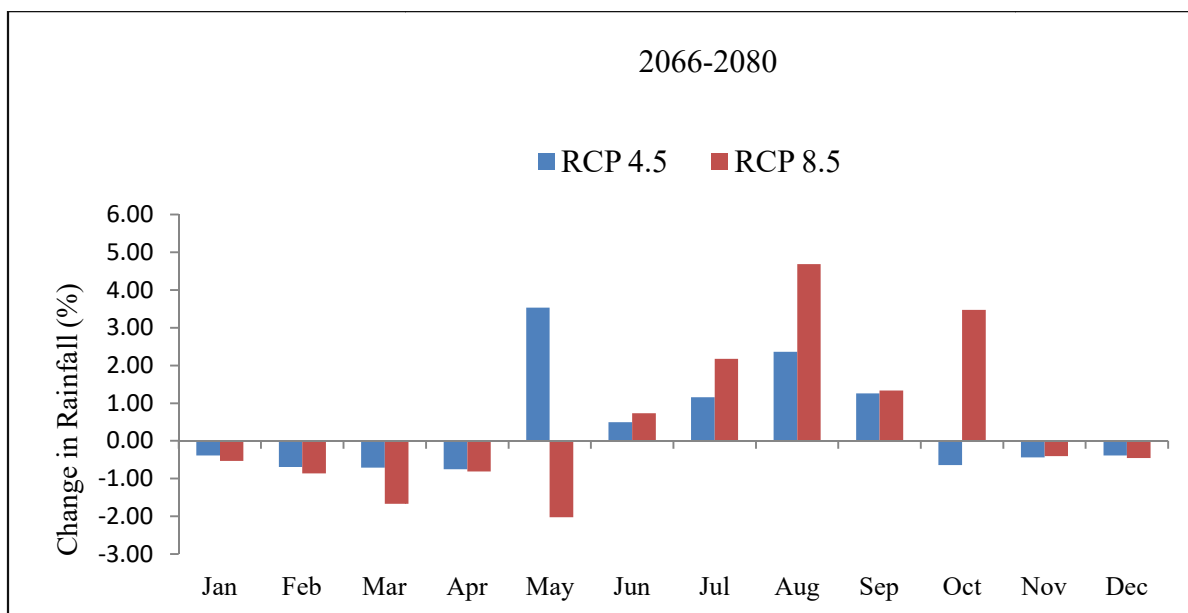


Figure 6.6: The change in rainfall 2080s under: a) RCP4.5 and b) RCP 8.5 scenario compared to the baseline (1981–2005).

Table 6. 2: Average annual precipitation of future projected periods respect to the baseline (1981-2005)

	Baseline (1981-2005)	2036–2050		2066–2080	
		RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Average annual rainfall	1131	1108	1160	1147	1162
Absolute difference (mm)		-30	29	16	31
Relative change (%)		-2	3	1	3

6.3.2 Changes of Projected maximum and minimum Temperature

In this study, the change in the projected period of maximum and minimum temperature under RCP4.5 and 8.5 scenarios are compared to the baseline (1981-2005). During 2050s in RCP 4.5, the change of average monthly maximum temperature ranges from 1.2°C (August) to 2.1°C (October). And the change of minimum temperature on a monthly average basis extends from 1.3°C (August) to 2°C (February). Under the RCP 8.5 scenario, the monthly maximum temperature ranges from 1.5°C (August) to 2.6°C (October). Change of average in monthly minimum temperature ranges from 1.7°C (August) to 2°C (May).

In the period 2080s under RCP 4.5 scenario, the maximum change of monthly average ranges from 2.9°C (August) to 4.5°C (October). And the change of minimum temperature on a monthly average basis extends from 1.8°C (August) to 3°C (October). Under RCP 8.5, the monthly maximum temperature ranges from 2.9°C (August) to 5.2°C (October). And the Change of average in monthly minimum temperature ranges from 2.9°C (August) to 4.5°C (October). Similarly, with a change in monthly minimum temperature, the change maximum temperature also shows a higher value in RCP 8.5 than RCP4.5 scenario. In addition, the mean annual temperature 2050s is expected to increase by 1.5°C and 1.8°C under RCP4.5 and RCP8.5 respectively and in the period 2080s is expected to increase by 2.1°C and 3.5°C under RCP4.5 and RCP8.5 respectively. The result of this study regarding on change in maximum and minimum temperature is consistent with previous researchers (Gashaw Gismu et al., 2020; Abeyou Wale et al., 2018). The monthly change in maximum and minimum temperature is shown in Fig 6.7 and 6.8 respectively.

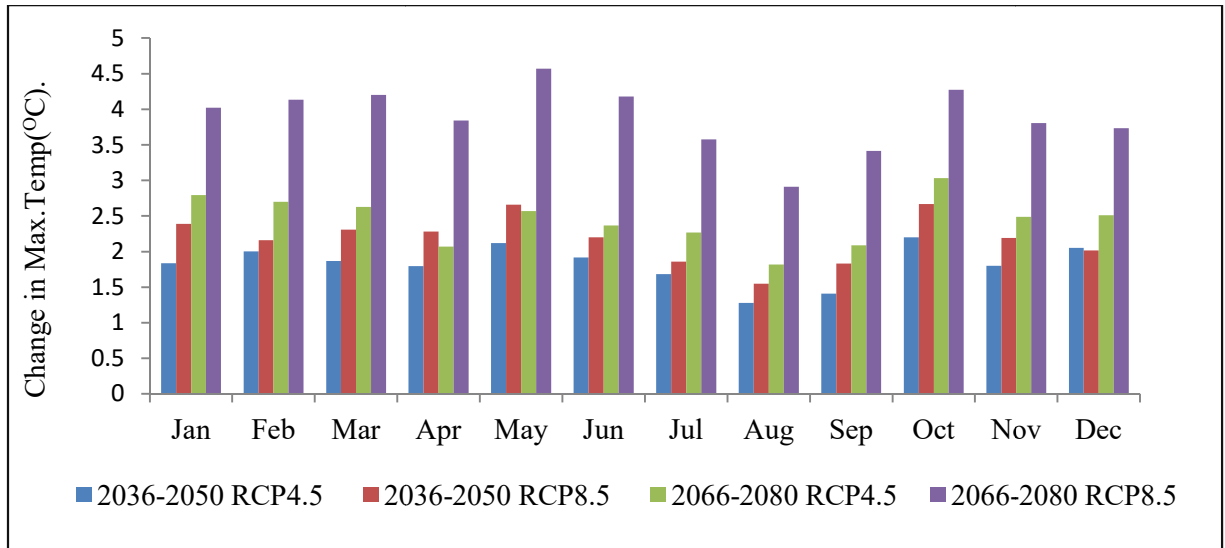


Figure 6.7: Change in monthly average maximum temperature compared to the baseline period (1981–2005).

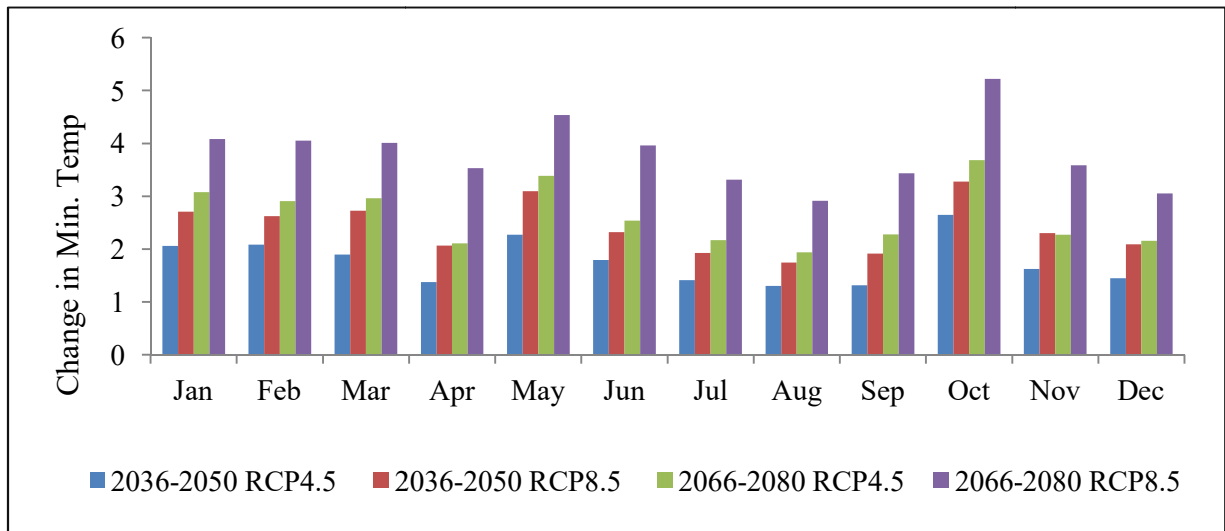


Figure 6.8: Change in monthly average minimum temperature compared to the baseline period

Table 6. 3: Change in average annual temperature of projected periods respect to the baseline period

	Baseline	2036–2050		2066–2080	
	(1981-2005)	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Average annual temperature (°C)	16.6	18.1	18.4	18.7	20.1
Absolute difference (°C)		1.5	1.8	2.1	3.5
Relative change (%)		8.7	10.8	12.4	21.1

6.4 The output of WetSpass Model

The WetSpass model result was on the basis of annual and seasonal outputs of water balance components includes: - Actual Evapotranspiration (AET), surface runoff and recharge of the baseline (1981-2005), and the selected future periods of midterm (2050s) and long term (2080s) under RCP4.5 and RCP 8.5. The annual average surface runoff, Actual Evapotranspiration, and groundwater recharge are described below.

6.4.1 Surface runoff under different climate scenarios

Surface runoff mainly depends on soil types, land use, slope, and amount of rainfall within the area. In the study area, maximum surface runoff occurs on clayey soils, while the lowest values are observed for sandy and loam soils. Surface runoff also spatially varies with the topography of the catchment. In all periods (baseline and future projected), the higher surface runoff is observed in the central and southern parts. Whereas lowest surface runoff observed runoff occurs in the northern parts around mount Entoto and Wechecha due to high vegetation coverage with sandy and loam soils types.

6.4.1.1 Surface runoff of the baseline period (1981-2005)

The annual surface runoff for the baseline period ranges from 0.9 mm to 663mm (Fig 6.9). The mean annual surface runoff was 396 mm and accounts for 35 % of the total precipitation (1131mm). In the dry season, it accounted for 27% of the total annual surface runoff while the remaining 73% occurred during the rainy season.

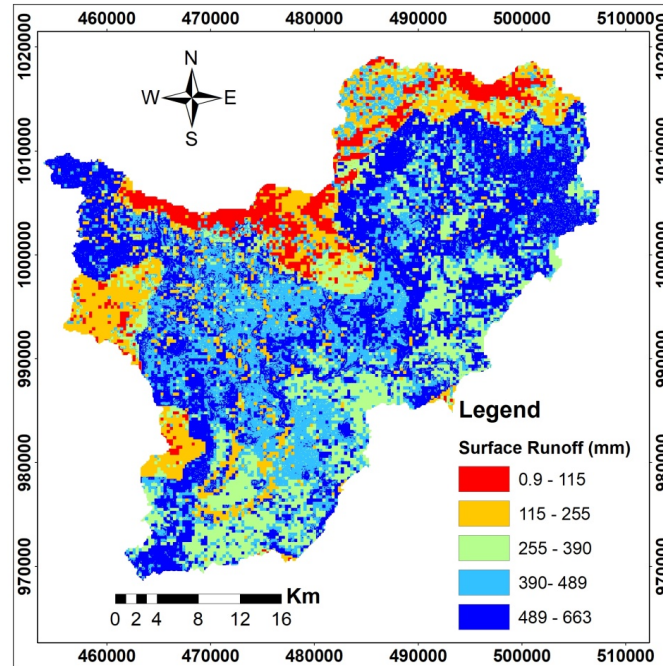


Figure 6.9: Annual surface runoff of the baseline (1981-2005)

6.4.1.2 Midterm surface runoff (2036-2050)

In the projection under RCP 4.5, the annual surface runoff ranges from 0.9 to 644 mm (Fig 6.10a) with a mean of 393mm. The annual surface runoff is expected to decrease by 3 mm (1%) compared to the baseline due to decreasing the change in annual precipitation by 2%, increasing in temperature by 1.5°C further increase PET by 41 mm (6%). In the projection under RCP 8.5, the annual surface runoff ranges from 0.9 mm to 671 mm (Fig 6.10b) with the mean annual of 412mm. The annual surface runoff is expected to increase by 16mm (4%) compared to the baseline as a result of a slight increase in precipitation by 3% and an increase in the mean annual temperature by 1.8°C. furthermore, the potential evapotranspiration is expected to 78 mm (10%) compared to the baseline period.

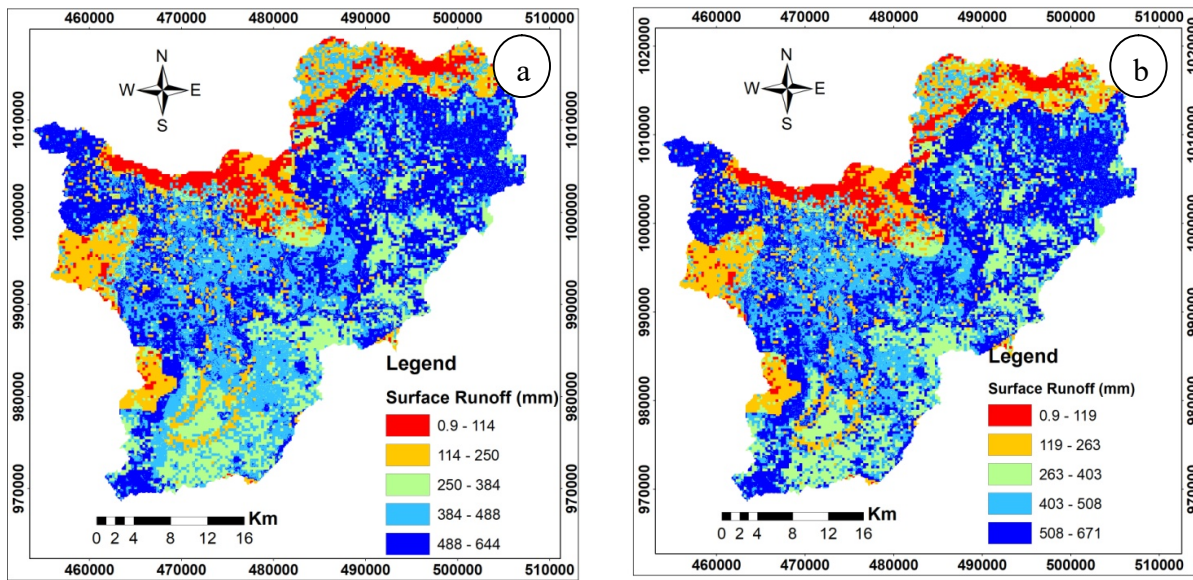


Figure 6.10: midterm annual surface runoff (2036-2050): a) RCP 4.5, b) RCP 8.5.

6.4.1.3 Long term surface runoff (2066-2080)

In the period 2080s under RCP4.5 scenario, the annual surface runoff ranges from 0.9 to 668 mm (Fig 6.11c) with a mean of 407mm. the surface runoff is expected to increase by 11mm (3%) compared to the baseline due to increasing the mean annual rainfall amount by 16mm (1%), increasing the mean annual temperature by 2.1^oC (12.4%) and potential evapotranspiration is expected increase by 91 (12%). Under RCP 8.5, the annual surface runoff ranges from 0.9 to 678 mm (Fig 6.11d) with a mean of 412 mm. The change in annual surface runoff is expected to increase by 16mm (4%) due to increasing the mean annual rainfall amount by 31 mm (3%) and rise of the mean annual temperature by 3.5^oC (21.1%). furthermore, the potential evapotranspiration is expected to increase by 175mm (23%) compared to the baseline period. In all projections, the change in surface runoff in RCP 8.5 is higher compared with RCP 4.5.

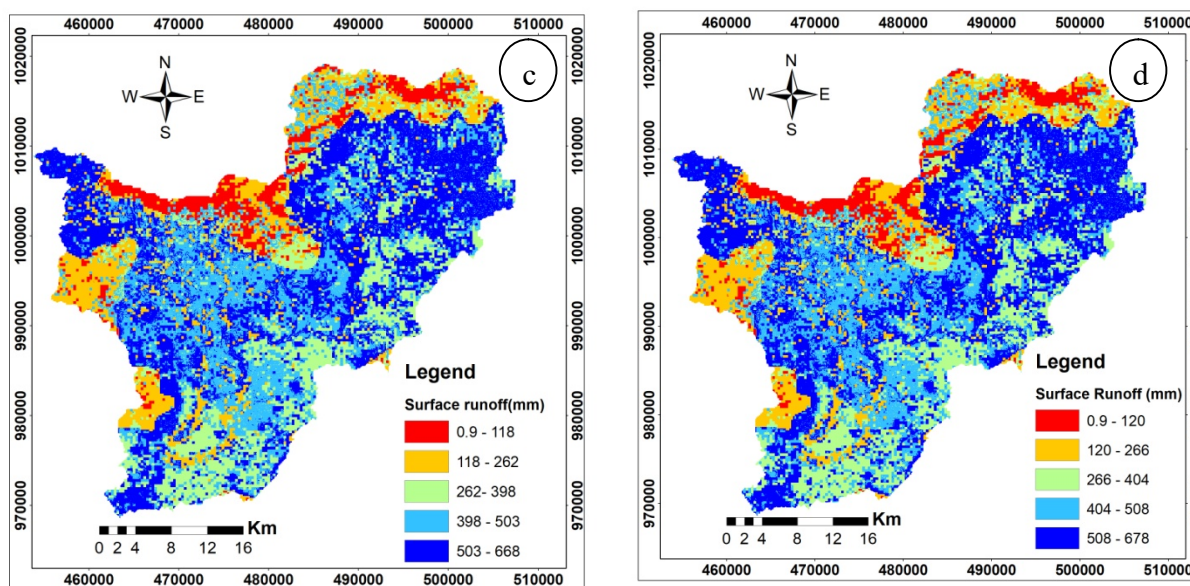


Figure 6.11: long term annual surface runoff (2066-2080): a) RCP 4.5, b) RCP 8.5.

Table 6. 4: Change in the projected surface runoff compared to the baseline period

	2036-2050		2066-2080	
	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Surface runoff (mm)	393	412	407	412
Absolute difference (mm)	-3	16	11	16
Change (%)	-1	4	3	4

6.4.2 Actual Evapotranspiration (AET) under different climate scenarios

Actual evapotranspiration is the total sum of evaporation (from soils, water bodies) and plant transpiration from the land surface of Earth. The rate of evaporation mainly depends on temperature, relative humidity and wind speed. The land surface evaporation rate depends on the type of soil and the extent to which the ground is saturated with water. It is difficult to measure the Actual Evapotranspiration (AET) directly, thus it is usually estimated from the Potential Evapotranspiration (PET). The WetSpass model simulates the total AET by adding the water intercepted by vegetation, the transpiration from vegetation and the evaporation from the bare soil between the vegetation.

The results of the WetSpass model show, the annual AET of the catchment is slightly increasing in two scenarios compared to the baseline as a result of the increase of temperature in all projections. The higher temperature leads to the higher potential evapotranspiration and the greater potential loss of water. The mean annual AET is low relatively in lowland areas of the southern and eastern part of the catchment while high on the higher elevation areas of the northwestern parts. The reason for this is that low elevation area receives low precipitation compared to high elevation areas and the availability of sufficient water due to precipitation results to high evapotranspiration. The open water bodies also show high AET because of the high evapotranspiration rate.

6.4.2.1 Actual evapotranspiration of the baseline period (1981-2005)

The result of WetSpass shows the minimum and maximum values of annual AET of the catchment 356 mm and 1042 mm, respectively (Fig 6.12). The mean annual AET is 454 mm and accounts for 42 % of the annual average precipitation of 1131mm. And also, the dry season AET accounts for about 58 % of the total annual of AET while the remaining 42% was released in the rainy season.

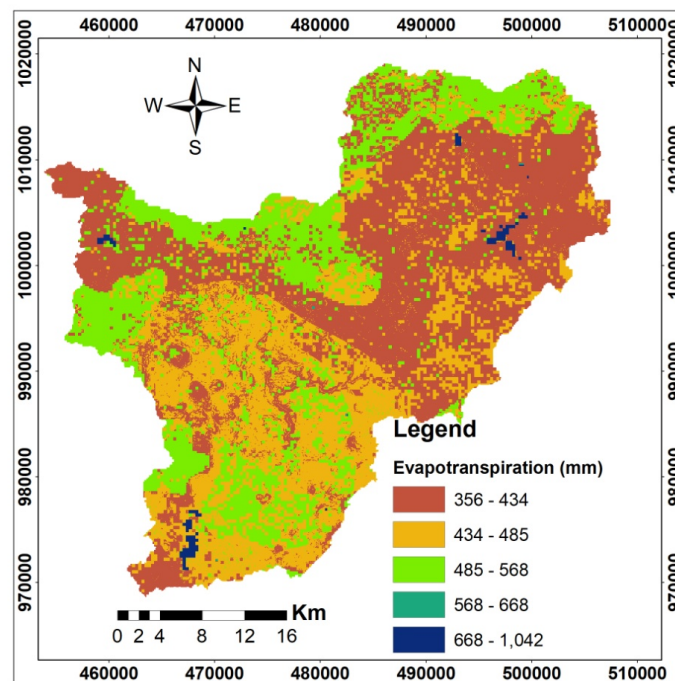


Figure 6.12: Annual AET of the baseline period

6.4.2.2 Midterm Actual evapotranspiration (2036-2050)

In the period 2050s under RCP4.5 scenario, the annual AET ranges from 339 to 1094 mm with a mean of 457mm (Fig 6.13a). The annual AET is expected to decrease by 12mm (3%) due to decreasing of precipitation by 2%, increasing in temperature by 1.5°C compared to the baseline period. The projection under RCP 8.5, annual AET extends from ranges from 351 mm to 1153 mm with a mean of 478mm (Fig 6.13b). The annual change of AET is expected to increase by 9 mm (2%) due to increasing in precipitation by 3% and increasing the mean annual temperature by 1.8°C. Furthermore, the potential evapotranspiration is expected to increase by 78 mm (10%) with respect to the baseline period.

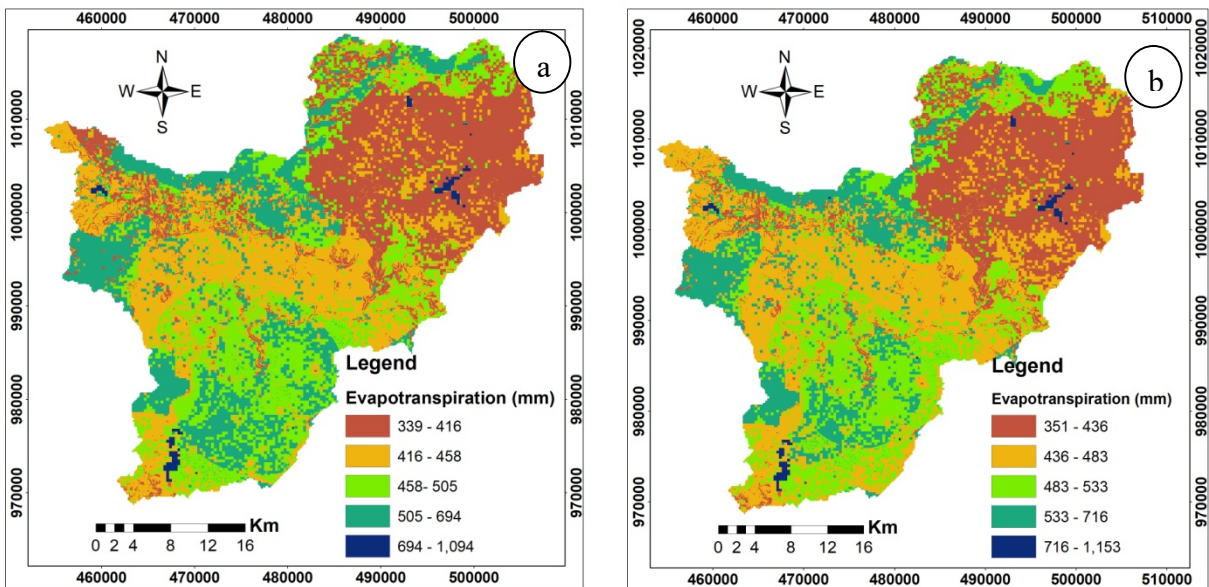


Figure 6.13: midterm annual AET (2036-2050): a) RCP 4.5, b) RCP 8.5.

6.4.2.3 Long term Actual evapotranspiration (2066-2080)

In projection 2080s under RCP4.5 the annual AET extends from 352 mm to 1152 mm with a mean of 472mm (Fig 6.14c). The change in annual AET is expected to increase by 3mm (1%) due to increasing the mean annual rainfall amount by 16mm (1%), increasing the mean annual temperature by 2.1°C (12.4%) and potential evapotranspiration increases by 91 (12%). Under RCP8.5, the AET ranges from 367 mm to 1165 mm with a mean of 679 mm (Fig 6.14d). The

change in annual AET is expected increased by 11 mm (2%) due to increasing the mean annual rainfall amount by 31 mm (3%) and rise of the mean annual temperature by 3.5°C (21.1%). furthermore, the potential evapotranspiration is expected to increase by 175mm (23%) with respect to the baseline period.

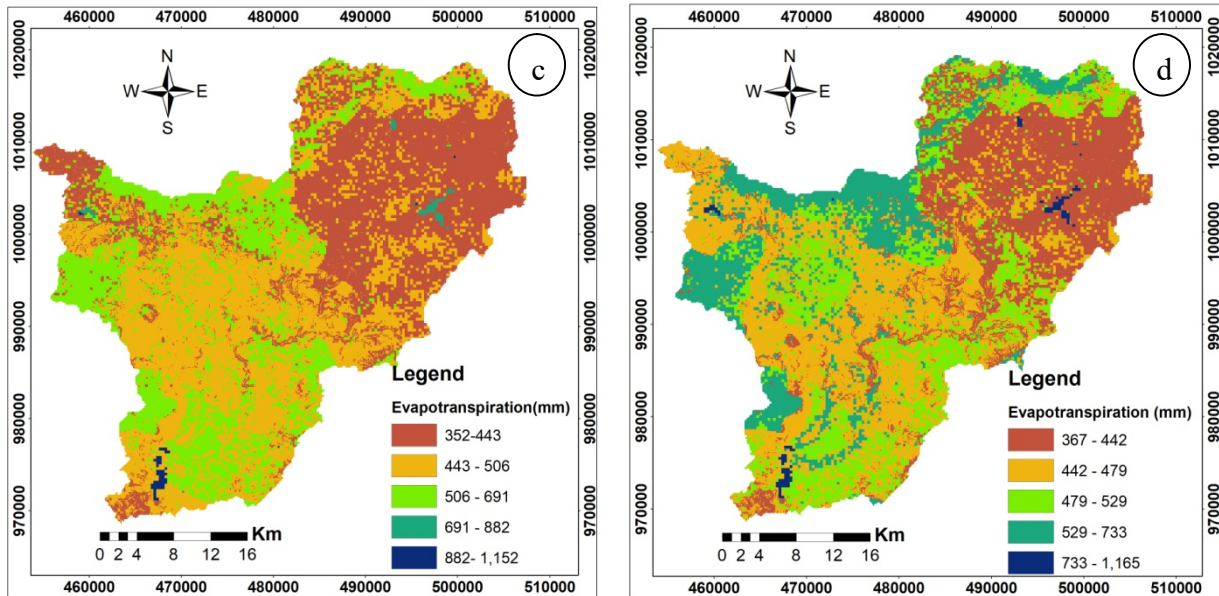


Figure 6.14: long term annual AET (2066-2080): c) RCP 4.5, d) RCP 8.5.

Table 6. 5: Change in the projected AET compared to the baseline (1981-2005)

	2036–2050		2066–2080	
	RCP4.5	RCP8.5	RCP4.5	RCP8.5
AET (mm)	457	478	472	479
Absolute difference (mm)	-12	9	3	10
Relative change (%)	-3	2	1	2

6.4.3 Groundwater Recharge under different climate scenarios

The model simulates the seasonal and annual long-term spatial distribution amounts of groundwater recharge by subtracting the seasonal and annual surface runoff and evapotranspiration from the seasonal and annual precipitation, respectively. The groundwater recharge of the catchment area was estimated for the baseline (1981-2005) and the selected future periods 2050s and 2080s under the two scenarios. The maximum recharges observed

from areas with high forest coverage. The northern part of the catchment characterized high rainfall during rainy season, which shows high groundwater recharge.

6.4.3.1 Groundwater recharge of the baseline (1981-2005)

The model result shows the annual groundwater recharge for the baseline period ranges from 0 to 723 mm with an average of 266 mm (Fig 6.15). The annual recharge is about 23 % of the annual average precipitation of 1131mm. According to Molla Demlie et al (2007), the annual mean groundwater recharge of Akaki catchment was estimated using chloride mass balance method the result was showed 265 mm of the Annual ground recharge, which amounts to 23% of the mean annual areal precipitation of the catchment. Similarly, the WetSpass model has efficiently simulated the water balance components in the catchment.

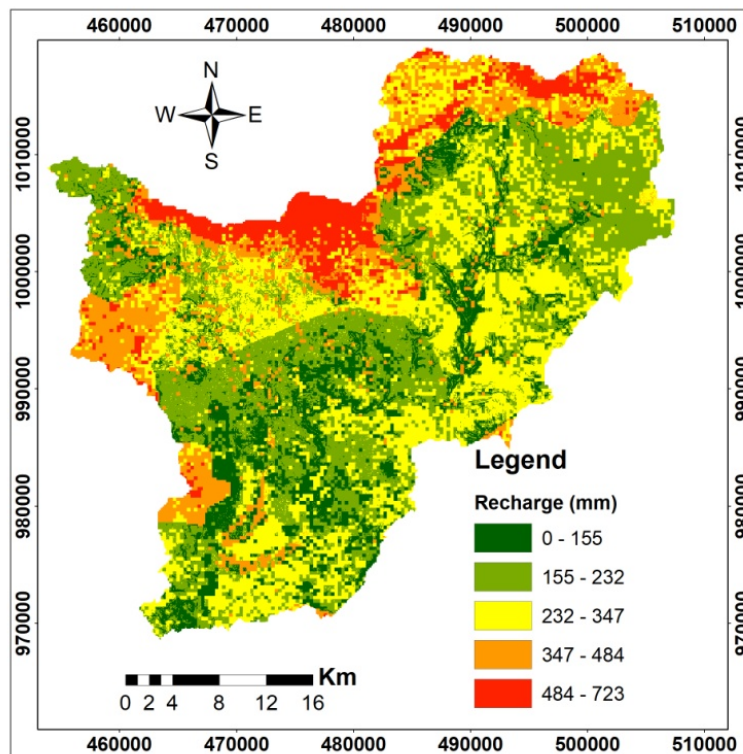


Figure 6.15: Baseline groundwater recharge

6.4.3.2 Midterm Groundwater recharge (2036-2050)

The projection under RCP 4.5, the annual groundwater ranges from 0 mm to 666 mm with a mean of 257mm (Fig 6.16a). Compared to the baseline, the annual groundwater recharge was decreased by -8mm (-3%) due to decreasing the total annual rainfall amount by 30mm (2%) and increasing the mean annual temperature by 1.5°C (8.7%). Furthermore, the potential evapotranspiration also increases by 41mm (6%). The projection under RCP 8.5, the annual groundwater ranges from 0 mm to 679 mm with a mean of 269mm (Fig 6.16b). It expected to increase by 5 mm (2%) due to increasing the mean annual rainfall amount by 29mm (3%), increasing the mean annual temperature by 1.8°C (10.8%), and increase the potential evapotranspiration by 78 mm (10%) respect to the baseline period.

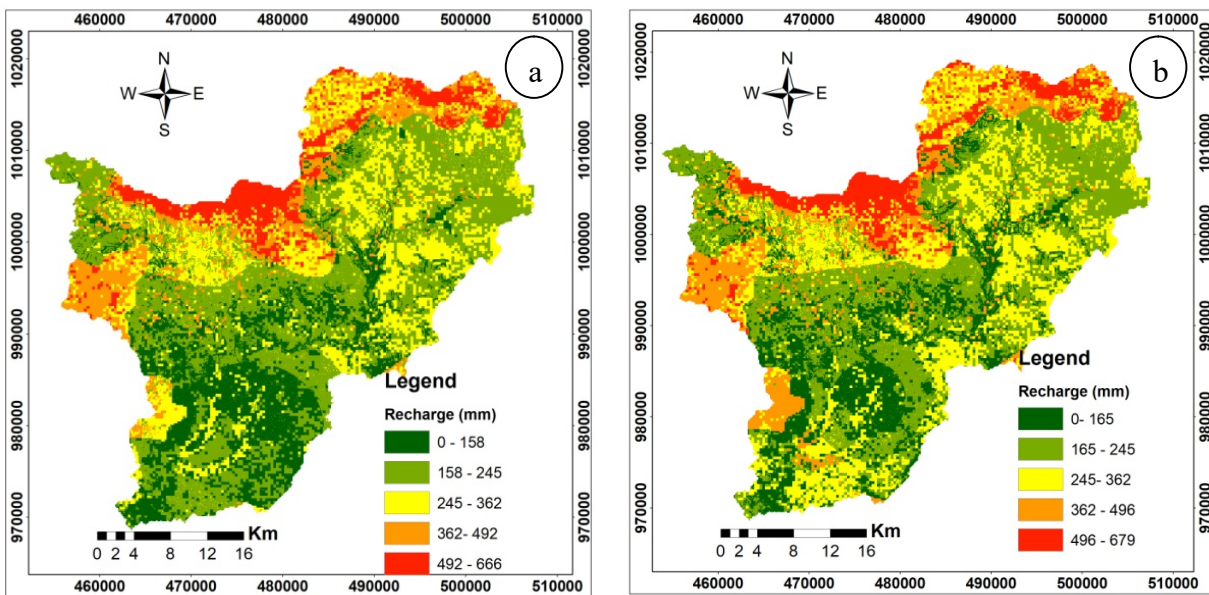


Figure 6.16: midterm groundwater recharge: (2036-250): RCP4.5 (a), RCP8.5 (b)

6.4.3.3 Long term Groundwater recharge (2066-2080)

The projection under RCP4.5, the annual groundwater recharges ranges from 0 mm to 689 mm with a mean of 268 (Fig 6.17c). The annual groundwater recharge is expected to increase by 3 mm (1 %) due to increasing the mean annual rainfall amount by 16mm (1%), increasing the mean annual temperature by 2.1°C (12.4%), and potential evapotranspiration increases by 90

(12%). The projection under RCP 8.5, the annual groundwater recharges ranges from 0 mm to 653 mm with a mean of 270 (Fig 6.17d). The annual groundwater recharge is expected increase by 5 mm (2%) due to increasing the mean annual rainfall amount by 31 mm (3%), increasing the mean annual temperature by 3.5^oC (21.1%) and the potential evapotranspiration was increased by 175mm (23%) respect to the baseline period.

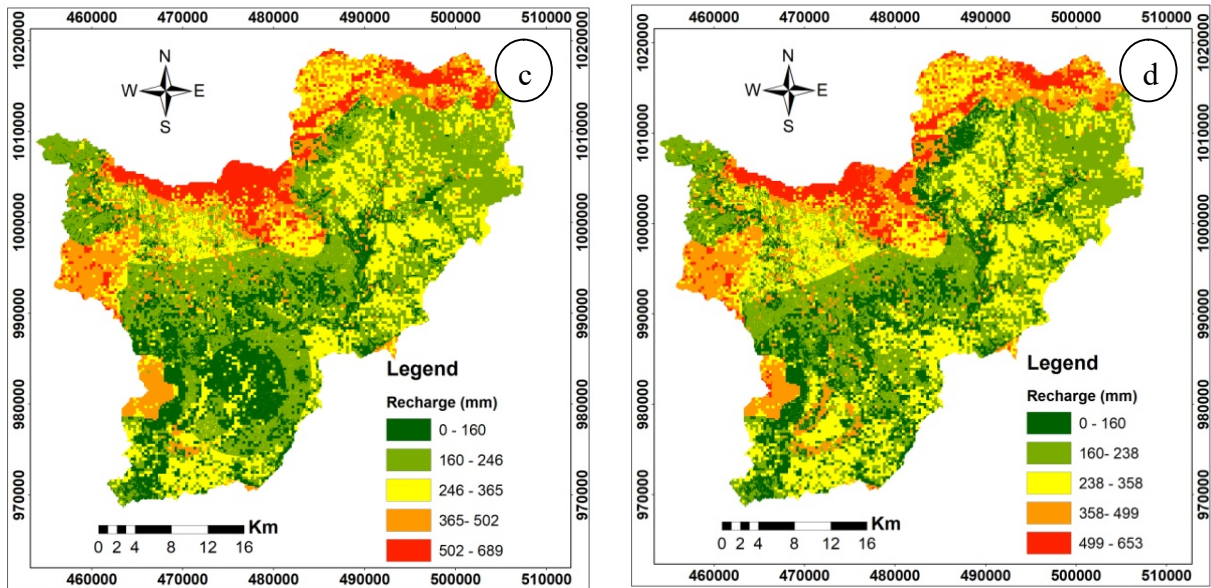


Figure 6.17: long term groundwater recharge: (2066-2080): RCP4.5 (a), RCP8.5 (b)

Table 6. 6: Change in the projected groundwater recharge compared to the baseline period

	2036–2050		2066–2080	
	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Annual groundwater recharge (mm)	257	269	268	270
Absolute difference (mm)	-8	5	3	5
Relative change (%)	-3	2	1	2

Table 6. 7: Monthly annual average WetSpas simulated water balance components of the baseline (see the projected periods at appendix D.1 and D.2)

water balance components	Dry season	Rainy season	Annual (mm)
Precipitation	318	812	1131

Actual evapotranspiration (AET)	196	273	469
Surface runoff	108	288	396
Groundwater recharge	4	261	266
Difference	P -ET-S -R (1131-469-396-266=0)		

6.5 Impact of climate change on groundwater Recharge

In this study, the impact of climate change on groundwater recharge was assessed based on climate change scenarios using RCM model output that was downscaled from the GCM model for the catchment discussed in previous sections. The WetSpass model simulation result for the 1981 to 2005 period was used as a baseline period against which the climate impact was assessed. The monthly precipitation and minimum and maximum temperature from the RCM for the future two periods of 15 years interval: 2036-2050 and 2066-2080 were directly used as input for the WetSpass model. From the result of the model, the groundwater recharge shows an increasing trend in all scenarios, except in the period 2050s under RCP4.5. But the model simulations considered only future precipitation, maximum and minimum temperatures scenarios by assuming other parameters are constant. But change of land use land cover and wind speed will contribute great impacts on groundwater recharge. But only land use groundwater recharge also controlled by many factors such as topography, soil type, vegetation cover and climate driven parameters such as temperature, rainfall, evapotranspiration. Changes in precipitation and temperature can significantly alter groundwater recharge. This study presented that there is a considered effect of climate changes on the based on future (Temperature and rainfall) values which has an impact on recharge values.

Chapter Seven

Conclusion and Recommendation

7.1 Conclusion

The overall objective of this thesis work was assess the impacts of climate change on groundwater recharge of Akaki catchment, for the baseline and projected periods 2050s and 2080s For climate impact assessment, the MIROC5 (GCM) outputs were analyzed under two scenarios RCP 4.5 and RCP 8.5. The Average simulated rainfall, maximum and minimum temperatures of the bias corrected MIORC5 model are in good agreement with the observed value of each station for the same baseline period (1981-2005).

The result from the MIROC5 model is indicated that both minimum and maximum temperature show an increasing trend in the future time horizons for all scenarios. This an increasing trend of both maximum and minimum temperature also leads to an increase in evapotranspiration. Therefore, slightly increasing temperature and evapotranspiration may reduce the groundwater recharge potential. Unlike to maximum and minimum temperature, the precipitation shows an increase or decrease in the projected periods. The change in mean monthly and annual precipitation is more pronounced in RCP8.5 than RCP4.5.

The groundwater recharge was estimated by using WetSpass hydrological model. The WetSpass model estimates the seasonal and annually surface runoff, actual evapotranspiration and groundwater recharge. The PET was calculated from temperature by using the Thornthwaite method. The model output in the baseline period (1981-2005), the mean annual surface runoff was 396 mm, mean annual AET is 454 mm and the annual groundwater recharge was 266mm and accounts 35 %, 42% and 23% of the total precipitation respectively.

In the projection periods 2050s under RCP 4.5 scenario, the mean annual surface runoff, actual evapotranspiration and groundwater recharge was 393mm, 457 mm and 257 mm respectively. Under RCP 8.5 scenario, the mean annual surface runoff, actual evapotranspiration (AET) and groundwater recharge was 412mm, 478mm and 269 mm respectively. In the projection periods 2080s under RCP 4.5 scenario, the mean annual surface

runoff, actual evapotranspiration and groundwater recharge was found to be 407mm, 472mm and 268mm respectively. Under RCP 8.5 scenario, the mean annual surface runoff, actual evapotranspiration and groundwater recharge was found to be 412mm, 479mm and 270mm respectively. These differences in water balance components are due to varieties in hydrometeorology amount with differences in the biophysical properties of the catchment. In this study, it has been tried to evaluate in the supply side of groundwater management but the demand side should be taken in to account. Because increasing abstraction rate, extensive urbanization coupled with rapid population growth in the study area, also have a negative influence on groundwater resources. Thus, the need for effective groundwater management is very critical.

7.2. Recommendation

It was indicated that, the future likely changes in temperature is expected an increasing trend in both periods under RCP4.5 and RCP8.5. Similarly, the precipitation also will slightly increase except RCP4.5 in 2050s. Due to rapid population growth, the demand of water will be expected increased in the catchment. This will in turn have a serious impact on water availability in the catchment and surrounding areas. So, it needs to set a number of policies, strategies, programs will be designed for reducing water losses and rationing water use in order to balance both the water user and water supplier. It also recommended peoples must have to create awareness and understanding about the groundwater resources how to manage and utilize it.

The following list shows the most important issues which are not included in this study but need to be addressed in future researcher.

The GCM outputs, emission scenarios, and method of bias corrections have a certain level of uncertainty. In this study analysis was done one using GCM output with two emission scenarios for assessing the climate change impacts but not addressing a selection of two or more GCMs outputs. Therefore, further study should reduce the uncertainty by the use of different GCM outputs, emission scenarios and bias correction methods.

This study was used the same land-use cover data for all periods (baseline and projected) as WetSpass model input. But in the fact that land uses land cover is not constant. Land use land

cover may vary from time to time as a result of different factors such as extensive urbanization. Therefore it needs to project the future land use/cover in order to better understand impacts. Hence, recommended predicting the future land use land cover combined with climate change to accurate estimation of groundwater recharge and other hydrologic parameters.

In this study, the groundwater recharge estimation was done by Wetpass hydrologic modeling. It recommends for further research activities should be carried out using the other hydrological models, such as Arc SWAT, HECHMS, and WEAP for further investigation.

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Appendix

Appendix A: Meteorological data used for WetSpass modeling

Rainfall (mm) at Addis Ababa Bole Station

Latitude: 476413, Longitude: 9992272, Elevation: 2354

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1981	0.0	42.6	254.7	79.0	18.4	56.9	273.9	256.1	180.5	24.7	0.0	2.7
1982	26.6	96.4	90.2	48.1	73.5	63.6	220.3	221.6	142.8	19.0	40.7	4.9
1983	12.4	41.2	28.9	113.7	186.9	56.1	217.9	213.7	202.2	35.9	0.0	1.5
1984	0.0	0.4	11.6	11.6	135.0	334.2	317.9	180.4	98.8	0.0	0.0	7.0
1985	35.1	0.0	49.1	132.3	92.8	110.9	209.8	260.8	168.6	29.8	0.0	0.4
1986	0.0	37.6	56.2	216.6	37.7	175.2	167.9	222.3	107.4	31.6	0.0	2.5
1987	0.0	49.1	180.1	85.7	154.6	71.9	155.9	98.1	57.0	16.6	0.0	0.4
1988	4.7	33.4	6.7	157.9	34.7	93.2	181.4	265.3	187.3	57.3	0.0	0.0
1989	3.4	33.7	58.4	143.3	0.0	88.1	218.1	318.6	150.0	36.8	0.0	7.9
1990	3.2	161.1	60.4	144.5	25.2	48.3	194.2	293.6	143.0	46.1	2.1	0.0
1991	0.2	29.6	134.1	15.0	7.7	107.5	279.4	287.9	123.1	4.4	2.1	0.0
1992	14.5	28.0	35.0	58.6	55.0	82.2	254.8	223.3	157.0	64.4	2.2	0.4
1993	11.7	52.1	11.6	168.3	91.5	157.2	209.5	291.7	190.1	24.1	0.0	0.0
1994	0.0	0.0	52.9	70.0	29.0	112.4	242.3	199.3	99.4	0.5	11.0	0.0
1995	0.0	81.3	73.1	133.3	95.9	77.4	165.5	256.9	97.0	0.0	0.0	29.3
1996	20.5	15.8	134.4	96.0	124.6	290.2	346.3	312.7	211.4	0.2	0.4	0.0
1997	29.1	0.0	22.1	66.8	44.8	128.0	257.0	160.7	94.7	58.6	15.3	0.0
1998	66.6	40.0	43.8	99.8	197.7	111.6	270.7	236.8	173.4	139.4	0.0	0.0
1999	4.4	0.0	35.0	17.8	30.5	104.6	294.0	270.5	62.8	127.1	0.0	0.0
2000	0.0	0.0	17.6	87.8	95.2	102.1	192.9	221.9	157.5	19.6	7.5	0.0
2001	0.0	10.3	174.3	14.8	116.7	166.0	289.4	207.3	113.3	10.6	0.0	0.0
t	30.6	25.9	79.4	36.6	49.6	115.5	213.9	233.6	72.6	0.5	0.0	32.8
2003	4.8	-	48.9	111.5	18.0	111.0	204.3	238.4	130.2	4.6	0.0	33.3
2004	-	11.7	32.4	-	7.0	114.5	240.6	230.1	122.1	50.0	0.6	0.0
2005	55.4	14.1	41.8	116.2	164.6	159.1	174.3	248.0	77.6	25.8	7.2	0.0

Rainfall (mm) at Addis Ababa Observatory Station

Latitude: 471986, Longitude: 997321, Elevation: 2457

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1981	0.0	75.5	176.0	82.9	3.9	50.1	266.5	320.9	182.1	13.3	0.0	5.2
1982	48.7	80.9	57.8	103.7	115.9	31.9	259.3	257.9	133.8	64.4	43.2	12.8
1983	18.3	21.7	48.7	117.0	237.0	109.3	199.3	244.7	160.9	26.3	0.0	8.8
1984	0.0	8.0	8.8	8.4	127.8	220.8	296.1	295.6	142.4	0.0	4.4	16.3
1985	14.2	0.0	17.5	96.3	83.7	112.2	270.4	327.7	205.9	58.0	3.3	1.2
1986	0.0	35.7	88.0	197.6	125.4	179.5	180.1	-	127.8	36.1	0.0	-
1987	0.5	63.4	248.9	82.4	241.3	92.9	196.5	254.4	115.2	21.3	0.8	0.3
1988	9.7	53.4	5.3	144.6	16.6	106.2	277.9	299.3	229.7	59.9	0.0	0.0
1989	0.8	75.9	75.7	154.4	0.5	120.9	357.7	325.3	187.7	14.8	0.0	7.6
1990	0.8	155.9	59.2	106.4	20.0	88.8	218.7	268.6	184.0	16.2	6.0	0.0
1991	0.0	74.5	106.6	34.7	-	-	248.9	262.6	126.4	3.4	0.0	50.0
1992	20.2	33.7	20.2	41.0	52.0	109.1	248.5	294.7	209.4	69.7	0.0	2.9
1993	10.8	67.2	16.1	157.9	97.2	208.3	274.0	426.5	243.3	62.1	0.0	4.5
1994	0.0	0.0	82.4	82.3	63.3	123.4	308.9	225.0	142.0	0.5	14.7	0.0
1995	0.0	69.0	41.5	174.4	68.2	102.9	190.2	314.9	136.1	0.0	0.0	-
1996	28.1	5.2	106.8	128.2	122.0	258.5	266.4	338.7	294.2	0.2	0.2	-
1997	39.2	0.0	24.5	51.3	38.5	104.0	272.6	194.3	113.8	62.4	50.3	1.5
1998	55.2	20.5	49.0	48.5	154.2	124.4	285.4	260.0	213.6	126.9	0.0	0.0
1999	2.9	0.3	28.8	16.3	23.8	119.6	-	305.3	88.4	75.4	0.0	0.0
2000	0.0	0.0	17.6	49.9	110.0	144.5	244.8	306.2	250.6	46.4	21.1	0.0
2001	0.0	12.2	210.8	25.0	168.0	216.2	428.0	246.4	131.7	13.7	0.0	0.0
2002	14.7	21.0	90.2	56.3	63.1	172.5	256.9	215.9	108.8	0.2	0.0	16.5
2003	10.5	53.3	62.6	99.3	20.2	151.8	291.8	233.3	193.3	0.8	1.5	54.9
2004	24.8	20.3	49.5	139.9	30.1	141.9	238.5	272.6	164.0	76.9	0.0	0.0
2005	45.9	51.6	83.2	160.9	133.7	179.8	246.0	315.2	162.5	-	4.4	0.0

Rainfall (mm) at Akaki Beseka Station

Latitude: 476486, Longitude: 979917, Elevation: 2057

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1981	0.0	13.3	179.8	132.0	1.3	49.2	402.6	165.0	223.1	5.0	0.0	0.0
1982	12.1	35.4	39.5	94.6	75.2	63.5	238.8	255.9	125.2	25.8	11.0	8.1
1983	1.8	33.3	20.2	142.1	175.0	83.0	237.7	275.3	146.7	0.0	0.0	0.0
1984	0.0	0.0	40.4	5.1	130.0	215.3	277.9	227.1	71.7	0.0	0.0	1.9
1985	3.6	0.0	32.4	71.8	96.6	96.5	303.0	324.1	164.3	1.6	0.0	0.0
1986	0.0	95.4	67.7	148.7	83.2	143.4	189.4	216.5	86.1	9.4	0.0	0.0
1987	0.0	65.6	181.9	81.2	187.7	69.3	202.0	246.9	82.5	4.4	0.0	0.0
1988	0.0	44.5	0.0	96.0	23.8	124.6	255.9	278.1	253.5	35.4	0.0	0.0
1989	2.1	63.8	53.8	226.3	7.1	58.6	264.2	301.0	170.9	37.9	0.0	0.0
1990	7.7	120.6	48.4	159.1	37.3	78.9	280.7	222.9	107.3	5.8	1.2	0.0
1991	0.0	37.6	62.4	11.6	45.6	90.4	263.7	308.5	113.3	4.4	0.0	56.5
1992	33.5	24.2	30.5	15.5	25.6	100.4	218.4	276.0	86.7	43.3	0.2	0.0
1993	1.2	53.9	5.6	118.4	54.6	116.5	218.0	251.5	118.3	20.5	0.0	0.0
1994	0.0	0.0	62.7	72.2	20.2	131.2	219.3	181.0	94.5	0.0	11.0	0.0
1995	0.0	25.4	62.7	102.1	20.9	95.7	279.0	242.3	79.5	0.0	0.0	4.8
1996	15.3	0.3	79.7	38.8	90.5	240.1	292.5	234.1	119.0	1.9	0.0	0.0
1997	27.6	0.0	29.5	102.7	25.2	57.0	203.6	203.4	127.7	114.9	10.3	0.0
1998	32.7	30.2	19.6	69.3	159.9	116.9	207.8	280.0	118.5	36.9	0.0	0.0
1999	1.3	1.8	91.8	12.1	45.4	92.8	282.6	300.7	61.7	65.0	0.0	0.0
2000	0.0	0.0	29.1	93.0	64.9	100.1	188.9	210.0	124.1	17.2	23.4	3.8
2001	0.0	20.7	121.2	23.6	118.0	142.6	257.5	145.0	64.9	2.2	0.0	0.0
2002	31.1	10.5	87.8	53.9	76.6	108.0	167.1	166.3	52.3	0.0	0.0	17.7
2003	19.6	24.8	23.9	114.0	1.4	125.4	325.1	307.4	113.4	0.0	0.0	40.8
2004	15.6	15.8	61.4	154.5	15.4	95.2	150.3	189.1	80.9	4.8	3.4	0.7
2005	28.8	7.3	47.9	112.2	140.7	139.9	218.7	231.4	152.7	9.1	15.2	0.0

Rainfall (mm) at Entoto Station

Latitude: 474400, Longitude: 1004200, Elevation: 2903

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1989	4	76	105.4	133.3	5.8	98.2	409.5	323.4	293.9	11.7	-	20
1990	0	156.6	42.8	117.9	17.6	100.5	324.5	499.7	180.8	-	1.5	0
1991	12.8	64.9	156.2	37.5	39	171.2	258.5	395.2	146.7	1.4	0	44.2
1992	52.7	31.5	14.6	42.7	84.6	131.6	247.8	387	188.4	42.4	0.7	8.1
1993	15.3	44.6	5.7	147.5	49	123.3	266.1	407.6	183.2	28.7	0	0
1994	0	0	62.2	56	91	154.8	336.3	307.2	142.5	0.3	24.4	0
1995	0	96.3	29.7	186.1	83.7	98	297	222.1	133.7	5	0.2	22.7
1996	31.1	12.2	121.6	78.3	95.2	242.7	387.2	493.9	184.7	1.2	0.6	0
1997	21.2	0	18.6	77.3	27.4	77.2	256.3	240.8	89.3	88.3	90	0.2
1998	25.3	25.3	45.2	47	149.5	149.2	369	376.3	204.8	44.5	0	0
1999	15.8	6.3	34.9	25.4	37	127.7	283.1	280.3	105	58	0.2	0
2000	0	0	5.2	108	91.4	110.7	303.8	359.1	132.8	17.2	33.5	1.7
2001	20.6	5.5	147.5	29.8	141.7	164.3	285.6	321.4	92.5	52.4	0	1.8
2002	17.9	50.4	88.8	67.4	49.2	138.7	293.1	262.9	92.1	10.7	0	28
2003	5.2	47.7	57.1	117.3	13.9	188	370.8	248.9	141.1	0	6.3	25.6
2004	28.8	31.3	46.7	124.6	13.8	166	271.9	334.7	124.8	49.7	1.1	1.6
2005	8.3	11.4	42.8	98.6	143.9	106.4	241.8	339.3	134.4	19.6	8.2	0

Rainfall (mm) at Sendafa Station

Latitude: 502257, Longitude: 1011809, Elevation: 2569

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1981	0.0	8.9	246.3	94.3	0.0	24.0	413.6	241.0	-	9.3	0.0	5.4
1982	39.4	84.7	54.8	31.7	64.5	31.3	232.6	282.9	-	42.7	14.5	14.1
1983	1.4	25.4	43.1	91.6	167.6	71.1	247.1	430.4	124.0	4.7	0.0	0.0
1984	0.0	0.0	45.2	0.0	78.4	169.1	340.3	184.9	109.3	0.0	0.0	1.2
1985	9.5	1.3	38.6	158.9	157.9	76.4	394.1	451.5	106.0	10.8	0.0	0.0
1986	0.0	28.1	117.3	193.7	32.3	164.7	270.9	244.5	143.2	0.0	0.0	0.0
1987	0.2	33.1	128.9	80.5	110.1	55.7	223.6	143.6	105.3	8.7	0.0	0.0
1988	0.0	32.9	0.9	132.9	22.1	104.6	451.1	330.2	237.6	5.2	0.0	0.0

1989	18.0	10.1	43.3	112.0	21.4	46.3	357.5	339.4	139.9	10.2	0.4	0.6
1990	21.5	190.4	35.7	148.4	38.2	87.8	282.7	469.9	-	3.8	2.4	0.0
1991	15.9	20.5	118.1	0.5	34.5	72.7	216.8	9.4	134.5	-	0.0	5.6
1992	10.7	46.5	1.0	-	-	69.6	253.2	357.9	151.6	55.5	0.0	0.0
1993	4.3	105.2	0.0	-	-	-	457.2	353.2	153.8	13.7	0.0	0.0
1994	0.0	0.0	0.0	64.1	11.0	130.7	337.7	184.1	122.0	0.0	6.4	0.0
1995	0.0	11.4	106.2	116.7	42.4	22.5	230.8	388.8	-	0.0	0.0	0.0
1996	69.4	5.6	99.3	-	-	187.2	339.2	338.6	121.4	0.0	0.0	0.0
1997	44.5	0.0	29.4	60.0	44.8	149.7	303.8	251.1	84.7	72.0	34.6	0.0
1998	28.9	23.3	5.8	27.0	38.2	68.8	359.1	289.7	152.0	98.9	0.0	0.0
1999	0.0	1.2	56.3	11.8	25.4	144.7	441.6	365.2	-	79.6	0.0	0.0
2000	0.0	0.0	35.5	44.0	87.9	166.0	352.2	373.4	113.9	5.0	10.0	0.0
2001	0.0	35.3	154.1	9.2	134.9	149.5	335.5	276.8	27.4	9.8	0.0	0.0
2002	21.2	3.4	67.2	20.6	60.9	144.4	246.8	289.1	85.4	0.0	0.0	27.4
2003	75.5	0.0	29.7	122.9	1.7	120.6	304.4	373.4	122.4	0.0	0.0	19.7
2004	15.2	7.1	2.2	118.9	0.0	69.8	315.0	319.0	30.6	0.0	0.0	0.0
2005	24.5	22.3	12.3	136.1	150.2	57.7	381.3	282.9	73.3	34.6	0.0	0.0

Monthly Maximum Temperature of Addis Ababa Bole Station

Latitude: 476413, Longitude: 9992272, Elevation: 2354

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1981	24	24.4	22.7	23.2	25.2	25.5	20.7	21.1	20.9	22.7	22.7	22.7
1982	22.9	23.2	25	23.7	24.1	23.7	21.5	20.4	21.9	21.7	22.2	22.5
1983	23	24	24.6	24.2	24	23.7	22.8	20.6	21.6	22.1	22.7	22.2
1984	23.2	24.4	25.6	26.7	24.3	22.1	20.4	21.7	21.4	23	23.2	22.5
1985	23.4	23.9	25	22.9	23.5	23.3	20.1	20	21.4	22.2	23	22.9
1986	23.5	24.1	24.1	22.5	-	21.9	-	-	21.6	22.8	23.1	23.1
1987	22.9	24.3	23.2	23.6	23.7	22.7	22.1	21.7	23.1	23.9	-	24.3
1988	24.7	-	27.3	25.1	25.8	23.4	21	21	21.2	21.9	22.5	22.8
1989	22.7	23.2	24.5	23	24.9	23.6	20.7	21.2	-	22.8	23.1	22.8
1990	24	23.2	23.9	23.6	25.3	23.5	21.4	21.4	21.9	23	23.5	23.6

1991	25	24.8	25.6	25.6	-	-	21.3	21	22	23.1	22.7	22.9
1992	22.5	23.4	25.7	25.8	26.2	-	21.1	19.7	21	21.9	22.2	23.1
1993	23.4	23.3	26.4	24	23.8	22.6	20.9	21.1	21.2	22.9	23	23.5
1994	-	25.7	25.9	26.1	26.7	23.1	21.2	20.8	22	23.3	23.5	23.5
1995	24.2	25.4	25.1	23.9	25.2	24.5	21	21.5	22.3	23.8	24	23.9
1996	23.6	26.4	25	24.7	24.5	21.1	20.9	21.4	22.1	23.6	23.3	23.1
1997	23.4	25.2	26	24.5	26.9	24.9	21.7	21.9	23.3	23.1	-	24.2
1998	24.3	25	25.4	26.6	25.2	24.7	22.3	21.9	21.9	22.2	22.8	23.2
1999	24.7	26.7	25.5	27.6	26.9	24.6	20.5	20.6	22.1	21.9	22.7	22.7
2000	-	25.5	27.3	25.7	25.4	23.1	21.5	20.6	21.1	22.5	22.9	23.8
2001	23.5	25.2	24	25.5	24.3	22.5	21.5	21	22.9	24.7	24.2	24.2
2002	24.2	26.2	25.7	26.7	27	24.9	23	21.8	22.4	24.3	24.3	23.8
2003	24.3	26.2	26.3	25.1	26.8	24.5	21.2	20.8	21.9	23.7	23.6	-
2004	25.1	-	-	23.9	26.8	-	21.5	21.5	22.2	22.3	23.7	24
2005	24.1	26.6	26.4	25.9	24.1	23.4	21.1	22.1	22.4	23.6	22.9	23

Monthly Minimum Temperature of Addis Ababa Bole Station

Latitude: 476413, Longitude: 9992272, Elevation: 2354

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1981	6.2	8.4	12.1	11.4	10.2	10.5	11	11.1	11.5	8.3	5.6	5.1
1982	8.7	10.7	9.8	10.8	10.6	9.6	9.7	9.6	9.1	6.6	7.5	7.9
1983	6.6	10.4	11.7	11.4	11.3	10.4	10.2	11.4	10.7	8.6	6.6	5.4
1984	4.8	4.4	9.8	10.4	12	11.1	10.7	10.3	9.5	6	6.2	5.2
1985	6.2	7.3	10.5	11.2	10.7	10.3	10.5	10.8	9.9	7.9	5	5.6
1986	4.4	9.8	9.3	11.5	10.4	9.7	8	7.6	-	3.7	5.2	6.3
1987	6	8.5	11.3	10.3	10.8	10.2	11	11.1	10.4	8.5	5.8	-
1988	7.4	10.9	9.4	11.5	10.2	10.4	11.6	11.2	10.4	8.1	3.9	4.5
1989	5.5	8.1	9.8	10.7	9.3	9.8	10.8	10.6	9.9	8.4	5.8	8.4
1990	6.1	10.9	9.9	10.6	9.9	9.8	10.8	10.9	10.5	7.5	6.7	4.7
1991	8.1	9.6	11.2	11	-	10.7	11.6	11.2	10.3	7.2	5.2	6.2

1992	8.6	10	10.8	10.7	10.5	9.8	10.5	11.6	9.7	8.1	6.2	7.3
1993	8.3	9.3	8.7	11.4	10.8	10.4	11.1	10.8	10.1	8.3	5.5	4.8
1994	5	7.3	10.6	10.9	10.9	10.9	11.6	11.2	9.6	7	6.7	4.9
1995	5.2	9.5	10.5	12	11.1	10.2	11.4	11.5	10	8.3	6.3	7.8
1996	8.9	7.7	11.1	10.5	11.1	11.3	11.1	11	9.8	7.1	6.3	5.7
1997	9.3	6.1	10.3	11.2	11.1	11.7	11.3	11.5	10.6	10		6.6
1998	9.8	11.7	12	12.1	12.6	11.2	11.7	12.3	11	9.2	4.7	3.4
1999	6.7	7.3	10.4	10.4	10.5	10.3	10.5	10.4	9.9	9.2	5.4	5.6
2000		5.8	10.2	12.1	11.1	10.1	11	10.8	10.6	8.9	6.8	8.9
2001	6.8	7.8	10.8	10.9	11.3	10.5	11.1	11.6	9.8	8.6	5.9	6.4
2002	7.7	8.7	10.9	11.4	11.8	10.8	11.2	10.9	10.5	8.9	6.5	9.6
2003	8.5	9.8	10.3	11.8	11.4	10.9	11.5	11.9	11.4	8.2	7.4	6
2004	9.9	8.7	10.3	11.9	11.1	11.2	11.4	11.5	10.9	8.3	7	7.8
2005	8.5	8.6	11.2	11.7	12.1	11	11.5	11.8	11.5	8.7	7.4	5.8

Monthly Maximum Temperature of Addis Ababa Observatory Station

Latitude: 471986, Longitude: 997321, Elevation: 2457

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1981	24.4	24.7	22.4	22.7	25.3	25.3	20.4	20.9	20.8	22.3	22.9	23
1982	23.4	23.7	24.8	23.1	24.2	24	21.1	20.4	21.6	21.8	22.7	22.8
1983	23	24.3	25.3	24.1	23.9	23.4	22.3	20.3	21.2	22	22.8	22.4
1984	23.4	25.1	26.1	27.2	24.2	21.7	20.3	21.2	21.5	23	23.2	22.5
1985	23.8	24.3	24.9	22.9	23.4	23.4	20	20.1	20.9	22	22.8	22.6
1986	23.9	24.5	23.9	22.5	24.4	21.8	21.4	21.2	21.9	22.8	23.4	23.6
1987	23.4	24.5	23.2	23.5	23.7	22.8	21.9	--	23	24	24.1	24.1
1988	24.2	24.6	27	24.9	25.8	23.2	19.9	20.9	21.1	22	22.5	22.6
1989	23	23	24.5	22.4	24.8	23.5	20.4	21.3	21.1	22.3	22.8	22.3
1990	23.3	22.6	23.6	23.5	25.4	23.5	21.2	20.9	21.2	22.5	23	23.1
1991	24.5	24.4	24.3	25	-	-	20.5	20.9	22.1	22.9	22.8	22.3
1992	22.4	23.3	25.7	25.5	25.5	23.7	20.7	19.7	21	21.7	22	22.8
1993	23.2	22.7	25.8	23.2	23.6	22.2	20.9	20.9	20.7	22.4	22.8	23.2

1994	24.6	26.2	25.3	24.9	25.6	22.4	20.3	20	21.6	23.4	23.3	
1995	24.7	25.5	25.5	23.5	25.2	24.4	20.4	21	22.1	23.8	24.6	24
1996	23.2	26.7	24.7	24.5	24.3	21.7	20.9	21.3	22	24	23.8	24.1
1997	24.2	25.5	26.5	24.4	26.8	24.6	21.8	22	23.6	23.3	22.6	24.1
1998	24.4	25.7	25.4	26.8	25.4	24.8	21.5	21.4	21.8	22.2	23.1	23.1
1999	24.4	26.6	25.2	27.2	26.2	24.7	21.2	21.5	22.5	21.9	23	23.5
2000	24.9	26.1	27.3	25.7	25.3	23	21.6	20.5	21.5	22.2	23	23.8
2001	24.5	25.9	23.7	25.4	24.5	22.5	21.6	21.2	22.6	23.9	24	24.3
2002	24	26.2	25.1	25.7	26.2	24.2	22.6	21.2	22.3	24.2	24.3	23.5
2003	24.4	26.3	25.3	24.6	26.7	24	21	21	21.6	23.5	23.4	22.8
2004	24.5	24.9	25.7	23.7	26.1	23.1	21.3	21.4	21.8	22.5	23.5	23.7
2005	23.8	26.5	25.8	25.6	24	23.7	21.4	22.1	21.4		23.3	23.7

Monthly Minimum Temperature of Addis Ababa Observatory Station

Latitude: 471986, Longitude: 997321, Elevation: 2457

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1981	9.9	10.4	12.3	12.4	12.7	11.9	11.7	11.7	11.4	10.3	9	8.7
1982	10.4	11.7	11.7	12.3	12.7	11.6	11.3	11.3	11.7	10.3	10.1	10
1983	9.1	11.7	13.1	13	13.1	12.4	12	12.4	11.8	10.7	9.7	8.7
1984	7.9	8.3	12.4	12.5	13.1	11.5	11.2	11.4	11.2	10	8.5	7.3
1985	8.2	8.3	11	11.2	11.2	10.5	9.8	9.9	10.1	9.3	7.9	7.5
1986	7	10.5	10.4	11.3	11.7	10.8	10.4	10.3	10	9	8.4	8.4
1987	7.8	10.1	11.9	12.3	12.4	11.9	11.8	11.9	12.5	11	9.3	9.2
1988	10.2	12.5	11.9	12.8	12.5	11.7	12.1	11.7	11.5	10.5	7.8	7.8
1989	7.8	9.9	11.5	11.8	12	11.2	11.3	11.2	11.3	10.2	8.9	10.5
1990	9.1	11.9	11.4	11.9	12.4	10.9	11.4	11.1	11.3	9.5	9.2	7.7
1991	10.4	11.6	12.4	13	13.3	12.3	12	11.9	11.6	9.7	8.3	8.9
1992	10	11.2	12.4	12.4	12.7	11.3	11	11.8	10.9	10.1	8.8	9.2
1993	10	10.8	11	12.2	12.3	11.4	11.3	11.3	11	10.1	8.2	7.5
1994	7.8	9.2	11.9	12.1	12.1	11.2	11.5	11.1	10.6	9.3	8.5	7
1995	7.4	10.4	11.4	12.6	12.3	11.4	11.7	11.8	10.6	10	8.5	9.2

1996	9.9	9.8	11.9	11.5	12.2	11.5	11.4	11.2	10.9	9	8.2	7.8
1997	10.3	7.9	11.7	11.5	11.6	12	11	11.1	11.4	11	10	8.1
1998	10.6	12	12.7	12.8	13.2	12	12.1	12	11.2	10.6	7.7	
1999	8.5	9.6	11.4	12	12.2	11.2	10.9	10.9	10.9	9.5	7.3	7.2
2000	7.4	8.2	10.2	12.1	11.7	10.6	11	11	11.3	12.3	12.1	8.9
2001	8.5	9.2	11.7	11.9	11.8	10.8	11.1	11.6	10.6	10.1	7.8	8.4
2002	8.7	10.2	11.7	12.3	12.9	11.4	11.3	13	14.5	12.8	8.7	10.4
2003	9.7	10.9	11.3	12.4	13.3	11.7	11.7	11.8	11.4	9.3	8.4	7.7
2004	10.3	8.9	10.3	12.2	12.2	11.3	11	11.3	10.9	8.9	7.8	8.1
2005	8.3	9.3	11.8	12.5	12.5	11.4	11.3	11.4	11.3		7.9	6.3

Monthly Maximum Temperature of Entoto Station

Latitude: 474400, Longitude: 1004200, Elevation: 2903

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1989	18.4	18.2	19.3	17.2	19.8	17.4	15.6	16.6	17.5	18.1	19.3	-
1990	19.7	18.6	19.5	19.6	20.9	18.6	16.8	16.2	17.3	-	18.8	19.3
1991	19.9	19.5	19.3	19.9	20.5	19.1	15.9	16.3	17.3	19	19	18.9
1992	19.2	19.1	20.2	19.4	19.2	-	15.5	14.5	15.8	16.9	16.9	17.9
1993	17.8	17.8	20.5	17.5	18	16.6	15.5	15.2	15.2	17.1	17.8	18.3
1994	19.2	20.3	19.5	19.7	20.1	17.1	15.5	15.4	16.3	18.2	17.9	18.4
1995	19.4	19.5	19.7	17.8	19.3	18.8	15.5	15.7	16.5	18.4	19	18.5
1996	17.6	20.8	19.2	18.9	18.5	16.2	16	15.3	16.2	17.8	17.7	18
1997	18.2	19.8	20.6	18.8	20.7	18.8	16	16.4	17.7	17.9	17.2	18.8
1998	19.1	20.1	20.1	21.1	19.5	18.6	15.9	15.9	16.4	16.9	18.1	18.2
1999	18.9	21	19.8	20.9	20.4	18.8	15.7	15.9	16.5	16.3	17.7	18.3
2000	19.1	20.2	21.2	19.7	19.6	17.7	16.5	15.8	16.1	17.6	18	19.2
2001	19.5	21.3	18.4	20.3	19.6	17.1	16.6	16.8	18.2	18.7	19.4	19.8
2002	19.2	21.1	19.8	20.8	21.4	19.2	17.7	16.5	17.7	19.5	20.4	19
2003	19.9	21.7	20.8	20	22	19	16	16.6	16.7	19.4	19.9	19.5

2004	20.3	20.6	21.6	19.3	21.5	18.2	16.6	16.7	17.4	17.9	20	20.3
2005	20.2	23	21.9	21.7	19.1	18.7	16	17.3	17.8	19.6	20.2	20.5

Monthly Minimum Temperature of Entoto Station

Latitude: 474400, Longitude: 1004200, Elevation: 2903

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1989	6.6	7.9	9.1	8.6	9.8	8.5	8	7.8	8.6	7.6	7.5	-
1990	7.2	9	8.8	9.5	10.2	8.6	7.9	8.1	8.5		8.4	7.3
1991	8.7	8.8	9	10	10.1	9.4	8.7	8.4	8.6	8.2	7.3	7.7
1992	7.4	7.8	7.8	7.6	9.8	-	8.2	7.6	5.9	5.6	5.6	6.1
1993	6.5	5.3	4.4	4.1	4.3	3.7	2.3	2.4	2.5	4.1	4.1	6.2
1994	8.4	8.5	9.5	9.9	10.3	8.8	8.8	8.7	9	8.4	7.8	7.4
1995	8.2	9.2	9.5	9.7	10.3	10.1	8.7	8.9	9.1	8.5	8.2	8.2
1996	8	9	9.2	9.8	10	8.8	8.1	8.5	8.9	8.3	7.9	7.7
1997	8.6	7.9	10	9.5	9.9	9.6	8.7	8.6	9.5	9.1	8.5	7.8
1998	9.2	10	10.7	11	11	9.8	8.9	8.9	9.1	8.9	8	7.4
1999	7.9	9.6	9.2	9.7	10.2	9.1	7.5	8.2	8.9	8.6	7.1	7.2
2000	8.1	8.7	9.1	9.2	9.8	8.8	8.1	8.2	8.9	8.3	7.8	7.6
2001	7.5	8.6	8.8	9.8	9.8	8.5	8.1	9	9.2	8.7	7.4	7.8
2002	7.6	9.4	9.4	9.5	10.3	9	8.7	8.4	9	8.8	8.1	8.6
2003	8.3	9.5	9.7	9.9	11.2	9.1	8.6	9	9	8.7	7.8	7.3
2004	9	8.3	8.9	9.6	10.4	9.2	8.3	8.8	8.8	8.1	7.7	7.7
2005	7.9	9.4	9.7	9.8	9.4	9	8.9	8.9	8.9	8.1	7.3	7.2

Appendix B: Well data

Bore hole name	ID	Easting	Northing	Elevation(m)	SWL
AA-AAU	BHT-536	473400	999600	2498.433	21
AA-Abay Mesk Soft Drinks	BHT-695	473100	992600	2288.946	36
AA-Adwa flour mill	BHT-739	476000	980900	2067.121	13

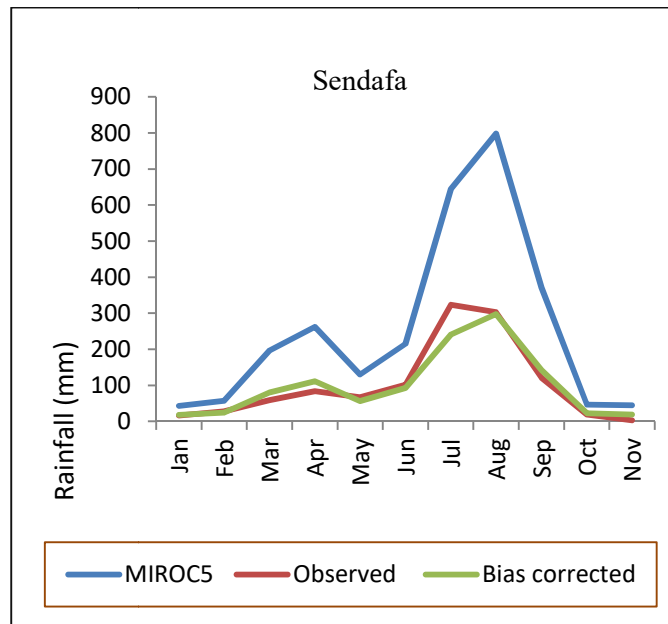
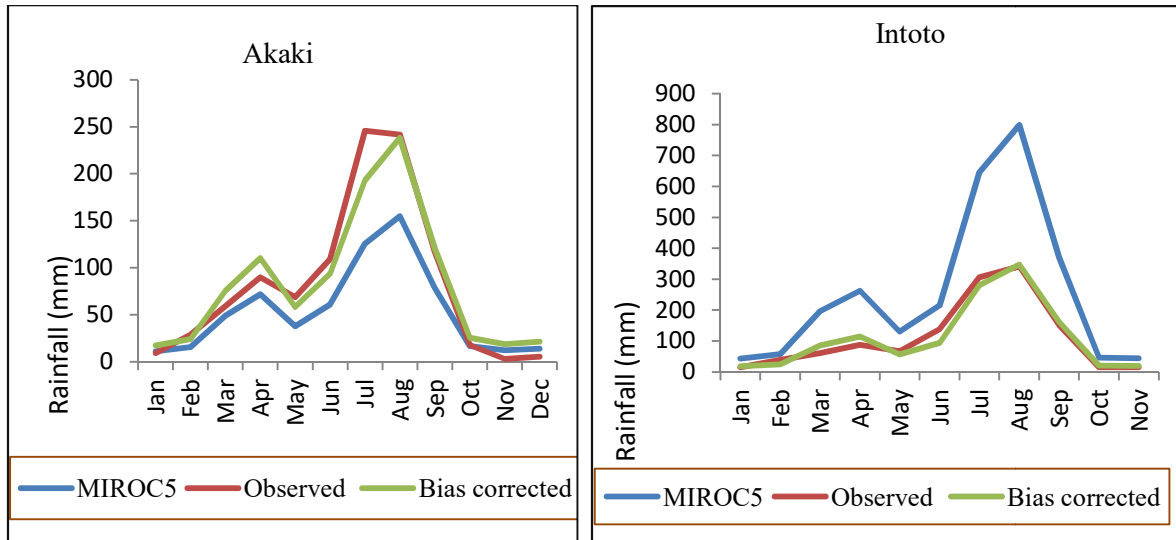
AA-Albergo Italia	BHT-683	471300	996200	2352.587	6
AA-Alert-3 Well	BHT-691	468100	993200	2301.436	45
AA-Anbessa Transport	BHT-682	471200	995700	2342.271	3
AA-Anokorcha-99	BHT-1045	480029	998401	2466.287	20
AA-Ayat-99	BHT-1044	489127	999697	2441.264	39
AA-Bole Med	BHT-922	476800	994200	2345.133	52
AA-Brewery-2	BHT-659	471500	995900	2349.323	17
AA-Brewery-3	BHT-660	471400	995800	2344.702	12
AA-brewery-4	BHT-661	471400	996000	2347.967	23
AA-Brewery-6	BHT-663	471550	995950	2352.319	23
AA-Brewery-7	BHT-664	471500	995800	2347.852	16
AA-Brewery-1	BHT-658	471600	995800	2351.648	19
AA-British Embassy-1	BHT-627	476500	998250	2447.766	22
AA-British Embassy-2	BHT-628	476450	998100	2436.949	11
AA-Building College	BHT-638	470100	996100	2350.143	30
AA-Burayu Spring Water	BHT-419	462743	1002521	2622.047	35
AA-Cement factory-3	BHT-701	473050	991800	2280.638	94
AA-Civil Aviation	BHT-549	469800	996200	2370.423	7
AA-Coca Cola factory-2	BHT-637	470000	996400	2352.183	14
AA-Coffe Abyssina	BHT-971	475800	1001500	2569.893	97
AA-ETHARSO-1	BHT-704	470250	991500	2234.099	8
AA-ETHARSO-3	BHT-706	470300	991200	2227.982	10
AA-Ethio-Marble industry-1	BHT-619	468800	1001007	2537.514	18
Aa-Ethio-Marble Industry-2	BHT-620	468900	1001007	2547.88	72
AA-Ethiopian iron	BHT-784	476426	980749	2062.36	4
AA-Fanta Well field F7	BHT-372	481337	1001017	2635.358	23
AA-French Embassy	BHT-614	474300	1001005	2519.913	22
AA-General Winget School	BHT-618	468300	1001003	2544.218	41
AA-Genet Hotel	BHT-566	472000	995100	2331.271	44
AA-Ghion Hotel-3	BHT-649	473300	996300	2346.768	59

AA-Hashim Nuru	BHT-561	469725	994250	2327.643	17
AA-Hilton Hotel	BHT-919	474250	996800	2386.196	40
AA-Hope Enterprise-2	BHT-687	466300	993100	2335.588	60
AA-Jehova Witness	BHT-956	483350	999064	2500.913	59
AA-Kality Airforce-1	BHT-734	476400	984800	2133.212	12
AA-Repi-99	BHT-1035	465741	989188	2253.412	3
AA-Water III Borehole Bh	BHT-667	477162	976038	2065.449	42
AA-Water III Borehole 01	BHT-821	477972	974859	2084.491	59
AA-Water III Borehole BH02	BHT-822	478399	975589	2077.348	53
AA-Water III BH03a	BHT-823	480517	977974	2104.562	65
AA-Water III BH23	BHT-842	477477	977216	2067.848	44
AA-Water III BH3b	BHT-824	478713	974977	2087.381	64
AA-Water III Testwekk-B14	BHT-814	480900	978800	2133.613	86
AA-Water III Testwell-B10	BHT-808	461500	1001023	2592.28	82
AA-Water III Testwell-B5	BHT-803	481200	980000	2160.127	11
AA-Water III Testwell-B8	BHT-806	487300	995300	2364.742	88
AA-West German Embassy	BHT-625	475600	998900	2422.463	20
AA-Worwdw 17 kebele 17	BHT-973	476235	995275	2352.389	84
AAWSA F1 at Fanta	BHT-1010	479000	981400	2127.971	10
AAWSA F3 at Fanta	BHT-1009	479700	981700	2141.094	20
AAWSA Keraniyo No.2	BHT-963	463908	995127	2461.175	40
AA-Yekatit 12 Hospital-1	BHT-623	473300	999300	2478.983	18
Akaki Indo-European Textil	BHT-731	476369	981717	2089.531	7
Akaki Mesfin Z Dairy	BHT-603	481507	976220	2129.65	120
Akaki Meta Sab Utility	BHT-738	476500	981500	2062.465	73
Legadadi-Dini Heriakos	BHT-1002	486000	1000707	2486.356	12
Legadadi-NAS Food Fac	BHT-993	488150	1002300	2475.48	26
Legetafo	BHT-1114	486723	1000881	2437.09	32
Mekane Iyesus	BHT-702	470465	991100	2222.885	16
Military Food Service	BHT-1017	473900	985100	2170.956	8

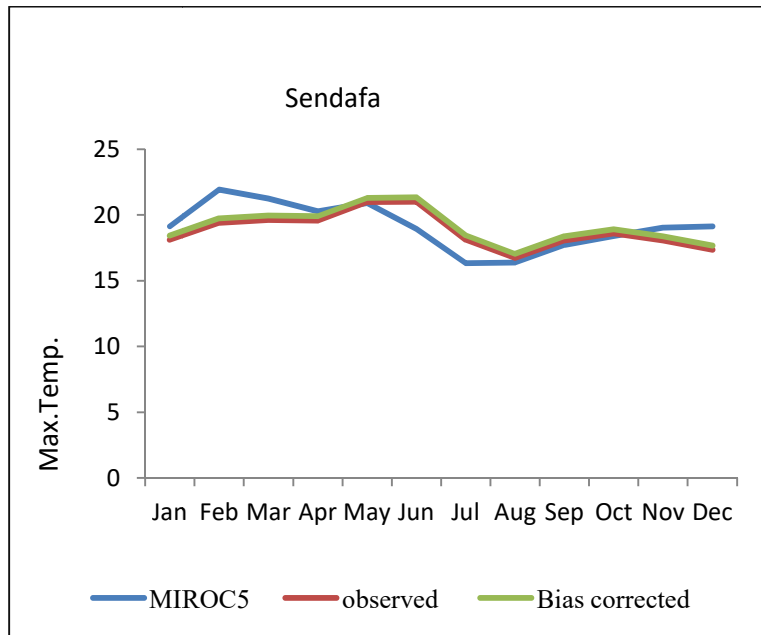
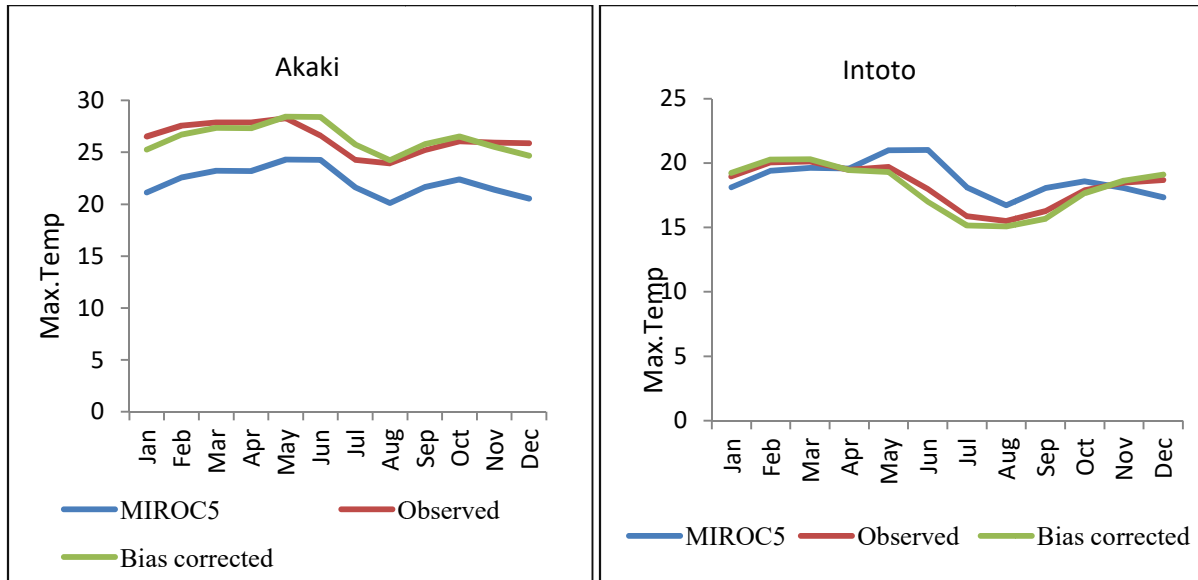
Minilik Hospital	BHT-741	475200	999200	2450.116	39
Ministry of Public Works	BHT-749	472500	996600	2369.683	7
NMWC Spare Parts 7	BHT-782	478462	977506	2081.841	50
Old airport (Army)	BHT-678	469300	995500	2358.315	16
Progress/Edget Cotton Fac	BHT-692	471000	993800	2305.371	68
Repi Soap factory	BHT-688	466250	993050	2338.448	50
SEDE(Plant B)-1	BHT-720	474000	989100	2225.917	18
SEDE(Plant B)-2	BHT-721	474100	989000	2220.497	35
Selam Technique	BHT-1096	481519	999648	2511.271	5
Sendafa Police College #2	BHT-787	502600	1011700	2569.867	82
St.Josephis School	BHT-650	473400	995800	2347.337	6
St.Poulos Hospital	BHT-621	469900	1001000	2589.755	7
Stars Business	BHT-681	481205	976968	2143.986	121
Summit;Medhanialem	BHT-1109	485733	994302	2301.054	74
Tatek	BHT-352	457162	1001115	2629.477	7
Telecommunication	BHT-698	474300	993300	2318.562	126
Tikur Abay Shoe	BHT-525	466200	1001008	2540.19	0
TW2 Test well No.2	BHT-947	473576	972821	2096.258	74
Voice of Revolutionary	BHT-689	467200	993600	2331.669	48
WF01 PW1	BHT-1343	473595	981135	2073.19	11
WF01-PW11	BHT-1350	472245	977865	2059.354	31
WF01-PW18	BHT-1360	471918	979657	2057.633	0
WF01-PW2	BHT-1344	474204	980459	2071.926	21
WF01-PW8	BHT-1349	473583	979260	2066.083	16

Appendix C: Bias correction of RCM

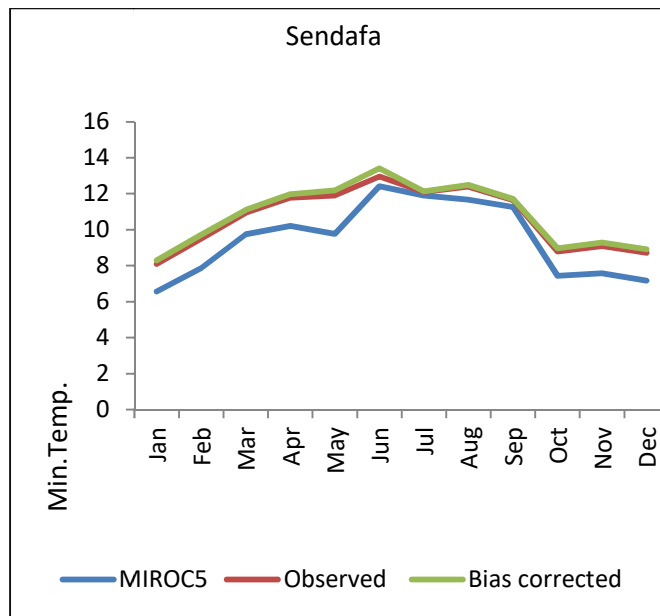
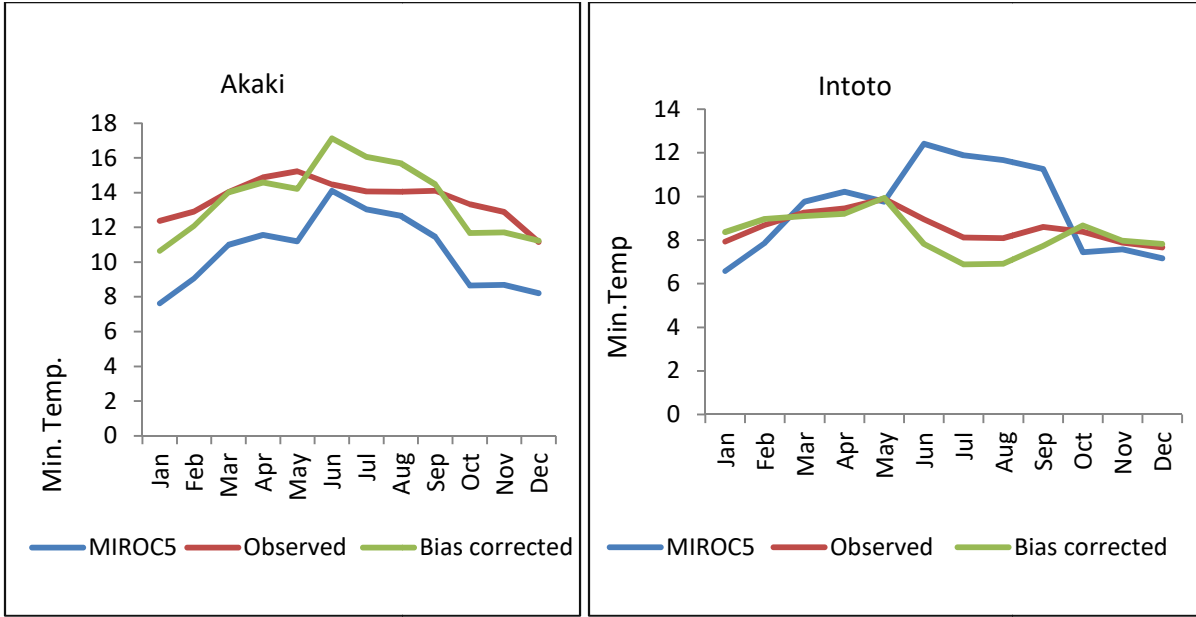
Appendix C.1: Bias correction for precipitation (Akaki, Intoto Sendafa stations)



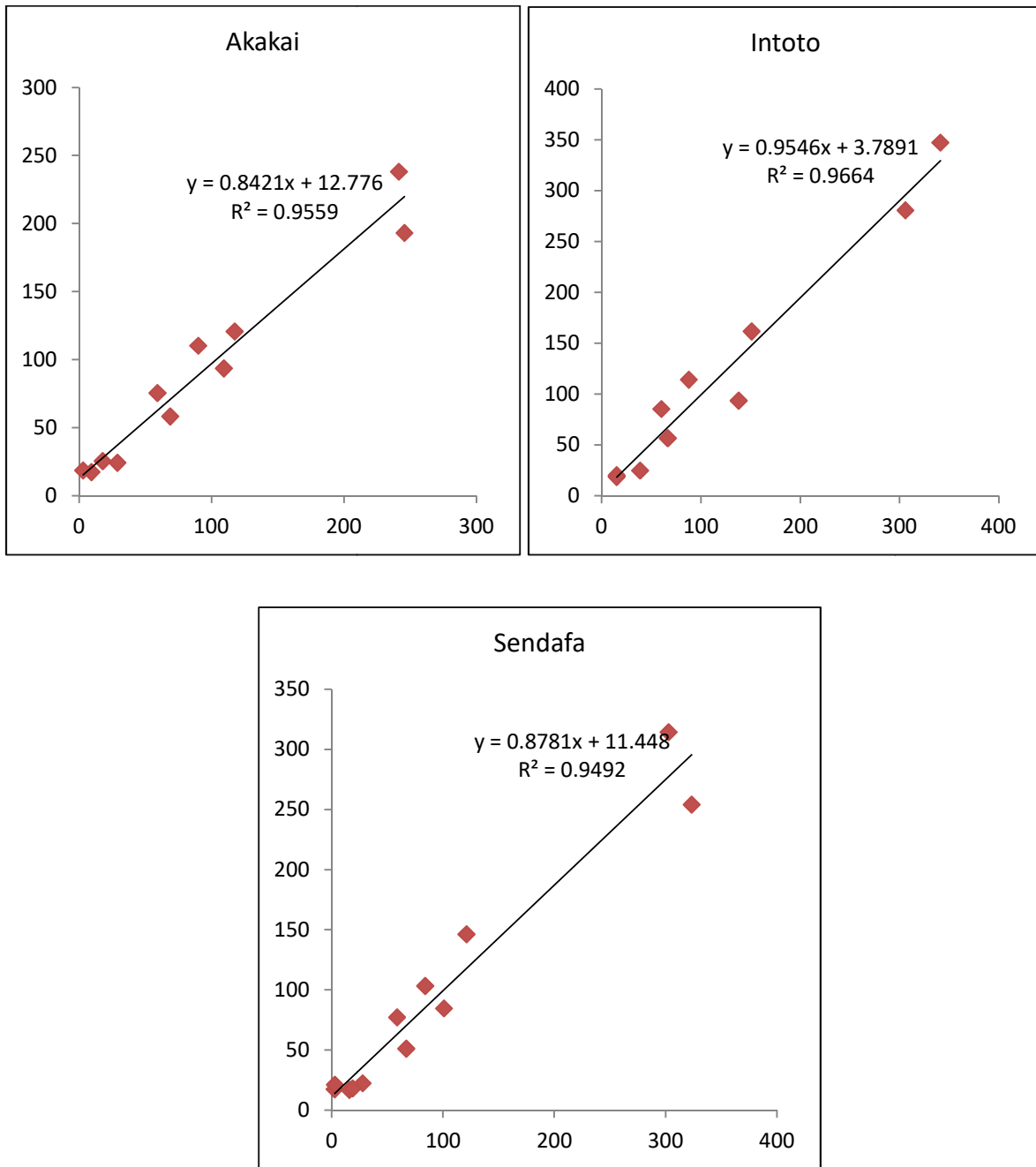
Appendix C.2: Bias correction for maximum temperature (Akaki, Intoto Sendafa stations)



Appendix C.3: Bias correction for minimum temperature (Akaki, Intoto Sendafa stations)



Appendix C.4: R^2 between observed and bias corrected Rainfall (Akaki, Intoto Sendafa stations)



Appendix D: Future water balance components

Appendix D.1: Midterm water balance components of 2050s

Hydrologic process	2036-2050					
	RCP 4.5			RCP 8.5		
	summer	winter	Annual	summer	winter	Annual
Precipitation	294	814	1108	326	834	1160
Actual evapotranspiration (AET)	199	258	457	205	273	478
Surface runoff	110	284	393	113	299	412
Groundwater recharge	4	254	257	4	266	269
Difference	P-ET-S-R=1			P-ET-S-R=1		

Appendix D.2: long term water balance components of 2080s

Hydrologic process	2066-2080					
	RCP 4.5			RCP 8.5		
	summer	winter	Annual	summer	winter	Annual
Precipitation	319	828	1147	294	868	1162
Actual evapotranspiration	195	277	472	191	288	479
Surface runoff	107	300	407	104	308	412
Groundwater recharge	4	264	268	4	267	270
Difference	P -ET-S-R=0			P -ET-S-R=0		