



**IMPACTS OF CLIMATE CHANGE DYNAMICS ON AVAILABILITY OF  
WATER IN THE DIDESA RIVER CATCHMENT, WESTERN ETHIOPIA**

**MSc THESIS**

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COLLEGE OF AGRICULTURE**

**HAWASSA, ETHIOPIA  
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**THESIS SUBMITTED TO FACULTY OF ENVIRONMENT, GENDER**

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The assistance and help received during the courses of this investigation have been duly acknowledged. Therefore, I recommended that it be accepted as fulfilling the requirement.

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## **STATEMENT OF THE AUTHOR**

I, the undersigned, declare that this study is original and has not been submitted for any other degree award to any other university before and that all the sources and method used for the thesis has been duly acknowledged.

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## **ACRONYMS AND ABBRVIATIONS**

Arc SWAT	Soil and water assessment tool Integrated with Arc GIS
CNRM	Center National de Recherchs
CMIP5	Coupled Model Inter-comparison Project Phase 5
CORDEX	Coordinated Regional Climate Downscaling Experiment project
DEM	Digital Elevation Model
EC_ERTH	European Community Earth System
FDC	Flow Duration Curve
GCM	General Circulation Model
GHG	Greenhouse Gases
GIS	Geographic Information Systems
HRU	Hydrologic Response Units
IPCC	Intergovernmental Panel on Climate Change
MoWIE	Ministry of Water, irrigation and Energy
MPI	Max Planck Institute
NMA	National Meteorological Agency
NS	Nash-Sutcliffe efficiency
PPM	Parts per million
PET	Potential Evapotranspiration
RCM	Regional Climate Model
RCMO	Regional Climate Model Output
RCP	Representative Concentration Pathways
RMSE	Root Mean Square Error

RSR	Root mean square standard deviation ratio
SCS	Soil Conservation Service
SRES	Special Report on Emission Scenarios
SWAT	Soil Water Assessment Tool
WCRP	World Climate Research program

# IMPACTS OF CLIMATE CHANGE DYNAMICS ON AVAILABILITY OF WATER IN THE DIDESA RIVER CATCHMENT, WESTERN ETHIOPIA

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Advisor: Teramage Tesfaye (PhD)

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## ABSTRACT

*Recently, the Coordinated Regional Climate Downscaling Experiment (CORDEX) initiative has made multiple Regional Climate Models' (RCMs') outputs available for end users across the African continent. But their accuracy has to be evaluated before running climate simulations in impact studies. Therefore, in this study the impact of climate change projections on stream flow over the Didesa catchment of Abay basin were evaluated using three independent regional climate model. The performance of all models was assessed in different stepwise approaches: First, the performance of the RCM simulation results were evaluated in Didesa catchment of Abay basin using bias, Root Mean Squared Error (RMSE), and Coefficient of Variation (CV). The second evaluation was based on the combined influence of corrected RCM simulated temperature and rainfall on hydrological simulations of mean stream flow under current (1989–2018) climatic data or condition. Then, the hydrological simulations of projected mid-term (2021–2050) and long-term (2051–2080) climate conditions were compared with the baseline with two emission scenarios of Representative Concentration Pathways (RCP4.5 and RCP8.5). Findings of this study indicated that the annual rainfall bias of the models varies between -21.9% and 15%, suggesting high variation. Based on the finding, climate change studies may benefit from the use of multi model simulation. Biases of most of the models proved that correction for the systematic error of RCM outputs must be made before the model outputs could be utilized by users. Compared to the base line period, all the models indicated that the total annual rainfall increases in midterm period (2021–2050) and long term (2051–2080) as projected under the RCP4.5. In long-term periods, climate models predicted that a decrease in rainfall in all seasons of the year except for summer season under RCP8.5 scenario, where as rainfall is predicted to increase when compared to the base line period. The stream flow projections are made for both periods in the future with two emission scenarios of RCP4.5 and RCP8.5. On the other hand, RCMs outputs indicated that the maximum and minimum temperatures were projected to increase over the catchment for both future periods of both scenarios with largest increase under RCP8.5. Under all models of RCP8.5 in the midterm and long term periods, the change of mean annual temperature ranges from 1.56°C to +2.27°C and 0.43°C to +3.62°C, respectively. From the stream flow projection relative to the baseline period, the change in mean annual stream flow from both future period are mostly positive, indicating increase in available discharge in the river under RCP4.5 and RCP8.5 scenarios. Flow duration curves showed that there is the probability of occurrence of high flows in both future periods under RCP4.5 and RCP8.5 scenarios relative to the baseline period. The overall conclusion of the study is that Didesa catchment of Abay basin is likely to experience more flow in the future than baseline period.*

Keywords: Abay, Catchment, Basin, CORDEX, Climate change, Didesa, Stream flow, RCM, RCP,

# CHAPTER ONE: INTRODUCTION

## 1.1. Background

Weather is the state of the atmosphere at a given time while climate is the average weather over a period of time (Thorpe, 2005). The Intergovernmental Panel on Climate Change (IPCC) in its Fifth Assessment Report (AR5) has shown an increase of 0.85°C in the global mean temperature since 1880 until 2012 (IPCC, 2013). These changes in global temperature have accompanied by changes in climate patterns and systems in different ways (Feng et al., 2014). Many regions have experienced changes in rainfall leading to frequent occurrence of floods (Min et al., 2008) or droughts, otherwise (Dai, 2011). These changes in climate system will have strong impact on local and regional hydrological regimes in many regions of the world (Hu et al., 2013).

IPCC in its Fifth Assessment Report (AR5) finding indicates that developing countries will be more vulnerable to climate change. In Ethiopia, climate change related impacts are more likely to exacerbate unintended consequences. Because of the less flexibility to adjust the economic structure and being largely dependent on climate variable-dependent economic and development activities like agriculture, the impact of climate change has far reach implication in Ethiopia.

Increased industrial activity and excessive deforestation during the last century had increased concentration of CO<sub>2</sub> gases in Earth's atmosphere (IPCC, 2007). This has in turn initiated large scale disruptions of atmospheric processes resulting in change of global temperature and rainfall or among other variables (IPCC, 2007). Therefore, there is a need to quantify and assess the future scenarios of climate change and its impact on water resources of the country in general and the basin in particular because the country's future development relies largely on this resource.

According to Tadege (2007), the current climate variability is already imposing a significant challenge to Ethiopia by affecting food security, water and energy supply, poverty reduction and sustainable development efforts, as well as by causing natural resource degradation and natural disasters. Therefore, assessing the impact of climate change on its water resources such as of Didesa river catchment can provide important information to be considered in development plans in water resources, agriculture and to overcome the impacts of intensifying recurrent droughts. This gives an opportunity to plan appropriate climate change adaptation strategies that must be taken ahead of time based on the projected climate change.

Several studies have attempted to evaluate the impacts of climate change in Ethiopia (Beyene et al., 2010; Abdo et al., 2009; Belay, 2011). However, none of these studies use ENSEMBLE model predictions, which provide mean of forecasting robust simulations for weather and climate prediction uncertainties. Particularly, no impact assessment of climate change study had been performed for the Didesa catchment, despite some studies on other parts of the Abay basin (Abdo et al., 2009). Therefore, this study aimed at assessing the impact of climate change on the water resource of Didesa river catchment and generated essential input information that can assist for the effort in managing the catchment.

## **1.2. Statement of the problem**

Climate change impact studies on water resources in Ethiopia has largely focused on existing information on the upper part of Abay basin as compared to the lower part of the basin including Didesa river catchment. Didesa river catchment is one of the highest socio-economic development sites due to its high potential for irrigation in southwest Ethiopia. However, in recent years, high climatic variability induced negative impacts on availability of water resources and subsequently

poses a challenge on decision making for planning, design and operation of irrigation scheme. Hence, a better understanding and projection of all the systems which can lead to a sustainable and optimal use of water for the intended purpose in countries like Ethiopia where frequent floods are common, is very important. As part of the river in Ethiopia, Didesa river catchment experienced basin-wide seasonal flooding mainly due to recurrent of intense rainfall. As a consequence, flooding spilling from Didesa river catchment and its tributaries in the down basin are remaining as a major problem major problem (Tesfaye and Wondimu, 2014). However, research on the western part of the country, particularly over the Didesa river basin, the river which contribute substantial amount of water flow in to the Abay river basin, is inadequate.

Therefore, this study was designed to investigate impacts of climate change on Didesa river catchment. It also illustrated the general trends of the past climate conditions such as rainfall, maximum temperature and minimum temperature compared to baseline climatic condition and the possible future climate change projection and their potential impacts on the stream flow of Didesa river at sub-regional scale based on Regional Climate Model (RCM) outputs and Representative Concentration Pathways (RCPs), as archived in Coordinated Regional Climate Downscaling Experiment (CORDEX)-Africa project domain.

### **1.3. Significance of the study**

This research could contribute to address valuable information on the climate change impact on Didesa river catchment and assessing future water resources availability using regional climate model technique from the two emission scenarios projection. Investigating climate change impact at local level was therefore, the main investigation topic of this study. As such, the study could provide an opportunity to define the degree of vulnerability of local water resources and plan

appropriate adaptation and mitigation measures in advance. Moreover, this would give enough room to consider possible future climate change related risks in all phases of water resource development projects at the local scale.

## **1.4. Objectives of the study**

### **1.4.1. General objective**

The main objective of this research was to evaluate the impact of climate change on stream flow in Didesa river catchment using the Regional Climate Model Outputs (RCMO).

### **1.4.2. Specific objectives**

1. To evaluate coherence of regional climate model simulations of rainfall over Didesa river catchment as compared to ground observation.
2. To project future trends in rainfall and temperature as compared to a baseline period in the catchment.
3. To analyze and evaluate the climate change impacts on stream flow over Didesa river catchment for two specified mid- and long-term future periods, 2021 - 2050 and 2051 - 2080, based on its flood peaks and flow duration curve (FDC)

## **1.5. Research questions**

The research questions addressed in this study were;

1. Is there any linkage between global warming and local climatic change signal and their impacts on the level of water flow in the Didesa river catchment?
2. What is the trend in temperature and rainfall between 2021 and 2050, and also between 2051 and 2080 compared to baseline period (1989 -2018) over Didesa river catchment?

3. How the water availability is likely to change in the future as compared to the baseline period over Didesa river catchment?
4. What are the most likely scenarios to be effective to minimize climate change related risks in mid and long-term periods in order to secure the water resources availability in the catchment?

### **1.6. Limitation of the study**

Climate change emission scenarios used in this study project has their own uncertainty and limitations that may produce error on catchment water balance. Data collected from meteorological stations and hydrological stations also has its own drawback due to missing and shorter time of observations.

### **1.7. Organization of the thesis**

This thesis work is organized in five chapters. Chapter one introduces the study with its relevance, statement of the problems and objectives. Chapter two deals with literature review. Chapter three gives brief description of the study area, material and methodology adopted for the study. Results and discussions on the data are presented in chapter four. Finally, chapter five ends with general conclusion and recommendation of the study as well as proposition for the future research.

## **CHAPTER TWO:LITERATURE REVIEW**

### **2.1. Climate change and variability**

Climate change refers to an increase or decrease in the average weather elements caused by land use changes and the anthropogenic increase in the concentrations of greenhouse gases (GHGs), particularly carbon dioxide (CO<sub>2</sub>) in the Earth's atmosphere. Warming of the Earth's surface is indisputable as evident from observed increase in global average air temperature, ocean temperatures and other observations (IPCC, 2007). Climate change is going to have an impact on the hydrological cycle, which is sensitive to wind and temperature. Proper understanding of basic aspects of climate change and how it impacts extreme events, which reflected on the hydrological cycle, is important. African's climate scientists face further challenge in the role of natural and human derived land cover changes on the continent which strongly modify the regional climates (Xue, 1998).

The extent to which climate change can affect the environment, society, and economy is increasing. Long-term climate change has observed at continental, regional, and ocean basin scales, due to increasing concentration of GHG particularly carbon dioxide. These include changes in rainfall amounts and timings, arctic temperatures, wind patterns, and aspects of extreme weather like heavy rainfall, drought, and heat waves (IPCC, 2007). The pattern of rainfall is not distributed evenly across the world and is governed by atmospheric circulation patterns and moisture availability. These two factors are impacted by temperature so that the pattern of rainfall is expected to change due to changing temperature. The changes include rainfall amount, type, intensity and frequency. For instant, rainfall amount and intensity have increased in eastern part

of North America, South America and northern Europe while decreased in the Mediterranean, southern parts of Africa, and southern Asia (Trenberth et al., 2007).

Increasing global average air and ocean temperature can change the type of rainfall during the winter season (IPCC, 2007). The pattern of rainfall is changing from snow to rain in northern regions and mountainous area so that recurrent and intensity of rains events have increased even in places where total rainfall amounts have decreased (Barnett et al., 2008). All these changes are associated with increasing global temperature since warmer air can hold and carry more water vapor (Santer et al., 2008). As a consequence, it is now widely acknowledged that climate change has impacts on water resources availability and management throughout the world, in the near and an extended terms. Some of the sectors under concern include urban water supply, irrigated agriculture and hydropower production (Jasper et al., 2004).

Current climate variability is already imposing a significant challenge to Ethiopia by affecting food security, water and energy supply, poverty reduction and sustainable development efforts, as well as by causing natural resource degradation and frequent natural disasters (Tadege and Endalkachew, 2007). However, studies related to the impact of climate change and variability in Ethiopia water resources in general and major rivers in particular are limited. Therefore, assessing the impact of climate change on the water resource of Didesa river catchment will be expected to have importance information to be considered in development plans in water resources, agriculture and to overcome the impacts of intensifying recurrent droughts. This gives an opportunity to plan appropriate adaptation of measures that must be taken ahead of time based on the projected climate change.

## 2.2. Causes of climate change

Climate change is due to both natural that means internal or external processes of the climate system as well as anthropogenic forcing example increase in concentrations of greenhouse gases associated with human activities. Natural factors such as volcanic eruptions, changes in the Earth's orbit, and the amount of energy released from the sun have affected the Earth's climate. Human-activities related climate change is a problem that is facing our planet, and it has aggravated after the beginning of 1750s or industrial revolution and therefore influencing the Earth's climate (<http://www.epa.gov/climatechange/basicinfo.html>). The emission of greenhouse gases has accelerated the magnitude of climate change and made our weather more intense. However, the world's dependence on fossil fuel for energy, transportation, and manufacturing has created a major obstacle to switch to renewable energy. Consequently, it becomes apparent that the observed warming over the last 50 years was likely due to an increase in greenhouse gases concentrations. The irradiative forcing of the climate system is dominated by the long lived greenhouse gases (GHG) such as Carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O), and other halocarbons. Carbon dioxide (CO<sub>2</sub>) is the most anthropogenic GHG. Global GHG emissions due to human activities have grown since the beginning of industrial revolution, with an increase of 70% between 1970 and 2004 (IPCC, 2007).

Global increase in CO<sub>2</sub> concentrations is primarily due to high fossil fuel use, with land-use change providing another significant contribution. An increase in CH<sub>4</sub> concentration is predominantly due to agricultural activities and fossil fuel use. An increase in N<sub>2</sub>O concentration is primarily due to agricultural activity. Increases in the atmospheric concentrations of GHGs and aerosols, land cover and solar radiation alter the energy balance of the climate systems and are drivers of climate change. They affect the absorption, scattering and emission of radiation within

the atmospheric layer and at the Earth's surface. The resulting positive or negative changes in energy balance due to these factors are expressed as irradiative forcing, which is used to compare warming or cooling influences on global climate systems (IPCC, 2007). In general, with warmer weather, water demand is anticipated to increase while water supply is anticipated to decrease (Peterson and Keller, 1990).

We need to transfer our energy to renewable energy to prevent climate change from progressing by preventing any future changes from happening, but adaptation is a major thing we need to do. Scientists, environmentalists, communities, as well as policy makers need to diligently and cooperatively to live up to these challenges and combat climate change (Kaddo and Jameel, 2016) so as to minimize its effect on water catchments.

### **2.3. General circulation model (GCM) and regional climate model (RCM)**

General Circulation Models (GCM) also known as Global Climate Models (GCMs) representing physical processes in the atmosphere, ocean and land surface are the most advanced tools currently available for simulating the response of the global climate system due to an increase in GHG concentrations. GCMs are the most appropriate tools to generate climate change projection in the future (Arnell et al., 2002). Only GCMs in conjunction with nested regional models or other downscaling methods such as Regional Circulation Models (RCM) possessed strong potential to provide geographically and physically consistent estimates of regional climate change, which best fits in flood analysis (IPCC, 2007).

Dependable climate change information is usually required at finer spatial scales than that of a typical GCM grid-cell in order to formulate adaptation policies in response to climate change impacts. GCMs do not capture detail requirements for regional and national assessments. Climate

models, both global and regional, are the primary tools that aid in our understanding of the many processes that govern the climate systems (Abdo et al., 2009). Climate is one of the most challenging geophysical systems to simulate because of the number of interacting components and the wide range of time and spatial scales of relevant processes and their complexity (Laprise, 2008). A significant spatial scale problem exists between the scale of the GCMs (200-400km) and the scales of interest for impacts and adaptation studies, which are often only tens of kilometers or less (Evans, 2011).

Regional Circulation Models (RCM) provides finer and temporal details than GCM. RCM represents important components of the climate system. Higher resolution exists for RCM within the study area than GCM because land coverage information is available only for limited region of the country. The RCM is 'nested' within a GCM (IPCC, 2007). There exists a high degree of compatibility between GCM and RCM in terms of their physics and dynamic schemes (Arnell et al., 2002). The GCM and RCM make use of the same grid scale dynamics and sub-grid scale physics except for certain parameterization constants which require different scaling in the RCM to account for higher resolutions (Jones et al., 2001).

Regional Climate Models (RCMs) are developed based on the same representations of atmospheric dynamical and physical processes as GCMs. They have higher spatial resolution in the order of 10-50km that can cover a sub-global domain. As a result of the higher spatial domain, RCMs provide a better description of orographic effects, land-sea surface contrast and land-surface characteristics (Christensen, 2007). Moreover, they enhance the simulation of atmospheric circulations and climatic variables at fine spatial scales which shows their improved ability to reproduce present day climate (Xu, 2000). However, there is still some limitations such as: (i) the inheritance of systematic errors in the driving fields provided by global models, (ii) lack of two-

way interactions between regional and global climate (iii) the algorithmic limitations of the lateral boundary interface (iv) computational demanding, and (v) further downscaling requirement for impact studies.

Currently, there are many different available RCMs for various regions developed at different modeling centers of the world. However, the uncertainty issues remain another drawback in use of RCM. Due to this fact, several international efforts have been made to quantify uncertainties through model inter-comparison. More recently, a new project called CORDEX (Coordinated Regional Climate Downscaling Experiment) has been initiated by the world climate research program simulations at 50km resolution for multiple regions.

Due to the availability of numerous numbers of such RCMs, a number of studies have been conducted in the past. Teutschbein and Seibert (2012) provided a recent review on the use of RCMs for hydrological models. They recommend that a bias correction is necessary for using the outputs in any hydrological models as RCMs are susceptible to systematic model errors caused by imperfect conceptualization and spatial averaging within grid cells. These biases are typically due to the occurrence of too many wet days with low-intensity rain or incorrect estimation of extreme temperature in RCM simulations. Thus, bias corrections were carried out for RCMs output to the nearby observed stations on the watershed; then the future changes in maximum and minimum temperature and precipitation were assessed in the catchment and the bias corrected RCM outputs is used in SWAT hydrologic model in order to understand the hydrologic behavior of the Didesa river catchment for the scenario periods.

## **2.4. Creating regional climate change scenarios for use in impact models**

Climate change impacts assessment models require climate information for the periods between which the change is being estimated. Information for such assessment is obtained in two ways; the first is the use of current climate information-historical data. The use of observed climate as an input rather than model-simulated climate gives better impact models to produce the current or past situations. To create the required future climate information, combination of changes derived from the model simulations of present and future climate with the observed 'baseline' climate should be done (Arnell et al., 2002).

The second approach is using climate model data for both periods (current and future) and the impact of climate change in that sector estimated based on the generated future data. Improved models have resulted improvement in control simulations, making this approach increasingly attractive and competitive. Knowledge of performance of the climate model and an assessment of the projected climate changes is invaluable when selecting a method to provide climate information (Arnell et al., 2002). It is desirable to develop from the coarse scale driving model when developing scenarios from RCM experiment for use in impacts models.

In Ethiopia, a strategy on reducing land degradation and transforming agricultural productivity through improved water management have had implemented since the 1990s (Lakew et al., 2005). As a result, various water infrastructures (Berhanu et al., 2014) such as water harvesting technologies, hydropower, and small-scale irrigation schemes had been established. These implemented water harvesting technologies were planned to have a profound influence on hydrological response and, in general, on the socio-economy of the country. However, occurrences of frequent droughts coupled with the unpredictable climate variables especially

rainfall and runoff were indicated to be the major threats for sustainable development and management (Gebrehiwot et al., 2011). Hence, we predicted the future Didesa river catchment stream flow using RCM for sustainable development planning.

## **2.5. Emission scenarios**

Emission scenarios are images of future alternative features (IPCC, 2000). Four different narrative storylines were developed to describe consistently the relationship between the forces driving emission and their evaluation and to add context for the scenario quantification. There are four main story lines, namely: A<sub>1</sub>, A<sub>2</sub>, B<sub>1</sub> and B<sub>2</sub> (IPCC, 2007).

The A<sub>1</sub> storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income.

The A<sub>2</sub> storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing global population. Economic development is primarily regionally oriented and per capita economic growth and technological change is more fragmented and slower than in other storylines.

The B<sub>1</sub> storyline and scenario family describes a convergent world with the same global population that peaks in mid-century and declines thereafter, as in the A<sub>1</sub> storyline, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies.

The B<sub>2</sub> storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population at a rate lower than A<sub>2</sub>, intermediate levels of economic development, and less rapid and more diverse technological change than in the B<sub>1</sub> and A<sub>1</sub> storylines. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels (Houghton, 2001).

RCP scenarios (RCP2.6, RCP4.5, RCP6 and RCP8.5) are named according to the radiative forcing target level for 2100. RCP2.6 is defined as a peak in radiative forcing at 3 W/m<sup>2</sup> before 2100 that declines to 2.6 W/m<sup>2</sup> (around 490 ppm CO<sub>2equiv</sub>) by 2100. The definitions of the RCP4.5 and RCP 8.5 are described as stabilization without an overshoot pathway to 4.5 W/m<sup>2</sup> (around 650 ppm CO<sub>2equiv</sub>) after 2100 and as a rising radiative forcing pathway leading to 8.5 W/m<sup>2</sup> (around 1370 ppm CO<sub>2equiv</sub>) by 2100 (Van Vuuren et al., 2011).

## **2.6. CORDEX Project**

In 2009, World Climate Research Program (WCRP) has initiated Coordinated Regional Climate Downscaling Experiment (CORDEX: <http://wcrp-cordex.ipsl.jussieu.fr/>) with the intention of producing an ensemble of high-resolution climate change projections by downscaling GCM simulations from Coupled Model Inter-comparison Project Phase 5 (CMIP5) data archive (Taylor et al., 2012) on 25km and 50km grid spacing for 14 regions of the globe. Africa was selected as the first target region for the WCRP in CORDEX (Giorgi et al. 2009).

CORDEX consists of two phases: in the first phase downscaling centers are asked to downscale a reference verification period using Interim European Center for Medium-Range Weather Forecasts (ECMWF), Re-Analysis (ERA-Interim) data (Dee et al., 2011). And in the second

phase, they use data from the Coupled Model Inter-comparison Project phase 5 (CMIP5) and GCMs from the period 1950-2100. Nikulin et al. (2012) evaluated the ability of ten RCMs over Africa and concludes that all RCMs simulate the seasonal mean and annual cycle quite accurately. Likewise, it is verified that the mean of multi-model outputs do better than individual simulation (Laprise et al., 2013) and we used three RCMs and their ENSEMBLE mean to evaluate the impact of climate change dynamics on availability of Didesa river catchment.

## **2.7. Hydrological models**

There are many different reasons why modeling of the rainfall-runoff processes of hydrology is needed. The main reasons behind are a limited range of hydrological measurement techniques and a limited range of measurements in space and time (Brazier et al., 2000). Therefore, it is necessary to develop means of extrapolating from those available measurements in space and time to ungauged catchments and used to assess the likely impact of future hydrological change. Hydrological models are the characterizations of the real world system. As Brazier et al. (2000) clearly stated that many rainfall-runoff models are carried out purely for research purposes as a means of enhancing knowledge about hydrological systems. Further, the researchers also added that other types of models are developed and employed as tools for simulation and prediction aiming ultimately to allow decision makers to improve decision making about hydrological problems. Before developing the hydrological models, it is vital to understand how the catchment responds to rainfall under different conditions. On the basis of process description, the hydrological models can be classified in to three main categories (Cunderlik, 2003), as briefly described below.

## **I. Lumped models**

Parameters of lumped hydrologic models do not vary spatially within the basin then basin response is evaluated only at the outlet, without explicitly accounting for the response of individual sub-basins. The parameters often do not represent physical features of hydrologic processes and usually involve certain degree of empiricism. These models are not usually applicable to event-scale processes. If the interest is primarily in the discharge prediction only, then these models can provide just as good simulations as complex physically based models.

## **II. Distributed models**

Parameters of distributed models are fully allowed to vary in space at a resolution usually chosen by the user. Distributed modeling approach attempts to incorporate data concerning the spatial distribution of parameter variations together with computational algorithms to evaluate the influence of this distribution on simulated rainfall-runoff behavior. Distributed models generally require large amount of (often unavailable) data. However, the governing physical processes are modeled in detail, and if properly applied, they can provide the highest degree of accuracy.

## **III. Semi-distributed models**

Parameters of semi-distributed (simplified distributed) models are partially allowed to vary in space by dividing the basin in to a number of smaller sub-basins. The main advantage of these models is that their structures are more physically-based than the structure of lumped models, and they are less demanding on input data than fully distributed models.

Hydrologic models can be further divided into event-driven models, continuous-process models, or models capable of simulating both short-term and continuous events. Event-driven models are designed to simulate individual rainfall-runoff events. Their emphasis is placed on infiltration and surface runoff. Typically, event models have no provision for moisture recovery between storm

events and, therefore, are not suited for the simulation of dry-weather flows. On the other hand, continuous-process models simulate instead a longer period, predicting watershed response both during and between rainfall events. They are suited for simulation of daily, monthly or seasonal stream flow, usually for long-term runoff-volume forecasting and for estimates of water yield (Cunderlik, 2003).

Generally, for this study, semi-distributed model is selected because of their structure are more physically-based than the structure of lumped model, and they are less demanding on input data than fully distributed models, which may most likely fit to study the climate change impact on the river flow like Didesa river catchment in Ethiopia .

## **2.8. Hydrological model selection criteria**

There are various criteria which can be used for choosing the right hydrological model for a specific problem. These criteria are always driven from research problems, since every project has its own specific requirements and needs. Further, some criteria are also user-dependent (and therefore subjective). Among the various project dependent selection criteria, there are four common and fundamental one that must be always answered (Cunderlik, 2003):

1. The importance of the required model outputs to the project and therefore to be estimated by the model (Does the model predict the variables required by the project such as long-term sequence of flow?)
2. Hydrologic processes that need to be modeled to estimate the desired outputs adequately (Is the model capable of simulating single-event or continuous processes?)
3. Availability of input data (Can all the inputs required by the model be provided within the time and cost constraints of the project?)

4. Price (Does the investment appears to be worthwhile for the objectives of the project?)

## **2.9. Soil and water assessment tool ( SWAT) hydrological model**

The SWAT model is a physically based model and requires data such as weather variables, soil properties, topography, vegetation and land management practices occurring in the catchment (Arnold et al., 1998). The model was developed for continuous simulation, as opposed to single event models. The physical processes associated with water flow, sediment transport, crop growth and nutrient cycling are directly modeled by SWAT using the above mentioned input data.

Some of the advantages of the model includes: modeling of un-gauged catchments, prediction of relative impact scenarios (alternative input data) such as changes in management practices, climate, and vegetation on water quality, quantity or other variables. SWAT also has a weather simulation model that generates daily data for rainfall, solar radiation, relative humidity, wind speed and temperature from the average monthly variables of these data. This provides a useful tool to fill in missing daily data in the observed records.

The amount of soil water is usually measured in terms of water content as percentage by volume or mass, or as soil water potential. This soil water content is highly depends on the water balance values given in Equation3 below. Mostly rainfall is taken as source of soil water content. Reduction of runoff, actual evapotranspiration and ground water from rainfall influence the availability of water in the soil. Therefore, SWAT model quantitatively revealed the value of soil water content (SW) depends on the above water balance values. From soil field capacity to the stress point, it is easy to get the water content. From the stress point to the permanent wilting point of plants, it is much harder to draw water from the soil and their growth is stunted. Below the permanent wilting point, no further water can be removed and the plant dies.

**Percolation** is the downward movement of water in the soil. SWAT calculates percolation for each soil layer in the profile. Water is allowed to percolate if only the water content exceeds the field capacity of that layer (Neitsch et al., 2002).

**Surface runoff** occurs whenever the rate of rainfall exceeds the rate of infiltration. SWAT offers two methods for estimating surface runoff: the Green and Ampt method of the flow of air and water through soils (Green and Ampt. 1911) and the Soil Conservation Service (SCS) curve number procedure (Arnold et al., 1998). Using daily or sub daily rainfall, SWAT simulates surface runoff volumes and peak runoff rates for each hydrological response unit (HRU). The SCS curve number method was used to estimate surface runoff because of the unavailability of sub daily data for Green and Ampt's method.

**Lateral flow** is common in areas with high hydraulic conductivities in surface layers and an impermeable or semi-permeable layer at a shallow depth. Rainfall will percolate vertically up to the impermeable layer and develops a saturated zone stored above this layer. This is called a perched water table, which is the source of water for lateral subsurface flow. SWAT incorporates a kinematic storage model for subsurface flow (Neitsch et al., 2002).

## **2.10. Flow duration curve(FDC)**

A FDC is one of the most informative methods of displaying the complete range of river discharges from low-flows to flood events. It is a relationship between any given discharge value and the percentage of time that this discharge is equaled or exceeded. (Vogel et al., 2007) have described FDC as simply a non-parametric cumulative distribution function of daily stream flows at a site. For gauged catchments, FDCs are constructed by reassembling the stream flow time series values in decreasing order of magnitude. All ranked flows are plotted against their ranks

which are again expressed as a percentage of the total number of time steps. For un-gauged catchments, FDCs can be constructed using various methods, such as:

- (I) Regional regression approach, which generally involves developing regional mathematical models by relating low-flow indices or FDCs with catchment physiographic and climatic characteristics.
- (II) Regional prediction curve, where FDCs for a number of gauged catchments of varying size in a homogeneous region can be converted to a similar scale, superimposed and averaged to develop a composite regional curve. To make curves from different catchments comparable, all flows are standardized by catchment area, mean or median flow or other flow index.
- (III) Low-flow estimation from synthetic stream flow time series - the alternative approach to low-flow estimate at un-gauged sites is to utilize a time-series simulation method to generate a satisfactorily long length of stream flow data and to calculate a set of low-flow indices and/or FDCs from the simulated series.

When analyzing stream flow to construct an installation such as a reservoir and headwork on a river, two questions are frequently asked:

1. How often will the stream flow occur in the future?
2. What will be the magnitude of the stream flow?

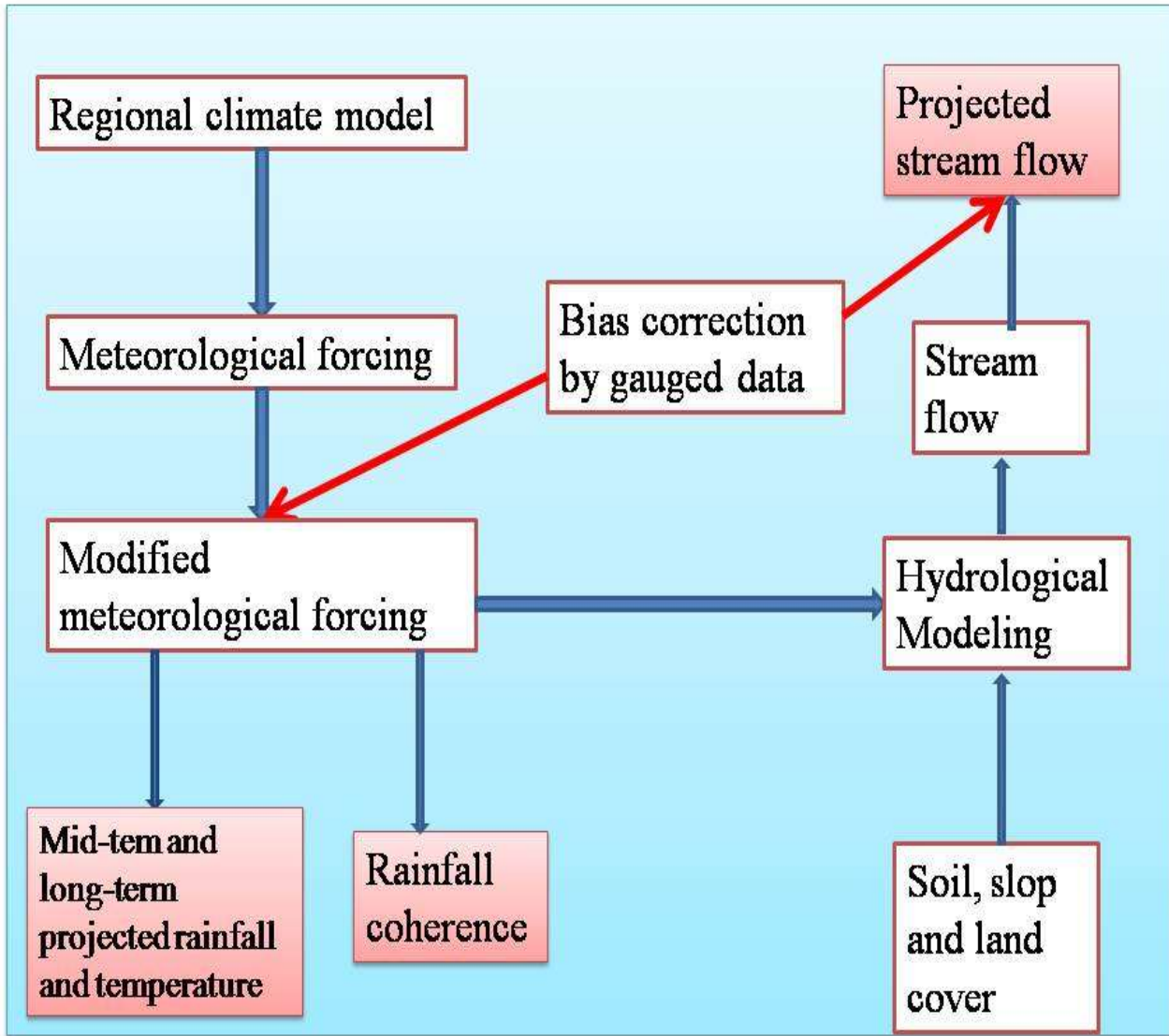


Figure 1. Conceptual framework of a stepwise selection and use of regional climate models

## **CHAPTER THREE: MATERIALS AND METHODS**

### **3.1. Description of the study area**

From the assessment of land use/land cover, major land cover types identified include moderately cultivated, dense woodland, intensively cultivated land, wooded grassland, open woodland, natural forest cover, natural forest with coffee, coffee farm with shade trees, riverine forest, bamboo forest, plantation forest, settlement, shrub land and open grassland. Different land use types in different land cover have been identified in the sub basin (Timketa, A., 2016). These include mixed cultivation, coffee production, livestock production, subsistence and commercial forest products utilization, non-timber products utilization, beekeeping, Wildlife management and utilization, infrastructure development, mining and investment activities on different activities.

### **3.2. Location of the study area**

Didesa river catchment is geographically located between 07°40'N and 10°00'N, and 35°30'E and 37°15'E. The elevation of the catchment ranges between 612 and 3200 meter above sea level. The catchment drains in to four Zones in Oromiya National Regional State (Jima, Illubabor, East Wollega, and West Wollega) as well as Benishangul Regional State. Didesa river catchment, which is the largest tributary of Abay, contributes roughly a quarter of the total flow of Abay.

The total catchment area of the river is estimated to be 29,874.3 km<sup>2</sup>. It is originated from the mountain ranges of Gomma in southwestern Ethiopia. The main upper streams namely; Temsa and Yebbu rivers from south flow eastwards for about 75kms until they are joined by the eastern tributaries such as Wama, Indris, Anger and Debana. Then after, turning rather sharply to the north until it reaches the Abay River. To the north-east direction, the main tributary of Didesa River with the largest catchment area is Anger river (Figure 2)

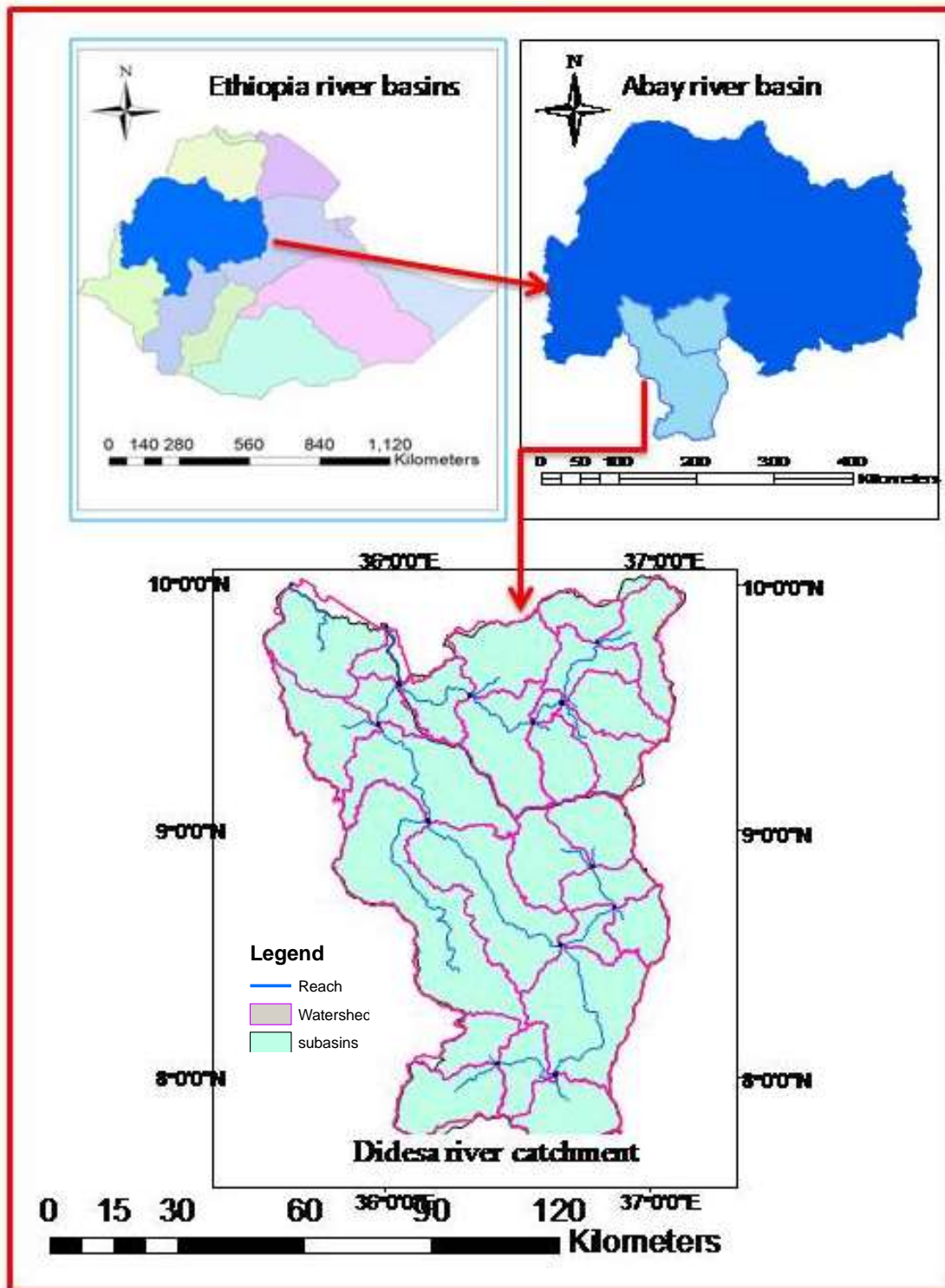


Figure 2. Map of the study area

**Table 1. Materials used for this research**

<b>Data Type</b>	<b>Source</b>	<b>Period</b>	<b>Description</b>	<b>Remark</b>
<b>Climate</b>	National Meteorological Agency (NMA)	1989-2018	Daily rainfall, Maximum and minimum temperature	Some periods have Missing data
<b>Hydrology and water resources</b>	Ministry of Water, Irrigation and Electricity of Ethiopia	1993-2015	Daily river flow Data	Some periods have Missing data
<b>Land use land cover</b>	Land use land cover, (FAO, 2012)	2012	Land use classification map	
<b>Soil</b>	Soil geo-database of Ethiopia, prepared by (Belte., et al, 2013).	2013	Soil classification map	Single layer
<b>DEM</b>	NASA		ASTER DEM	90mx90m
<b>Arc-SWAT</b>	SWAT2012 Version			
<b>Arc-GIS</b>	10.20 Resolution 0.440			

### 3.3. Research design

The parameters of semi-distributed (simplified distributed) models were partially allowed to vary in space by dividing the basin in to a number of smaller sub-basins. The main advantage of these models is that their structure is more physically-based than the structure of lumped models, and they are less demanding on input data than fully distributed models. For these reasons, semi-distributed (simplified distributed) model was selected and used.

### 3.4. Data availability and analysis

Meteorological data were collected from number of stations of NMA (Figure 3) while river discharge and flow data were collected from Ministry of Water, Irrigation and Energy (MoWIE). The most important time series data necessary for this research was long years rainfall and temperature as well as water flow in the river under study.



Figure 3. Selected weather stations of Didesa river catchment

For projecting future hydrologic regime of the catchment the hydrologic model was calibrated and validated using observed climate variable in Arc-SWAT hydrological model. Before model calibration data quality checking through homogeneity and consistency test, filling of missing data were conducted.

**Filling of missing climate data**

In this study, missing of observed rainfall and temperature values were estimated by using grid data. The process then informed SWAT to generate weather data for that day. The model generated a set of weather data for each sub basin.

**3.4.1. Quality and consistency check of rainfall data**

**Homogeneity test on station-based climate data**

The consistency and homogeneity of rainfall data from individual stations were evaluated. Homogeneity for some stations were tested by computing non-dimensional of rainfall data by dividing the monthly time series data and averaged rainfall amount of the respective year (FigureA:1 in appendix).

$$P_i = (\bar{P}_i / P) * 100 \dots\dots\dots (1)$$

Where:-

P<sub>i</sub> = Non dimensional value of rainfall for month i

P = Monthly time series average

$\bar{P}_i$  = Over years averaged monthly rainfall of the station and plotted to compare the stations

included in to compare the stations include in the computation of rainfall with each other

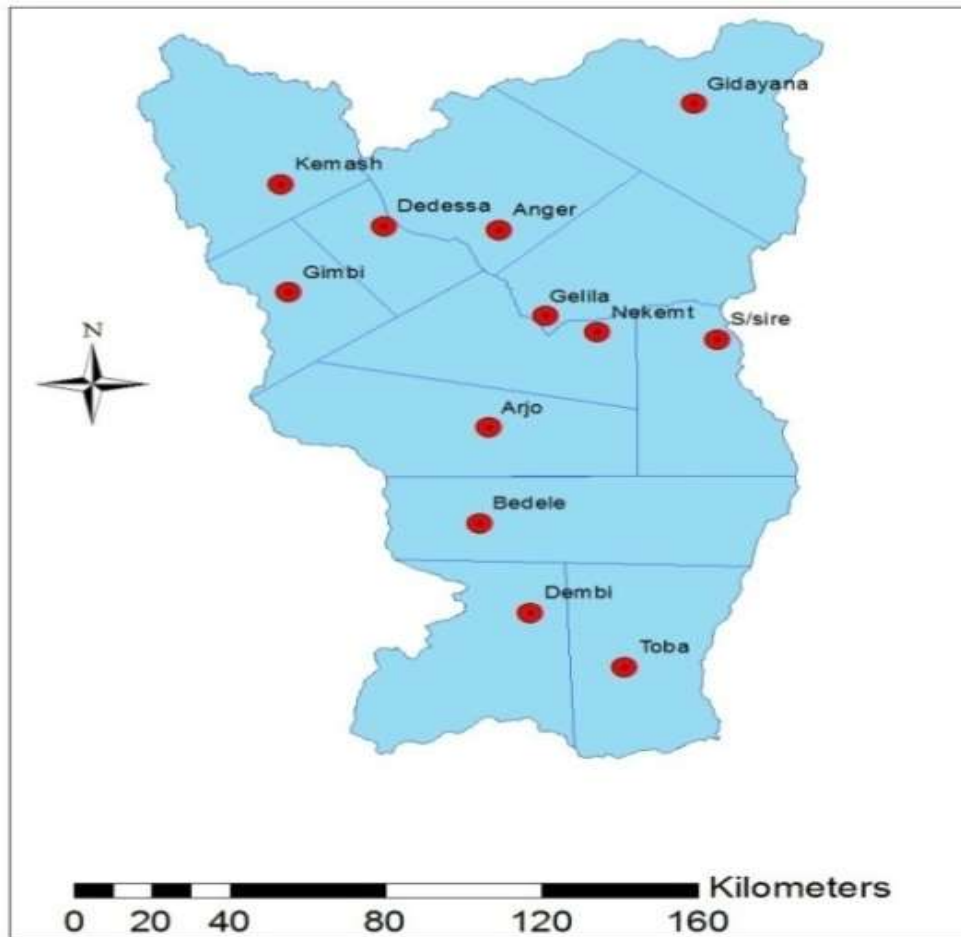
**3.4.2. Estimation of areal total rainfall of the catchment**

In order to achieve accurate estimation of the spatial distribution of rainfall, the Thiessen polygon method was considered (Allen et al., 1989). The method weighs each gauge in direct proportion

to the area it represents of the total basin without consideration of topography or other basin physical characteristics. Station weights are scalar factors used to transform point rainfall observed at this rainfall gauging stations into an associated mean rainfall over an area that the station data are assumed to represent. The area represented by each gauge is assumed to be that which is closer to it than to any other gauge (Table 2). If there are n stations with rainfall value  $P_1, P_2, P_3, \dots, P_n$  and  $A_1, A_2, A_3, \dots, A_n$  are the area of the respective Thiessen polygons, the average rainfall over the catchment  $P_{av}$  is computed as (Figure 4):

$$P_{av} = \frac{P_1A_1 + P_2A_2 + P_3A_3 + \dots + P_nA_n}{A_1 + A_2 + A_3 + \dots + A_n} \dots\dots\dots (2)$$

Where: -  $P_iA_i / A_i$  = weight factor for each station



**Figure 4. Thiessen Polygons for Didesa river catchment**

**Table 2. Rainfall stations and their corresponding area**

No	Station name	Area in km <sup>2</sup>	% area of covered
1	Anger	2481.67	8.31
2	Arjo	2748.40	9.20
3	Bedele	2976.30	9.96
4	Dembi	2520.15	8.44
5	Didessa	2342.98	7.84
6	Gelila	2183.36	7.31
7	Gidayana	3236.45	10.83
8	Gimbi	2342.99	7.84
9	Kemash	2677.23	8.96
10	Nekemt	2047.17	6.85
11	S/sire	1844.03	6.17
12	Toba	2473.52	8.28

### **3.4.3. Data processing in the RCMs**

For climate change data processing the following steps were used.

1. The first step was downloading simulated daily maximum and minimum temperatures and daily amounts of rainfall from CORDEX project at spatial grid resolution of 0.44 degree (~50 Km)
2. The second step was extracting the RCM overlapping grids that fall into the study area for the selected gauging stations from step one. Then, basin average climate model time series data was calculated using area weighted average.
3. The third and final step was calculating the biases for the historical and future scenarios. In this step the bias correction is for daily rainfall and temperature data.

Bias correction procedures employ a transformation algorithm for adjusting RCM output. The underlying idea is the identification of possible biases between observed and simulated climate variables, which is the basis for correcting both control and scenario RCM runs. Bias correction methods are assumed to be stationary, i.e., the correction algorithm and its parameterization for current climate conditions are also valid for future conditions. The following bias correction methods to adjust RCM simulations were used that is linear scaling approach which defined as equation 3 and 4 below.

$$P_{cor} = P_{unc} * P_{obs,ctr} / P_{rcm,ctr} \text{ and } \dots\dots\dots (3)$$

$$T_{cor} = T_{unc} + T_{obs,ctr} - T_{rcm,ctr} \dots\dots\dots (4)$$

Where  $P_{cor}$  is corrected rainfall,  $P_{unc}$  is uncorrected rainfall,  $P_{obs,ctr}$  and  $P_{rcm,ctr}$  are the mean value of observed and simulated rainfall, respectively, and  $T$  stands for temperature.

**3.4.4. Performance measures of CORDEX Africa rainfall simulations**

The performance of the CORDEX rainfall simulations was statistically tested using Bias, Root Mean Squared Error (RMSE), correlation coefficient and coefficient of variation (CV) of the models and their perspective formulae are indicted from equation number 1 to equation number 4 in appendix.

**3.4.5. Hydrological modeling using SWAT**

The simulation of the hydrology of a watershed has been done in two separate divisions (Richtie, 1972). One was from the land phase of the hydrological cycle that controls the amount of water, sediment, nutrient and pesticide loadings to the main channel in each sub-basin. Hydrological components simulated in land phase of the hydrological cycle are canopy storage, infiltration, redistribution, evapotranspiration, lateral subsurface flow, surface runoff, ponds, tributary channels and return flow. The second division was routing phase of the hydrologic cycle that can

be defined as the movement of water, sediments, nutrients and organic chemicals through the channel network of the watershed to the outlet. In the land phase of hydrological cycle, SWAT simulates the hydrological cycle based on the water balance Equation (5).

$$Swat = SW_o + \sum_1^i (R_{day} - Q_{surf} - E_a - W_{seep} - Q_{qw}) \dots\dots\dots (5)$$

Where:-

- Swat is the final soil water content (mm),
- SW<sub>o</sub> is the initial soil water content on day i (mm),
- R<sub>day</sub> is the amount of rainfall on day i (mm),
- Q<sub>surf</sub> is the amount of surface runoff on day i (mm),
- E<sub>a</sub> is the amount of evapotranspiration on day i (mm),
- Q<sub>qw</sub> is the amount of return flow on day i (mm) and
- W<sub>seep</sub> is the amount of water entering the vadose zone from the soil profile on day i (mm).

Using the above equation the soil moisture content for the given area was simulated.

**Peak discharge** or the peak surface runoff rate is the maximum volume flow rate passing a particular location during a storm event. SWAT calculates the peak runoff rate with a modified rational method. In rational method it is assumed that a rainfall of intensity i begins at time t = 0 and continues indefinitely, the rate of runoff will increase until the time of concentration,

t = t<sub>conc</sub>. The modified rational method is mathematically expressed as shown in Equation (6)

$$Q_{peak} = act * Q_{surf} * area / (3.6 t_{conc}) \dots\dots\dots (6)$$

Where:-

- Q<sub>peak</sub> is the peak runoff rate (m<sup>3</sup>/s),
- act is the fraction of daily rainfall that occurs during the time of concentration (m<sup>3</sup>/day),
- Q<sub>surf</sub> is the surface runoff (mm),

- Area is the sub-basin area (km<sup>2</sup>),
- $t_{conc}$  is the time of concentration (hr), and
- 3.6 is a conversion factor.

**Potential Evapotranspiration-** there is many methods that are developed to estimate Potential Evapotranspiration (PET) (Monteith, 1965; Allen, 1986; Allen et al., 1989). Three methods are incorporated into SWAT:

- The Penman Monteith method,
- The Priestley-Taylor method, and
- The Hargreaves method.

In this study, potential evapotranspiration was calculated with the Hargreaves’ approach due to missing or unavailability of weather data for the stations used. Because Hargreaves method can use for stations having with only temperature but no other variables enables to calculate potential evapotranspiration. Hargreaves derived an equation to calculate potential evapotranspiration using only temperature, which is a measurement that can be made most accurately, and extraterrestrial radiation ( $R_a$ ) using the relation:

$$PET_{hg} = 0.0023 * R_a * (T_{mean} + 17.8 * \sqrt{T_{max} - T_{min}}) \dots\dots\dots (7)$$

Where:-

- $PET_{hg}$  is the potential evapotranspiration by the Hargreaves method (mm/day),
- $R_a$  is the extra-terrestrial radiation (watts/m<sup>2</sup>);
- $T_{mean}$  is the average temperature (°C);
- $T_{max}$  and  $T_{min}$  are the maximum and minimum temperature (°C), respectively.

**Groundwater:** the simulation of groundwater is partitioned into two aquifer systems i.e. an unconfined aquifer (shallow) and a deep-confined aquifer in each sub basin. The unconfined

aquifer or shallow contributes to flow in the main channel or reach of the sub basin. Water that enters the deep aquifer is assumed to contribute to stream flow outside the watershed (Arnold et al., 1995). The water balance for a shallow aquifer was calculated with equation 8.

$$A_{qsh, i} = A_{qsh, j-1} + W_{rchrg} + Q_{gw} - W_{deep} - W_{pump, sh} \dots \dots \dots (8)$$

Where:

- $A_{qsh, i}$  is the amount of water stored in the shallow aquifer on day i (mm),
- $A_{qsh, i-1}$  is the amount of water stored in the shallow aquifer on day i-1 (mm),
- $W_{rchrg}$  is the amount of recharge entering the aquifer on day i (mm),
- $Q_{gw}$  is the groundwater flow, or base flow, into the main channel on day i (mm),
- $WR_{evap}$  is the amount of water moving into the soil zone in response to water deficiencies on day i (mm),
- $W_{deep}$  is the amount of water percolating from the shallow aquifer into the deep aquifer on day i (mm), and
- $W_{pumpsh}$  is the amount of water removed from the shallow aquifer by pumping on day i (mm).

**Routing phase of the hydrological cycle:-**

The second phase of the SWAT hydrologic simulation, the routing phase, consists of the movement of water, sediment and other constituents (e.g. nutrients, pesticides) in the stream network. As an optional process, the change in channel dimensions with time due to down cutting and widening is also included. The rate and velocity of flow was calculated by using the Manning’s equation (Williams, 1969).

The main channels or reaches are assumed to have a trapezoidal shape by the model. Two options are available to route the flow in the channel networks: the variable storage and Muskingum

options. Both are variations of the kinematic wave model. While calculating the water balance in the channel flow, the transmission and evaporation are also well considered by the model (Williams, 1969).

The variable storage method uses a simple continuity equation in routing the storage volume, whereas the Muskingum routing method models uses the storage volume in a channel length as a combination of wedge and prism storages. In the latter method, when a flood wave advances into a reach segment, inflow exceeds outflow and a wedge of storage is produced. As the flood wave recedes, outflow exceeds inflow in the reach segment and a negative wedge is produced. In addition to the wedge storage, the reach segment contains a prism of storage formed by a volume of constant cross-section along the reach length.

The variable storage method was adopted. The method was developed by (Williams, 1969) and used in the ROTO (Arnold et al., 1995) model. Storage routing is based on the continuity equation:

$$V_{\text{stored}} = V_{\text{in}} - V_{\text{out}} \dots\dots\dots 9$$

Where:

- $V_{\text{in}}$  is the volume of inflow during the time step ( $\text{m}^3$  water),
- $V_{\text{out}}$  is the volume of outflow during the time step ( $\text{m}^3$  water), and
- $V_{\text{stored}}$  is the change in volume of storage during the time step ( $\text{m}^3$  water). Detail of the equation was given in SWAT manual (Arnold et al., 1995).

**Watershed delineation:-**

As mentioned in previous sections, the watershed delineation was carried out based on an automatic delineation procedure based on a Digital Elevation Model (DEM). Default threshold sub-basin area that is suggested by the model was used to define the minimum drainage area to

form the origin of a stream. The watershed was divided into sub-basins and Hydrologic Response Units (HRUs). The total area of the delineated basin was reported by the delineator.

### **3.4.6. SWAT model data input and preparation**

#### **A. Model Input**

The spatially distributed data (GIS input) needed for the Arc SWAT interface include the Digital Elevation Model (DEM), soil data, land use and stream network layers. Data on weather and river discharge was also used for prediction of stream flow and calibration purposes.

#### **B. Land Cover**

The land use map of Didesa catchment was extracted from MERIS, 2009 to produce the land use map of the study area. Like with the DEM, the land cover was then cropped to fit the study area by overlying the watershed. MERIS land use data was prepared as per requirement of SWAT model and was reclassified using SWAT2012 land use database.

#### **C. Soil**

SWAT model basically needs the soil data to define hydrological response unit (HRUs). The soil map for this study was obtained from the GIS-based hydrological zones and soil geo-database of Ethiopia. In order to integrate the soil map within the SWAT model, it was necessary to make a User Soil Database. In this database all types of soils in the study area was represented, and coupled with their characteristics of the soil types of the study area with their corresponding area in hectare and percent.

#### **D. Hydrological response unit (HRU) definition**

The HRU definition was performed through the HRU analysis 'module that requires the land use/land cover, the soil and slope of the basin. There are three options available in ARCSWAT for the definition of HRUs (Neitsch et al., 2005). We adopted the method that considers spatial

variability of the processes and the datasets were prepared in spatial format and linked to the Arc SWAT. Based on the soil, land cover and slope data the definition of HRU was performed that assigns a unique value for each unit in the sub basin. As the area has lots of ranged topography, we considered four classes of slope i.e. 0-5%, 5-10%, 10-15% and  $\geq 15\%$ . The multiple HRU definition criteria were then performed for most applications the default settings for land use threshold (20%), soil threshold (10%) and slope threshold (20%) for slope of individual sub basin area (Arc SWAT, 2012). Overall, there were 209 HRUs defined in the entire watershed within 22 sub-basins.

### **E. Sensitivity analysis**

A sensitivity analysis was used as a screening tool for reducing the number of parameters to be adjusted during calibration. The sensitivity of different parameters is impacted by topography, geomorphology of the landscape, size of the watershed, land-use variations and human impacts. Before running the calibration, we analyzed the sensitivity of the parameters by using the Latin hypercube one-factor-at-a-time (LH-OAT) method of SWAT (van Griensven et al., 2006). The sensitivity analysis was performed on 13 SWAT model parameters that may have the potential to influence the flow of the river in the catchment.

### **F. Calibration**

Physically based semi distributed model SWAT generally have a large number of parameters which are not directly measurable and must therefore be estimated through model calibration, i.e. by fitting the simulated outputs of the model to the observed outputs of the watershed by adjusting the model parameters. A measure of the fit between the simulated and observed outputs is called calibration. The goal of calibration was to find those values for the model parameters that minimize or maximize the specified calibration criterion values. In the research, the SWAT model

calibration and validation was performed using automated calibration and validation developed in SWAT Calibration and Uncertainty Program (SWAT-CUP). Sequential Uncertainty Fitting version 2 (SUFI-2) algorithms was selected in SWAT-CUP that found out the most favorable model parameters within the uncertainty ranges of 95% after incorporating the possible parameter ranges.

SWAT developed by (Moriiasi et al., 2007) assumed an acceptable calibration for hydrology at  $R^2 > 0.6$  and Nash and Sutcliff (NS)  $> 0.5$ . These values were also considered in this study as adequate statistical values for acceptable calibration. The model performance statistics should be percentage bias ( $P_{BIAS}$ )  $< \pm 25\%$ ,  $R^2 > 0.6$  and  $NS > 0.5$ , root mean square error standard deviation ratio (RSR)  $< 0.70$  for monthly simulation period.

### **G. Validation**

Validation is the process of testing model performance of the calibrated model parameter set against an independent set of measured data. The model was validated using datasets from 2008 to 2015 at the location of study area. The goodness of fit was evaluated with NS efficiency, coefficient of determination ( $R^2$ ), RSR,  $P_{BIAS}$ .

### **H. Model Performance**

The performance of a model was evaluated on the extent of its accuracy, consistency and adaptability (Goswami et al., 2005). The model simulation was evaluated using efficiency criteria such as,  $R^2$ , NS,  $P_{BIAS}$  and RSR. The  $R^2$  coefficient and NS simulation efficiency measure how well trends in the measured data are reproduced by the simulated results over a specified time period and for a specified time step. The range of values for  $R^2$  is 1.0 (best) to 0.0. The  $R^2$  coefficient for n time steps is calculated as Formula 5 in appendix

The NS simulation efficiency for n time steps was calculated as formula 6 in appendix. The statistical index of modeling efficiency (Ns) values range from 1.0(best) to negative infinity. The  $P_{BIAS}$  over a specified period with total days was calculated from measured and simulated values of the quantity in each model time step as formula 7 in appendix.

A value close to 0% is best for  $P_{BIAS}$ . A negative value indicates model over estimation and a positive value indicate model under estimation. RMSE Observation RSR also another performance rating can be described as follows: RSR standardizes RMSE using the observations standard deviation, and it combines both an error index and the additional information recommended by (Moriiasi, 2007). Normalized RMSE, which is RSR, was calculated as the ratio of the RMSE and standard deviation of measured data, as shown in Formula 8 in appendix.

RSR incorporates the benefits of error index statistics and includes a scaling /normalization factor, so that the resulting statistic and reported values can apply to various constituents. RSR varies from the optimal value of 0, which indicates zero RMSE or residual variation and therefore perfect model simulation, to a large positive value. Lower RSR implies the lower the RMSE and the better the model simulation performance.

### **3.5. Flow duration curve (FDC) construction**

Next, we evaluated the impact of climate change on flow characteristics, the FDC prepared on monthly base. For such analysis, the FDC was classified into different segments following the subjective classification proposed by (Yilmaz et al.,2008).The classification included high-flow segment (0-20% flow exceedance probability) characterizing watershed response to large precipitation events; mid segment (20-70% flow exceedance probability) representing flows controlled by moderate precipitation events coupled to medium term base flow; and a low flow

segment (70-100% exceedance probability) representing a catchment response dominated by long term base flow during the extended dry periods.

The following equation was used to construct the flow duration curves:

$$P (\%) = M * 100 / (n + 1) \dots\dots\dots (10)$$

Where, P is the probability of flow that is equal to or exceeds a specified value (% of time), M is the rank of events, and n is the number of events in a specified period of time. In the present study, the monthly time series were used to construct the flow duration curves for the base period (1986–2015) and for the two window periods: the 2021-2050 and 2051-2080.

## **CHAPTER FOUR: RESULTS AND DISCUSSIONS**

### **4.1. Evaluation of the regional climate models simulation**

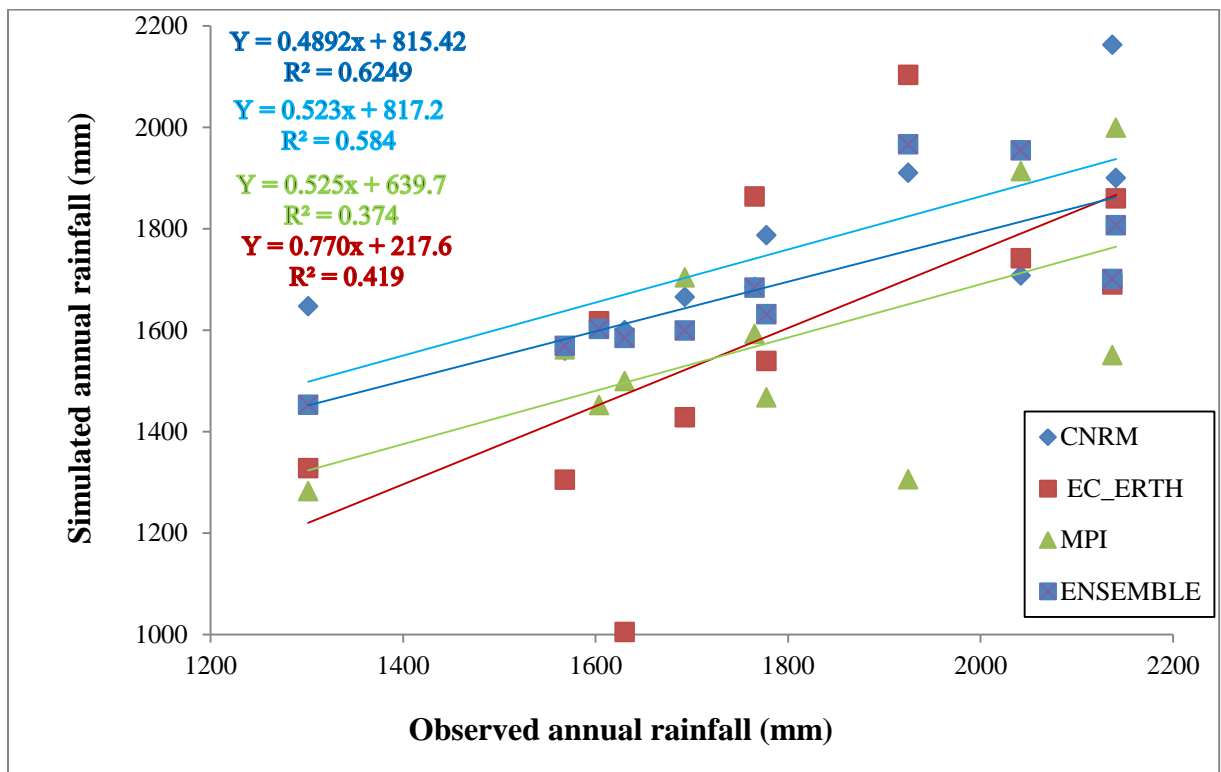
#### **4.1.1. Annual rainfall amount**

We first compared basin mean annual rainfall amount of Didesa river catchment as obtained from gauged data and model. A 30 year mean annual rainfall (i.e.in the period of 1989 – 2018), gauged, rainfall amount by Thiessen areal rainfall computations was 1719.88 mm. When comparing the gauged mean annual rainfall to model counterparts (Table 3), there exist large differences showing over estimation as large as 1990.93 mm (15.76%) but also under estimation at 1343 mm (21.91%) for respective RCMs. It can be seen that all the models except CNRM model underestimated the observed Didesa river catchment annual rainfall amount.

Also simulation bias showed large differences with the largest bias (-21.29%) for MPI (Max Planck Institute) which suggests the presence of a systematic error is less than a quarter of the annual rainfall amount. The smallest bias (-9.13%) was shown for ENSEMBLE which suggests that basin wide rainfall is well captured and represented. For standard error mean, ENSEMBLE model has the smallest value (6.2mm)whereas EC-EARH resulted in the largest value (8.23mm) which implies the result varies from model to model (Table 3) because of their characteristics.

GCM-RCM models capture inter annual rainfall variability over the study area. We, therefore, compared the annual rainfall variability from models to gauge based counter parts by means of CV (Appendix B: 4). Results showed that the CV of the gauged based rainfall for all stations was 19.7% for the 30 year period. The models and their ENSEMBLE showed lower CV values than for gauged rainfall except EC\_ERTH.

Overall, we could say that the climate models tend to underestimate real observations in the inter-annual rainfall variability. However, this under estimation is only by less than 3.5%. In terms of bias and standard error of mean, the ENSEMBL of models performed best whereas the EC\_EARTH model performed poorest (Table 3). This also supported by the results of correlation coefficient where almost all correlations were greater than 0.58 for all models, suggesting that outputs of the models well matched the observations at annual base Figure 5.



**Figure 5. Correlation of observed and model simulated rainfall at Didesa river catchment**

This result is consistent with the conclusions by Alemseged and Tom (2015), indicating the annual base correlation coefficient values in model MPI cannot be considered as high even though some models can performance good at the Upper Abay basin.

The study showed that for Didesa river catchment the bias of the ENSEMBLE mean rainfall amount is lower than that of the three models. However, it underestimated the observed mean

annual rainfall amount by almost 10%. As compared to most individual models the ENSEMBLE can capture the rainfall variability. The low CV of the ENSEMBLE mean rainfall (16.5%) suggests that variability is suppressed as compared to all separate models.

Further, using ENSEMBLE mean led to somewhat reduced standard error of mean of 6.2mm which is smaller than that of the separate models. Generally, as can be stated by (Kim et al., 2014) the ENSEMBLE mean of simulated rainfall is often to result in better accuracy than using simulations of individual models. Likewise the ENSEMBLE mean result indicates a better accuracy than using simulations of individual models.

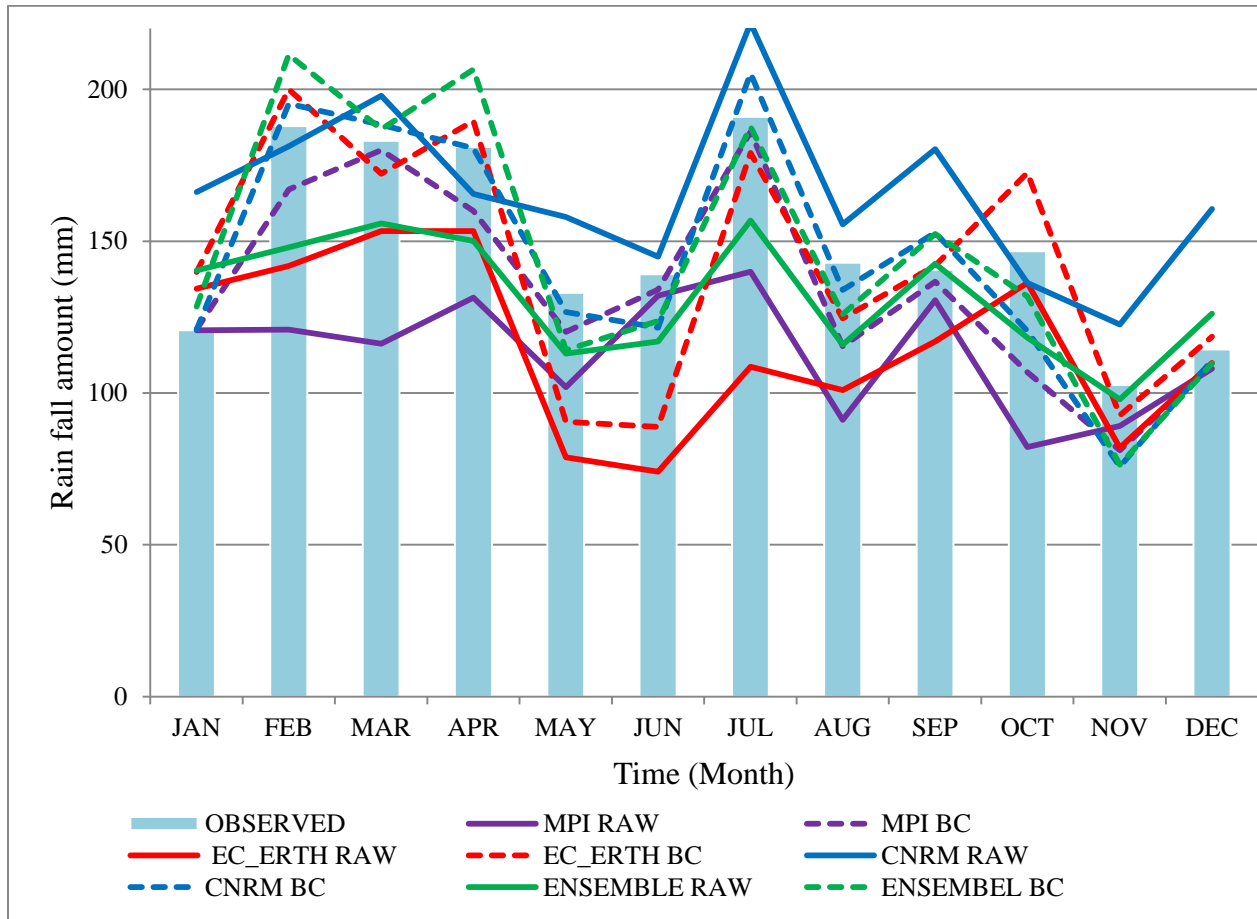
**Table 3. Performance of the CORDEX-RCM simulations in capturing and representing mean annual rainfall over the Didesa river catchment over the period 1989–2018**

	<b>Mean annual rainfall (mm)</b>	<b>Bias (%)</b>	<b>CV (%)</b>	<b>Standard error of mean(mm)</b>	<b>Correlation (-)</b>
<b>Gauged</b>	1720	-	19.7	8.49	-
<b>CNRM</b>	1990	15.15	16.8	7.78	0.75
<b>EC_EARTH</b>	1343	-21.89	25.5	8.23	0.63
<b>MPI</b>	1354	-21.27	18.1	6.89	0.58
<b>ENSEMBLE</b>	1563	-9.13	16.5	6.2	0.78

#### **4.1.2. Evaluation of corrected rainfall and temperature**

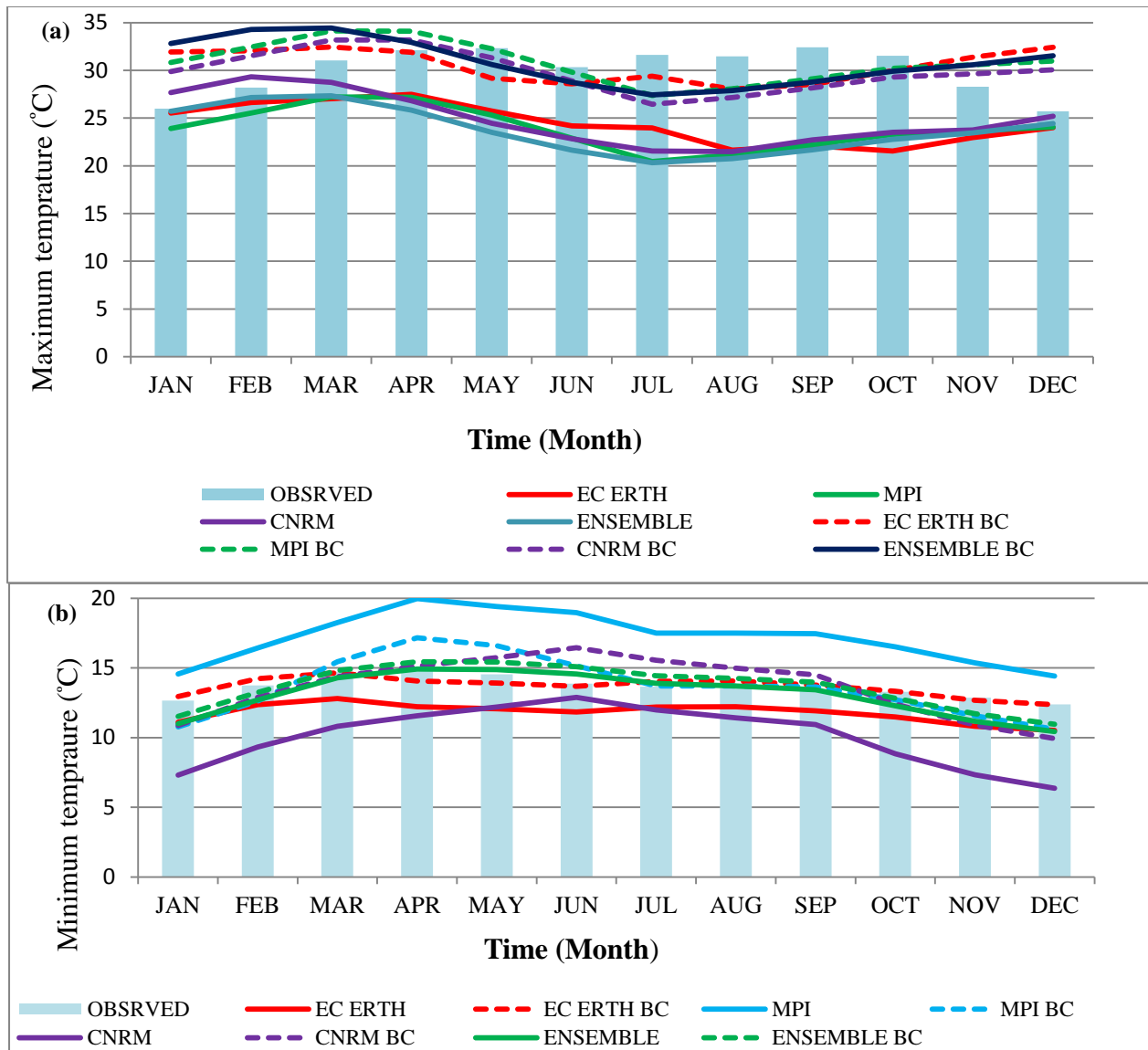
The daily bias corrections between the observed and simulated variables during the control period for each RCM models were applied. The bias correction was done on RCM-simulated rainfall, maximum and minimum temperature. The linear scaling approach methods were used for the ten extracted nearby grids. Figure 5 and 6 illustrated linear scaling of the grids extraction. Results showed that (1) for rainfall, the linear scaling method significantly corrects the biased raw RCM; and (2) similar results were obtained for minimum temperature and maximum temperature, and for those ten extracted grids. Therefore, when we compared here using all stations grid the

frequency-based statistics of observed, RCM-simulated (raw) and corrected rainfall data (Figure 5 and 6). The results showed that the raw RCM simulation deviates from observation data, with over and underestimation of all the statistics.



**Figure 6. Long term mean monthly historical bias corrected and bias uncorrected areal rainfall stations plot at Didesa river catchment**

The bias correction methods improve the raw RCM-simulated rainfall and temperature. However, there are differences between RCMs in their corrected statistics. The models capture the observation after correction than the raw RCMs. Thus, the bias correction methods improve the raw RCM-simulated rainfall.



**Figure 7. Long-term mean monthly bias uncorrected and bias corrected historical maximum (a) and minimum (b) temperature areal plot at Didesa river catchment**

Figure 7 showed climatology of corrected temperatures for both the validation of historical, and the reference data set. It appears that the bias correction works very well in terms of monthly averages because the climatology and corrected data related very well.

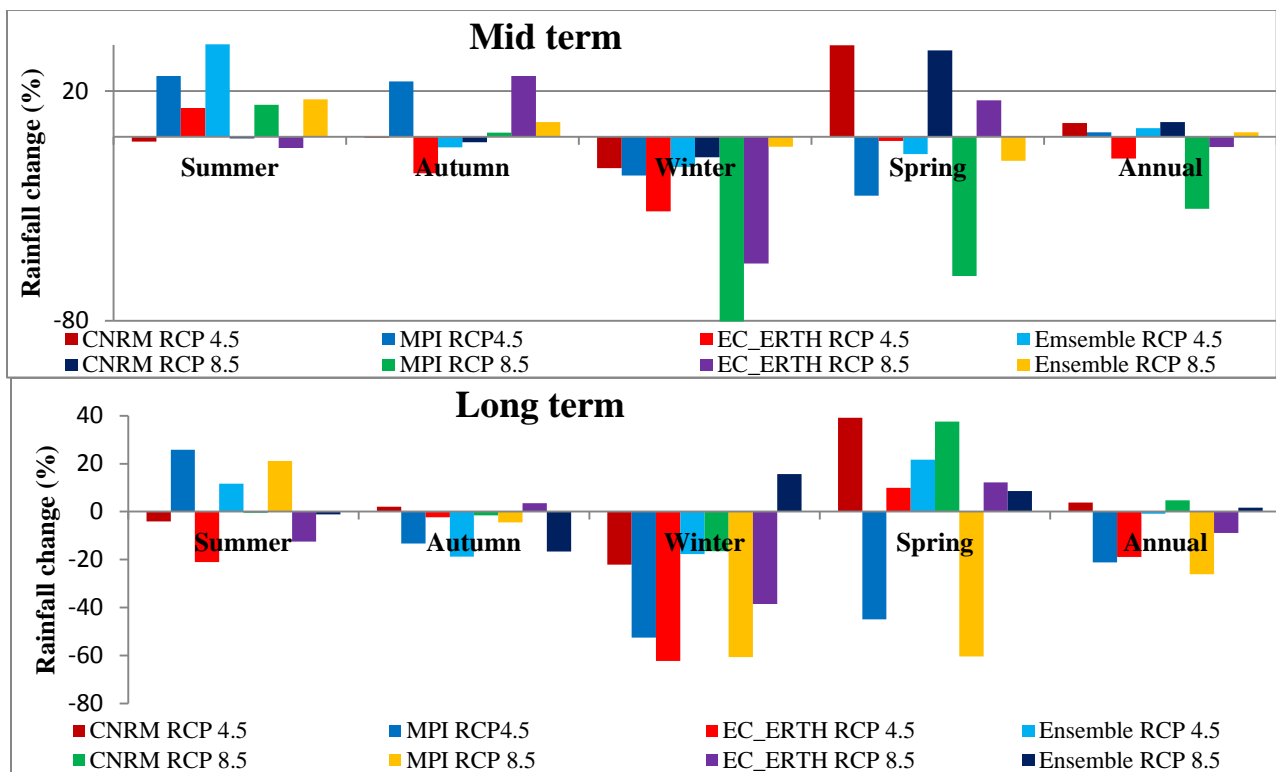
Again, for all stations, the bias corrected mean daily maximum temperature and minimum temperature was compared with the raw mean daily maximum temperature and minimum temperature. From Figure 7 and Figure 9 in appendix it can be inferred that the performance of

temperature was better and almost the same as observation data and here also all the models captured the observation than the raw RCMs. Thus, the bias correction methods improved the raw RCM simulated maximum and minimum temperature.

## 4.2. Future climate change projection

### 4.2.1. Seasonal and annual rainfall anomalies

In order to investigate the changes in mean seasonal and annual areal rainfall of the catchment, the statistical analysis were made on rainfall patterns for each season in Ethiopia. Under current study the seasons were classified into four. These are: summer (June-August), autumn (September-November), winter (December-February) and spring (March-May).



**Figure 7. Anomalies of bias corrected mean seasonal and annual rainfall in the mid-term (2021-2050) and long term future (2051-2080) periods**

The areal rainfall total of the catchment was calculated by developing Thiessen polygon using 11 meteorological stations. Accordingly, the areal rainfall from observed and all projected rainfall for

the mid-term and long-term averaged and compared with observed results. The anomalies of bias corrected mean annual and seasonal rainfall and temperature over the entire Didesa river catchment during the future periods of 2021-2051 and 2051-2080 were presented in Figure 8.

Figure 8 illustrates that among all the RCMs, MPI model projected the largest decrease in mean annual rainfall under RCP 8.5 scenario in the mid-term period (-31.23%) and in long-term period (-26.1%). In contrast, the model EC\_ERTH projects the smallest decrease in mean annual rainfall (-18.9%) under RCP4.5 scenario in the long term period. On the other hand, the largest increase in mean annual rainfall was projected under model CNRM (+6.44%) with RCP8.5 scenario in the mid-term period. In particular, a decrease of mean annual rainfall in both future periods' ranges from -8.83% to -31.23% when computed over the gauging stations under all models for the respective future periods. In mid-term period projected an average increase of +3.79% under CNRM RCP4.5 and +2% under CNRM RCP8.5.

In long term period projected an increase of +3.76% under CNRM RCP4.5 and an increase of +4.79 % under CNRM RCP8.5. The result showed that the percentage change of the mean annual rainfall in Didesa river catchment in mid-term and long-term periods and indication for increasing trend despite the fact that few models projected a declining annual rain fall. Looking at the seasonal temporal scale, all RCMs projects an increasing rainfall trend in some seasons and a decreasing trend in other season under both scenarios of RCP4.5 and RCP8.5 with respect to the control period of 1989-2018 (Figure 8).

During the spring season under RCP4.5 scenario in the mid future period only one of the model CNRM (39.90%) projects increase in mean seasonal rainfall which is in agreement with the results presented by (Abdela2013) on Gilgal Gibeibe III catchment. The researcher indicated that

there is an increase in the projected precipitation while two models and ENSEMBLE i.e. MPI, EC\_ERTH and RCM ENSEMBLE mean predicted reduction in mean seasonal rainfall ranging (-8.43% to -58.93%) . Under RCP 8.5 scenario also model CNRM projected an increase in mean seasonal rainfall by (+6.44%) while MPI, EC\_ERTH and RCM ENSEMBLE mean predicts a decrease in seasonal rainfall. In the long term period, during the spring season all the RCMs and the ENSEMBLE predicts a decrease in mean seasonal rainfall in both scenarios that ranges from -8.43% to -58.93% and -4.39% to -35.40% under RCP 4.5 and RCP 8.5 scenarios, respectively.

During winter season under both RCP4.5 and RCP 8.5 scenario in the mid future period only on CNRM RCP8.5 and EC\_ERTH RCP8.5 models projected an increase in mean seasonal rainfall of (+37.62%) and (+15.8) respectively, while rest of the models and ENSEMBLE mean predicts the decrease in mean seasonal rainfall (ranging from -7.41% to -93.43% in mean seasonal rainfall in both scenarios. During autumn season under RCP4.5 scenario only MPI shows increase of (+0.73%) and under RCP8.5 scenario MPI (+1.87%) and EC\_ERTH (+26.52%) in the mid future period where as rest of the models and their ENSEMBLE decreasing ranging from (-0.3% to -9.17%) and (-2.29% to -6.88%) under RCP4.5 and RCP8.5 scenarios, respectively. During summer season- under RCP4.5 scenario in the midterm period only MPI model shows an increase by (+19.79%) whereas all models and their Ensemble predicts decrease in mean seasonal rainfall ranging (-0.81% to -2.0%). Under RCP8.5 scenario only one model CNRM shows decreasing by (-0.69%) whereas all models and their ENSEMBLE predicts an increase in seasonal rainfall ranging (+4.79% to +15.19%).

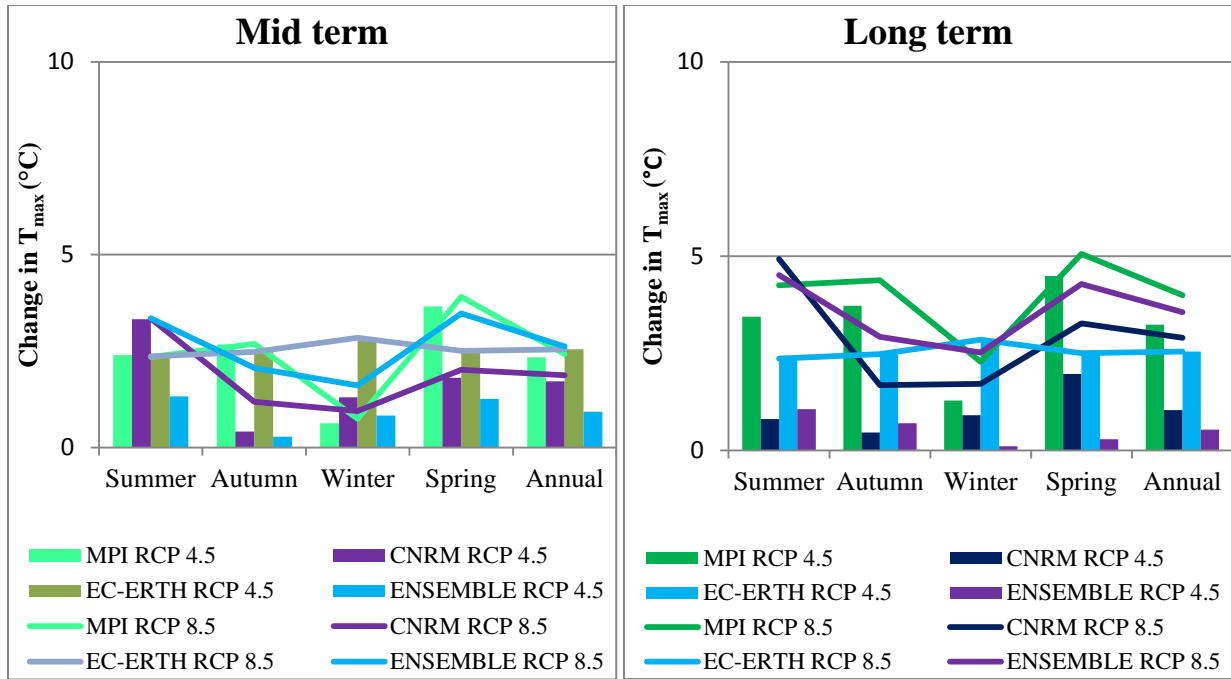
On the long period, under RCP4.5 and RCP 8.5 only model CNRM predicts an increase in mean seasonal rainfall of (+25.80%) and (+21.09%) respectively, whereas all models and their

ENSEMBL predict a decrease of rainfall ranging (-4.13% to -20.97%) under RCP4.5 and (-0.41% to 17.59%) under RCP8.5.

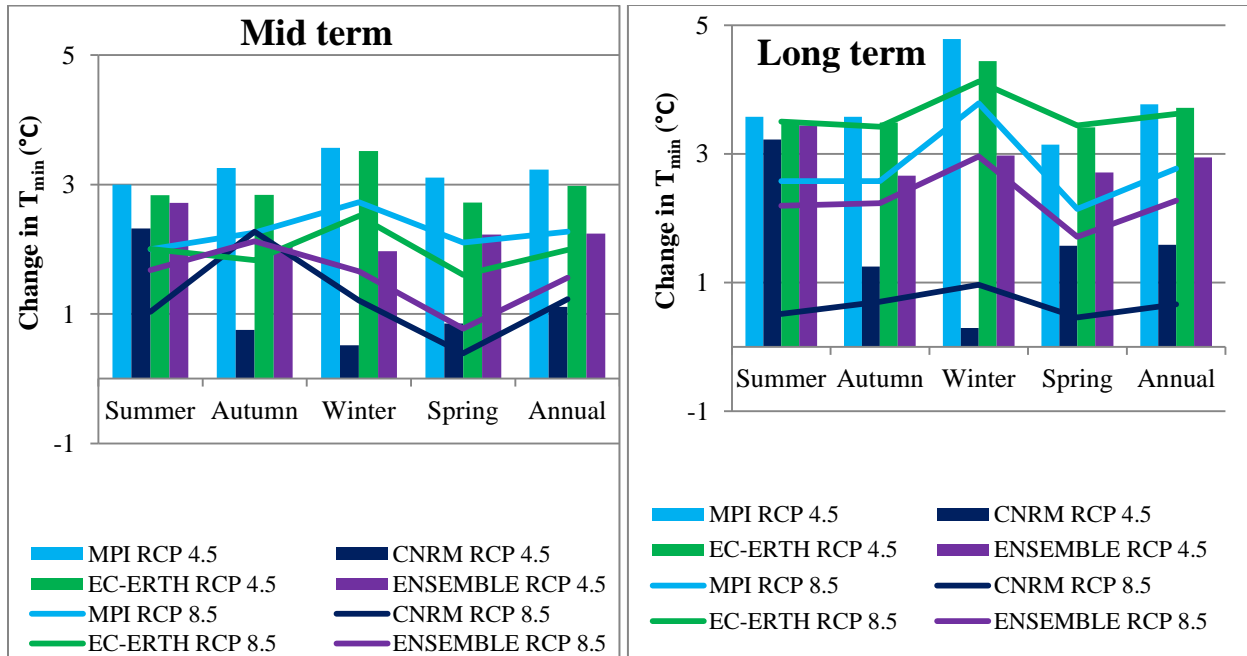
From the above result it can be seen that among the seasons spring Season distinguished as the largest decrease in mean seasonal rain fall during the midterm periods under RCP4.5 and RCP8.5 scenario in most of the models which shows time shift of rainfall this result is differ with the work by Abdela (2013) on the basin, whereas winter season distinguished as the largest decrease in mean seasonal rain fall during the long term periods under RCP4.5 and RCP8.5 scenario in most of the models. In summer season, an increase in mean seasonal rainfall is predicted in all Models with very few exceptions under RCP8.5 scenario and decrease under RCP4.5 during the mid-term period.

#### **4.2.2. Annual and Seasonal Temperature Anomalies**

Looking at the seasonal distribution of the RCMs simulated temperature for two specified future periods as in Figure9 and 10 showed that all RCMs and ENSEMBLE mean projected an increase in the mean seasonal maximum and minimum temperature with respect to the control period except CNRM.



**Figure 8. Anomalies of bias corrected mean maximum seasonal and annual temperature changes under models and scenarios, by mid and long term**



**Figure 9. Anomalies of bias corrected mean minimum seasonal and annual temperature Change under models and scenarios by near and mid term**

The change of mean annual maximum temperature ranges from 0.66°C to 2.55°C and 0.01°C to 3.23°C under all RCP4.5 models in the midterm and long term periods respectively. While under all models of RCP 8.5 in the midterm and long term periods the change of Mean annual maximum temperature ranges from 0.90°C to 2.63°C and 2.11°C to 3.99°C respectively. In the same manner, the change of Mean annual minimum temperature ranges from 0.51°C to 3.23°C and 1.35°C to 3.77°C under all models of RCP 4.5 in the midterm and long term periods respectively. While under all models of RCP 8.5 in the mid-term and long term periods the change of Mean annual minimum temperature ranges from 1.56°C to +2.27°C and 0.43°C to 3.62°C, respectively.

Among all RCMs, the MPI model projects the largest increase in mean annual maximum and minimum temperature under RCP4.5 for maximum temperature (3.23°C) and for minimum temperature (3.77°C) and under RCP8.5 EC\_ERTH for maximum temperature (3.99°C) and MPI (3.77°C) for minimum temperature) in the mid and long term periods.

The ENSEMBLE mean model projects the smallest increase in mean annual maximum temperature under RCP4.5 in mid-term period (0.54°C), whereas CNRM model projects the smallest increase mean annual minimum temperature under RCP8.5 in long term period (0.43°C). The largest increase in both maximum and minimum temperature is projected by the entire models under RCP8.5 in the long term period when compared to the RCP 4.5 scenario with respect to the control period 1989-2018. For the seasonal distribution as shown in Figure 9 and 10, the increase in maximum and minimum temperature is depicted by most RCMs under RCP4.5 and RCP8.5 scenarios. But the magnitude varies between models and RCPs.

**During the Winter** shown in Figure9, the average seasonal maximum temperature increase by  $0.83^{\circ}\text{C}$  under RCP 4.5 and  $1.61^{\circ}\text{C}$  under RCP8.5 in midterm period,  $0.11^{\circ}\text{C}$  and  $2.52^{\circ}\text{C}$  in long term.

**During the spring** shown in Figure 9, the average seasonal maximum temperature increase by  $1.26^{\circ}\text{C}$  under RCP 4.5 and  $3.48^{\circ}\text{C}$  under RCP8.5 in midterm period,  $0.28^{\circ}\text{C}$  and  $4.28^{\circ}\text{C}$  in long term. There is a tendency towards greater warming in spring season under both scenarios of RCP4.5 and RCP8.5 when compared to winter season in the midterm period and long term periods. The results of projected seasonal minimum temperature presented in Figure13, shows positive trend in all seasons, whereas all models project an increase in minimum temperature when compared to the control period.

**During the autumns** shown in Figure 9, the average seasonal maximum temperature increase by  $0.28^{\circ}\text{C}$  under RCP 4.5 and  $2.06^{\circ}\text{C}$  under RCP8.5 in midterm period,  $0.7^{\circ}\text{C}$  and  $2.9^{\circ}\text{C}$  in long term.

**Finally, during summer** as shown in Figure 9, under RCP4.5 and RCP8.5 scenarios, CNRM model is the warmest RCMs in the midterm period and CNRM under RCP8.5 shows lowest increase long term period. In average seasonal maximum temperature increase by  $1.33^{\circ}\text{C}$  under RCP4.5 and  $3.35^{\circ}\text{C}$  by the RCP8.5 for the near term period and  $1.07^{\circ}\text{C}$  for RCP4.5 and  $4.51^{\circ}\text{C}$  for RCP8.5 under the mid-term period shows the highest increasing trend of all models. From the above result, it can be concluded that in the both period under both scenarios the average mean seasonal maximum temperature has a greater variation on season than annual. While in both periods the spring season has a tendency of greater warming. As shown on Figure 9 and Figure 10 maximum and minimum temperature changes projected by MPI are larger than the other RCMs all-round the year under both scenarios in all future periods.

### **4.2.3. Monthly rainfall anomalies**

The anomalies of bias corrected mean monthly rainfall over the entire Didesa river catchment during the future periods are presented in Figure 5 in appendix for RCP4.5 and RCP8.5 scenarios. Referring Figure 5 in appendix, EC\_ERTH and ENSEMBLE mean models suggests that a significant increase in rain fall is considered in the summer month of July during the midterm period under RCP4.5 scenario where as August the months with high rain fall in historical period shows decrease in mean ran fall in both scenarios and periods. From Figure 5 in appendix monthly rain fall anomaly shows there is a shift variation from January to December under all ENSEMBLE mean of futures.

### **4.2.4. Monthly temperature anomalies**

The projected anomalies of models bias corrected for monthly maximum and minimum temperature over the entire Didesa river catchment for the period 2021-2050 and 2051-2080 were presented in Figure 6 and 7 in appendix. For the monthly maximum temperature, there is decrease at some months of the year and increase under others most months of the midterm and long term periods under RCP4.5 and RCP8.5 scenarios (appendix Figure 6).

The change maximum temperature ranging from  $0.10^{\circ}\text{C}$  to  $4.69^{\circ}\text{C}$  and  $0.03^{\circ}\text{C}$  to  $4.50^{\circ}\text{C}$  for midterm and  $0.03^{\circ}\text{C}$  to  $5.42^{\circ}\text{C}$  and  $0.40^{\circ}\text{C}$  to  $5.75^{\circ}\text{C}$  for long term under RCP 4.5 and RCP8.5 scenarios respectively of all models and their ENSEMBLE mean. Similarly, the results of all models and the ENSEMBLE mean for minimum temperature presented in Figure 7 in appendix depicts that, there is a decrease at some months of the year and increase under others months of the mid-term and long term periods under RCP 4.5 and RCP8.5 scenarios. The minimum temperature change range is from  $0.18$  to  $3.73^{\circ}\text{C}$  and  $0.09$  to  $3.0^{\circ}\text{C}$  for midterm and  $0.09$  to  $5.58$

°C and 0.24 to 4.58°C for long term under RCP4.5 and RCP8.5 scenarios respectively of all models and their ENSEMBLE mean.

### **4.3. Results of SWAT Model**

#### **4.3.1. Sensitivity analysis**

Before running the calibration, we analyzed the sensitivity of the parameters by using the Latin Hypercube One-factor-At-a-Time (LH-OAT) method of SWAT (van Griensven et al, 2006). This approach combines the advantages of global and local sensitivity analysis methods and can efficiently provide a rank ordering of parameter importance. The sensitivity analysis is performed on 13 SWAT model parameters that may have the potential to influence the flow of rivers in the catchment. The ranges of parameter variation are based on the SWAT manual (Abbaspour et al, 2004).

After setting up the SWAT-CUP using SWAT model outputs and incorporating all input parameters simulations were carried out with SUFI2 by running 1000 simulations and sensitivity analysis was run for the period 1993-2007 that is one third of data we have which we have to use for calibration. From global sensitivity analysis result the most sensitive parameter to change in discharge during calibration process was the CN parameter. CN is the most important parameter during calibration, the catchment will be not affected due to changes in land use is representative of CN and infiltration in the watershed. The value of CN calibration results near average of  $\pm 0.2$  of its original value which is -0.06 depending on the type of land use Table 4. A value closer to zero denotes more significance.

**Table 4. First ten flow-sensitive parameters and fitted values in ranked order**

<b>Parameter name</b>	<b>Lower and Upper value</b>	<b>Fitted values</b>
<b>r__CN2.mgt</b>	-0.2 - 0.2	-0.0600
<b>v__ALPHA_BF.gw</b>	0.0 - 1.0	0.3900
<b>v__GW_DELAY.gw</b>	30.0 -45.0	261.0000
<b>v__GWQMN.gw</b>	0.0 - 2.0	0.4600
<b>v__GW_REVAP.gw</b>	0.0 - 0.2	0.0220
<b>v__ESCO.hru</b>	0.8 - 1.0	0.8100
<b>v__CH_N2.rte</b>	0.0 - 0.3	0.0510
<b>v__CH_K2.rte</b>	5.0 - 13.0	61.2500
<b>v__ALPHA_BNK.rte</b>	0.0 - 1.0	0.7700
<b>r__SOL_AWC(1).sol</b>	-0.2 - 0.4	0.3100

Note-sensitive parameter shows multiply by 1+ the given fitted value.

v- Sensitive parameter shows replace the value by the given fitted value

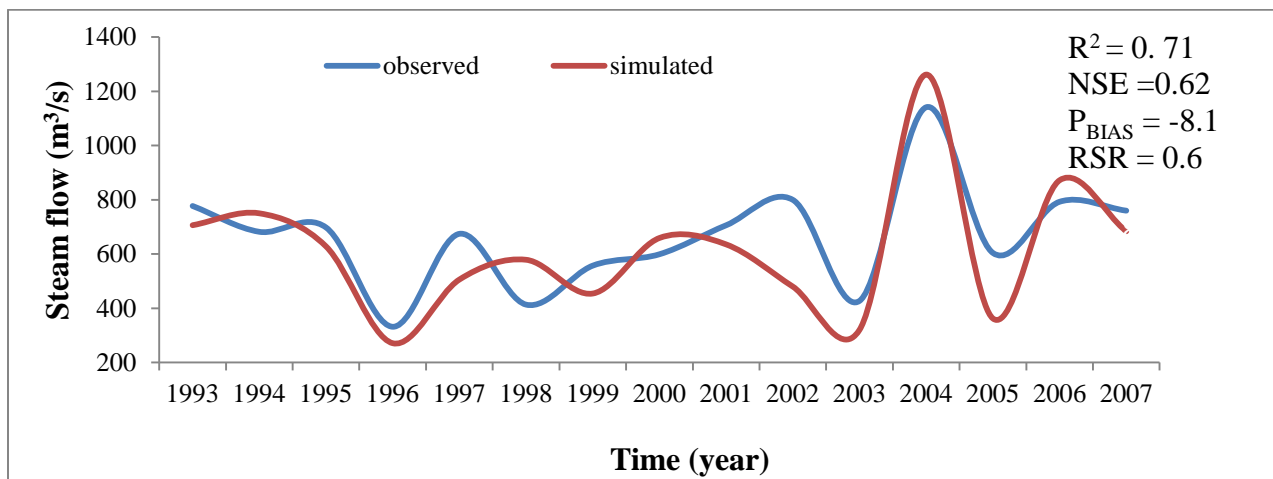
### **4.3.2. Monthly river flow calibration**

Based on the Global sensitivity analysis, the top-ranked 10 relatively more sensitive parameters (Table 4) were optimized using the SUFI2 algorithm in the SWAT-CUP. In SUFI2 all uncertainties such as model input, model conceptualization, model parameters, and measured data are mapped onto the parameter ranges as the procedure tries to capture most of the measured data within the 95% prediction uncertainty (Abbaspour et al., 2004).

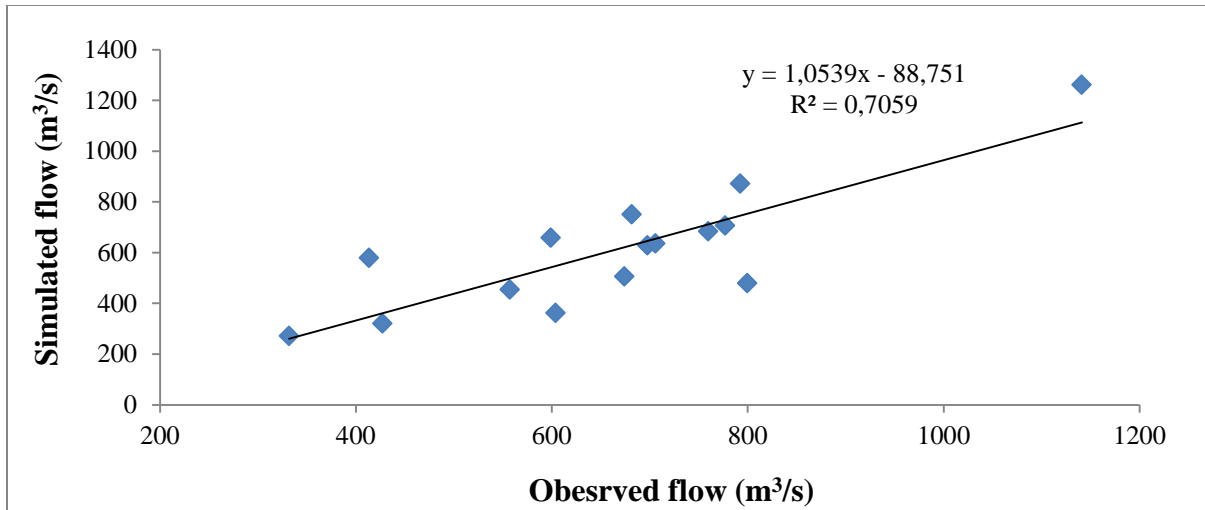
Before starting to generate flow for climate study, it is necessary to calibrate the model parameters. After setting up all model input parameters, the next step is to check quality and results of calibration. The calibration was performed using SUFI-2 Sequential Uncertainty Fitting Procedure version 2 (SUFI2) which was developed by Abbaspouret al. (2004). The calibration is

carried out for fifteen years (15yrs) period from January 1<sup>st</sup>, 1993 to December 31<sup>st</sup>, 2007 considering three years as warm up period starting from 1990.

The calibration statistics of the simulated flow indicates that  $R^2$  and NS values were found as 0.705 and 0.69 whereas  $P_{BIAS}$  and RSR were 1.67 and 0.65, respectively for monthly simulations in the calibration period. The general performance ratings for recommended statistics for a monthly time step as suggested by Moriasi et al. (2007) indicated that  $R^2 > 0.6$ ,  $NS > 0.5$ ,  $P_{BIAS}$  and RSR where the values are listed on Figure 11. Based on the recommendations, the present results were found to be within acceptable performance. However, the values need to be further validated in order to take as final calibration value. In general, we summarized the monthly calibration results in Figure 12 and Figure 13 for gauged catchment at Angar near Nekamt station.



**Figure 10. Calibration result of average monthly simulated and measured flow at the outlet of the sub basin, where gauging station is located.**



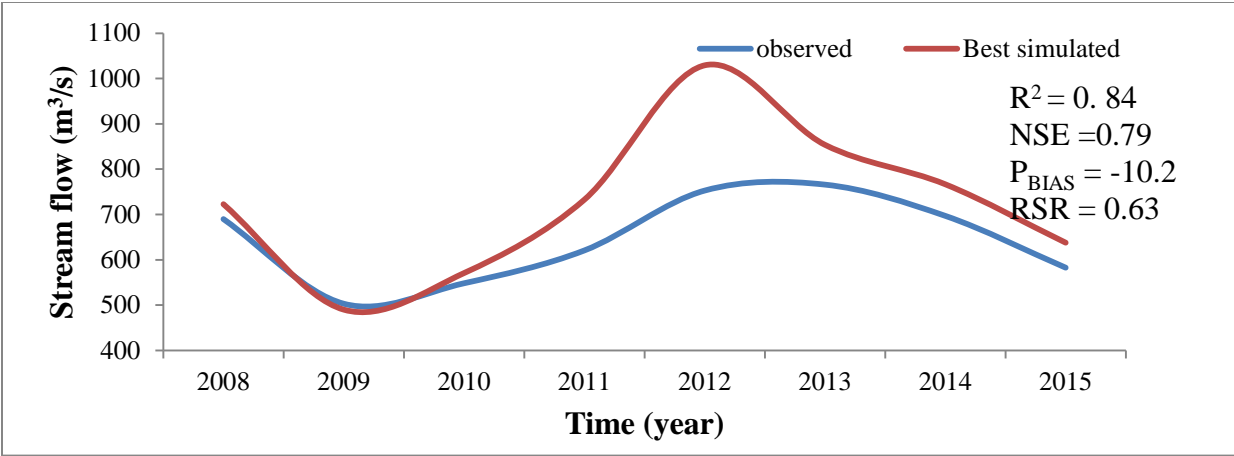
**Figure 11. Values of  $R^2$  for the calibration period**

### **4.3.3. Results from monthly river flow validation**

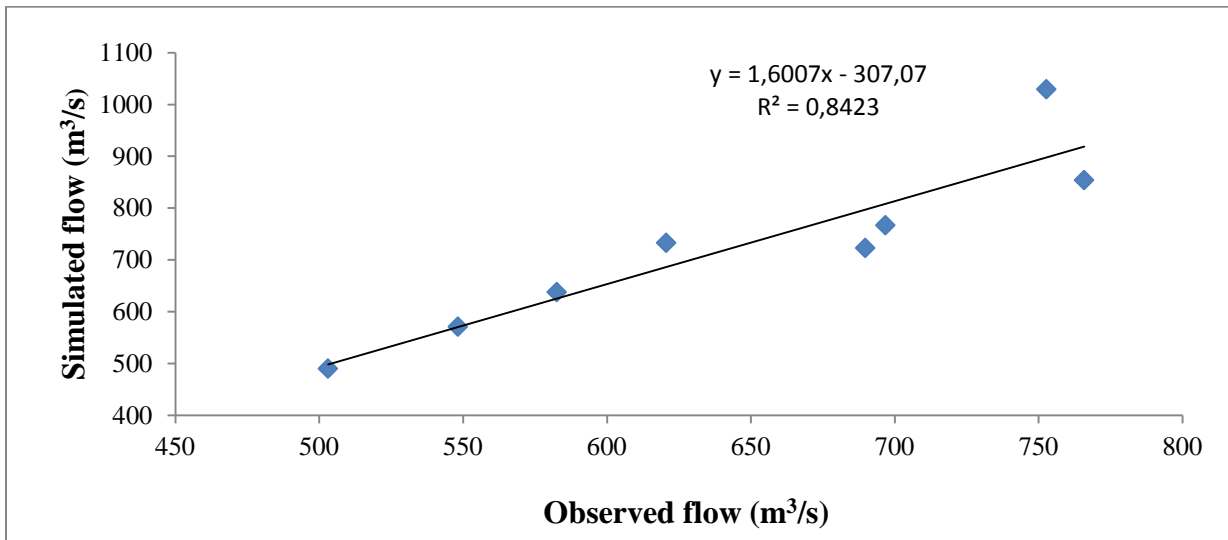
Validation proves the performance of the model for simulated flows in the period's different from the calibration period without any further adjustment in the calibrated parameters. The validation was performed for eight years (8yrs) period from January 1<sup>st</sup>, 2008 to December 31<sup>st</sup>, 2015. The validation statistics of the simulated flow indicates that  $R^2$  and NS value were found as 0.84 and 0.79, whereas  $P_{BIAS}$  and RSR were -10.2 and 0.63, respectively for monthly simulations in the validation period, which showed strong resemblance between predicted stream flow and measured value.

The calibration and validation results depicted in Figure 11 and Figure 13 showed that SWAT successfully simulated reasonable monthly stream flow at Angar station near Nekamt. This is demonstrated by all statistical stream flow evaluations. The statistical parameters computed in this respect fulfilled the requirements suggested by Moriasi et al. (2007) for  $R^2 > 0.6$ ,  $NS > 0.5$ ,

$P_{BIAS} < 25\%$  and  $RSR < 0.7$ . Figure 13 and Figure 14 showed validation of the model parameter for gauged catchment (2007-2015)



**Figure 12. Validation result of monthly simulated and measured flow at the outlet of the sub basin, where the gauging station is located**

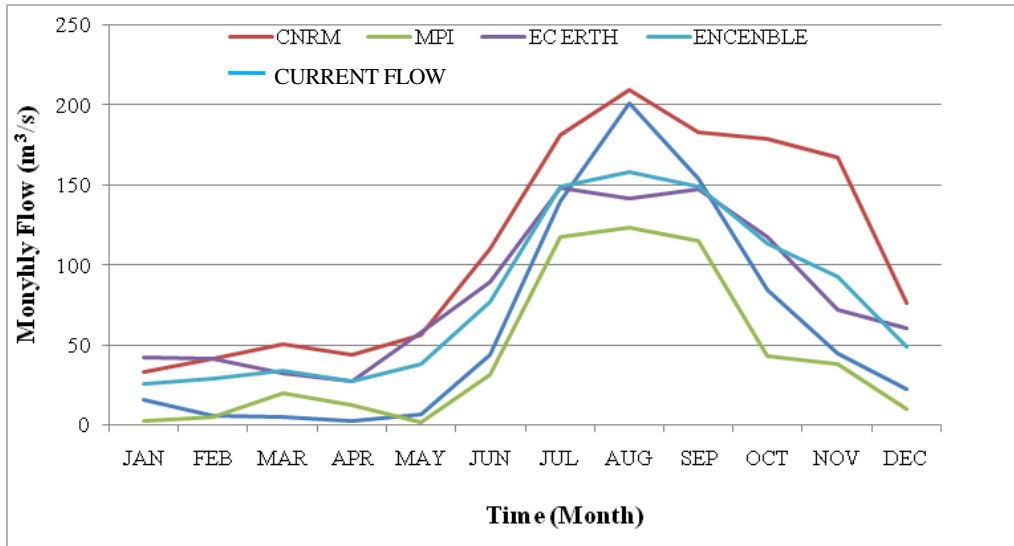


**Figure 13. Values of  $R^2$  for validation period**

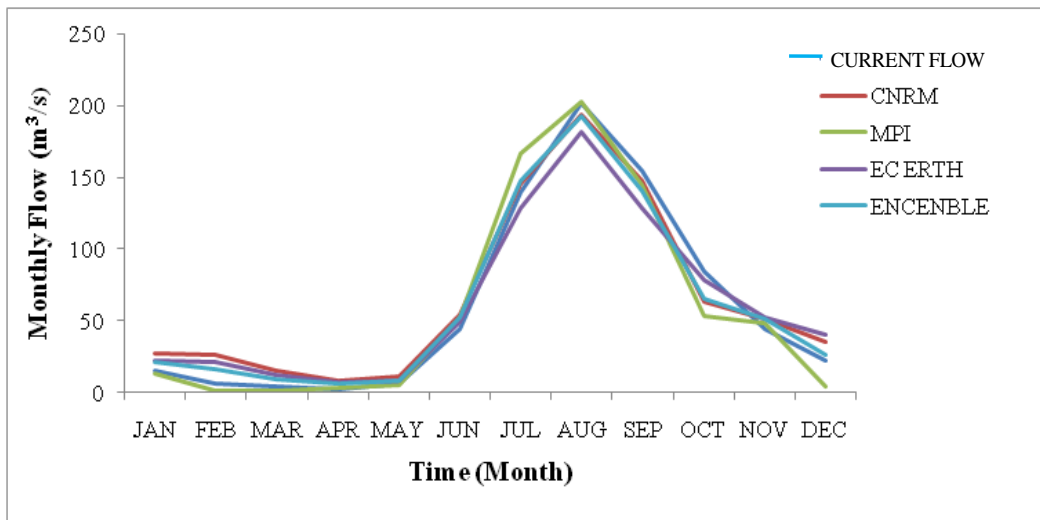
#### **4.3.4. Validation of bias correction according to the hydrological performance**

After a separate evaluation of the applied rainfall and temperature bias correction method, we analyzed their combined effect on resulting stream flow characteristics. This was done by forcing the SWAT model with each possible combination of raw and corrected RCM simulated rainfall and temperature. For each SWAT run, we calculated the performance of the models efficiency for long-term monthly mean values of stream flow simulations. All the simulations were conducted at Angar station near Nekamt, where the model calibrated parameters were obtained. The stream

flow simulated by the bias corrected and the raw RCMs was plotted in Figure 14. This figure depicted that there is a significant difference between raw RCM and observed flow data. Hence, the results of flow simulated after correction in Figure 16 showed the Nash-Sutcliff efficiency, the correlation coefficient, R, and the  $P_{BIAS}$  values yield better results of performance rate than the raw RCM for the future stream flow results in Figure 15.



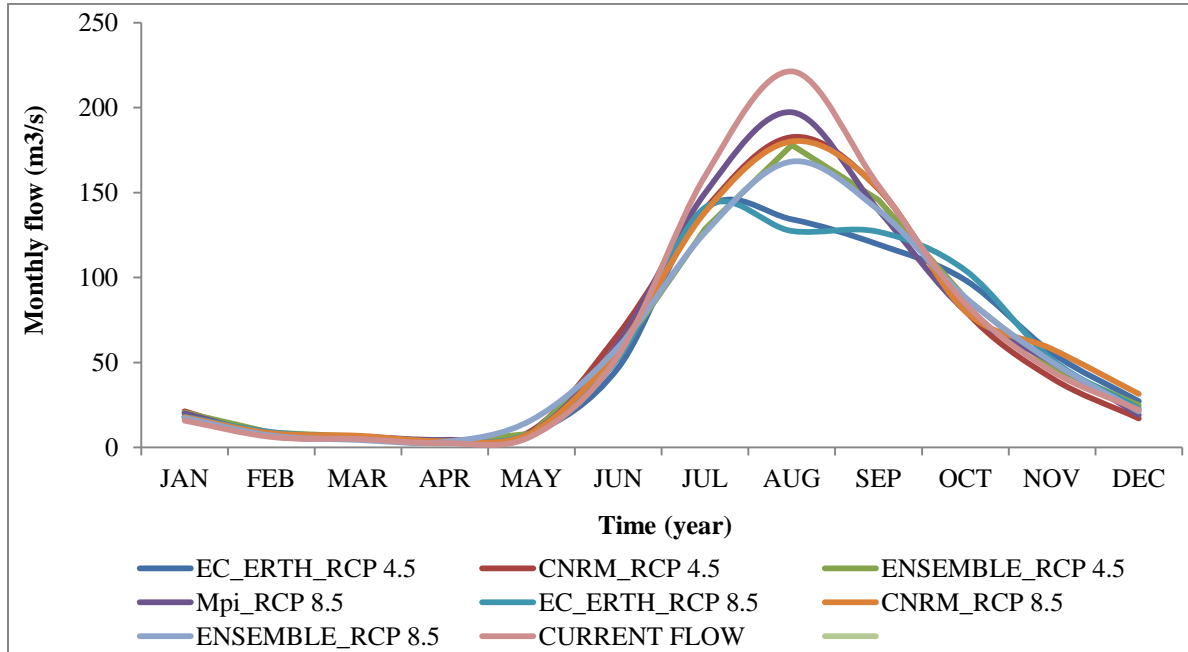
**Figure 14. Results of SWAT forced with bias-uncorrected for mean monthly historical flow RCM simulations**



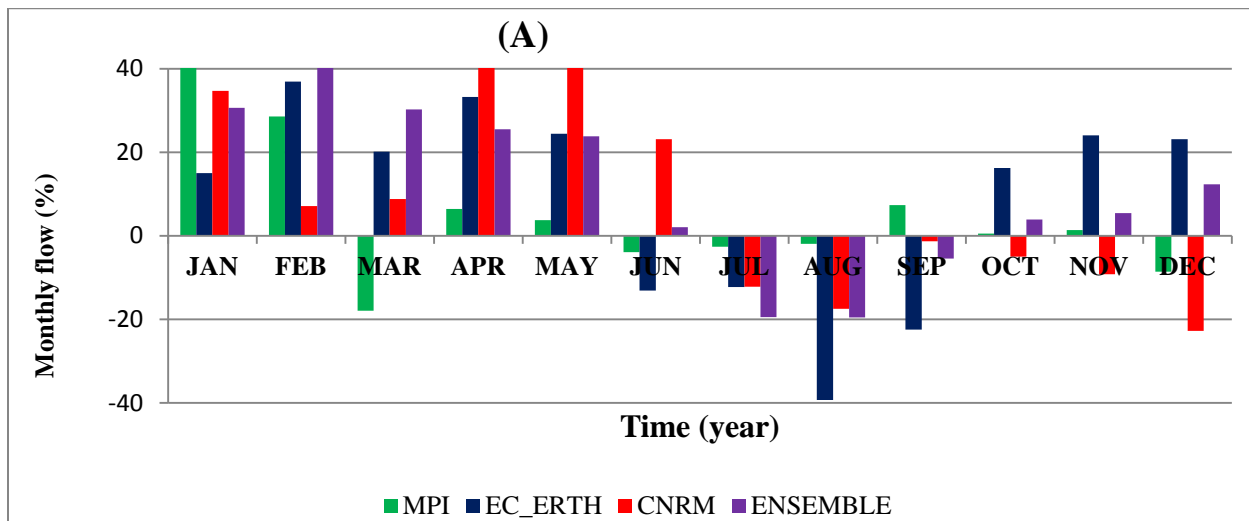
**Figure 15. Results of SWAT forced with bias corrected for mean monthly historical flow RCM simulations**

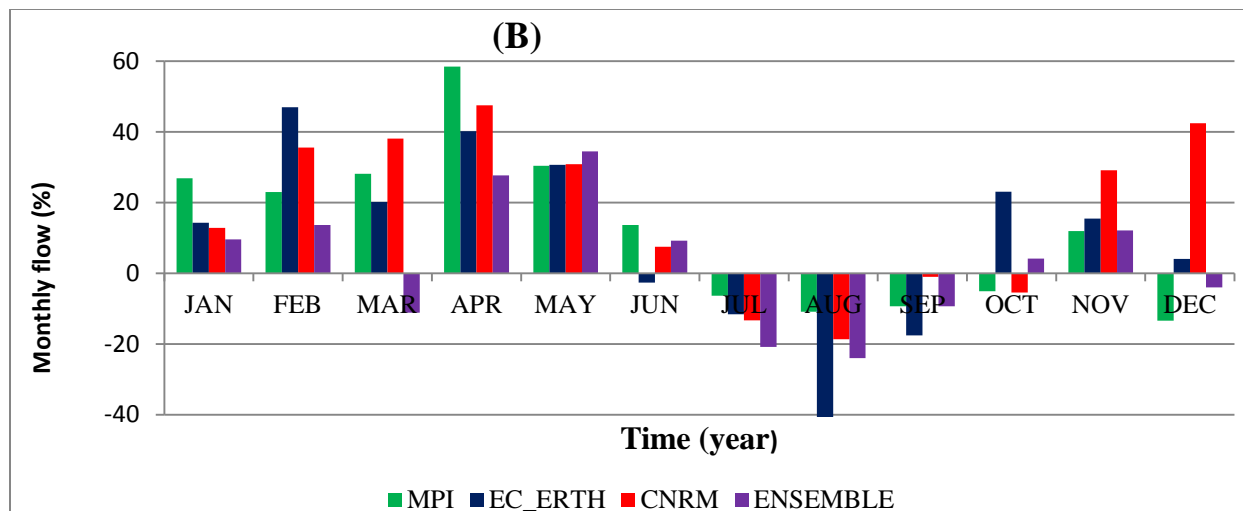
### 4.3.5. Monthly water flow simulated using SWAT for Didesa river catchment

Figures 17 and 18 below present the average monthly river flow as calculated under different conditions, percentage change from simulated flow under both scenarios for Mid-term period.



**Figure 16. Comparisons of observed and projected monthly flow under RCP4.5 and RCP 8.5 scenarios in the mid-term period**

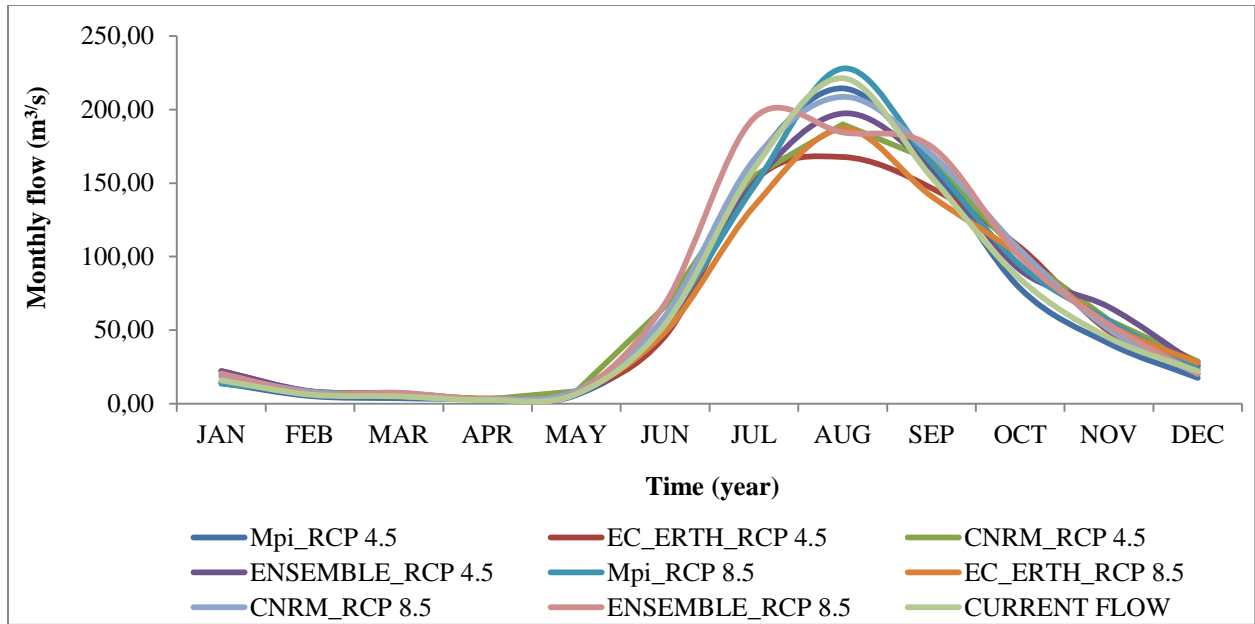




**Figure 17. Change in monthly flow under RCP4.5 and RCP8.5 scenario in the midterm period**

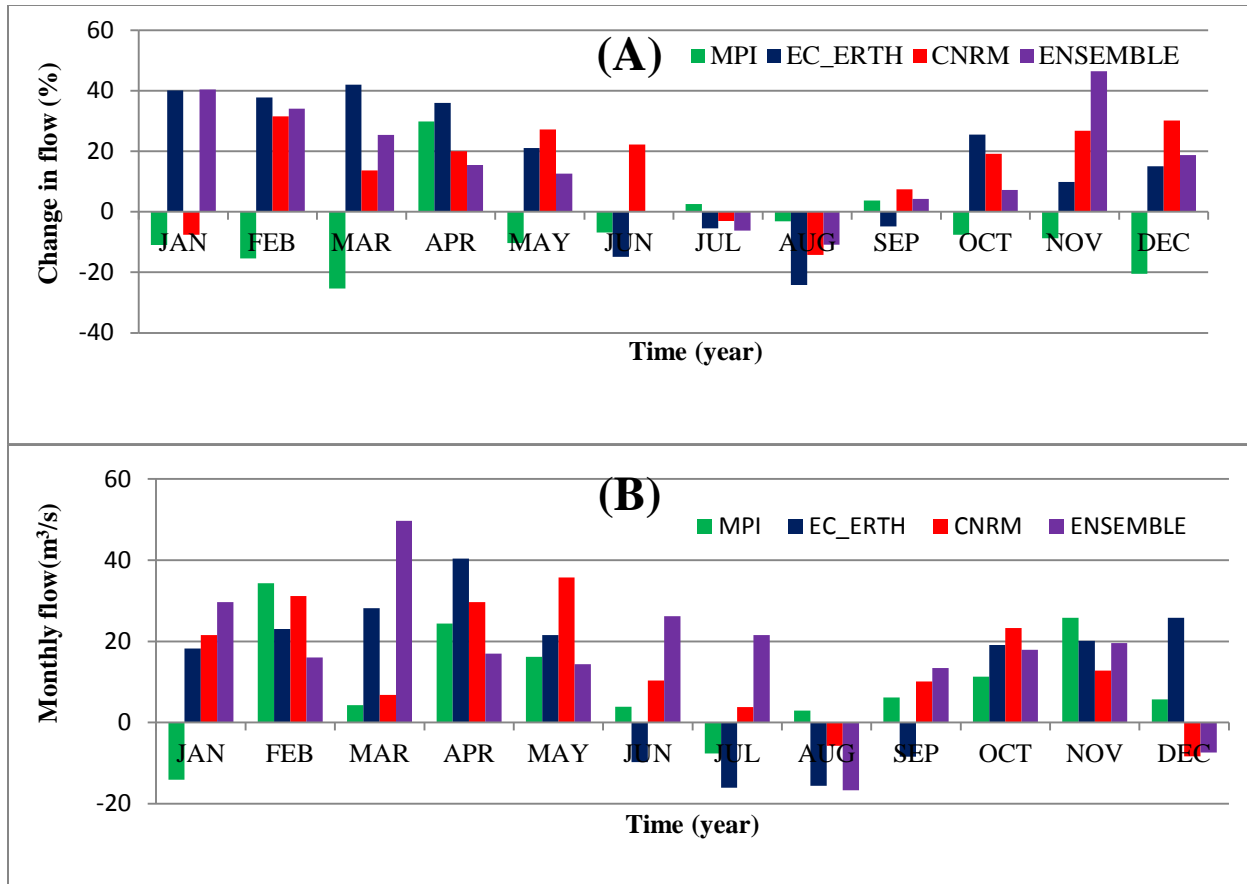
The monthly mean percentage change of models ENSEMBLE result showed that the month of August is likely to experience lower than the current stream flow under both midterm and long-term periods, with the change of -19.57% and -23.97% reduction, respectively. As August is the month when stream flow usually attains peak, under future climate change scenario, water withdrawal in this month needed to be properly managed in order to keep sufficient amount of water that could be utilized during the dry months, or stored and utilized along the lower river catchment regions (Figures 18 and 19).

Because of the highest mean flow in August were projected by most RCMs to be decreased by -17.48% in CNRM, -39.30% in EC\_Earth, -19.57% in ENSEMBLE mean and -1.77% in MPI under RCP4.5. Whereas, under RCP 8.5, the projection showed that there will be a decreasing of stream flow by -18.62% in CNRM, -42.42% in EC\_Earth and -23.97% in ENSEMBLE, implying that in August the river catchment is more likely to experience drier than the baseline period.



**Figure 18. Comparisons of observed and projected monthly flow under RCP4.5 and RCP8.5 scenarios in the long term period**

Our analyses revealed that during low stream flow months, the models projected higher stream flows than the baseline values. In this case, the models simulated an increasing stream flow for January by 30.59% and 9.56%, February by 40.35% and 13.67%, and March by 30.28% and -11.09%, under RCP 4.5 and RCP 8.5 climate change projection scenario, respectively (Figure 20). Overall results therefore tended to indicate that although January to March is dry and low stream flow season, most of the models are projected for more stream flow than the climatologically values, which is an indicative for more dependable inflow during dry season as well as an extension of wet season into dry season.



**Figure 19. Change in monthly flow under RCP4.5 (A) and RCP8.5 (B) scenarios in the Long-term period**

The monthly mean percentage change of ENSEMBLE models result showed that the month of August is likely to experience lower than the current stream flow under both midterm and long-term periods, with the change of -10.84% and -16.65% reduction, respectively. As August is the month, when stream flow usually attains peak, under future climate change scenario, water withdrawal in this month needed to be properly managed in order to keep sufficient amount of water that could be utilized during the dry months, or stored and utilized along the lower river catchment regions (Figures 20).

Because the highest mean flow in August were projected by most RCMs a decrease of the flow by -14.2% in CNRM, -24.21% in EC\_Earth, -1.084% in ENSEMBLE mean and -3.13% in MPI

under RCP4.5. Whereas, under RCP 8.5, the projection showed that there will be a decreasing of stream flow by -5.72% in CNRM, -15.58% in EC\_Earth, -16.65% in ENSEMBLE and -2.96% in MPI RCMs, which showed in August the river catchment is more likely to experience drier than the baseline period.

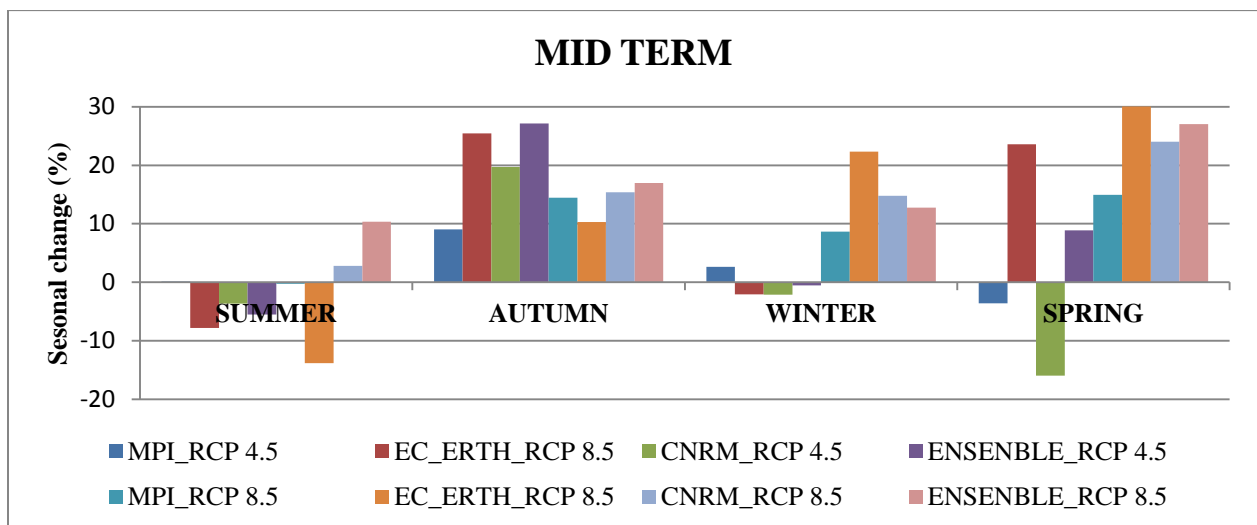
Our analyses revealed that during low stream flow months, the models projected higher stream flows than the baseline values. In this case, the models simulated an increasing stream flow for January by 4.48% and 25.42%, February by 34.10% and 16.05%, and March by 29.63% and 49.70%, under RCP4.5 and RCP 8.5 climate change projection scenario, respectively (Figure 20). Although January to March is dry and low stream flow season, most of the models are projected for more stream flow than the climatologically values, which is an indicative for more dependable inflow during dry season as well as an extension of wet season into dry season.

#### **4.3.6. Seasonal stream flow change**

On seasonal scale, mean seasonal stream flow showed an increasing trend during low stream flow seasons (Figures 21 and 22). For example, in autumn season, stream flow showed a considerable increase on an average change inflow from all models under RCP4.5 and RCP8.5 scenarios due to an increasing in mean seasonal rainfall under RCP4.5 and RCP8.5 scenario. In contrast, the volume of stream flow in the Didesa river catchment is projected to decline during the main rain season, particularly in Summer under EC\_Earth under both mid-term and long term climate change projections (Figures 21 and 22). Summer stream flow is projected to decrease on average from all models by 5.5% and 13.80% under RCP4.5 and RCP8.5 scenarios where as all RCMs model projected the largest increase inflow during autumn season under both RCP8.5 RCP4.5 scenarios.

From Figure 21, it is clear that, in the mid-term future during most of the seasons the stream flow is projected to increase on average under RCP8.5 except during summer season. In autumn season, the volume of stream flow is projected to increase by 9.05%-27.25%. This indicates the projected increase in stream flow during autumn season is expected to enhance water availability despite the fact that three quarter of inflow is generated during summer season.

It is clear that, in both future periods during most of the seasons the stream flow is projected to increase on average under RCP4.5 except during summer season as showed in Figure 21. The volume of stream flow is projected to increase by 30.1% in spring, 27.15% in autumn and 22.34% in winter. This indicates the projected increase in stream flow during autumn season is expected to enhance water availability despite the fact that three quarter of inflow is generated during summer season. By midterm and long term the autumn season supposes to have more flows under all scenarios. In both future periods an increasing trend in magnitude in autumn and decrease in summer shows seasonal shift in flow. Figure 21 and Figure 22 indicates like rainfall, the changes are more pronounced under RCP 8.5 because of it is high RCP.



**Figure 20. Seasonal changes in flow by mid-term, expressed in percentage**

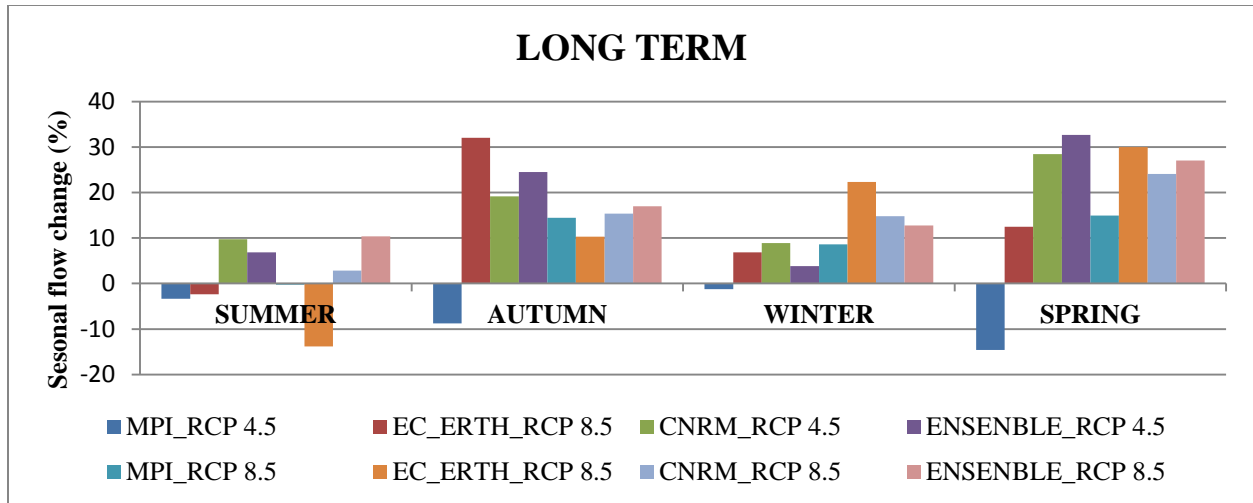


Figure 21. Change in Seasonal Stream low under long-term time scale.

#### 4.3.7. Annual stream flow change

In addition to monthly and seasonal patterns, annual discharge pattern were equally interesting to observe as the results were depicted in Figure 23.

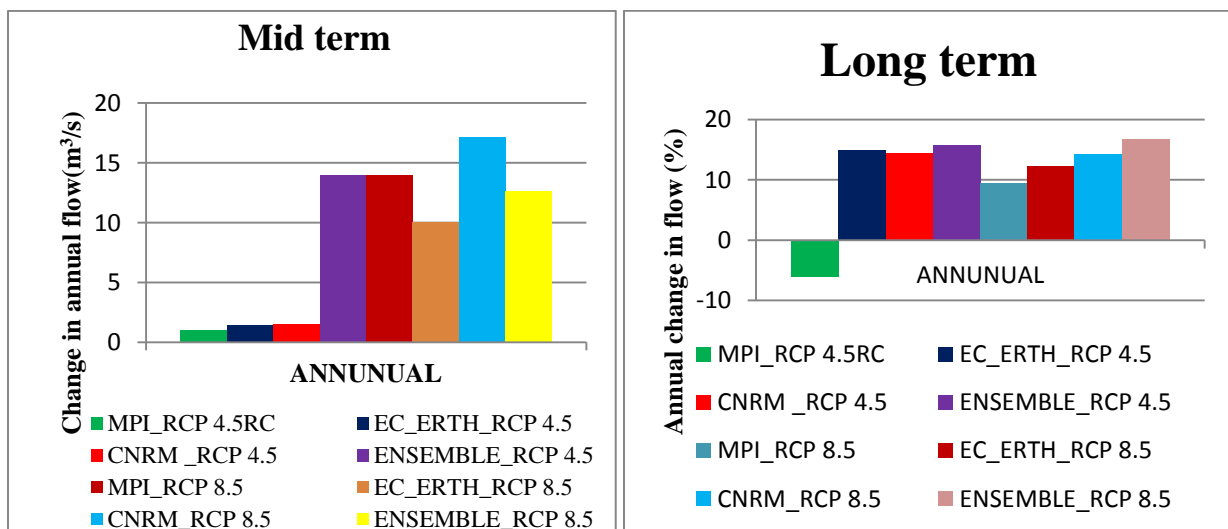


Figure 22. Average annual discharge by the mid-term and long term periods

The above Figures 23 showed that the average annual discharge computed between observed (1989-2018) and projected (2021-2050 and 2051-2080) flow averaged of 30 years as compared to

reference time period using RCMs climate scenarios derived by EC\_Earth, MPI, CNRM and ENSEMBLE mean.

On annual scale, mean seasonal stream flow showed an increasing trend in the mid-term period under RCP4.5 and RCP8.5 scenarios the annual flow would be expected to increase in all Models and their RCMs ENSEMBLE mean except CNRM-RCP4.5 which showed the smallest of all (Figures 23). The result for this change in mean annual flow is, the increased in mean annual rainfall of the basin from these scenarios. This result indicates that the increased rainfall from these scenarios offsets the loss of water by the increased surface air temperature due to evapotranspiration.

Under RCP4.5 scenario ENSEMBLE mean the projected increase in mean annual stream flow of the catchment would be 1.05% by MPI, 1.39% by EC\_Earth, 1.53% by CNRM and 5.4% and Under RCP8.5 scenario ENSEMBLE mean the projected increase in mean annual flow of the catchment would be 17.14% by CNRM, 10.06% by EC\_Earth, 13.95% and by MPI 12.65%.

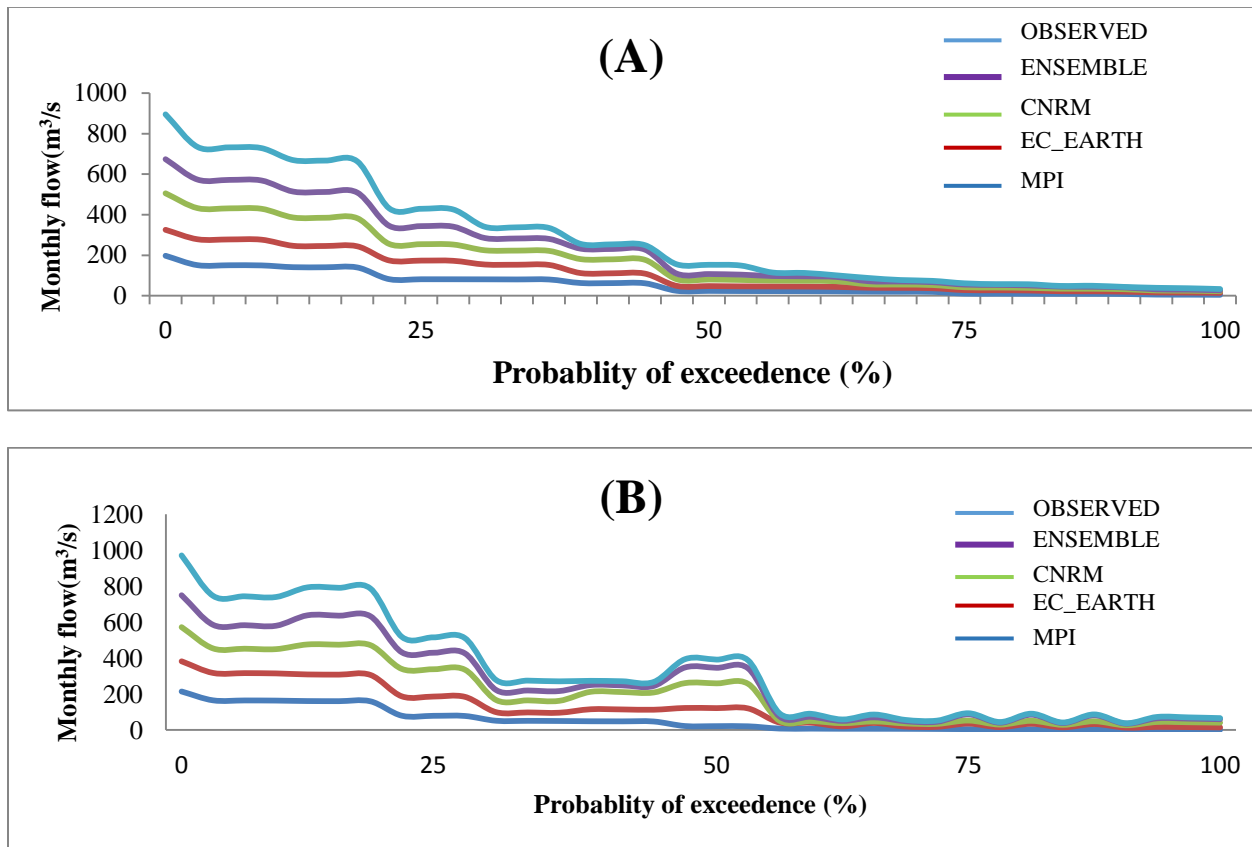
In long term period under RCP4.5 and Rcp8.5 scenarios, the annual flow would be expected to increase in all models and their RCMs ENSEMBLE mean (Figure 23) except RCP4.5 which project decrease in annual flow because of decrease in annual rainfall. The result for this change in mean annual stream flow is the increased in mean annual rainfall of the basin from these scenarios. This result indicates that the increased rainfall from these scenarios offsets the loss of water by the increased surface air temperature due to evapotranspiration.

Under RCP4.5 scenario, ENSEMBLE mean projected an increase in mean annual flow of the catchment that accounted for 14.3% by CNRM, 8.97% by EC\_Earth and 14.29% by the RCMs

and Under RCP8.5 scenario ENSEMBLE mean the projected increase in mean annual flow of the basin would be 14.25% by CNRM, 12.20% by EC\_Earth, 9.44% by MPI and 16.67%.

#### 4.3.8. Flow duration curve

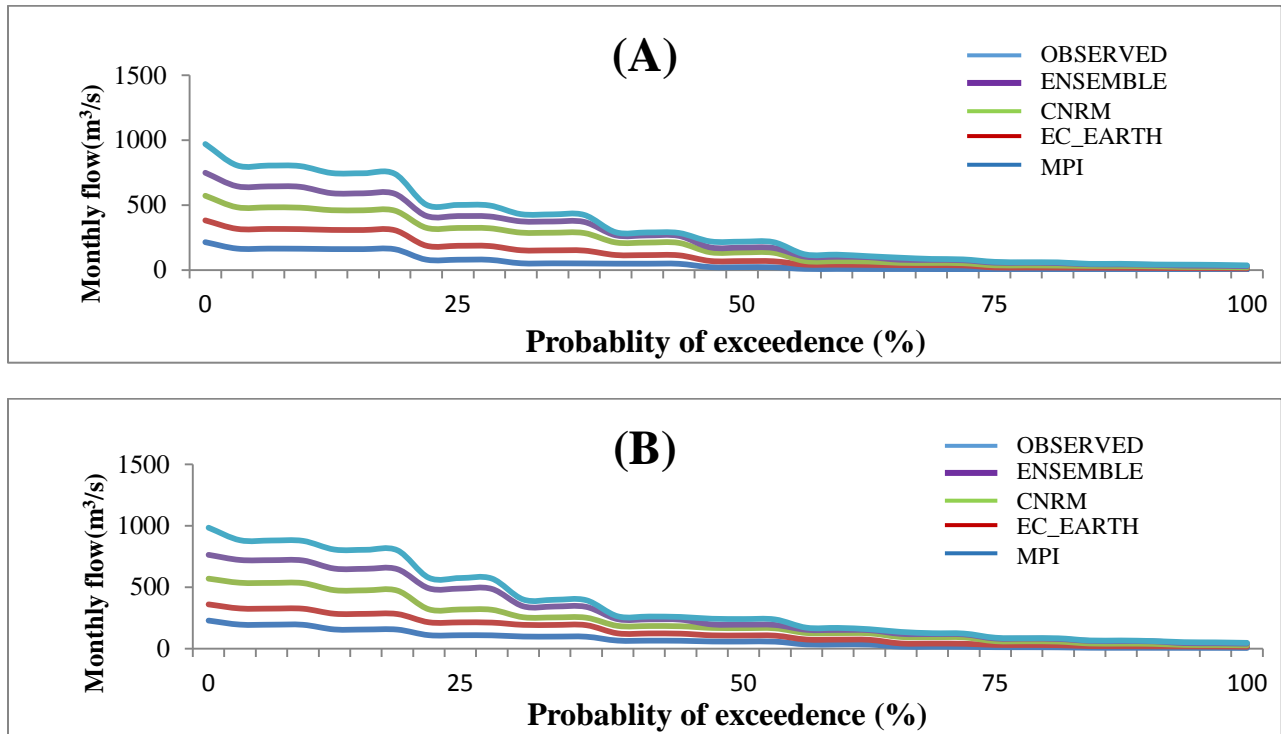
The effects of the two future scenarios were evaluated by constructing FDCs for monthly flow. Figures 24 and 25 showed the comparison of flow duration curves during the baseline period (1989–2018) and the two future periods (2021-2050s and 2051-2080s) under RCP4.5 (A) and RCP8.5 (B) scenarios at the Anger station near Nekamt outlet.



**Figure 23. FDCs of the Didesa river catchment as generated by RCP4.5 (A) and RCP8.5 (B) for the long-term climate change projection scenario (2021-2050)**

This comparison showed that the probability of occurrence of flood and magnitudes of flow was higher for both future periods under both scenarios. In both cases, high flow and mid flow were projected to increase in midterm period while in long term period high flow is projected to

decrease on the RCP4.5 (A) and RCP8.5(B). This decrease long term flow under RCP4.5 (A) is most likely due to the decrease in long term annual rainfall. However, low flow was predicted to decrease under all scenarios and futures in the basin.



**Figure 24. FDCs of the Didesa river catchment as generated by RCP4.5 (A) and RCP8.5 (B) for the long-term climate change projection scenario (2051-2080)**

Thus, the flow duration curve under future period changes in high flow (1.25% – 26.15%) in RCP4.5(A) and (4.5% – 9.5%) in RCP8.5(B) under the midterm period and (1.24% – 8.92%) in RCP4.5(A) and (4.64% – 13.69%) in RCP8.5(B) in the long term period show that the frequency of flood and their magnitudes will increase in all future periods. Therefore, proper utilization and management of the increased flow can actually increase hydropower production and irrigation in the basin.

## **CHAPTER FIVE: SUMMERY, CONCLUSION AND RECOMMENDATIONS**

### **5.1. SUMMARY**

This research analyzed the availability of stream flow in the Didesa river catchment under two climate change scenarios both for mid and long-term periods in the twenty-first century. Future rainfall amounts and temperature status within the catchment were projected using three Coupled Model Inter comparisons Project phase 5 (CMIP5), GCMs coupled with a physically based distributed hydrologic model (SWAT). Performance of rainfall simulations that were generated using these models were evaluated using statistical parameters.

The statistical tests were made for basin-wide averaged annual rainfall amount so as to assess the performance of climate models and their skill to capture and represent annual and seasonal rainfall distributions in the river basin. The finding of the present study indicated that with the exception of some models, which found to be over or underestimated, many models well simulated the observed mean annual rainfall in the basin.

In terms of bias and standard error of the mean, the ENSEMBLE models mean performed best. Our results also suggested that unlike other river catchments in Ethiopia, seasonal amount is highly likely to increase in the Didesa river catchment as clearly generated using ENSEMBLES of multiple models. In contrast, simulated rainfall from some individual models only captured certain aspects of projected rainfall change satisfactorily. Climate change assessment in Didesa river catchment showed a significant monthly and seasonal variation as compared to annual changes. Given the fact that climate change is highly uncertain, our findings also revealed that there were varying projected values widely with models, scenarios and time frames.

Seasonal rainfall distribution clearly showed that the downward trend of projected future rainfall scenarios for the period 2051-2080 is very critical as the seasonal rainfall totals for summer season is more likely to be drier than baseline climatology under both RCPs scenarios. In fact, there is a seasonal shifting and enhancing of rains towards the dry season, the winter season, in this case.

## **5.2. Conclusions**

It was found that on average temperature in mid-term future is projected to increasing by 1.58 °C and 2.09°C under RCP4.5 and RCP 8.5, respectively while in long term future is projected to increasing by 1.74 °C and 2.92°C under RCP4.5 and RCP 8.5, respectively. Likewise, as compared to the base line period, the ENSEMBLE mean from the models indicated that annual rainfall totals was projected to increase more during the midterm term period (2021-2050) than the long term (2051-2080) as projected under both scenarios.

In general relative to the baseline period, the annual rainfall amounts over the Didesa river catchment are projected to increase both during the midterm and long term future periods under RCP4.5 and RCP8.5 scenarios, indicating increase in available stream flow. Flow duration curves showed that there is the probability of occurrence of high flows in both future periods under RCP4.5 and RCP8.5 scenarios relative to the baseline period.

The overall conclusion of the study is that Didesa catchment of the Abay basin is likely to experience more flow in the future than baseline period. The outcomes suggest that it is important to consider the influence of climate change on water resources to frame appropriate guidelines for planning and management.

### **5.3. Recommendations**

- 1.** The observed uncertainty associated with inter-model variability across GCMs when a single RCM is used for downscaling reduced spread in the results of the rainfall. This emphasizes the importance of using the CORDEX-Africa multi-GCM/multi-RCM in order to assess the robustness of the climate change signal and, possibly, to identify and quantify the many sources of uncertainty.
- 2.** This study indicates that there exists a difference in the result found between RCPs in one RCM used. So that, further analysis should be undertaken with Multi RCM with more RCPs and more bias correction method so as to give a clear picture about the result.
- 3.** Climate change is likely to alter discharge, resulting the important aspect on water availability in stream usage, particularly for hydropower generation availability. In this study the hydropower usage of the catchment is not considered as it is one of the water use components, further work should be done on the impacts of climate change on hydropower production.
- 4.** In this study, the impact of climate change projection was assessed by assuming that the land cover will remain the same for the past as well as for future periods. The study also didn't consider any soil parameters change at future time horizons. However, in real world the change of land cover and soil parameter will occur due to natural and human influences. Therefore, a study considering the change of land cover and soil parameter would increase the confidence of projected result.
- 5.** Didesa catchment of the Abay basin is likely to experience more stream flow in the future than baseline period so that it is important to consider the influence of climate change on water resources to frame appropriate guidelines for planning and management to ministry of agriculture and ministry of water resources irrigation and energy.

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## Appendix:A Figures

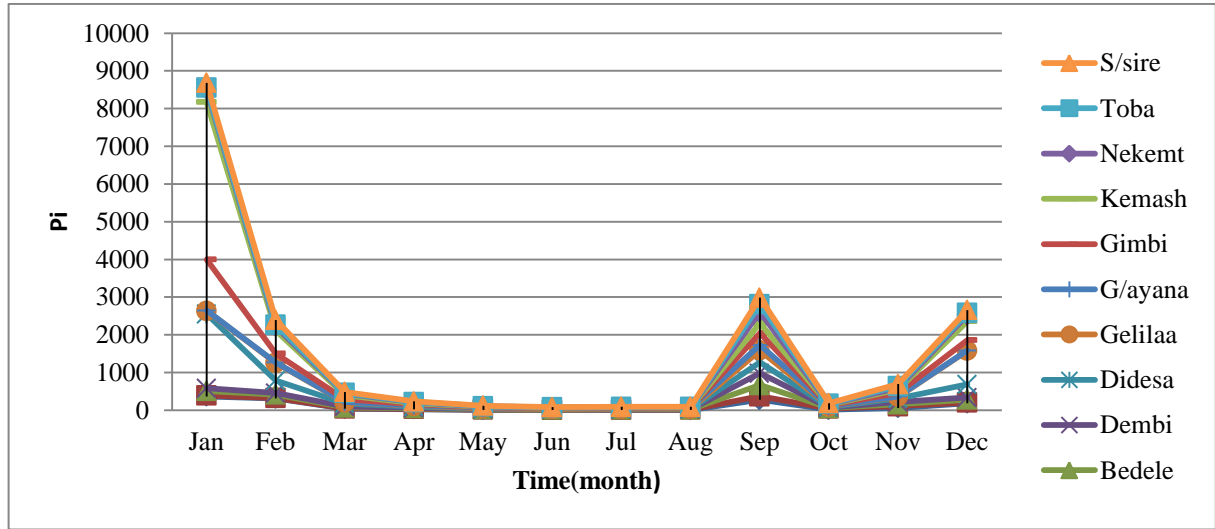


Figure1. Rainfall homogeneity test on stations confined within the catchment



Figure 2. Delineated basin and its 22 sub-basins

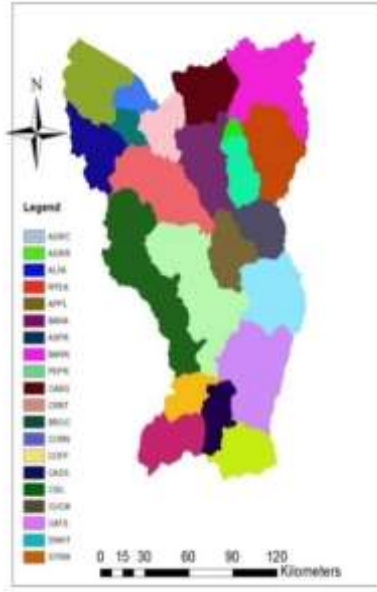


Figure 3. Land cover map for Didesa river catchment

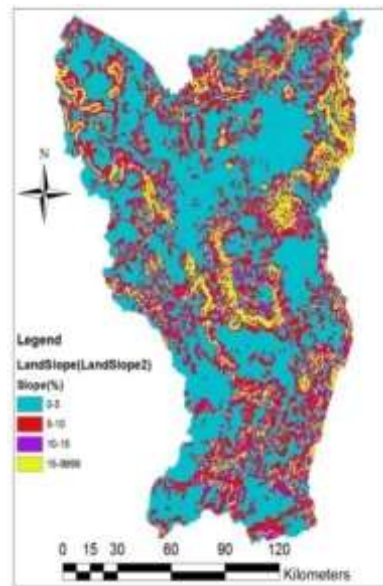


Figure 4. Slope map for Didesa river catchment

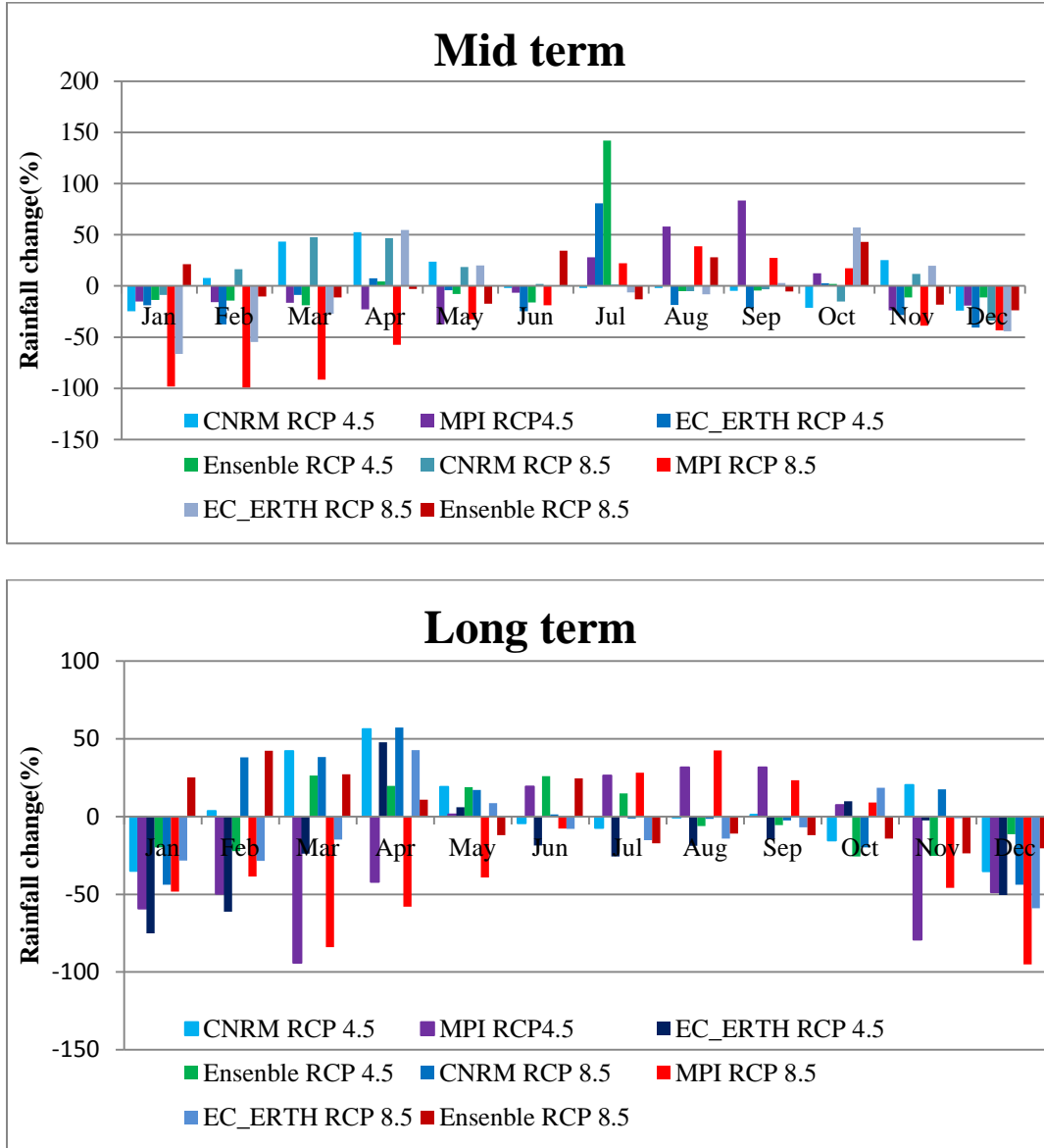
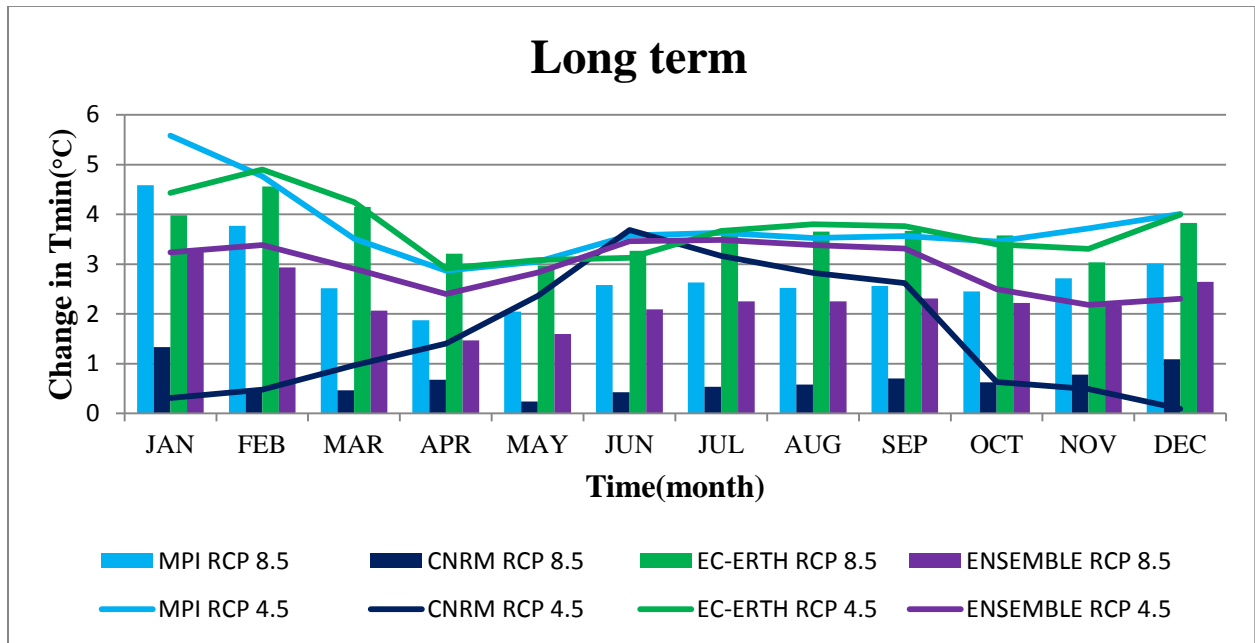
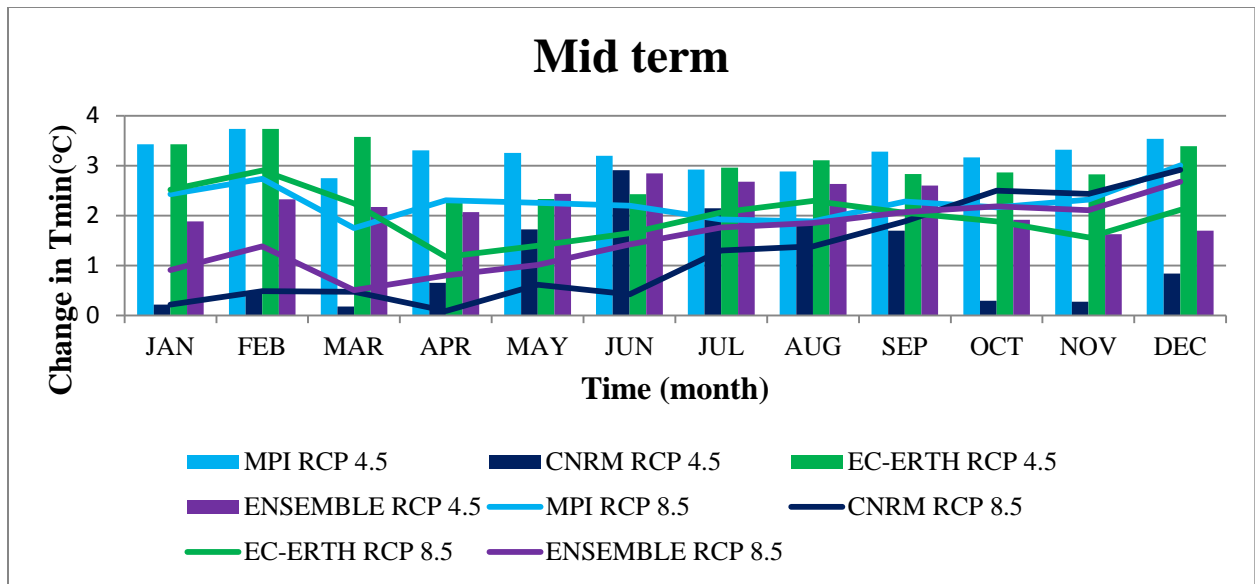


Figure 5. Monthly rainfall changes under the two climate change scenarios, for mid and long-term periods



**Figure 6. Monthly minimum Temperature change by the mid and long future period (2021-2050 and 2051-2080) as generated by all RCMs models**

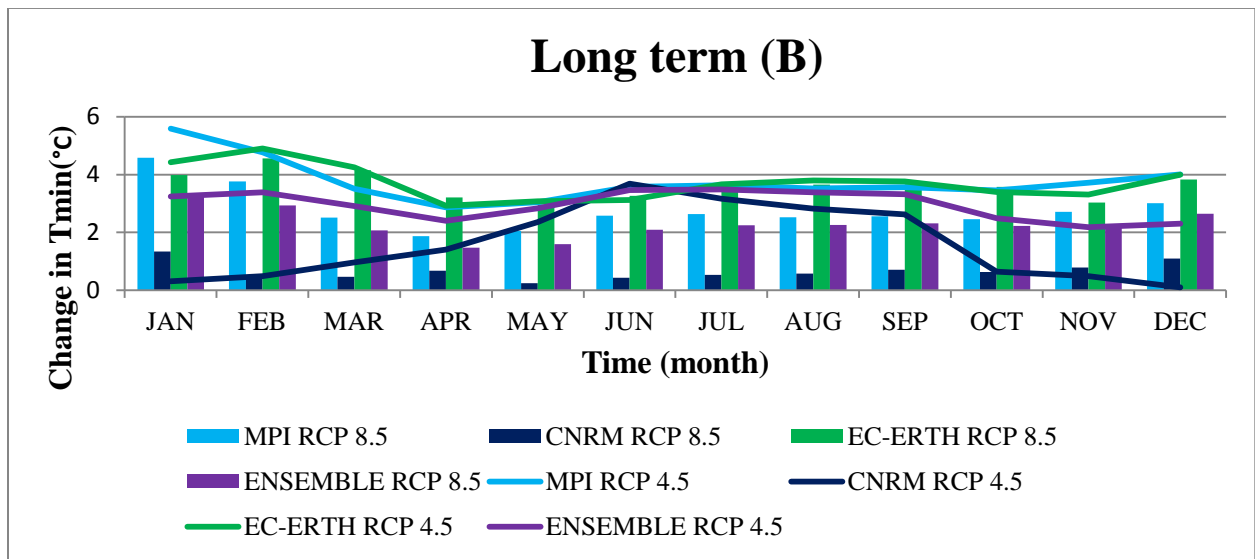
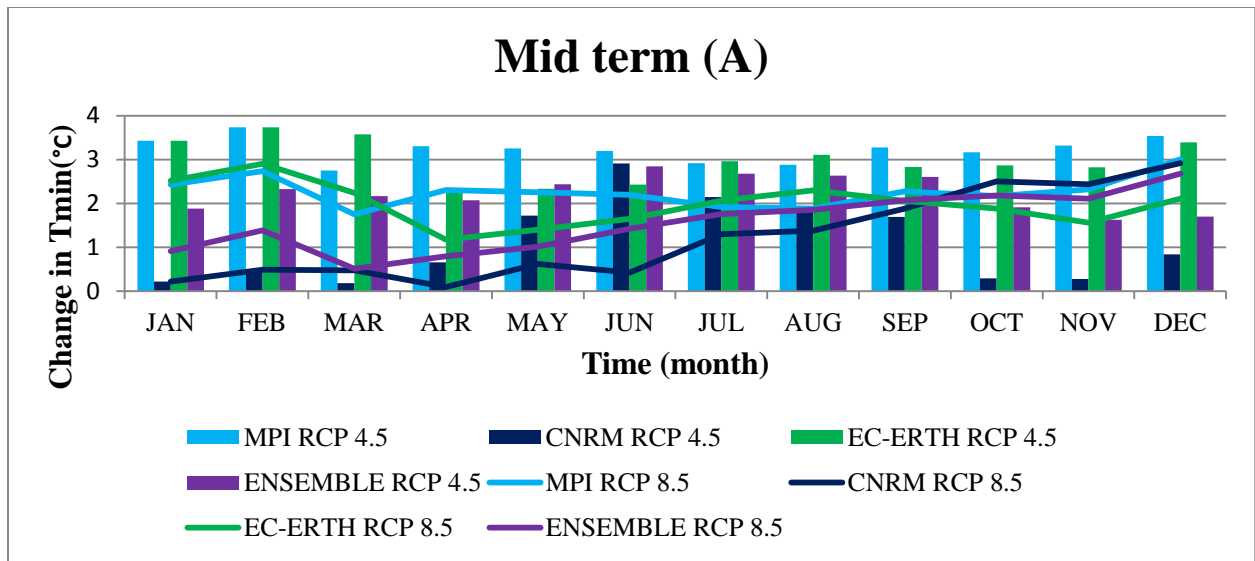


Figure 7. Monthly minimum Temperature change by the mid and long future period (2021-2050 and 2051-2080) as generated by all RCMs models

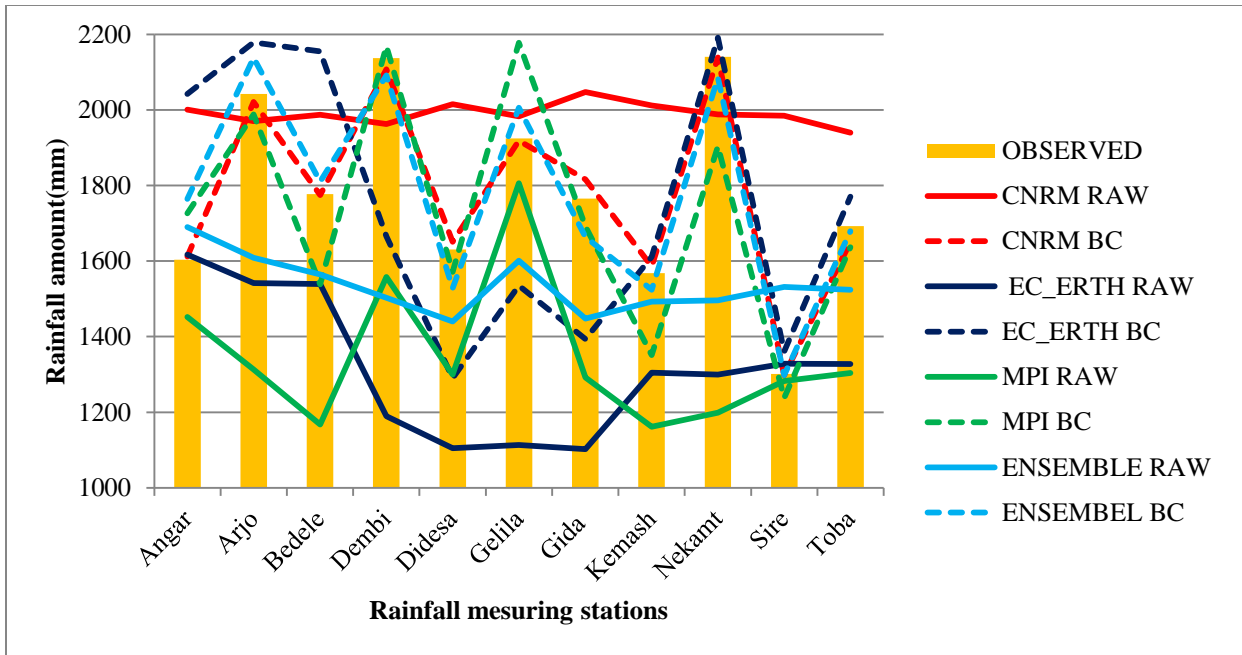


Figure 8. Long-term mean rainfall annual historical observed, simulated (raw) and their Bias correction

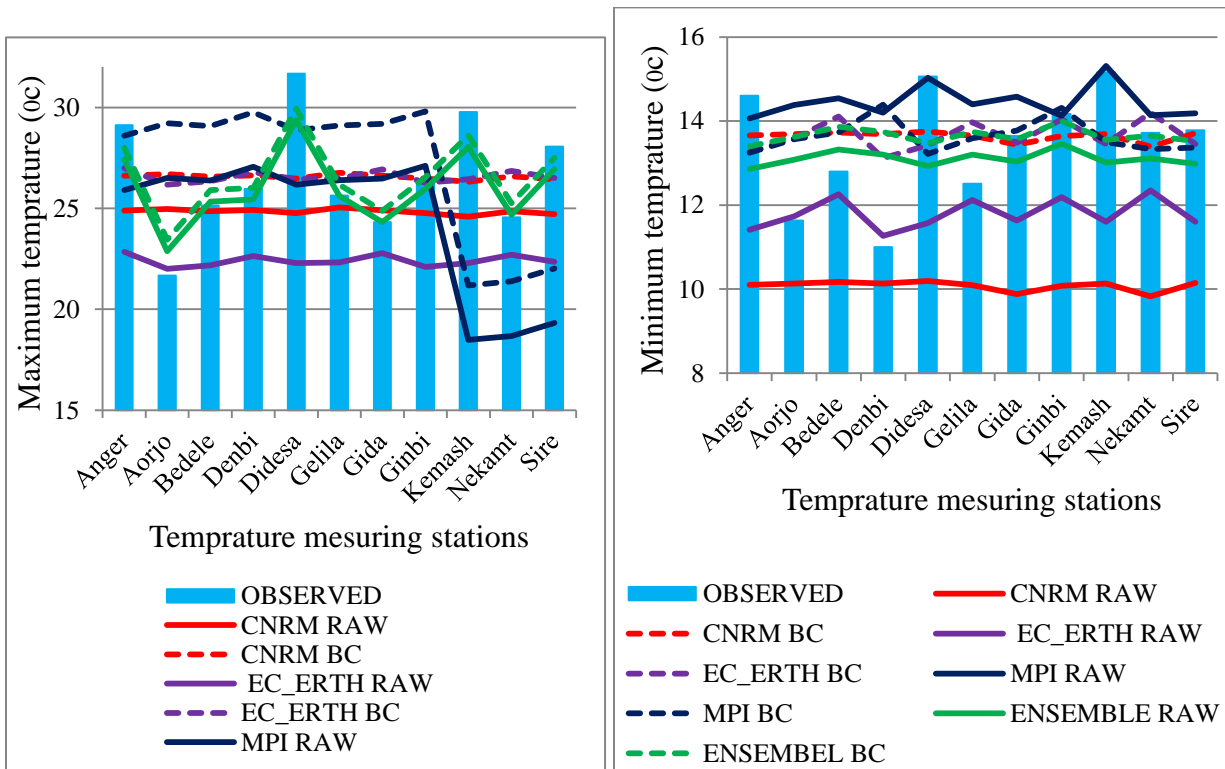


Figure 9. Long-term mean maximum and minimum temperature annual historical observed, simulated (raw) and their Bias correction

## Appendix:B Common formulas

1. Bias =  $100 * \frac{(Rrcm - Rgauge)}{Rgauge}$
2. RMES =  $\sqrt{\frac{\sum_1^n (Rrcm - Rgauge)^2}{N}}$
3. Correl =  $\frac{\sum_1^n (Rrcm - Rrcmav)(Rgauge - Rgaugeav)}{\sqrt{\sum_1^n (Rrcm - Rrcmav)^2 (Rgauge - Rgaugeav)^2}}$
4. Cv =  $100 * \frac{\sigma}{R}$
5. r2 =  $\frac{\sum_1^n (Qsi - Qsav)(Q0i - Q0av)}{\sum_1^n (Qsi - Qsav)^2 (Q0i - Q0av)^2}$
6. Ns =  $1 - \frac{\sum_1^n (Q0i - Qsi)^2}{\sum_1^n (Q0i - Q0i)^2}$
7. PBIAS =  $100 * \frac{\sum_1^n Q0i - \sum_1^n Qsi}{\sum_1^n Q0i}$
8. RSR =  $\frac{\sqrt{\sum_1^n (Qos - Qsim)^2}}{\sqrt{\sum_1^n (Qos - Qosav)^2}}$
9. NSE =  $1 - (RSR)^2$

## Appendix: C Didesa river catchment rain fall data

Year	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Total
1989	3.5	0	45	139.75	215.6	251.25	313.9	277	273.35	79.35	18.7	62.9	1680.3
1990	4.45	1.15	42.7	115.5	87.15	215.25	355.8	467.7	311.45	67	21.75	27.96	1717.86
1991	2.6	10.35	36.35	116.1	240.5	292	332.75	349.35	220	61.4	7.75	16.65	1685.8
1992	7.25	0.45	51.25	149.35	213.05	311.35	321.1	251.95	202.7	108.85	24.55	70.5	1712.35
1993	0.65	17.9	25.8	161.3	186.85	389.1	240.05	379.1	293.05	136.15	24	24	1877.95
1994	28	1.75	34.95	131.3	256.85	254.85	364	300.75	164.55	81.1	40.5	40.8	1699.4
1995	54	2.15	70.95	47.15	225.55	284.6	248.2	352.1	224	93.55	25.25	6.65	1634.15
1996	20.15	2.15	84.7	156.5	238.95	297.45	260.25	285.65	252	54	22.6	11.5	1685.9
1997	7.75	0.45	35.05	154.1	224.15	330.05	317.4	187.8	176.05	190.55	85.05	62.8	1771.2
1998	5.05	61	28.05	140.45	197.9	373.4	320.8	255.35	329.25	193.8	27.8	5.85	1938.7
1999	26.7	82.2	60.3	159.9	315	283.05	180.45	230.45	241.1	213.85	12.4	4.45	1809.85
2000	39.9	0.65	71.45	111.6	303.7	486.9	328.1	349.95	302.4	212.9	39.35	9.85	2256.75
2001	45	13.2	25.4	79.55	161.8	326.05	322.85	392.2	305.45	202.4	106.25	25.1	2005.25
2002	1.15	10.55	37.45	76.2	69.75	282.2	337.05	249.2	173.6	69.85	18.7	66	1391.7
2003	0.15	23.75	80.3	119	71.45	269.4	297.75	320.05	249.2	27.75	45	60	1563.8
2004	44.63	18.7	46.35	56.5	181.15	205.3	256.25	240	183.85	77.95	15.75	45.95	1372.38
2005	30	50	70.25	39.55	157	289.7	263.6	249.8	266.4	107.95	29.25	23.9	1577.4
2006	45.67	120.8	128.3	97.2	261.3	307.55	256.05	239.15	160.5	95.7	44.3	73.35	1829.87
2007	58.75	27.2	127.4	78.8	147.75	324.4	276.3	233.15	209.4	67.35	41.4	75.2	1667.1
2008	52.74	80.2	50.05	174.85	273.1	311.65	257.75	207.95	267	120.4	141	45.8	1982.49
2009	65.9	81.35	118.1	106.3	79.55	258.5	240.4	303.1	322.45	197.4	117.55	24.2	1914.75
2010	52.8	109.05	151.8	113	220.4	305.95	305.3	240.5	264.2	120.6	54.35	89.54	2027.44
2011	35.7	60	125.9	44.55	187	279.45	311.3	290.4	243.6	119.85	62.25	30.7	1790.65
2012	55.78	40	145.5	133.6	187.7	218.25	299.25	262.05	278	133.55	34.4	52.35	1840.38
2013	5.85	52.1	131.7	96.95	312	249.5	279.05	271.8	274.8	113.2	46.2	20	1853.15
2014	78.9	61.9	90.4	61.9	187.4	252.9	299.45	358.3	288.5	85.95	66.85	31.45	1863.9
2015	37	31.75	47.05	71.3	212.95	269.75	328.25	275.8	193.4	112.15	47.3	35.95	1662.65
2016	88.45	120.2	44.85	141.6	212.35	295	312.45	288.45	307.5	205.7	37.25	32.2	2086
2017	46	120.45	118.9	79.6	141.8	323.65	375.2	266.15	307.85	143.35	135.3	48	2106.25
2018	73.5	86.6	151.1	125.4	185.9	332.75	268.8	253.75	176.25	153.6	74.75	58.25	1940.6

### Appendix: D Angar near Nekamt station stream flow data

<b>Year</b>	<b>JAN</b>	<b>FEB</b>	<b>MAR</b>	<b>APR</b>	<b>MAY</b>	<b>JUN</b>	<b>JUL</b>	<b>AUG</b>	<b>SEP</b>	<b>OCT</b>	<b>NOV</b>	<b>DEC</b>	<b>AVE</b>
<b>1993</b>	15.81	6.20	5.01	2.53	6.62	54.08	159.73	221.31	154.03	84.73	44.85	22.11	64.75
<b>1994</b>	7.98	2.30	2.16	2.31	16.37	22.63	49.64	142.99	130.91	231.81	54.17	18.58	56.82
<b>1995</b>	9.33	3.79	2.09	3.52	7.46	44.16	88.51	226.91	151.08	112.79	33.04	15.18	58.16
<b>1996</b>	9.03	3.81	2.61	2.69	2.55	10.81	52.44	73.84	95.54	52.50	16.82	9.18	27.65
<b>1997</b>	5.05	1.84	2.07	0.86	0.33	18.34	80.86	172.42	247.61	132.73	11.05	1.21	56.20
<b>1998</b>	0.11	0.13	1.19	1.30	6.34	16.88	70.59	133.15	96.75	58.14	19.12	9.67	34.45
<b>1999</b>	4.97	2.10	3.17	1.48	3.42	28.79	84.02	122.36	189.20	78.89	28.18	10.55	46.43
<b>2000</b>	7.33	2.82	1.45	1.21	3.13	48.95	93.77	140.13	126.83	101.23	49.31	22.96	49.93
<b>2001</b>	9.88	4.32	3.14	4.07	8.60	60.38	149.21	149.31	196.47	87.34	22.06	11.16	58.83
<b>2002</b>	6.66	2.71	1.48	7.32	21.72	71.46	206.89	212.57	134.42	73.93	43.05	17.50	66.64
<b>2003</b>	8.71	3.61	3.50	3.77	3.75	13.37	28.84	93.54	148.61	84.61	23.24	11.56	35.59
<b>2004</b>	6.38	2.35	1.27	1.61	15.71	52.05	131.82	177.50	340.32	141.83	18.06	12.25	75.10
<b>2005</b>	8.16	3.03	2.43	2.02	12.29	35.61	57.66	145.88	215.36	86.20	23.81	11.56	50.33
<b>2006</b>	6.40	2.70	1.17	1.36	21.24	25.81	59.23	332.55	245.49	63.88	20.90	11.88	66.05
<b>2007</b>	11.89	4.56	4.53	2.42	13.85	52.84	110.13	181.93	143.29	165.34	48.37	20.57	63.31
<b>2008</b>	8.65	3.05	2.13	2.92	11.92	33.40	69.07	184.95	141.00	172.30	43.61	16.88	57.49
<b>2009</b>	7.04	2.83	2.34	1.78	1.44	14.58	66.65	123.13	171.58	92.61	13.93	5.19	41.92
<b>2010</b>	3.38	1.36	2.15	1.21	3.37	21.34	78.49	142.64	177.86	89.92	19.45	7.14	45.69
<b>2011</b>	7.39	3.08	2.59	2.25	5.05	46.04	109.00	137.27	170.84	89.16	33.18	14.89	51.73
<b>2012</b>	8.27	3.52	2.31	5.69	15.16	65.92	178.05	180.94	165.45	80.63	32.56	14.33	62.74
<b>2013</b>	6.98	2.69	1.62	1.66	16.41	37.82	82.90	218.64	267.05	97.30	20.92	11.90	63.83
<b>2014</b>	8.31	3.25	2.58	2.24	13.37	35.94	77.54	186.28	218.61	108.37	26.88	13.56	58.08
<b>2015</b>	6.71	2.64	2.24	2.18	6.03	31.37	83.63	145.14	154.30	106.93	29.22	12.31	48.56

### Appendix: E Didesa River catchment Maximum temperature data

<b>Year</b>	<b>JAN</b>	<b>FEB</b>	<b>MAR</b>	<b>APR</b>	<b>MAY</b>	<b>JUN</b>	<b>JUL</b>	<b>AUG</b>	<b>SEP</b>	<b>OCT</b>	<b>NOV</b>	<b>DEC</b>	<b>AVE</b>
<b>1989</b>	26.70	27.85	28.60	29.50	26.70	23.51	24.49	25.56	23.85	24.86	28.09	26.70	27.85
<b>1990</b>	28.18	28.68	30.27	30.00	27.84	25.13	23.29	23.15	23.46	25.78	27.12	28.18	28.68
<b>1991</b>	29.75	30.04	31.16	28.25	25.50	25.00	25.10	24.20	24.76	25.50	26.32	29.75	30.04
<b>1992</b>	28.04	28.19	30.10	28.41	26.70	24.70	22.76	22.66	23.61	23.77	25.16	28.04	28.19
<b>1993</b>	27.08	27.16	29.59	26.85	25.52	23.14	22.32	22.76	23.47	24.70	26.36	27.08	27.16
<b>1994</b>	28.69	29.40	28.60	29.40	26.05	22.60	21.63	21.76	23.40	25.47	25.54	28.69	29.40
<b>1995</b>	29.30	29.86	29.72	29.95	28.10	24.37	24.78	24.76	24.19	27.02	27.02	29.30	29.86
<b>1996</b>	27.72	29.92	29.31	28.35	24.19	22.93	22.50	22.67	23.52	25.12	25.98	27.72	29.92
<b>1997</b>	27.66	29.09	29.92	28.26	25.21	23.75	23.00	23.25	25.35	25.67	26.45	27.66	29.09
<b>1998</b>	27.77	29.34	29.98	31.18	27.04	25.53	22.94	22.91	24.27	24.72	26.26	27.77	29.34
<b>1999</b>	28.67	31.07	30.71	30.35	25.57	24.29	22.49	22.46	24.29	24.57	26.46	28.67	31.07
<b>2000</b>	29.06	30.31	30.89	27.89	25.53	23.48	22.30	22.17	23.91	25.36	25.30	29.06	30.31
<b>2001</b>	27.30	29.25	28.98	28.98	27.36	23.50	23.41	22.85	24.35	24.98	25.95	27.30	29.25
<b>2002</b>	27.37	29.68	29.30	29.36	27.45	23.51	23.33	22.60	24.31	25.24	26.76	27.37	29.68
<b>2003</b>	28.65	30.19	29.97	29.82	25.09	26.51	26.52	21.97	23.55	25.99	26.89	28.65	30.19
<b>2004</b>	28.70	29.56	30.59	28.54	27.43	26.40	22.32	22.24	26.59	26.40	25.60	28.70	29.56
<b>2005</b>	27.95	30.24	31.87	27.71	28.45	25.40	23.99	25.00	25.84	26.57	27.64	27.95	30.24
<b>2006</b>	28.30	30.50	31.40	28.40	29.25	29.45	26.40	26.05	25.95	27.70	27.40	28.30	30.50
<b>2007</b>	26.97	28.51	29.86	28.38	26.25	27.25	20.96	21.20	24.58	25.25	25.59	26.97	28.51
<b>2008</b>	28.20	28.61	29.42	26.44	25.16	23.73	26.10	22.29	23.54	24.63	26.01	28.20	28.61
<b>2009</b>	27.20	29.25	28.02	27.88	28.28	24.96	26.75	22.59	24.03	28.20	25.78	27.20	29.25
<b>2010</b>	28.82	29.62	28.51	30.73	28.62	26.14	26.48	26.31	23.43	25.21	25.64	28.82	29.62
<b>2011</b>	27.32	29.94	29.99	29.65	26.65	26.06	23.90	22.43	23.63	26.85	25.95	27.32	29.94
<b>2012</b>	28.74	29.95	26.65	28.74	26.72	26.53	22.46	26.90	25.75	25.41	27.62	28.74	29.95
<b>2013</b>	28.54	29.68	28.84	27.88	26.13	26.21	22.53	22.14	25.72	24.84	25.75	28.54	29.68
<b>2014</b>	28.57	29.44	29.11	29.15	28.95	24.72	22.97	22.84	26.17	28.95	27.88	28.57	29.44
<b>2015</b>	27.90	28.40	27.35	30.30	29.85	27.85	23.60	23.45	24.50	25.55	26.00	27.90	28.40
<b>2016</b>	28.15	28.85	31.65	29.85	29.25	24.00	24.65	23.45	24.25	25.55	27.15	28.15	28.85
<b>2017</b>	29.80	28.90	27.05	28.80	26.00	24.60	22.80	23.45	24.20	25.30	25.85	29.80	28.90
<b>2018</b>	27.50	29.15	29.25	28.20	29.90	23.10	22.55	25.05	24.65	25.05	26.90	27.50	29.15

### Appendix: F Didesa River catchment Minimum temperature data

<b>Year</b>	<b>JAN</b>	<b>FEB</b>	<b>MAR</b>	<b>APR</b>	<b>MAY</b>	<b>JUN</b>	<b>JUL</b>	<b>AUG</b>	<b>SEP</b>	<b>OCT</b>	<b>NOV</b>	<b>DEC</b>	<b>AVE</b>
<b>1989</b>	11.60	13.15	14.90	14.75	14.61	13.42	13.49	13.60	13.15	13.36	13.16	11.60	13.15
<b>1990</b>	13.51	13.89	14.39	15.51	15.75	14.57	14.28	13.96	13.65	13.72	11.67	13.51	13.89
<b>1991</b>	13.38	14.01	15.91	15.25	15.20	14.50	13.30	13.80	13.88	13.37	12.97	13.38	14.01
<b>1992</b>	13.08	12.90	15.40	15.88	15.44	14.40	17.74	13.44	12.54	17.86	11.71	13.08	12.90
<b>1993</b>	11.94	12.80	15.16	14.79	14.82	14.25	14.27	13.85	14.21	14.05	14.17	11.94	12.80
<b>1994</b>	14.11	15.10	15.20	12.70	14.92	14.86	14.30	14.12	14.20	13.95	13.46	14.11	15.10
<b>1995</b>	13.99	14.67	15.39	16.56	15.39	14.76	14.26	14.18	14.00	13.91	13.71	13.99	14.67
<b>1996</b>	12.36	14.28	14.95	15.08	14.15	14.17	13.80	13.54	13.91	13.46	13.23	12.36	14.28
<b>1997</b>	15.72	16.41	17.82	17.86	16.58	15.78	15.92	16.14	11.56	12.22	12.17	15.72	16.41
<b>1998</b>	15.02	16.04	17.22	18.06	17.31	16.83	15.69	16.34	12.74	12.98	15.30	15.02	16.04
<b>1999</b>	14.37	16.18	16.18	16.56	15.20	15.03	14.95	14.93	12.24	14.71	14.34	14.37	16.18
<b>2000</b>	14.45	16.00	16.96	16.83	15.29	15.01	12.27	12.49	12.67	15.14	14.81	14.45	16.00
<b>2001</b>	12.78	12.73	15.88	16.15	12.56	14.32	14.31	11.52	14.08	12.27	13.68	12.78	12.73
<b>2002</b>	12.61	12.68	13.45	13.44	13.14	12.68	14.66	14.34	14.18	13.79	13.30	12.61	12.68
<b>2003</b>	12.84	12.58	13.76	13.14	13.37	14.47	12.27	14.39	12.09	13.52	13.34	12.84	12.58
<b>2004</b>	12.86	13.74	13.54	12.13	15.75	14.57	10.97	12.27	13.87	13.31	12.03	12.86	13.74
<b>2005</b>	12.36	12.56	13.36	12.63	15.57	14.20	13.59	13.66	13.74	13.35	12.85	12.36	12.56
<b>2006</b>	12.65	14.05	14.05	14.95	14.05	13.75	11.45	13.70	11.85	11.95	11.00	12.65	14.05
<b>2007</b>	12.55	13.12	15.40	14.95	14.55	11.25	13.90	13.39	13.46	12.98	12.50	12.55	13.12
<b>2008</b>	10.70	12.76	13.45	14.90	14.20	14.10	13.85	14.34	14.41	13.53	12.35	10.70	12.76
<b>2009</b>	11.77	13.93	14.39	14.98	13.57	14.74	11.40	14.30	11.47	13.42	12.48	11.77	13.93
<b>2010</b>	10.11	14.62	13.42	13.67	14.51	12.04	11.53	12.36	14.36	12.37	13.09	10.11	14.62
<b>2011</b>	11.76	12.48	11.45	14.72	15.35	12.04	14.45	14.18	13.17	13.44	12.80	11.76	12.48
<b>2012</b>	11.85	12.74	14.12	13.42	13.26	11.44	12.13	12.66	14.24	12.87	12.95	11.85	12.74
<b>2013</b>	12.25	13.22	13.97	14.54	14.35	12.93	14.59	12.67	12.31	13.59	12.80	12.25	13.22
<b>2014</b>	12.18	13.17	14.87	15.03	15.13	14.83	11.77	12.42	14.42	12.45	12.68	12.18	13.17
<b>2015</b>	12.00	13.20	15.30	14.90	11.20	11.65	14.40	14.75	12.60	11.50	12.25	12.00	13.20
<b>2016</b>	12.15	13.20	12.55	15.80	12.70	14.70	12.65	11.45	14.50	12.30	11.75	12.15	13.20
<b>2017</b>	12.25	14.10	14.70	16.15	12.45	12.05	14.60	12.65	14.50	12.35	12.50	12.25	14.10
<b>2018</b>	12.05	14.05	13.75	14.95	15.75	14.75	14.60	13.20	14.45	12.00	11.60	12.05	14.05

## **BIOGRAPHICAL SKETCH**

The author was born in January 15, 1984 in Kelem Wolega Zone of Oromia National Regional State, Dale Sedi District. He attended his elementary education at Arere Denbal elementary School, secondary education at Alem Tefari secondary school and preparatory at Kelem Compressive secondary school in 2003. After successfully accomplished the Ethiopian School Leaving Certificate Examination, he joined Arba Minch University. He graduated with a BSc degree in Meteorology Science in July 2006.

Soon after graduation, he was employed by the National Meteorology Agency as Early Warning and Forecast Analysis Expert in Assosa Meteorological Branch Directorate where he served from August 2006 to December 2008 and Meteorological Branch Directorate Director from January 2009 to September 2018. In 2018, he joined Hawassa University, College of Agriculture for his study of M.Sc. degree in Climate Change and Sustainable Agriculture.