ASSESSMENT OF CLIMATE CHANGE IMPACT ON THE WATER BALANCE OF LAKE HAWASSA WATERSHED

M.Sc. THESIS

KIFLE KARITE ONGOCHO

HAWASSA UNIVERSITY, HAWASSA, ETHIOPIA

July, 2023

ASSESSMENT OF CLIMATE CHANGE IMPACT ON THE WATER BALANCE OF LAKE HAWASSA WATERSHED KIFLE KARITE ONGOCHO

A THESIS SUBMITTED TO THE DEPARTMENT OF WATER RESOURCES AND IRRIGATION ENGINEERING

HAWASSA INSTITUTE OF TECHNOLOGY, SCHOOL OF GRADUATE STUDIES
HAWASSA UNIVERSITY

HAWASSA, ETHIOPIA

IN PARTIAL FULFILLMENT OF THE

REQUIREMENTS FOR THE

DEGREE OF

MASTERS OF SCIENCE IN WATER RESOURCES ENGINEERING AND MANAGEMENT

July, 2023

SCHOOL OF GRADUATE STUDIES

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Dr. Mulugeta Dadi (PHD)	_________________	_______________
Name major advisor	signature	Date
Mr. Alene Mitiku (MSc)	__________________	_______________
Name of Co-advisor	signature	Date

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Dr Mulugeta Dadi	______________	______________
Name of Major Advisor	Signature	Date
______________________	______________	____________
Name of Internal Examiner-I	Signature	Date
______________________	______________	____________
Name of Internal Examiner-II	Signature	Date
______________________	______________	______________
Name of External examiner	Signature	Date
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Declaration

I hereby declare that this MSc thesis is my original work and has not been presented for a degree in any other university, and all sources of material used for this thesis have been duly acknowledged.

Name: Kifle Karite

Signature: ________________________

Date: __________________________

This MSc thesis has been submitted for examination with my approval as thesis advisor.

Name: Dr Mulugeta Dadi

Signature: _____________________________

Place and date of Submission: ____

ACKNOWLEDGEMENT

Above all, I would like to thank the almighty God, for his unlimited mercy up on me and giving the chance to learn and accomplish this work. Then, I wish to express my deepest gratitude to my major advisor Dr. Mulugeta Dadi and co-advisor Mr. Alene Mitiku for their guidance, support and encouragement throughout my research work.

I would like to express my deepest thanks to my friend Mr. Agegnehu Mitiku for his materials provision, continuous support and encouragement from the very beginning to end of this research.

I would like to thank the National Meteorological Agency of Ethiopia and Ministry of Water, and Energy for their provision of metrological and hydrological data to conduct this work.

At the last, but not least, I have a special thanks to my lovely wife and my little children for their love and support throughout the study.

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LISTS OF ABBREVIATIONS AND ACRONYMS

AR	Assessment Report
CanESM2	Canadian Earth System Model of second generation
CN	Curve Number
DEM	Digital Elevation Model
ET	Evapotranspiration
HadCM3	Hadley Centre Coupled Model3
HRU	Hydraulic Response Unit
IPCC	Intergovernmental Panel on Climate Change
GIS	Geographic Information System
GCM	Global climate model
MoWIE	Ministry of Water, Irrigation and Energy
NMA	National Metrological Agency
NCEP	National Center for Environmental Prediction
NSE	Nash-Sutcliffe Efficiency
PET	Potential Evapotranspiration
RCP	Representative Concentration Pathways
SRES	Special Report on Emission Scenarios
SCS	Soil Conservation Service
SUFI-2	Sequential Uncertainty Fitting Version 2
SWAT	Soil and Water Assessment Tool

SWAT-CUP	SWAT Calibration of Uncertainty Program
SDSM	Statistical Downscaling Model
SNNPR	Southern Nations, Nationalities & peoples region
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
WGEN	Weather Generator
WWDSE	Water Works Design and Supervision Enterprise

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ABSTRACT

Assessing the climatic change impact on the water balance of a watershed is vital to develop sound management plans in current and future periods. The main objective of this study was assessing the climatic change impact on the water balance of Lake Hawassa watershed. The study was focused on the projection of climate variables, assessing the historical and future water balance components, and also evaluating the impacts of climate change on the stream flows of Lake Hawassa watersde. The Soil and water Assessment Tool (SWAT) mode was used for assessing the water balance components and to evaluate the climate change impact on the stream flows of Lake Hawassa catchment. SDSM (statistical downscaling model) was used under General circulation model set up for climate modeling.

The water balance components of the watershed were computed in gauged and unguaged catchments. According to the SWAT model result in the gauged catchment, the historical average annual precipitation, surface runoff and the evapotranspiration (ET) were 1068.3mm, 155.11mm and 688.3mm respectively. In 2080 for RCP 8.5 the average annual precipitation, Surface runoff and ET will be 972.15mm, 143.17mm, and 812.19mm respectively.

The climate change impact on the water balance components of Lake Hawassa watershed was evaluated for RCPs 2.6, 4.5 & 8.5 emission scenarios in the three time periods (i.e. 2020 (2022-2040), 2050(2041-2070) and 2080(2071-2099). The result from climate model showed a general increasing trend for maximum and minimum temperatures and decreasing trend for precipitation in all the three time periods for all the three emission scenarios. The impact of climate change on the seasonal stream flows of the watershed will generally increases in the Kiremt season in 2020 and 2050 for all scenarios but decreases in Bega and Belg seasons for all time period in all RCPs. The future annual precipitation, Surface runoff, lateral flow, shallow groundwater recharge and water yield will be decreased up to 9 % and 9.9 % respectively and the increase in ET may reach up to 22% at the end of 2099 for RCP_8.5. Due to climate change the future water availability will be reduced in Lake Hawassa watershed. Therefore, the design and implementation of appropriate adaptation and mitigation strategies to the watershed by the decision makers may reduce the adverse effect of climate change.

Keywords: Water balance, Climate change, SWAT, SDSM, CanESM2, Lake Hawassa watershed

1. INTRODUCTION

1.1. Background

Ethiopia has suffered the consequences of climate change and climate variability at various periods over the last century, the recurrence of the impacts has shown increasing tendency over the last 40 years. Observational evidences show that many vital water resources such as Lakes and rivers are decreasing. Though part of the cause may blame on the highly increasing demand, climate change/variability has shown putting significant pressure on the water resources (Gobena,et al., 2019).

In Ethiopia, climate change has the potential to impact negatively on water availability, stability, access, utilization, and demand. Recent studies also showed that the country is highly sensitive to changes in precipitation and temperature. As a result, river flows and runoff to lakes are likely to decrease in the future and be insufficient to meet future demands for water of the ever-increasing population in the country. Climate fluctuations also affect the use of agricultural land associated with irrigation; complicate the design, operation, and management of water-use systems. This in turn has the potential to disrupt livelihoods, increase poverty and the marginalization of the poor and escalate inequality. Many concerns and issues surround water resources are increasingly linked to climate change. Given the economic role of the water resources, climate risk will be too costly to be tolerated and urgent measures must be taken to mitigate the impacts adopting feasible strategies.

Growing population density, excessive water use and catchment land-use change are putting increasing pressure on the Ethiopian Rift valley lakes and the rivers draining into them (Ayenew, 2004).

Lake Hawassa is one of the extensively impacted Ethiopia Rift Valley Lakes. Perhaps the most notable recent changes in the Hawassa watershed were the Lake Hawassa level rise and the flooding of Hawassa town in 1998. The impacts were reported to be of both natural and anthropogenic origin. However, little was done to scientifically address these effects. The investigation entail understanding the hydrologic regime shift caused by the climate variability in the recorded meteorological parameters and anthropogenic factor as in the land use land cover change in the watershed (Belete, 2013).

Water balance estimation is an important tool to assess the current status and trends in water resource availability in an area over a specific period of time. Furthermore, water balance estimates strengthen water management decision-making by assessing and improving the validity of visions, scenarios and strategies (https://sswm.info/sswm-university-course/module-4-sustainable-water-supply/).

Water balance study and assessment of the lake level fluctuation in space and time are essential both for the proper design of flood-protection structures and for sustainable use of the water resources (Ayenew, et al., 2006). In this regard, many studies have been carried out. The hydrogeology of the lakes district in the Main Ethiopian Rift (MER), including Lake Hawassa, was studied by the Ethiopian Geological Survey (Chernet, 1982). Other relevant works include a master plan study of Awassa Town which addresses design flood protection issues and sanitation problems (NUPI, 1994) and a geothermal report on the Rift (UNDP, 1973). Rough estimates of groundwater outflow and water balance have been made by some authors (Nidaw, 1996; Geremew, 2000; Ayenew, 2001, 2002). Lake level fluctuations and the general hydro-geology and engineering geology have been studied by the Ministry of Water Resources (WWDSE, 2001) and the Ethiopian Geological Survey (Dessie & Tessema, 2003). The Lake water has been abstracted for supplementary irrigation, the total amount of water abstraction is negligible compared to all other water balance components (Belete et al., 2017). For better management of the Lake water, the hydrologic components which play a significant role in the Lake level fluctuations need to be understood (Gebreegziabher, 2004 and Lijalem et al., 2007). None of these studies addressed the water balance components of the lake watershed in detail recently in terms of climate change.

Water balance is used to calculate the change in the amount of precipitation that goes into discharge, evaporation, and storage. There are various methods and models to calculate the water balance of the hydrological system (Devi et al., 2015). However, physically-based models as SWAT, MIKE SHE (MIKE System Hydrologique European), and tRIB (TIN-based Real-time basin simulator) need a large number of parameters to describe the physical characteristics of the catchment and suffer from scale relation problem (Tina, 2016). While the SWAT model is not like the others, but it can generate water quantity and quality depending on LULC and soil type under different climatic conditions.

There were a little investigation in water balance assessments in this catchment and not recently. Therefore, this study focused in assessing the water balance of Lake Hawassa watershed in the context of climate change and evaluated the impacts of climate change on the water balance of the catchment by using SWAT hydrological model and SDSM regional climate modeling framework.

1.2. Statement of Problem

The International Panel on Climate Change (IPCC) Fifth Assessment Report WGII found that recent reports from the Famine Early Warning Systems Network (FEWS NET) indicate that there has been an increase in seasonal mean temperature in many areas of Ethiopia (IPCC, 2014). According to the UNDP climate change country profiles, the average annual temperature in Ethiopia increased by 1.3°C between 1960 and 2006 (McSweeney et al, 2010). Daily temperature observations also show an increase in the average number of 'hot' days and 'hot' nights per year. There is no statistically significant trend in observed average rainfall in any season (McSweeney et al, 2010). Daily rainfall records are insufficient to identify current trends in daily rainfall (McSweeney et al, 2010).

By affecting certain components of the hydrological cycle, especially precipitation and runoff, a change in climate can alter the spatial and temporal availability of water resources. Climate change that reduces either the overall quantity of water or the timing of when water is available for use will have important effects on agriculture, industrial and urban development.

The climate of Hawassa watershed is changing due to land use change, intensive cultivation and urbanization as a result of population growth which has an impact on hydrologic response. The transformation of forested land into agricultural activities and urbanization has a great influence on the land use land cover of the watershed as well as on basin hydrology.

Several researchers have studied the water balance of Lake Hawassa. In these investigations the researchers assess the historical water balance components of the Lake. Some of them try to assess the impact of climate change on the hydrology of Hawassa watershed but they did not attempt to assess the water balance in the context of climate change in detail.

Since the climate and land use land cover are continuously changing over the time and the studies are not recent studies the estimated water balance must be updated for better management of water resources.

1.3. Objectives of the study

1.3.1. The General objective

The General objective of this study is to assess the climate change impact on the stream flows of Lake Hawassa watershed.

1.3.2. Specific objectives are:

- To project future climate variables (minimum temperature, maximum temperature and precipitation).
- To estimate the historical (1991-2021) annual & seasonal water balance components of Lake Hawassa watershed.
- To estimate the future annual & seasonal water balance components based on the projected climate variables
- To evaluate the impacts of climate change on the stream flows of Lake Hawassa watershed.

1.5. The research questions

As stated earlier in the statement of the problem there was an increasing in the concentration of greenhouse gases in the atmosphere, the climate of the Earth is changing; temperature is increasing and the amount and distribution of rainfall is being altered. Therefore the water balance component of Lake Hawassa watershed was changing. To address these, the following questions are raised.

- What will be the amount of projected climate variables?
- What are the amounts of historical water balance Components Lake Hawassa watershed?
- What will be the average seasonal & annual water balance components of the Lake Hawassa watershed in the next 78 years?
- How the climate changes affect the stream flows of Lake Hawassa watershed?

1.6. Scope of the Study

The scope of this research was limited to the assessment of the climate change impact on the stream flows of Lake Hawassa watershed.

The aim of this study is to estimate the historical & the future seasonal & annual variations of Stream flows of Lake Hawassa watershed based on the historical data, projected future climate data and to evaluate the climate change impact on the stream flows of the catchment.

1.7. Significance of the study

This study provides insight to the responses of climate changes on the water availability in Lake Hawassa watershed. Understanding of climate change effects on the hydrology of the catchment would help watershed managers, agricultural producers and policy makers to do best adaptation strategy plan. This is an important step towards the development of strategies for sustainable water resources management.

2. LITERATURE REVIEW

2.1. Water balance

Water balance is the ratio between water in flow and outflow estimated for different space and time scales, i.e. for the Earth as a whole, for oceans, continents, countries, natural-economic regions, and river basins, for a long-term period or for particular years and seasons. Water balance is the most important integral physiographic characteristic of any territory, determining its specific climate features, typical landscapes, possible water management and land use. (I.A. Shiklomanov, 2009)

Analysis of water balance components for individual territories and time intervals is of great importance for studies of the hydrological cycle or water circulation in the atmosphere – hydrosphere – lithosphere system, as well as the underlying process influenced by natural factors and human activities.

Precipitation, evaporation, river runoff and groundwater outflow not drained by river systems are basic components determining water balance. Besides these components, there are minor components, too, e.g. moisture due to atmospheric water vapor condensation, deep artesian water outflow or conversely, recharge of deep aquifers, water losses for animal survival, etc. According to investigations, however, these components are very small if related to large river basins, regions and the globe—they are of no importance for water balance computation (I.A. Shiklomanov, (2009).

The assessments of water balances of large regions with sufficient accuracy are reduced to reliable determination of the main water balance components, i.e. precipitation, evapotranspiration and runoff (surface and subsurface) (I.A. Shiklomanov, (2009).

The study of the water balance structure of lakes, river basins, and groundwater forms a basis for the hydrological substantiation of projects for the rational use, control and redistribution of water resources in time and space. Knowledge of the water balance assists the prediction of the consequences of artificial changes in any hydrologic regime such as streams, lakes, and groundwater. Information on the current water balance of river and lake watersheds for short time intervals (season, month and weekly) is used for operational management of reservoirs and for the compilation of hydrological forecasts for water management (UNESCO, 1974).

An understanding of the water balance is also extremely important for studies of the hydrological cycle. With water balance data it is possible to compare individual sources of water in a system, over different periods of time, and to establish the degree of their effect on variations in the water regime.

In quantitative terms, the hydrologic cycle can be represented by a closed equation which represents the principle of the conservation of mass. Many forms of this expression, called the water balance equation, are possible by subdividing, consolidating, or eliminating some of the terms, depending on the purpose of computation.

The annual water budget of any hydrologic regime was estimated from inflow and outflow components of the hydrologic cycle. Rainfall, runoff and evaporation are the major components of natural hydrologic cycle. However, due to the importance of water for life, water abstraction is incorporated to these natural processes. The water balance equation can be written, from continuity equation at any time, which is governed by the conditions that the water volume remains constant. The continuity equation intern governed by conservation of matter, which described by equilibrium between added water volume (depth), lost water volume (depth) and change in volume (depth) and described as (Solkolov et al., 1974)

$$Q_i(t) - Q_o(t) = \frac{\Delta S}{\Delta t} \qquad 2.1$$

Where, Q_i = inflow (mm), Q_o = outflow (mm), $\Delta S/\Delta t$ = the rate of change in storage over a finite time step in (mm/month or year) of the considered control volume in the system.

2.1.1. Water balance Estimation

There are different methods for estimation of water balance of any hydrologic regimes. The methods of estimation of water balance are function on the hydrologic regime, and evaluated either from watershed (soil water balance model) for land surface or continuity equation for small reservoir or lakes. Soil water balance model requires having information on the parameters like rainfall, evapotranspiration and soil water storage capacity on a time manner (daily, monthly and annual). For a more advances soil water balance model, groundwater seepage, land use and soil characteristics (soil conductivity and soil moisture content at different pressure heads) etc. is, necessary to calculate the water balance (waternet, 2003).

The continuity (storage) equation is more important and can be used for reservoir and lakes. It involves measuring of all inflow and outflow components of the system. Estimation of any losses from a lake could be made by measuring all inputs, such as rainfall, inflow from streams, and groundwater inflow; all outputs, such outflow from the lake as stream, groundwater and evaporation from the lake; and the change in storage between two time periods, which could be evaluated using the lake levels measured at the beginning and end of the time period.

The general form of the equation represented by (waternet, 2003):

$$\Delta S = P + Q_{Si} + Q_{Gi} – E_o - Q_{So} - Q_{Go} \qquad 2.2$$

Where: E_o = Evaporation (mm), P = Rainfall (mm), Q_{si}, Q_{Gi} = Surface and ground water inflow respectively, into the boundary (mm), Q_{So}, Q_{Go} = Surface and ground water outflow respectively, from the boundary (mm), ΔS = Net change of storage volume within the boundary (mm).

Water balance can be estimated by different hydrological models. Hydrological models can be emperical, conceptual and physical based models. Emperical models atempt to relate rainfall as an input to runoff and runoff as an out put with a litle attempt to simulate the individual hydrological proceses involved.(eg. Black box types(SLM, LPM, unit hydrograph). Coceptual models were introduced in hydrology to improve the black box system models in theoretical approach. The primary approach is to transform rainfall to steram flow through a number of interconnected mathematical functions each representing certain componenets of the hydrologic cycle. (eg. SMAR, NAM,HBV). Physical based models have a particular advantages for the study of basin change impacts. The physical data input parametrs have physical meaning and can be measured in the field (eg. SWAT, MIKE SHE..). In this study the SWAT hydrological model was used to assess the water balance components and the climate change impact on the water balance in Lake Hawassa watershed.

2.1.2. Uncertainty in the water balance

Water balance estimates of a catchment or a lake involves different parameters and variables recorded in hydro meteorological stations and sometimes obtained from model calibrations. However, human or instrumental errors are associated with such estimates.

A comprehensive analysis was reported by UNESCO (1974) and Winter et al. (1981), about uncertainties in estimating the water balance of a lake may have a wide range of errors, depending on gauge placement, gauge spacing, and aerial averaging technique.

Errors in estimating evaporation can also vary widely depending on the instrumentation and methodology. The energy budget is the most accurate method of calculating evaporation with errors of the orders of 5% when applied to periods less than a month (UNESCO, 1974). If pans are used that are located at a distance from the lake of interest, errors can be considerable. Annual pan -to-Lake Coefficient should be used for monthly estimating evaporation (Maidment, 1993).

The same is also true for other components of water budget such as surface runoff (inflow and outflow recording gauge), quantifying water abstraction from the lake for different uses, inflow and outflow estimation techniques and groundwater etc. are contribute errors on estimation of water balance.

2.2. Previous studies in the study area

There are few hydrological investigations on lakes of the Ethiopian Rift valley Lakes basin. According to Ayenew & Gebreegziabher (2006) interests to study Lake Hawassa watershed grew with the lake level rise and the danger imposed upon Lake Hawassa. Water Works Design and Supervision Enterprise assigned by the SNNRS government conducted a study on Lake Hawassa level rise in. This study concluded that open water evaporation is about 164.566 Mm^3 per year, change in storage was about 9.5 Mm^3 per year and outflow from the lake in the form of groundwater is about 71.5 Mm3/year (WWDSE, 2001).

Gebreegziabher (2005) estimated water balance of the catchment using WTRBLN model and concluded precipitation about 1398 Mm^3 per year, while surface and sub- surface runoff 482 Mm^3 per year and actual ET constitute about 916 Mm^3 per year. The average annual water balance of the lake from spreadsheet hydrological model showed that evaporation constitutes about 131 Mm^3 while precipitation, river discharge and net ground water outflow components constituted about 106 Mm^3 and 83 Mm^3 and 43 Mm^3 respectively. These two attempts conclude the water balance component in wide variations.

Water resources estimates by different researchers in the watershed indicate that there is wide range of variations, including measured parameters. For instance, WWDSE (2001) estimated yearly rainfall to be 80.6 Mm^3 while Gebreegziabher (2005), Ayenew et al., (2007) and Daniel (2006) estimated it in the order of 100-106 Mm^3. Another huge difference is in the estimate of Evaporation. Daniel (2006) reported 178.9 Mm^3 while Gebreegziabher (2005) indicated 131 Mm^3 per year. Surface runoff estimates as well as with high variation, ranging from 83 Mm^3 per year according to

Gebreegziabher (2005) to 164.6 by WWDSE (2001). These variations require investigations for the adequate resource quantification and management.

Except Gebreegziabher the investigators did not attempt to compute the water balance components of the Whole watershed and Gebreegziabher takes the runoff from un gauged catchment as a groundwater outflow. And also the previous researchers did not attempt to assess the water balance in the context of climate change. To compute the water balance of the watershed it is better to use a comprehensive hydrological modeling framework.

2.3. Climate change impact on water balance

The Intergovernmental Panel on Climate Change (IPCC) fifth assessment report has shown an increase of 0.85°C in the global mean temperature since 1880 until 2012 (Kaufmann et al., 2002, Stocker, 2014. These changes in global temperature have been accompanied by changes in climate in different ways (Feng et al., 2014). Many regions have experienced changes in precipitation leading to the frequent occurrence of floods (Min et al. 2008) and droughts (Dai 2011, 2013). These changes in the climate system will have a strong impact on local and regional hydrological regimes in many regions of the world (Dibike & Coulibaly, 2005, Hu et al., 2013). The IPCC also has projected that if greenhouse gas emissions, the leading cause of climate change, continue to rise, the mean global temperatures will increase 1.4 – 5.8°C by the end of the 21st century(IPCC, 2007) (IPCC, 2007).

The IPCC finding indicates that developing countries, such as Ethiopia will be more vulnerable to climate change. Because of the less flexibility to adjust the economic structure and is largely dependent on agriculture, the impact of climate change has far reach implication in Ethiopia. Increased industrial activity and excessive deforestation during the last century and a half have increased the concentration of carbon dioxide in Earth's atmosphere. This has, in turn, initiated large-scale atmospheric processes resulting in a change of global temperature and precipitation (among other variables). Changes in Earth's climate system can disrupt the delicate balance of hydrologic cycle and can eventually lead to increased occurrence of extreme events (such as flood, droughts, heat waves, summer and ice storms, etc.) (Bernstein. et al, 2008).

There have been few studies performed on the part of Hawassa watershed for climate change impact in Tikur Wuha Sub-Watershed. Which include a studies done by Diriba (2015) using only one GCM model (HadCM3) of the IPCC fourth assessment report (AR4); under three Special Report on Emission Scenarios (SRES) (A1B, A2 & B1) and the study concluded that the river flow will increase at the end of 2099 and had recommended further studies has to carry out using ensemble of GCM output and also Alemayehu (2019) studied Stream flow projections for future time periods for Tikur Wuha result in mean annual stream flow may increase by 15.43, 23.48, and 25.42% in 2020s, 2050s, and 2080s, respectively, from the baseline period for RCP 4.5 scenario, whereas for RCP8.5 Scenario, it will be expected to increase by 29.58, 34.20, and 38.72 % for the 2020s, 2050s, and 2080s, respectively. On the other hand the investigation by Mesfin, 2014 by using RCM output of A1B scenario and HBV hydrological model that the stream flow will decrease by -3.8% and -4.4% in gauged catchments and by -4.1% and -13.7% in un-gauged catchments in 2030 and 2090 time horizons respectively. However, Studies performed at the regional scale, which is based on the IPCC fifth assessment report(AR5) to investigate the future changes of hydrologic regimes, and water resources availability under climate change in Tikurwuha Sub-watershed with respect to RCPs are still limited. Therefore, studies that fill these gaps and provide information are very important. In this study I have tried to compute the future water balance components of Lake Hawassa watershed based on IPCC fifth assessment report (AR5).

2.4. Model Selection, Merits and Demerits of the Models

The choice of a suitable hydrological model depends on the function that the model needs to serve. There are several hydrological models simulating the hydrological process at different spatial and temporal scales. There are various criteria which can be used for choosing the proper hydrological model for a specific problem. Further, some criteria are also user-dependent and subjective, such as the personal preference for graphical user interface, computer operation system, input-output management and structure and clarity for users.

The selection of hydrological model taking into consideration the following four fundamental selection criteria (Cunderlik and Simonovia, 2007):

- Required model outputs important to the project and therefore to be estimated by the model (Does the model predict the variables required by the project such as peak flow, event volume and hydrograph, long-term sequence of flows…),
- Hydrologic processes that need to be modeled to estimate the desired outputs adequately (Is the model capable of simulating land use/cover change, regulated reservoir operation, snow accumulation and melt, single-event or continuous processes?),

- Availability of input data (Can all the inputs required by the model be provided within the time and cost constraints of the project?),
- Price (Does the investment appear to be worthwhile for the objectives of the project?)

For this study I followed hydrological and climate modeling approaches. Soil and Water Assessment Tool (SWAT) was selected for water balance assessment and impact analysis and also SDSM (statistical down scaling model) was used under General circulation model (GCM) set up For climate modeling and climate change scenarios.

SWAT model is not new, it has been successfully applied in Ethiopian watersheds; for instance the model was used within in Blue Nile Basin (Setegn 2008, Rahel 2007, Betriel, et al., 2011), central Ethiopia (Geleta, 2010) and other part of the country to model the hydrological process, sediment yield and estimate water balance. The overall performance of the model in most cases appears to be reasonable. For a particular interest, the major components of the model are discussed as follows. More detailed theoretical background on the models components, descriptions of hydrological processes and Input/output file documentations are found in Neitsch et al., (2005) for SWAT2005.

2.4.1. Hydrological Component of SWAT

Generally, simulation of the hydrology of a watershed can be separated in two major components: The Land phase and The Routing phase of the hydrologic cycle. The Land phase of the hydrologic cycle is simulated based on the water balance equation (2.1) that controls the water movement in the land and determines the water, sediment, nutrient and pesticide amount that will be loaded into the main stream.

$$SW_t = SW_0 + \sum_{t=1}^{t}\left(R_{day} + Q_{surf} - E_a - W_{seep} - Q_{gw}\right) \text{ ----------- (2.1)}$$

Where $\mathbf{SW_t}$ is the final soil water content (mm H_2O),

$\mathbf{SW_o}$ is the initial soil water content on day ***i*** (mm H_2O),

t is the time (days),

$\mathbf{R_{day}}$ is the amount of precipitation on day ***i*** (mm H2O),

$\mathbf{Q_{surf}}$ is the amount of surface runoff on day ***i*** (mm H_2O),

$\mathbf{E_a}$ is the amount of evapotranspiration on day *i* (mm H2O),

$\mathbf{W_{seep}}$ is the amount of water entering the vadose zone from the soil profile on day ***i*** (mmH_2O), and $\mathbf{Q_{gw}}$ is the amount of return flow on day ***i*** (mm H_2O).

Hydrological components simulated in land phase of the Hydrological cycle are canopy storage, infiltration, redistribution, and evapotranspiration, lateral subsurface flow, surface runoff, ponds and tributary channels return flow.

2.4.1.1. Surface Runoff Generation

Surface runoff or overland flow is a flow that occurs along a sloping surface and it occurs whenever the rate of water application to the ground surface exceeds the rate of infiltration. It is the major component of the hydrologic cycle. SWAT provides two surface runoff computation methods; a modification of the Soil Conservation Service (SCS) Curve Number (CN) method (SCS 1972) or the Green &Ampt infiltration method (Green and Ampt, 1911). The CN method was initially developed for small agricultural watersheds and the CN varies non-linearly with the moisture content of the soil. It drops to zero as the soil approaches the wilting point and increases to near 100 as the soil approaches saturation, with higher CNs associated with higher runoff potential watershed. This method is widely used (Arnold, et al., 1998, Lukman, 2003). In this method, the ratio of actual retention to maximum retention is assumed to be equal to the ratio of direct runoff to rainfall minus initial abstraction. This can be mathematically expressed as (USDA 1985).

$$Q_s = \frac{(R_d - I_a)^2}{(R_d - I_a + S)} \qquad (2.2)$$

For $R_d > I_a$

$Q_s = 0$, For $R_d \leq I_a$

Where $\mathbf{Q_s}$ is the accumulated runoff (mm), $\mathbf{R_d}$ is the rainfall depth for the day (mm), $\mathbf{I_a}$ is initial abstraction (mm, surface storage, canopy interception, infiltration prior to runoff) and **S** is the potential maximum moisture retention after runoff begins (mm).

To remove the necessity for an independent estimation of initial abstraction, a linear relationship between $\mathbf{I_a}$ and **S** was suggested by SCS as, $\mathbf{I_a = \lambda S}$ and where $\boldsymbol{\lambda}$ is an initial abstraction ratio. The values of $\boldsymbol{\lambda}$ vary in the range of 0 and 0.3.

The variable **S** varies with antecedent soil moisture and other variables, it can be estimated as;

$$S = \frac{25400}{(CN)} - 254 \qquad (2.3)$$

With this consideration the surface runoff equation becomes:

$$Q_s = \frac{(R_d - 0.2S)^2}{(R_d + 0.8S)} \qquad (2.4)$$

The CNs for different land use and land cover, soil groups and antecedent moisture conditions are provided with ArcSWAT2005 manual that takes in account of soil infiltration rate when thoroughly wetted, and slope adjustments (J. Williams, 1995).

2.4.1.2. Lateral Subsurface Flow

Lateral subsurface flow or interflow is stream flow contribution which originates below the surface but above the zone where rocks are saturated with water. Interflow in the soil profile is calculated simultaneously with redistribution. It can have an important influence on storm hydrographs particularly when vertical percolation is retarded by a shallow, less permeable soil layer.

SWAT incorporates a kinematic storage model (Sloan and Moore, 1984) to compute subsurface flow as a function of the drainable volume of water, saturated hydraulic conductivity, soil slope, hill slope length, and drainable porosity. This model simulates subsurface flow in a two-dimensional cross-section along a flow path down a steep hill-slope. The kinematic wave approximation of saturated subsurface/lateral flow assumes that the lines of flow in the saturated zone are parallel to the impermeable boundary and the hydraulic gradient equals the slope of the bed. The equation to compute lateral flow is given as:

$$q_t = 0.024 * \left(\frac{2.\mathrm{SW}.\mathrm{K_s}.\mathrm{Sl}}{\emptyset_\mathrm{d}.\mathrm{L_h}}\right) \tag{2.5}$$

Where, $\mathbf{q_t}$ is lateral flow (mm/day), **SW** is drainable volume of soil water (mm), **Sl** is slope (m/m), $\emptyset_\mathrm{d}$ is drainable porosity (mm/mm), $\boldsymbol{K_s}$ is saturated hydraulic conductivity (mm/ hrs.) and $\boldsymbol{L_h}$ is the hill slope length (m).

Lateral flow is significant in areas with soils having high hydraulic conductivities in surface layers and an impermeable or semi permeable layer at a shallow depth. In such a system, rainfall will percolate vertically until it encounters the impermeable layer. The water then ponds above the impermeable layer forming a saturated zone of water and this saturated zone is then the source of water for lateral subsurface flow.

2.4.1.3. Return Flow

Return flow or base flow is the volume of stream flow originating from groundwater. SWAT2005 partitions groundwater into two aquifer systems: a shallow, unconfined aquifer which contributes return flow to streams within the watershed and a deep, confined aquifer which contributes return flow to streams outside the watershed (Arnold et al., 1993).The latter can be seen as a loss of the watershed system. Water percolating past the bottom of the root zone is partitioned into two fractions and each fraction becomes recharge for one of the aquifers. In addition to return flow, water stored in the shallow aquifer may replenish moisture in the soil profile in very dry conditions or be directly removed by plant. Water in the shallow or deep aquifer may be removed for different uses.

The contribution of ground water to stream flow is simulated by creating a shallow aquifer storage which is recharged by percolation from the unsaturated zone, and discharges to the reach of the watershed. The water balance for the shallow aquifer is:

$$Aq_{shi} = Aq_{shi-1} + W_{rec} - Q_{gw} - W_{rev} - W_d - WU_{sa} \quad 2.6$$

And groundwater flow into the main channel on day "***i***" is calculated using:

$$Q_{gw,i} = Q_{gw,i} * W_{rec} (1 - e^{-\alpha\Delta t}) \quad 2.7$$

Where; $\mathbf{Aq_{shi}}$ and $\mathbf{Aq_{shi-1}}$ is the shallow aquifer storage (mm) on day ***i*** and ***i-1*** respectively, $\mathbf{W_{rec}}$ is the recharge entering the aquifer on day ***i*** (mm), $\boldsymbol{Q_{gw}}$ is the groundwater flow or base flow, into the main channel on day ***i*** (mm), $\boldsymbol{W_{rev}}$ is the amount of water moving into the soil zone in response to water deficiencies on day i (mm), $\boldsymbol{W_d}$ is the amount of water percolating from the shallow aquifer into the deep aquifer on day *i* (mm), $\boldsymbol{WU_{sa}}$ is the water use from the shallow aquifer (mm), $\boldsymbol{\alpha}$ is the recession constant which describes the lag flow from the aquifer and $\boldsymbol{\Delta t}$ is the time step and $\boldsymbol{\alpha}$ can be best estimated by analyzing measured stream flow during periods of no recharge in the watershed.

2.4.1.4. Flow Routing

Second component during the simulation of the hydrology of a watershed is the routing phase of the hydrologic cycle. Flow may be supplemented by the fall of rain directly on the channel and/or addition of water from point source discharges. SWAT uses Manning's equation to define the rate and velocity of flow. The channel cross section and longitudinal slope are computed from the digital elevation model (DEM). Once the model determines flow to the main channel, it is routed through the stream network of the watershed using a command structure similar to that of HYMO (a problem-oriented computer language for building hydrologic models) (Williams and Hann, 1973). Arnold et al., (1996) developed the Routing Outputs to Outlet (ROTO) model that latter merged to SWAT2005 to route the flows through channels and reservoirs in order to support an assessment of the downstream impact of water management. Flow is routed through the channel using a variable storage coefficient method developed by Williams (1969) or the Muskingum routing method.

2.4.2. General Circulation Models (GCMs)

The General Circulation Models (GCMs) used to simulate the present and project future climate with forcing by greenhouse gases and aerosols, typically divide the atmosphere and ocean into a horizontal grid with a resolution of 2 to 4º latitude and longitude, with 10 to 20 layers in the vertical. In general, most GCMs simulate global and continental scale processes in detail and provide a reasonably accurate representation of the average planetary climate. Over the past decade, the sophistication of such models has increased and their ability to simulate present and past global and continental scale climates has substantially improved. Nevertheless, while GCMs established significant skill at the continental and hemispherical scale and incorporate a large proportion of the complexity of the global system, they are inherently unable to represent local sub-grid scale features and dynamics, such as local topographical features and convective cloud process (Dibike & Coulibaly, 2005).

As a consequence, two sets of techniques have emerged as a means of deriving local–scale surface weather from regional–scale atmospheric predictor variables. Firstly; statistical downscaling is analogous to the "model output statistics" (MOS) and "perfect prog" approaches used for short–range numerical weather prediction. Secondly, Regional Climate Models (RCMs) simulate sub–GCM grid scale climate features dynamically using time–varying atmospheric conditions supplied by a GCM bounding a specified domain. Both approaches will continue to play a significant role in the assessment of potential climate change impacts arising from future increases in greenhouse–gas concentrations.

Dynamical downscaling involves the nesting of a higher resolution Regional Climate Model (RCM) within a coarser resolution GCM. The RCM uses the GCM to define time–varying atmospheric boundary conditions around a finite domain, within which the physical dynamics of the atmosphere are modeled using horizontal grid spacing of 20–50 km. The main limitation of RCMs is that they are as computationally demanding as GCMs (placing constraints on the feasible domain size, number of experiments and duration of simulations). The scenarios produced by RCMs are also sensitive to the choice of boundary conditions (such as soil moisture) used to initiate experiments. The main advantage of RCMs is that they can resolve smaller–scale atmospheric features such as orographic precipitation or low–level jets better than the host GCM. Furthermore, RCMs can be used to explore the relative significance of different external forcing such as terrestrial–ecosystem or atmospheric chemistry changes (Wilby and Dawson, 2007).

Statistical downscaling starts with the premise that the regional climate is the result of interplay of the overall atmospheric, or oceanic, circulation as well as of regional topography, land-sea distribution and land use. As such, empirical statistical downscaling seeks to derive the local scale information from the larger scale through inference from the cross-scale relationship using some random or deterministic functions. In most cases, the regional climate is seen as a random process conditioned upon a driving large-scale climate regime. Therefore, the confidence that may be placed in downscaled climate change information is foremost dependent on the validity of the large-scale fields from GCM (Cunderlik 2003).

Statistical downscaling methodologies have several practical advantages over dynamical downscaling approaches. In situations where low–cost, rapid assessments of localized climate change impacts are required, statistical downscaling (currently) represents the more promising option.

2.4.2.1. Statistical Downscaling Model (SDSM)

SDSM is a user-friendly software package designed to implement statistical downscaling methods to produce high-resolution monthly climate information from coarse-resolution climate model (GCM) simulations. The software also uses weather generator methods to produce multiple realizations (ensembles) of synthetic daily weather sequences.

SDSM can be used while impact assessments require small-scale climate scenarios, provided quality observational data and daily GCM outputs for large-scale climate variables are available.

SDSM uses a multi-linear regression method to develop a statistical relationship between predictors and predictands. The model enables performing multiple processes such as data quality control, screening of predictors, model calibration, and scenario generator. Screening of the predictors is one of the most challenging tasks in SDSM, particularly for precipitation, and the accuracy of the model highly depends on the selected predictors. The selection of a predictor is based on the scatterplots, correlation and partial correlation analysis, and the statistical significance ($P < 0.05$) of the predictand-predictor relationships. Taking a single predictand (e.g. daily T-max) and screened NCEP predictors. The model produces up to 100 daily weather ensembles, which are considered to be equally plausible. The weather ensembles are generated by linear regression models and stochastic methods of bias correction (Tavakol-Davani et al., 2013).

According to Wilby and Dawson (2007), SDSM reduces systematic biases of GCM predictors by normalizing them with the baseline period. Depending on the length of the available daily data, the model can be calibrated on monthly, seasonal, and annual time scales under conditional (e.g. precipitation) and unconditional process (e.g. T-max and T-min).

3. MATERIALS AND METHODS

3.1. Study Area Description

3.1.1. Location

Lake Hawassa watershed is located in the central North-East of the Ethiopian Rift Valley Basin (Figure 3.1) and covers an area of 143,651 ha. It contains five sub-watersheds: Namely Dorebafena-Shamena, Wedesa-Kerama, Tikurwuha, Lalima-WendoKosha and Shashemene Toga. Geographically, the watershed is situated between 6°48'46" – 7°13'55" North latitude and 38°16'44" - 38°43'32" East longitude in the Sidama Regional State (part of former Southern Nations, Nationality and Peoples Regional State (SNNPRS) and Oromia Regional State. The watershed is bordered by Ziway-Shalla sub basin in the north, Abaya-Chamo sub basin in the south, Wabi-Shebelle-Genale sub basin in the east, and Omo-Gibe sub basin in the west. According to the traditional agro ecology classification, the eastern part of the watershed as moist Woina Dega (mid highland) while the western part is dry Woina Dega (Degife et al., 2019).

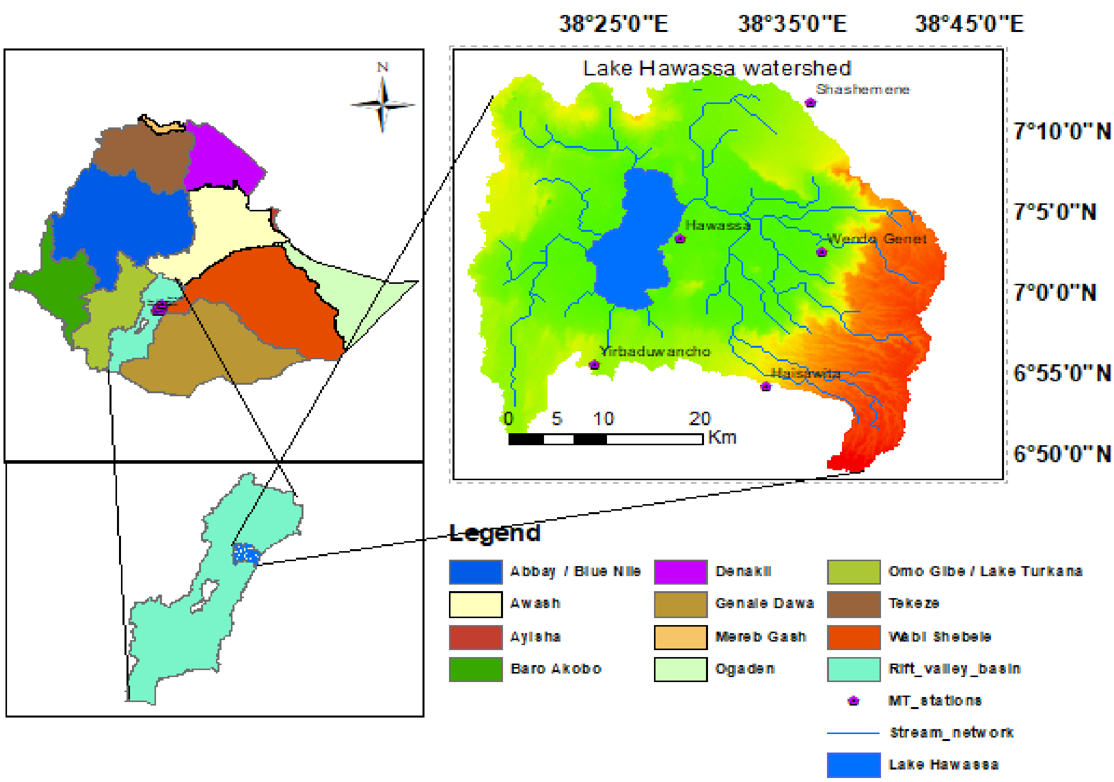


Figure 3.1: Map of the study area.

3.1.2. Climate

Lake Hawassa watershed is characterized by a sub-humid and seasonal variation type climate with three main seasons. The long rainy season in the summer from June-September is known locally as Kiremt and is primarily controlled by the seasonal migration of the inter-tropical convergence zone (ITCZ), which lies to the north of Ethiopia at this period. The wet period (locally named as Kiremt) represents 50-70% of the mean annual total rainfall. The dry period (locally named as baga) extends between October and February when the ITCZ lies to the south of Ethiopia (Legesse et al., 2004). During March and May, the "small rain" season (locally named as belg) occurs when about 20-30% of the annual rainfall falls. The climate in the area varies from dry to subhumid according to the Thornthwaite's system of defining climate or moisture regions (Dessie, 1995).

As computed from the long-term (1973-2010) rainfall record of Hawassa meteorological station, the annual average magnitude is computed to be 961 mm and distributed as 50% for Kiremt (June-September); 20% for Bega (October-February) and 30% for Belg season (March - May) (Belete M, 2013).

Temperature fluctuates between -2.8 °C and 34 °C. The daily sunshine hours vary between 7.5 hours in August and 11.7 hours in May, November and December. Monthly average relative humidity values range between 37% and 78%. The average monthly wind speed, at 2 m height, range between 0.43 and 1.4m/s directed dominantly from northeast to southwest. The reference evapotranspiration (ETo) at Hawassa is 1529.52 mm/year. The minimum ETo is 108.2 mm in the month of July and the maximum is 148.7 mm in the month of March (Yonas, 2020).

3.1.3. Topography

The topography of Lake Hawassa watershed is flat to gently undulating but bounded by steep escarpments. The altitude ranges from 1,571m at Lake Hawassa to 2,962m on the Eastern escarpment. According to the FAO slope classification method; 21% of the watershed is flat (0-3%), 36.7% is gentle slope (3-8%), moderately sloping 23.3% is (8-15%) & 13% (15-30%) and only 6% steep Slope (>30%).

3.1.4. Soil

The major soil types of the watershed are Andosols, Cambisols, Leptosols and Luvisols. Andosols in the watershed are deep, well drained and fertile soils with pH value of 6.7- 7.3. This soil type covers 21.1% of the total area, highly productive and found in mostly up land agricultural fields and forest area. Cambisols are the dominant soil type, covering about 45% of the watershed area. This soil type is very deep, well-drained and having neutral to slightly alkaline pH. It is found on gentle sloping to level plains where it is intensively cultivated with annual and perennial crops. Luvisol is dominant on level plain in the eastern part of the watershed that account for 25% of the total watershed area. This soil type is very deep, well drained, has neutral to strongly alkaline pH depth wise from top to bottom. It covers intensively cultivated fields with annual and perennial crops. Leptosols cover only about 1% of the watershed. These soil types are described in Table 3.1.

Table 3.1 Major Soil types of Hawassa watershed (Yonas, 2020)

Soil Name	Soil type description
Andosol	Well to excessively drained; moderately deep to very deep(pumice below 45cm); dark grayish brown to dark yellowish brown; medium and coarse textured; sub angular blocky and massive structured; developed on rolling plain (0-15% slope)
Cambisol	Well to excessively drained; moderately deep to very deep(gravely and pumice below 60cm); dark reddish brown, grayish brown and very dark gray; fine to coarse textured; weak to moderate fine and medium sub angular blocky structured; non calcareous Cambisols developed on a level to very steep topography (0-15%)
Leptosol	Excessively to well drained; very shallow; dark brown to very dark yellowish brown; medium textured; weak to moderate medium sub angular blocky structured; friable moist; slightly sticky and slightly plastic wet; slightly to non-calcareous Leptosols developed on a hill with slope >8%
Luvisol	Well drained; deep to very deep; dark brown to dark reddish brown; fine and medium textured; moderate, fine to coarse sub angular blocky structured; non-calcareous Luvisols developed on medium to high gradient mountains with slope of 5-30%.

3.1.5. Land use land cover

According to basin plan study of Hawassa watershed (MoWR, 2010), the land use is dominated by cultivation which occupied 62% in area. While plantation forests in the Wendo Koshe hills and around Wondo Genet comprised 4%, dense and open shrubland in the Wendo Koshe hills and west of Chelelelka covered 5% of the land. Grassland in association with open grassland in the Wendo Koshe hills, marshland at Chelelelka, smallholder cultivation in the eastern hills and wooded grassland in the eastern hills account for 22% of the total area. Furthermore, marshland covered 1.8% in Chelelelka and around Lake Hawassa, shrubs (3%), bare land 6%, urban areas just under 2% and Lake Hawassa itself occupied just over 6% of the sub-basin.

3.2. Data

Table 3.2.Data sets and source of data

No.	Data type	Data source	Temporal resolution	Spatial resolution	Duration
1	Meteorological data maximum and minimum temperature, rainfall, rrelative humidity, solar radiation &wind speed	National Meteorological Agency (NMA)	daily		1991-2021
2	Hydrological data, i.e. stream flow	Ministry of water and Energy	daily		1991-2014
3	Land use and land cover	Landsat 8 from Earth Explorer-USGS (https://earthexplorer.usgs.gov/)		30m x30m	
4	Soil map and their hydraulic properties	Ministry of water and Energy			
5	DEM(digital elevation mode)	From http://earthexplorer.usgs.gov/		30m x30m	

3.3. Research Methodology

3.3.1. Methodological Flow Chart

The procedure described below was followed to assess the current and future water balance components and to evaluate the impact of climate change on the water balance in lake Hawassa watershed. The procedure of the work is presented in the following flow chart.

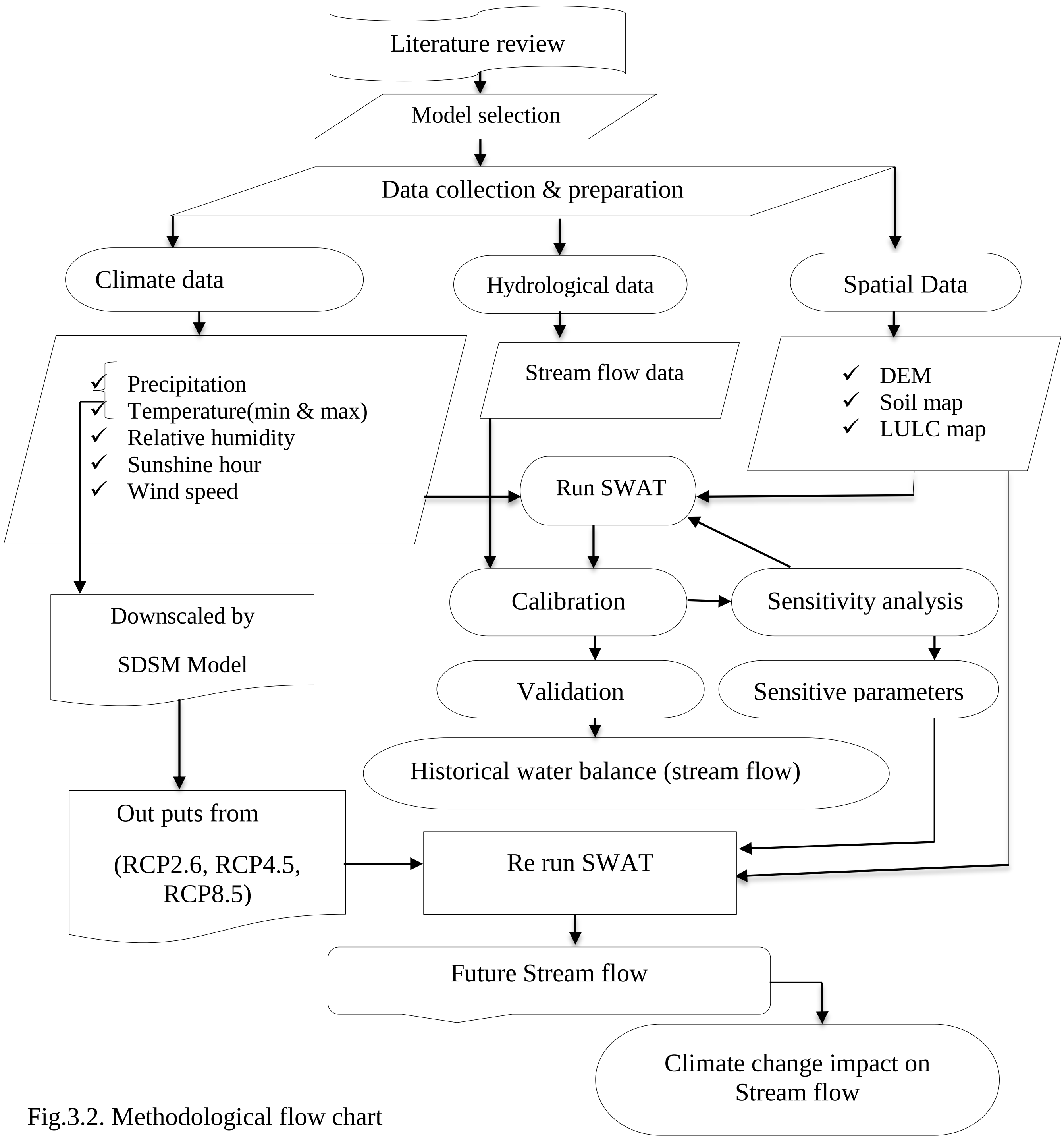


Fig.3.2. Methodological flow chart

3.3.2 Data processing

3.3.2.1. Metrological Data processing

All the collected daily maximum temperature, minimum temperature and precipitation data have been weighted using Thiessen polygon technique in GIS software. The Thiessen polygons for Lake Hawassa watershed showing the area of influence of each of the five weather stations: Hawassa (37%), Haisawita (14.1%), Shashemene (18.6%), Wondo Genet (22.3) and Yirba Duwancho (8%). Using the area coverage of each station weighted mean maximum temperature; minimum temperature and precipitation have been used for calibration, validation and scenario generation.

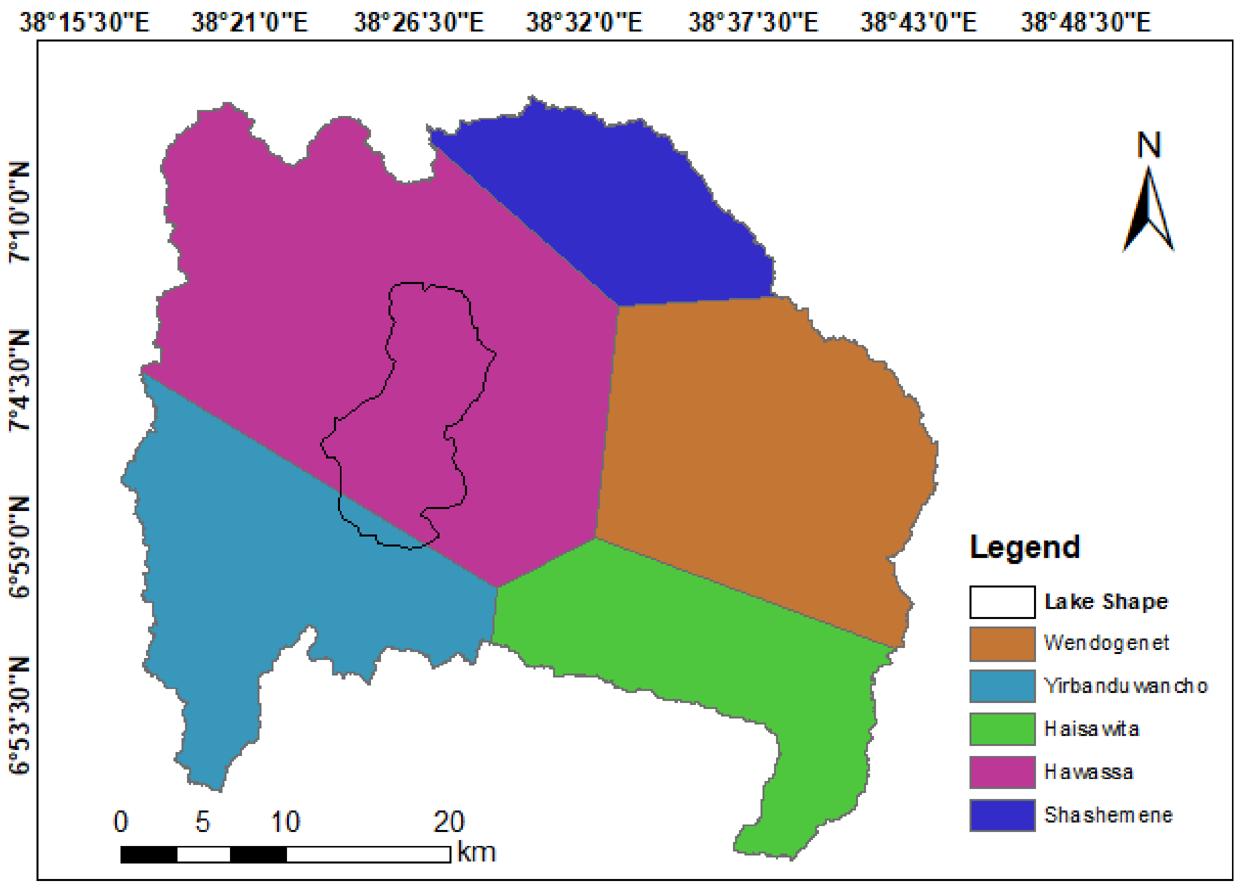


Figure 3.3: Thiessen polygons for Lake Hawassa watershed Metrological stations.

3.3.2.2. Filling of missed data

Missing data occurs due to interruption of measurements caused by natural and human induced factors. Missed precipitation of a station was estimated from the observations of precipitation at some other stations as close to and as evenly spaced around the station with the missing record as possible since it is necessary to fill in this missing record. There are a number of methods available for estimating missed rainfall data like arithmetic mean method, normal ratio method and inverse distance weighting method.

For this study normal ratio method was used to fill missing data because the mean annual precipitation at any of the index station differs from that of mean annual precipitation of missed station by more than 10% (Equation 3.1)

$$P_X = \frac{N_x}{N}\left(\frac{P_A}{N_A} + \frac{P_B}{N_B} + \frac{P_C}{N_C} + \cdots + \frac{P_N}{N_N}\right) \text{--} (3.1)$$

Where, P_X is the precipitation for the station with missed record, P_A, P_B, P_B ….., P_N are the corresponding precipitation at the index stations and , N_A, N_B, N_C,………., N_N and N_X are the long term mean monthly precipitation at the index stations and at station x.

The temperature, relative humidity, sunshine hours, and wind speed data were filled with station average and linear regression methods.

3.3.2.3. Homogeneity Test

Non-homogeneous data series for hydrological and climate change impact assessment may amplify real variations. The collected data said to be homogenous, if the measurements have been consistently done by the same method, with the same instrumentation, at the same time and place, and in the same environment. The causes of variation can be either human or natural. These include alterations to land use and relocation of the observation station. The homogeneity test of time series may be classified into two groups as absolute method and relative method. In the absolute method, the test applies to each station separately. In the relative method, the neighboring stations are also used in testing (Wijngaard et al., 2003). According to Peterson et al., (1998), the recommended method to apply homogeneity has been tested with respect to neighboring stations that is supposedly homogeneous. For this study the homogeneity test was carried out by non-dimensional method. The non-dimensional of the month’s value is carried out as:

$$P_i = \frac{\overline{P_i}}{\overline{p}} * 100 \text{--} (3.2)$$

Where, Pi is Non-dimensional value of rainfall for month i, $P\bar{i}$ is over year averaged monthly rainfall at the station i and $\bar{p}$ is the over year average yearly rainfall of the station.

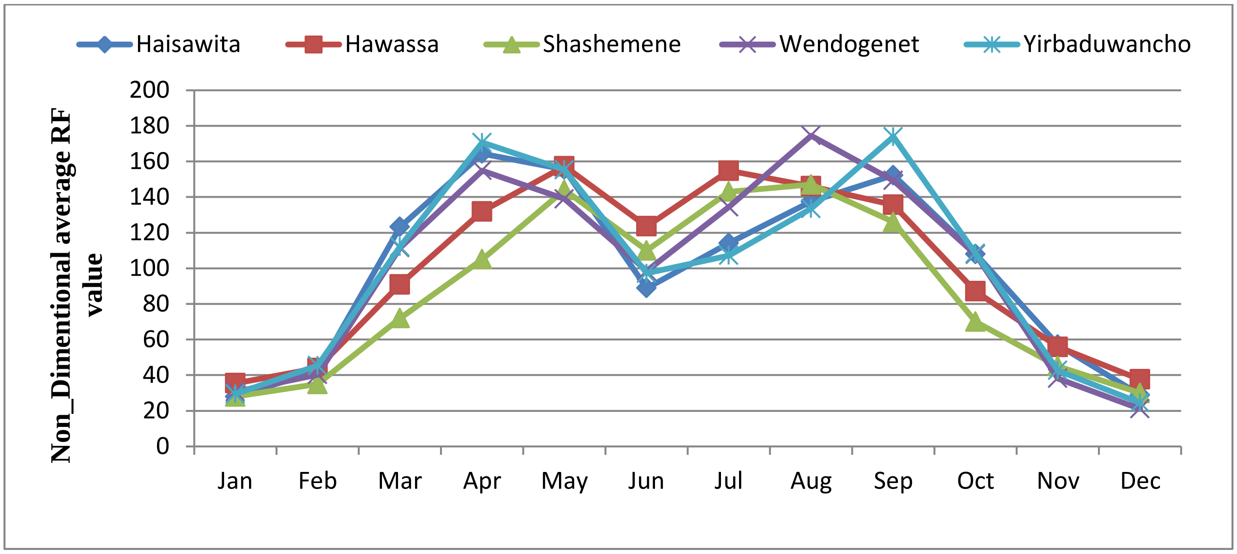


Figure 3.4: Homogeneity tests for selected weather stations at Hawassa watershed.

From the above figure the selected rainfall stations were non-dimensional values and plotted together to analyze their homogeneity in which all the stations shows homogeneous trend.

3.3.2.4. Data consistency test

The consistency of time series data analyzed based on the theory that a plot of two cumulative quantities that are measured for the same time period should be a straight line and their proportionality remain unchanged, which is represented by the slope. To check the consistency of data, the double mass curve was used to correct rain gauge data for the given station. In this study the consistencies of the data set of stations described in the above section 3.3.2.1 were checked using double mass-curve method. As shown in figure 3.6 the precipitation data in all the five stations were consistent since the slope of the lines are fairly smooth with no station displaying a long-lasting break.

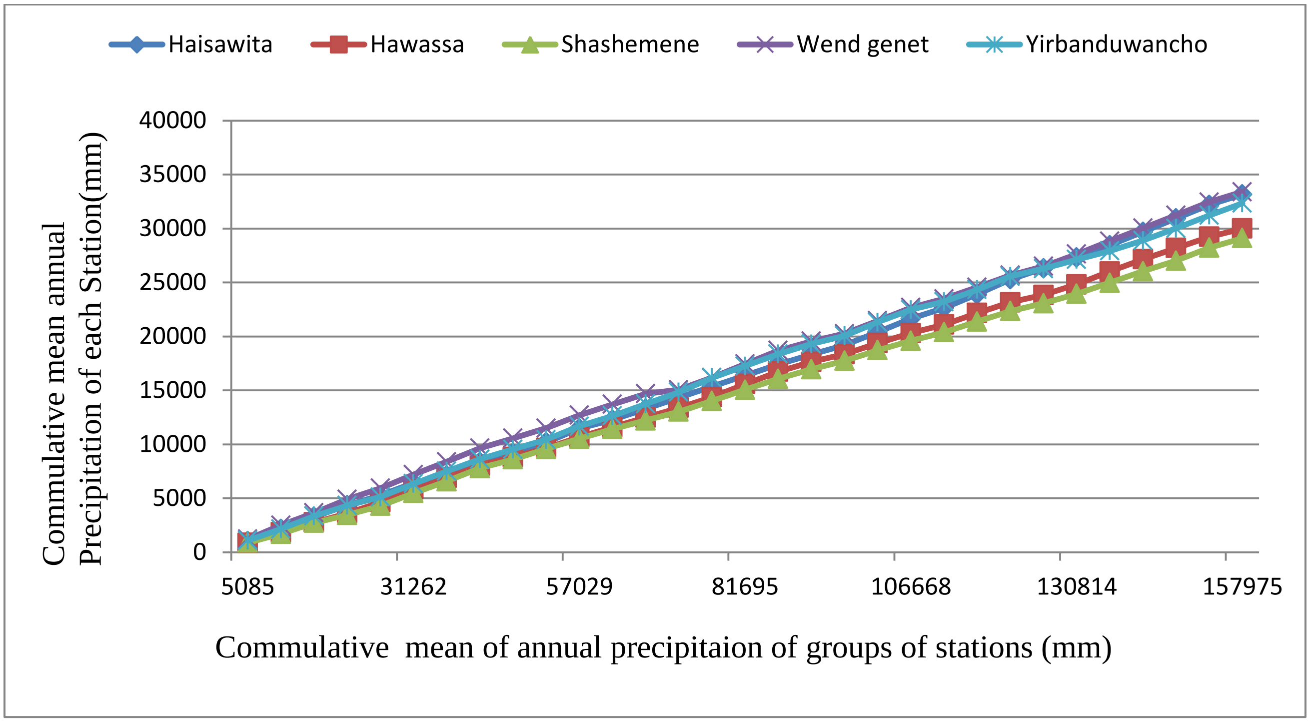


Figure 3.5 Double mass curve plots for five stations

3.4. Model selection and Modeling Approach

The selection of models was discussed in section 2.4 and According to the selection criteria two modeling approaches (hydrological modeling approach and climate change modeling approach) were selected for this study. For hydrological modeling approach SWAT model and for climate modeling SDSM (statistical down scaling model) under General circulation model (GCM) set up were used and climate change scenarios were downloaded freely from http://www.sdsm.org.uk.

3.5. Hydrological (SWAT) model setup and analyses

The Soil and Water Assessment Tool (SWAT) model is used to investigate the water balance of Lake Hawassa watershed and also used to analyze the impact of climate change on water balance components.

SWAT is a semi-distributed, continuous time, rainfall runoff model developed by the USDA Agricultural Research Service (ARS) and simulations are performed using a daily time step. In addition, the movement of water, sediment, and agricultural chemical yields are simulated depending on varying soils, land use and management in complex watersheds over long time periods (Dixon and Earls, 2012).

For this study ArcSWAT 10.4 version was used. ArcSWAT is a restructured version of SWAT model that runs within ArcGIS. It provides a graphical user – interface that allows for the GIS data to be formatted for use in SWAT model simulations. The model is more flexible in terms of watershed discretization, configuration, and spatial representation of processes, as well as in defining management schedules, operations, and database maintaining. Advantages include improved anthropogenic water use and management, flexibility in management schedules and operations, easier printing of outputs, and rapid model calibration (Arnold et al., 2012).

The model set up is using readily available spatial and temporal data which was described in section 3.4.1.1. After the data was collected and prepared, the model setup was done for all input data by following steps which were used for SWAT model setup: (1) project setup (2) watershed delineation, (3) HRU definition, (4) weather data definition, (5) SWAT simulation (Arnold et al., 2012).

3.5.1. SWAT model inputs

The SWAT model input data are spatial, weather and hydrological data. The spatial data are Digital Elevation Model (DEM), soil data and land use/ cover. Weather data are precipitation, Maximum & minimum temperature, relative humidity, solar radiation & wind Speed data. And the hydrological data are the Stream flow data for calibration and validation of the simulated output. All the spatial data set were projected in addendum to UTM Zone 37, which is the transverse Mercator projection parameter for Ethiopia, using ArcGIS 10.4.1.

3.5.1.1. Digital elevation model (DEM)

The digital elevation model (DEM) is one of the input data for ArcSWAT model. For this study, the digital elevation model was downloaded from Earth Explorer-USGS (https://earthexplorer.usgs.gov/) with the grid resolution 30mx30m for watershed delineation and stream network processing in ArcSWAT model.

DEM is defining the topography of the watershed by describing the elevation of any point at a given specific spatial resolution in the digital file which was used for SWAT model to delineate the watershed in to a number of sub-basins based on elevation, to calculate the flow accumulation and stream networks.

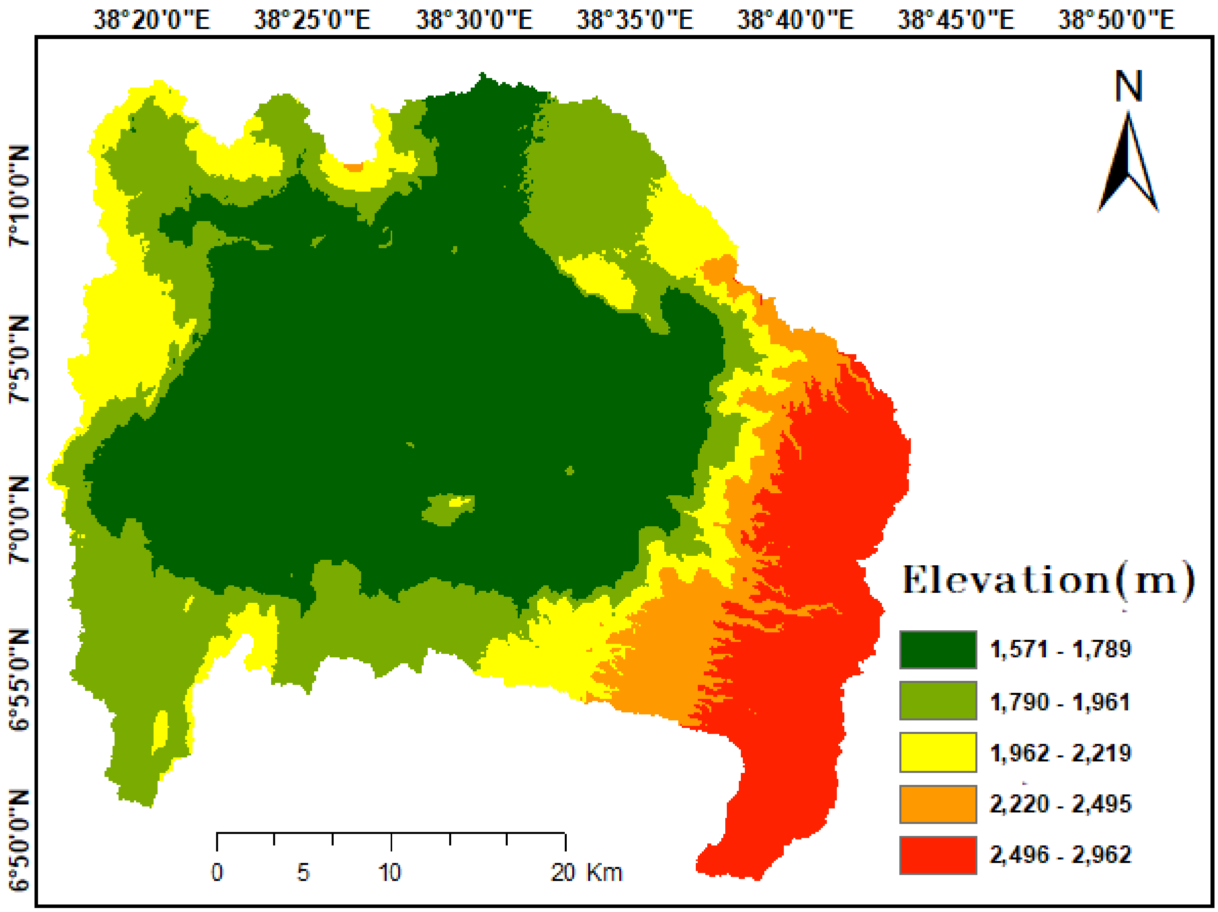


Figure 3.6: Digital Elevation Model (DEM) of the Lake Hawassa watershed which was prepared in Arc map.

3.5.1.2. Land use/cover data

The land use/cover map is one of the input data for the SWAT model with inclusive properties which gives the spatial extent and classification of the various land use/cover classes of the study area. For this study land use/cover map were prepared from landsat8 of 2021 with a 30mx30m spatial resolution by pixel-based supervised classification method which is applied based on Maximum Likelihood Classification (MLC) algorism using several sample training areas for individual land cover class. In addition to map preparation, the land use lookup table was prepared with SWAT code of land use database. The land use/cover map of the Hawassa watershed is shown below (Figure 3.7).

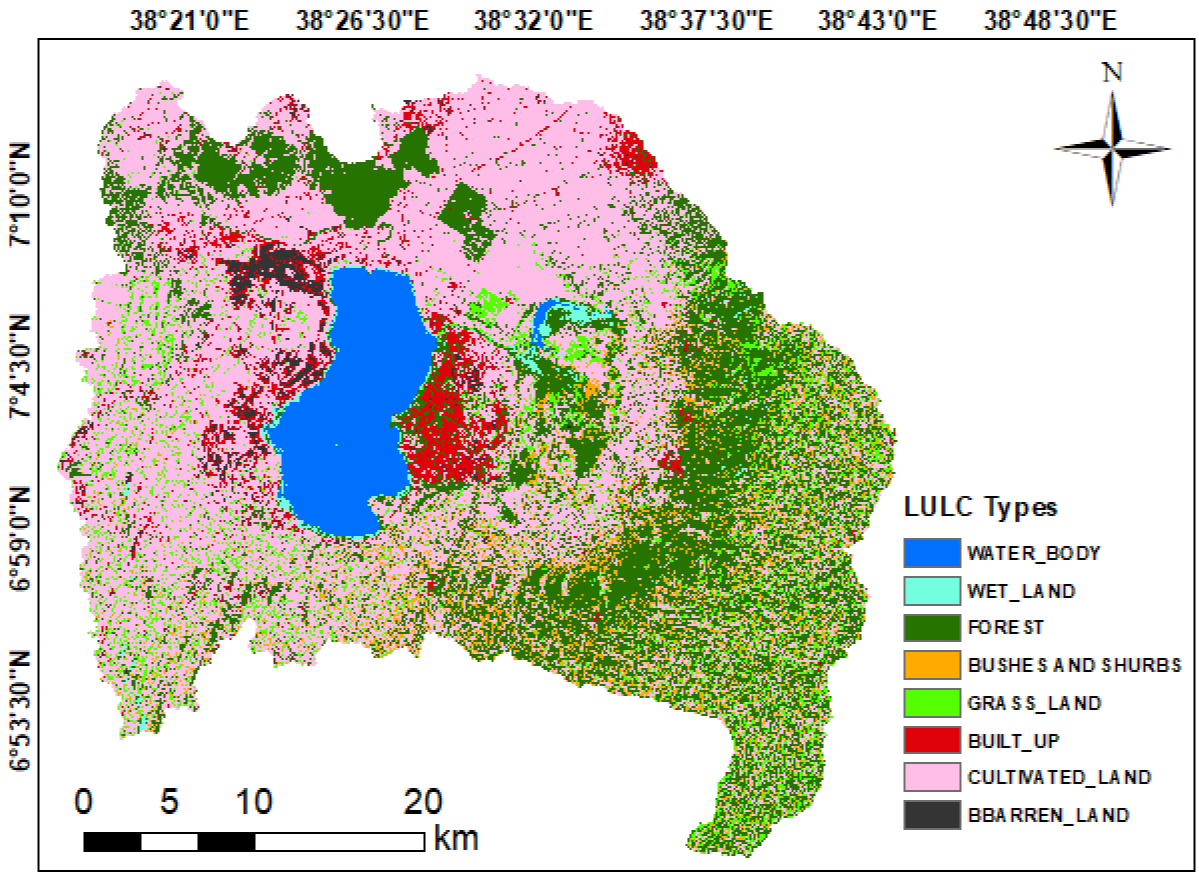


Figure 3.7 Land use land cover map of Lake Hawassa watershed.

Table 3.3: Land use/cover lookup table

Land use/cover Type	SWAT Name according To SWAT data base	Area(km^2)	%Area	SWAT code
Water Body	Water	93.7	6.52	WATR
Wet Land	Wetlands mixed	11.1	0.77	WETL
Forest	Forest mixed	391.2	27.23	FRST
Bushes and shrubs	Range - Brush	75.3	5.24	RNBG
Grass land	Range - Grasses	112.0	7.8	RNGE
Built up	Residential-High Density	64.6	4.5	URHD
Cultivated Land	Agricultural Land-Generic	665.1	46.3	AGRL
Bare Land	Barren	23.6	1.64	BARR

3.5.1.3. Soil data

Soil governs runoff generation in the watershed. SWAT model requires different soil physical and chemical properties of soil texture, available water content, hydraulic conductivity, bulk density and organic carbon content for different layers of each soil type. The soil database were extracted and collected from Harmonized World Soil Database (HWSD) and FAO soil Classification of world soil. The collected soil properties were edited to ArcSWAT2012 soil database. After the soil database has been adjusted for ArcSWAT software, the soil lookup table has been prepared with similar names of the database.

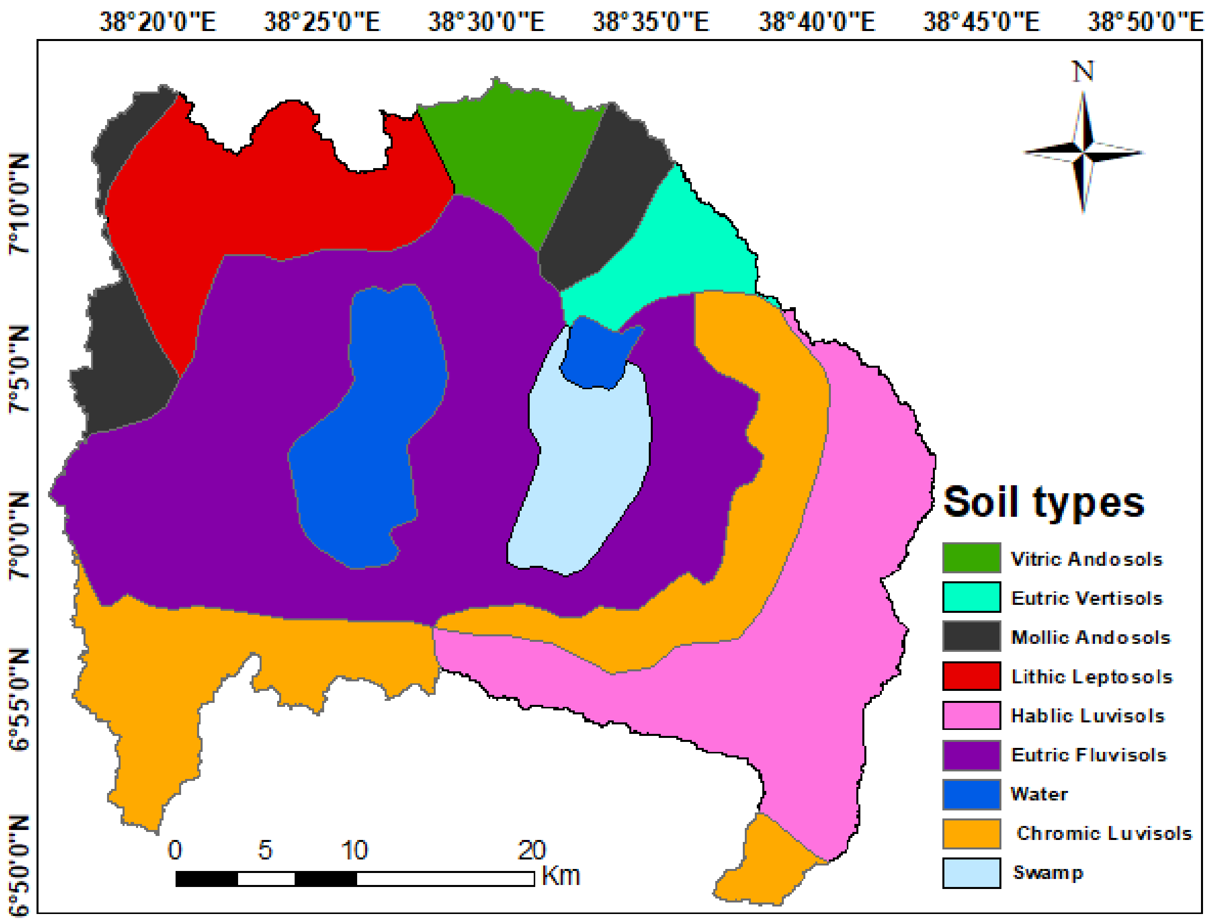


Figure 3.8: Soil map of the Lake Hawassa watershed

3.5.1.4. Weather Data

Weather data required for SWAT model are daily rainfall, maximum and minimum temperature, wind speed, relative humidity, solar radiation. For this study all the weather data was collected from five meteorological stations (Hawassa, Haisawita, Shashemene, Wendogenet and Yirbaduwancho stations). And finally the data sets were prepared for ArcSWAT interface in text format (Arnold et al., 2012).

3.5.2. SWAT Model set up

3.5.2.1. Watershed delineation

Watershed delineation using DEM is the initial step in SWAT model for watershed simulation. The watershed delineation process includes five major steps: DEM setup, stream definition, outlet and inlet definition, watershed outlet selection and definition and calculation of sub-basin parameters. SWAT allows the user to delineate the watershed and sub-basins using DEM to carry out advanced GIS functions to aid the user in dividing watersheds into several hydrological connected sub-basins for use in watershed modeling by SWAT model (Arnold et al., 2012).

The DEM of Lake Hawassa watershed was loaded into ArcGIS 10.4.1. Stream network was defined for the whole DEM by ArcSWAT model using the concept of flow direction and accumulation. The size, number of sub-basins and details of stream network depends on threshold area (Winchell et al., 2007). The user should define the threshold area to define the minimum drainage area required to form the origin of stream. The smaller threshold area gives more detail of the drainage network, large numbers of the sub-basin and Hydrologic Response Unit (HRU). But this demands more processing time. For this study we divided and delineate the catchment into both gauged and un-gauged. For both catchments the threshold area of 1,900ha was taken. The model automatically delineated the gauged Catchment in to 15 subs –catchments and the unguaged catchment in to 19 sub-catchments with the areas of 62,099.28ha and 72,406.35ha respectively (Figure 3.9).

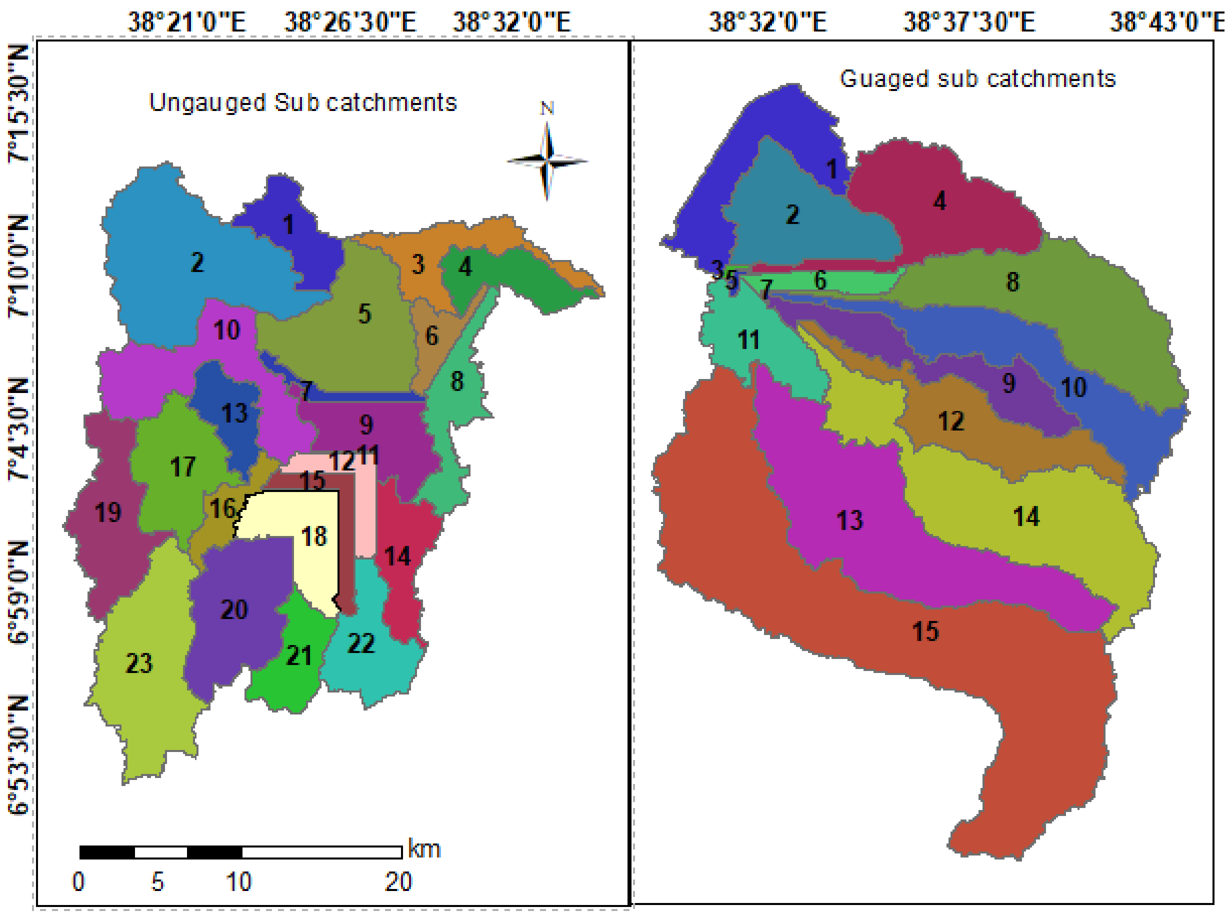


Figure 3.9: Sub catchments of the study area

3.5.2.2. Hydrologic response unit (HRU) analysis

After the completion of watershed delineation the HRU analysis was takes place. HRU analysis requires land use, soil and slope data and divides each sub-basin in to number of HRU with a unique land use/cover, soil and slope combination. The land use/cover and the soil maps were reclassified in Arc SWAT. The land slope of the study area were also classified in to five slope classes according to FAO slope classification system (i.e. 0-3%, 3-8%, 8-15%, 15-30% & >30%) and made to overlay with land use/cover and soil maps to subdivide the study watershed into hydrologic response units (HRUs). In this study, the threshold values for land use (15%), soil (10%), and slope (15%) were utilized to balance the representation detail of land use, soil, and slope with the complexity brought on by the increased number of HRUs. Subdividing areas in to hydrologic response units enables the model to reflect the evapotranspiration and other hydrologic conditions for different land use, soils and slopes. The HRUs are the elementary units with unique land cover, soil and slope angle lumped together. Finally 208 and 203 HRUs were defined for gauged and un-gauged catchments respectively.

3.5.2.3. Weather data definition

Weather generator

Weather generator (WGEN) in SWAT model used to generate climatic data and to fill missing values in the measured records (Sharpley et al., 2003). For this study Hawassa meteorological station was synoptic station which has full weather data and generates data for the other stations having precipitation and temperature data only. Weather generator data of the study area was calculated using WGEN excels macro. Download the WGEN excel macro from SWAT (https://swat.tamu.edu/) to develop weather generator (WGEN user) for the study area.

The weather generator developer called precipitation statistical analysis model (PCP STAT) was used to statistical analyzing of daily precipitation data needed to create user weather station files for SWAT model. Dew point (dew02) was additional software for weather generator. It is used for generating average daily maximum and minimum temperature, humidity and dew point in month. The available sunshine hour data was converted to solar radiation by using Angstrom- Prescott empirical equation. The Angstrom- Prescott empirical equation described as follows.

$$R_S = \left(a_s + b_s \frac{n}{N}\right) R_a \qquad (3.3)$$

Where, R_s is solar or shortwave radiation [MJm-2day-1], n - Actual duration of sunshine [hour], N - Maximum possible duration of sunshine or daylight hour [hour], R_s - Extra-terrestrial radiation [MJm-2day-1], a_s - Regression constant, expressing the fraction of extra-terrestrial radiation reaching the earth on overcast days (n=0), a_s +b_s - Fraction of extra-terrestrial radiation reaching the earth on clear days (n=N).

Weather stations geo-referenced using latitude, longitude and elevation data. Prepared weather parameters have been loaded into a WGEN user of SWAT database and the missed weather data for the rest stations found in the study area automatically generated.

3.5.2.4. SWAT model simulation

After weather data definition, the SWAT input tables were written into the model. Some SWAT default input files were edited manually before the model was run for simulation. Finally, the model was run for 31 years (1991 to 2021) by fixing the warm up period of three years. The simulated result cannot be directly used for further analysis (White & Chaubey, 2005). Therefore, the simulated result should be evaluated through sensitivity analysis, model calibration and validation.

3.5.3. SWAT model calibration, validation and performance evaluation

The SWAT model calibration is a set of parameters adjustment to provide the best possible correspondence between recorded and simulated flow from a catchment. In this study, the SWAT model calibration and validation were 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 finds out the most favorable model parameters within the uncertainty ranges of 95% after incorporating the possible parameters ranges. The stream flow data from 1994-2005 and the sensitive parameters which govern the watershed were obtained and ranked according to their sensitivity rank was used for calibration.

Model validation is testing of calibrated model results with independent set of measured data (stream flow) without any further adjustment of parameters. For this study five years (2006-2010) of flow data used for validation period.

The model performance was evaluated through a set of objective functions that measure the goodness-of-fit between simulated and observed hydrograph. For this study, model simulation was evaluated using efficiency criteria such as coefficient of determination (R^2), Nash and Sutcliffe simulation efficiency (NSE), and PBIAS. In general, R^2 and NSE were used to evaluate the model ability to reproduce the pattern of the observed hydrograph. The PBIAS was used to quantify the error between observed and simulated stream flow. The coefficient of determination R^2, Nash-Sutcliffe coefficient of efficiency (NSE), and PBIAS were estimated by:

$$R^2 = \left(\frac{\sum_{i=1}^{n}(Q_{obs}-\bar{Q}_{obs})^2-\sum(Q_{sim}-\bar{Q}_{sim})^2}{\sum(Q_{obs}-Q_{sim})^2}\right) \text{--} \quad (3.1)$$

Where; Q_{obs}= observed discharge, Q_{sim}=Simulated discharge, $\bar{Q}_{obs}$= mean of observed discharge, $\bar{Q}_{sim}$=mean of simulated discharge, R^2 indicates how the simulated data value correlated to the observed data. The range of R^2 extends from 0 (unacceptable) to 1(best).

$$NSE = 1 - \frac{\sum(Q_{obs}-Q_{sim})^2}{\sum(Q_{obs}-\bar{Q}_{obs})} \text{---} \quad (3.2)$$

Where; Q_{obs}= observed discharge, Q_{sim}=Simulated discharge, $\bar{Q}_{obs}$= mean of observed discharge, NSE = Nash - Sutcliffe coefficient of efficiency. Nash-Sutcliffe efficiency can range from -∞ to 1, an efficiency of NSE =1 Corresponding to a perfect match of modeled discharge to the observed data. The closer the model results to 1 the more accurate the model is.

PBIAS = $\sum \frac{\sum(Q_{obs}-Q_{sim})}{\sum Q_{obs}} * 100$-- (3.3)

Where: Q_{sim} is the simulated value, Q_{obs} is the observed value. A value close to 0% is best for PBIAS. A negative value indicates model overestimation and a positive value indicate model underestimation.

Table 3.4: Model performance evaluation criteria ((Moriasi et al., 2007; Santhi et al., 2001)

Rating	R^2	ENS	BBIAS
Very good	0.75 - 1	0.75 - 1	< ±10%
Good	0.65 - 0.75	0.65 - 0.75	±10% - ±15%
Satisfactory	0.60 – 0.65	0.50 – 0.65	±15% - ±25%
Unsatisfactory	< 0.60	< 0.50	> ±25%

3.5.4. Sensitivity Analysis

Sensitivity analysis is a method of identifying the most sensitive model parameters that have a significant effect in model calibration. Model sensitivity analysis can be useful in understanding which model inputs are most important and to understand potential limitations of the model.

In this study, stream flow sensitivity analysis performed by SWAT_CUP using SUFI-2 algorithm. The sensitivity analysis was carried out for a period of twelve years (January 1, 1994 to December 31, 2005). Global sensitivity analysis uses t-stat and p-values to determine the sensitivity of each parameter (Abbaspour, 2014). The t-stat provides a measure of the sensitivity (larger in absolute values are more sensitive) and the p-values determine significance of the sensitivity. A p-value close to zero has more significance (Abbaspour, 2014).

3.5.5. Transferring sensitive calibrated parameters to un- gauged catchments

Following calibration and validation of the SWAT model in the gauged Tikurwuha River catchment; the final calibrated sensitive parameters were transferred to SWAT model with in the Edit SWAT input part by selecting the parameters and edit the value of the sensitive parameters to estimate the water balance of the un-gauged catchments of the Lake watershed.

3.6. Water Balance

The study of water balance is the application of the principle of conservation of mass in hydrology and the equilibrium can attain between inflow and outflow components and the change in storage for each interface of time of any hydrologic regimes. The water balance components of the lake watershed were computed in SWAT model. As described in the above section 2.4.1 SWAT model have two major components: The Land phase and The Routing phase of the hydrologic cycle. The Land phase of the hydrologic cycle is simulated based on the water balance equation (2.1) that controls the water movement in the land.

The SWAT model estimates average annual basin values for different water balance components of the Watershed. Precipitation was the input, whereas surface runoff, lateral soil flow, groundwater flow, shallow aquifer recharge, deep aquifer recharge and actual evapotranspiration were outputs. The sum of surface runoff, lateral soil flow and groundwater contributions minus transmission loss (water lost from tributary channels in the HRU via transmission through the bed and becomes recharge for the shallow aquifer during the time step) is the total water yield, whereas the change in soil water storage is the difference between inflow and outflow.

The water balance was simulated for the base period of 31 years 1991 to 2021 on daily time step. First we simulate the gauged catchment and calibrating the result with the observed discharge and then we transfer the calibrated sensitive parameters in to the SWAT model to simulate the unguaged catchments water balance.

3.7. General circulation model (GCM) set up and climate change scenarios

Climate change scenario was obtained from GCM of the World Climate Research Program's (WCRP's) Coupled Model Inter-comparison Project phase 5 (CMIP5) multi-model dataset (Wilby and Dawson, 2007). For this study, canESM2 (Canadian Second Generation Earth System Model) which was freely available at the Canadian climate change scenario group website **(**http://ccdsdscc.ec.gc.ca/?page=pred-canesm2**)** was used and downscaled to the site level using the Statistical Downscaling Model (SDSM). The model results were available for RCP2.6, RCP4.5 and RCP8.5 scenarios. The results were used to produce the future period scenarios.

This model was applied in this study because of the GCM model is widely applied in many climate change impact studies in our country, The results of CanESM2 can be easily downscaled using SDSM (Dile et al., 2013) and the model provides daily predictor variables which can be used for the

Statistical Downscaling Model. The model provides large scale daily predictor variables which could be used for the statistical downscaling model (SDSM) (Wilby and Dawson, 2007), and also a single run was downloaded for each scenario, and data were extracted for the pixel containing the observation stations. Lastly, the model has given 20 ensemble model result when statistically downscaled and correctly used RCP scenario that have high climate mitigation policy (Riahi et al., 2007) and RCPs offer a better understanding in terms of the concentration of future greenhouse gases for running climate models than previous scenarios (Meinshausen et al., 2011).

3.7.1. Downscaling Techniques and predictor variables selection

For this study, SDSM 4.2.9 decision support tool for the assessment of regional climate change impacts developed by Wilby and Dawson (2007) was used to downscale large-scale predictors and it was freely downloaded from http://www.sdsm.org.uk/. SDSM develops statistical relationships, based on multiple linear regression techniques, between large-scale (predictors) and local (predictand) that is precipitation, maximum and minimum temperature for this study which was used as an input for hydrological modeling.

Large-scale predictor variable information is freely obtained from the Canadian climate impact scenario group with web address of: http://ccdsdscc.ec.gc.ca/?page=pred-canesm2/. The National Center for Environmental Prediction (NCEP_1961-2005) reanalysis data and CanESM2 predictor variables for the RCP2.6, RCP4.5 and RCP8.5 are obtained. The required predictor data that represents the watershed were downloaded from the nearest average location of the watershed (Wilby and Dowson, 2007).

The choice of appropriate downscaling predictor variables was undertaken through the screen variable option of SDSM using correlation analysis, Partial correlation analysis, and scatter plot partial correlation analysis for selected predictors to get the level of correlation with each other. These statistics identify the amount of explanatory power of the predictor to explain the predictand (Wilby and Dawson, 2007). Finally, the scatter plot will carry out to identify the nature of the association (linear, nonlinear, etc.), whether or not data transformation(s) may be needed, and the importance of outliers. In this study, predictors with relatively high partial correlation value, and a P-value less than 0.05 are selected.

SDSM model has two processes called conditional and unconditional processes to be specified before the analysis takes place. In case of daily temperature the predictand-predictor process is not regulated by the intermediate process, so, the unconditional process was used, whereas, for daily precipitation where the amounts depend on the occurrence of wet-day, then the conditional process was chosen (Benestad et al., 2008). Significance value is used to test the significance of predictor–predictand correlations and it was set as the default of the probability level at 0.05 ($p<0.05$). Several analyses were made by selecting a maximum of 6 out of 26 predictor variables at a time till best predictor-predictand correlations were found even though up to 12 predictors are possible to select at a time (Wilby and Dowson, 2007).

3.7.2. SDSM model calibration and validation

The downscaling model was calibrated based on multiple linear regression equations between daily predictand data (meteorological station data) and GCM predictor variables (GCM model outputs). In this study calibration was done by using selected Screen Variables and level of the variance in the local predictand of daily precipitation, maximum and minimum temperature of the stations described in the above section 3.3.2.1. Daily data were used for model calibration for data representing the current climate condition of the period 19 years (1991-2009). The event threshold is set to 0°C for temperature and 0.1 mm/day for precipitation in order to treat trace rain days as dry days (Wilby and Dawson, 2004).

The Weather Generator enables the verification of calibrated models (assuming the availability of independent data) as well as the synthesis of artificial time series representative of present climate conditions. The Weather Generator can also be used to reconstruct predictands or to infill missing data. Each time serious data of the observed climate variable is linked to the regression model weights to generate the synthetic time series data into a serious of ensembles (runs). The results among the ensembles differ based on the relative significance of the deterministic and stochastic components of the regression models and mainly due to the stochastic component of the downscaling (Wilby and Dawson, 2007).

In this study validation was done based on 12 years of simulation for years (2010–2021). The result of the weather generator was used to validate the calibrated model using independent observed data not used during the calibration procedure and the synthesized artificial weather time series data representing the present condition.

3.7.3. Scenario generation

The period from 1991-2021 were considered as a base period whereas the period from 2022-2100 were considered as future periods. The future periods have been divided into three time horizons; from the 2020s (2022-2040), 2050s (2041-2070), and 2080 (2071-2099) and analyses were made for each time horizon for the RCP 2.6,RCP 4.5 and RCP 8.5 emission scenarios. The Scenario Generation process produces daily base data for maximum temperature, minimum temperature and precipitation for the entire period 1991-2099 including the future time periods. Each predictand is generated based on the calibration result and the daily atmospheric predictors of the CanESM2. The calibration result is used based on the assumption that predictor-predictand relationships under the current condition remain valid under future climate conditions.

4. RESULT AND DISCUSSION

4.1. Projected climate Change results

4.1.1. Predictor variable selection

The selected predictors from National Centers for Environmental Prediction (NCEP) data were chosen to calibrate the SDSM model. Screening was done for each station based on partial correlation and P-value. Predictors were selected when they showed a significant relationship with the predictand variables (i.e., rainfall, maximum temperature, and minimum temperature). In this study, predictors with relatively high partial correlation value, and a P-value less than 0.05 were selected.

For Hasiawita Station Surface air flow strength & Specific humidity at 850 hpa[1] were selected for daily precipitation while Surface wind direction, mean temperature at 2m and surface divergence are the predictors that were used for maximum and minimum temperature.

In Hawassa station 500 hPa wind direction and 850 hPa vorticity were the predictors selected for precipitation. The predictors that were used in predicting minimum and maximum temperature were 850 hPa wind direction, 850 hPa vorticity, 500 hPa meridionalvelocity and Mean temperature at 2m.

500 hPa geopotential height & Surface specific humidity are the predictors that were selected to predict Wendogenet station precipitation. Yirbanduncho station precipitation had a significant relationship with 850 hPa vorticity and Specific humidity at 850 hPa pridictors.

Surface zonal velocity and 850 hPa geopotential height were selected for Shashemene station precipitation, whereas 850 hPa geopotential heights, Surface specific humidity, Surface zonal velocity and 850 hPa wind direction were selected for temperature prediction.

4.1.2. SDSM model calibration and validation

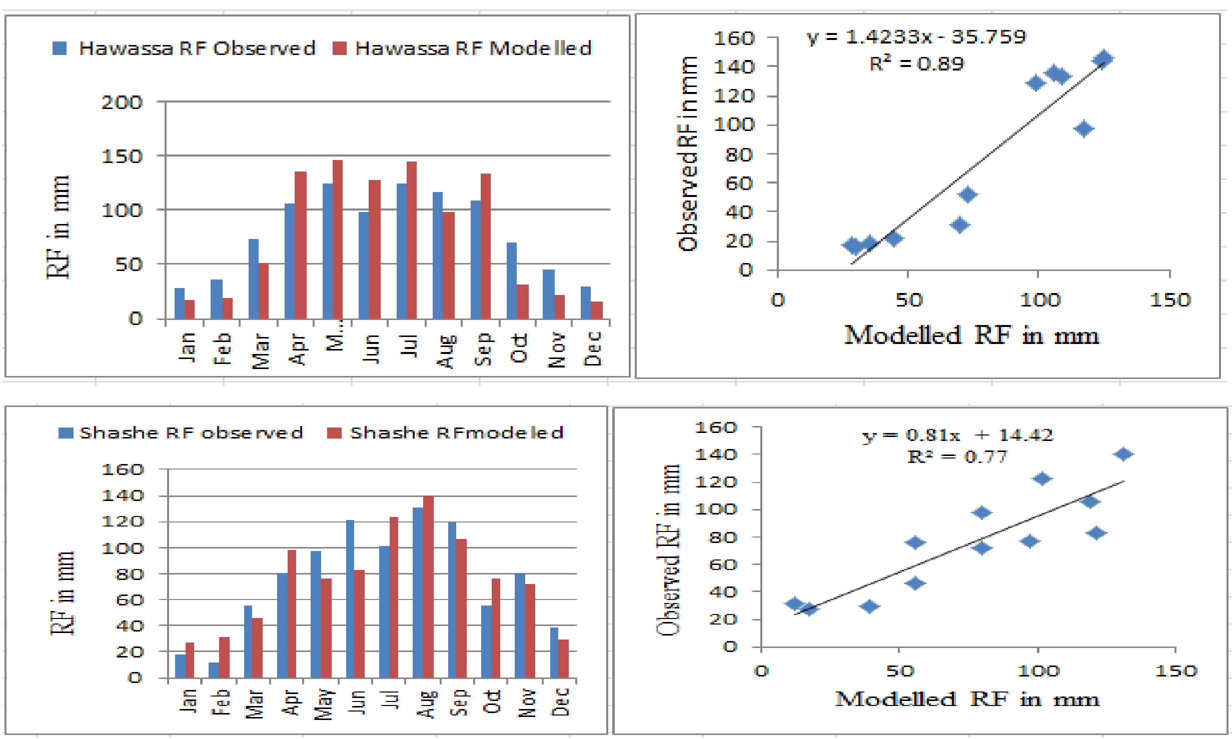
The SDSM calibration was done for the observed climate data from 1991-2009 for 19 years at a monthly model type in order to see the monthly temporal variations. Monthly precipitation, maximum and minimum temperature values were generated based on the above selected predictor variables of the NCEP data. 20 ensembles were generated and the average of these ensembles was taken as a simulated result for each predictand variables. The results showed that, modelled

[1] hpa is a unit of pressure, 1 hPa = 1 mbar = 100 Pa

precipitation, maximum and minimum temperature had good agreements with the observed results in all of the stations. However, the calibration result of precipitation showed relatively lesser agreement as compared to the maximum and minimum temperature, due to the fact that precipitation is a conditional process that is dependent on other intermediate processes like on the occurrence of humidity, cloud cover and/or wet-days. But unconditional processes like temperature are not regulated by other intermediate processes (Wilby and Dawson, 2007). The overall agreement was very good which are summarized in the following table 4.1 and figures 4.1.

Table 4.1: Calibrated precipitation, maximum and minimum temperature

Pridictand	R^2 for calibration				
	Hawassa	Haisawita	Shashemene	Wendogenet	Yirba
Precipitation	0.89	0.86	0.77	0.81	0.82
Tmin	0.94	0.92	0.93		
Tmax	0.94	0.91	0.95		



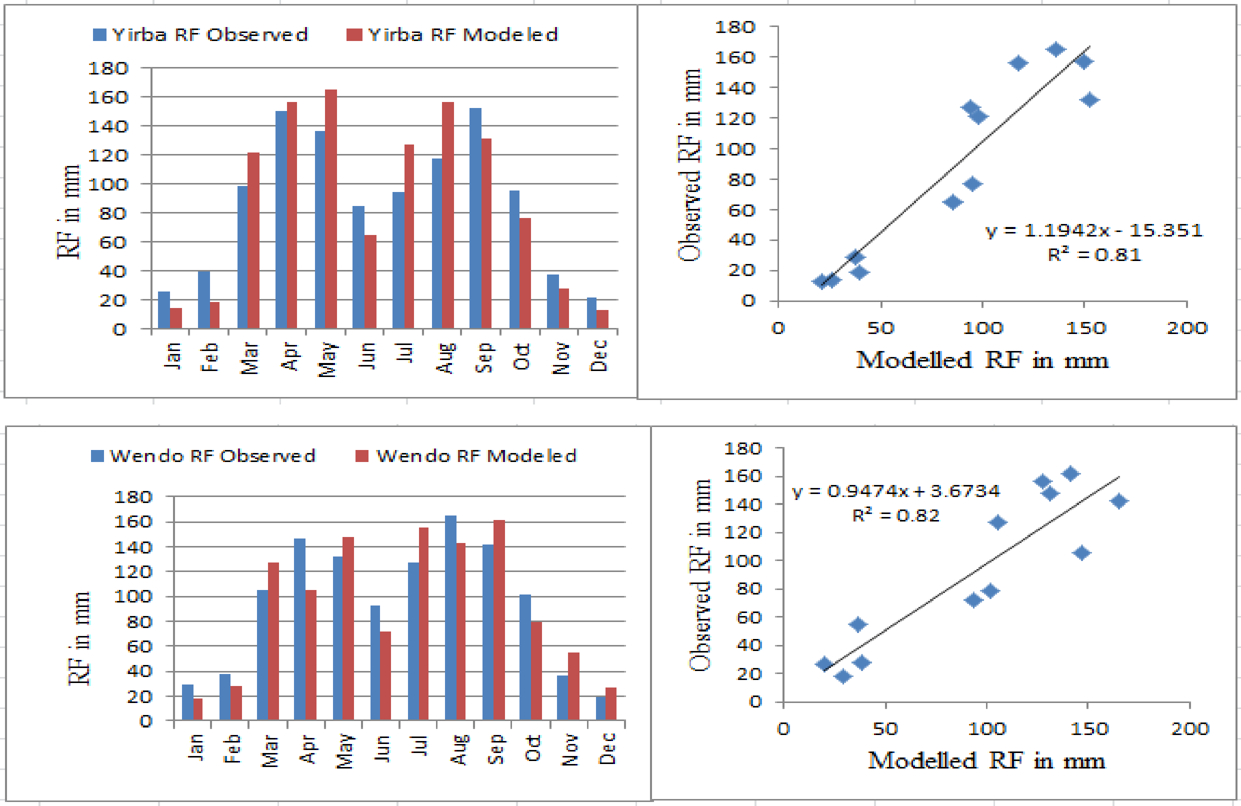


Figure 4.1: The observed and modeled precipitation of the five stations in Hawassa watershed

Validation was done using an independent observed data for the period of twelve years from 2010 to 2021. Here also twenty ensembles (runs) of daily values were generated and the averages of these ensembles were taken for the comparison. The correlation coefficients that were found during the calibration are also maintained during the validation as shown in Table 4.5. A good agreement was also found between the observed and simulated precipitation, minimum and maximum temperature.

Table 4.2: Validated precipitation, maximum and minimum temperature

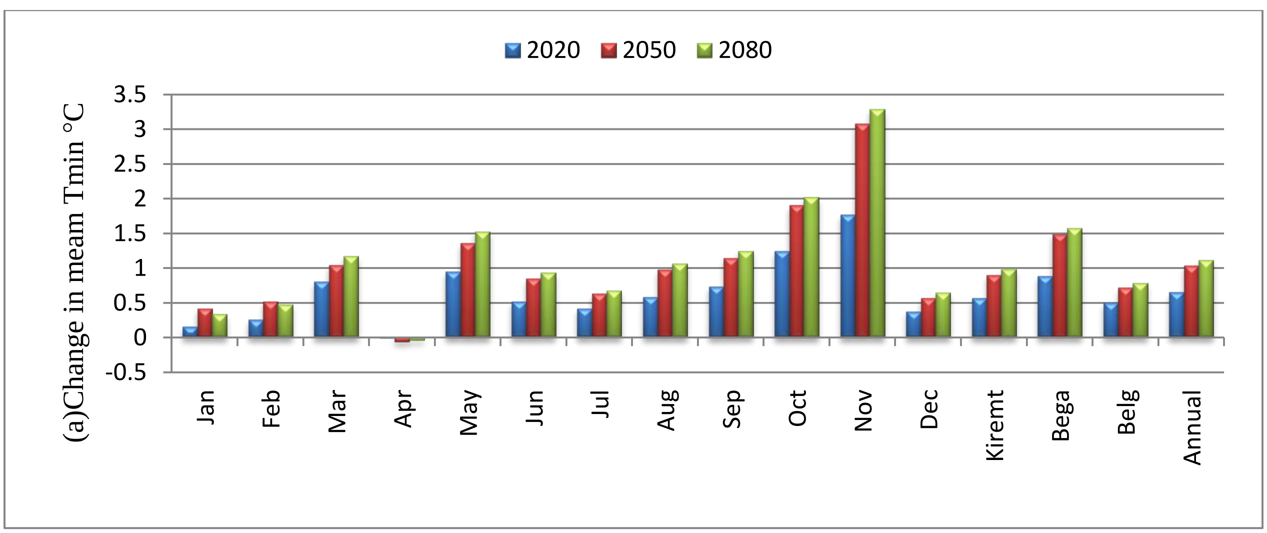
Pridictand	R^2 for validation				
	Hawassa	Haisawita	Shashemene	Wendogenet	Yirba
Precipitation	0.88	0.84	0.76	0.78	0.77
Tmin	0.92	0.91	0.92		
Tmax	0.93	0.91	0.91		

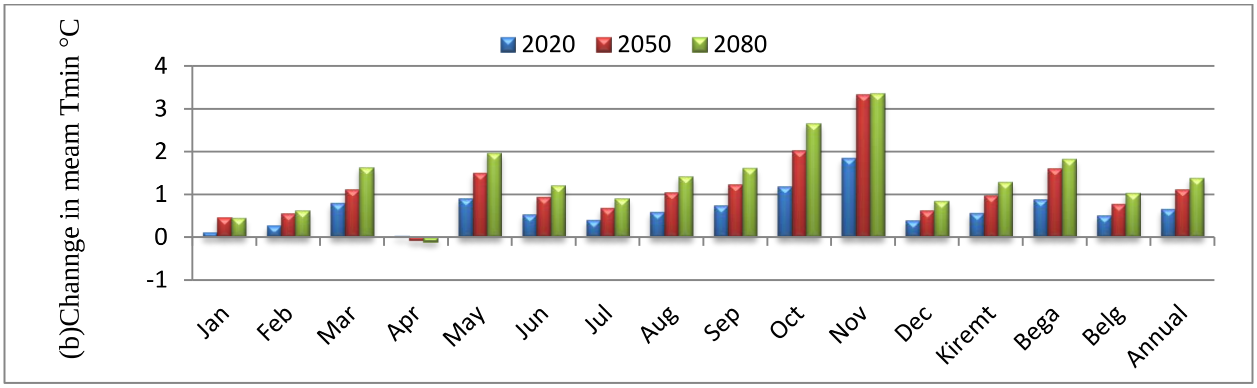
4.1.3. Future Monthly, Seasonal & annual climate variables

The climate scenario for the future period was generated from statistical downscaling using the GCM predictor variables for the three emission scenarios for the period of 2022-2099 for 78 years based on the mean of 20 ensembles. In this study the meteorological station records of the study area from 1991-2021 was taken as a base period within which the comparison was made. The observed climatological data collected from Ethiopian meteorological agency contain more consistent time series records from 1991 than the period before 1991 and this is why the period from 1991-2021 was taken as a base period.

4.1.3.1. Minimum Temperature

The results for monthly mean minimum temperature showed an increasing trend for the three scenarios and three time periods for Hawassa station. But there will be a decreasing trend in April for both time periods 2050 and 2080 in all the three scenarios. The highest increment of minimum temperature was projected on RCP_8.5 scenario in the month of November 3.74°C, 2080s period. The annual mean minimum temperature in this station increases from 0.64°C - 2.16°C. For Haisawita and Shashemene stations annual mean minimum temperature increases from 0.44°C - 1.21°C and 0.61°C – 1.43°C respectively. But the seasonal mean minimum temperature for Kiremt, Bega and Belg shows general increasing trend over all the catchment in all senarios. This generally shows an increasing trend which is in line with previous studies conducted on Bilate watershed of the Central Rift Valley of Ethiopia (Tekle, 2010). The study also consistent with the study conducted by (Tesfalem et al., 2018) on the hydrology of Lake Ziway catchment using CMIP5 RCP scenarios which indicates a general increasing under RCP-4.5 scenarios.





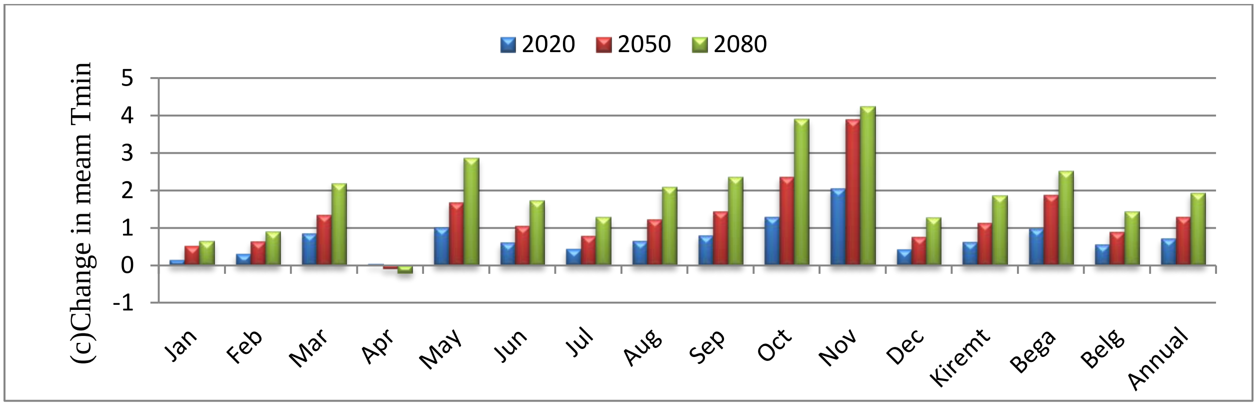


Figure 4.2: Change in mean monthly seasonal and annual minimum temperature from the baseline period for canESM2 RCP2.6 (a), RCP4.5 (b) and RCP8.5 (c) at Hawassa station.

4.3.3.2. Maximum Temperature

The mean monthly and annual change in maximum temperature for the future period for all scenarios will increases as shown in Figure 4.6 (a, b, c). For Hawassa station annual average maximum temperature change increases from +0.34°C to +1.01°C, Whereas for Haisawita and Shashemene stations the mean maximum temperature change will be increases from (0.2 – 1.76) °C and (0.13-1.93) respectively. As it can be seen from the results for annual mean maximum temperature showed an increasing trend for the three scenarios (RCP2.6, RCP4.5 and RCP8.5) with respect to monthly maximum temperature, the downscaled maximum temperature in all scenarios indicates that there might be an increasing trend in months, January February, May, Jun, July, August, September and December but a decreasing trend in March, April, October and November from 2022 to 2099 in Hawassa station.

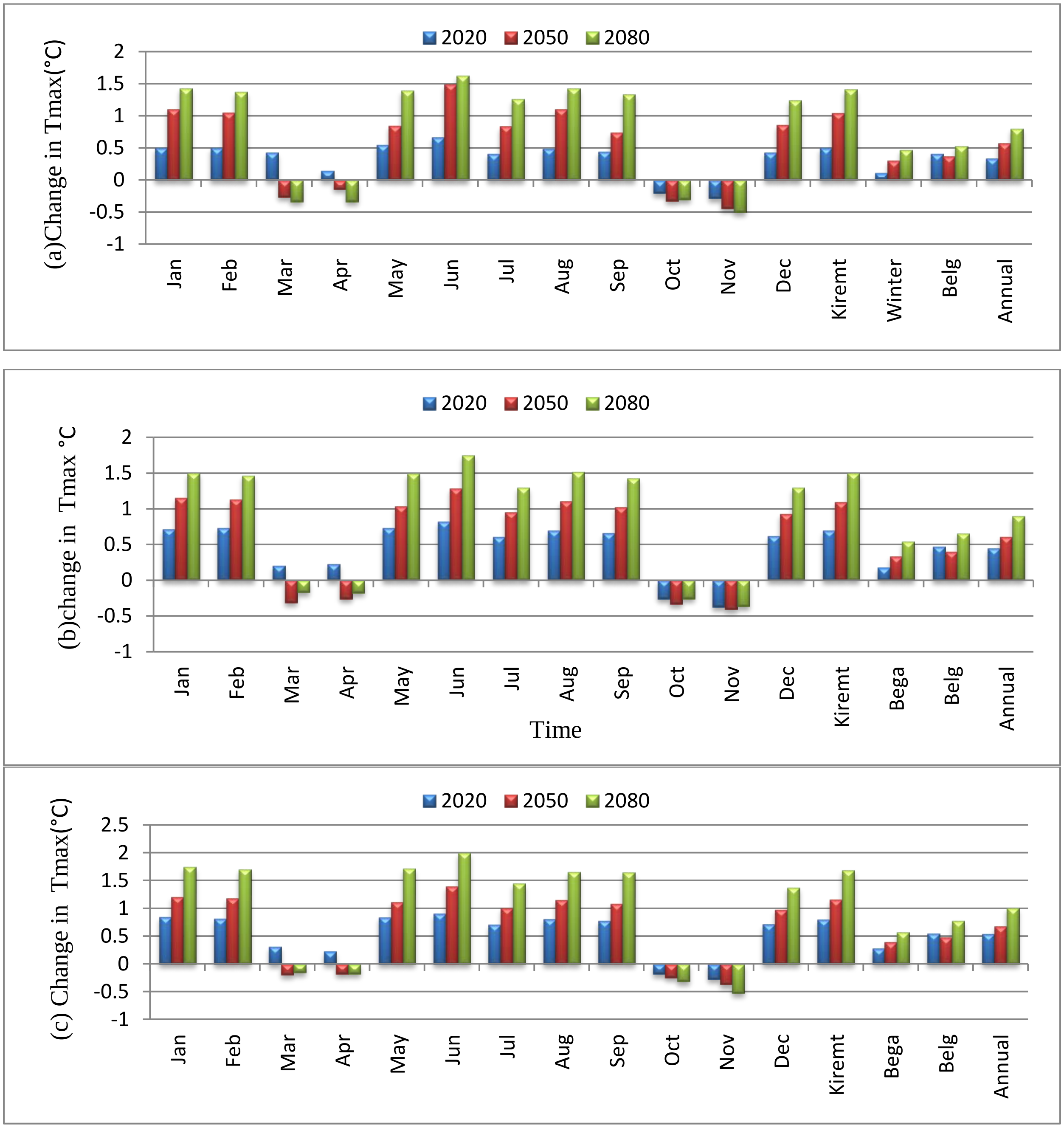


Figure 4.3: Change in mean monthly, seasonal and annual maximum temperature from the baseline period for canESM2 RCP2.6 (a), RCP4.5 (b) and RCP8.5 (c) at Hawassa station.

For Haisawita station the downscaled mean maximum temperature increases in the months of January, February, May, Jun and October in all RCPs for the three time periods from 0.2 to 1.76 °C. But the mean maximum temperature shows a slight decrement in the months of March, April, July, and September from 0.04 to 0.8 °C. In shashemene Station the mean maximum temperature increases in all the eight months for all RCPs and time horizons except in March, Jun, July and

January which will be decreases. But the seasonal average maximum temperature will increase in all stations nearby the catchment for all the time horizons in all scenarios.

Generally the downscaled mean maximum temperature shows an increasing trend in this watershed which is in line with the previous work by Alehu and Bitana, (2023) the climate change impact on water balance of Lake Hawassa catchment. The result also consistent with the investigation by (Mesfim, 2014) on Lake Hawassa Catchment by using RCM output of A1B scenario the monthly maximum temperature simulation indicates an overall increase pattern of 0.1 to 1.4°C at 2030s and 1.5 to 3.15°C at the 2090s. And also similar to an analysis those Belay et al., (2012) conducted in the Rift Valley basin, which concluded that daily temperature occurrences will increase under future scenarios.

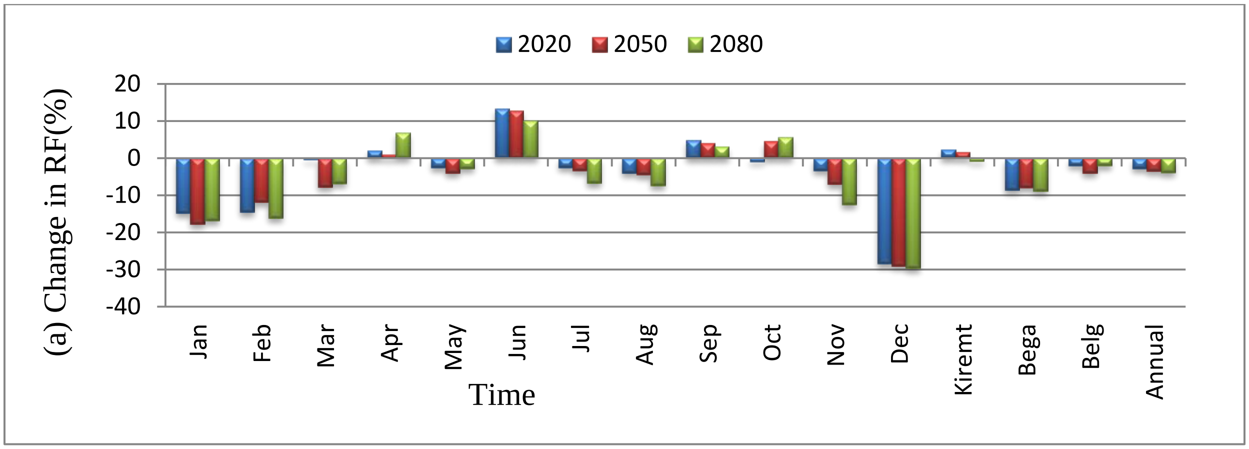
4.3.3.3. Precipitation

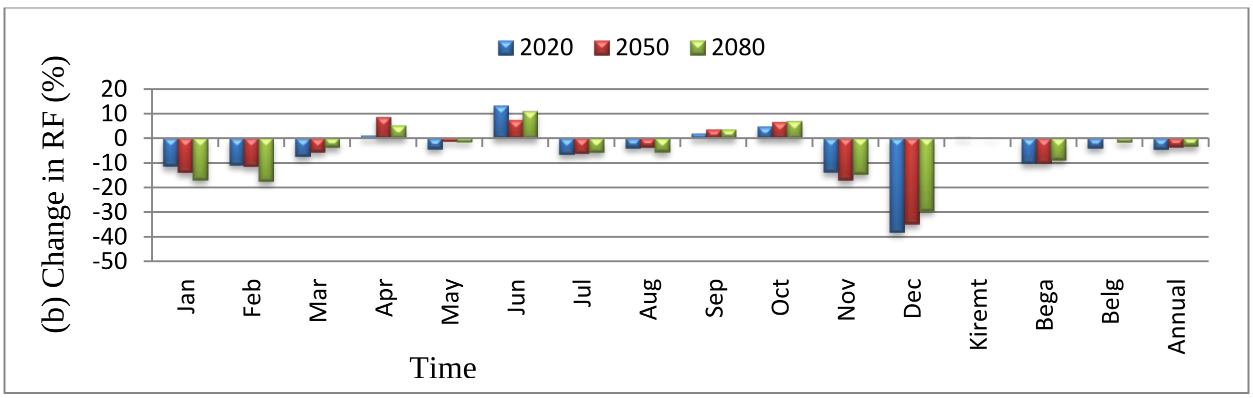
The future projected annual precipitation shows a general decreasing trend. As it can be seen from Figure 4.7 (a, b and c) the results for annual percentage change in precipitation showed decreasing trend for the three scenarios (RCP2.6, RCP4.5 and RCP8.5). In 2020s (2022-2041) the decrement of annual percentage changes of precipitation were -4.25%, -6.21% and -5.05% for RCP2.6, RCP4.5, and RCP8.5 scenarios respectively. In 2050s (2041-2070) the decrement of annual percentage changes of precipitation were -5.22%, -5.55% and -5.74% for RCP2.6, RCP4.5 and RCP8.5 scenario respectively. In 2080s (2071-2099) the decrements of annual percentage changes of precipitation were -6.05%, -5.64% and -4.3% for RCP2.6, RCP4.5 and RCP8.5 scenario respectively.

On monthly basis, the percentage change in precipitation increases in some months and decreases in some other months. The percentage changes in precipitation decreases in the months of January, February, March, May, July, August, November and December, but increases in April, June and September months for the future periods for all scenarios. There is also slight decrement in October in RCP_2.6 in the three future periods but increases in RCP_4.5 and RCP_8.5 scenarios in the three future periods.

On the seasonal bases the future precipitation of Hawassa station shows slight increments in RCP_ 2.6 for 2020 and 2050 but for over all the catchment the seasonal precipitation shows a decreasing trend for all time horizons in all scenarios.

The general decrement in the downscaled annual precipitation result was consistent with the result reported by (Tesfalem et al., 2018) on the hydrology of Lake Ziway catchment using CMIP5 RCP scenarios which shows a general decreasing trend under the three GCMs outputs (HadGEM2-ES, CSIRO-MK 3-6-0 and CCSM4) for future periods 2020s, 2050s and 2080s. And also the result confirms that the occurrence of warming across Ethiopia reported by (Conway, 2000) and decline in precipitation up to 25% by (Monireh et al., 2013).





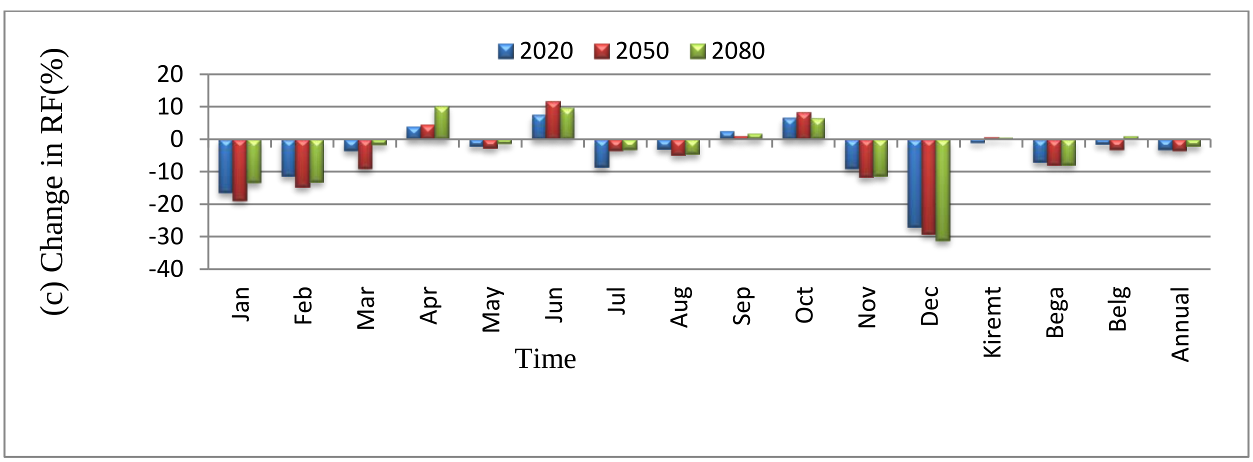


Figure 4.4: Percentage change in monthly, seasonal and annual precipitations in the future three times periods from the base period for canESM2 RCP2.6 (a), RCP4.5 (b) and RCP8.5 (c) at Hawassa station.

4.2. SWAT Model Results

4.2.1. Calibration and Validation

Flow calibration was performed for a period of twelve years from January 1, 1994 to December 31, 2005. However, flow was simulated for thirty-one years from January 1, 1991 to December 31, 2021 with in which the first three years was considered as a warm up period. Flow validation was performed for a period of five years from January 1, 2006 to December 31, 2010. The parameters were allowed to vary during the calibration process within acceptable ranges until an acceptable fit between the measured and simulated values was obtained; no changes were made to the calibrated parameters during the 5-year of validation. The calibration and validation performance evaluation results were shown in Table 4.3.

Table 4.3: Summary of model performance result for monthly flow of Tikurwuha river at Dato gauging station (1994- 2009)

Model performance indicators	**Calibration**	**condition**	**Validation**	**condition**
R^2	0.74	good	0.71	good
NSE	0.79	Very good	0.76	Very good
PBIAS	-11.3	good	-13.4	good
P- factor	0.73		0.71	
r- factor	0.77		0.75	

The calibration and validation results for the gauged station in the above Table 4.3, shows that there is a good agreement between the simulated and observed flows. The general performance rating of recommended statistics for monthly time step as suggested by (Moriasi et al, 2007) indicates R^2>0.6, and ENS>0.5, and PBIAS<±25. Based on this recommendation, the results were in acceptable range. The calibration and validation result were in line with the result reported by Alemayehu, 2019 that the R^2 and PBIAS values were 0.79 & -13.9 for calibration and 0.86 & -11.4 for validation respectively in Tikurwuha River. (Lencha,S.M, et al,.(2022) also reported the R^2 , NSE & BPIAS values of 0.8 & 0.76 & -11.6 during calibration & 0.8, 0.76 & -3.9 during validation respectively for Tikurwuha River.

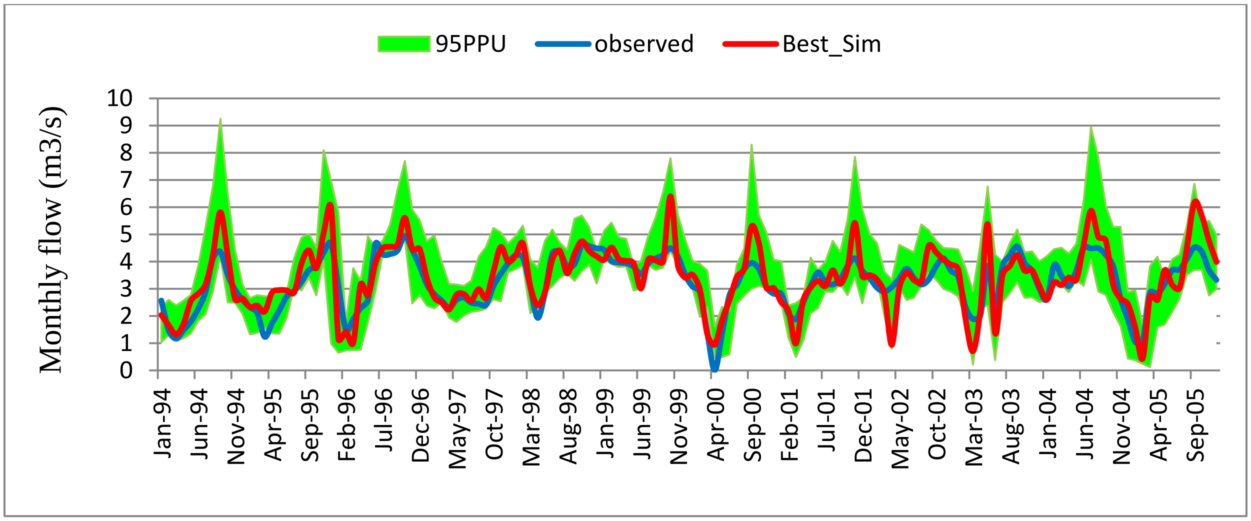


Figure 4.5: Observed and simulated monthly flow hydrograph during calibration at Dato gauging station (1994-2005)

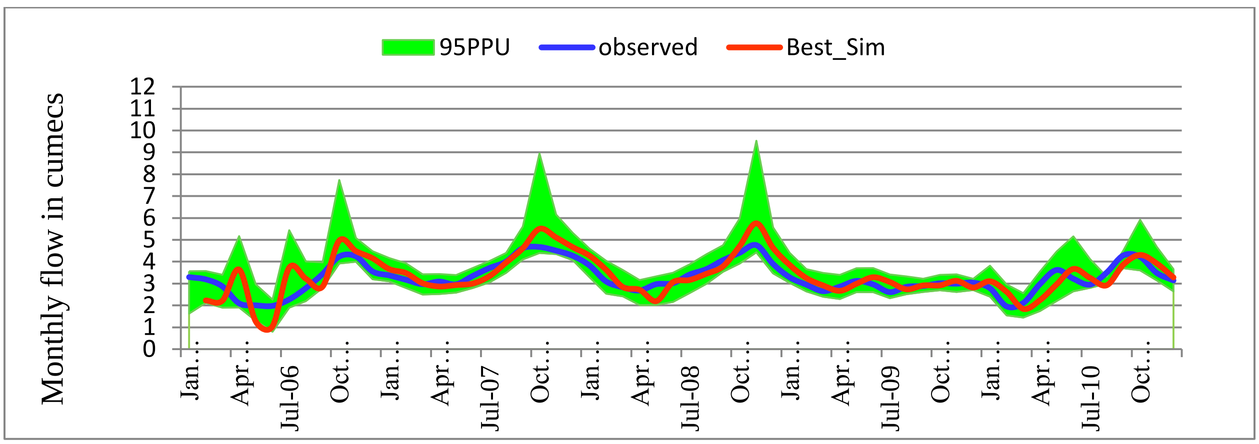


Figure 4.6: Simulated and observed monthly discharge at Dato gauging station during validation

4.2.2. Sensitive parameters

The Lake Hawassa watershed model parameter with the highest sensitivity was determined through sensitivity analysis. It was carried out for a 12-year calibration period (January 1, 1994 to December 31, 2005). The ranks of the parameters were assigned based on the findings of the SUFI-2 sensitivity analysis and the p-value and t-statistics. P-value denotes the significance of the sensitivity, and t-stat gives the parameter sensitivity measurement (Abbaspour, 2014). The parameter is more sensitive when the t-absolute statistic's value is larger, and the parameter is more significant when the p-value is closer to zero. Twelve variables were chosen to test the sensitivity analysis, & Table 4.4 below ranks the variables that affect runoff in the research area.

Table 4.4: Sensitive parameters in Hawassa watershed

Parameter Name	t-Stat	P-Value	rank
EPCO	4.8400	0.0000	1
SOL_Z	-4.3090	0.0000	2
ALPHA_BF.gw	3.0748	0.0028	3
CN_2	2.8987	0.0047	4
CH_N2	-2.3476	0.0211	5
CH_K2	2.0818	0.0403	6
ESCO	2.0351	0.0449	7
SOL_K	1.7545	0.0828	8
OV_N	-1.7232	0.0884	9
HRU_SLP	-1.5168	0.1329	10
SOL_AWC	1.2059	0.2311	11
SOL_BD	0.8485	0.3985	12
GW_DELAY	-0.2335	0.8158	13

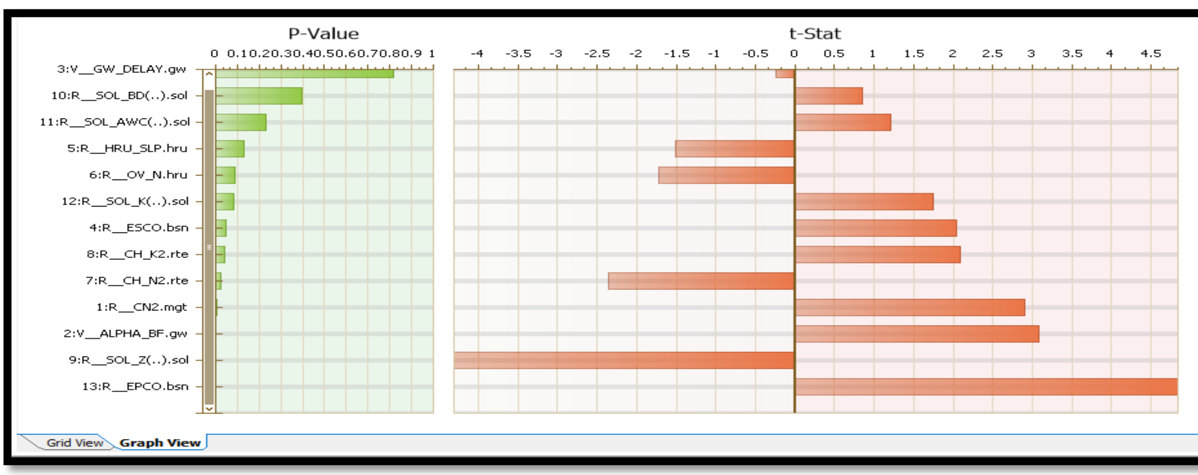


Figure 4.7: Global sensitivity results according to SWAT-CUP during calibration.

The 12 most sensitive parameters have a meaningful effect on the monthly flow simulation of the gauged River. Plant uptake compensation factor (EPCO), Depth from soil surface to bottom of layer (SOL_Z), Base flow alpha factor (ALPHA_BF), SCS runoff Curve number CN_2, Manning’s n value for the main channel CH_N2, Effective hydraulic conductivity in main channel (CH_K2), Soil evaporation compensation factor ESCO, Manning's "n" value for overland flow (OV_N), Mean Slope steepness HRU_SLP, Saturated hydraulic conductivity (SOL_K), were highly sensitive parameters that significantly affect surface runoff.

4.2.3. Uncertainty Analysis

Uncertainty analysis was also done using SWAT-CUP of SUFI-2 on measured stream flow data. All uncertainties are quantified by the measured values of p and r- factors. The P-factor is the percentage of measured data bracketed by the 95% prediction uncertainty (95PPU) and the r-factor, which is the average thickness of the 95PPU band divided by the standard deviation of the measured data. The results of P-factor and R-factor for monthly discharge are also shown in Table 4.1. The thickness of the 95PPU (r-factor) had a value of 0.77 and 0.75 during calibration and validation respectively. The respective p- factor value had also 0.73 and 0.71 during calibration and validation which is a good result. A value close to 1 is recommended for r-factor with a P-factor greater than 0.70. From the calibration and the validation results, it is deduced that the model represented the hydrological characteristics of the sub-watershed at gauging station and the results can be used as a baseline for further analysis.

4.2.4. Historical water Balance Components of the Lake watershed

Lake Hawassa watershed has two major sub catchments (gauged and un-gauged). The historical water balance was studied for these two catchments. The eastern part of the watershed is the Tikurwuha River catchment which is the only gauged catchment in the watershed and the un-gauged catchment is situated on west of the Lake Hawassa.

4.2.4.1. Average water balance components of gauged catchment

The historical period for this study was the past 31 years from 1991-2021. The major annual water balance components estimated in the model were precipitation, surface runoff, and ET. The result was summarized in the following table 4.5, 4.6 and in the appendix F & G.

According to the Arc SWAT model simulation result in the gauged catchment the average 31 years annual precipitation input to the catchment was 1068.3mm and the average evapotranspiration from the total watershed was about 688.3mm. While the other water balance components surface runoff was 155.11mm. 64.4% of the annual precipitation is lost through evapotranspiration from the watershed for the respective period.

4.2.4.2. Average water balance components of un-gauged catchment

The SWAT model can also estimate average annual basin values for different water balance Components of the un-gauged catchment. As discussed in section 3.5.5 the calibrated sensitive parameters were transferred from gauged catchment to un-gauged catchments, then the SWAT model simulates the water balance components of the un-gauged catchment.

According to simulation result the estimated average annual precipitation was 1043.2mm which was an input to catchment and the ET losses from the catchment was 771.5mm, on the other hand surface runoff from the catchment was 170.08mm.

Table 4.5 Average annual historical water balance components of Lake hawassa watershed(1991-2021)

No.	Water balance components	Gauged	Unguaged
1	Precipitation	1068.3mm	1043.21 mm
2	surface runoff	155.11 mm	170.08 mm
7	ET	688.3 mm	771.51mm

The stream flow of gauged and un-gauged catchments also computed monthly and seasonally. As we can see from table 4.6 the highest stream flow was recorded in Kiremt season (i.e. from June to September in both catchments. But the lowest flow was recorded in gauged catchment during Belg season (from February to May). In un-gauged catchment the lowest flow was recorded during Bega season. This is because there is no perennial river in un-gauged catchment.

Table 4.6 Average monthly & Seasonal Stream flows of the watershed

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Kiremt	Bega	Belg
Gauged	12	8	9	10	12	13	14	15	17	16	15	13	60	56	39
Un-gauged	4	7	9	21	22	15	19	20	24	18	10	3	77	34	59

4.3. Future Water Balance components under climate change

In this study, Hawassa lake watershed water balance was computed for the baseline period (1991-2021) and the three future time periods 2020s (2022-2040), 2050s (2041-2070) and 2080s (2071-2099) under RCP_2.6, RCP_4.5 and RCP_8.5 scenarios. The SWAT hydrologic model was re-run for each future data periods and the SWAT parameters identified during the base calibration period also used. The GCM model outputs that were downscaled by SDSM model (i.e., daily precipitation, minimum and maximum temperature) were used as an input weather data for SWAT model.

The climate variables such as wind speed, solar radiation, and relative humidity and the spatial data Such as DEM, soil and LULC data were assumed constant throughout the future simulation periods. The assessment was done in both gauged and un-gauged catchments. The annual simulation results of water balance components in the future three time horizon for the three RCP scenarios were summarized in the Tables 4.6, 4.7 and 4.8 below.

For RCP_2.6 the annual average precipitation in gauged catchment would be 1023.43mm, 1010.29mm and 997.79mm respectively in 2020, 2050 and 2080 future time horizons. Where as in un-gauged catchment annual average precipitation will be 994.81mm, 983.44mm and 977.29mm in the three time horizons.

As we can see from table 4.6 the estimated annual surface runoff values will be 149.22mm, 142.35mm, 133.67mm in gauged catchment and 163.03mm, 158.61mm, 157.93 in un-gauge catchments for 2020, 2050 and 2080 respectively. The estimated evapotranspiration amount was clearly shown in table 4.6.

Table 4.7 Average annual water balance components and seasonal stream flows of Lake Hawassa watershed for RCP_2.6

Water balance Components (mm)	Gauged				Unguaged			
	Base line	2020	2050	2080	Base line	2020	2050	2080
Precipitation	1068.30	1023.43	1010.29	997.79	1043	994.81	983.44	977.29
Surface runoff	155.11	149.22	145.49	143.01	170	163.03	158.61	157.93
ET	688.30	750.25	764.01	780.53	771.51	856.38	871.81	884.92
Seasonal stream flow								
Kiremt	59.84	63.01	63.67	58.52	76.93	79.85	78.91	74.87
Bega	56.35	51.30	50.66	50.04	34.41	31.02	29.49	29.18
Belge	38.93	34.92	34.57	34.41	58.66	52.15	50.21	53.89

Table 4.8 Average annual water balance components and seasonal stream flows of Lake Hawassa watershed for RCP_4.5

Water balance Components (mm)	Gauged				Unguaged			
	Base line	2020	2050	2080	Base line	2020	2050	2080
Precipitation	1068.30	1015.95	1007.41	984.97	1043.00	996.07	979.38	976.25
Surface runoff	155.11	147.97	147.51	144.72	170.00	161.16	160.99	159.29
ET	688.30	765.39	773.65	783.97	771.51	864.09	861.01	880.29
Seasonal Stream flow								
Kiremt	59.84	61.27	62.94	58.58	76.93	79.08	79.47	74.39
Bega	56.34	50.71	50.20	50.05	34.41	30.63	30.49	30.58
Belge	38.93	35.99	34.37	36.09	58.66	51.45	51.04	54.32

Table 4.9: Average annual water balance components and seasonal stream flows of Lake Hawassa watershed for RCP_8.5

Water balance Components (mm)	Gauged				Unguaged			
	Base line	2020	2050	2080	Base line	2020	2050	2080
Precipitation	1068.30	1012.75	999.93	972.15	1043.00	984.59	961.65	949.13
Surface runoff	155.11	147.51	146.27	143.17	170.00	158.10	156.06	153.17
ET	688.30	772.27	787.42	812.19	771.51	902.67	925.04	941.24
Seasonal stream flow								
Kiremt	59.84	61.09	61.87	58.76	76.93	79.31	79.00	75.47
Bega	56.35	51.28	50.14	49.71	34.41	29.52	28.73	28.42
Belge	38.93	35.14	34.26	34.70	58.66	49.27	48.32	49.28

As it can be seen from the above tables 4.6, 4.7 & 4.8 the annual average estimated amounts of water balance components in gauged and un-gauged catchments such as precipitation and Surface runoff will generally shows decreasing trend whereas evapotranspiration shows an increasing trend as compared to the base period . The decreases in precipitation is due to the result of climate change that the projected amount of precipitation in the future periods shows the decreasing trend for all scenarios in the whole watershed.

The decrement in the surface runoff is due to the decrement in precipitation. Since precipitation is the main input for the other water balance components in the watershed. The increments in evapotranspiration are directly related with the increasing trend in minimum and maximum temperature in future periods for all RCPs.

4.4. Impact of climate change on the water balance components

Climate change is a statistical significant variation in either the mean state of the climate or in its variability, persisting for an extended period.

Impact of climate change on Lake Hawassa water balance components were assessed based on climate change scenarios downscaled for the watershed by using SDSM model as discussed in previous sections. Future climate variables were downscaled for Hawassa watershed stations and future assessment of climate change on main water balance components (precipitation, surface runoff & ET). The result of climate change impact on the water balance components were discussed as follows.

4.4.1. Impact of climate change on the annual water balance components

Precipitation is one of the major water balance component which SWAT model simulates. As we can see from the simulation results of the SWAT model for the three RCPs in all the future time periods the annual precipitation shows decreasing in both gauged and un-gauged catchments. Therefore climate change will show the negative impacts on precipitation. The decreasing trend in precipitation and increments in temperature will be result in decrement and increment in other water balance components.

Table 4.10 a: Annual percentage change of water balance components under RCP_2.6

Water balance Components	**gauged**			**un-gauged**		
	2020	2050	2080	2020	2050	2080
Precipitation	-4.2%	-5.4%	-6.6%	-4.6%	-5.7%	-6.3%
surface runoff	-3.8%	-6.2%	-7.8%	-4.1%	-6.7%	-7.1%
ET	+9.0%	+11.0%	+13.4%	+11.0%	+13.0%	+14.7%

Table 4.10b: Annual percentage change of water balance components under RCP_4.5

Water balance Components	gauged			un-gauged		
	2020	2050	2080	2020	2050	2080
Precipitation	-4.9%	-5.7%	-7.8%	-4.5%	-6.1%	-6.4%
surface runoff	-4.6%	-4.9%	-6.7%	-5.2%	-5.3%	-6.3%
ET	+11.2%	+12.4%	+13.9%	+12.0%	+11.6%	+14.1%

Table 4.10 c: Annual percentage change of water balance components under RCP_8.5

Water balance Components	gauged			un-gauged		
	2020	2050	2080	2020	2050	2080
Precipitation	-5.2%	-6.4%	-9.0%	-5.6%	-7.8%	-9.0%
surface runoff	-4.9%	-5.7%	-7.7%	-7.0%	-8.2%	-9.9%
ET	+12.2%	+14.4%	+18.0%	+17.0%	+19.9%	+22.0%

As clearly shown in the above tables 4.9 a, b & c the runoff will be decreased from -3.8% to -9.9%, On the other hand the evapotranspiration will be increased. The percentage change of ET will be from (+9% to +22%) in gauged and un-gauged catchments.

4.4.2. Impact of climate change on the seasonal stream flow

The seasonal variation of stream flow of the projected climate from the baseline period was computed for Kiremt, Bega and Belg seasos (Table 4.10 a, b, and c). As shown in the table 4.10a the Kiremt season average stream flow of gauged catchment (Tikurwuha River) may increase by 5.3%, 6.4% and decrease by 2.2% from the baseline period in the 2020s, 2050s and 2080s, respectively for RCP - 2.6. For Bega and Belg seasons the stream flow may decrease by 9%, 10.1%, 11.2% and 10.3%, 11.2%, 11.6% in 2020s, 2050s and 2080s respectively for 2.6 scenarios.

The Kiremt season average stream flow of un-gauged catchment may increase by 3.8%, 2.6% and decrease by 2.7% from the baseline period in the 2020s, 2050s and 2080s, respectively for RCP -

2.6. For Bega and Belg seasons the stream flow may decrease by 9.8%, 14.3%, 15.2% and 11.1%, 14.4%, 8.4% in 2020s, 2050s and 2080s respectively for 2.6 scenarios.

The impact of climate change on the seasonal stream flow of the watershed will generally increases in the Kiremt season in 2020 and 2050 for all scenarios but it will be decrease in Bega and Belg seasons for all time period in all RCPs.

Table 4.11a percentage change of seasonal stream flows for RCP_2.6

Seasons	Gauged			Un-gauged		
	2020	2050	2080	2020	2050	2080
Kiremt	5.3%	6.4%	-2.2%	3.8%	2.6%	-2.7%
Bega	-9.0%	-10.1%	-11.2%	-9.8%	-14.3%	-15.2%
Belg	-10.3 %	11.2%	-11.6%	-11.1%	-14.4%	-8.4%
Annual	-3.8%	-6.2%	-7.8%	-4.1%	-6.7%	-7.1%

Table 4.11b percentage change of seasonal stream flows for RCP_4.5

Seasons	Gauged			Un-gauged		
	2020	2050	2080	2020	2050	2080
Kiremt	2.4%	5.2%	-2.1%	2.8%	3.3%	-3.3%
Bega	-10%	-10.9%	-11.2%	-11%	-11.4%	-11.1%
Belg	-7.5%	-11.7%	-7.3%	-12.3%	-13%	-7.4%
Annual	-4.6%	-4.9%	-6.7%	-5.2%	-5.3%	-6.3%

Table 4.11 c percentage change of seasonal stream flows for RCP_8.5

Seasons	Gauged			Un_gauged		
	2020	2050	2080	2020	2050	2080
Kiremt	2.1%	3.4%	-1.8%	3.1%	2.7%	-1.9%
Bega	-9%	-11%	-11.8%	-14.2%	-16.5%	-17.4%
Belg	-9.7%	-12%	-10.9%	-16%	-17.6%	-16%
Annual	-4.9%	-5.7%	-7.7%	-7%	-8.2%	-9.9%

The general decrement in annual precipitation and the increments in ET were consistent with the previous study conducted by (Alehu and Bitana, 2023) on lake Hawassa catchment to assess the climate change impact on the water balance of lake under RCP_4.5 and RCP_8.5 that shows decrease in precipitation & ET. This also in line with the investigation by (Tekle et al., 2019) on Comparative Assessment of the Effect of Climate Change and Human Activities on Stream flow Regimes in Central Rift Valley Basin by using five regional climate models (RCMs) in the coordinated regional climate downscaling experiment (CORDEX)-Africa in RCP4.5 and RCP8.5 scenario that shows that the decrement in precipitation result in the reduction of stream flow.

The runoff simulations result showed a reduction in the Hawassa watershed compared to the baseline period (Tables 4.6, 4.7 & 4.8). This may be due to a general decrease in rainfall and an increase in temperature in the future periods. The highest decrease in annual runoff was simulated up to -9.9%. This shows that the direction of changes in stream flow follows the direction of changes in rainfall. Since the stream flow is highly influenced by rainfall, a decreasing trend of rainfall caused a corresponding decrease in stream flow for the future period. This result was consistent with the report by (Tekle,2010) on Bilate watershed of the Central Rift Valley of Ethiopia that the average total annual flow volume at the out let of the watershed might decrease up to 18.1% and 16.3% for A2a scenario and 17.7% and 16.8% for B2a scenario of 2011-2040 and 2041-2070 periods respectively . The study also in line with the study conducted by (Tesfalem et al., 2018) on the hydrology of Lake Ziway catchment using CMIP5 RCP scenarios which indicated the flow reduction in Meki river and Kata river under RCP-4.5 And RCP_8.5. And also with the study conducted by (Elias, 2017) on Impact of climate change on Lake Chamo Water Balance by using GCM output of A1B scenario reveals the decreasing pattern of lake water storage due to decrease of inflows components such over lake precipitation and surface water inflow in all the future time horizons. The investigation by (Eshetu, 2020) also support this result which was done in assessing the impact of climate change on water resources of upper Awash River sub-basin by using SDSM output of HadCM3 for A2a and B2a scenario that concludes a mean annual flow reduction (ranging from 13.0 to 29.4%) is also expected in the future for the three studied benchmark periods under both emission scenarios

4.5. Limitation of the study

In this study the impact of climate change on the water balance of Lake Hawassa Specifically on the stream flow was assessed by using statistical down scaling model. During the assessment of future water balance the simulations considered only future climate change scenarios by assuming all spatial data and other climatic variables such as wind speed, solar radiation and relative humidity remain constant for the future time periods. The study used only SDSM climate model to downscale GCM outputs and also SWAT model which had their own uncertainty that may produces error on water balance component.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. CONCLUSIONS

The knowledge of climate change impact on the water balance of watershed is very important to develop sound management plans in current and future time periods. This particular study tried to assess the climate change impact on the water balance of Lake Hawassa watershed. According to the SWAT simulation result in the gauged catchments or the Tikurwuha sub catchments' historical 31 years (1991-2021) average annual amounts for precipitation, Surface runoff and evapotranspiration (ET) were 1068.3mm, 155.1mm & 688.3mm respectively. In un-gauged catchments (the western part of the watershed) average annual precipitation was 1037mm, Surface runoff 170.1mm and evapotranspiration (ET) 771. 64.4% and 73.97% of the annual precipitation is lost through evapotranspiration from the gauged and un-gauged catchments respectively.

The future water balance components were computed in all the three RCPs for 2020, 2050 &2080 time horizons. For RCP_ 2.6 in gauged catchment the future average annual average precipitation will be 1023.43mm, 1010.29mm, and 1010.23mm, The Surface runoff will be 149.22mm, 145.49mm, 143.01mm and the ET will be 750.25mm, 764.01mm & 780.53mm respectively in 2020, 2050 and 2080. For unguaged catchments the future average annual precipitation will be 994.84mm, 983.44mm, and 977.29mm, The Surface runoff will be 163.03mm, 158.61mm, 157.93mm, and the ET will be 856.38mm, 871.81mm & 884.92mm respectively in 2020, 2050 and 2080.

For the medium emission scenario(RCP_ 4.5) in gauged catchment the future average annual average precipitation will be 1015.95mm, 1007.41mm, and 984.97mm, The Surface runoff will be 147.97mm, 147.51mm, 144.72mm, and the ET will be 765.39mm, 773.65mm & 783.97mm respectively in 2020, 2050 and 2080. For unguaged catchments the future average annual precipitation will be 996.07mm, 979.38mm, and 976.25mm, The Surface runoff will be 161.16mm, 160.99mm, 159.29mm and the ET will be 864.09mm, 861.01mm & 880.29mm respectively in 2020, 2050 and 2080.

For the highest emission scenario(RCP_ 8.5) in gauged catchment the future average annual average precipitation will be 1012.8mm, 999.9mm, and 972.2mm, The Surface runoff will be 147.5mm, 139.1mm, 128.4mm and the ET will be 772.27mm, 787.42mm & 812.19mm respectively in 2020, 2050 and 2080. For unguaged catchments the future average annual precipitation will be 984.6mm, 961.7mm, and 949.1mm, The Surface runoff will be 158.1mm, 156mm, 153.2mm and the ET will be 902.67mm, 925.04mm & 941.24mm respectively in 2020, 2050 and 2080.

The climate change impact on the water balance components of Lake Hawassa watershed was evaluated for RCPs-2.6, 4.5 & 8.5 emission scenarios in 2020, 2050 and 2080 time horizons. The annual result from climate model showed a general increasing trend for maximum and minimum temperatures and decreasing trend for precipitation in all the three time periods for all the three emission scenarios. Temperature and precipitation are the most climate variables that affect the water balance of Lake Hawassa watershed.

The increment in temperature and decrement in precipitation will negatively affect the future water balance components the Lake watershed. The impact of climate change on the seasonal stream flow of the watershed will generally increases in the Kiremt season in 2020 and 2050 for all scenarios but decreases in Bega and Belg seasons for all time period in all RCPs. The future annual precipitation, Surface runoff will be decreased up to 9 % and 9.9 % respectively and the increment in the ET may reach up to 22% at the end of 2099 for RCP_8.5. Therefore, due to the climate change the future water availability will be reduced in Lake Hawassa watershed.

5.2. RECOMENDATIONS

In this study the impacts of climate change on the water balance of Lake Hawassa watershed were assessed. Knowing the impacts of climate change on water balance of a watershed in the long term for the future is useful to recommend better alternative and complementary action of climate change. As the result shows the major water balance components such as precipitation and Surface runoff will be decreased, while ET will be increased. This shows the future water availability will be reduced.

- Therefore implementation of appropriate climate change adaptation and mitigation strategies in the Lake Hawassa watershed may reduce the adverse effect of climate change.
- Since Watershed based integrated water resources management approach is the part of the whole climate change adaptation option and may ensure sustainability, the plan and practice of integrated water resources management approach by decision makers may reduce the negative impact of climate change.

- Different stakeholder's participation and awareness creation for the society at all levels of the water resources development and management activities might be very important to reduce adverse effect and ensure stability.
- In this study the only statistical down scaling method was applied to downscale the GCM outputs. Since there are different downscaling methods and GCM output, it is better to apply different downscaling methods and GCM output to make comparison between them at the same study period. Therefore, future study needs a group of Specialists in different disciplines (climate specialists and hydrologists) to get the most accurate result in terms of the climate change impact on the hydrology of this watershed.
- The model outputs used in this study have a certain level of uncertainty related to model assumptions, and simulations considered only future climate change scenarios by assuming all spatial data and other climatic variables such as wind speed, solar radiation and relative humidity remain constant for the future time periods. Therefore, if future study considers the land use/cover change and other climate variables best result might be expected.

6. REFERENCES

Abbaspour. (2014). User Manual for SWAT-CUP, SWAT Calibration and Uncertainty Analysis Programs. Swiss Federal Institute of Aquatic Science and Technology. Duebendorf, Switzerland, pp101.

Abiye, T. A. (2008). Environmental resources and recent impacts in the Awassa collapsed caldera, Main Ethiopian Rift. Quaternary international, 189(1), 152-162.

Alehu, B.A., Bitana, S.G. Assessment of Climate Change Impact on Water Balance of Lake Hawassa Catchment. Environ. Process. 10, 14 (2023). https://doi.org/10.1007/s40710-023-00626-x.

Alemahehu, M. (2019). Stream Flow Response to Climate Change on Tikur Wuha Catchment, Rift Valley of Ethiopia. Journal of Environment and Earth Science Vol.9, No.8, 2019

Arnold, J.G., R. Sirinivasan, R.S. Muttiah, and J.R. Williams. "Large Area Hydrologic Modeling and Assessment – Part I: Model Development." Journal of the American Water Resources Association (JAWRA) 34(1), 1998: 73-89.

Arnold, J. G., Haney, E.B., Kiniry, J. R., Neitsch, S.L., Srinivasan, R., Neitsch, S. L., & Williams, J. R. (2012). Soil and Water Assessment Tool (SWAT) theoretical documentation version 2012. Texas Water Resources Institute Technical Report No.439, pp650. College Station, Texas.

Ayenew, T., & Gebreegziabher, Y. (2006). Application of a spreadsheet hydrological model for computing the long-term water balance of Lake Awassa, Ethiopia. Hydrological sciences journal, 51(3), 418-431.

Belete, M. (2013). The impact of sedimentation and climate variability on the hydrological status of Lake Hawassa, South Ethiopia. (PhD), Universitäts-und Landesbibliothek Bonn, Bonn.

Belete, M., Diekkrüger, B., & Roehrig, J. (2017). Linkage between water level dynamics and climate variability: the case of Lake Hawassa hydrology and ENSO phenomena. Climate, 5(1), 21.

Benestad, R.E., Hanssen-Bauer, I. and Chen, D. 2008. Empirical-statistical downscaling. World Scientific Publishing Company.

Conway, D. (2000). Some aspects of climate variability in the North-East Ethiopian highlands-Wollo and Tigray. SINET, Ethiopian Journal of Science 23, 139–161.

Cunderlik. (2003) "Hydrological model selection for the CFCAS project Assessment of water Resources Risk and Vulnerability change climatic condition." Water Resources Research Report No.046.

Cunderlik, J. & Simonovia, S. P. (2007). Hydrological Models for Inverse climate change Impact Modelling. Winnipeg, Manitoba, August 22-24, 2007: The 18th Canadian Hydro technical Conference on Challenge for Water Resources Engineering in a World.

Dessie, N. (1995). Hydrogeological Investigation of Lake Hawassa Catchment. Addis Ababa University, Addis Ababa.

Dibike, Y. B. &. Coulibaly, P., (2005). Hydrologic impact of climate change in the Saguenay Watershed: comparison of downscaling methods and hydrologic models, Journal of Hydrology.

Dixon, B. and Earls, J. 2012. Effects of urbanization on stream flow using SWAT with real and simulated meteorological data. Applied Geography, 35(1-2): 174-190.

Elias Gebeyehu. (2017). Impact of climate change on Lake Chamo Water Balance, Ethiopia. International Journal of Water Resources and Environmental Engineering, 9(4), 86-95.

Eshetu Ararso, (2020). Assessing the impact of climate change on water resources of upper Awash River sub-basin, Ethiopia.

Gebreegziabher, Y. (2005). Assessment of the water balance of Lake Awassa catchment, Ethiopia. (MSc), ITC, Enschede, The Netherlands.

Gupta. 1 1 .V .. Sorooshian. S .. Yapo. P.O .. 1998. Toward improved calibration of hydrologic models: multiple and noncommcnsuratc measures of information. Water Resources Research p4 (4). 751-763.

IPCC, (2007). The Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva, Switzerland.

IPCC 5th Assessment Report (2014), Working Group II Impacts, Adaptation and Vulnerability: http://ipcc-wg2.gov/AR5/.

Jones FE (1992) Evaporation of Water: with Emphasis on Applications and Measurement. Lewis Publ., Inc., Chelsea, MI, 200pp.

Lencha, S.M.; Ulsido, M.D.; Tränckner, J. (2022) Estimating Point and Nonpoint Source Pollutant Flux by Integrating Various Models, A Case Study of the Lake Hawassa Watershed in Ethiopia's Rift Valley Basin. Water 2022, 14, 1569. https://doi.org/10.3390/w14101569.

McSweeney et al, (2010); UNDP climate change profile for Ethiopia: http://www.geog.ox.ac.uk/research/climate/projects/undp-cp/index.html?country=Ethiopia&d1=Reports

Mesfin Mengesha, (2014). Assessments of Climate Change Impact on Water balance (Case study on Lake Hawassa, Ethiopia).

Monireh, F., Karim, CA., Saeid, AV., Mohammad, RF., Alexander, JBZ., et al. (2013). Modeling impact of climate change on fresh water availability in Africa. J. Hydrol 480, 85-101.

Moriasi D.N., Arnold J.G, Liew M.W., Bingner R.L., Haremel R.D. and Veith T.L. (2007). Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations, Journal of American Society of Agricultural and Biological Engineers, 50: 885-900.

MoWIR. (2010). Lake Hawassa Sub-basin Integrated Watershed Management Feasibility Study. Rift Valley Lakes Basin Integrated Resources Development Master Plan Study Project. Volume 1: Main Report. The Federal Democratic Republic of Ethiopia-Ministry of Water Resources.

Neitsch S, Arnold J, Williams J, Kiniry J, King, K (2011) Soil & Water Assessment Tool Theoretical Documentation Version 2009. Technical Report No. 406. Texas water resources institute.

NMSA. (1996). "Climatic and Agroclimatic Resources of Ethiopia." Meteorological Research Report Series, Addis Ababa.

Peterson, A. T., Navarro, A. G., A., G., & Benitez, H. (1998). The need for continued scientific collecting; a geographic analysis of Mexican bird specimens. Ibis,, 140(2): pp.288-294.

SCS, USDA. (1972). Chap. 4-10 in National Engineering Handbook Hydrology Section 4.

Setegn, SG. (2008). “Hydrological Modeling in the Lake Ethiopia using SWAT model." The Open Hydrology Journal 2: 49-62.

Setegn SG, Rayne D, Melesse AM, Dargahi B (2011) Impact of climate change on the hydroclimatology of Lake Tana Basin, Ethiopia. Water Resour Res 47:1–13. https ://doi.org/10.1029/2010W R009248

Shiklomanov I.A. (2009). Encyclopedia of Life Support Systems (EOLSS), Hydrological cycle – Vol. II - World Water Balance. : http://www.eolss.net/Eolss-sampleAllChapter.aspx.

Solkolov, A.A and T.G. Chapman, 1974. Methods for Water Balance Calculation, UNESCO – Studies and reports in hydrology, No 17, Parice.

Tekle, A. 2010. Assessment of climate change impact on water availability of Bilate watershed, Ethiopian Rift, Valley Basin. Msc thesis, Arbaminch university,Arbaminch.

Takele, G., Maurice, N., Benedict, M., and Fiseha, B., (2019) Comparative Assessment of the Effect of Climate Change and Human Activities on Stream flow Regimes in Central Rift Valley

Basin, Ethiopia." American Journal of Water Resources, vol. 7, no. 1 (2019): 23-29. doi: 10.12691/ajwr-7-1-4.

Tesfalem, A., Brook, A., Abraham, W., & Alemayehu, M. (2018) Impacts of Climate Change Under CMIP5 RCP Scenarios on the Hydrology of Lake Ziway Catchment, Central Rift Valley of Ethiopia.

UNESCO. 1974. Methods of Water Balance computations. An International Guide for research and practice. UESCO Press, Paris.

White, K.L. & Chaubey. (2005). Sensitivity analysis, calibration, and validations for a multisite multivariable SWAT model. Journal of American Water Resources Association. 41: 1077–1089.

Wijngaard, J. B., Klein, T., A., M. G., & Konnen, G. (2003). Homogeneity of 20th century European daily temperature and precipitation series. International Journal of Climatology, 23(6): pp.679-692.

Wilby, R.L. and Dawson, C.W. (2008). SDSM 4.2—A Decision Support Tool for the Assessment of Regional Climate Change Impacts. Statistical Downscaling Model SDSM Version 4.2.

Wilby, R.L. and Dawson, C.W. 2007. SDSM 4.2-A decision support tool for the assessment of regional climate change impacts. User Manual. London, UK.

Wilby, R.L., Dawson, C.W. 2004. Using SDSM - A decision support tool for the assessment of regional climate change impacts.

Winchell, M., R.,Srinivasan, R. Di Luzio, M. and Arnold, J. G. (2007). Arc SWAT Interface for SWAT2005.Grassland, Soil & Water Research Laboratory, USDA Agricultural Grassland, Soil & Water Research Laboratory, USDA Agricultural.

Winter, T.C. (1981). Uncertainties in Estimating the Water Balance of lakes. Water resources Bulletin 17,No.1:82-115.

Williams, J.R. (1995). Computer models of Watershed hydrology. The EPIC model. In: V.P. Singh (eds.).

Williams, J.R, and R.W Hann. (1973). "HYMO a problem-oriented computer language for building hydrologic models." Water Resources : 79-85.

Williams, J.R. (1995). The EPIC Model. Highlands Ranch, CO: Water Resources Publications.

Yonas G. (2020). Impact of Climate and Land Use/Cover Changes on the hydrology of Lake Hawassa Watershed (Central Ethiopian Rift): A Thesis Submitted to Ethiopian Institute of

Water Resources Presented in Fulfillment of the Requirement for the Degree of Doctor of Philosophy.

Web site sources

http://ccdsdscc.ec.gc.ca/?page=pred-canesm2

http://earthexplore r.usgs.gov/

https://sswm.info/sswm-university-course/module-4-sustainable-water-supply/

http://www.sdsm.org.uk/.

https://swat.tamu.edu/

APPENDICES

A. Yearly historical Rain fall data for Lake Hawassa watershed

Year	Haisawita	Hawassa	Shashemene	Wend genet	Yirbanduwancho
1991	1017.9	866.9	589.45	1211.7	799.4
1992	1120.3	962.3	810.2	1296.4	1044.5
1993	1135.2	928.4	1022.8	1138.1	1198.4
1994	1066.7	861.5	724.4	1256	991.1
1995	915.9	1004.4	852.7	1025	781.5
1996	1176.6	1189.1	1183.2	1261.1	1230.9
1997	654.1	1054.1	1087.1	1193.2	1158.4
1998	1265.3	1148.3	1212.7	1256	1108.2
1999	818.9	808.9	814.8	916.5	915.7
2000	1003.8	821.5	962.2	943.5	903.6
2001	1291.9	1021.7	962.2	1203.6	1240.8
2002	792.6	919.3	902.3	998.9	964.9
2003	1029	888.9	775.2	976.7	1097.5
2004	1027.9	897.7	820.6	374.1	1092.4
2005	1027.9	1002.6	995.3	1132	1338.1
2006	1027.9	1197.9	1040.5	1266	1079.8
2007	1027.9	1152.7	1012.1	1240.2	1115.2
2008	930.2	915.3	889.4	853.1	931.3
2009	860.5	703.7	786.8	697.4	763.3
2010	1201.22	1032.3	968.6	1203	1258.3
2011	1244.1	922.9	887.1	1220	1156.6
2012	1000.7	785.4	776.9	816.8	744.5
2013	1254.8	1072.3	998.7	1076.9	1118.8
2014	1388.7	1002.7	965.4	1103.5	1223
2015	1017.75	671.8	723.3	835.4	706.93
2016	1017.75	980.1	878.8	1127.6	857.6
2017	1122.3	1183.1	1028.1	1199.2	794.9
2018	1249.85	1156.8	1058.2	1199.2	963.3
2019	1246.95	1038.1	986.6	1199.2	1132
2020	1246.95	1038.1	1203.1	1216.1	1205
2021	971.28	768.1	882.6	949.6	1122

B. Hawassa station monthly maximum temperature in °C

	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
1991	29.4	28.1	28.7	29.3	28.0	26.1	23.3	25.1	26.0	27.8	29.2	28.1
1992	28.5	28.5	30.5	29.7	27.4	26.3	24.3	23.7	24.9	25.8	27.1	28.5
1993	27.6	26.9	30.9	27.8	26.9	25.0	24.4	24.8	25.8	26.9	30.2	29.8
1994	30.5	31.7	30.8	29.5	26.7	24.7	23.5	24.5	26.2	28.3	28.3	29.3
1995	30.4	30.7	30.0	27.3	28.0	27.0	24.3	24.7	25.9	27.6	29.3	29.2
1996	28.3	30.8	29.4	27.7	26.8	24.1	23.8	24.3	25.2	27.1	28.1	28.7
1997	28.9	30.3	30.8	26.9	27.5	25.7	23.9	25.5	26.7	26.5	26.4	27.3
1998	27.8	28.9	30.0	29.7	27.3	26.3	24.3	24.0	25.4	25.3	27.5	28.1
1999	29.1	31.4	28.1	29.1	27.2	26.1	23.6	25.0	25.6	25.0	27.2	28.0
2000	29.5	30.7	31.8	28.8	26.1	25.7	24.7	24.8	25.1	25.6	27.2	28.3
2001	28.6	30.2	28.3	28.4	26.9	24.8	24.4	24.5	25.9	26.7	28.2	28.9
2002	28.2	30.9	28.8	28.6	27.5	25.7	26.3	25.4	26.1	28.3	29.8	28.3
2003	28.4	31.3	30.6	28.1	28.3	25.6	24.2	24.9	26.1	28.2	29.2	27.3
2004	28.9	28.8	30.2	27.3	28.6	25.9	25.3	25.5	25.5	26.7	28.6	28.6
2005	28.9	31.5	30.0	29.4	25.9	25.6	24.6	25.7	26.0	27.3	28.0	28.5
2006	30.1	31.3	29.3	27.3	27.7	26.2	24.5	24.7	25.2	26.7	27.6	27.5
2007	28.5	29.3	30.4	28.2	27.7	25.3	24.6	24.3	25.1	26.7	27.8	27.7
2008	29.5	29.5	31.6	29.4	26.3	25.6	24.4	24.8	25.5	26.6	26.6	27.8
2009	28.4	30.0	31.3	29.2	29.0	27.6	26.1	25.8	26.3	27.7	29.5	28.1
2010	28.5	28.1	27.7	28.0	27.0	26.2	24.4	25.0	25.2	27.7	28.7	28.2
2011	28.7	30.6	30.2	30.4	27.6	26.2	25.5	24.6	25.3	28.2	27.8	27.6
2012	29.7	30.8	31.8	28.0	28.3	26.6	24.9	24.9	25.2	27.8	29.1	29.1
2013	29.9	31.4	30.3	28.8	26.7	26.1	24.3	24.7	26.2	26.8	28.0	28.0
2014	29.7	29.6	29.6	28.7	27.1	26.7	25.2	25.2	25.3	26.3	27.4	27.5
2015	28.7	31.0	31.5	30.8	28.5	26.1	26.1	26.8	27.1	28.5	29.0	28.4
2016	28.8	30.7	32.3	28.1	26.7	26.0	25.3	25.3	26.6	27.4	28.1	27.8
2017	29.0	29.9	31.6	31.6	28.5	27.7	26.1	26.6	26.3	27.9	28.5	28.3
2018	29.1	30.2	28.1	27.1	27.8	25.0	24.9	25.7	26.6	28.0	27.5	28.3
2019	29.8	31.2	31.7	29.7	29.1	26.4	25.6	25.2	25.9	26.9	27.9	27.8
2020	28.9	30.1	29.8	29.0	28.0	26.1	24.3	24.7	26.0	27.4	28.1	28.1
2021	29.2	30.0	31.3	29.6	27.6	26.7	23.5	25.9	25.3	27.2	27.8	28.2

C. Hawassa station monthly minimum temperature in °C

	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
1991	11.6	12.1	13.4	12.8	14.0	15.1	14.3	13.7	12.9	9.5	9.4	9.6
1992	12.4	13.6	12.8	14.3	13.5	14.0	13.9	14.8	12.7	13.1	10.5	11.0
1993	12.1	12.3	9.7	14.1	14.1	14.2	14.3	13.7	12.8	12.8	9.3	9.2
1994	9.7	11.6	13.0	13.8	14.3	14.5	14.2	14.7	14.0	10.1	10.0	8.9
1995	9.8	12.7	13.6	14.9	13.1	13.6	14.2	14.5	13.0	12.3	8.3	10.6
1996	12.1	10.5	13.0	14.0	14.1	14.3	14.5	14.4	13.7	10.9	8.8	9.6
1997	12.4	10.0	13.3	13.9	13.2	13.6	14.2	14.2	13.2	13.6	13.8	11.3
1998	13.3	14.3	13.9	14.8	15.7	14.7	15.7	15.9	14.5	14.4	8.9	7.8
1999	10.2	9.9	13.8	12.5	13.6	14.0	14.3	13.7	13.8	14.0	9.3	9.3
2000	9.6	10.6	11.1	14.1	14.0	13.7	14.3	14.0	13.4	14.0	10.5	9.7
2001	11.6	11.3	14.0	14.4	14.2	14.6	14.8	15.0	13.1	13.8	10.3	10.9
2002	12.4	11.8	14.0	13.5	14.8	14.5	14.4	14.2	13.4	12.8	9.8	13.2
2003	11.8	11.6	13.2	14.3	14.2	14.3	14.6	14.5	14.0	11.9	11.2	10.4
2004	12.9	11.6	12.2	14.7	13.2	13.9	14.0	14.3	13.6	11.5	11.6	11.4
2005	11.3	11.4	13.8	14.0	15.0	14.6	14.2	14.7	14.4	13.1	9.5	7.8
2006	11.8	12.4	13.8	14.6	13.9	14.3	15.0	14.7	14.5	14.2	11.4	12.4
2007	12.7	12.9	12.2	14.2	14.8	15.0	14.8	14.6	14.3	11.1	10.7	9.0
2008	10.5	11.7	11.4	14.1	14.6	14.4	14.7	14.5	14.2	12.8	11.1	10.3
2009	11.8	12.4	12.9	14.3	14.4	13.9	14.2	14.7	14.7	13.2	10.7	13.6
2010	13.0	15.3	14.7	15.6	16.3	15.1	15.2	15.3	14.4	13.5	11.1	10.9
2011	12.6	11.8	13.4	14.3	15.1	15.3	14.7	14.9	14.7	12.3	13.0	9.9
2012	12.6	11.8	13.4	14.3	15.1	15.3	14.7	14.9	14.7	12.3	13.0	9.9
2013	12.2	12.2	15.6	15.1	15.1	15.4	15.1	14.9	14.2	13.5	12.0	9.4
2014	12.1	13.5	13.4	13.1	14.1	14.0	15.3	14.0	14.7	14.2	12.3	10.7
2015	11.2	13.0	14.5	14.8	15.4	15.8	14.8	15.3	15.3	14.7	13.9	13.5
2016	15.3	14.7	15.5	16.6	16.1	14.7	15.8	15.4	15.3	14.9	12.1	11.2
2017	9.7	14.5	14.5	14.8	15.8	15.5	16.0	15.5	15.6	15.1	11.7	8.8
2018	11.3	13.3	13.9	15.6	15.6	15.4	15.0	15.2	14.5	13.9	15.6	11.6
2019	15.4	12.9	14.6	15.4	14.9	16.2	14.9	15.1	14.9	13.3	13.3	12.6
2020	13.1	13.7	15.6	15.3	15.5	15.3	15.2	15.4	15.0	13.9	11.4	11.4
2021	11.5	13.0	13.4	15.2	15.7	15.1	15.4	14.9	15.1	13.6	11.7	11.9

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D. Historical water balance components of gauged catchment

Year	PRECIP mm	PET mm	ET mm	SURQ mm	WYLD mm	LAT_Q mm	GW_Q mm
1991	997.1	1078.6	543.7	135.3	405.7	62.3	208.1
1992	1215.3	1283.1	626.6	146.5	444.4	92.9	200.1
1993	1111.9	1079.5	661.6	142.5	435.4	72.3	200.5
1994	1044.7	1111.7	653.2	144.6	477.8	65.3	257.9
1995	897.0	1141.5	654.3	107.4	279.5	51.1	145.0
1996	1152.1	1123.2	628.7	157.7	444.8	78.1	249.0
1997	640.5	1146.4	652.2	117.7	65.5	27.2	20.6
1998	1138.8	1121.8	683.5	186.5	481.8	83.9	241.3
1999	801.8	1156.6	659.4	218.4	198.1	40.7	101.9
2000	982.7	1151.6	627.6	109.3	358.9	57.4	172.2
2001	1164.7	1151.8	601.5	155.7	531.9	83.8	262.3
2002	776.6	1170.7	650.2	214.4	255.9	41.8	127.7
2003	1007.6	1180.2	662.0	101.5	278.4	55.9	121.0
2004	1006.4	1147.1	686.3	198.2	420.6	62.2	230.2
2005	1176.7	1162.0	684.5	164.8	491.3	81.5	225.0
2006	1322.9	1307.6	816.0	133.2	530.0	92.5	264.3
2007	1345.2	1336.5	751.0	197.1	580.8	85.2	225.5
2008	910.8	1150.1	674.0	176.8	355.1	53.0	165.3
2009	842.6	1199.4	626.1	78.5	190.1	43.7	87.9
2010	1138.4	1109.1	678.2	186.7	547.1	76.5	273.8
2011	1118.5	1167.2	664.0	183.1	542.7	68.3	221.2
2012	982.1	1161.6	634.7	142.1	439.2	67.7	249.4
2013	1135.0	1136.2	628.6	202.5	473.0	77.6	242.8
2014	1256.8	1259.7	747.4	126.7	536.3	78.6	231.0
2015	996.8	1135.7	641.9	142.5	365.1	57.6	165.0
2016	1341.6	1392.1	810.4	168.6	551.0	89.8	202.7
2017	1098.8	1156.7	622.6	153.9	480.8	62.9	224.0
2018	1124.2	1100.1	661.0	162.2	551.5	80.4	258.9
2019	1121.8	1031.5	611.9	181.9	550.1	85.3	245.8
2020	1314.1	1385.9	810.1	174.0	493.1	71.3	217.8
2021	952.5	981.7	665.5	96.9	412.4	70.3	245.2
Average	1068.3	1168.3	668.3	155.1	424.8	68.3	202.7

E. Historical water balance components of un-gauged catchment

Year	PRECIP mm	PET mm	ET mm	SURQ mm	WYLD mm	LAT_Q mm	GW_Q mm
1991	1019.74	1271.23	878.55	169.87	395.03	51.27	174.94
1992	1245.48	1275.45	732.60	160.04	411.41	57.85	194.58
1993	1037.29	1273.41	792.56	159.27	392.00	48.66	185.13
1994	1068.67	1309.17	791.92	171.34	388.75	53.73	164.74
1995	917.59	1343.66	788.97	181.19	399.68	47.61	171.94
1996	1078.77	1320.11	750.08	170.47	397.41	52.69	175.31
1997	655.31	1347.01	477.17	78.80	162.53	25.91	58.88
1998	1267.63	1315.51	813.39	213.29	452.87	52.57	188.07
1999	820.40	1359.10	679.17	151.36	368.53	54.43	163.80
2000	1005.64	1352.98	869.37	147.34	395.60	51.14	198.18
2001	1194.28	1351.42	728.75	175.76	399.03	53.40	170.93
2002	794.16	1368.61	677.69	181.16	383.13	24.74	178.29
2003	1030.81	1374.73	799.19	132.79	370.81	49.11	189.97
2004	1029.71	1357.90	814.40	185.84	413.26	53.13	175.35
2005	1155.90	1365.28	816.20	174.17	407.29	52.17	182.02
2006	1125.87	1302.33	763.24	176.13	420.17	51.95	193.15
2007	1178.92	1348.87	786.87	174.32	420.30	52.23	194.80
2008	931.91	1353.59	735.25	174.14	404.79	48.34	183.38
2009	862.09	1308.29	779.48	165.16	354.33	45.24	144.99
2010	1169.42	1309.98	786.21	172.91	393.20	49.42	171.94
2011	1046.62	1365.40	795.42	189.96	415.41	46.48	180.53
2012	1004.55	1389.07	810.67	165.77	390.37	45.78	179.78
2013	1057.41	1332.14	759.75	194.50	417.25	51.08	172.73
2014	1091.26	1347.75	795.85	185.33	423.45	55.33	183.85
2015	1020.08	1334.70	787.64	173.31	411.26	52.78	186.23
2016	1075.31	1283.54	877.78	178.72	408.74	55.80	175.28
2017	1024.31	1338.32	797.29	173.61	391.07	53.39	165.13
2018	1052.50	1291.54	790.51	165.04	370.75	51.31	155.46
2019	1149.72	1326.41	756.32	169.22	401.26	52.78	180.32
2020	1247.06	1274.26	768.31	178.12	425.01	54.48	193.47
2021	974.70	1158.39	716.20	183.68	396.36	46.26	167.48
Average	1043.00	1324.20	771.51	170.08	392.94	49.71	174.21

F. Monthly and Seasonal projected Stream flows of Lake Hawassa for RCP_2.6

			gauged			un-gauged		
	Base	2020	2050	2080	Base	2020	2050	2080
Jan	12.15	11.02	10.92	10.79	4.26	3.83	3.65	3.61
Feb	8.48	7.61	7.53	7.50	7.27	6.47	6.22	6.68
Mar	9.16	8.22	8.14	8.10	9.24	8.16	7.91	8.49
Apr	9.53	8.55	8.46	8.42	20.54	18.28	17.58	18.88
May	11.76	10.55	10.44	10.39	21.62	19.24	18.50	19.84
Jun	13.08	13.77	13.92	12.79	14.73	15.29	15.13	14.34
Jul	14.30	15.06	15.22	13.99	18.91	19.62	19.42	18.39
Aug	15.34	16.15	16.32	15.00	19.67	20.42	20.20	19.14
Sep	17.11	18.02	18.21	16.74	23.63	24.53	24.17	22.99
Oct	16.22	14.77	14.58	14.40	17.62	15.89	15.10	14.94
Nov	14.53	13.24	13.07	12.91	9.71	8.74	8.32	8.23
Dec	13.45	12.26	12.09	11.94	2.83	2.55	2.42	2.40
Kiremt	59.84	63.01	63.67	58.52	76.93	79.85	78.91	74.87
Bega	56.35	51.30	50.66	50.04	34.41	31.02	29.49	29.18
Belg	38.93	34.92	34.57	34.41	58.66	52.15	50.21	53.89
Annual	155.11	149.22	148.89	142.97	170.00	163.03	158.61	157.93

G. Monthly and Seasonal projected Stream flows of Lake Hawassa for RCP_4.5

			gauged			un-gauged		
	Base	2020	2050	2080	Base	2020	2050	2080
Jan	12.15	10.93	10.82	11.34	4.26	3.79	3.77	3.78
Feb	8.48	7.85	7.50	7.86	7.27	6.39	6.32	6.73
Mar	9.16	8.47	8.07	8.49	9.24	8.08	8.04	8.55
Apr	9.53	8.79	8.40	8.83	20.54	17.95	17.87	19.02
May	11.76	10.88	10.39	10.90	21.62	19.02	18.81	20.02
Jun	13.08	13.40	13.75	12.81	14.73	15.14	15.21	14.24
Jul	14.30	14.65	15.03	14.00	18.91	19.43	19.53	18.28
Aug	15.34	15.71	16.14	15.02	19.67	20.22	20.32	19.02
Sep	17.11	17.52	18.02	16.75	23.63	24.29	24.41	22.85
Oct	16.22	14.59	14.45	14.21	17.62	15.68	15.61	15.66
Nov	14.53	13.08	12.95	12.73	9.71	8.64	8.60	8.63
Dec	13.44	12.10	11.98	11.78	2.83	2.52	2.51	2.51
Kiremt	59.84	61.27	62.94	58.58	76.93	79.08	79.47	74.39
Bega	56.34	50.71	50.20	50.05	34.41	30.63	30.49	30.58
Belg	38.93	35.99	34.37	36.09	58.66	51.45	51.04	54.32
Annual	155.11	147.97	147.51	144.72	170.00	161.16	160.99	159.29

H. Monthly and Seasonal projected Stream flows of Lake Hawassa for RCP_8.5

			gauged			un-gauged		
	Base	2020	2050	2080	Base	2020	2050	2080
Jan	12.15	11.06	10.85	10.81	4.26	3.62	3.55	3.51
Feb	8.48	7.61	7.46	7.60	7.27	6.10	5.96	6.10
Mar	9.16	8.22	8.06	8.15	9.24	7.76	7.57	7.76
Apr	9.53	8.67	8.38	8.48	20.54	17.25	16.85	17.26
May	11.76	10.64	10.35	10.46	21.62	18.16	17.94	18.16
Jun	13.08	13.36	13.53	12.85	14.73	15.18	15.13	14.45
Jul	14.30	14.60	14.79	14.04	18.91	19.49	19.42	18.55
Aug	15.34	15.66	15.86	15.07	19.67	20.28	20.20	19.29
Sep	17.11	17.47	17.69	16.80	23.63	24.36	24.27	23.18
Oct	16.22	14.76	14.42	14.27	17.62	15.15	14.71	14.55
Nov	14.53	13.23	12.92	12.79	9.71	8.35	8.10	8.02
Dec	13.45	12.24	11.96	11.84	2.83	2.40	2.36	2.34
Kiremt	59.84	61.09	61.87	58.76	76.93	79.31	79.00	75.47
Bega	56.35	51.28	50.14	49.71	34.41	29.52	28.73	28.42
Belg	38.93	35.14	34.26	34.70	58.66	49.27	48.32	49.28
Annual	155.11	147.51	146.27	143.17	170.00	158.10	156.06	153.17