ESTIMATION OF GROUNDWATER RECHARGE AND POTENTIALS UNDER CHANGING CLIMATE IN WERII WATERSHED, TEKEZE RIVER BASIN

MSc THESIS

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I hereby certify that I have read and evaluated this thesis entitled **Estimation of Groundwater Recharge and Potentials under Changing Climate in Werii Watershed, Tekeze River Basin** prepared under my guidance by **Gebremedhin Gebremeskel Haile**. I recommend that it be submitted as fulfilling the thesis requirement.

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Final approval and acceptance of the thesis is contingent up on the submission of the final copy of the thesis to the Council of Graduate Studies (CGS) through the Institute of Technology Graduate Council (IGC).

DEDICATION

This thesis is dedicated to my parents, for their never-ending love, support and encouragement

STATEMENT OF THE AUTHOR

By my signature below, I declare and affirm that this Thesis is my own work. I have followed all ethical and technical principles of scholarship in the preparation, data collection, data analysis and compilation of this Thesis. Any scholarly matter that is included in the thesis has been given recognition through citation.

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ACRONYMS AND ABBREVIATIONS

AR5	Fifth Assessment Report
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
CMIP5	Coupled Model Inter Comparison Project Phase 5
DEM	Digital Elevation Model
ESM	Earth System Models
FAO	Food and Agricultural Organization
GCM	General Circulation Model
GHG	Green House Gases
GIS	Geographic Information System
GPS	Global Positioning System
IAM	Integrated Assessment Models
IPCC	Inter-Governmental Panel for Climate Change
IWMI	International Water Management Institute
MoWIE	Ministry of Water Irrigation and Energy
MPIM	Max-Planck Institute for Meteorology
NGO	Non-Governmental Organizations
NMA	Ethiopian National Meteorological Agency
PET	Potential Evapotranspiration
RCM	Regional Climate Model
REMO	Regional climate Model
SRES	Special Report for Emission Scenario
UNFCCC	United Nations Framework Convention on Climate Change
WetSpa	Water and Energy Transfer between Soil Plant and Atmosphere
WetSpass	Water and Energy Transfer between Soil, Plants and Atmosphere under quasi-Steady State

BIOGRAPHICAL SKETCH

Mr. Gebremedhin Gebremeskel Haile was born to his father Gebremeskel Haile and his mother Gebriel Tekleab in Maygundi, South of Enticho town, Tigray Regional State on April 20, 1986. He finished elementary school in his home village. After finishing high school in Enticho secondary school, Mr. Gebremedhin went to Haramaya University to pursue his undergraduate degree in Soil and Water Engineering and Management.

Immediately after graduating in 2006, he started working in Tigray Bureau Of Agriculture, Atsibi-wonberta Woreda district office as Soil and Water Conservation Expert and as Supervisor for two and half years.

Mr. Gebremedhin was working as an Assistant Researcher at Mekelle Agricultural Research Center, Tigray Agricultural Research Institute. He then joined Haramaya University in September 2013 to study his Master of Science degree in Irrigation Engineering.

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ABSTRACT

This study was conducted in Werii watershed (1797 km^2) of Tekeze river basin, through integrative use of hydrological and climate models with the objective of estimating the impact of climate change on groundwater recharge and groundwater potentials. Statistical downscaling model (SDSM) was used to downscale precipitation and temperature outputs from REMO (REgional climate MOdel) which in turn was used as input to the WetSpa model to simulate future water balance changes based on A1B and B1 SRES emission scenarios. Abyiadi, Adwa, Hawzen and Adigrat meteorological stations was selected based on proximity to the watershed and data availability. Under A1B scenario, precipitation is likely to increase in each station by 11%, 34%, 31% and 20% at Abyiadi, Adwa, Hawzen and Adigrat stations respectively by 2050. Precipitation will also increase under B1 scenario with consistent rate as that of A1B. Change in maximum temperature is investigated higher at Hawzen for A1B (0.16°c) and B1 (0.2°c) and smaller at Adigart (0.05°c for A1B and 0.02°c for B1). Maximum temperature is expected to be in the range of -0.01°c to 0.2°c. Similarly, minimum temperature will change increasingly and positively with maximum change observed at Hawzen station for A1B (0.34°c) and B1 (0.29°c) and smaller change at Adigrat (0.07°c for A1B and 0.09°c for B1). Future likely climate change projections in precipitation and temperature is positive and will show increasing trend in the period from 2015 to 2050. A fully distributed hydrological model, WetSpa is used to simulate the reference period and future (2015-2050) water balances. At the watershed level, precipitation, recharge and actual evapotranspiration will show 13%, 2-5% and 15-18% increment respectively for both scenarios. Moreover, the baseflow will also increase by 14% and 8% for A1B and B1 scenarios respectively. The surface runoff will show decrement within the range of 22-24%. A spatially distributed water balance model, WetSpass, was also used to estimate long term average seasonal groundwater recharge. The average annual long term groundwater recharge is estimated as 30.06 mm of which 19.51 mm occurs during wet and 9.55 mm occurs during dry seasons. About 77% of the annual rainfall is received in the rainy season, however, only 65% of the total recharge occurs in the rainy season. The annual average precipitation (717 mm) is distributed as 90.7% (650.16 mm) evapotranspiration, 6% (44.06mm) runoff, and 4.2% (30.06mm) recharge. WetSpa and WetSpass were compared and their simulations were found consistent. Increased exploitation of these groundwater resources which is equivalent to the water resources increment is recommended. However, optimal allocation of the groundwater resources is useful to sustain the water resources in the watershed.

Key words: Climate change, Groundwater potential, Recharge, REMO, SDSM, Werii watershed, WetSpa, WetSpass

1. INTRODUCTION

Water is a basic and fundamental entity for living things as there is no living creature which did not depend on water directly or indirectly for survival. Alcamo *et al*., (1997) indicated that water plays an essential role in the existence of human beings. That is why people become more vulnerable to shortage of water, if there is no water in access. Even if the total water resources in the world are estimated to be 1.36 Billion Km^3 (Raghunath, 2006) its spatial and temporal distribution remains uneven. Higher rate of population growth, enhanced living standards, extreme water pollution and the global climate change have made water endangered these days. Anthropogenic impacts play an important role for these issues to occur as a result of unsustainable and unwise use of water resources especially in the past century.

Ethiopia has an estimated groundwater potential of 2.6 Billion m^3 (Awulachew *et al*., 2007) even if it is lower as compared to the surface water potential. This indicates that there is ample amount of water with regards to its geographical positions. However, this water potential has threatened by the impact of climate change. Different authors (Soliman, 2009; Melesse, 2011) indicated that climate change in the Upper Blue Nile basin of Ethiopia would occur and would shift and reshape the annual and seasonal climate patterns and variation in rainfall, reduced reservoir yield and erratic rainfall. Similarly, Kebede *et al*., (2013) indicated that an increasing trend of annual maximum temperature and annual future rainfall with seasonal variations was observed in Baro-Akobo Basin, Nile Basin. Variations in frequency; distribution and intensity of rainfall are now a common phenomenon in the country. Furthermore, the country's economy mainly dependent on rain-feed agriculture, as a result people remains food insecure and the country is not possibly to achieve the millennium development goals in all sectors if it likely to continue.

The groundwater recharge is the residual flow of water added to the vadose zone or water table resulting from the evaporative, transpirative and runoff losses of the rainfall. Thus groundwater recharge is a sensitive function of the climatic factors, local geological formation, and topography and land use types of the area under consideration (Dragoni and Sukhija, 2013). The regime has a direct relationship with precipitation and physicochemical properties of soil. As precipitation gets varied due to variations in climate change as a result of temperature and evapotranspiration, there is possibly variation in groundwater recharge. Recharge in a watershed is a function of many different factors such as amount, distribution and frequency of rainfall across the watershed, land cover and land use, the area of bare soil, vegetation type, soil type and soil properties and the like. Thus, recharge is not static but dynamic witch varies in space and time. When one goes across various locations across a watershed recharge gets varied accordingly. The amount of groundwater recharge occurring at a given location is typically expressed as a depth of water across the watershed. Recharge amounts are expressed over some time. Recharge rate is expressed as a volume (depth) per given time.

Due to variations and distribution of rainfall, drought in Ethiopia is a frequently recurring phenomenon. The spatial distribution and the frequency of its occurrence have increased in recent years (Walraevens *et al*, 2009). Due to this case, Ethiopia in general and Tigray in particular were suffering from shortage of food due to erratic rainfall, unsustainable use of water resources and lack of scientific technologies especially during the 1980's. Being part of the region, Werii watershed is the place which is extremely affected by drought resulted from unwise use of these resources. This is experienced with unforeseen bad weather conditions and improper management of land and water resources in the region. The people did not have any opportunity to solve these limitations of proper management of land and water resources in any cases during that time. Now a days, the practice of modern irrigation and improved agricultural practices are introducing as a mechanism to address these food security problems by the people, governmental and NGOs. The regional government and NGOs are trying to expand the system of irrigation through use of surface as well as groundwater in the watershed, due to this, there are changes observed in the people's livelihood. To achieve these objectives, knowledge of the available ground and surface water resources and the capacity to use them; the conservation of the surface runoff and groundwater recharge and the impact of climate change as well are needed to be taken in to consideration. Some researches were conducted to investigate climate change impacts of groundwater and recharges in Tekeze river basin at the Giba catchment (Adem, 2006; Walraevens *et al*., 2009; Tesfamichael *et al*., 2010) found alongside of Werii watershed. However, there were no researches made to study the groundwater processes and the impact of climate change in the Werii watershed. It can be said that the groundwater studies regarding its potential, recharge rate and the impact of climate change on it were totally untouched. Agriculture serves as a livelihood and ensures the food security of the people in the area; therefore studying of the availability of water resources is quite essential. However, unless the available water resources are utilized with a balanced approach of the supply and demand and with a careful consideration of sustainability, satisfying the needs of current and future generation will remain under question. Nevertheless, for planning sustainable use of water resources, the impact of climate change has to be considered. In Werii watershed there is currently a higher demand of supplemental and full irrigation for the production of food crops due to erratic nature of the rainfall and the area relying on available water resources. Though the groundwater is one of the resources, it was not properly estimated. Therefore, detail study about the whole aspect of groundwater potential for irrigation use to grow high value crops and fruit production, livestock consumption and forage development have paramount importance for the people. The available water in the watershed and its recharge rate and the impact of climate change studies as well needs to be conducted. It will be better implication for the people in the watershed to use it for their benefit based on the results obtained from the study.

It was believed that this study would focus in a specific watershed (Werii watershed) but the result would benefit the local community, local districts, NGOs and the policy makers as well. It would be also helpful to know the impacts of climate change on groundwater resources and recharge. Moreover, the application of hydrological and climate models to be involved in this study could be verified, so that it would be considered for related other future studies in the region.

Hence, the overall objective of the study was to estimate groundwater potential, groundwater recharge, and impact of climate change on water resources in Werii watershed.
The specific objectives were:-

- To estimate groundwater potential available in Werii watershed
- To estimate annual and seasonal groundwater recharge in the watershed, and

- To investigate the impacts of climate change on groundwater recharge and potentials of Werii watershed

2. LITERATURE REVIEW

2.1. Water Resources and Hydrologic Cycle

Water the most powerful substance for living things has a 1.36 Billion Km^3 of water resources globally, from this 97.2% is salt water mainly in oceans and 2.8% is available as freshwater (Raghunath, 2006) world wide. Even if the water available in water bodies, such as ocean and great lakes stores plenty of water in amount, it is not directly useful for human beings. The immediate use of water for human being is the one stored as groundwater and the remaining water found in land surfaces, lakes and streams as fresh water.

Ethiopia is quite rich in water resources and its drainage pattern is of great importance for its neighboring countries. It has 12 river basins with a total annual water resources estimated at 111 Billion m^3 of which 75.5 Billion m^3 is in the Nile basin (Yazew, 2005). In addition the country release an annual runoff volume of 122 Billion m^3 of water (Awulachew *et al.*, 2007), the Abay, Baro-Akobo, Omo-Gibe and Tekeze being the main river basins contributing runoff to the neighboring countries.

Water by nature is renewable natural resources found in three phases as liquid, solid and vapor which are mostly explained by hydrologic cycle. The hydrologic cycle is a circulation of water in the lithosphere, hydrosphere, biosphere, cryosphere and atmosphere. It is defined as the pathway of water as it moves in its various phases through the atmosphere to the earth, over and through the land, to the ocean, and back to the atmosphere (National Research Council, 1991) cited in (Karamouz, 2003). As there is no loss or gain of water in the hydrologic cycle it can be considered as a closed system water circulation system for earth.

The hydrological cycle also defined as a water transfer cycle occurs continuously in nature; at which the phenomena of evaporation and evapotranspiration, precipitation and runoff takes place during the water transfer system (Raghunath, 2006). Water first evaporates from the surfaces of water bodies and transpires from surface vegetation as a vapor. Then the vapor rises up to the atmosphere, condenses and form clouds and then through process of condensation, results precipitation back to the earth surface. This precipitation flows as runoff to the oceans or infiltrates into the soil to be a groundwater. This system of water circulation starts its cycle again and again and will not be stop at one time.

2.1.1. Groundwater resources

Adem and Batelaan (2006) indicated that groundwater is a major source of water supply and food production on irrigated agricultures worldwide. It plays an important role in sustaining rivers, lakes and wetlands during dry periods and is also essential for many ecosystems. Water is naturally stored in land surfaces as lakes, streams, reservoirs, ponds and ocean, and as groundwater in deep aquifers and saturated and unsaturated soils.

The groundwater is the water stored at underground/subsurface of the earth. It can also be defined as it is the water found below the surface of the land which exists in pores between sedimentary particles and in fissures and aquifers of solid rocks. The total groundwater of the world is estimated to be 10.53 Million km^3; and the groundwater comprises 99% of the earth's available fresh water resources (Delleur, 1998). The groundwater is therefore essential for storing the fresh water required by human. Groundwater can also be stored in the saturated zone of the soil which serves as a largest reserve of drinkable water. This water can be accessed for human by different mechanisms as form of springs, tapped by wells or drilled from boreholes. It is less contaminated by wastes and can sustain the flow of surface water during dry periods.

Ethiopia is considered as a water tower of Africa next to Zaire, due its plenty of water resources available on the surface and groundwater beyond the erratic rainfall it has. The total groundwater storage potential in Ethiopia is estimated to be 1 trillion m^3 (kebede, 2013). In contrary, Awulachew *et al.*, (2007) have indicated that as compared to surface water resources, Ethiopia has lower Groundwater potential, which is estimated 2.6 to 6.5 Billion m^3 but this figure appears to be extremely underestimated. The total exploitable groundwater potential is high as compared to other countries in Africa. But knowledge available on groundwater resources of Ethiopia is scanty. There is also a defined agreement among the authors on the available groundwater potentials and the like. It needs to have a very detailed study on this issue so that enough information is available.

2.1.2. Groundwater recharge

For efficient and sustainable management of the groundwater resource, understanding and quantification of groundwater recharge have paramount importance (Obuobie *et al.*, 2008). Water flows from higher water content to lower water content due to gravity, soil water tension and hydraulic gradient. This is observed in groundwater recharge as it moves and enters in to aquifers, saturated soil and unsaturated soil zones. Groundwater recharge is a movement of any water that enters into the groundwater system from any direction i.e. up, down or laterally (Lerner 1997, Adem and Batelaan, 2006; Russell, 2010). Recharge begins from rainfall infiltrates through diffuse and preferential soil pathways passes through the root zone and soil matrix, and then reaches the plane of the water table. Batelaan *et al.* (2004) and Russell (2010) described recharge as it is often the smallest component of the water balance and is calculated as the residual after subtracting evapotranspiration and runoff from precipitation. Hence, it is part of a water balance system that can be computed with the help of the continuity equation.

The accurate estimation and quantification of groundwater recharge involves identification of hydrological and biophysical characteristics in the hydrological cycle. Factors that affects groundwater recharge include, rate and duration of precipitation, application of irrigation water, soil moisture content, geological formation, soil properties, depth of water table and aquifer properties, vegetation, land use, topography and land slope (Obuobie *et al.*, 2008). Consideration of these characteristics is a prerequisite in groundwater recharge estimation.

2.1.3. Estimation of groundwater recharge

Groundwater recharge estimation is extremely important for efficient and sustainable management of groundwater systems. For estimating groundwater recharge a variety of methods exist. Different scientists (Nakashima *et al.*, 2001; Scanlon *et al.*, 2002; Christoph *et al.*, 2011; Ahmadi *et al.*, 2013) have used different methods to estimate groundwater recharge.

Scanlon *et al*., (2002) classified groundwater recharge methods based on hydrological zones from which the recharge data is obtained. These zones are surface water, unsaturated zone and saturated zone. The groundwater recharge estimation methods are further classified into physical techniques, tracers and numerical modeling within each of the hydrologic zones. The detail of the appropriate techniques for groundwater recharge estimation is provided in Table 1. The detail description of each of the recharges estimation techniques is found in (Lerner, 1990; Scanlon *et al*., 2002)

Table 1: Appropriate techniques for estimating groundwater recharge in regions with arid, semiarid, and humid climates (Source; Scanlon *et al*., 2002)

Hydrologic zone	Groundwater recharge estimation techniques /methods	
	Arid and semiarid climate	Humid climate
Surface water	Channel water budget	Channel water budget
	Seepage meters	Seepage meters
	Heat tracers	Baseflow discharge
	isotopic tracers	isotopic tracers
	Watershed modeling	Watershed modeling
Unsaturated zone	Lysimetres	Lysimetres
	Zero-flux plane	Zero-flux plane
	Darcy's law	Darcy's law
	Tracers [historical (^{36}Cl,^{3}H), environmental (Cl)]	Tracers (applied)
	Numerical modeling	Numerical modeling
Saturated zone	_	Water-table fluctuations
	_	Darcy's law
	Tracers [historical (CFCs, ^{3}H/^{3}He), environmental (Cl,^{14}C)]	Tracers [historical (CFCs, ^{3}H/^{3}He)]
	Numerical modeling	Numerical modeling

Christoph *et al*., (2011) introduced a new approach for investigation of the unsaturated zone through a combined use of laboratory and field techniques in arid environments. This technique uses direct push techniques to get undisturbed soil samples, extraction of pore water for isotope analyses and application of Time Domain Reflectometry (TDR) to determine soil moisture content. Combination of these techniques resulted a better quantification of present and historic groundwater recharge.

Similarly, Ahmadi *et al*., (2013) used water balance principle (rainfall-groundwater level relationship) based approach to estimate groundwater recharge. These methods are WTF (Water Table Fluctuation), DHB (Distributed Hydrological Budget) and HB (Hydrological Budget). These methods were useful, easy to use, cost effective, simple, requiring few data such as groundwater level measurements, rainfall, aquifer properties and groundwater extraction datasets. Use of these methods helps to provide irrigation return flow percentage and contribution of precipitation to natural groundwater recharge.

The groundwater estimation techniques have their own characteristics during recharge estimation. There must be factors that can help to choose which method should be selected in the course of the study. Hence, several factors such as the goal of the recharge study, the required accuracy and reliability, space and time scale, the range of the expected recharge estimates, the time to be spent on the study and the financial resources available should be considered, for accurate estimation of groundwater recharge (Lerner *et al*., 1990 and Scanlon *et al*., 2002).

Hydrologic models are among those methods which are frequently used for groundwater estimation. Groundwater recharge modeling techniques can be used to estimate recharge based on time series data from hours to years. The application of groundwater recharge modeling techniques are important for forecasting recharge in the future time horizon (Obuobie *et al*., 2008). There are a number of hydrological models available today for estimation of groundwater recharge. These models are designed to work based on spatial and temporal distributions of the complex systems of groundwater recharge. Models can be categorized as conceptual, distributed, undistributed or stochastic etc. based on their physical parameterization and model structure. Most of the models are basically rainfall-runoff models and or hydrological models. Most of the time, the terms rainfall-runoff models and or hydrological models are used interchangeably in literatures.

2.2. Groundwater Recharge Models

2.2.1. WetSpa Model

WetSpa is an acronym for **W**ater and **E**nergy **T**ransfer between **S**oil, **P**lants and **A**tmosphere. It is a physically based and distributed hydrological model for predicting the Water and Energy Transfer between Soil, Plants and Atmosphere on regional or basin scale and daily time step, developed in the Vrije Universiteit Brussels, Belgium (Batelaan *et al.*, 1996 and Wang *et al.*, 1997). The model is physically based and simulates hydrological processes of precipitation, interception, depression, surface runoff, evapotranspiration, infiltration, percolation, interflow, groundwater flow (Liu and De Smedt, 2004). It simulates continuously both in time and space, for which the water and energy balance are maintained on each raster cell (Figure 1).

Historical climate and physical data such as precipitation and potential evapotranspiration, minimum and maximum temperatures and discharge data and grid maps of elevation, land use and soil type of higher resolution are used as an input for this model on each pixel. During simulation a simple linear reservoir method will be employed for determination of the groundwater flow. According to Liu and De Smedt (2004) and Nyenje and Batelaan (2009) river flow hydrographs, soil moisture, infiltration rates, groundwater recharge, surface water retention and runoff are the main outputs of the WetSpa model.

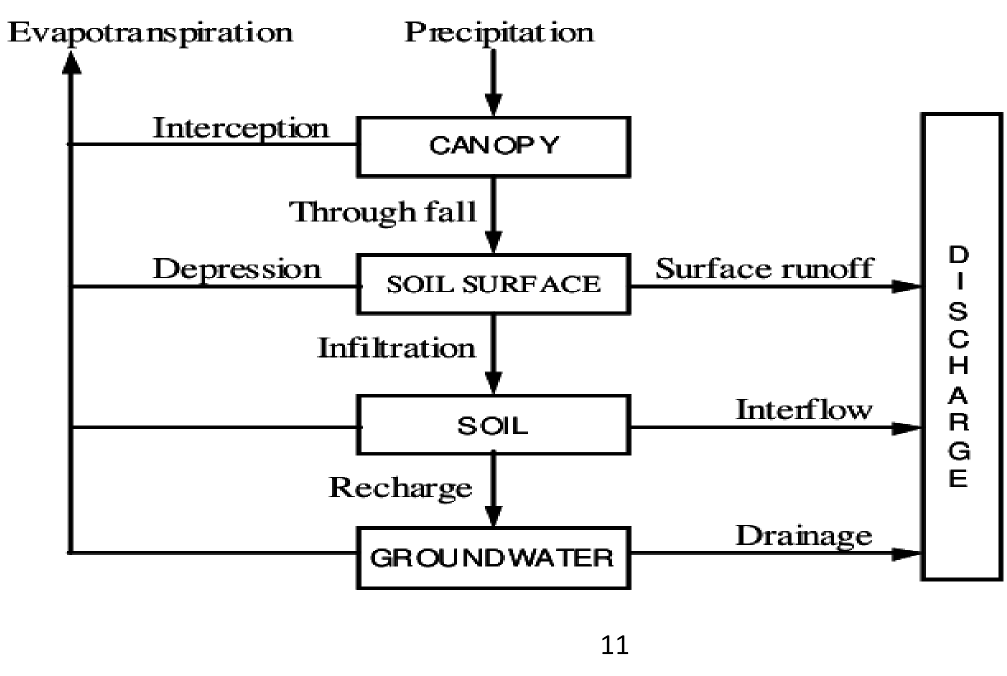


Figure 1: Structure of WetSpa Extension at a pixel cell level (Liu and De Smedt, 2004)

Different authors (Adem and Batelaan, 2006; Bahrem and De Smedt, 2008; Nyenje and Batelaan, 2009; Jaroslaw and Batelaan, 2011) have studied hydrological processes and groundwater recharges and associated impacts of climate change using the WetSpa distributed hydrological model. As a result, these researches were shown remarkable results through using this model. The model is user friendly and easily compatible with ArcView GIS software. This is the reason why WetSpa model is selected in this research to study the impacts of Climate change on groundwater potential and groundwater recharges.

2.2.1.1. Application of WetSpa model

In this study, WetSpa (Wang *et al*., 1997; Liu and De Smedt, 2004) model was employed for the groundwater potential and recharge estimation. WetSpa is a physically based and distributed hydrological model for predicting water and energy transfer between soil, plants and atmosphere on regional or basin level developed in the Vrije Universiteit Brussels, Belgium (Wang *et al*., 1997). This hydrologic model is GIS based and is compatible with the use of Arc-View GIS environment. It simulates hydrological processes of precipitation, interception, surface runoff, infiltration, evapotranspiration, percolation, interflow, groundwater flow (Liu and De Smedt, 2004).

The model conceptualizes a basin hydrological system, based on physical and empirical relationships, being composed of atmosphere, plant canopy, soil zone, root zone and saturation groundwater zone divided into grid cells/raster in order to deal with the heterogeneity of the basin. Data inputs to the model are digital maps prepared with the help of GIS and remote sensing packages and parameter files from spreadsheet tables with their specific extensions (Tesfamichael *et al*., 2010). The digital maps are seasonal or daily records of meteorological parameters such as precipitation, potential evapotranspiration, temperature and wind speed, groundwater level, land-use, soil, slope and topography. The parameter tables are time series data that have an attribute data for the model which contains land-use type as rooting depth, leaf area index, vegetation height; soil parameter for each textural soil class as field capacity, wilting point, permeability and runoff for all combinations of land-uses, slope, and soil type.

In this study, the spatial groundwater potential is investigated using the WetSpa model based on groundwater balance equations (Liu and De Smedt, 2004) expressed as

$$SG_S(t) = SG_s(t-1) + \frac{\sum_{i=1}^{N_s}[RG_i(t)A_i]}{A_s} - EG_s(t) - \frac{QG_S(t)\Delta t}{1000A_s} \qquad (1)$$

Here SGs(t) and SGs(t^{-1}) are groundwater storage of the watershed at time step t and t^{-1} (mm), Ns is the number of cells in the watershed, A_i is the cell area (m^2), As is the watershed area (m^2), RGi (t) groundwater recharge (mm), EGs(t) is the average evapotranspiration from groundwater storage of the watershed (mm), and QG_i (t) is the groundwater discharge (m^3/s). At root zone level water balance is used for controlling runoff, interflow and groundwater recharge for each grid cell calculated (Nyenje and Batelaan, 2009) as:

$$D\frac{\Delta\theta}{\Delta t} = P-I-S-E-F-R \qquad (2)$$

Where:

D is the root zone depth; Δ θ is the change in soil moisture content; Δt is the time interval; P is the precipitation; I is the initial abstraction (interception and depression losses); S is the surface runoff; E is the actual evapotranspiration; F is the interflow; and R is the percolation out of the root zone. The percolation out of the root zone recharges the groundwater storage, which then contributes to groundwater discharge forming the base flow of a stream hydrograph (Liu and De Smedt, 2004). Recharge is estimated based on the relationship between hydraulic conductivity and effective saturation (Brooks and Corey, 1966):

$$\mathbf{R} = \mathbf{K_s}\left(\frac{\theta-\theta r}{\theta-\theta r}\right)^{(2+3B)/B} \qquad (3)$$

Where:

R is the recharge or percolation; Ks is the saturated soil hydraulic conductivity; θr is the residual moisture content; B is the pore size distribution index.

In WetSpa model, the general watershed water balance system is expressed as

$$\mathbf{P = RT+ET+\Delta SS+\Delta SG} \qquad (4)$$

Where P is the total precipitation in the watershed over the simulation period (mm), RT and ET are total runoff and total evapotranspiration (mm), ΔSS is the change in soil moisture storage for the watershed between the start and the end of the simulation period (mm), and ΔSG is the change in groundwater storage of the watershed (mm). Changes in the storage of interception, depression and channel flow is neglected when dealing with simulation of relatively longer time period,

2.2.1.2. WetSpa model evaluation criteria

Statistical measures provide quantitative estimates for the goodness of fit between observed and predicted values, and are used as indicators of the extent at which model predictions match observation (Liu and De Smedt 2004). While calibrating, it is useful to have a good method of evaluating the results. Finally the model performance was evaluated for both calibration and validation in different ways including; visual comparison between observed and predicted parameter values or evaluation of peak flow rate and time to the peak, bias measurement, model confidence, and the model efficiency. There are criteria's set for WetSpa model evaluations mentioned below.

2.2.1.2.1. Model bias

It is a relative mean difference between predicted and observed stream flows for a sufficiently large simulation sample, reflecting the ability of reproducing water balance. It is an important criterion for comparing whether a model is working well or not through measuring under or over prediction for a set of predictions systematically. Model bias is given by the equation

$$MB = \frac{\sum_{i=1}^{N}(Qs_i - Qo_i)}{\sum_{i=1}^{N} Qo_i} \qquad (5)$$

Where MB is the model bias, Qs_i and Qo_i are the simulated and observed stream flows at time step i (m^3/s), and N is the number of time steps over the simulation period. Model bias measures the systematic under or over prediction for a set of predictions. A lower MB value indicates a better fit, and the value 0.0 represents the perfect simulation of observed flow volume.

Model bias has the ability to clearly indicate performance of a model. Model bias values tends to vary more during dry periods than during wet periods for streamflow (Gupta *et al.*, 1999). It is useful to consider the behavior of this criteria when using split-sample data for calibration and for validation. Model simulation values can be accepted if it is between -0.25 and 0.25 for streamflow (Moriasi *et al.*, 2007).

2.2.1.2.2. Model confidence

Model confidence expressed by coefficient of determination, which is one of the important criteria in assessment of continuous model simulation. It is calculated as the sum of the squares of the deviations of the simulated and observed discharges from the average observed discharge.

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(Qs_i - \overline{Qo})^2}{\sum_{i=1}^{N}(Qo_i - \overline{Qo})^2} \qquad (6)$$

where R^2 is the model determination coefficient, $\overline{Qo}$ is the mean observed stream flow over the simulation period. R^2 represents the proportion of the variance in the observed discharges that are explained by the simulated discharges.

R^2 value varies between 0 and 1, with a value close to 1 indicating a higher level of model confidence having less error of variance and model simulation values greater than 0.5 are considered acceptable (Santhi *et al.*, 2001). R^2 is very sensitive to outliers and less sensitive to additive and proportional difference values between simulated and observed data (Legates and McCabe, 1999). However, R^2 have been widely used for model evaluation

2.2.1.2.3. Nash-Sutcliffe efficiency

Nash and Sutcliffe (1970) pointed out model evaluation criteria called Nash-Sutcliffe coefficient which is used to describe how well discharges are simulated by the model. This efficiency criterion is commonly used for model evaluation. The equation can be described as

$$NSE = 1 - \frac{\sum_{i=1}^{N}(Qs_i - Qo_i)^2}{\sum_{i=1}^{N}(Qo_i - \overline{Qo})^2} \qquad (7)$$

Where NSE is the Nash-Sutcliffe efficiency used for evaluating the ability of reproducing the time evolution of stream flows or discharges. The NSE value can range from a negative value to 1, with 1 indicating a perfect fit between the simulated and observed hydrographs.

NSE is used to calibrate highly variable flow regimes characterized with extreme high flows and extreme low flow events. Hence, NSE found to be the best objective function for reflecting the overall fit of a hydrograph. Model simulation can be judged as satisfactory if NSE > 0.50 (Moriasi *et al*., 2007)

2.2.2. WetSpass model

WetSpass stands for Water and Energy Transfer between Soil, Plants and Atmosphere under quasi-Steady State (Batelaan and De Smedt, 2001, 2007). It was built upon the foundations of the time dependent spatial distributed water balance model WetSpa (Batelaan *et al*., 1996; Wang *et al*., 1997). WetSpass is a physically based model for estimation of the long-term average spatial patterns of surface runoff, actual evapotranspiration and groundwater recharge which is suitable for studying long-term effects of land-use changes on the water regime in a watershed (Batelaan and De Smedt, 2001, 2007; Batelaan and Woldeamlak, 2007; Aish *et al*., 2010). The application of this model is compatible and integrated with the GIS ArcView software during simulation process.

WetSpass is developed as to regional groundwater models are quasi-steady state used to simulate infiltration–discharge relations based on long-term average recharge input data. This model simulates water balance components, surface runoff, actual evapotranspiration and groundwater recharge based on distributed data. WetSpass estimates spatial groundwater recharge at seasonal and annual scales. WetSpass was successfully applied in Belgium

(Batelaan and De Smedt, 2001) and other environments as in Gaza Strip, Palestine (Aish *et al*., 2010) and Geba catchment, Ethiopia (Tesfamichael *et al*., 2010). Based on those authors groundwater recharge was successfully estimated which is the main interest of this research.

2.2.2.1. Application of WetSpass model

In this study, WetSpass model was used to estimate spatial groundwater recharge at seasonal and annual scales based on some relationships. The description and formulas below are based on Batelaan and De Smedt (2001) and used by (Tesfamichael *et al*., 2010) in the Northern part of Ethiopia. Total water balance per raster cell and season are calculated using

$$ET_{raster} = a_v ET_v + a_s E_s + a_o E_o + a_i E_i \quad (8)$$

$$S_{raster} = a_v S_v + a_s S_s + a_o S_o + a_i S_i \quad (9)$$

$$R_{raster} = a_v R_v + a_s R_s + a_o R_o + a_i R_i \quad (10)$$

$$P = I + S_V + T_V + R_V \quad (11)$$

Where:- ET_{raster}, S_{raster} and R_{raster} evapotranspiration, surface runoff, and groundwater recharge [LT^{-1}] with subscript relating to a cell (raster), vegetation (v), bare soil (s), open water (o) and impervious area (i). The coefficient, a, expresses the contribution of each land use. Moreover, P, I, Sv, Tv and Rv (Equation 7) represents the total seasonal precipitation, the interception by vegetation (precipitation that evaporates from the wet surface of the vegetation), the surface runoff over the land surface beneath the vegetation, the actual transpiration of the vegetated surface and groundwater recharge expressed in [LT^{-1}] units respectively.

$$ET_{tot} = I + T_V + E_S \quad (12)$$

ET_{tot} is the total actual evapotranspiration, I is evaporation of water intercepted by vegetation, Tv transpiration of vegetation cover and Es is evaporation from the bare soil between the vegetation.

Recharge is the entry of water into the saturated groundwater zone at the water table surface and is calculated as a residual term of the water balance system in the model. The model determines the long-term average spatially distributed recharge as a spatial variable depending on soil texture, land-use, slope, meteorological conditions (Batelaan *et al*., 2004).

$$R_v = P - S_V - ET_V - I \qquad (13)$$

ETv is the actual evapotranspiration [LT^{-1}] given as the sum of transpiration, Tv, and the evaporation from bare soil in between the vegetation Es [LT^{-1}].

From the discussions so far, spatially distributed hydrological parameters as groundwater recharge, surface water retention and runoff, soil moisture, infiltration rates and river flow hydrographs are the main outputs from the WetSpa /WetSpass models.

2.3. Climate Change

Climate change is now a days an overwhelming global issue. Everything, living or non-living in one or another way relates with the subject of climate change. It is because the global warming, an indicator for the climate change, is a common phenomenon unlike the past times. Increase in temperature of the atmosphere, oceans, and landmasses of planet earth are main symptoms of global warming. At present earth appears to be facing a rapid warming, which mostly believed as results of human-induced activities. The chief cause of this warming is thought to be the burning of fossil fuels, such as coal, oil, and natural gas from which greenhouse gases are released into the atmosphere (IPCC, 2013).

It is difficult to blame global warming is caused by a specific hurricane or flood or drought or forest fire, it is a collective evident that, it is due to a distinct anthropogenic influence (Bates *et al*., 2008; Casper, 2010; IPCC, 2013). It doesn't mean that the natural hazards are not contributing to the climate change, but human-induced climate changes are tremendously higher and complex.

Since the 1999s the intergovernmental panel for climate change (IPCC, 1990, 1995, 2001, 2007 and now 2013) releases different climate change related assessment reports. These reports have forced policy makers to take action on the climate change that threatens the earth. Meanwhile, based on the new evidence of climate change from different independent scientific analyses, from observations of the climate system, paleoclimate archives, theoretical studies of climate processes and simulations using climate models, the IPCC has released a new assessment report. As a result, the Working Group I of the IPCC's releases its Fifth Assessment Report (AR5) outlined and has projected the climate change that could be occurred on the globe during the twenty first century.

Therefore, according to IPCCs Fifth Assessment Report (IPCC, 2013), warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, sea level has risen, and the concentrations of greenhouse gases have increased. Moreover, each of the last three decades has been successively warmer at the Earth's surface than any preceding decade since 1850. In the Northern Hemisphere, 1983–2012 was likely the warmest 30-year period of the last 1400 years. Ocean warming dominates the increase in energy stored in the climate system, accounting for more than 90% of the energy accumulated between 1971 and 2010. The rate of sea level rise since the middle ninetieth century has been larger than the mean rate during the previous two millennia. Over the period 1901 to 2010, global mean sea level rose by 0.19m.

The situation of the future climate change that we will face is almost trouble and anxiety unless urgent mitigation measures are taken. Due to the impact of climate change it is possible to say that the world will become worst and threatens the existence of life. Mostly surprising is that the majority of this change of climate is due to human-induced problems through releasing of greenhouse gases to the atmosphere, land use change emissions through forest fire and aerosols.

The SRES (Special Report for Emission Scenarios) are climate change projections developed by IPCC starting from 1990s (IPCC-TGICA, 2007; IPCC, 2013). These scenarios are due to emissions from greenhouse gases, aerosol precursor which produces global warming. The emission scenarios were developed based on population, economy, technology, energy and land used as deriving forces. According to IPCC, (IPCC-TGICA, 2007; IPCC, 2013) the emission scenarios are categorized in to four families based on their unique characteristics for the twenty first century.

A1 Scenario: Globalization, globalized human wealth, intensive (market forces). This family is described as the world will record a very rapid economic growth with efficient technology use and global population that peaks in middle century and declines afterwards. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: Fossil intensive (A1FI), Non - fossil energy sources (A1T), or Balance across all sources (A1B).

A2 Scenario: Regionalization, regionalized human wealth, intensive (clash of civilizations). The storyline and scenario describes a very heterogeneous world with a self-reliance and preservation of local identities.

B1 Scenario: Globalization, sustainability and equity globalized and extensive (sustainable development). It has similar trends of global population increment with A1 storylines. The scenario is characterized with rapid changes in economic structures towards a service and information economy and resource-efficient technologies.

B2 Scenario: Regionalization, sustainability and equity regional, extensive (mixed green bag). This scenario family describes the world emphasizes on local solutions to economic, social, and environmental sustainability, global population increases at a rate lower than A2storylines with intermediate levels of economic development.

These emission scenarios are used as indicating future likely impacts of climate change ranged from the relatively less effect of climate change to the very worst effect of climate change conditions that would possibly appear in the future.

2.3.1. Impacts of climate change on recharge and groundwater resources

Impact of climate change on groundwater can only be realized if the relationships and sensitivity of the hydrodynamics of groundwater with climate systems are well understood. The hydrologic cycle is highly sensitive to climate change because the components of the hydrologic cycle are vulnerable to changing climate. Findings of the IPCC (2013), strongly suggests that climate change has the potential to deteriorate the groundwater availability, water quality and water supplies. Being the most potable water for mankind, if groundwater severely affected by the climate change, it goes to threaten the survival of life on earth.

In many countries of the world the use of groundwater resources for public water supply constitutes an important potable water. However, many factors affect future groundwater and groundwater recharge as changes in precipitation and temperature regimes, coastal flooding, urbanization, land use changes and changes in cropping system (Holman, 2006). Similarly, Herrera-Pantoja and Hiscock (2008) concluded that future climate may present a decrease in potential groundwater recharge that will increase stress on local and regional groundwater resources. As a result attention to the groundwater resources remains inevitable to overcome the problem with some solutions.

Many studies have been conducted to investigate the impact of climate change in water resources, stream flow and land use/land cover changes in the upper Blue Nile of Ethiopia. In the upper Blue Nile of Ethiopia, climate change has observed to shift the time of rainfall patterns and of the groundwater recharge and temperature has observed increasing trends in the mean annual, rainy and dry seasons (Tekleab *et al.*, 2013). However, land use change is rather the main anthropogenic factor which has significantly affect groundwater and the rate of ground water recharge in the basin (Gebremicael *et al.*, 2013). These changes contributed tremendous effects on the groundwater potentials and corresponding groundwater recharges in Ethiopia.

Therefore, groundwater is a vital water resource and awareness needs to be raised on its vulnerability to overexploitation, pollution and most importantly, climate change (Nyenje and Batelaan, 2009). The change in climate and weather conditions in the atmosphere and hydrosphere leads to changes in precipitation patterns and this leads to changes in groundwater and this leads to changes in groundwater recharge. As groundwater recharge has direct relationships with rainfall, the more rainfall rains the more water infiltrates the soil to the groundwater and hence the more recharged water stored in the water table.

2.3.2. Use of climate models to study the likely impacts

Models are physical or mathematical simplifications of natural systems used for analyzing physical parameter data. It also describes equations of physical systems and techniques that provide a means for quantitative explorations or predictions that will help in decisions making. Projections of changes in the climate system are made using a hierarchy of climate models ranging from simple climate models, to models of intermediate complexity, to comprehensive climate models and Earth System Models (IPCC, 2013). Moss *et al.*, (2010) described climate models as there are a wide variety and complexity of models which are numerical representations of the earth's natural systems used to study how climate responds to changes in natural and human-induced perturbations.

These climate models help to project future likely impacts of climate change in the planetary system. Groundwater recharge is one among others that is highly influenced by climate change as a result of effects on the atmospheric and rainfall patterns. Consequently, there are improvements on the climate models in time and space in predicting future climate change impacts that may occur. According to IPCC (2013) Climate models have improved since the fourth assessment report for future prediction and for studying preceding climatic situations. In the climate system models are known to reproduce observed continental and local scale atmospheric patterns and trends over many decades.

2.4. REMO (Regional Climate Model)

REMO stands for **Re**gional **MO**del, it is a climate model developed, to forecast climate changes, at the Max-Planck Institute for Meteorology (MPIM) in Hamburg, Germany (Jacob, 2001). The regional climate model REMO is based on the *Europamodell*, the former numerical weather prediction model of the German Weather Service (Majewski, 1991). REMO is a hydrostatic limited area model that has been designed for applications at the synoptic scale (Jacob, 2001). The quality of the REMO simulation is achieved by using perfect boundaries which are considered as reality in local scale levels. The regional climate model is nested into the driving fields to harmonize the fields under consideration. The Model is therefore works based on primitive equations related with temperature, surface pressure, horizontal wind components, water vapor content and cloud water content as prognostic variables (Jacob *et al.*, 2001). The model equations are then transformed based on a geographical latitude/longitude grid with a terrain-following vertical coordinate during application.

REMO, the regional climate model, have used in Western, Eastern and Northern Africa (Paeth and Thamm, 2007; Paeth *et al.*, 2005a, 2005b, 2007, 2009; Kebede *et al.*, 2013). As a result, REMO has proved its applicability even at low altitudes in West Africa after having adjusted to some of its parameters on tropical weather and climate (Paeth *et al.*, 2005a). Similarly, the climate data downscaled from REMO and observational data are showed similarity in the wet and dry summer monsoon seasons in West Africa. Paeth *et al.*, (2009) in the study conducted on regional climate change in Tropical and Northern Africa due to greenhouse forcing and land use changes using REMO, has compared with a present day global simulations and concluded that, REMO is used with a six times higher resolution, Spatially detailed patterns of future land use changes are prescribed and Transient forcing is realized by REMO than by global simulations (GCM).

Generally with comparison of observational and REMO model data sets, REMO have lots of advantages and perspectives: a realistic boundary conditions and high spatial resolution is available over a large area. The data can be considered to be fully consistent in a physical-dynamical sense down to the synoptic scale. Moreover, REMO is now ready to carry out to simulate West and North African climatic features (Paeth, 2005a, 2005b).

The REMO user capacity covers regions of Tropical and Northern Africa from 15°S–45°N and extends up to 30°W–60°E (Paeth *et al.*, 2007). As Ethiopia is belongs to this region, the

REMO dataset can also be used for our case. Due to this, Kebede *et al*., (2013) has used this regional climate model to model climate system in Baro-Akobo river basin of Ethiopia and revealed successful works. Based on this, for this study REMO will be used as a dataset for the determination of future climate change projections and likely groundwater impacts by downscaling REMO in to the basin of interest.

2.4.1. Use of data from REMO model

The main concern of this research is to estimate the effect of climate change on the groundwater recharging rate and its hydrologic counterparts in the watershed using data sets available from REMO. REMO is a climate model developed, to forecast climate changes, at the Max-Planck Institute for Meteorology (MPIM) in Hamburg, Germany (Jacob, 2001). Jacob and Podzun (1997) have described the model as it is based on the fundamental scientific equations in terrain-following hybrid coordinate systems. Paeth et al., (2007) in the study for regional modelling of future African climate, the model has run at 0.5° horizontal resolution with 20 terrain-following vertical levels with a model domain includes northern part of Africa. REMO is a dataset from which climatic projections are downscaled that can be calibrated and validated based on the observed and simulated data for selected predictable variables (Paeth et al., 2007; Kebede et al., 2013). The model accommodates temperature, precipitation, evapotranspiration, relative humidity; surface land pressure and radiation which tend to be downscaled to the point scale/station scale for the application of future climate changes. The data necessary for the study will be obtained from the REMO database (available at http://www.remo.rcm.de)

2.5. Climate Data Downscaling Approach

Downscaling of climate scenarios refers to a process of taking global information on climate response to changing atmospheric composition, and translating it to a finer spatial scale that is more significant in the context of local and regional impacts. According to Wilby *et al*., (2004) and Wilby and Dawson, (2007), there are two general approaches used in downscaling regional climate models.

Dynamical downscaling approach:- this approach is a method of extracting local scale information by developing and using regional climate models (RCMs) with the coarse general circulation models (GCM) data used as boundary condition. It simulates climate processes over the region of locality or basin with a high resolution regional climate model. 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's of 20–50 km (Wilby and Dawson, 2007). RCMs have been developed that as it can attain horizontal resolution finer and finer as compared to GCMs resolution. The advantage of dynamical downscaling method is that a regional climate model can simulate local fine scale feedback processes which are not verified with statistical methods. Performance of this downscaling is however highly dependent on the quality of the data input.

Statistical downscaling approach:- in this method the large scale climate features available are statistically related to fine scale climate for the area of interest. Statistical downscaling assures development of statistical relationships between local climate variables (predictands) and large scale climate variables (predictors) (Wilby *et al*., 2004). It also provides an application of predictands-predictor relationships to the output of GCM and RCM experiments to simulate local climate characteristics. The most common method of statistical downscaling is when predictands are simulated as a function of predictors. This kind of downscaling is useful especially for impact assessment modeling studies for reproducing different climatic statistics at basin/local level. Therefore, statistical downscaling models are used as a decision support tool as to which the historical climate data available and the downscaled climate data have relationships or not through calibration and validation of the models.

According to Wilby *et al*., (2004), Wilby and Dawson (2007), Xu *et al*., (2005) and Kebede *et al*., (2014) the statistical downscaling model provides a consistent estimates of temperature extremes and precipitations in seasonal and site level. Statistical downscaling model have advantages of ease of computationally, can easily crafted and used for specific uses, direct regional incorporations of observational records as well as it uses basic standard statistical procedures (Wilby and Dawson, 2007).

Therefore in this study, the statistical downscaling model (SDSM) will be used to downscale future climate change scenarios, which will be obtained from the REMO regional climate model in the watershed. Result of the SDSM will be used as input to analyze the impact of climate change to groundwater potential and groundwater recharge.

2.5.1. SDSM model evaluation criteria

After having run the SDSM model, two methods of evaluation of performance of the model were done. In the first case, the model by itself has its own evaluation criteria, the coefficient of determination (R^2) and explained variance (*EV*). Coefficient of determination (R^2) is expressed as a squared ratio between the covariance and the multiplied standard deviations (Krause *et al.* 2005). Explained variance (*EV*) is estimated as one minus the ratio of residual variance under the modeling and the residual variance under the null model (Gelman and Pardoe 2006).

Moreover, the data out puts of the model were evaluated through using the standard deviation (STD) and mean absolute error (MAE). Mean absolute error is a quantity used to measure how close simulated forecasts are from the observed data (Willmott and Matsuura 2005).

It is given by

$$\text{MAE} = \frac{1}{n}\sum_{i=1}^{n}|fi - yi| \qquad (14)$$

where, fi is the predicted value and yi is the observed value.

The optimum value for mean absolute error is 0.0. Hence, values closer to 0 is appropriate for calibration.

2.6.Models Calibration and Validation

Model calibration is the process of minimizing differences between observation and model output by tuning model parameters. This process of changing parameter values are used to obtain simulated results that most likely reflect observed values. The general approach to calibration is one of trial-and-error in which various values for each parameter are tried, their effects are noted and appropriate changes are made to improve agreement between simulated and recorded values (Morgan, 1995; Johnson, 1998). The procedure is to manipulate and compare the simulated parameter values against recorded values using both numerical and graphical methods. According to (Morgan, 1995; Johnson, 1998) numerical and graphical methods are used to compare simulated and recorded values over the simulation periods. The calibration process requires a procedure to evaluate the success of a given calibration and another procedure to adjust the parameter estimates for the next validation. The criterion of success for calibration is subjective to a judgment based on statistical measuring of goodness of fit.

Model verification involves checking the validity of the parameter values for a period not originally simulated. Once the calibration process has been used to estimate the best values for the model parameters, the outcome needs to be evaluated to determine if the results provide adequate information for the intended period. Validation consists of an objective test on how well the model outputs fit the data by using data that were not used for calibration process. The usual method is to test the performance of the calibrated model on a selected portion of the data that were not used during the calibration processes. Calibration data fit values are used to simulate for the intended portion of time for future time periods that will likely yields simulated and verified values (Johnson, 1998). Through calibrating the parameter values over the longer simulation periods, a verification value will immediately be obtained for the next simulation period.

3. MATERIALS AND METHODS

3.1.Description of Study Area

3.1.1. Location

Werii watershed, where this study was conducted is located in Tekeze river basin of Tigray regional state, Northern Ethiopia (Figure 2). Werii watershed is found in the border between central and eastern administrative zones of Tigray region. The watershed touches five administrative districts of Ahferom, and Ganta-Afeshum at the upper stream catchment and Worie-Lekhe, Hawzen and Kola-Tembien at the downstream. The area covered by the watershed is 1797 km^2. The gauging station (13.843 °N, 39.016 °E) is situated at the old road bridge which connects Abyiadi and Adwa towns.

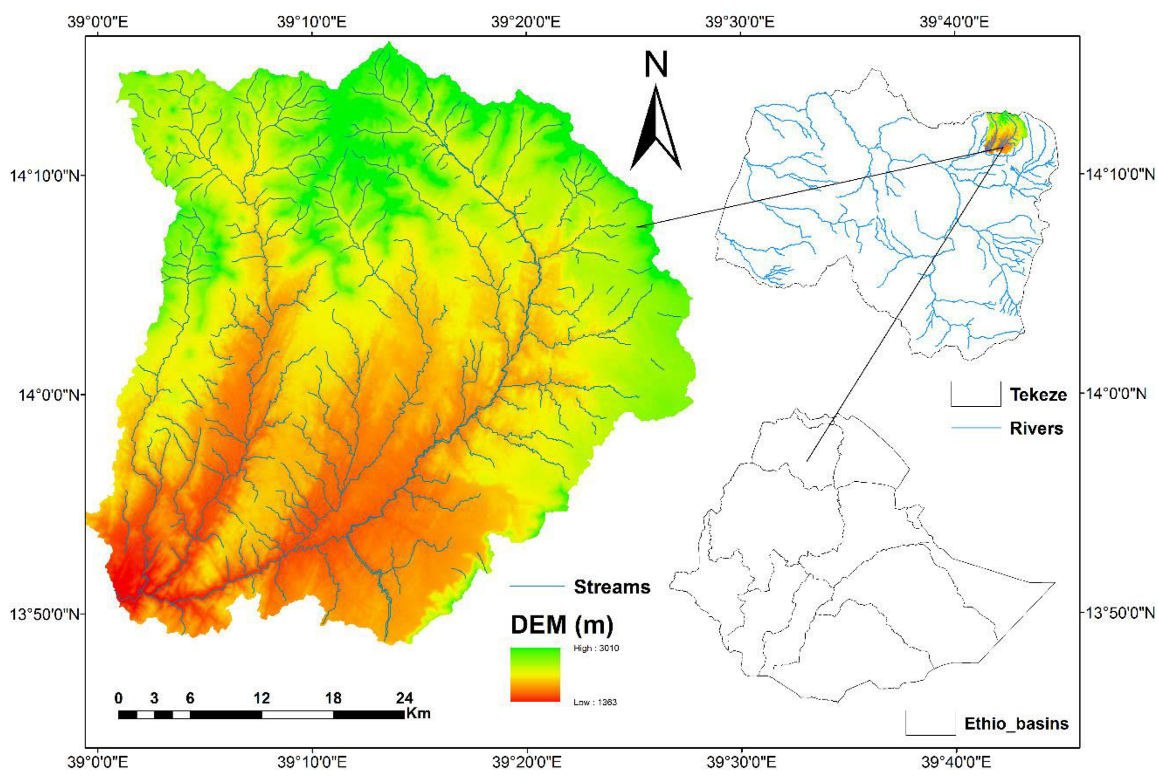


Figure 2: Location map of Werii watershed (1797km^2), DEM and river networks.

3.1.2. Topography

The topography of the watershed is highly vulnerable to soil erosion by water and become eroded due to steep land features. It is characterized by undulating terrain and steep slopes, fragile environment, erratic rainfall and sparse vegetation coverage which in turn facilitates soil erosion by water. The elevation of the watershed ranges from 1363 to 3010 m.a.s.l (Figure 3) and the mean elevation is 1951 m.a.s.l. The longest flow path along the watersheds outlet is 299km in length. This stretches from the top upstream of the watershed to the gauging station. As depicted in Figure 4, the slope of the watershed ranges from 0 to 319% with mean slope of 19%.

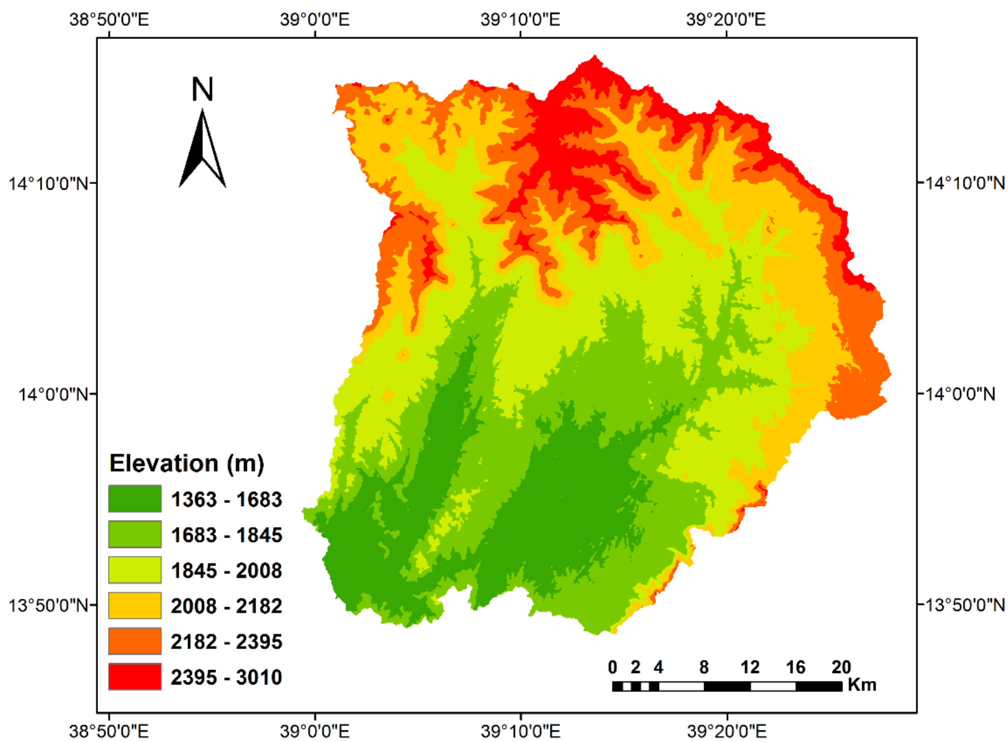


Figure 3: Topography map of Werii watershed (meters above sea level)

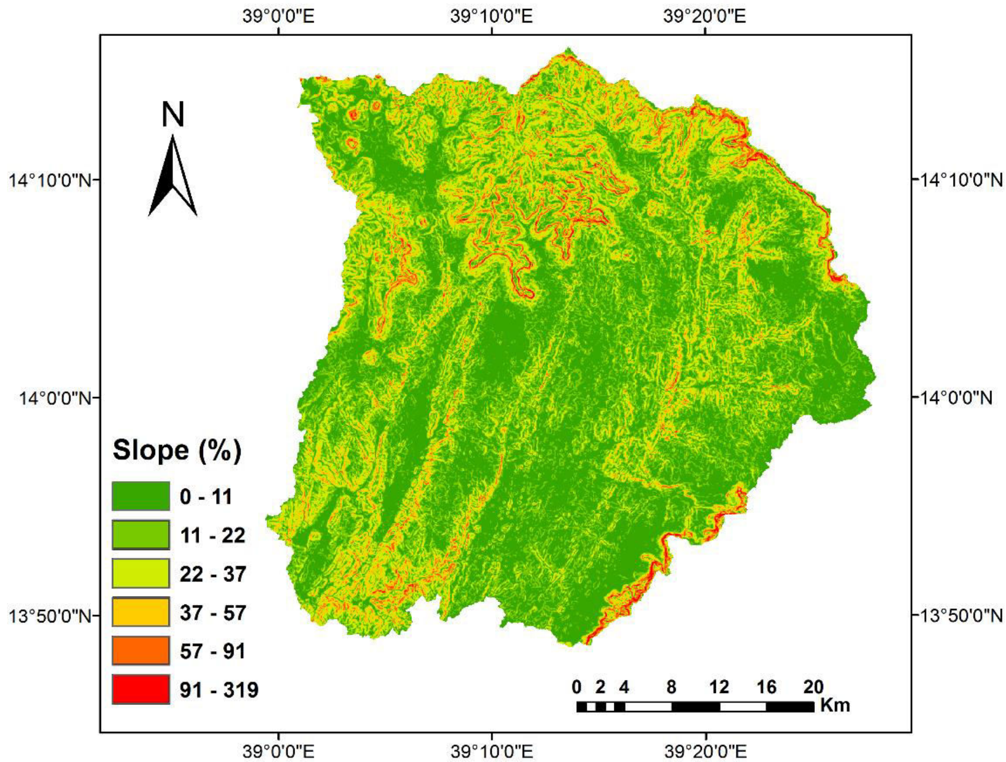


Figure 4: Slope map of Werii watershed

3.1.3. Climate

The Ethiopian climate system is traditionally classified based on existing altitudinal range and temperature. Hence, there are five climatic zones in the country. The *Berha* zone is a very hot and hyper-arid region with less than 500 m.a.s.l. and *Kola* zone is also a hot and arid region ranged between 500-1500 m.a.s.l. altitudes. Similarly, *Woina-Dega* is an optimum temperature from 1500-2500 m.a.s.l. altitude. *Dega* and *Wurch* zones are found in highland regions with 2500-3000 and greater than 300 m.a.s.l. altitudes respectively (NMA, 2001). Accordingly, Werii watershed is laid in between *Kola* and *Wurch* with majority falls at *Woina-Dega* zone (Figure 3 and 6).

Rainfall distribution is uni-modal and mostly erratic with dry and wet seasons characterized by arid and semiarid climatic environments (Figure 5). Most of the time, this erratic rainfall starts at June and reaches its peak at middle of July and ends up at late September. The annual average rainfall of the watershed varies between about 414 mm-974 mm with an average of 717 mm per year. The watershed receives about 77% of the annual rainfall in summer season from June to September (JJAS) and remaining 23% rains in winter season from October to May. Unless early growing crops are cultivated, the quality and quantity of crop yields are hindered by water stress.

Moreover, the average annual temperature of the watershed is found to be 18.4 °C (Figure 6). The relationships created between temperature and altitude shows that the elevation is inversely related to temperature regime in the watershed. Due to that, temperature at the western part, lower altitude, of the watershed is higher than that of eastern part.

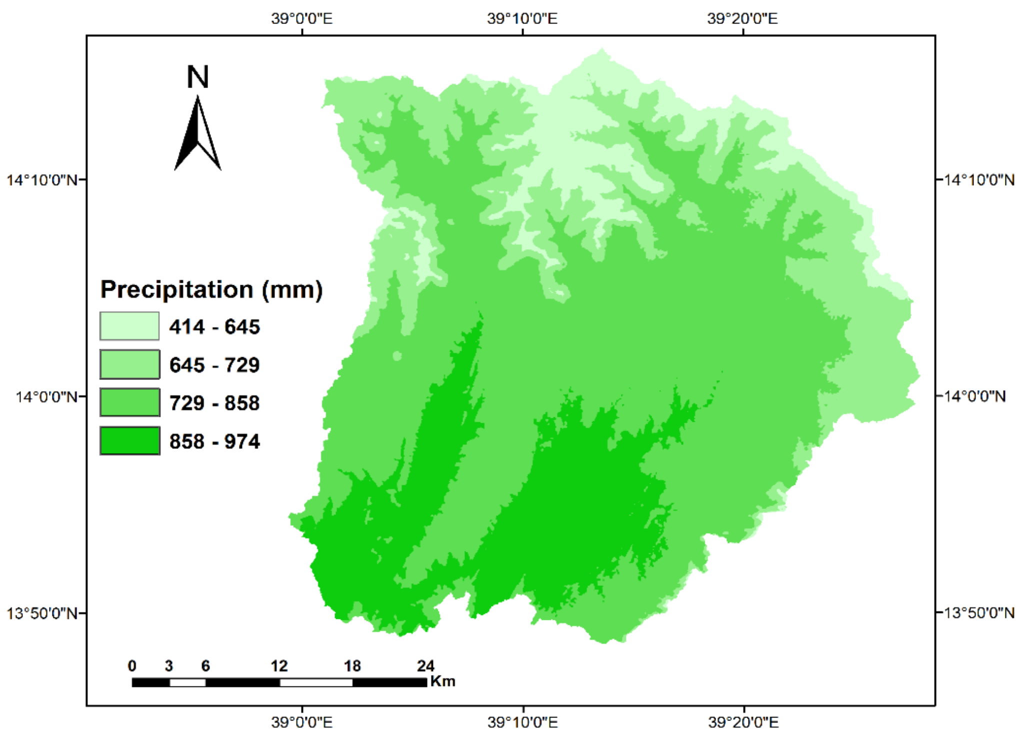


Figure 5: Average annual rainfall of Werii watershed

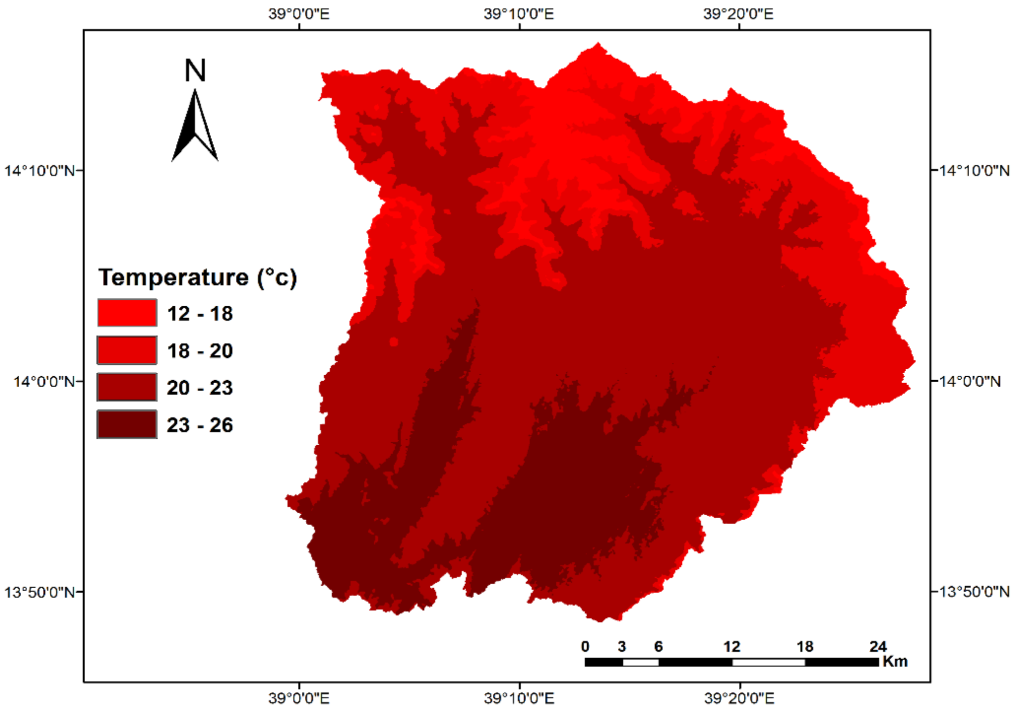


Figure 6: Average annual temperature of Werii watershed

3.1.4. Drainage networks

Werii River which belongs to the watershed is a main tributary to the Tekeze river basin to the southwest at 13°41`N and 38°33`E outlet. Tekeze river basin is considered as one of water sources for the Nile basin after joining the Blue Nile in Sudan. Werii watershed is surrounded by Geba watershed in the southeastern part, Mereb River basin in the North and Middle Tekeze river basin in the Western part.

Adi-Ahferom Mountain is a place where drainage water appears to drain in to two opposite sides, Werii watershed to the south and Mereb River basin to the north of the mountain. As a result, Werii watershed emerges from the top of Adi-Ahferom Mountain and drains west wards and finally joins Tekeze River basin. Werii, Tsedia, Chiemit, Misuema and Mayiere are the main intermittent tributaries of the watershed which contribute flow water in west direction to the outlet (Figure 7).

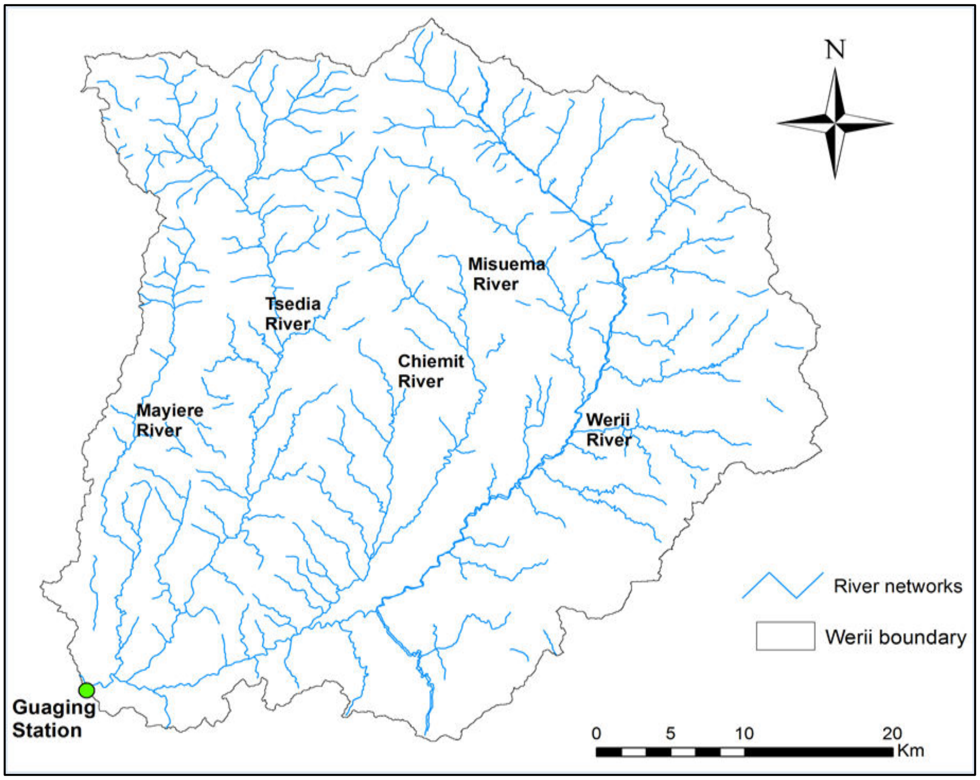


Figure 7; Map of Werii watershed with its drainage networks, major rivers and gauging station

3.1.5. Land use

There are five land use /land cover types recognized from the land use map of Werii watershed (Figure 8). The crop land at which agriculture practice takes places, is the dominant land use type in the watershed which comprises 41.4% of the total watershed area. Shrub and forest land use types also covers respectively 28% and 27% of the total land in the watershed. Bare land and grassland are found in a small land coverage with a 2.7 and 0.5% respectively. The agricultural system is rain-fed agriculture dependent in rainfall mostly composed of mixed agriculture which basis on the *Gesho (Rhamnus prinoides)* farming system and highland crops in the upstream catchment. In the downstream parts of the basin a mixed agriculture is also practiced with less practice of irrigation along the river side and cultivation of lowland crops. Wheat *(Triticum vulgare)*, barley *(Hordeum vulgare)*, Faba bean *(Vicia faba),* Chick pea *(Cicer arietinum)* and Lentil *(Lens culinaris)* are among the crops which are highly cultivated in the upper stream. However, in the downstream area spices, *Teff (Eragrostic tef)*, finger millet (*Eleusine coracana*), maize (*Zea mays*) and sorghum (*Sorghum bicolor*) are produced.

Vegetation coverage is sparse composed of bushes, shrubs and tall trees such as eucalyptus (*Eucalyptus globulus*). There is also a traditional agroforestry system especially at the downstream part of the watershed. Nitrogen fixing trees such as *Acacia albida* are also widely grown in the cultivable lands in a traditional manner in Werii. These trees are used for different purposes beyond the nitrogen fixation such as for farm equipment. Land use/land cover of the watershed is mostly cultivated, forest land and pasture lands. However, very small miscellaneous land use types which do not have unique uses are also common and considered as bare land in this study.

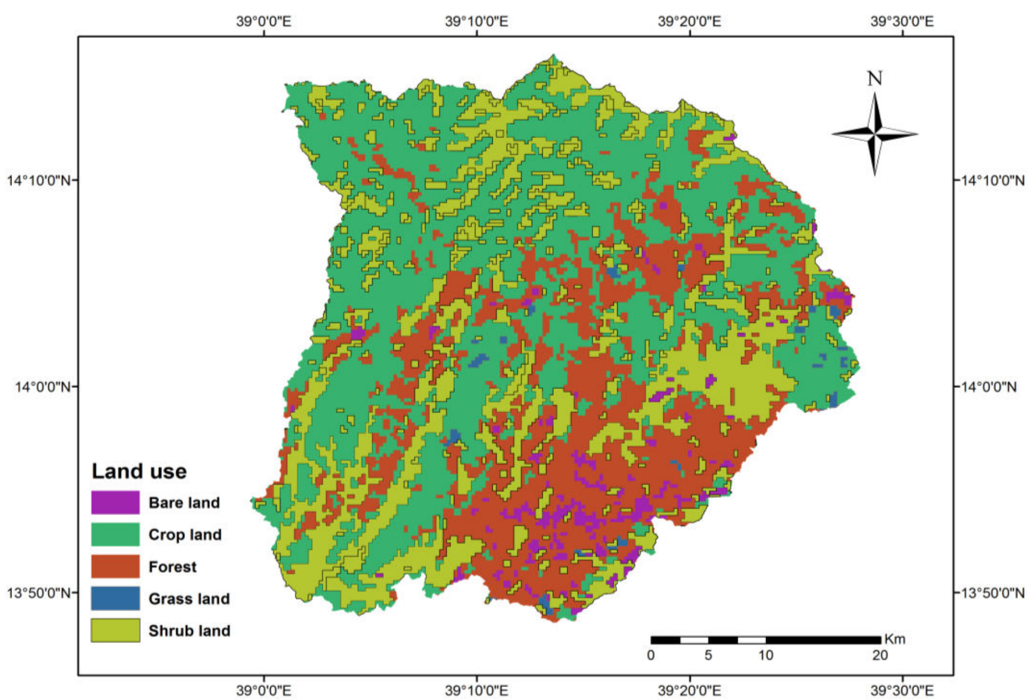


Figure 8: Land use map of Werii watershed

3.1.6. Soil types and geological formation

According to the USDA soil classification system five soil types are identified in the watershed. These soil types are sandy loam, silt clay loam, silt, silty loam and clay. Silt clay loam, sandy loam and silty loam are the dominant soil types which comprises 49.5%, 26.4% and 21.1% of the watershed area respectively. Silt and clay are insignificantly found in the watershed with 2.7% and 0.3% from the total area of the watershed. Most parts of the upper stream of Werii watershed is dominated by sandy loam and silty clay loam and the lower parts of the watershed is silt and silty loam. Clay is found in the lower and upper tip of the watershed (Figure 9).

Geological formation of the study area is dominated by the oldest and sparsely distributed Paleozoic sedimentary rocks known as Edaga-Arbi Tillites (Tesfamichael *et al*., 2010). This rock is well exposed in the entire watershed.

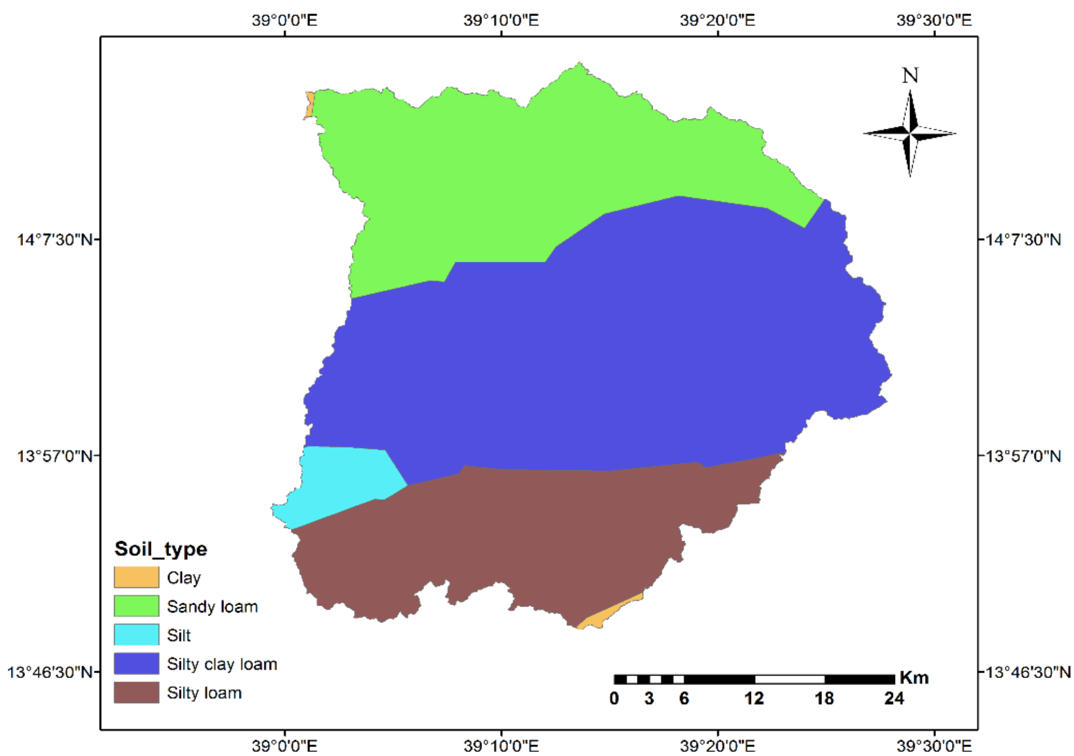


Figure 9: Soil map of the Werii watershed

3.1.7. Present-day situation

As it has been explained in the previous sections the watershed were characterized as poorest areas ever especially in the late 1980s. However, since 1990s concomitant with change of government in Ethiopia, there are improvements in the sustainability and use of natural resources and had enhanced the livelihoods of the people. These improvements were due to change of policies and strategies in the country. Based on that, agriculture led industrialization strategy, on environmental rehabilitation as soil and water conservation, area closure and afforestation, expansion of irrigation have shown tremendous changes in the watershed. Improved animal production practices are commonly available in the watershed even if the distribution differs among the households. Cattle, equines and small ruminants rearing and productions are practiced throughout the watershed.

3.2. Data Availability and Materials

For this research the following data were collected; historical daily precipitation and potential evapotranspiration, minimum and maximum temperatures, daily discharge and daily large-scale RCM predictors from REMO to predict future climate changes. Moreover, 30m resolution DEM, land use and soil type of the study area were used as an input for the models. Primary data like average groundwater depth and location of gauging station was collected at field level using appropriate data collection methods.

3.2.1. Meteorological and hydrological data

Secondary data inputs for the models employed in this study were acquired from Ethiopian Ministry of Water, Irrigation and Energy (MoWIE) and the Ethiopian National Meteorological Agency (NMA). These meteorological data were collected from the meteorological stations found in and around the watershed. Precipitation, minimum and maximum temperature data are among the meteorological data collected from the Ethiopian Meteorological Service Agency. Moreover, the hydrological data, the available flow net data of the watershed's gauging station, were collected from the Ethiopian Ministry of Water, Energy and Irrigation.

3.2.2. Land use and soil data and sources

Since WetSpa is a distributed hydrological model hence it makes use of DEM, slope, soil type and land use types of the study area. The elevation grid map at 30m resolution was obtained from the elevation data bases of the ASTER (http://aster.usgs.gov). The soil and land use maps were also obtained from FAO Africover data base (http://www.africover.org./index.htm).

3.2.3. Climate scenario data

The climate scenario data for the base period and future A1B and B1 SRES emission scenarios were obtained from REMO (http://www.remo-rcm.de). The REMO predictor variables are provided in grid format from which the data used for downscaling were taken from. Therefore, by taking use of the geographical coordinates of REMO predictor variables versus meteorological stations, the exact point of intersection between the stations and REMO has been known and used as a downscaling point at that location. The predictands variables were taken from meteorological stations which were selected for this study. These climate scenario data were used to investigate the relative change between the current and future study period. The output of the future climate impact was then used to estimate the hydrological impacts in the WetSpa model.

3.2.4. Materials and models

The materials GPS for taking geographic-coordinate values in (altitude, latitude and longitude) and Digital camera for field photographs was used during the duration of the study. Meanwhile ArcGIS 10, Arc-view 3.2, WetSpa Model, WetSpass Model, SDSM 4.2, xls to dbf converter and a data set REMO was employed for the study.

3.2.5. Estimation of missed data

Data were checked if there is missed data. The consistency of records at the station was tested by a double mass curve by plotting the cumulative annual (or seasonal) record at station against the concurrent cumulative values of mean annual (or seasonal) record for a group of surrounding stations. The missed records of the station were adjusted by multiplying the recorded values of the data by the ratio of slopes of the straight lines. Hence, if there is missed rainfall data values from the rain gauge stations double mass curve method was adopted to correct and adjust the reported rainfall values. Similar, procedures were adopted for the other climatological data series.

3.3. General Approaches of the Study

In order to effectively implement the study, the structural setup of the approach (input/output relationships) is shown in Figure 3. The figure shows the schematic representations of the steps to be conducted in this research. It is designed to show how the parameters are interlinked each other the flow of the system for estimating ground water potentials and groundwater recharge and the impact of climate change on water resources.

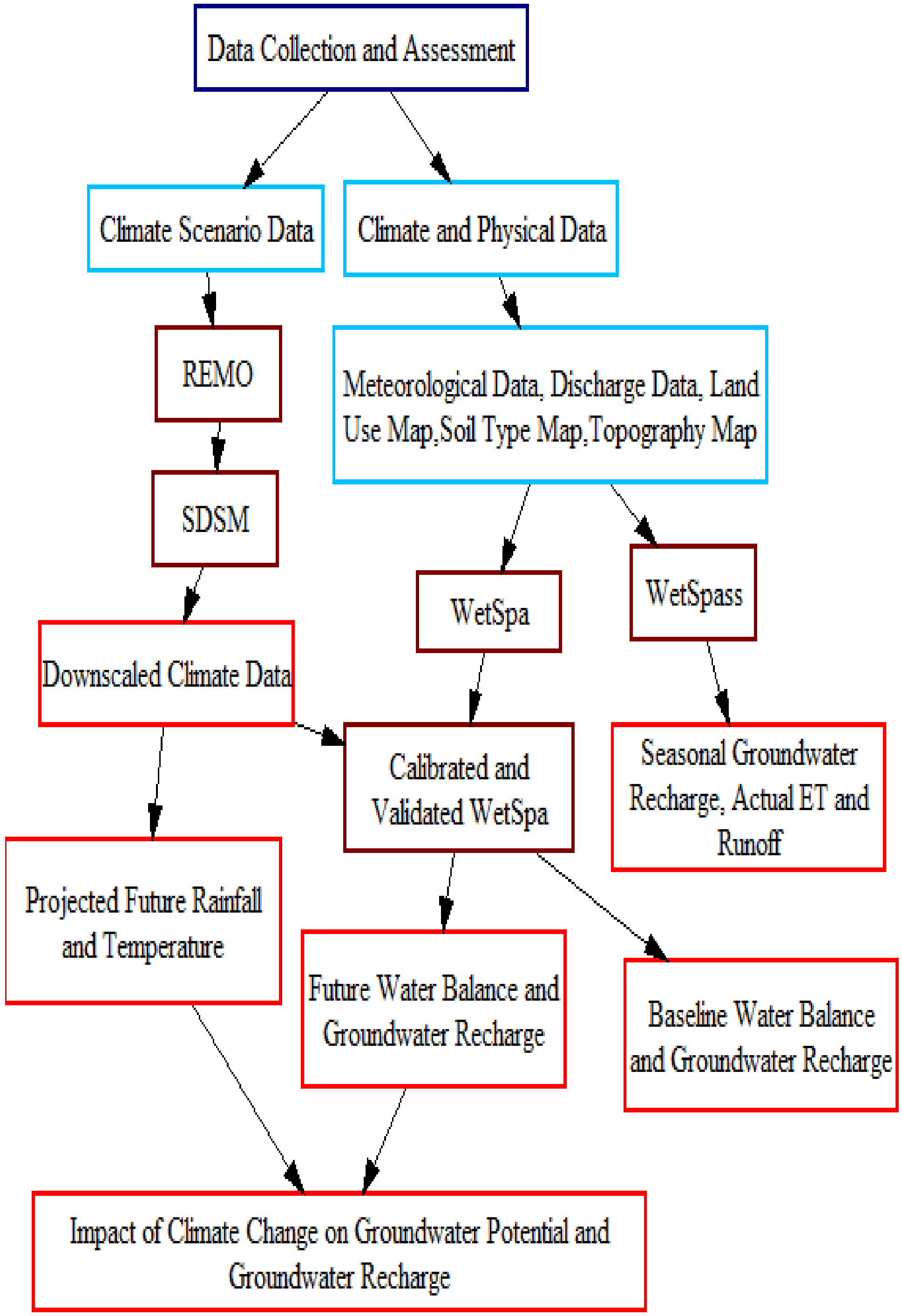


Figure 10: Structural setup of the experiment

3.4. Hydrologic and Climate Models

The physically based distributed hydrological models WetSpa and WetSpass were used in the study of groundwater recharge rate and water balance components of the watershed. It is conceptualized based on groundwater parameters such as precipitation, discharge rate, interception, surface runoff, infiltration, evapotranspiration, percolation and interflow and groundwater flow. For the impact of climate change on groundwater recharge, the climate parameters from REMO were used after downscaling using the SDSM for future (2015-2050) climatic conditions. The following sections discuss on the descriptions of the models separately.

3.4.1. SDSM model and downscaling

This research work used two storyline emission scenarios A1B and B1. These A1B and B1 SRES emission scenarios were selected for this study due to the basin was believed to experience of such emission and socio economic scenarios in the future. Data was collected from selected meteorological stations indicated in Table 2. Precipitation and temperature history data recorded for the period (in between 1972-2000) was used as a base line. Accordingly, REMO was downscaled for the A1B and B1scenarios. Downscaled data and base period observations were compared, for graphical fitness and statistical analyses to the best agreement of the parameters. After calibration of the model, the relationships created between predictor and predictands was applied for downscaling future climate change scenarios occurred in the watershed for the next 35 years (2015-2050) based on A1B and B1 scenarios.

3.4.1.1. Rainfall and temperature downscaling

Precipitation and temperature are the most vital elements of the climate system. Make use of these elements in the study of climate change is inevitable and takes use of time series data obtained from meteorological stations. In Ethiopian context meteorological stations having longer history data are found in urban and surrounding areas. These situations does not permit to study climate change in remote rural areas through using long series baseline data. Since, recent years onwards however, there are established meteorological stations in almost all representative areas in the country. These could not create a possibility to study climate change and variability impacts as climate study needs longer time series data.

Although, Werii watershed is relatively found in a remote area, the meteorological stations selected to study existing and future rainfall and temperature change in the entire watershed are relatively found in and around the watershed. Fortunately, this creates a possibility to study such changes through using scientific methods by means of available data and models. Climate change study makes use of available meteorological data. There are several meteorological stations in and nearby of the watershed. Most of these stations are either established in recent times or have a lot of missing data to be selected for the study. There must be some mechanisms on how to choose which meteorological stations should be incorporated in the study. As a result, Stations; Hawzen, Abyiadi, Adwa and Adigrat are the carefully chosen meteorological stations based on data availability and proximity to the watershed. These stations have had relatively longer base line data (Table 2). However, continuous and long term databases are hardly found in the study area as it was a site of instability during 1980s. That is why, data were not recorded totally, during the record periods of 1985-1991 in almost all the stations.

Table 2: Meteorological stations and data periods used in the study area

Stations	Elevation (masl)	Latitude (degree)	Longitude (degree)	Precipitation (years range)	T_max (years range)	T_min (years range)
Abyiadi	1829	13.53	39.01	1973-1984, 1992-2000	1973-1984, 1992-2000	1973-1984, 1992-2000
Adwa	1911	14.16	38.90	1973-1984, 1992-2000	1973-1984, 1992-2000	1973-1984, 1992-2000
Hawzen	2242	13.98	39.43	1973-1983, 1992-2000	1973-1983, 1992-2000	1973-1983, 1992-2000
Adigrat	2497	14.26	39.45	1973-1982, 1992-2000	1973-1982, 1992-2000	1973-1982, 1992-2000

3.4.1.2. Rainfall and temperature data used for model calibration and validation

The meteorological data available in meteorological stations were used for calibration and validation of the statistical downscaling model. The historical database of rainfall and temperatures observed variable and revealed different in each stations. The non-continuous data record were used separately for calibration and validation purpose easily in the SDSM model. Time series data with longer periods were used for calibration and the lesser for validation of the model as depicted in Table 3.

Table 3: Data periods (year range) used for calibration and validation purposes for each station

Available Data	Abyiadi	Adwa	Hawzen	Adigrat
Calibration	1973-1984	1973-1984	1973-1983	1973-1982
Validation	1992-2000	1992-2000	1992-2000	1992-2000

3.4.1.3. Identification of predictor variables for downscaling

Rainfall and temperature data were stored at, and brought from Ethiopian National Meteorological Agency (NMA) for research purposes. Local climate station data (predictands) were used to downscale the regional climate data produced from REMO. Each predictands parameter are downscaled with corresponding predictor variables data obtained from REMO archives. Arc GIS software were used to investigate the REMO raster nodes surrounding each meteorological stations. Accordingly, for downscaling the predictands, one REMO nodes were selected as a predictor variable, to each station data except for the Adigart station. Two REMO nodes were used for the Adigrat station as it is laid in between two REMO nodes of equal distance. In principle, the predictands rain fall was downscaled by predictor variable rainfall from REMO and this works for all the remaining predictands variables. The meteorological stations, REMO nodes and Werii watershed in Tekeze river basin and the Tigray regional map is explained in Figure 11. Future rainfall and temperature change was downscaled for A1B and B1 SRES emission scenarios in 2050. A1B and B1 emission scenarios were considered as an experimental treatment used as an indication for climate significances in the watershed from 2015-2050.

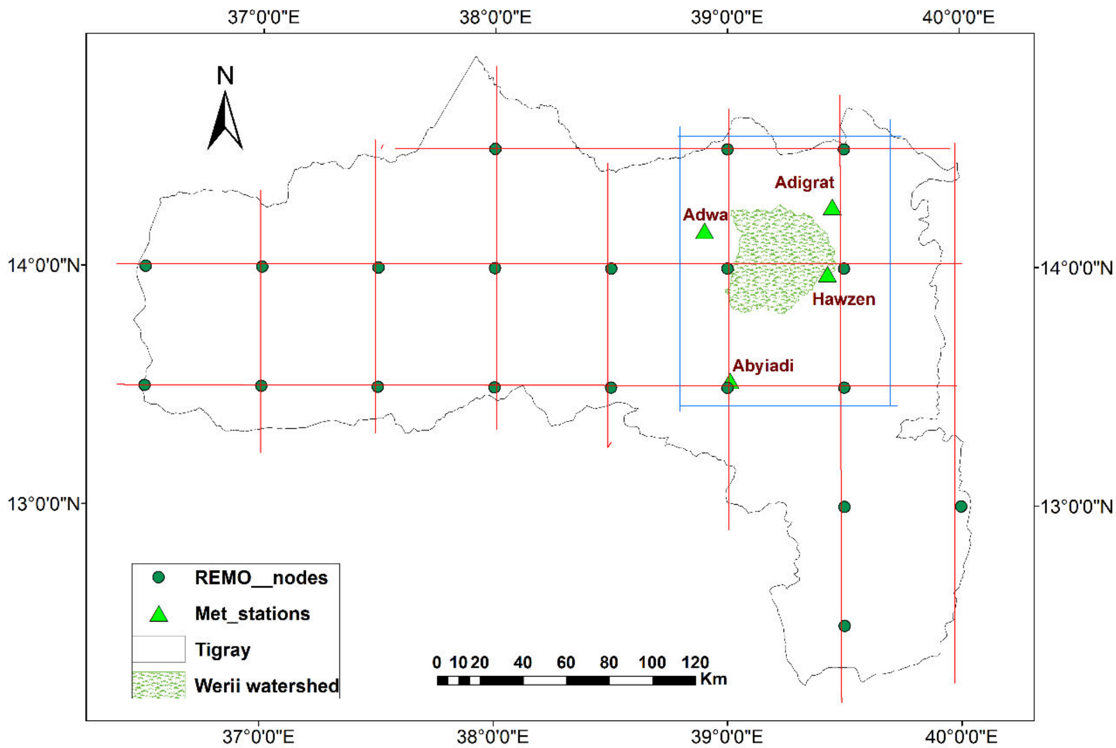


Figure 11: Grids of REMO and meteorological stations in Werii watershed as indicated in Tigray

The observed climatic data of each of the meteorological stations and their corresponding REMO data considered to be downscaled are depicted in Figure 13. The average monthly rainfall of the stations in both calibration and validations periods, were observed highest during rainy seasons in the months of June and July (Figure 13). This situation explains the uni-modal rainfall distribution observed in the entire watershed. The observed average monthly rainfall data ranges from zero during dry season to a maximum of 32.2 mm during rainy season. Rainfall starts to fall during the month of June, continues up to late September and this season is considered as rain season at which cultivation of crops are possible. Average monthly temperatures were evaluated in minimum and maximum temperatures separately (Figure 13) in each of the calibration and validation periods. As a result, the minimum (4.9°C) and maximum (31°C) average monthly temperatures were obtained from Adigrat and Adwa stations respectively, among the meteorological stations. The average monthly temperatures are perceived lesser during months of November, December and January. Meanwhile higher mean monthly temperatures were recorded in the months of March to May and September to October.

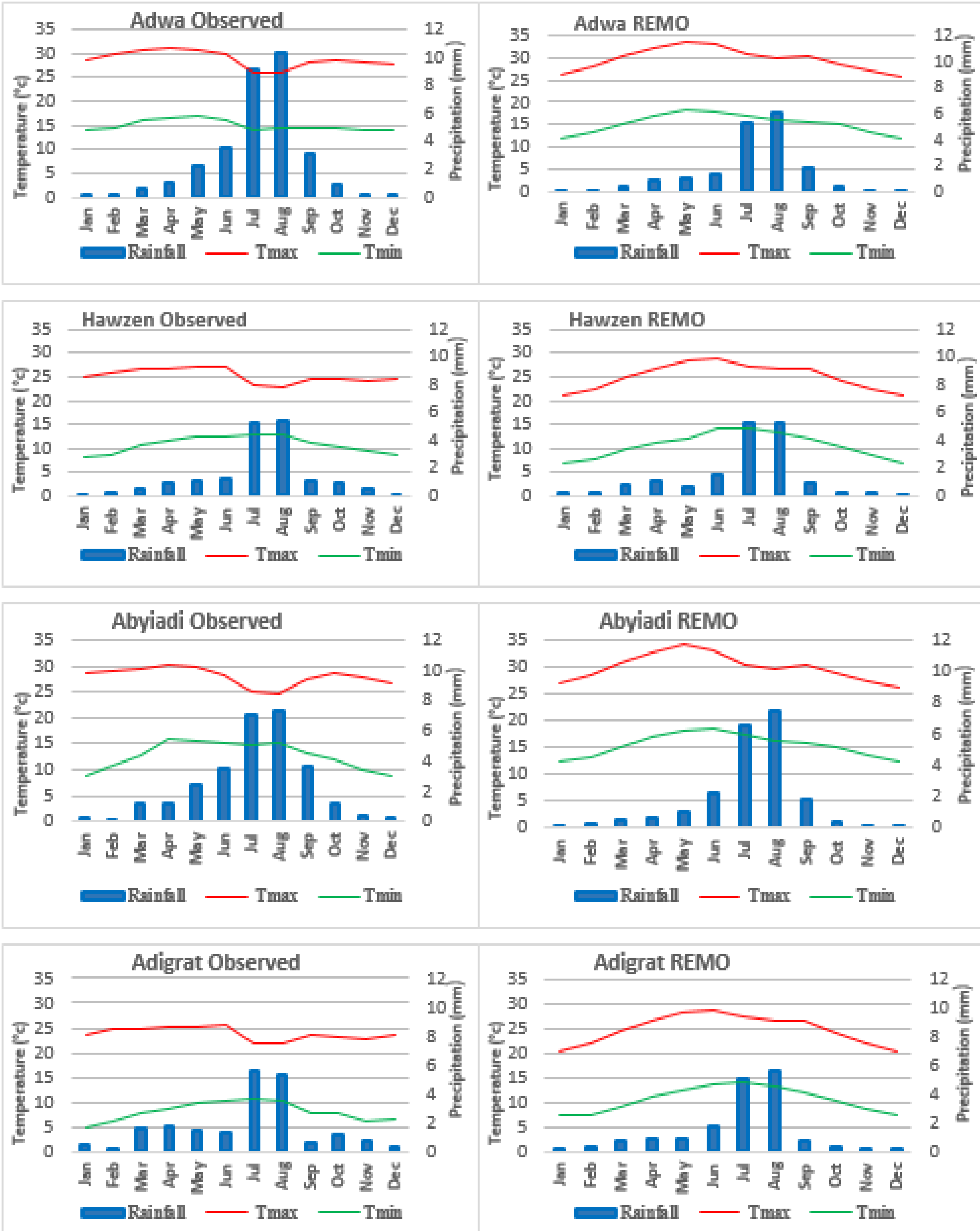

Adwa Observed
Adwa REMO
Hawzen Observed
Hawzen REMO
Abyiadi Observed
Abyiadi REMO
Adigrat Observed
Adigrat REMO
Temperature (°c)
Precipitation (mm)
35 30 25 20 15 10 5 0
12 10 8 6 4 2 0
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Rainfall Tmax Tmin

Figure 12: Observed average monthly rainfall, Tmax and Tmin of each meteorological stations and corresponding REMOs.

3.4.1.4. Estimation of potential evapotranspiration

After downscaling daily minimum and maximum temperatures, potential evapotranspiration time series data were estimated for use in the WetSpa model. The PET time series data was calculated through use of the Hargreaves equation (Allen *et al.*, 1998).

$$PET = 0.0023\ (Tmean + 17.8)\ (Tmax - Tmin)\ 0.5\ Ra \qquad (15)$$

where, PET is the potential evapotranspiration (mm day^{-1}); Tmean, Tmax and Tmin are average, maximum and minimum temperatures (°c) respectively; Ra is extraterrestrial radiation (mm day^{-1}).

The downscaled average daily PET time series data for all the stations, together with precipitation and observed discharge were used as an input for the WetSpa model for simulation of the hydrological water balance components response for the watershed. These climate data were generated based on the SRES emission scenarios for the future climate change projections from 2015-2050 in future basis.

3.4.1.5. Application of Thiessen polygon in WetSpa model

The four meteorological stations at Adigrat, Hawzen, Adwa and Abyiadi are selected based on data availability and proximity to the Werii watershed. To use the stations climatic data to the watershed modeling process in WetSpa a Thiessen polygon method was developed and used accordingly. This method were used in the Arc GIS software to determine how much part of the watershed is covered by each of the meteorological stations (Figure 14). The Thiessen polygon method clearly identifies areal weight coverage of each meteorological station. Accordingly, the meteorological stations with corresponding percentage of areal coverage are; Adigrat (15%), Hawzen (52%), Adwa (31%) and Abyiadi (2%). Hawzen station has covered more than half of the watershed area whereas Abyiadi has covered only small part of the watershed.

The geographical coordinates of each meteorological stations and the delineated watershed boundary through use of the application of Thiessen polygon in arc GIS helps to capture the grids for daily precipitation and Potential evapotranspiration for use of the modeling process in WetSpa.

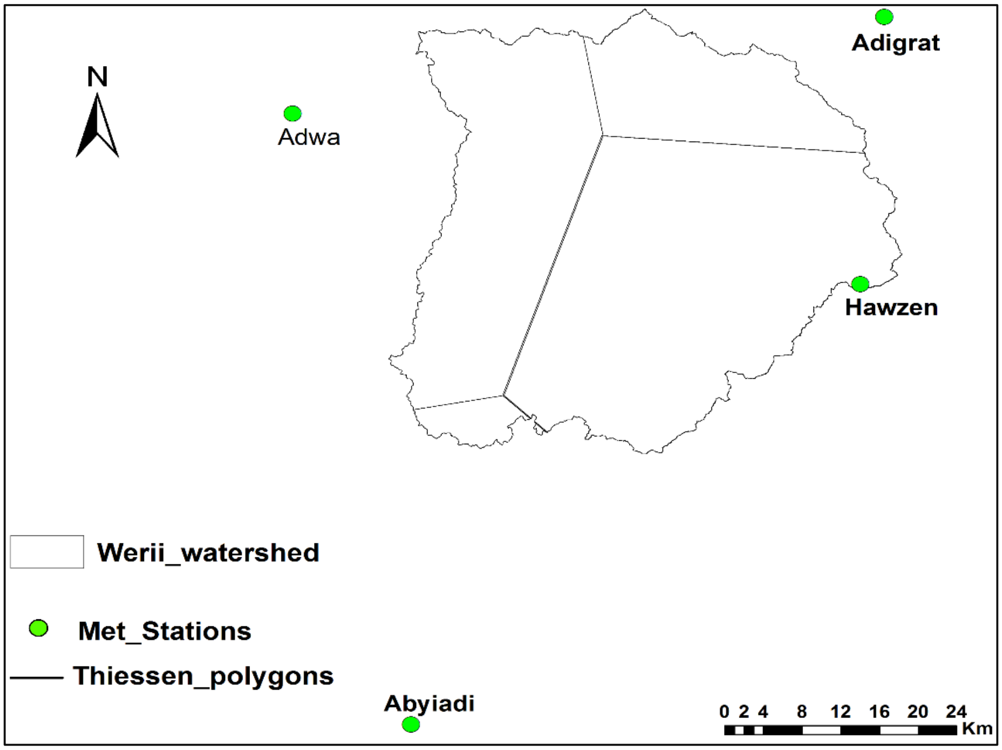


Figure 13: Thiessen polygon, areal coverage of meteorological stations for climate data

3.4.1.6. WetSpa model input parameters and sources

Baseline water balance system of Werii watershed was estimated through using distributed hydrological model WetSpa. This model applies non-spatial hydro-meteorological data sets and spatial biophysical features of the watershed. A distributed spatial features of DEM, soil type and land use maps of the watershed were employed with the help of Arc view GIS. For the elevation map a high resolution ASTER 30 DEM were used and Soil type map was taken from FAO digital archives. The land use map is taken from the Ethiopian land cover data set, derived from the original raster based global land cover of Africa archive (http://www.africover.org./index.htm). Currently, it is the most recent and finer resolution global dataset on land cover extremely useful tool for land cover based analysis and modelling. Slope map of the watershed was derived from topography map with the help of Arc GIS of the spatial analyst. Topography, slope, land use and soil maps of Werii watershed are given in figures 3, 4, 8 and 9 respectively.

Regarding the hydro-meteorological data, discharge data were available from one recording station at the outlet of Werii watershed. Precipitation data were also available from four meteorological stations (Abyiadi, Adwa, Hawzen and Adigart) found in and around the watershed. Temperature were not used in the model run as snow melting is not present in the watershed. Potential evapotranspiration were estimated using Hargreaves equation (Allen *et al*., 1998). These data were provided in a daily data basis in the model running process.

The available average monthly precipitation and potential evapotranspiration derived from all stations and discharge data measured at the outlet of the watershed, for the separate calibration and validation periods, is presented in Table 4 and 5 respectively. This figures are provided to illustrate the available measured data that were used for the purpose of calibration and validation processes of the WetSpa model.

Table 4: Measured average monthly rainfall, PET and discharge data of the watershed for calibration period

Months	Rainfall(mm)	PET(mm)	Discharge(m^3/s)
Jan	0.15	4.06	0.67
Feb	0.18	4.70	0.98
Mar	1.25	5.04	1.95
Apr	1.04	5.29	1.55
May	1.54	5.23	2.19
Jun	2.34	5.11	5.99
Jul	6.71	4.30	37.78
Aug	6.77	4.15	90.55
Sep	2.33	4.57	27.40
Oct	0.47	4.53	2.56
Nov	0.56	3.96	1.94

Dec	0.21	3.79	1.24

Table 5: Measured average monthly rainfall, PET and discharge data of the watershed for validation period

Months	Rainfall (mm)	PET (mm)	Discharge (m3/s)
Jan	0.30	4.13	0.65
Feb	0.07	4.70	0.41
Mar	0.38	5.18	0.41
Apr	1.26	5.28	0.67
May	1.29	5.41	0.89
Jun	1.79	5.28	1.80
Jul	7.48	4.19	64.24
Aug	9.52	4.29	91.45
Sep	2.65	4.86	17.77
Oct	0.84	4.50	1.43
Nov	0.41	4.01	0.70
Dec	0.27	3.83	0.37

Finally, the WetSpa model produces, current river flow hydrographs and spatially distributed hydrological and physiographic characteristics of the watershed such as soil moisture, infiltration rates and groundwater recharge. Moreover, future changes of daily precipitation, potential evapotranspiration, average temperature, river flow discharge and base flow responses are also presented after having the model well calibrated for the purpose.

The general physiographic features of the watershed which incorporates watershed boundary, major contributing river networks and gauging station at the outlet is presented in Figure 7. Moreover, watershed physical parameters with their corresponding values and data sources are briefly listed in Table 6. The meteorological data ranges for each of the stations and their measurement and sources are presented as well in Table 6.

Table 6: General characteristics of watershed and data periods used in the WetSpa model

Parameters	Magnitudes /time periods	Sources
Area	1797 km^2	Arc GIS delineation
Perimeter	299 km	Arc GIS delineation
Lowest elevation	1363 masl	Arc GIS delineation
Mean watershed elevation	1951 masl	calculation
Highest elevation	3010 masl	Arc GIS delineation
Out let (gauging station)	13.843^{o}N and 39.016^{o}E	Measurement
DEM	30 m X 30 m	ASTER
Soil map	1:250,000	FAO
Land cover map	300 m/2005	FAO
Discharge (m^3/s)	1974-1977 and 1998-2000	MoWIE
Rainfall (mm/day)	1974-1977 and 1998-2000	NMSA
Potential evapotranspiration (mm/day)	1974-1977 and 1998-2000	Estimation

3.4.1.7. WetSpass model input data

WetSpass is a physically based model which basically involves up to date physical and empirical relationships for its efficiently running processes. Groundwater models such as WetSpass used for analyzing groundwater systems are often steady state and, therefore, need long-term average groundwater depth inputs. Long term average hydro meteorological data and spatial patterns of watershed physical maps are the main inputs of the model.

In order to work with the model efficiently, all data has to be prepared in a seasonal manner. The land use and soil grid maps are supported by attribute lookup table data available in the literature. Through investigating the watershed and its uni-modal rain falling conditions, Werii watershed is characterized with definite summer and winter seasons. Hence, four months of June, July, August and September (JJAS) are considered as summer (rainy season) and the remaining eight months are considered as winter (dry season) in Ethiopian condition.

Grid maps and parameter tables are required as inputs for the WetSpass model and are prepared with the help of Arc GIS software tools. These grid maps are land-use, soil, slope, topography and seasonal groundwater level, precipitation, potential evapotranspiration and wind speed. The input files prepared as parameter tables were arranged in the database file format (.dbf).

WetSpass model considers depth of groundwater table from the land surfaces. The depth of groundwater table in Werii watershed were considered in this modeling. Generally, it is estimated deeper than twenty meters from the surface in the intact watershed. Different studies in Ethiopia indicates that depth of groundwater is far below the ground surfaces. For example, in a study conducted at Dire Dawa (Tilahun and Merkel, 2009) groundwater depth were taken as twenty meter similarly another study conducted at Geba catchment (Tesfamichael *et al*., 2010) a fifty meter deep ground water depth were taken. Geographically, Geba catchment is found in the vicinity of Werii watershed. These groundwater depth makes insignificant effect in the WetSpass model run. But, in order of model running possible, a twenty five meter deep groundwater level map was prepared as an input grid map to the model.

The elevation map of Werii watershed spreads from 1363m up to 3010m above sea level. It is characterized with an undulating terrain with erosional features. Similarly, the slope map is derived from elevation map explained as ragged with very steeply landscapes (Figure 3). The spatial topography and slope map of the watershed is prepared and used in the WetSpass model (Figure 3 and 4). Moreover, FAO based land use and soil map has been prepared and used in the WetSpass model as explained in the Figure 8 and 9. The elevation map was also obtained from 30m resolution ASTER map.

To run WetSpass model, nineteen input files are required. Fifteen of them are maps prepared in grid format of 100m cell size with 510 and 518 number of row and columns respectively. The remaining four files are attribute lookup tables inserted as dbf format. These input data are presented hereafter in detail.

3.4.1.8. Physical and meteorological grid maps

WetSpass model uses grid maps prepared based on seasonal, summer and winter and without seasonal basis. Topography, slope and soil type grid maps are inherently non-seasonal that couldn't show variability when season changes. In contrary, land use, precipitation, temperature, potential evapotranspiration, wind speed and ground water depth are variable in nature when time goes up. As a result, these data were prepared separately in winter and summer so as to show the existing feature of the watershed that may appear when the season changes overtime.

Table 8 explains the annual and seasonal average values of precipitation, PET and temperature. Seasonal precipitation, potential evapotranspiration and average temperature were made available in grid map were produced by universal kriging interpolation method. As a result, the average grid maps of the meteorological data were developed based on the interpolation technique. Wind speed and depth of ground water were taken as one value grid map for the separate seasons of winter and summer. As a result the average summer and winter season weed speed for the watershed was taken as 1.63 and 1.55 m/s respectively. Table 7 indicates average annual and seasonal wind speed values for each meteorological stations. Similarly, depth of ground water was also taken as twenty five meter below the surface for simply model run only.

The watersheds physiological parameters of land use, soil type, topography and slope were also prepared with the help of Arc GIS tools. These data were obtained from the remote sensing technology and FAO based land use and soil maps clipped or masked by Werii watershed boundary.

Table 7: Mean annual and seasonal wind speeds (m/s) at four stations in Werii watershed

Station	Elevation (m)	Winter (m/s)	Summer (m/s)	Annual (m/s)
Abyiadi	1829	1.6	1.7	1.65
Adwa	1911	1.4	1.6	1.5
Hawzen	2242	1.6	1.5	1.55
Adigrat	2497	1.3	1.7	1.5
Mean		1.48	1.63	1.55

3.4.1.9. Parameter tables

There are four types of parameter table prepared in appropriate format for the effective model running process. Summer and winter land use data (Table 9 and Table 10 respectively), soil parameters data (Table 11) and runoff coefficient data were made ready as attribute lookup tables for the input of the model. These different biophysical data are obtained and reviewed from scholarly published literatures. However, some of the seasonal land use parameter values are readjusted so as to fulfill the conditions in the study area as it has been used by (Tesfamichael *et al.*, 2010). The highlighted portion of the table indicates the amended values for the study watershed. The developed grid maps and the parameter data together make the required interaction among each other so as to produce appropriate average values during the simulation processes. As a result the output grid maps were simulated with the help of spatial analyst tool in the arc view GIS environment.

Table 8: Average annual and seasonal precipitation, potential evapotranspiration and temperature data of each Met stations

Stations	Elevation (masl)	Average Precipitation (mm)			Average PET (mm)			Average daily temperature (°c)		
		winter	summer	annual	winter	Summer	annual	winter	summer	annual
Abyiadi	1829	99.640	712.50	812.14	1141.02	570.31	1711.33	22.80	21.61	22.40
Adwa	1911	225.34	627.88	853.22	1195.38	552.01	1747.39	20.15	20.08	20.13
Hawzen	2242	118.02	417.34	535.36	1064.36	544.29	1608.65	17.84	18.60	18.10
Adigrat	2497	220.64	446.56	667.20	1070.59	544.27	1614.86	15.09	16.47	15.56
Mean	2120	166	551	717	1118	553	1671	18.97	19.19	19.05

Table 9: Summer land-use parameter table for Werii watershed

NUMBER	LUS_TYPE	RUNOFF_VEG	NUM_VEG_RO	NUM_IMP_RO	VEG_AREA	BARE_AREA	IMP_AREA	OPENW_AREA	ROOT_DEPTH	LAI	MIN_STOM	INTERC_PER	VEG_HEIGHT
7	Bare land	bare soil	4	0	0.7000	0.2000	0.0000	0.0000	0.0500	0.10	110.00	27.00	0.0010
21	Crop land	crop	1	0	0.9000	0.0000	0.2000	0.0000	0.4000	2.00	180.00	35.00	0.7000
33	Forest	forest	3	0	0.8000	0.0000	0.2000	0.0000	2.5000	7.50	375.00	50.00	10.0000
23	Grass land	grass	2	0	0.7000	0.0000	0.2000	0.0000	0.3000	2.00	100.00	10.00	0.2000
36	Shrub land	grass	2	0	0.8000	0.0000	0.2000	0.0000	0.6000	6.00	110.00	42.00	2.5000

Table 10: Winter land-use parameter table for Werii watershed

NUMBER	LUS_TYPE	RUNOFF_VEG	NUM_VEG_RO	NUM_IMP_RO	VEG_AREA	BARE_AREA	IMP_AREA	OPENW_AREA	ROOT_DEPTH	LAI	MIN_STOM	INTERC_PER	VEG_HEIGHT
7	Bare land	bare soil	4	0	0.2000	0.4000	0.0000	0.0000	0.0500	0.00	110.00	1.00	0.0010
21	Crop land	crop	1	0	0.2000	0.0400	0.4000	0.0000	0.3500	2.00	180.00	20.00	0.6000
33	Forest	forest	3	0	0.8000	0.1000	0.1000	0.0000	2.0000	4.50	350.00	38.00	10.0000
23	Grass land	grass	2	0	0.3000	0.2000	0.0500	0.0000	0.3000	2.00	170.00	20.00	0.2000
36	Shrub land	grass	2	0	0.2000	0.8000	0.0000	0.0000	0.6000	0.00	110.00	30.00	2.0000

Land-use table attributes

Luse_type = Land Use Type; Runoff_veg = Runoff Vegetation; Num_veg_Ro = Runoff class for vegetation type; Num_imp_Ro = Impervious Runoff class for impervious area types; Veg_area = Vegetated Area; Bare_area = Bare Area; Imp_area: Impervious Area; Openw_area: Open-water Area; Root_depth = Root depth; Lai = Leaf Area Index; Min_stom= Minimum Stomatal Opening; Interc_per = Interception Percentage; Veg_height = Vegetation Height

Table 11: Soil parameter attribute tables

NUMBER	SOIL	FIELDC APAC	WILTING PNT	PAW	RESIDUAL WC	A1	EVAPO DEPTH	TENSION HHT	P_FRAC _SUM	P_FRAC _WIN
12	Clay	0.46	0.33	0.13	0.090	0.21	0.05	0.37	0.95	0.85
1	Sandy loam	0.21	0.09	0.12	0.041	0.44	0.05	0.15	0.09	0.01
6	Silt	0.30	0.10	0.20	0.040	0.35	0.05	0.61	0.09	0.01
8	Silty clay loam	0.36	0.19	0.17	0.040	0.29	0.05	0.33	0.62	0.41
4	Silty loam	0.29	0.10	0.19	0.015	0.40	0.05	0.21	0.26	0.07

Soil table attributes

Number = Soil type number; Soil = Soil type (texture); Fieldcapac = Field capacity; Wiltingpnt = Wilting Point; PAW = Plant available water content; Residualwc = Residual water content; A1 = Calibration parameter dependent on the sand content of the soil; Evapodepth = Bare soil evaporation depth; Tensionhht = Tension saturated height; P_frac_sum = Fraction of summer precipitation contributing to Hortonian runoff; P_frac_win = Fraction of winter precipitation contributing to Hortonian runoff

4. RESULTS AND DISCUSSION

4.1. Rainfall and Temperature Change Projections; Application of Climate Downscaling

4.1.1. SDSM model calibration results and likely future climate changes

Calibration of a model is used to investigate a good agreement among the parameters in the model in this particular study. The calibration process was implemented based on an average of twenty ensembles in the SDSM model. In this study, precipitation, maximum and minimum temperatures were calibrated and future likely impacts of climate change were downscaled based on the good agreement of calibration results. Each meteorological stations were generated a twenty synthetic ensembles for each of the A1B and B1 SRES emission scenarios on daily time series basis for the period of 35 years (2015-2050). The following sections presents the calibration results and future changes in climate for each meteorological stations with corresponding changes for the climate variables.

4.1.1.1. Precipitation (rainfall)

Rainfall is the most variable and fundamental element in the climate system and its characteristics is not well manipulated in easy way. The diversity of rainfall patterns is inherent and naturally explained as erratic in this region. Before and after calibration results for rainfall of the stations considered in the watershed is explained in Figure 14. Moreover, the validation results of the SDSM model is also depicted in Figure 15.

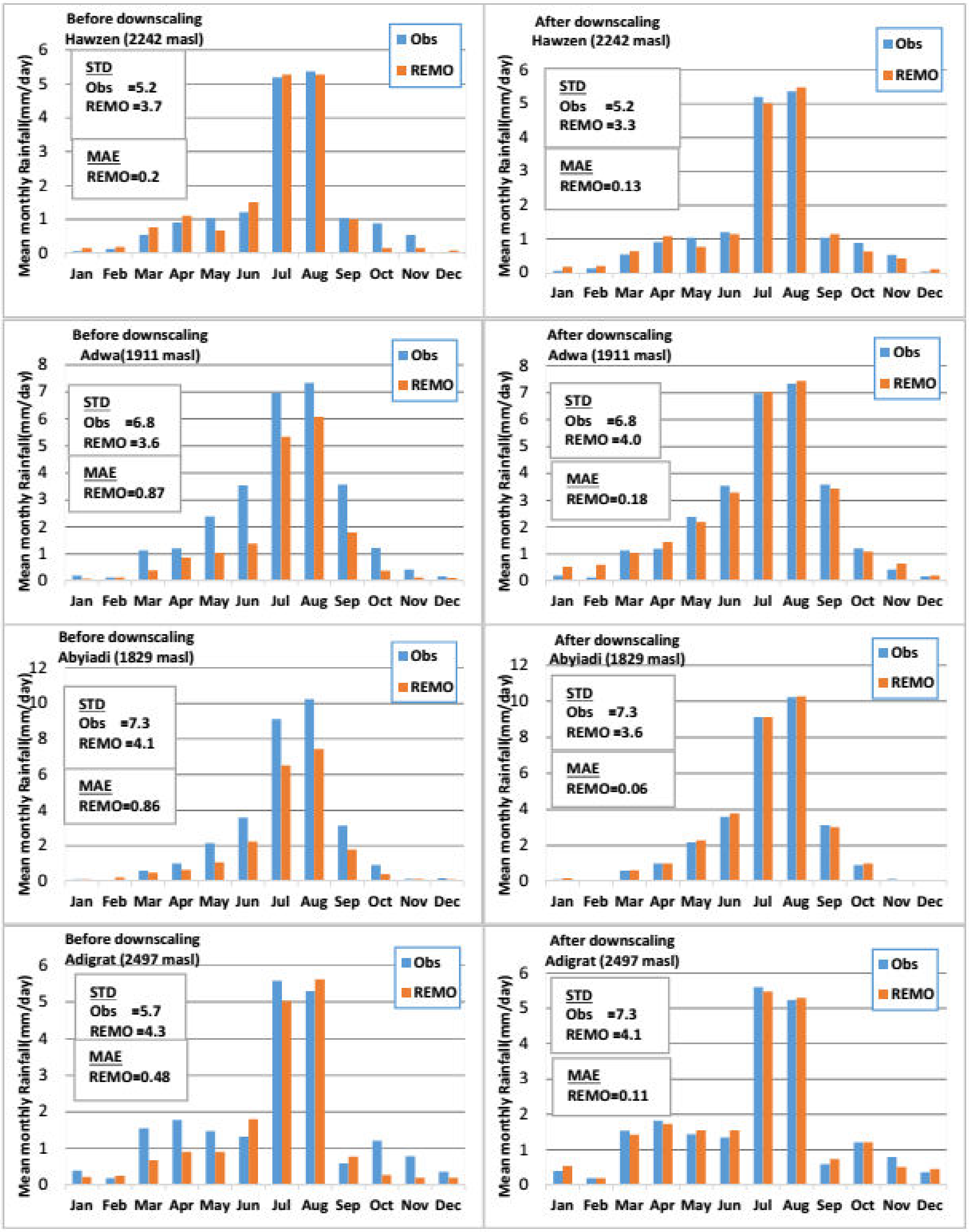


Figure 14: Before and after downscaling of each meteorological stations Observed and REMO Precipitation data. STD=Standard deviation, MAE= Mean absolute error

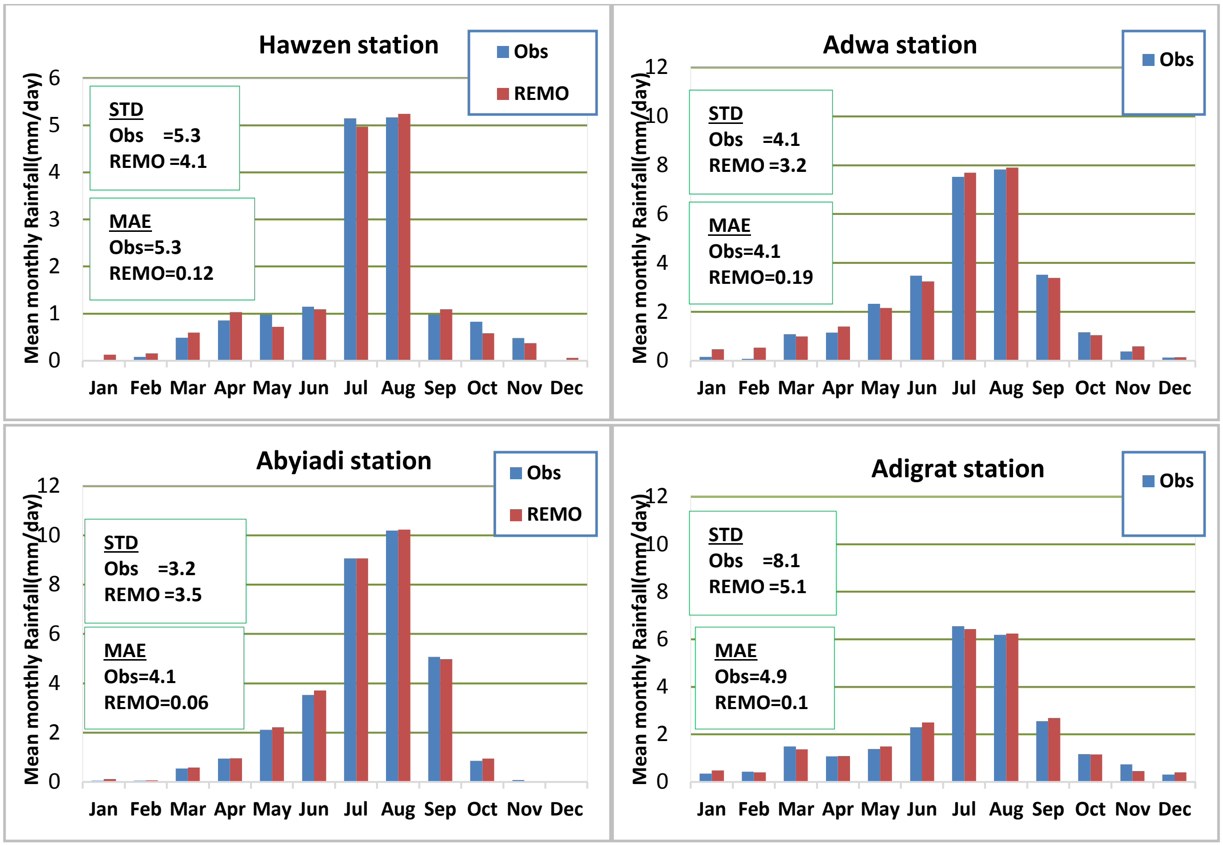


Figure 15:Validation results for precipitation for each of the station; STD=Standard deviation, MAE= Mean absolute error

Rainfall was downscalled for the periods ranging from 2015-2050. As it has been dipicted in Figure 16, the maximamum change of rainfall in the period was simulated for Adwa and Hawzen stations for the SRES emmision scenarios, A1B (34% and 31% respectivelly) and B1 (both 33%). Minimum ranifall change was also observed in Abyiadi station for A1B (11%) and B1 (10%) . In the future climate sytem, negative change in rainfall is seldom in the watershed.

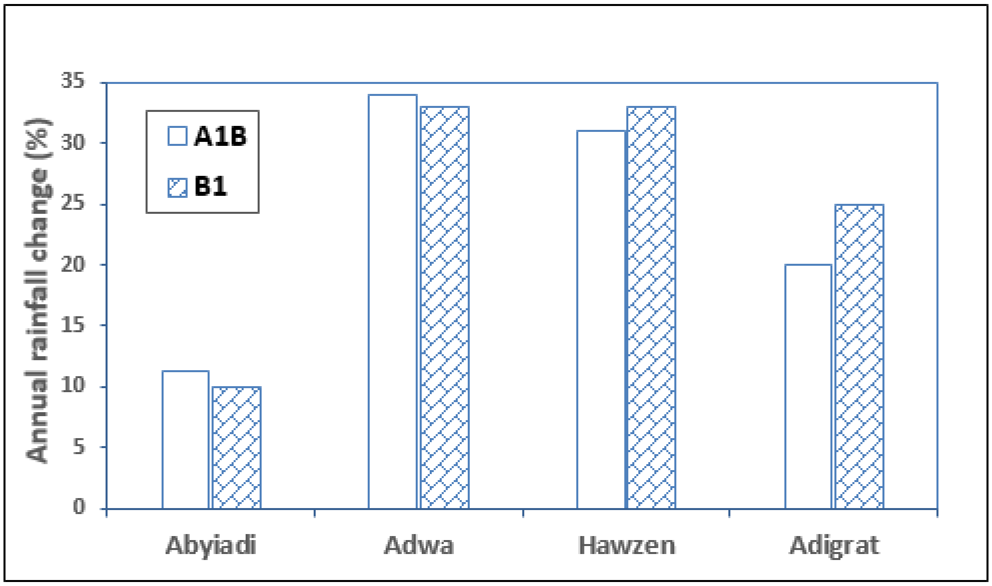


Figure 16: Projected Percentage Change in Annual Rainfall from base period for A1B and B1 scenarios

Therefore, rainfall is expected to increase in the course of the time and this trend is consistent with the IPCC report on climate change (Nyenje and Batelaan,2009; IPCC, 2013). Similarly, Kebede *et al.*,(2013) indicated that overall annual future rainfall trend would increase for both of the A1B and B1 SRES scenarios.

Table 12: Comparison of base period (observed and downscaled) annual rainfall and rainy days values for all stations.

Stations	Model run	Mean annual rainfall (mm)	Rainy days (days/year)
Abyiadi	Observation	956	81
	REMO	985	79
Adwa	Observation	867	94
	REMO	830	77
Hawzen	Observation	521	57
	REMO	507	46
Adigrat	Observation	632	73
	REMO	619	57

Meanwile, the SDSM model was produced possible rainy days and the amount of mean annual rainfall for each of the stations for the station data and REMO as explained in Table 12. The rainy days and mean annual rainfall was estimated for the observed station data and for the regional climate, REMO.

4.1.1.2. Maximum temperature

Before and after calibration of the maximum temperature is presented in Figure 17. In order to exactly find the best fits for each of the meteorological stations, a trial and error method was conducted for the sensitive parameters of variance inflation and bias correction in the SDSM model. Moreover, the validation results of the SDSM model for maximum temperature was undertaken and depicted in Figure 18.

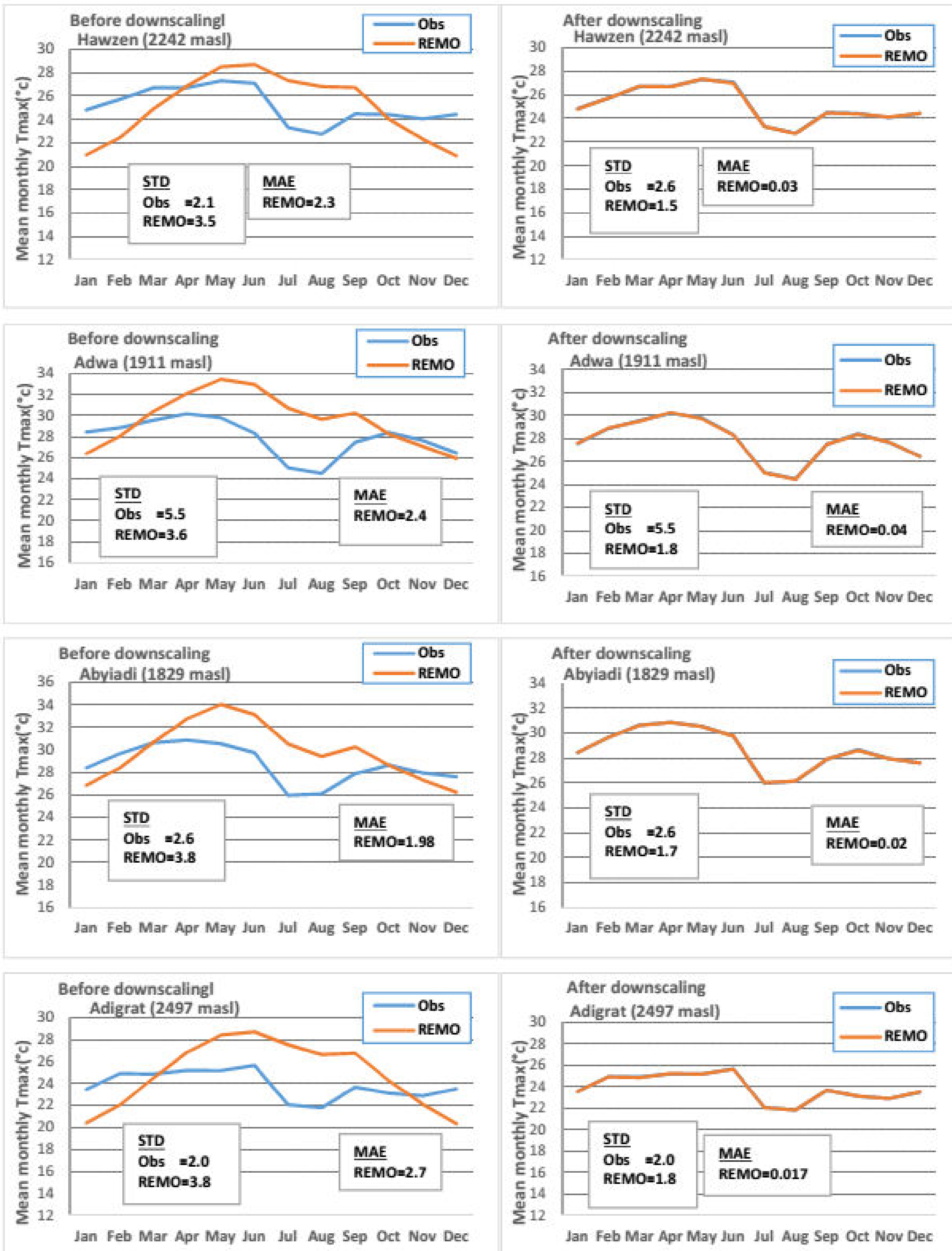


Figure 17: Before and after downscaling of each meteorological stations Observed and REMO maximum temperature data. STD=Standard deviation, MAE= Mean absolute error

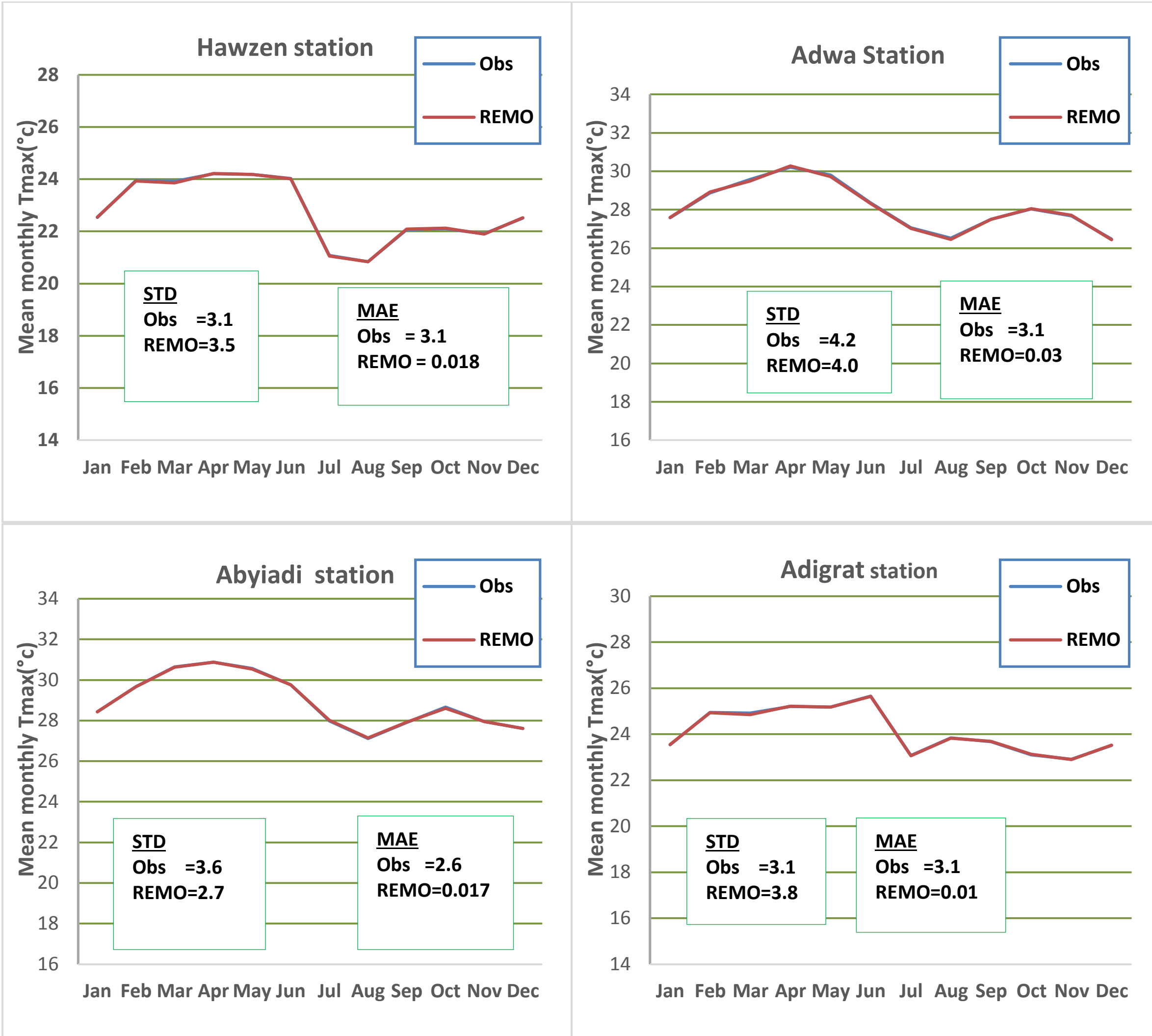


Figure 18: Validation results for maximum temperature for each of the station; STD=Standard deviation, MAE= Mean absolute error

After having calibrated the model, a future change in maximum temperature is identified for both A1B and B1 SRES emission scenarios for each of the stations (Figure 19). As a result, maximum does not show a systematic increase or decreasing trend however it coincides to be increased in the future as the majority of the stations revealed increasing even if it is not showed high significance. Higher change in maximum temperature is observed in Hawzen station for A1B (0.16°c) and B1 (0.19°c). Smaller change in maximum temperature is investigated at Adigart and Abyiadi stations. A negative change is also appeared at Adwa station for B1 (-0.01°c) emission. Generally, maximum temperature is expected to be in the range of -0.01°c to 0.19°c in the watershed in the future period (2015-2050) and this result is consistent with (Paeth *et al*, 2005; Paeth and Thamm 2007; Nyenje and Batelaan, 2009; Tekleab *et al*., 2013).

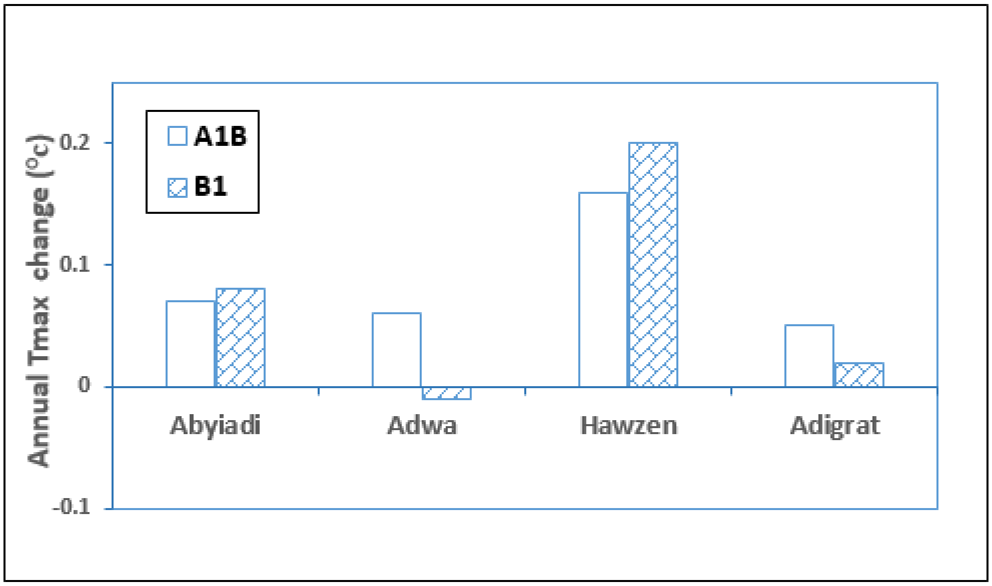


Figure 19: Projected Change in annual maximum temperature from base period.

4.1.1.3. Minimum temperature

Minimum temperature was also calibrated and downscaled in the SDSM model for this study. Downscaling (before and after) of the minimum temperature is explained in Figure 20 for each of the stations. A manual calibration method were conducted as usual to find out the best agreements among the parameters for each of the stations. Meanwhile, the validation results of the SDSM model for minimum temperature was conducted and depicted in Figure 21.

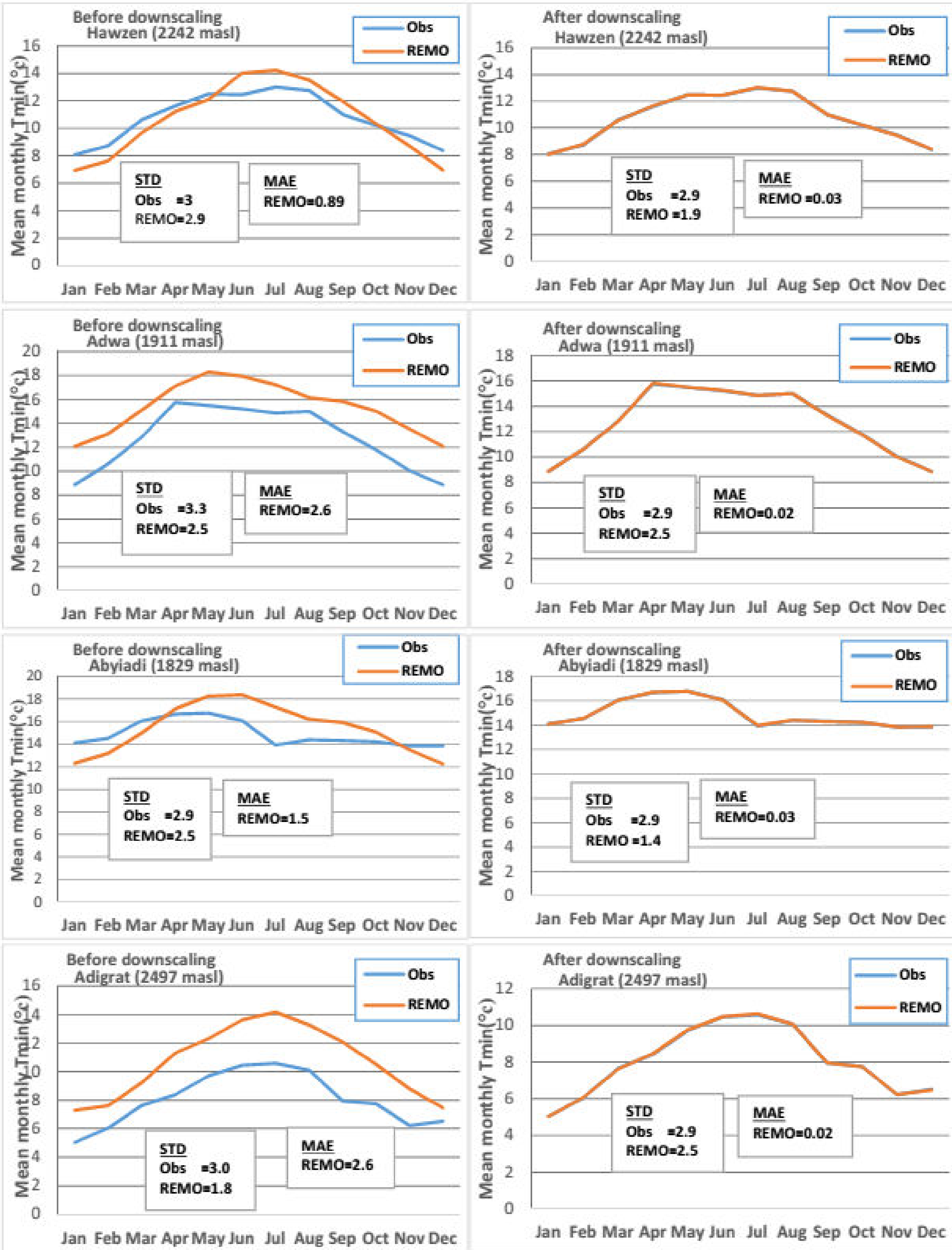


Figure 20: Before and after downscaling of each meteorological stations Observed and REMO minimum temperature data. STD=Standard deviation, MAE= Mean absolute error

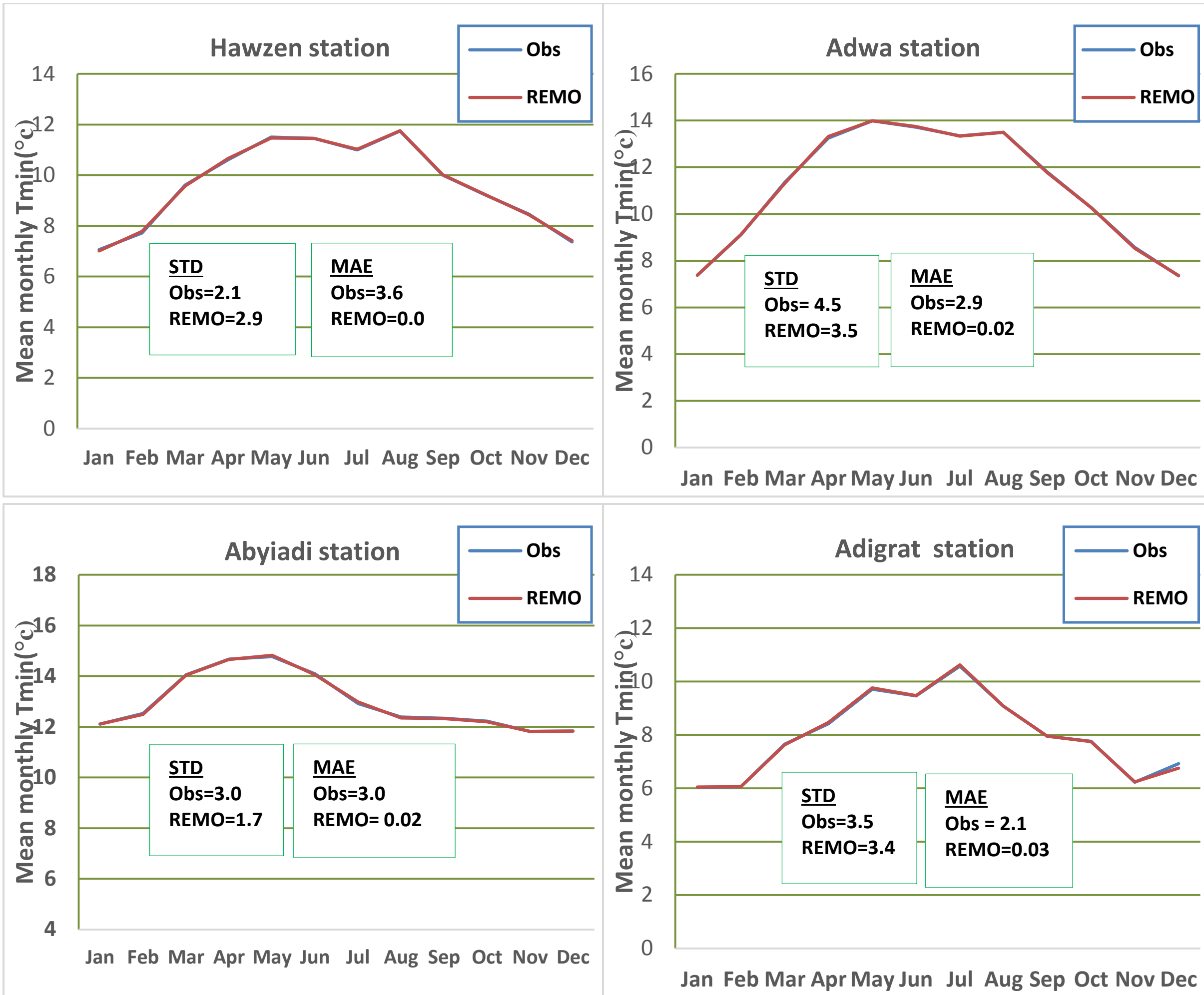


Figure 21: Validation results for minimum temperature for each of the stations; STD=Standard deviation, MAE= Mean absolute error

Future change in minimum temperature were also estimated based on the calibration results for the emission scenarios (Figure 22). As a result, maximum change in minimum temperature is observed in Hawzen station for A1B (0.34°c) and B1 (0.29°c). Similarly, smaller change were investigated in Adigrat and Abyiadi stations for both emission scenarios.

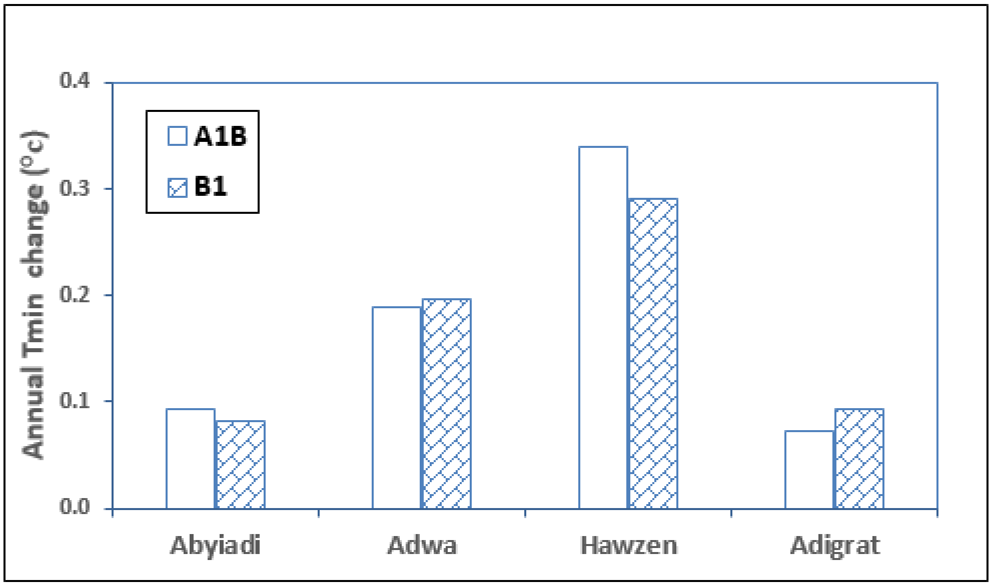


Figure 22 : Projected Change in annual minimum temperature from base period

Negative change in minimum temperature will hardly found in the future range of the study time. Generally, minimum temperature will change increasingly and positively (Paeth *et al*, 2005; IPCC, 2013, Tekleab *et al.*, 2013).

So far temperature is discussed separately as minimum and maximum temperatures and derived indicative results. It is now important to drive a combined average result for temperature based on the separately obtained results. Hence, temperature trend is increasing in general with greater change in minimum temperature for each of the stations and scenarios used in this study. This is consistent with the results obtained from (Paeth *et al*, 2005; Paeth and Thamm 2007; Nyenje and Batelaan,2009; IPCC, 2013, Tekleab *et al.*, 2013). Regarding the sensitivity analysis for SDSM model, the variance inflation and bias correction were the most sensitive parameters, for which the calibration process were conducted.

4.2. Estimation of Groundwater Resources Potential; Application of WetSpa Model

4.2.1. WetSpa model simulation process, physical parameter derivations and lookup tables

Gridded model parameter were derived from topography, land use and soil maps of the watershed automatically together with an attribute lookup tables prepared in dbf format. Hydrological features of the watershed as surface slope, hydraulic radius, flow direction, flow accumulation, stream network, and order as well as sub-catchments were delineated from the DEM.

The developed soil map of the watershed were also used to drive soil hydraulic conductivity, pore size distribution index, plant wilting point porosity, field capacity, and residual moisture for each grid cell. Similarly, the Manning's roughness coefficient interception storage capacity and root depth parameters are derived from the landuse map. In addition, a combinations of elevation, soil and land use grids are used to provide grids of potential runoff coefficient and depression storage capacity of the watershed by means of attribute lookup tables. So as to, compute the instantaneous unit hydrograph (IUH) flowed from each grid cell to the watershed outlet; travel time to the basin outlet, grids of flow velocity and standard deviation were generated at the final time step.

So far, the derivation of the parameters and coefficients related to the WetSpa model have explained here above. Parameter values that are taken as a threshold value and derived from other parameters and constant are listed in Table 13.

Table 13: Some parameters of the WetSpa model with common threshold values

Parameters with common threshold values	Unit	Value /estimated
Stream network delineating threshold	Cells	10
Sub catchments determining threshold value	Cells	1000
Upstream drained area by a particular cell	Km^2	> 0.1
Sub catchments	Total	96
Average sub catchment area	Km^2	18.7
Average hydraulic radius at upland cells	Meter	0.005
Average hydraulic radius at outlets	Meter	1.5
Time of concentration	Hour	58
Mean travel time for entire watershed	Hour	23
Manning's coefficient for lowest order	$m^{-1/3}$ s	0.055
Manning's coefficient for highest order	$m^{-1/3}$ s	0.025
Impervious area within an urban cell	%	30

In order to run the WetSpa model the input base maps must have similar area and cell size. Hence, same area and cell size of the watershed is created for the base maps of topography, land use and soil type. This helps the WetSpa model to perform the simulations properly. Accordingly, the watershed's base maps are made for 100m grid cell size with an average of 510 and 718 number of row and columns respectively.

4.2.2. WetSpa model calibration and validation

The most useful list of main calibration global parameters and corresponding measurement units of WetSpa model are given in Table 14. Interflow scaling factor (Ki) is a parameter for reflecting the organic matter in plants root zone associated with soil hydraulic conductivity. Groundwater flow recession coefficient (Kg) is a global parameter for reflecting catchment's groundwater recession regime and relative soil moisture parameter (K_ss) is related to field capacity for soil moisture content. Similarly, potential evapotranspiration is associated with a correction factor K_ep and G0 is the depth of initial groundwater storage. The maximum groundwater storage parameter (G_max) is dependent on groundwater depth and K_run is an exponent for reflecting the effect of small rainfall intensity on surface runoff. P_max is a modelling time dependent threshold for rainfall intensity.

Table 14: Main calibration global parameters of the WetSpa model

Parameter	Description	Unit
Ki	Interflow scaling parameter	-
Kg	Groundwater recession coefficient	-
K_ss	Relative soil moisture	-
K_ep	Correction coefficient for PET	-
GO	Initial groundwater storage	mm
G_max	Maximum groundwater storage	mm
TO	Base temperature for estimating snow melt	°C
K_snow	Degree day coefficient for calculating snow melt	mm/mm/°C/day
K_rain	Rainfall degree day coefficient	mm/mm/°C/day
K_run	Surface runoff coefficient	-
P_max	Threshold rainfall intensity	mm/day

Since snow melting and accumulation is not occurred in the watershed, temperature data was not taken as an input for the modeling process. The parameters generated as a function of temperature were not considered in the simulation. Hence, the global parameters as base temperature (TO) and degree day coefficient (K_snow) for estimating snow melt as well as the rainfall degree day coefficient (K_rain) were set to negative value (-1) to make it nonsense by the model.

For modeling process of WetSpa, appropriate model calibration and validation were undertaken. The hydro-meteorological data were deliberately divided so as to use for independent calibration and validation process. Hence, data recorded within similar time scale for all the meteorological parameters and spatial data derived from the base maps of topography, land use and soil texture were used for calibration as well as validation in the modeling processes.

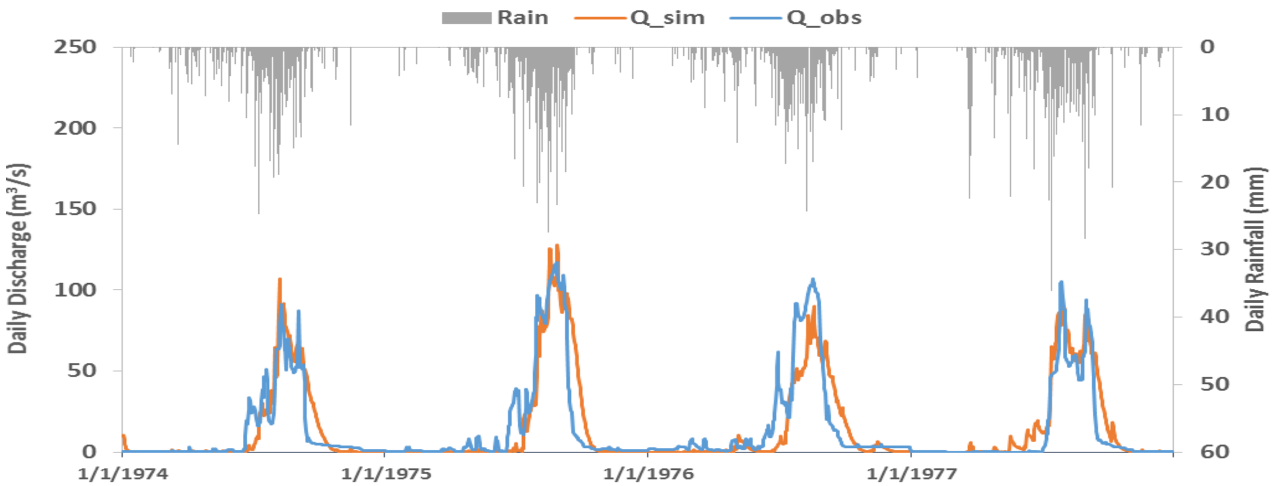
Table 15: Global model parameters and calibration result for the watershed

Parameters	Value range	Calibration result
Ki	0-12	1.0005
Kg	0-0.06	0.04595
K_ss	0-2	0.5378
K_ep	0-2	0.49925
GO	0-100	15.000
G_max	0-3000	7.00
TO	0-1	-1.00
K_snow	0-10	-1.00
K_rain	0-0.05	-1.00
K_run	0-5	3.500
P_max	0-500	250.00

The calibration and validation of WetSpa model was implemented by observing the graphical fitness between simulated and observed discharges (Figure 21) and through use of model performance evaluating criteria (Table 16). In both cases, the statistical and graphical comparisons of the observed and simulated discharge hydrographs have confirmed that WetSpa model is calibrated well in the modeling process. This calibration result was obtained with a repetitive trial and error method to fine-tune the global parameters within the range. Table 15 reveals the best fit agreement values created between observed and simulated discharges for the watershed.

The statistical model performance evaluation results for both calibration and validation processes are indicated in Table 16. Model bias (MB), model confidence (R^2) and Nash-Sutcliffe efficiency (NSE) were calculated as a model performance evaluating measures. Accordingly, the calculated values of these model performance criteria have shown very close to their optimum best fit values.

(a)



(b)

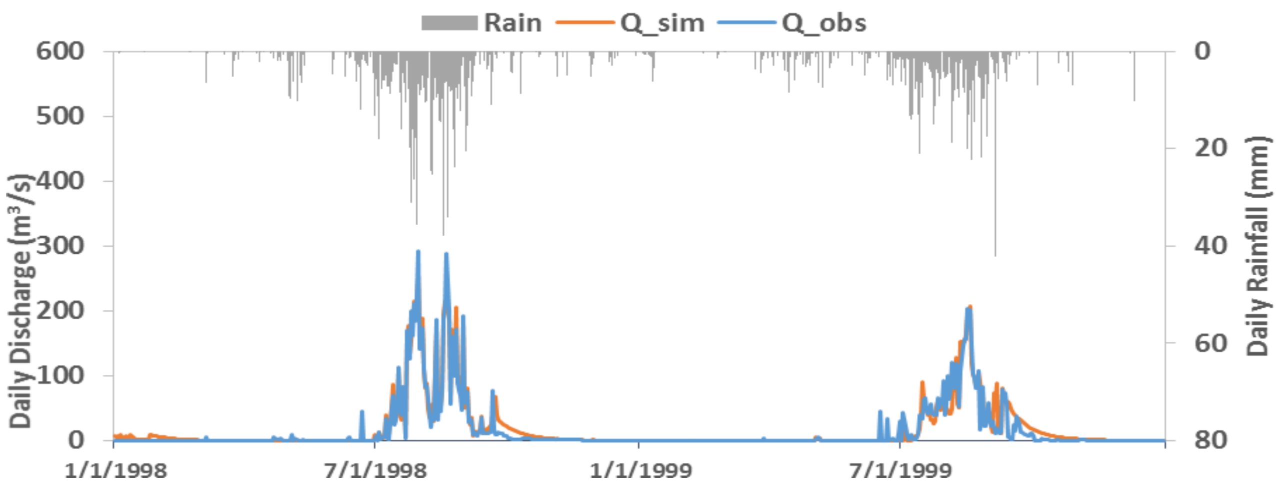


Figure 23: (a), Model calibration hydrograph from January 1974 to December 1977 and (b), Model validation hydrograph from January 1998 to December 1999 for Werii watershed

So far, the hydrograph, the model evaluation criteria of the observed and simulated discharges have showed that the model has well calibrated. The model can then be used to simulate future water balances change in the watershed.

Table 16: Model performance evaluation results for the calibration and verification of WetSpa model

Run	MB	R^2	NSE
Calibration	0.00	0.97	0.78
Verification	-0.098	0.91	0.75
Optimum	0	1	1

4.2.3. Sensitivity analysis for WetSpa model parameters

As mentioned earlier in this section, the WetSpa model has eleven global model parameters. These parameters have observed to show to which parts of the hydrograph were sensitive in the calibration process. Hence, the Ki and Pmax were very sensitive to the peak discharge used to calibrate the high flows. Whereas, the Kep and Kg were sensitive to the low flow volume and used to calibrate the baseflow of the hydrograph. The Kss was sensitive to the first year of the calibration period, in this case, 1977 and the G max was sensitive to the last year of the calibration period. The Krun and Pmax were non-sensitive to the watershed. Hence, through use of this sensitivity analysis the watershed biophysical properties were calibrated through use of WetSpa model.

4.2.4. Simulation of groundwater potentials in Werii watershed in the reference period

After having calibrated WetSpa model with a proper global model parameters, the water balance components were estimated based on the measured input parameters to the model. The daily precipitation, evapotranspiration and runoff for the separate calibration and validation periods are used as input hydro-meteorological parameters in addition to the spatial watershed gridded maps from which the water balance parameters and spatial grid maps are simulated. Total interception, surface runoff, infiltration, percolation, actual evapotranspiration, interflow, groundwater drainage, soil moisture storage and groundwater storage were then simulated for the watershed.

Hence, sum of each time step water balance components for each calibration and validation periods are simulated and presented in Table 17. The mean and maximum values of the water balances are also presented along with respective water balance component totals (Table 17). Similarly, total runoff, actual evapotranspiration, groundwater recharge, interflow and soil moisture are simulated as spatial distribution grid maps during the simulation process. As indicated in Table 17, the actual evapotranspiration (2606.5 mm), surface runoff (100.6 mm) and percolation (151.35 mm) were simulated as 89%, 3.4% and 5% of the total precipitation (2928.4 mm) respectively and this is consistent with the findings of (Tesfamichael *et al*., 2010; Beyene *et al*., 2011) at Giba catchment of Ethiopia.

Baseflow is a basic element in groundwater studies as it explains the behavior of water movements in the subsurface. It is obtained as a summation of interflow and groundwater flow simulated from the WetSpa extension. The base flow was produced from 7% (64.5 mm) interflow and 92.8% (895.8 mm) groundwater flow. The total runoff (996.4 mm) was simulated as 10% (100.6 mm) and 90% (895.8 mm) baseflow which has similar trend with (Nyenje and Batelaan, 2009). Due to uni-modal rainfall distribution in the watershed, the simulated total runoff is contributed by baseflow especially in the dry season.

Table 17: Water balance of the Werii watershed from measured, calibration and validation periods

Water balance components	Measured (1974-1977)	Calibration period (1974-1977)			Validation period (1998-1999)		
	Total (mm)	Total (mm)	Mean	Maximum	Total (mm)	Mean	Maximum
Precipitation	2940.9	2928.4	2.004	36.1	1740.9	2.385	42.12
Interception		353.9	0.242	2.22	168	0.23	1.87
Surface runoff		100.6	0.069	2.63	113.0	0.155	7.39
Infiltration		2402.3	1.644	32.5	1419.3	1.944	37.37
Evapotranspiration	6743.5	2606.5	1.306	4.82	1326.07	1.33	6.46
Percolation		151.35	0.773	16.9	102.87	1.051	24.05
Interflow		64.5	0.044	0.89	53.8	0.074	1.09
Groundwater flow		831.3	0.569	4.66	589.7	0.808	7.19
Baseflow		895.8	0.613	5.55	643.5	0.882	8.28
Total runoff	993.8	996.4	0.682	7.17	756.6	1.036	10.51

4.2.5. Investigations of climate change impacts on groundwater recharge and potentials

Running of WetSpa model produces the basic water balance components in two file formats i.e. in text file and spatial grid files. Thus, total actual evapotranspiration, groundwater recharge, surface runoff, interflow and soil moisture contents at the outlet are simulated on a current and future time scale basis in grid format while the rest of the water balances outputs are provided in text format. The simulated spatial grid files are further interpreted in arc GIS as indicated in Figures 24, 25 and 26 for spatial groundwater recharge.

The simulated water balance changes for future (2015-2050) periods for both the SRES emission scenarios A1B and B1 and the measured current (1974–1977) is illustrated in Table 18. The water balance components are analyzed and presented in annual average basis. Hence list of the main water balance components are provided and their future changes are analyzed based on the indicative SRES A1B and B1 emission scenarios.

Accordingly, precipitation of the study area is expected to increase by 13% in similar trend for both A1B and B1 scenarios. This result is consistent with the projections produced by SDSM model for each of the stations in Werii watershed. The actual evapotranspiration will also increase by 15% for A1B and 18% for B1 which showed similar projections as precipitation. This indicates as precipitation increase actual evapotranspiration will increase with similar trends in the time horizon.

Table 18: Annual water balance percentage change as compared to the reference period (1974–1977)

Water balance Components (mm)	Reference period (1974–1977)	Future A1B scenario (2015-2050)		Future B1 scenario (2015-2050)	
	Annual average (mm)	Annual average (mm)	Change (%)	Annual average (mm)	Change (%)
Precipitation	732.0925	824.98	13.0	824.75	13.0
Evapotranspiration	651.64	749.5	15.0	767.02	18
Recharge	37.8375	39.73	5.0	38.54	2.0
Surface runoff	25.14	19.55	-22.0	19.17	-24.0
Baseflow	223.95	255.30	14.0	241.97	8.0

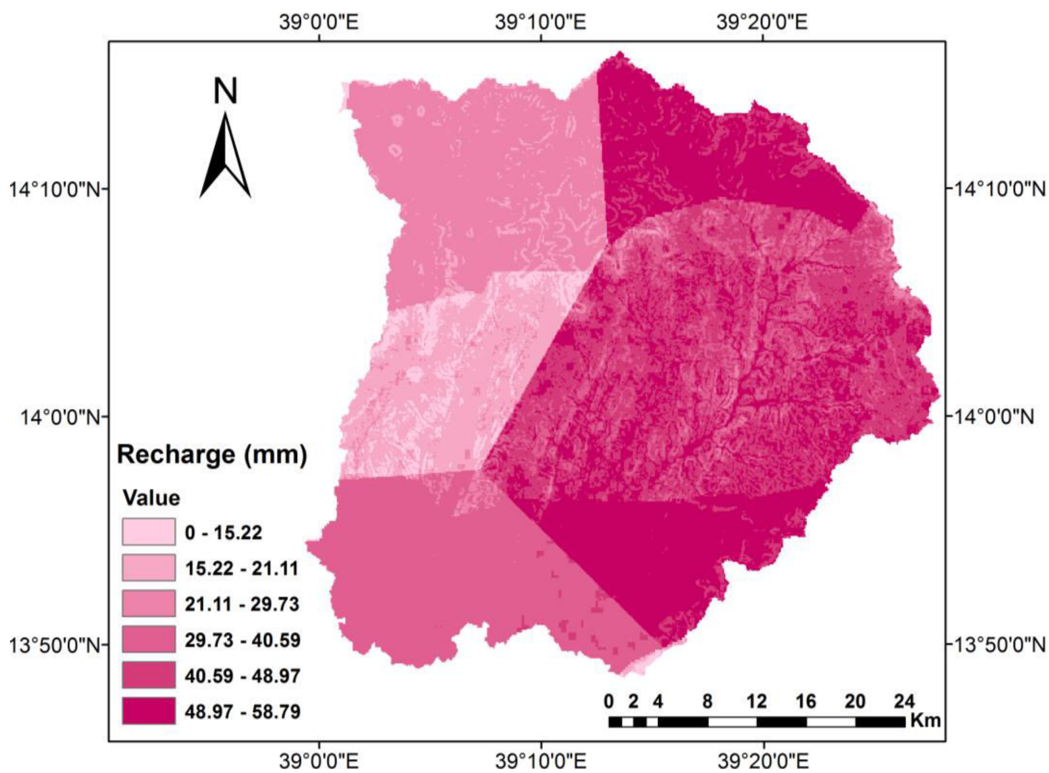


Figure 24: Average annual groundwater recharge in Werii watershed for the reference period (1974-1977)

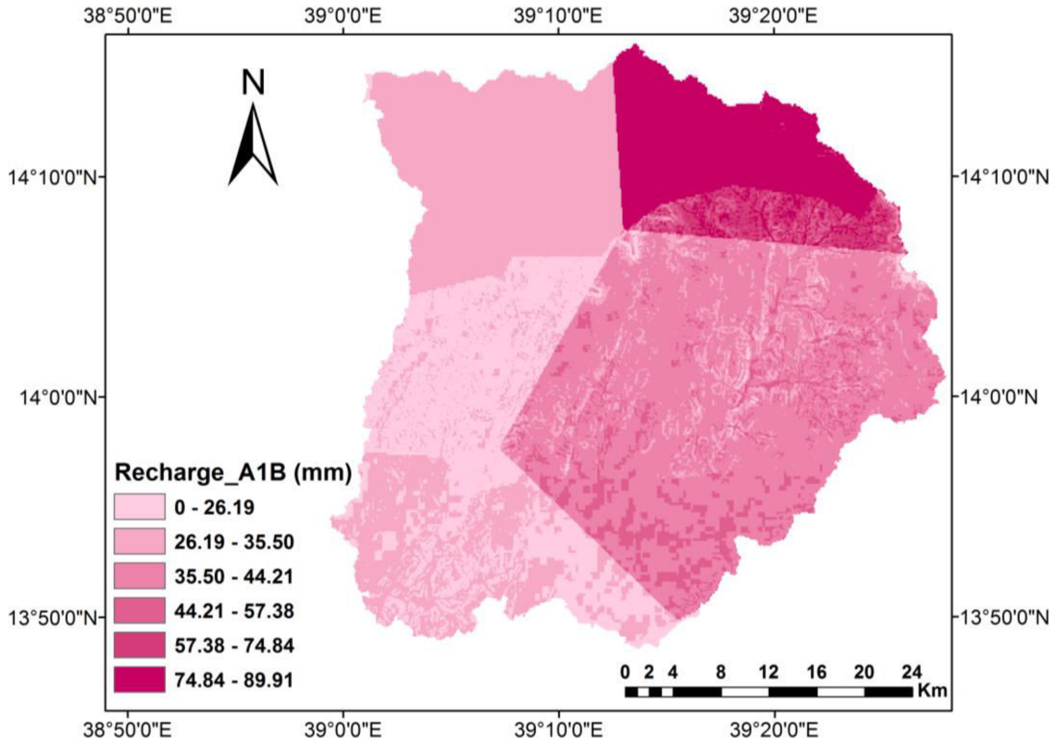


Figure 25: Future average annual groundwater recharge of Werii watershed for A1B scenario (2015-2050)

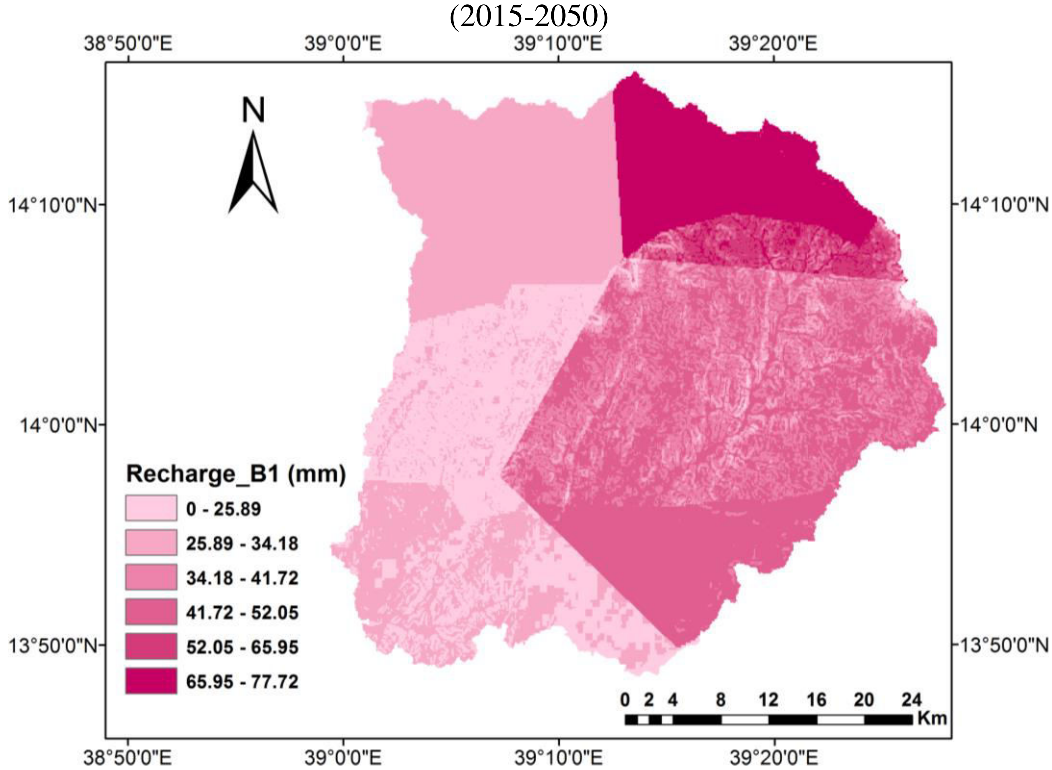


Figure 26: Future average annual groundwater recharge of Werii watershed for B1 scenarios (2015-2050)

The future groundwater recharge is expected to increase by 5% and 2% from the reference period for A1B and B1 SRES emission scenarios respectively. This will occur as a result of increment in precipitation in the time horizon. The spatial distribution of the total groundwater recharges for the reference period and for future A1B and B1 scenarios for the period ranged from 2015 to 2050 are depicted in Figures 24, 25 and 26. The higher groundwater recharge is observed in the northern and eastern part of the watershed for both scenarios. The southern and western parts of the watershed, however, showed lower groundwater recharges. As compared to the reference period the future spatial maps of groundwater recharge indicated consistent spatial changes. In future spatial groundwater recharge produced for A1B scenario has showed little change especially in the south eastern parts of the watershed (Figures 24 and 25). In general the groundwater recharge produced for both scenarios will increase and observed higher for A1B scenario. This result is consistent with findings of (Nyenje and Batelaan, 2009) indicated groundwater recharge will increase.

Moreover, the baseflow produced as a result of interflow and groundwater flow would show an increasing trend with A1B scenario (14%) higher than B1 (8%) scenario. The baseflow is more sensitive to A1B scenario as it is 6% higher than B1 scenario. According to (Nyenje and Batelaan, 2009) the baseflow would generally increase in the future and remain positive. Unlike baseflow the surface runoff will show a decreasing trends for both emission scenarios. As result, the surface runoff will decrease by 22% for A1B and by 24% for B1. Hence, risk of annual flooding is limited in the watershed due to decreased amount of surface runoff in the future.

It can be concluded that the future hydrological water balance changes will happen and will increase for the emission scenarios considered in this study. The precipitation, actual evapotranspiration and baseflow will show positive increment. The surface runoff, however, will decrease and flooding problems will not treat the watershed.

4.3. Estimation of Annual and Seasonal Recharge; Application of WetSpass Model

4.3.1. WetSpass model simulation

After running the WetSpass model effectively, spatial grid maps of the watershed has been produced in winter, summer and yearly basis. Effective run of WetSpass model produces eighteen grid maps continuously with only one run simulation. Hence, annual, winter and summer average values of surface runoff, actual evapotranspiration, interception, transpiration, soil evaporation, and recharge were produced for Werii watershed. These watershed based physiographical maps are raster-shaped, in which every pixel represents the magnitude of the respective water balance component at that cell in the watershed. The watershed simulated values are unique average values produced from each cell in the watershed. Hence, the following discussions explains the detail of this issues.

4.3.1.1. Surface runoff and interception

According to Batelaan and Woldeamlak (2007) surface runoff is dependent on the availability of vegetation, soil type and slope of the watershed. A spatial annual average surface runoff simulated by WetSpass model is presented in Figure 27 and get compared with annual precipitation in Figure 32. The seasonal and annual average mean values of surface runoff is depicted in Table 19 as well. The annual surface runoff extends from 0 mm/year to 150 mm/year with an average surface runoff 44.06 mm/year. By considering the area of Werii watershed (1797 km^2) the average surface runoff (44.06 mm) is equivalent to 79.2 million m^3. The maximum runoff observed in the watershed is found sparsely at a very steep areas in the watershed. The average surface runoff is 6% of the annual average precipitation (717 mm) in Werii watershed. Similar reports for surface runoff are available in literatures as 7% (Arefaine *et al*, 2012), 4.9% (Mustafa and Ali, 2013). About 96.3% of the surface runoff of Werii watershed was occurred at summer season and the remaining 3.7% is occurred at winter season.

Interception is occurred due to presence of vegetation when rainfall rains in the watershed. The spatial average annual interception in Werii watershed is presented in Figure 28 and the corresponding mean values of seasonal and annul interception is given in Table 19. The annual interception rate of the watershed is found to be in the range of 25 to 239 mm/year with an average interception rate of 33.66 mm/year. 92.3 % of the interception rate is simulated at summer season and the remaining 7.7% is occurred in winter season.

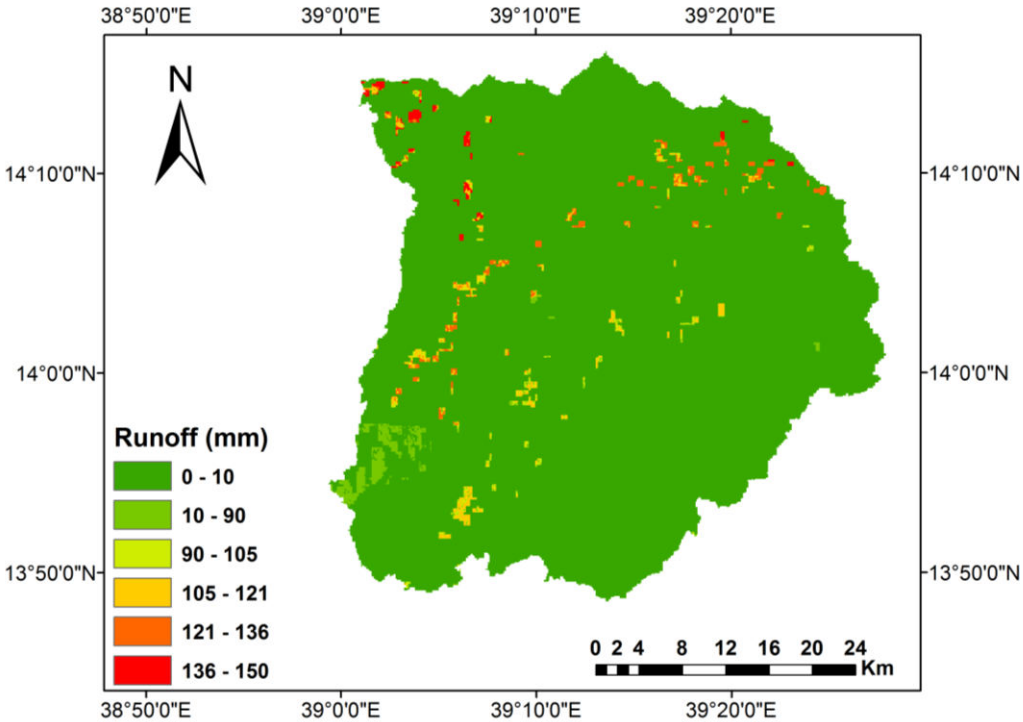


Figure 27: Average annual surface runoff in Werii watershed

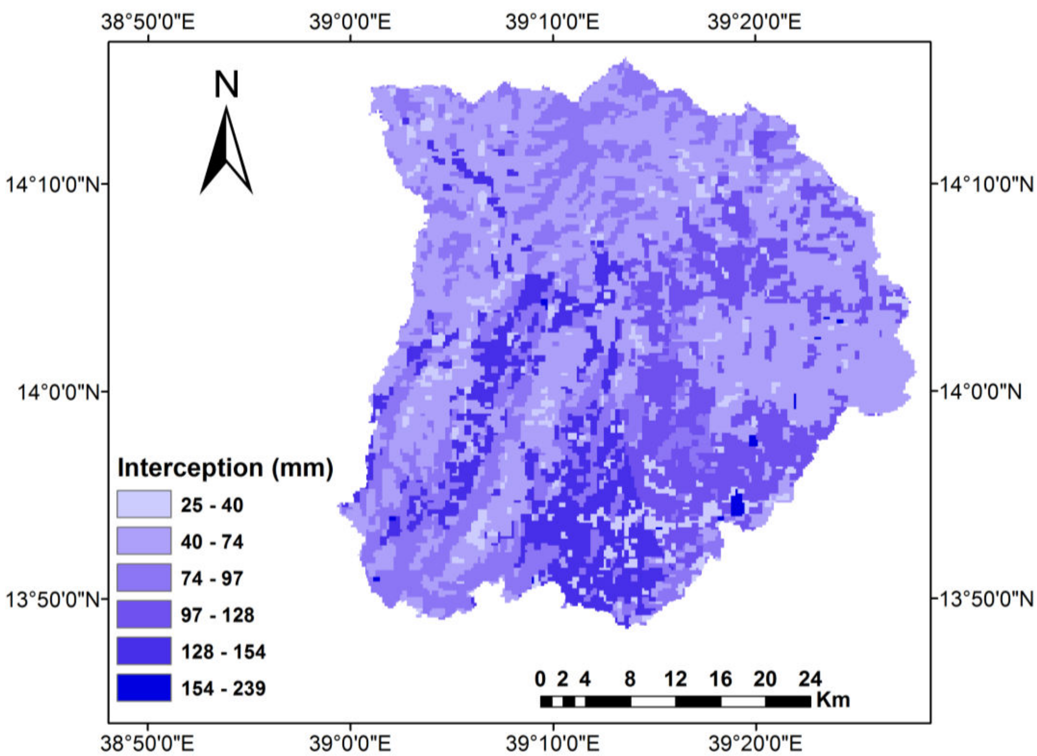


Figure 28: Average annual interception in Werii watershed

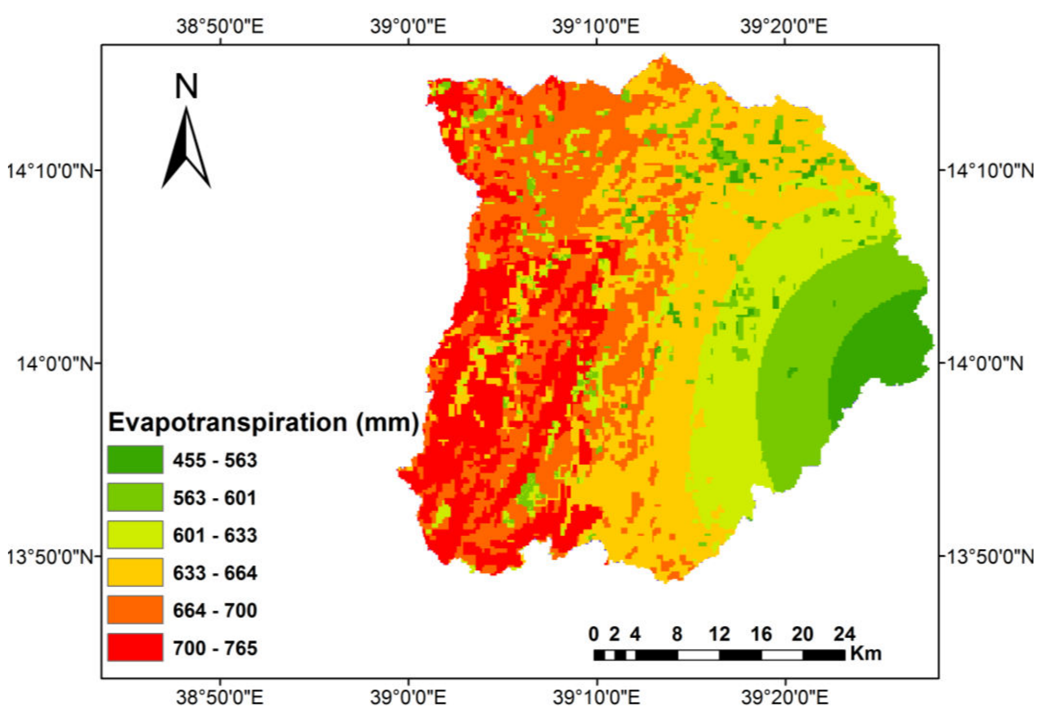


Figure 29: Average annual actual evapotranspiration in Werii watershed

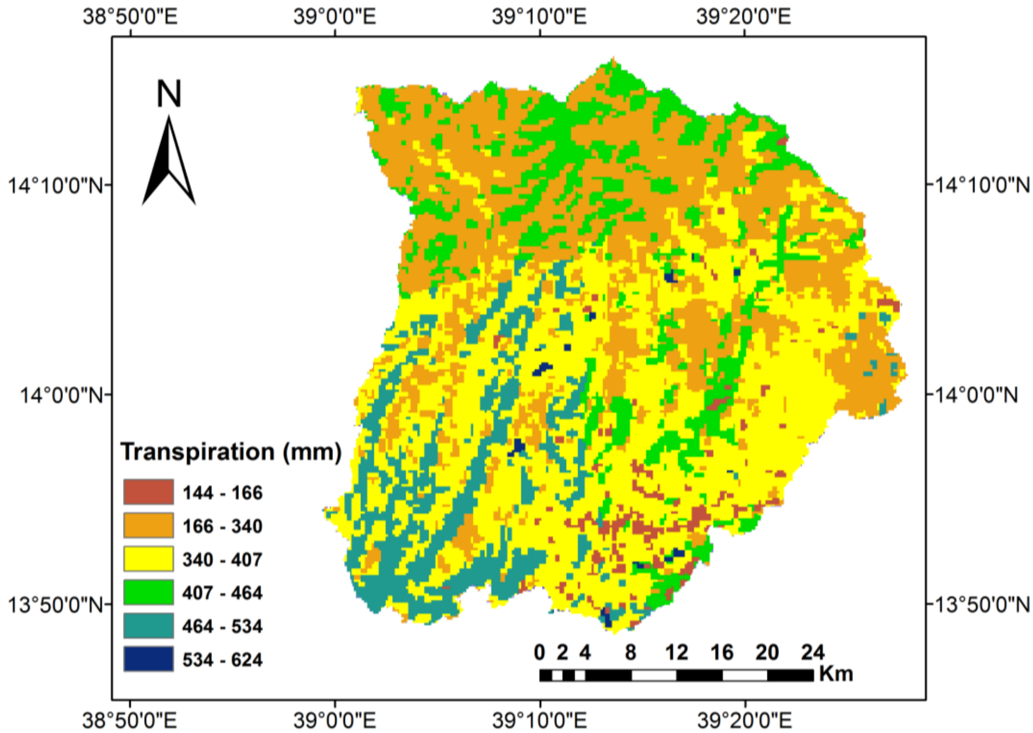


Figure 30: Average annual transpiration in Werii watershed

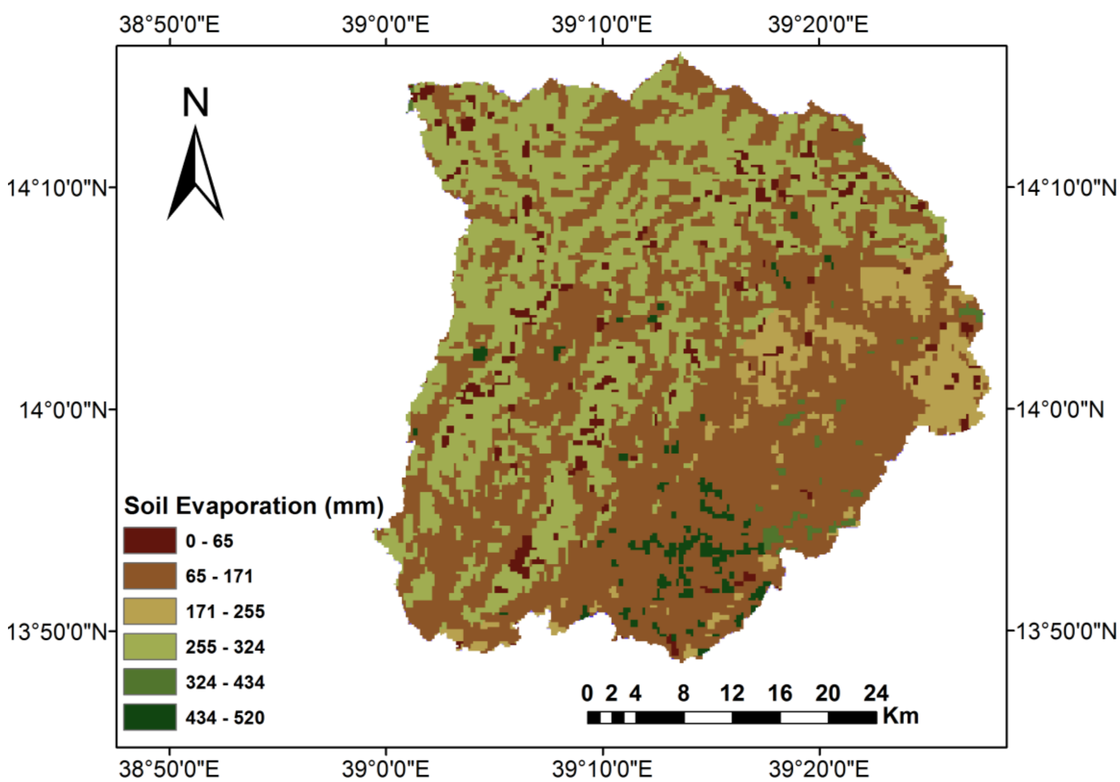


Figure 31: Average annual soil evaporation in Werii watershed

4.3.1.2. Actual evapotranspiration, transpiration and soil evaporation

When rainfall rains there is a water vapor that returns back to the atmosphere from either of water surfaces, soil surfaces or vegetation canopy. Annual actual evapotranspiration from land, water and vegetation surfaces was simulated by WetSpass model as explained in Figure 29 and 30. The corresponding seasonal and annual mean values are listed in Table 19. The minimum and maximum average values of annual evapotranspiration of the watershed is 455 mm/year and 765 mm/year, respectively. Moreover, the mean winter and summer seasons and annual evapotranspiration of the watershed is 158.89 mm, 491.27 mm 650.16 mm, respectively (Table 19). About 75.56% of the annual evapotranspiration was lost in summer season and the remaining 24.44% is releases in winter season. In general, this portion of water holds 90.7% of the total annual rainfall (717 mm). Similarly, Mustafa and Ali (2013) have reported that actual evapotranspiration is 94.6% of the annual precipitation. Hence, Actual evapotranspiration is takes much of the annual precipitation (Tilahun and Merkel, 2009; Tesfamichael *et al.*, 2010; Arefaine *et al*, 2012). This shows that evapotranspiration plays key role in water loss in the watershed due to the active solar radiation and dry winds in the watershed. As depicted in Figure 29, the eastern part of the watershed shows lower mean evapotranspiration as compared to the western part. Evapotranspiration is occurred due to solar radiation and radiation is high in lower altitude. This is the reason that the evapotranspiration of the western part of the watershed is lower than the eastern part.

Table 19: long term annual and seasonal averages of WetSpass simulated parameters

Hydrologic parameters (mm)	Seasonal average		Annual average (mm)
	Winter (mm)	Summer (mm)	
Precipitation	166	551	717
Runoff	1.64	42.42	44.06
Interception	2.66	31.06	33.66
Actual evapotranspiration	158.89	491.27	650.16
Transpiration	10.55	359.66	370.21
Soil evaporation	144.85	45.14	189.99

Recharge	9.55	19.51	30.06

Evapotranspiration takes place as a result of transpiration from vegetation cover and evaporation from water as well as soil surfaces. Therefore, it is needed to deal with these components separately. WetSpass model has simulated average transpiration and evaporation from soil as explained in Figures 30 and 31 respectively. Transpiration is occurred in the watershed (Figure 30) having annual average transpiration rate of 370.21 mm/year with average winter 10.55 mm and summer 359.66 mm (Table 19). About 97% of the transpiration has occurred at summer and the 3% loses at winter seasons.

Evaporation from soil was also simulated during WetSpass model running process for the watershed (Figure 31). Accordingly, annual average soil evaporation was estimated to be 189.99 mm/year with winter and summer averages of 144.85 mm and 45.14 mm respectively (Table 19). Unlike transpiration the soil evaporation is higher at winter than summer season. About 76% of the evaporation from soil escapes the soil surface during winter season and the rest evaporates at summer season.

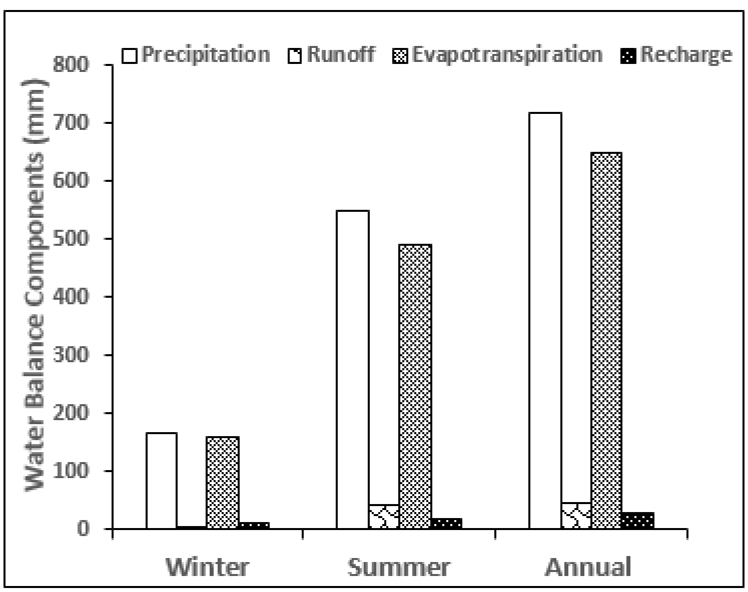


Figure 32: Precipitation, runoff, actual evapotranspiration and recharge for average winter, summer and annually.

4.3.1.3. Groundwater recharge

The average long term seasonal and annual groundwater recharge in the Werii watershed was simulated through WetSpass hydrological model. As a result, 9.55 mm of average winter and 19.51 mm of average summer groundwater recharge was simulated in Werii watershed (Table 19). The average annual simulated groundwater recharge is 30.06 mm. The average annual long term groundwater recharge for Werii watershed was simulated as 4.2% of the average annual precipitation (717 mm) in the watershed. Based on that, the groundwater recharge in Werii watershed was estimated 54.02 Million m^3. About 69% of the annual groundwater recharge of the watershed occurs during the wet season (summer), and the remaining 31% in dry season (winter). In the water balance system of the watershed, the precipitation amount was simulated to be 90.7% evapotranspiration, 6% runoff, and 4.2% recharge (Figure 32). Hence, 1712 l/s rate of recharge is estimated for the whole 1797 km^2 area of the watershed. Regarding future recharge, the watershed is expected to increase by 5% under A1B and 2% under B1 SRES emission scenarios from the reference period (see section 4.2.4 for detail)

The simulated average winter and summer groundwater recharge is presented in Figures 33 and 34 respectively. The western part of Werii watershed receives relatively higher rainfall during summer season and has positive groundwater recharge values. However, the simulated summer recharge in some places in the eastern part of the watershed have negative value (Figure 34) which indicates there is no groundwater recharge. This occurred due to discharge from the subsurface is greater than that of recharge at that place. Similarly PET from the subsurface is also greater than summer recharge. The combined effect of discharge and PET from the subsurface makes the summer recharge to have a negative value. It is obvious that subsurface groundwater is saturated if there is abundant rainfall in the watershed. The winter recharge in Figure 33, is significantly lower with majority of the watershed receives from 0 - 10 mm.

Similar studies in different parts have been conducted to estimate average groundwater recharge through use of WetSpass model by different scholars for their respective study watersheds. Accordingly, an average recharge of 28 mm, 5% of annual precipitation (Tilahun and Merkel, 2009); 37 mm, 6% of precipitation (Tesfamichael *et al.*, 2010); 0.27 mm, 0.5% of precipitation (Mustafa and Ali, 2013); 66 mm, 12% of annual precipitation (Arefaine *et al,* 2012) was found. Therefore, it can be said that WetSpass model has worked well in Werii watershed and has simulated hydrological water balance components efficiently.

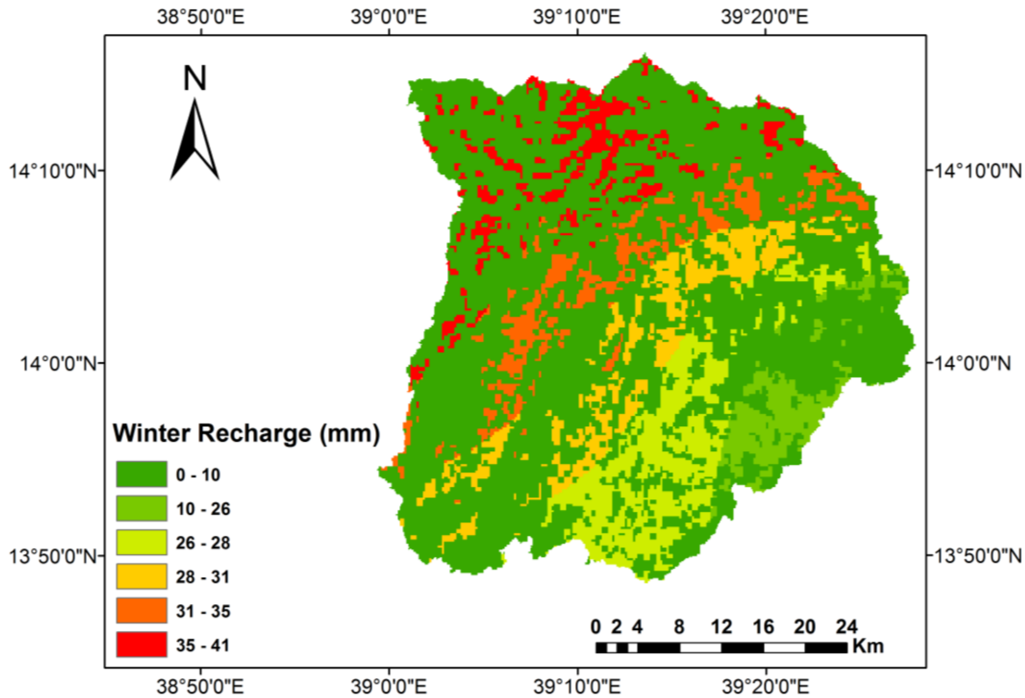


Figure 33: Simulated average winter recharge in Werii watershed

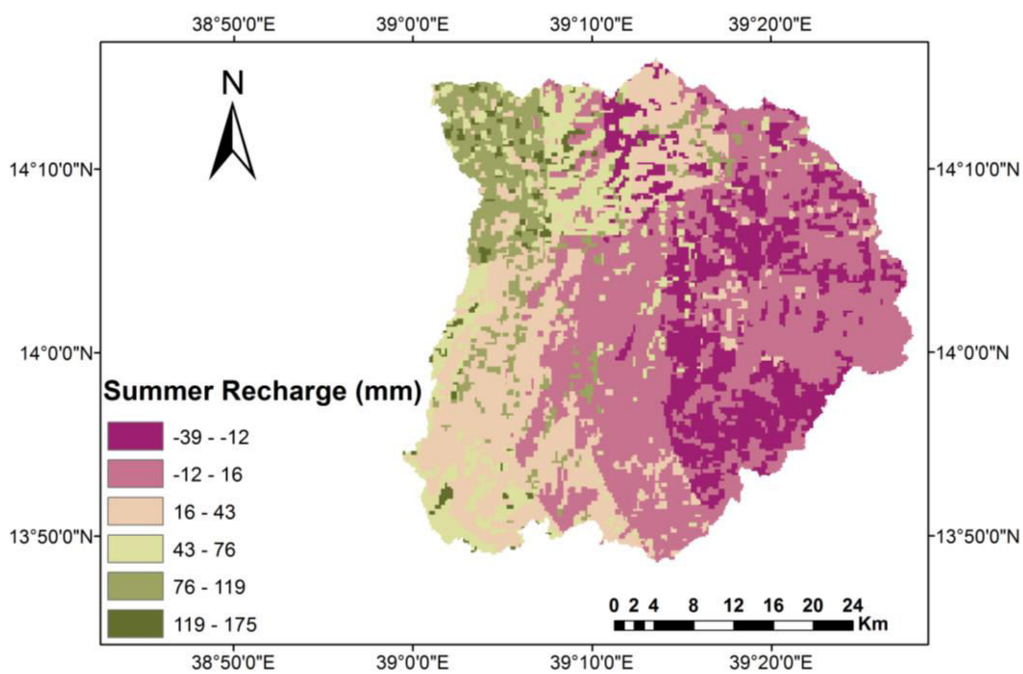


Figure 34: Simulated average summer recharge in Werii watershed

4.4. Model Comparison

WetSpa and WetSpass are hydrological models which simulates groundwater recharge, runoff and actual evapotranspiration among others. Both are physically based and distributed models for transfer of water and energy between soil, plants and atmosphere. WetSpa is time and space dependent spatially distributed model. Thus, WetSpass is built up on the foundations of WetSpa which simulates long term spatial average values for the hydrological elements (Batelaan *et al.*, 1996; Wang *et al.*, 1997). Table 20 briefly explains WetSpa and WetSpass simulations of the basic hydrological processes, listed for comparison, in the watershed.

Table 20: Simulation of water balance components from WetSpa and WetSpass models

Model	Recharge (mm)	Evapotranspiration (mm)	Runoff (mm)
WetSpa	37.84	651.64	25.14
WetSpass	30.06	650.16	44.06

The simulation of the water balance components are consistent and found with in similar trends with the exception of surface runoff (Table 20). The WetSpa simulated average values of groundwater recharge and actual evapotranspiration are more than that of WetSpass simulations. Nevertheless, the WetSpa simulated surface runoff is significantly higher than the WetSpass simulated result.

The average estimated annual groundwater recharge in Ethiopia is about 28,000 Million m^3 (24.8 mm) (Ketema and Tadesse, 2003) cited in (Obuobie *et al.*, 2008). The estimated recharge ranges from 10 mm to 120 mm. Hence, both models simulated consistent groundwater recharge estimates in Werii watershed.

5. SUMMARY, CONCLUSION AND RECOMMENDATION

5.1.Summary and Conclusion

The overall objective of this thesis work was to estimate spatial groundwater potential, average long term seasonal groundwater recharge, and impact of climate change on the groundwater resources in Werii watershed. Precipitation, minimum and maximum temperature change projections were investigated by the help of SDSM model by taking regional climate data from REMO. The future potential evapotranspiration was estimated based on the future maximum and minimum temperatures. A spatially distributed WetSpa model was employed to investigate the spatial groundwater potential and the water balance components. Similarly, WetSpass model was used to estimate seasonal long term groundwater recharge.

The main focus of downscaling climate data is investigation of present climate situations and future climate change impacts due to greenhouse gases emissions through converting coarse resolution climate data from REMO to point or watershed level. Hence, based on the local climate variables (predictands) a regional climate model REMO outputs were downscaled as predictor variables. The rainfall and temperature changes that will likely occur due to changes in climate for the period 2015 to 2050 was estimated. These projections were based on the SRES emission scenarios of A1B and B1 scenario output data for rainfall and temperature in the time horizon. Hence rainfall and temperature change projections were forecasted based on the emission scenarios considered as indicator treatments. This projections in rainfall, minimum and maximum temperature study was conducted in Werii watershed of Tekeze river basin, Ethiopia. Based on data availability and proximity to the watershed, Abyiadi, Adwa. Hawzen and Adigrat are selected from available meteorological stations from nearby and inside the watershed. To investigate the future climate change impacts for the separate meteorological stations, a statistical downscaling model (SDSM) was employed to downscale the regional climate outputs from REMO. Hence, available data from these stations was used separately for model calibration and validation processes. After downscaling, the future likely changes in precipitation for each of the meteorological stations, maximamum change was observed in Adwa station, 34% for A1B and 33% for B1 and Hawzen station 31% for A1B and 33% for B1. Minimum ranifall change was also observed in Abyiadi station for A1B

(11%) and B1 (10%) . In the future climate sytem, negative change in rainfall is seldom but expected to increase in the the future time horizon. Change in projected maximum temperature will also likely. As a result, maximum change in maximum temperature is observed in Hawzen station for A1B (0.16°c) and B1 (0.2°c). Smaller change in maximum temperature, however, is investigated at Adigart and Abyiadi stations. A negative change is also appeared at Adwa station for B1 (-0.01°c) emission. Generally, maximum temperature is expected to be in the range of -0.01°c to 0.2°c in the watershed.

Future change in minimum temperature were also estimated based on the calibration results for the emission scenarios. As a result, maximum change in minimum temperature is observed in Hawzen station for A1B (0.34°c) and B1 (0.29°c). Similarly, smaller change were investigated in Adigrat and Abyiadi stations for both emission scenarios. Negative change in minimum temperature will hardly found in the future range of the study time. Generally, minimum temperature will change increasingly and positively.

An investigation of the available water potentials at present and future time is quantified by water balance components determination and use of models. The main concern is to investigate the present and future (2015-2050) groundwater potential of Werii watershed (1797 km^2) through use of hydrological WetSpa model and regional climate, REMO model. The future groundwater potential by the end of 2050 was investigated after downscaling future rainfall and temperature from REMO model. The groundwater in future time is simulated after the WetSpa model is being calibrated well.

The downscaled average daily time series data for all the stations, considered in the watershed, as precipitation and potential evapotranspiration were used as an input for the calibrated WetSpa model for simulation of the discharge and baseflow responses. These climate data are generated based on the emission scenarios for the current and future climate change projections from 2015-2050 in future basis.

Due to the effect of climate change, the precipitation will show 13% increment. Groundwater recharge will increase from 2-5%. The actual evapotranspiration will also increase in the range of 15-18%. Moreover, the baseflow will also increase higher for A1B (14%) than B1 (8%). The surface runoff will show decrement within the range of 22-24%.

It can be concluded that the future hydrological water balance changes would happen and would increase for the emission scenarios considered in this study. The precipitation, actual evapotranspiration and baseflow would also show positive increment. The surface runoff, however, will decrease and flooding problems will not threat the watershed.

The long term seasonal groundwater recharge of Werii watershed (1797 km^2) was estimated through use of a grid based physically distributed model, WetSpass. The model applies up to date physical and empirical relationships of the watershed for its efficiently running processes. Obviously, long term average hydro meteorological data and spatial patterns of watershed physical grid maps are used as main inputs of the model. This makes use of WetSpass for analyzing watershed groundwater systems to be steady state. Nineteen model parameter variables were used as an input for the WetSpass model in grid and dBase file formats. Gridded base maps of topography, slope and soil are not varied and season independent and used for both seasons. Soil and runoff coefficient parameters in dbase files are also used in the model, season independently. Grid base maps and dbase files of land use were provided in separate winter and summer seasons. Precipitation, potential evapotranspiration, temperature, wind speed and groundwater depth were also prepared and employed by the model, in grid format for both winter and summer seasons.

After having run the WetSpass model, a spatially simulated summer and winter runoff, evapotranspiration, interception, transpiration, soil evaporation and finally recharge of the watershed under consideration are obtained. These model output results are annual and seasonal average values for each simulated parameters. As a result, the average winter and summer groundwater recharge is estimated as 9.55 mm and 19.51 mm respectively. The average annual long term groundwater recharge for Werii watershed was found to be 30.06 mm which is 4.2% of the average annual precipitation (717 mm) in the watershed. In the water balance system of the watershed, the precipitation amount is simulated to be 90.7% evapotranspiration, 6% runoff, and 4.2% recharge. Hence, a 1712 l/s rate of recharge is estimated for the whole 1797 km^2 area of the watershed. The simulated results of water balance components and hence the recharge, however, can be varied when there is a change in climate and land use processes of the watershed. Hence the results obtained from this study can be taken as an initial investigation in the ground water modeling of Werii watershed.

Finally the distributed hydrological models WetSpa and WetSpass were compared based on their simulated values for recharge, evapotranspiration and surface runoff. These two models simulated with in similar trend and were consistent each other and with other similar literatures. Hence both models can be used in agro-ecologically similar watersheds.

5.2.Recommendation

Generally, the future likely changes in precipitation and temperature is positive and will increase in the period from 2015 to 2050. Hence, people have to be aware of it and take actions as per necessary.

The water resources is potentially available in Werii watershed is useful for irrigation use, livestock consumption and potable water for the resident people. Wise use of these water resources potential have paramount importance. Hence, increased exploitation of these water resources which is parallel to the water resources increment is recommended provided that wisely use of the water resources is provided.

Knowing the annual and seasonal simulated long term average annual groundwater recharge and water balance components is useful in such a way that,

1. The average annual amount of incoming rainfall to the watershed should be planned on the bases of the residents demand for irrigation purposes, home use and livestock use and so on.
2. The future groundwater resources development and improvement should be based on the water balance results obtained from this modeling.
3. The simulated result is also useful for rainfall-runoff relationship modeling and hydrological change studies in the areas below ground surface.

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7. APPENDICES

7.1. Mean monthly precipitation Abyiadi station for SDSM calibration and validation periods

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1973	0.0	0.0	0.0	0.6	0.8	1.0	10.7	9.5	3.7	1.6	0.0	0.0
1974	0.0	0.1	0.6	0.1	2.7	3.5	5.8	12.6	1.4	0.0	0.0	0.0
1975	0.8	0.0	0.0	0.4	0.5	2.6	7.5	11.4	6.1	0.2	0.0	1.1
1976	0.0	0.0	2.0	0.3	1.6	4.6	5.8	4.6	2.5	0.2	0.5	0.0
1977	0.0	0.0	0.9	0.0	1.4	4.8	11.4	4.9	1.7	0.0	0.2	0.0
1978	0.0	0.0	1.7	0.1	1.3	4.5	11.9	5.1	2.4	0.4	0.0	0.0
1979	0.0	0.0	0.0	0.2	1.1	1.6	2.7	5.3	1.2	0.5	0.0	0.0
1980	0.0	0.0	0.1	2.5	0.8	0.9	5.6	4.2	0.5	0.4	0.0	0.0
1981	0.0	0.0	2.8	1.5	0.9	0.3	9.1	9.1	0.0	0.0	0.0	0.0
1982	0.0	0.0	0.8	2.2	1.6	2.7	8.3	9.1	3.3	0.0	2.0	0.0
1983	0.0	1.7	2.9	2.9	2.7	1.1	5.3	3.4	0.4	0.1	4.9	0.0
1984	0.0	0.0	1.4	0.7	1.2	1.4	5.0	5.8	0.3	1.6	0.0	0.0
1992	0.0	0.0	2.0	2.9	0.2	1.5	3.6	5.8	0.3	0.4	0.4	0.0
1993	0.0	0.0	0.0	0.9	2.6	3.2	3.6	5.8	0.7	2.8	0.0	0.0
1994	0.0	0.1	0.0	0.5	3.1	4.5	2.3	4.5	0.8	2.8	0.0	0.0
1995	0.0	0.0	2.3	2.2	1.5	1.6	10.8	13.6	1.4	0.2	0.0	1.1
1996	0.0	0.0	0.3	2.8	9.8	11.3	6.9	6.9	5.8	0.3	0.0	0.0
1997	0.0	0.0	0.0	2.0	2.1	2.2	7.4	4.1	0.1	5.0	0.2	0.0
1998	0.0	0.0	0.1	0.2	1.3	5.2	22.9	31.5	9.7	1.0	0.0	0.0
1999	0.5	0.0	0.0	2.0	2.1	1.8	10.1	15.3	3.6	0.0	0.0	0.0
2000	0.0	0.0	0.0	2.0	2.1	1.8	4.6	7.8	1.9	2.5	0.9	0.0

7.2. Mean monthly T_max Abyiadi station for SDSM calibration and validation periods

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1973	29.6	31.7	33.4	32.3	30.6	31.6	25.8	24.6	26.3	27.1	28.1	26.6
1974	28.3	29.9	29.5	31.6	29.5	29.8	24.8	23.8	26.6	28.4	27.6	27.8
1975	27.7	30.5	30.9	30.9	30.8	30.1	27.4	27.5	28.8	30.0	29.7	28.2
1976	28.3	30.5	30.8	30.9	29.3	28.6	25.6	25.4	27.2	29.2	27.4	28.2
1977	28.8	28.9	30.1	30.2	30.2	29.3	27.8	26.3	28.5	29.8	28.2	29.0
1978	29.7	29.1	30.7	32.1	32.0	30.5	27.4	25.4	26.7	26.5	26.6	26.8
1979	27.4	28.1	28.1	28.9	30.9	28.2	26.0	26.2	27.5	27.3	27.6	27.8
1980	26.9	29.4	29.1	30.2	29.2	27	29.6	30.3	29.6	29.5	30.1	31.7
1981	28.2	31.1	30.5	30.1	30.6	31.6	29.2	30.8	30.6	28.1	30.3	31.6
1982	29	28.4	30.5	24.8	28.6	31.6	26.1	23.4	24	24.3	28.4	26.8
1983	25	22.9	23.6	23.8	26.7	24.3	26.5	25.1	26.1	26.5	28	30.8
1984	28.2	27.7	28.3	28.4	33.5	27.3	26.8	27.7	26.7	22.4	24.7	28.8
1992	28.4	29.4	28.3	31.1	30.8	28.4	23.4	22.9	25.1	27.7	25.8	27.7
1993	27.0	29.2	30.1	30.6	30.3	28.6	28.4	26.7	28	33.5	29.4	22.4
1994	26.5	30.2	29.5	30.1	28.1	24.8	24.3	23.8	26.5	28.4	26.3	26.7
1995	28.6	28.4	30.1	32.8	31.6	29.9	28.2	27.9	30.0	30.0	29.7	28.2
1996	28.4	30.1	29.2	30.9	28.5	28.3	24.0	23.6	26.1	28.3	27.9	26.7

1997	28.0	29.7	31.4	29.6	31.2	30.9	28.6	28.7	30.1	31.0	29.6	28.4
1998	29.1	29.6	31.5	32.2	30.3	28.9	18.0	27.7	29.3	29.0	25.6	26.5
1999	27.7	29.4	31.4	29.6	31.3	30.5	27.9	27.9	28.5	28.8	27.9	26.7
2000	28.0	29.7	31.4	29.6	31.3	30.5	26.1	24.8	27.2	27.2	27.6	28.0

7.3. Mean monthly T_min Abyiadi station for SDSM calibration and validation periods

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1973	14.9	15.6	17.7	19.4	18.7	18.9	15.4	15.9	15.9	16.1	15.0	12.4
1974	14.3	15.1	16.1	18.5	18.4	17.5	14.9	14.8	15.8	16.5	15.0	13.5
1975	14.3	15.8	17.3	17.4	18.6	16.2	15.1	15.1	15.0	14.6	15.9	15.4
1976	15.3	16.4	16.6	16.6	15.4	17.0	15.9	16.0	16.4	17.8	16.5	15.5
1977	15.9	15.3	15.7	15.7	16.2	15.6	15.8	16.2	16.1	16.0	16.0	15.9
1978	16.7	17.1	18.2	19.5	19.7	20.3	17.4	15.2	15.4	15.2	15.1	14.9
1979	15.2	14.8	14.8	15.4	16.4	16.9	17.4	18.0	16.7	16.5	15.6	15.2
1980	13.3	13.6	11.8	11.1	11.9	14.4	13.3	11	17.9	15	16.9	15.6
1981	15.6	13.5	16.5	15.6	16.9	15.3	16.6	15.8	14.6	13.9	15.8	15.3
1982	14.2	15.3	15	15.9	14.1	14.5	15.8	15.1	14.4	14.8	15	15
1983	14.7	15	15.9	14.5	15	14.5	15.2	15.8	15	14.1	15.6	15
1984	11.6	13.3	12.6	12.8	12.5	15	14	13.5	12.2	13.1	11.9	10.5
1992	10.5	14.3	11	11.9	11.2	10.9	10.4	8.3	9.7	12.5	9.2	9.6
1993	9.5	15.1	15.7	16.2	15.6	15.8	16.2	16.1	16.0	16.0	18.4	17.8
1994	13.0	14.0	14.3	15.4	15.1	14.6	15.9	15.4	15.2	13.1	12.5	16.2
1995	15.1	14.2	14.5	15.6	15.2	15.2	14.3	15.4	16.1	14.6	15.9	15.4
1996	15.3	15.7	16.5	16.3	16.0	15.0	15.0	15.8	12.8	10.5	9.0	12.5
1997	13.5	13.9	16.5	17.0	17.4	11.7	7.2	10.0	11.1	12.3	13.9	14.0
1998	9.5	10.1	11.7	11.4	10.9	10.4	8.5	10.6	10.5	10.8	9.2	10.2
1999	10.0	10.9	16.6	17.0	17.5	17.3	8.9	9.3	9.3	9.6	9.0	12.4
2000	13.5	13.8	16.6	17.0	17.5	17.3	15.1	14.8	15.3	14.5	13.6	12.6

7.4. Mean monthly precipitation Adwa station for SDSM calibration and validation periods

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1973	0.0	0.2	0.5	0.9	1.9	5.5	11.0	9.9	1.6	0.5	0.0	0.0
1974	0.2	0.3	0.1	0.5	1.8	6.5	12.0	13.5	2.1	0.1	0.0	0.0
1975	0.0	0.5	0.2	0.8	1.7	7.2	11.2	11.0	1.8	0.4	0.0	0.0
1976	0.0	0.4	0.0	0.7	2.1	8.1	10.6	14.2	1.3	0.3	0.4	0.2
1977	0.1	0.1	0.0	0.0	2.0	9.4	12.3	13.5	1.5	0.5	0.1	0.1
1978	0.0	0.5	0.5	0.0	2.3	7.5	8.9	12.0	2.5	0.6	0.0	0.0
1979	0.3	0.0	0.5	0.2	2.2	6.5	7.5	13.5	2.1	0.1	0.0	0.0
1980	0.0	0.0	0.3	0.3	0.9	5.5	8.8	11.0	2.6	0.6	0.8	0.3
1981	0.0	0.0	0.1	1.0	0.8	5.0	7.9	10.1	2.0	0.2	0.3	0.3
1982	0.0	0.0	0.4	1.2	0.4	4.0	8.8	11.0	2.9	0.5	1.0	0.1
1983	0.0	0.0	0.3	1.3	0.6	8.5	5.5	12.0	2.6	0.8	0.2	0.2
1984	0.0	0.0	0.3	1.4	0.4	9.1	6.5	9.1	2.8	0.9	0.3	0.0
1992	0.0	0.8	2.1	1.8	6.2	10.1	4.2	10.4	0.6	0.1	0.0	0.0
1993	0.1	0.1	1.4	2.3	2.0	5.4	6.4	5.7	4.3	1.0	0.0	0.0
1994	0.0	0.2	0.0	0.6	1.4	4.1	6.5	10.5	4.4	0.0	0.6	0.0
1995	0.0	0.0	1.0	1.1	2.6	3.3	6.9	6.9	5.8	0.3	0.0	0.4

1996	0.4	0.0	3.5	2.1	3.1	5.1	5.9	7.8	4.3	0.1	1.5	0.1
1997	0.0	0.0	0.9	0.0	2.6	2.9	6.0	4.9	5.0	4.8	1.0	0.0
1998	0.0	0.0	0.4	0.1	1.5	3.5	12.5	11.6	4.1	0.6	0.0	0.0
1999	1.4	0.0	0.4	0.3	0.8	2.0	8.9	10.7	4.1	1.3	0.0	0.8
2000	0.0	0.0	0.1	3.1	1.0	3.1	5.9	7.0	3.8	2.8	0.7	0.3

7.5. Mean monthly T_max Adwa station for SDSM calibration and validation periods

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1973	29	28.4	30.5	24.8	28.6	28.6	28.6	26.1	21.2	23.7	22.6	27.1
1974	26.1	23.4	24	24.3	28.4	26.8	23.6	21.7	24.2	22.8	21.6	28.2
1975	25	22.9	23.6	23.8	26.7	24.3	24.6	22.7	24.8	22.1	23.4	25.9
1976	26.5	25.1	26.1	26.5	28	30.8	29.7	25.7	27.6	21.9	26.6	26.4
1977	28.2	27.7	28.3	28.4	33.5	27.3	29.4	26.5	24.8	21.1	26.4	26.8
1978	28	27.8	28.5	26.3	29.4	26.3	27.4	22.3	27.1	23.8	22	25
1979	24.8	23.8	28.4	31.1	30.6	30.1	32.8	30.9	28.6	26.7	33.5	30.8
1980	30.3	28.1	31.6	28.5	31.6	24.3	27.3	28.4	28.6	24.8	29.9	28.3
1981	26.1	26.5	26.8	23.4	28.4	24.3	28.2	24	23.4	25.1	27.7	22.9
1982	26.7	23.8	27.9	23.6	24	26.1	26.7	25.1	28	26.5	30	26.1
1983	24.3	26.5	22.4	27.7	33.5	28.4	30	28.3	28.4	28	24.7	25.8
1984	29.4	26.3	29.7	27.9	26.8	30.8	28.8	27.7	22.4	26.7	28.2	26.7
1992	31.7	30.6	30.1	29.8	24.1	22.2	24.7	26.2	25.5	26.6	29.0	26.8
1993	26.3	26.9	29.6	28.2	29.2	29.0	26.1	25.0	26.5	28.2	28.0	27.9
1994	28.4	29.4	30.3	31.1	30.8	28.4	23.4	22.9	25.1	27.7	27.8	27.7
1995	28.1	29.1	29.6	30.5	30.6	30.5	24.0	23.6	26.1	28.3	28.5	27.7
1996	27.5	30.2	29.5	30.1	28.1	24.8	24.3	23.8	26.5	28.4	26.3	26.7
1997	27.8	29.2	30.1	30.6	30.3	28.6	28.4	26.7	28.0	33.5	29.4	22.4
1998	30.2	27.0	31.7	31.6	31.6	31.6	26.8	24.3	30.8	27.3	26.3	24.7
1999	27.3	26.6	26.3	30.0	30.9	30.6	23.6	24.6	29.7	29.4	27.4	28.8
2000	27.9	29.1	31.0	28.7	30.8	30.0	24.7	23.1	25.6	26.7	26.6	25.7

7.6. Mean monthly T_min Adwa station for SDSM calibration and validation periods

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1973	8.1	8.6	8.1	9.4	7.3	11	9.2	8.7	11.2	10.1	11	9.2
1974	10.4	10.2	10	10	10.2	8.8	8.8	10	9.8	8.2	9.2	14.4
1975	13.3	13.8	10.7	11.2	14.4	10.7	11.2	10.5	10.6	10.7	10.5	11.2
1976	8.8	10.4	11.1	11.3	8.9	4.1	13.7	12.2	12.5	11.3	12.2	13.7
1977	10.3	10.7	10.8	10.4	10.4	11.5	15.3	12.5	12.9	11.2	10.1	8.3
1978	10.7	10.2	9.9	9.9	9.9	12.1	13.6	12.8	12.9	11.5	7.9	13.6
1979	8.4	8.3	8.1	8.1	8.2	12.6	14.2	12.9	8.4	8.5	8.5	14.2
1980	10.2	12.2	12	10.9	11.3	8.3	10.1	15	15.2	11.2	7.3	9.9
1981	8.1	9.8	11.5	7.2	8.5	8.5	14.5	8.5	10.8	12.1	13.2	10.1
1982	10.7	7.1	12.2	19.5	19.7	20.3	17.4	15.2	15.4	15.2	15.1	14.9
1983	10.2	10.8	14.8	15.4	16.4	16.9	17.4	18.0	16.7	16.5	15.6	15.2
1984	13.3	13.6	11.8	11.1	11.9	14.4	13.3	11	17.9	15	16.9	15.6
1992	15.6	13.5	16.5	15.6	16.9	15.3	16.6	15.8	14.6	13.9	15.8	15.3
1993	9.1	10.1	13.6	15.0	15.3	15.3	14.8	14.5	13.3	13.1	10.9	8.8

1994	8.7	11.0	11.8	16.9	16.6	15.0	15.0	15.2	12.6	11.9	10.4	8.1
1995	7.4	11.3	11.1	15.6	15.8	15.9	15.0	15.8	12.8	10.5	8.3	9.5
1996	8.3	10.3	11.9	15.6	14.6	14.1	14.7	15.0	12.5	10.5	9.7	8.4
1997	7.6	10.4	14.4	13.5	13.9	14.5	15.0	14.1	15.0	14.3	12.5	9.6
1998	9.5	10.0	13.3	16.5	15.8	15.8	15.9	15.6	14.0	11.0	9.2	7.7
1999	8.5	10.6	11.0	15.6	15.3	15.1	14.5	15.0	13.5	11.9	9.6	9.0
2000	8.7	10.8	13.1	14.9	15.4	15.8	14.6	14.8	11.6	10.8	9.3	8.2

7.7. Mean monthly precipitation Hawzen station for SDSM calibration and validation periods

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1973	0.0	0.1	0.9	1.2	1.5	2.5	5.0	1.0	1.5	1.3	1.0	0.1
1974	0.0	0.0	1.2	1.0	1.2	3.0	4.5	1.5	0.5	0.8	0.4	0.2
1975	0.0	0.5	1.5	1.9	2.0	2.8	8.9	1.5	0.8	2.0	1.5	0.0
1976	0.0	0.2	0.7	0.5	1.5	3.0	7.5	0.9	0.4	1.5	1.0	0.0
1977	0.0	0.0	0.8	0.3	1.8	1.5	6.8	7.9	0.7	1.2	0.0	0.1
1978	0.0	0.0	0.6	0.0	0.7	1.2	5.2	4.1	0.9	0.5	1.4	0.0
1979	0.5	0.0	0.1	0.0	1.2	1.3	1.8	5.0	2.0	1.2	0.0	0.0
1980	0.0	0.7	0.2	2.1	0.0	1.6	6.3	5.3	0.1	0.0	0.0	0.0
1981	0.0	0.0	1.9	0.3	1.0	0.3	10.2	4.9	0.6	2.4	0.1	0.0
1982	0.0	0.1	1.0	0.3	1.9	1.8	11.5	6.0	1.3	2.1	0.4	0.5
1983	0.0	0.5	0.9	0.2	2.1	1.7	12.5	7.1	1.9	3.1	0.9	0.1
1992	0.0	0.0	0.0	0.1	1.8	0.7	1.7	4.7	0.8	1.1	2.7	0.1
1993	0.0	0.3	0.7	3.8	0.9	1.2	4.4	4.4	1.5	0.6	0.0	0.0
1994	0.0	0.0	0.0	0.6	0.9	1.8	5.2	6.6	1.7	0.1	0.0	0.0
1995	0.0	0.0	1.3	2.0	0.9	1.6	10.2	6.5	1.9	0.6	1.5	0.0
1996	0.2	0.2	1.5	3.1	1.8	1.9	9.6	8.0	0.9	1.0	0.9	0.0
1997	0.8	0.1	0.5	1.5	1.7	2.5	7.5	7.5	1.5	2.4	1.2	0.0
1998	0.0	0.3	0.0	2.5	0.9	3.5	8.9	6.5	1.2	1.5	1.3	0.0
1999	0.0	0.0	0.6	0.3	0.5	5.5	7.5	5.5	2.0	0.7	0.8	0.0
2000	0.0	0.0	0.7	0.9	0.4	4.5	12.0	7.5	2.1	0.8	0.0	0.0

7.8. Mean monthly T_max Hawzen station for SDSM calibration and validation periods

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1973	24.9	25.7	25.1	25.6	21.9	21.7	22.6	22.1	22.7	27.4	26	24
1974	24.6	25.1	26.1	26.5	21.2	21.1	22.6	22.1	22.7	28.2	27.1	25
1975	24.4	25.9	21.7	22.3	24.2	23.8	21.6	21.9	23.2	23.2	23.9	25.3
1976	26.6	23.7	22.7	24.8	24.8	23.4	23.7	26.4	28.2	25.1	24.7	23.7
1977	24.5	26.2	25.7	27.6	27.1	26.6	22.8	22.0	24.2	24.2	23.6	23.6
1978	24.3	26.1	27.5	26.9	28.1	26.6	23.7	22.7	24.8	24.8	23.4	23.7
1979	23.2	25.5	26.7	26.7	27.0	28.6	24.9	23.3	24.7	24.1	24.4	25.3
1980	26.0	26.4	27.4	26.4	28.2	27.6	23.2	22.8	25.1	24.7	24.2	25.0
1981	25.6	26.1	26.0	26.6	27.1	28.1	23.9	23.4	24.7	23.4	23.6	24.0
1982	7.4	11.3	11.1	15.6	15.8	15.9	15.0	15.8	12.8	10.5	8.3	9.5
1983	8.3	10.3	11.9	15.6	14.6	14.1	14.7	15.0	12.5	10.5	9.7	8.4
1992	25.3	25.6	26.5	27.2	27.2	27.6	23.9	21.4	23.7	24.1	22.8	23.8
1993	23.7	24.5	26.5	24.8	25.9	25.9	22.8	23.4	25.2	25.3	25.4	25.0

1994	25.9	26.5	27.5	27.8	28.0	25.9	21.5	22.9	23.5	24.8	25.1	25.2
1995	26.2	26.1	25.5	26.4	26.1	25.7	27.5	26.7	27.4	26	24	22.8
1996	27.6	26.9	26.7	26.4	26.6	27.1	28.1	27	28.2	27.1	25	23.9
1997	26.6	26.6	28.6	27.6	28.1	22.8	23.7	24.9	23.2	23.9	25.3	23.9
1998	22	22.7	23.3	22.8	23.4	24.2	24.8	24.7	25.1	24.7	23.7	21.9
1999	24.3	24.8	24.1	24.7	23.4	23.6	23.4	24.4	24.2	23.6	23.6	21.9
2000	26.4	27.4	26.4	28.2	27.6	23.2	22.8	25.1	24.7	24.2	25.0	26.0

7.9. Mean monthly T_min Hawzen station for SDSM calibration and validation periods

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1973	8.1	9.1	9.6	10.5	10.6	10.5	14.0	13.6	12.1	12.3	8.5	7.7
1974	7.5	10.2	9.5	10.1	8.1	14.8	14.3	13.8	12.5	12.4	9.3	6.7
1975	7.8	9.2	10.1	10.6	10.3	12.6	12.4	12.7	12.0	13.5	9.4	10.4
1976	10.2	7.0	11.7	11.6	11.6	11.6	11.8	14.3	10.8	12.3	8.3	10.7
1977	3.9	3.4	4.1	2.9	5.7	8.3	13.4	13.3	10.9	11.3	9.4	8.9
1978	7.8	9.8	11.5	13.1	13.7	13.6	12.7	12.2	8.8	10.0	8.4	8.4
1979	9.5	9.9	12.1	12.6	14.2	14.2	13.8	12.5	12.9	11.2	9.0	8.7
1980	8.7	11.0	12.6	13.4	14.4	13.2	12.9	12.8	12.4	12.3	11.3	11.9
1981	10.1	9.2	13.1	13.4	13.7	13.6	13.7	12.9	12.7	10.4	9.1	7.7
1982	7.6	6.9	6.7	12.4	12.6	12.1	12.1	12.0	8.2	7.1	11.0	9.0
1983	6.6	12.6	8.6	12.6	12.1	12.8	13.7	14.9	9.2	9.9	10.3	9.0
1992	9.3	9.7	10.5	12.5	13.0	12.6	12.2	13.1	10.0	9.6	9.8	8.8
1993	8.0	8.6	10.5	12.4	12.1	12.0	12.6	12.1	10.4	8.6	6.9	6.7
1994	7.2	9.3	10.6	12.5	13.3	12.2	12.8	13.0	9.9	8.3	7.9	6.0
1995	6.2	6.1	9.5	11.4	12.1	12.7	13.5	12.7	12.4	6.0	14.0	8.0
1996	7.6	6.9	8.7	11.4	12.6	12.1	13.1	12	12.2	7.1	10.0	9.0
1997	6.6	6.6	8.6	12.6	12.1	13.8	13.7	12.9	13.2	9.9	12.3	9.0
1998	5	8.7	9.3	10.8	13.4	14.2	14.8	12.7	12.1	8.7	13.7	9.0
1999	4.3	7.8	10.1	12.7	13.4	13.6	13.4	12.4	12.2	11.6	13.6	9.0
2000	6.4	7.4	9.4	12.2	11.6	13.2	12.8	12.1	20.7	10.2	12.0	9.0

7.10. Mean monthly precipitation Adigrat station for SDSM calibration and validation periods

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1973	0.0	0.0	0.1	2.5	0.8	0.9	5.6	4.2	0.5	0.4	0.0	0.0
1974	0.5	0.0	2.8	1.5	0.9	0.3	9.1	9.1	0.0	0.0	0.0	0.0
1975	0.1	0.0	0.8	2.2	1.6	2.7	8.3	9.1	3.3	0.0	0.0	0.0
1976	0.0	1.7	2.9	2.9	2.7	1.1	5.3	3.4	0.4	0.1	4.9	0.1
1977	0.0	0.0	1.4	0.7	1.2	1.4	5.0	5.8	0.3	1.6	0.0	1.8
1978	0.1	0.0	2.0	2.9	0.2	1.5	3.6	5.8	0.3	0.4	0.4	0.0
1979	2.1	0.0	0.0	0.9	2.6	3.2	3.6	5.8	0.7	2.8	0.0	0.0
1980	0.0	0.5	0.5	2.5	1.5	4.2	10.0	5.5	0.7	1.9	1.1	0.0
1981	0.2	0.2	0.7	1.5	1.6	1.6	5.6	3.6	0.0	1.5	2.1	0.0
1982	0.3	0.1	0.8	0.9	1.9	0.3	6.5	7.1	0.3	1.8	0.7	0.2
1992	0.0	0.2	1.5	2.1	2.3	1.2	2.0	3.0	2.5	0.4	3.6	0.3
1993	0.0	0.0	1.3	2.3	3.3	2.2	1.1	1.2	2.3	0.5	2.6	0.1
1994	0.0	0.0	1.9	2.5	3.2	4.5	12.0	7.8	0.5	3.5	3.5	0.5

1995	0.2	0.1	1.5	2.1	3.1	5.5	11.0	7.1	0.9	5.4	2.7	0.0
1996	0.5	0.0	1.8	2.0	2.5	4.2	10.0	5.5	0.7	5.5	2.3	0.1
1997	0.5	0.0	2.8	1.5	1.9	1.6	5.6	3.6	0.0	6.8	2.7	0.0
1998	0.1	0.0	2.4	1.7	2.8	0.3	6.5	7.1	0.3	0.1	0.0	1.8
1999	1.1	0.1	0.4	0.8	0.0	0.3	3.1	4.0	0.3	0.1	0.0	0.0
2000	0.1	0.2	0.5	0.9	0.2	1.0	2.0	3.1	0.2	0.3	0.0	0.0

7.11. Mean monthly T_max Adigrat station for SDSM calibration and validation periods

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1973	25.2	27.0	28.0	26.6	26.0	27.1	22.4	22.1	25.4	22.9	23.7	22.8
1974	23.4	24.6	23.2	24.9	25.0	26.5	21.5	21.5	24.1	23.9	23.0	23.9
1975	23.8	25.5	26.1	25.4	25.7	24.2	22.6	21.9	22.5	23.0	23.2	23.9
1976	23.7	24.6	24.1	23.9	24.4	25.9	21.7	22.3	24.2	23.8	21.6	21.9
1977	23.2	24.6	25.3	25.4	24.4	24.7	22.2	21.5	23.2	22.4	22.3	21.9
1978	21.9	25.0	25.3	25.0	25.8	25.5	22.9	21.5	23.2	23.7	23.5	25.3
1979	25.3	24.6	24.1	25.2	24.9	25.8	22.9	21.5	24.3	24.7	23.9	25.3
1980	27.1	28.1	27	28.2	27.1	25.8	24.6	23.9	27.2	25.9	28	26.1
1981	26.6	26.6	28.6	27.6	28.1	25.9	24.1	24.5	27.6	25.9	25.9	25.7
1982	22.8	23.7	24.9	23.2	23.9	25	24.7	25	23.9	22.8	21.5	27.5
1992	24.2	24.8	24.1	24.7	23.4	20.5	20.5	24.3	24.1	25.3	24.8	26.0
1993	21.4	25.6	25.2	20.9	25.4	25.8	22.6	24.0	25.7	21.9	20.3	25.0
1994	22.0	25.1	23.9	20.7	25.1	26.6	22.9	25.7	25.6	22.1	21.7	26.9
1995	20.7	25.5	23.6	23.1	27.1	27.5	22.2	24.1	24.6	23.1	23.7	24.3
1996	24.1	23.9	25.4	24.9	25.7	25.3	25.2	24.8	21.6	24.9	24.2	25.6
1997	23.4	24.6	23.2	24.9	24.4	24.8	21.6	23.0	24.7	22.9	22.3	23.0
1998	23.0	24.1	24.9	25.7	25.1	25.6	21.9	21.7	22.6	22.1	22.7	21.9
1999	21.7	24.5	24.6	25.1	26.1	26.5	21.2	21.1	22.6	22.1	22.7	25.3
2000	24.1	23.9	24.4	25.9	21.7	22.3	24.2	23.8	21.6	21.9	23.2	24.6

7.12. Mean monthly T_min Adigrat station for SDSM calibration and validation periods

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1973	3.3	3.5	7.9	8.2	8.6	10.7	11.3	11.7	7.2	6.0	3.0	1.3
1974	3.7	4.2	6.5	7.0	10.4	9.0	9.6	9.6	4.9	5.3	1.6	1.9
1975	4.3	5.8	7.3	8.1	8.8	8.8	10.3	10.7	8.4	5.0	2.7	1.9
1976	2.2	6.6	9.2	8.6	8.8	10.4	10.7	10.2	8.3	7.3	7.2	6.0
1977	5.4	6.0	7.2	8.1	10.0	11.1	10.8	9.9	8.1	8.2	5.8	6.9
1978	4.9	6.4	7.9	9.4	9.8	11.3	10.4	9.9	8.1	11.3	11.3	10.8
1979	10.9	10.7	6.8	7.3	8.2	8.9	10.4	9.9	8.2	8.3	4.5	10.8
1980	5.4	9.8	9.9	11	9.2	4.1	11.5	12.1	12.6	13.1	2.9	5.1
1981	7.4	5.7	10.7	9.2	14.4	13.7	8.3	13.6	14.2	13.2	13.6	6.4
1982	9.7	7.8	9.9	8.7	13.3	12.2	12.5	12.8	12.9	10.9	8.8	7.9
1992	6.5	7.3	14.4	11.0	11.2	12.2	10.1	7.9	8.5	8.3	8.5	10.8
1993	7.1	9.2	13.3	9.2	14.4	13.7	8.3	13.6	14.2	13.2	13.6	6.4
1994	4.5	7.2	13.8	10.4	10.7	10.2	8.3	7.3	7.2	11.0	9.5	11.2
1995	8.1	7.9	8.6	10.2	11.2	12.2	10.1	7.9	8.5	8.3	8.5	10.8

1996	6.0	8.0	9.1	10.0	10.5	12.0	9.0	8.1	8.5	8.3	8.5	6.9
1997	3.7	4.2	6.5	7.0	10.6	10.9	11.2	9.8	9.5	9.8	9.2	7.8
1998	7.4	6.6	8.5	10.2	10.7	11.3	11.2	11.5	8.5	8.3	8.5	6.9
1999	4.9	6.3	8.6	10.2	11.2	12.2	10.1	7.9	8.5	8.3	8.5	10.8
2000	5.7	6.8	7.3	8.2	8.9	10.4	9.9	8.2	8.3	4.5	10.8	11.0

7.13. Mean monthly PET (mm) for calibration and validation periods for WetSpa model

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1974	4.1	4.6	5.4	6.2	6.0	5.5	5.2	5.0	5.2	5.0	4.3	3.8
1975	4.0	4.8	4.9	5.6	5.1	5.1	4.0	3.7	4.7	5.0	4.5	3.8
1976	4.1	4.9	5.4	5.2	5.6	6.0	5.9	5.7	5.8	5.4	4.5	4.0
1977	4.6	5.2	5.9	6.5	6.1	5.8	3.3	5.4	5.6	5.1	4.1	3.9
1998	4.3	5.1	5.4	5.2	5.6	5.4	5.7	5.6	5.5	5.2	4.5	3.8
1999	4.1	4.9	5.4	5.2	5.6	5.4	4.6	4.2	4.6	4.4	4.1	4.0

7.14. Mean monthly discharge (m^3/s) for calibration and validation periods for WetSpa model

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1974	0.0	0.0	0.0	0.1	0.4	0.2	29.4	69.6	6.3	1.5	0.7	0.5
1975	0.4	0.3	0.5	0.3	1.5	6.0	34.3	65.0	30.7	4.0	2.7	0.7
1976	0.7	1.1	1.3	3.1	1.8	8.8	24.7	109.6	44.3	2.5	2.2	0.1
1977	1.6	2.5	5.5	2.6	5.5	9.1	42.8	135.3	17.9	3.4	0.3	0.5
1998	0.8	0.7	0.7	1.6	2.3	1.9	71.1	111.6	21.6	2.9	1.4	0.9
1999	0.6	0.2	0.2	0.1	0.0	3.2	74.2	110.4	14.9	1.0	0.5	0.1