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ADDIS ABABA UNIVERSITY

COLLEGE OF NATURAL AND COMPUTIONAL SCIENCE

SCHOOL OF EARTH SCIENCE

THE IMPACT OF LAND USE/COVER CHANGE AND CLIMATE VARIABILILTY ON GROUND WATER RECHARGE, A CASE STUDY OF UPPER GIBE WATERSHED, ETHIOPIA

BY:

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GSR/9148/10

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A THESIS SUBMITTED TO

SCHOOL OF GRADUATE STUDIES OF ADDIS ABABA UNIVERSITY IN PARTIAL FULLFILMENT OF THE REQUIREMENT FOR THE DEGREE OF MASTERS OF SCIENCE IN REMOTE SENSING AND GEO-INFORMATICS.

ADDIS ABABA, ETHIOPIA

MAY, 2019

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ACRONYMS

AET	Actual evapotranspiration
AR5	Fifth Assessment Report
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
DEM	Digital Elevation Model
DFID	Department for International Development
ET	Evapotranspiration
EMA	Ethiopian Mapping Authority
NMA	National Meteorological Agency
FAO	Food and Agricultural Organization
GCM	General Circulation Model
GHG	Green House Gases
GIS	Geographic Information System
GPS	Global Positioning System
HELP	Hydrologic Evaluation of Landfill Performance
HYSEP	Hydrograph separation program
IPCC	Inter-Governmental Panel for Climate Change
IPCC-WGII	Inter-Governmental Panel for Climate Change -Working Group II
IWMI	International Water Management Institute
NGO	Non-Governmental Organizations
NMA	Ethiopian National Meteorological Agency
PET	Potential Evapotranspiration
SRES	Special Report for Emission Scenario
UNFCCC	United Nations Framework Convention on Climate Change
UNDP	United Nations Development Programme
USGS	United State Geological Survey
UNFCCC	United Nations Framework Convention on Climate Change
WEAP	Water Evaluation And planning System
WTF	Water Table Fluctuation
WetSpass	Water and Energy Transfer between Soil, Plants and Atmosphere under Quasi-Steady State

Abstract

The Impact of Land use/cover Change and Climate Variability on Groundwater Recharge: A Case Study of Upper Gibe Watershed, Ethiopia.

Fikadu Warku, Msc. Thesis

Addis Ababa University, May, 2019

This study aimed to quantify the impact of land use/cover change and long-term climate variability on annual groundwater recharge of Upper Gibe watershed using Wetspass model. Understanding the spatial distribution of groundwater recharge with the response to Land use/cover change, hydro meteorological variability, soil texture, topography, and groundwater elevation parameters is important for management, proper utilization and future planning of water resources. Input data for the model were prepared in the form of grid maps using 30 m grid size and the parameter attribute tables were adjusted to represent the upper Gibe watershed condition using expert knowledge and scientific literature. The results of the model showed that the long-term temporal and spatial average annual rainfall of 1461 mm was partitioned to 292 mm (20%) of surface runoff, 818 mm (56%) of evapotranspiration, and 350 mm (24%) of recharge at first phase while annual rainfall of 1360mm was partitioned to 290 mm (21.32%) of surface runoff, 783 mm (57.57%) of evapotranspiration, and 287 mm (21.11%) of recharge at second. For the third phase, an annual rainfall of 1303 mm was partitioned to 292 mm (22.4%) of surface runoff, 790 mm (60.6%) of evapotranspiration, and 221 mm (17%) of recharge for the upper Gibe watershed. The analysis of the simulated result showed that WetSpass works well to simulate water balance components of upper Gibe watershed and is especially suitable for characterization the effects of land use/cover changes and hydro meteorological variability on the water resource in the watershed. The study result provide baseline information for water resource experts and policymakers of the region for further investigation of water resources, design, sustainable developmental activities and for land use managing and planning purpose.

Keywords: - WetSpass model. Groundwater recharge. Upper Gibe watershed. Annual basis.

CHAPTER ONE

1. Introduction

1.1. Background of the study

Groundwater availability directly dependents on the amount of precipitation recharge to the ground. Groundwater recharge can be defined as the entry water into the saturated that is available at the water-table surface (Freeze and Cherry, 1979). Groundwater recharge is a hydrologic process where water moves downward from surface water to groundwater. The recharge is an important factor in evaluating groundwater resources, but it is often difficult to quantify (Batelaan and De Smedt, 2007). Groundwater recharge is one of the most important limiting factors for groundwater withdrawal and determines the groundwater development potential of an area (Döll and Flörke, 2005). Groundwater recharge connects atmospheric, surface and subsurface components of the water balance and is sensitive to both climatic and anthropogenic factors (Jyrkama and Sykes, 2007; Herrera-Pantoja and Hiscock, 2008; and Holman et al., 2009).

It is widely understood that climate, land use land cover changes, and human activities have profound impacts on hydrological cycles (Zhang et al., 2012). Climate variations can alter evapotranspiration, soil moisture, water temperature, precipitation patterns, humidity, flow routing times, peak flows, and flow volumes (Zheng et al., 2016). Land use/cover changes, which are mostly induced by human activities, affect hydrological processes such as evapotranspiration (ET), interception and infiltration, resulting in alterations of surface and subsurface flows (Chen, 2012; Niraula, 2015).

Climate variability also brings distinct changes to hydrological regimes and influences the spatial and temporal patterns of water resources in a region (Khoi and, Suetsugi, 2014). Climate change is one of the biggest challenges of human being and the ecosystem. Scientific organizations have been defining climate change in various ways. The United Nationals Framework Convention on climate change (UNFC, 1992) defines climate change as “a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods”. Hydrological processes occurring within the watershed are highly dynamic and their continuity or discontinuity presents a significant problem in describing and visualizing the spatial and temporal relations occurring between them. Land use/cover change is a primary anthropogenic disturbance, and greater scientific effort is needed to comprehensively explain how it will affect hydrological processes (León-Muñoz et al., 2013). Land use/cover changes alter surface runoff generation, result in changes in water demand and supply, and affect basin hydrological process, including soil infiltration capacity and groundwater recharge and discharge (Ghaffari et al., 2010; Wijesekara et al., 2012). Changes in catchments, including the expansion of urban areas, typically decrease base flow by changing groundwater flow pathways to surface water bodies (Lin et al., 2007). The hydrology of a watershed is affected by climate and land use land cover among other factors and there is now essential consensus that all of these factors and interactions are influenced by human activities (Tomer and, Schilling, 2009).

Land use/cover conversions may affect the atmosphere-vegetation-soil, water balance in the vicinity of the site, thus changing the amount of groundwater recharge and possibly the magnitude of the discharge. Land use/cover plays a key role in controlling the hydrologic response of watersheds in a number of important ways (Ghaffari et al., 2010). Changes in land use/cover can lead to significant changes in the Leaf Area Index (LAI), Evapotranspiration soil moisture content and infiltration capacity (Costa et al., 2003), surface and subsurface flow regimes including base flow contributions to streams (Tu, 2009) and recharge, surface roughness (Feddema et al., 2005), runoff (Burch et al., 1987), as well as soil erosion through complex interactions among vegetation, soils, geology, terrain and climate processes.

The impact of land use/cover changes in the regional water balance is the most vigorous research in the international hydrological fields, and lots of research indicates that large-scale land use/cover changes are the important factors resulting in the regional climate and hydrological cycle changes (Zhang, 2001). Recharges were estimated using Wetspass model. WetSpass model estimates long term annual/ seasonal average recharge as a function of land use/cover, soil type, topography, and hydro meteorological factors (Batelaan and De Smedt, 2007). It is a physically based model used for quantifying the long-term average, spatially varying, water-balance components such as: - surface runoff, actual evapotranspiration, and groundwater recharge.

Groundwater resource is sensitive to climatic factors, topography, soil properties, and land-use/cover types (Dragoni and Sukhija, 2013). Thus, a thorough understanding of watershed physical and biological characteristics is important. Accurate quantification of groundwater resources involves identification of hydrological and biophysical characteristics of the watershed. The modification of land use/cover in the upper Gibe watershed is increasing from time to time as result of human induced impact. Unsustainable use of the natural resource is becoming increasingly apparent and the key concern, particularly in developing countries (Todd and Mays, 2005) like in Ethiopia. Understanding time series variation of the water resources, especially runoff, evapotranspiration, and recharge, is important in Upper Gibe watershed. Such time series information will be great importance for the researchers: - hydrologist and policy makers plan and pass the right decisions timely.

1.2. Statement of the Problem

Land Use/cover and climate Changes remain critical environmental challenges that society must address (Mustard et al., 2004). According to the Intergovernmental Panel on Climate Change (IPCC, 2001), African countries are more vulnerable to climate changes due to lack of institutional capacity and economic development. Climate change alters the hydrological cycle, which influences the quantity and quality of water resources (Gleick and Adams, 2000; Xu, 2000). Therefore, land use/cover and climate changes have a direct influence on the water resource in complex ways that include recharge, evaporation and evapotranspiration, interception, runoff, precipitation, and transpiration. Besides ecosystem vulnerability, land use/cover changes are major determinants of global environmental change with potentially severe impacts on human livelihoods (Olson et al., 2008). Such changes manifest in climatological, hydrological and biodiversity responses. Vitousek et al., (1997) estimated that between 39 and 50% of terrestrial ecosystems have undergone modification due to anthropogenic influence. The main drivers of land use/cover change are socioeconomic development, population expansion, and pressures for land for agriculture (Lambin et al., 2003).

Like the rest of the world, Ethiopia is not an exception to these dynamics. For an effective and sustainable management of groundwater resources, an understanding of the role and impact of land use/cover and climate change on groundwater recharge is required. Land use/cover change and climate variability are observed in the Upper Gibe watershed due to deforestation, expansion of agricultural activity, rural and urban settlement expansion, and other socio-economic activities. However, the impacts of LULC and climate changes on groundwater recharge have not been quantified for the watershed. Therefore, this study was intended to quantify the impacts of land use land cover and climate changes on groundwater recharge using Wetspass model.

1.3. Research Questions That This Work Will Be Responding

- What is the rate and amount of land cover change in the area for the last -34 years?
- What is the impact of land use land cover change on groundwater recharge?
- Has there been a significant indication in climate change indicators such as precipitation, temperature, humidity, etc..,?
- If there is climate change in the study area, what is its impact on groundwater recharge and groundwater resource?
- The aggregated impacts of changes in the groundwater condition in the watershed.
- How groundwater recharge is affected by land use land cover change and climate variability?
- Has there been the impact of land use land cover change on groundwater recharge?

1.4. Objectives:

1.4.1. General Objective

The main object is to assess land use land cover and climate changes in the upper Gibe watershed, and quantify their impacts on groundwater recharge by using the WETSPASS hydrologic modeling technique.

1.4.2. Specific objectives:

- To analyze and drive the land use land cover dynamics (change) of the upper Gibe watershed from 1985 to 2019 quantitatively from multi-temporal satellite images.
- To compute the trend of climate change in the upper Gibe watershed from 1985 to 2018 using indicators.
- Quantify the impacts of land use land cover and climate changes on groundwater recharge in the upper Gibe watershed using a hydrologic model.

1.5. Significance of the study

This study is expected to build an understanding on the impact of land use/cover changes and climate variability on groundwater recharge. To increase awareness, capacity about land use/cover change and climate variability impact on ground-water recharge and their interdependence with each other in the upper Gibe watershed. Increase land use planning effectively in the upper Gibe watershed and characterize how one resource depends on the other resources. It's also for quantification of the average spatial variability, water-balance components: surface runoff, evapotranspiration, interception, and groundwater recharge. Land use/cover change and Climate variability trends in the study may be used as inputs for climate modeling, climate prediction, and climate-related disaster management activities should give much emphasis to enhance climate information for policy makers and development planners in the watershed.

1.6. Expected Result

- Understanding of LULC change and climate variability impact on ground water recharge
- Simulate hydrological response of under different climatic condition and LULC change
- LULC and climate change time series maps for the study area
- Groundwater recharge modeling maps of Upper Gibe watershed

CHAPTER TWO

2. LITERATURE REVIEW

2.1. Water Resources and Hydrologic Cycle

Water is transported from the atmosphere back to the Earth's surface as precipitation, falling as either rain or snow. Nowadays, the global hydrological cycle has been responding to the observed effects of global warming, which include increasing atmospheric water vapor content and changing precipitation patterns (Chemeda, 2010 and Chen, Z. 2014). The change in precipitation alters the hydrological systems, affecting water resources in both quantity and quality (Seleshi, 2004).Water link among the most dynamic process on the land surface. The global water cycle describes the circulation of water a vital and dynamic substance in liquid, solid and vapor phases as it moves through the atmosphere, the land, and the rivers, lakes, and oceans.

Water is the most powerful substance for living things and globally about, 1.36 Billion Km3 of water resources is available, from which 97.2% is salt water mainly found in oceans and 2.8% is available as freshwater (Raghunath, 2006). Water is constantly moving within and above the earth in a cycle called the hydrologic cycle. The circulation of water on earth, called the hydrologic cycle, involves the processes and pathways by which water evaporates from the earth's surface to the atmosphere and returns to the surface as precipitation or condensation. Not only is the hydrologic cycle a cycle of water, it is also a cycle of energy as well. The major components of the hydrological cycle include precipitation, evapotranspiration, infiltration, runoff, and condensation (Reddy, 2008).

The water sector in Africa includes the limited access to water due to insufficient infrastructure to provide a reliable supply of water for drinking, agriculture and other uses combined with limited governance capacity climate change and variability have the potential to impose additional pressures on water availability, accessibility, and demand in Africa. According to some assessments reported in IPCC-WGII (2007), the total populations at risk of increased water stresses across Africa for the full range of Special Report for Emission Scenarios (SRES) are projected to be 75-250 million and 350-600 million people by the 2020s and 2050s, respectively.

Based on various reports and six climate models and SRES scenarios, IPCCWGII (2007) indicates that there is likely to be an increase in the number of people who could experience water stress by 2055 in Northern and Southern Africa and a reduction of available water in Eastern and Western Africa. 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 total annual water resources estimated at 111 Billion m3 of which 75.5 Billion m3 is in the Nile basin (Yazew, 2005). In addition, the country releases an annual runoff volume of 122 Billion m3 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, 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 the earth. The hydrologic cycle represents the continuous movement of water between the atmosphere, the Earth's surface (glaciers, snowpack, streams, wetlands, and oceans) and soils and rock.

2.1.1. Groundwater resources

The term groundwater refers to water in soils and geologic formations that are fully saturated.
It can also be defined as 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 km3;- and the groundwater comprises 99% of the earth's available freshwater resources (Delleur, 1998).

The groundwater is therefore essential for storing the fresh water required by a human. Groundwater can also be stored in the saturated zone of the soil which serves as the largest reserve of drinkable water. This water can be accessed for human by different mechanisms as a 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 Democratic Republic of Congo (DRC), due to its plenty of water resources available on the surface and groundwater despite its erratic rainfall. The total groundwater storage potential in Ethiopia is estimated to be 1 trillion m3 (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. It needs to have a very detailed study on this issue so that enough information is available.

2.1.2. Groundwater recharge

Groundwater recharge is the process by which external water is added to the zone of saturation of an aquifer either directly into the formation or indirectly by way of another formation. Recharge can be broadly defined as water that reaches an aquifer crossing the water table from any direction, which contributes in addition to the groundwater reservoir (Lerner, 1997).

Groundwater is a critical source of fresh water throughout the world. Comprehensive statistics on groundwater abstraction and use are not available, but it is estimated that more than 1.5 billion people worldwide rely on groundwater for potable water (Clarke et al., 1996). Other than water stored in ice caps and glaciers, groundwater accounts for approximately 97% of fresh water on Earth (Shiklomanov and Rodda, 2003). As the world population continues to grow, more people will come to rely on groundwater sources, particularly in arid and semiarid areas (Simmers, 1990).

Long-term availability of groundwater supplies for burgeoning populations can be ensured only if effective management schemes are developed and put into practice. Quantification of natural rates of groundwater recharge (i.e. the rates at which aquifer waters are replenished) is imperative for efficient groundwater management (Simmers, 1990). Although it is one of the most important components in groundwater studies, the recharge is also one of the least understood, largely because recharge rates vary widely in space and time, and rates are difficult to directly measure. Groundwater is the largest reservoir of liquid freshwater on the planet and is critical for sustaining life on earth, as it is used to satisfy domestic, agricultural, industrial, and environmental water needs (Shiklomanov, 2000; Sophocleous, 2004).

Groundwater recharge has a fundamental role in sustainable groundwater resources development and management albeit other hydrologic, social, and economic factors have to be considered (Seiler and Gat, 2007). However, recharge rates are one of the most poorly constrained hydrological parameters in almost all groundwater flow and transport models (Anderson and Woessner, 1992), and the least understood, largely because recharge rates vary widely in space and time, and rates are difficult to measure directly (Healy, 2010). Groundwater recharge is the quantity which, in the long term, is available for both abstraction and supporting the base flow component of rivers (Rushton&Ward,1979). 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 into aquifers, saturated soil, and unsaturated soil zones. 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.

2.1.3. Quantification of Groundwater Recharge

Groundwater, as a dynamic system, is located beneath the Earth surface. Groundwater recharge estimation is extremely important for the efficient and sustainable management of groundwater systems. The rate, timing, and location of recharge are important issues in areas of groundwater contamination as well as groundwater supply. For estimating groundwater recharge a variety of methods exist. Different studies (Christoph *et al*., 2011 and Ahmadi *et al*., 2013) have used different methods to estimate groundwater recharge. Recharge is an important factor in evaluating groundwater resources but it is often difficult to quantify (Batelaan and De Smedt, 2007).

It moves under the control of many factors, which are studied in various fields of sciences such as hydrogeology, hydrology, and climatology (Kumar, 1977). Among the factors controlling the situation and fluctuation of groundwater, the recharge is an important parameter that needs to be assessed more fully. Recharge occurring in small and large scales, spatially and temporally, is influenced by several factors, such as meteorology, soil characteristics, geology, surface cover, slope, and depth of the groundwater level (Shukla, and Jaber, 2015).

Groundwater recharge estimation from precipitation is an integral part of hydrology and hydrogeology (Xi, et al., 2008). Although, precipitation is the most important source of groundwater recharge (Kumar and Seethapathi, 2002) the accuracy of currently attainable techniques for measuring recharge are not completely acceptable. Furthermore, there are indirect measurements of recharge due to the lack of universal standard methods. Nevertheless, a number of methods were the models and equations for determining the groundwater recharges can be classified into three groups: physical models, calculated from base flow; chemical models, measurements of water-soluble substances; and numerical models, using numeric methods, such as HELP, RORA, PULSE, PART, HYSEP, WEAP and WTF.

Estimating the groundwater for various climates such as arid, semiarid, and tropical has its own advantages and disadvantages (Risser, et al., 2008). 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 the saturated zone.

The groundwater recharge estimation methods are further classified into physical techniques, tracers, and numerical modeling within each of the hydrologic zones. 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 (Scanlon et al., 2002). Groundwater recharge modeling techniques can be used to estimate recharge based on time series data from hours to years.

The applications 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. The WetSpass model determines the long-term average spatially distributed recharge as a spatial variable dependent on the soil texture, land-use, slope, and meteorological conditions, taking into account the influence of the spatial variability of the land surface on the groundwater system (Batelaan and De Smedt, 2004).

2.2. Groundwater Recharge Models

2.2.1. WetSpass model

WetSpass modeling method is used to estimate groundwater recharge of the study area. As WetSpass modeling was developed for temperate regions by Batelaan and DeSmedt (2001, 2007), which has different climatic and land conditions compared to the tropics;- some input parameters modification is used to apply it in the tropical region. The available groundwater models are used for analyzing groundwater systems in both steady state flow and transient flow, so they need average recharge values as input. The WetSpass model can be used to estimate the groundwater recharge from precipitation.

The WetSpass model is a physically based model was used to estimate the groundwater recharge, surface runoff and actual evapotranspiration (Batelaan; De Smedt, 2001). A good understanding of groundwater simulation processes with coupling the WetSpass model with the groundwater flow simulation model-MODFLOW to understand the groundwater flow characteristics, groundwater level variations and the aquifer storage (Rwanga, 2013).

The estimated output groundwater recharge from WetSpass model can be coupled with steady-state groundwater models. The WetSpass model on its calculation depending on the water balance equations of vegetation surfaces, bare area, open water area, and an impervious surface; it was used to estimate the groundwater recharge in the watershed (Aish et al., 2009). The WetSpass hydrological model was coupled with (MODFLOW) groundwater model to determine the effect of groundwater recharge variation on the groundwater level.

The water table level was predicted with different climate change scenarios which include a variety of recharge and precipitation (Mogheir and Ajjur, 2013). 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.
In recent years, how land-use change and climate variability has affected the hydrological cycle and hydrological components has been studied based on the WetSpass model worldwide. For example, Wang et al., (2012); Gebreyohannes et al., (2013) and Zomlot et al., (2015) evaluated the spatial distribution of water resources, including groundwater recharge, evapotranspiration, and surface runoff, based on WetSpass model. In addition, Zomlot et al., (2017) assessed the importance of different controlling factors in groundwater recharge. Dams et al., (2013) evaluated the hydrological dynamics using WetSpass and remote sensing techniques to interpret the impervious surface changes. 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 (Gebreyohannes et al., 2010). Based on those authors groundwater recharge was successfully estimated which is the main interest of this research.

2.2.2. Application of WetSpass model

WetSpass uses long-term average climatic data together with topographic elevation, LULC, soil textures, and vegetation to simulate average spatial patterns of surface runoff, soil evaporation, transpiration, interception and groundwater recharge in the area. It is a physically based model for estimation of the long term average spatial patterns of the groundwater recharge, surface runoff and evapotranspiration from long term average meteorological data together with land use, soil and groundwater depth maps by employing physical and empirical relationships (Batelaan and Woldeamlak, 2004; De Smedt et al., 2001).

A physically based quasi-steady state time-independent model, WetSpass, has been used to estimate the long-term average spatially varying water balance components. Parameters such as LULC and soil types are connected to the model as attribute tables of the land-use and soil raster maps. Now a day, energy and water transfer among plants, soil, and the atmosphere under a quasi-steady state (WetSpass) model, has been used widely for groundwater recharge assessment and other water balance components. The model is especially suitable for studying the long-term effects of land use changes and climate variability on the water balance in a watershed, hence, it is able to support water management decision making. WetSpass can be performed in a sequential manner by exchanging recharge and groundwater depth. The WetSpass model determines the long-term average spatially distributed recharge as a spatial variable dependent on the soil texture, landuse/cover, slope, meteorological conditions and groundwater elevation. This is primarily to take into account the influence of the spatial variability of the land surface on the groundwater system (Batelaan and Woldeamlak, 2004).

A model with spatially distributed parameters (i.e., a raster model) provides information on the diversity of effective infiltration, as well as precipitation, effective infiltration, surface runoff, and evapotranspiration, whose spatial distribution is assigned to raster cells with a homogeneous structure, which functions as balance cells. The significance of the impact of climatic and environmental factors is defined by the scale of a particular study (Graf, 2012). The WetSpass model has been shown to help better characterize evapotranspiration, runoff, and recharge, including its variety over geographical areas with the interrelation of its influencing factor in the world.

2.3. Climate variability

Climate variability refers to changes in the average state and other aspects of the climate over space and time beyond that of individual weather events. According to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5), the average temperature trends on a global scale showed a warming trend of 0.85°c (0.65 –1.06°c) over the period 1880 to 2012 (IPCC, 2013). Variability can be due to natural climate processes (internal variability), or natural or human-induced external changes (external variability).

East Africa is identified as one of the regions at greatest risk globally from the impacts of climate change (Hinkel et al., 2012). Most coastal areas are low-lying and will experience significant inundation even with modest rises in sea level. The most recent climate change projections (IPCC, 2014a; Cai et al., 2014) anticipate an accelerated rise in global mean sea level in coming decades (Watson et al., 2015) combined with an increase in higher annual temperatures. Africa, due to low adaptive capacity, policy and high sensitivity of socio-economic systems, is one of the most vulnerable regions highly affected and to be affected by the impacts of climate change (IPCC, 2014).Climate change is a change of climate which is attributed directly or indirectly to human activity. It alters the composition of the global and/or regional atmosphere and natural climate variability observed over comparable time periods. Climatic variability are the types of changes (temperature, rainfall, occurrence of extremes); magnitude and rate of the climate change that causes the impacts on the area of public health, agriculture, food security, forest hydrology and water resources, coastal area, biodiversity, human settlement, energy, industry, and financial services. Changes in the physical and socio-economic system have been identified in many regions (UNFCCC, 2007).

The Africa continent is most impacted by climate change (Niang et al., 2014) and that change could become more intense and frequent in some areas (Gizaw and Gan, 2017). Such a change appears to have occurred already in parts of eastern Africa (Funk et al., 2015; Nicholson, 2016). According to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), the global average surface temperature is likely to rise by 1.8°c to 4.0 °c by 2100. Africa and Asia are thought to be the two continents most vulnerable to climate change, with sub-Saharan Africa having the highest levels of chronic poverty in the world and South Asia containing the majority of the world's chronically poor (CPRC, 2004).

In Africa, climate change is a reality (Besada and Sewankambo, 2009). The Intergovernmental Panel on Climate Change (IPCC) has predicted that temperatures across Africa are expected to increase by 2 to 6°c within the next 100 years and rainfall variability is expected to increase, resulting in regular flooding (Hulme et al., 2001). The IPCC report on Regional Climate Projections of 2007 states that by 2050 the average temperatures in Africa continent are expected to rise by 1.5 to 3°c and, the warming of Africa is very likely to be severe than other regions (Gemeda, and Sima, 2015). The impacts of climate change in Africa are so worrisome that studies have considered the continent as the most vulnerable in the world. For instance, Africa has been classified as one of the regions of the world most vulnerable to the impacts of climate change owing to its high exposure and poor adaptive capacity (Niang et al., 2014). One continent of the world where the impact of climate change is hitting hard is Africa (Clements, 2009).

Countries in Africa are more affected by climate change due to their dependence on agriculture as well as their poor financial, technical and institutional capacity to adapt (Rose, 2015; Singh and Purohit, 2014). Most countries in Africa that mainly depend on agriculture, climate change will pose considerable risks to their livelihood (Hummel, 2015). The elongated and heightened droughts in Eastern Africa;- exceptional floods in Western Africa;- reduction of rainforests in equatorial Africa;- and a rise in ocean acidity across Africa's southern coast coupled with extremely altered weather patterns and climate extreme events threaten agricultural production, food security, healthy-water, and energy security, which as a result weaken African's capacity to grow and develop (Besada and Sewankambo, 2009).

Africa has been the lowest source of Greenhouse gas emission owing to the lack of industrial development (Gemeda and Sima, 2015). However, it is the most vulnerable to the impacts of climate change (Bewket, 2012; Clements, 2009; Hummel, 2015; Niang et al., 2014; Rose, 2015; Singh and Purohit, 2014). Countries in the Horn of Africa are often considered to be among the most vulnerable but are also considered to be the least prepared for adverse global environmental change in the word (Aklilu, and Alebachew, 2008). In the Horn region, Ethiopia has been typically considered as a home of famine, especially beginning from the last three decades of the 20th century, principally as a result of increasing vulnerability to extreme events that relate to changing climatic conditions.

Ethiopia is among the largest countries of Africa and it is characterized by a wide variety of landscapes, with marked contrasts in relief and altitudes ranging from about 155 m below sea level of Assale Lake, in the Danakil depression, to about 4,533 m a.s.l. at Ras Dejen (EMA, 1988). For these reasons and given its geographic position close to the equator and the Indian Ocean, the country is subjected to large spatial variations in temperature and precipitation. The pastoralist peoples, inhibiting the low land areas of the country, with the harsh and precarious conditions of limited livelihood choices in their settings, have particularly become increasingly vulnerable to persistent poverty in recent decades partly due to their recurrent exposure to the adverse effects of climate variability and change.

2.3.1. Impact of Climate Variability on Groundwater Recharge

The hydrologic cycle is highly sensitive to climate change because the components of the hydrologic cycle are vulnerable to changing the climate. The effect of climate change on water resources, and consequently on water availability, is one of the most challenging aspects of long-term sustainable water management. The principal focus of climate change research with regard to groundwater has been on quantifying the likely direct impacts of changing precipitation and temperature patterns (Yusoff et al., 2002). Findings of the IPCC (2013), strongly suggests that climate variability has the potential to deteriorate the groundwater availability, water quality, and water supplies. In many countries of the world, the use of groundwater resources for public water supply constitutes important potable water.

The effective water management policies and planning of sustainable water development require knowledge gained through sustained and accurate monitoring of climate conditions and water resources (Taylor et al., 2009). Groundwater and surface water resources are hydraulically connected and that groundwater is often ignored in water resources management activities, initiation or expansion of climate and water monitoring activities as well as integration of groundwater into River Basin Management plans are needed (Taylor et al., 2009).However, many factors affect 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 climate variability 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. For instance, groundwater-residence times can range from days to tens of thousands of years or more, which delays and disperses the effects of climate and challenges efforts to detect responses in the groundwater to climate variability and change. However, Renewable groundwater is directly tied to near-surface hydrologic processes; it is thus intricately tied to the overall hydrologic cycle and could be directly affected by the climatic change (Braune et al., 2009). Groundwater, of course, cannot be considered in isolation - impacts of climate change not necessarily related to groundwater, such as changing land use and population density, will have an effect on groundwater. The climate variability substantially modifies the hydrological processes and consequently, having an impact on groundwater quantity and quality. While climate change will alter hydrological conditions due to changes in the major climate variables (air temperature, precipitation, and evapotranspiration), groundwater resources were impacted by climate change not only through their interaction with surface water bodies (e.g., lakes and rivers), but also, indirectly, through the recharge process (Jyrkama and Sykes, 2007). Therefore, quantifying climate change impacts on groundwater recharge was important for the evolution of the hydrological variables that interact with the groundwater system (river stages, groundwater recharge, pumping, pollutant leaching).

2.4. Land use/cover change

Land use and land cover change (LULCC) ;- is a general term for the human modification of Earth's terrestrial surface. Land cover refers to the physical and biological cover over the surface of the land, including water, vegetation, bare soil, and/or artificial structures. Land use is a more complicated term. Natural scientists define land use in terms of syndromes of human activities such as agriculture, forestry and building construction that alter land surface processes including biogeochemistry, hydrology, and biodiversity. The growth of population and the increasing of socio-economic had created pressure on land use/land cover which lead to unplanned and uncontrolled changes in LULC (Seto, 2002).

Land use and land cover change, from here on addressed as ‘land use/cover change’, is a general term for the human modification of Earth's terrestrial surface (Ellis, 2013). LULC has two separate terminologies that are often used interchangeably (Rawat and Kumar, 2015). In developing countries like Ethiopia, due to a lack of policies, land use/cover change is a relatively uncontrolled process compared to developed countries. Land cover refers to the biophysical characteristics of the earth’s surface, including the distribution of vegetation, water, soil, and other physical features of the land. Such land cover change can affect terrestrial hydrology by changing the evaporation-to-runoff ratio.

While land use refers to the way in which land has been used by humans and their habitat, usually with an emphasis on the functional role of land for economic activities (McConnell, 2015; Arsanjani, 2011). Studies on the changes in different land uses are important for forest monitoring and in overall environmental monitoring (Lal and Anouncia, 2015). In recent years, LULC change study has emerged as an important research question as it can cause environmental alteration and modification on a greater scale. Land resources are intensively utilized by mankind and have resulted in significant changes in land use land cover (Bronstert, 2004). Information relating to LULC change can play a vital role in natural resources management (Iqbal and Khan, 2014; Kantakumar and Neelamsetti, 2015; Lin et al., 2015). In developing countries, most importantly in Ethiopia, the resource bases such as forest, lands, and water, are declining considerably and information regarding the rate of depletion is often lacking (FAO, 2009). Understanding the spatiotemporal land use/ cover status of an area is an important procedure to implement future land use planning conservation measures.

2.4.1. Impact of land use /cover change on Groundwater Recharge

In addition to climate, land use/cover change is one of the human interventions altering the quality and quantity of both surface and groundwater. The impact of land use and land cover changes on the regional water balance is the most vibrant research in the international hydrological fields. Such work indicates that the regional vegetation ecosystem changes caused by land use and land cover changes remarkably affect the regional hydrological cycle (Wang, 2005). At the one hand, LULC changes provide social and economic benefits, while generating unintended multi-directional impacts on water balance components.

Groundwater is a major source of drinking water across the world and plays a vital role in maintaining the ecological value of many areas (IPCC, 2001). However, the quantity and quality of groundwater are changing due to human activity (Gehrels et al., 2001) jeopardizing the suitability of the groundwater system as a source of drinking water and affecting natural reserves. Assessing the impact on the groundwater system and predicting the magnitude of change in the future is, therefore, a major scientific challenge (Tang, 2005). Land-use and land-cover changes are one of the main human-induced activities altering the groundwater system (Calder, 1993). Forest clearance for firewood, subsistence agriculture, commercial agricultural expansion, urbanization, and overgrazing by livestock are some of the changes that have a huge impact on water resources, the productivity of land, and damage on ecosystems (Chhabra et al. 2006).

Estimation of groundwater recharge is of great importance in water resources management, especially for areas in which groundwater is vital for the local water supply. Exact estimation of regional groundwater recharge requires a good understanding of the hydrological processes in the area, which could be greatly altered by global change and human activities (Nolan et al., 2007). The mechanism of land use and land cover changes in the catchment impacting on hydrological process become important fields in the development of hydrology (Hoff, 2002). Land use /cover change influences the runoff routing process (Costa et al, 2003). Land use/cover changes affect water resources mainly through vegetation interception, evapotranspiration, runoff, surface infiltration, soil moisture status, and so forth, thereby affecting the process of watershed hydrology and water resource cycles (Shi et al., 2014). For instance, forest removal can influence soil infiltration and further alter the runoff generation process increasing impervious surface areas due to urbanization can decrease the infiltration rate and concentration time and thus result in increased surface runoff (Jones, 2003).

Impacts of land use/cover change on African climate include a reduction in surface water transpiration and increases in surface temperature (Maynard and Royer, 2004), which have impacted hydrological systems, particularly in East Africa. Assessing the impacts of climate and LUC changes on groundwater recharge process has been important research focusing on hydrological studies (Tranga et al, 2017). Land use/cover changes are directly linked to changes in the hydrological processes, such as evapotranspiration, interception, and infiltration, etc., and then to the impact of groundwater recharge, base flow, and streamflow (Woldesenbet et al., 2017).

Land use/ cover changes in watershed systems can cause local, measurable changes in watershed systems. Different studs have indicated that the land cover/use change is also related to hydrological and climate changes at the global, regional and local scale. It is also responsible for releasing greenhouse gases to the atmosphere and increases the release of carbon dioxide to the atmosphere caused by deforestation, especially when followed by the expansion of agriculture (Nunez et al., 2008). It is, therefore, essential to detect land use/cover change accurately, at an appropriate scale, and in a timely manner in order to better understand their impacts on groundwater recharge and its systems. The effects of the land use/cover and climate change on hydrological processes are set to increase in the future due to the increased clearance of virgin forest lands for agriculture and the rise of global warming (Fischer, 2013). Most findings show that changes in land use/cover and climate variability affect hydrological processes such as evapotranspiration, interception, and infiltration, resulting in spatial and temporal alterations of surface and subsurface flow patterns (Khoi and Suetsugi 2014; Marhaento et al., 2017a). The Intergovernmental Panel on Climate Change (IPCC, 2007) reported that tropical regions, including Ethiopia, are one of the most vulnerable areas for future water stress due to extensive land-use and climate changes.

CHAPTER THREE

3. Materials and Methods

3.1. Description Of the study area

The study area is located in the Omo Gibe basins in the upper Gibe River. The watershed is part of the headstream area of the Gibe River. Geographically, it is bounded between 8° 30' 0" to 9˚30′ 0″ N Latitude and 36° 30' 0" to 37°40′ 30″ E Longitude, and it has an altitudinal range from 1531m to 3113m above mean sea level (Figure 3.1). In administrative term, the upper Gibe watershed is located in Oromia region, the major part in West Shoa Zone and a small part in East Wollega zone. It covers the total drainage area of 3566 km^2 and situated at about 250km southwest of Addis Ababa.

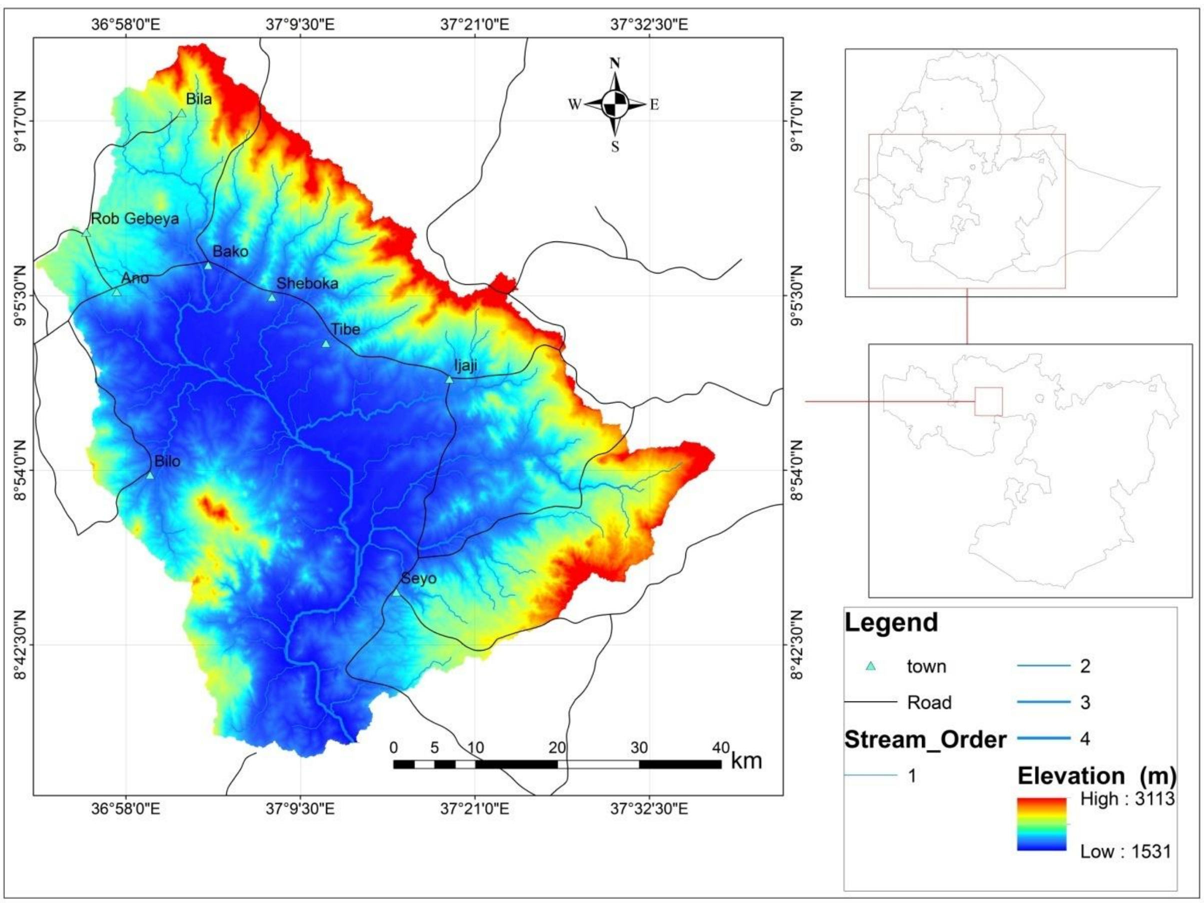


Figure 3.1: Location map of Upper gibe watershed

3.1.1. Topography

The topography of watershed is characterized by diverse topographic natures. Eastern and Western left parts of the watershed are undulating terrain mountainous, steep slopes and middle part of the watershed is characterized by gentle slopes. Topographic nature of the study area shown in (figure 3.2).

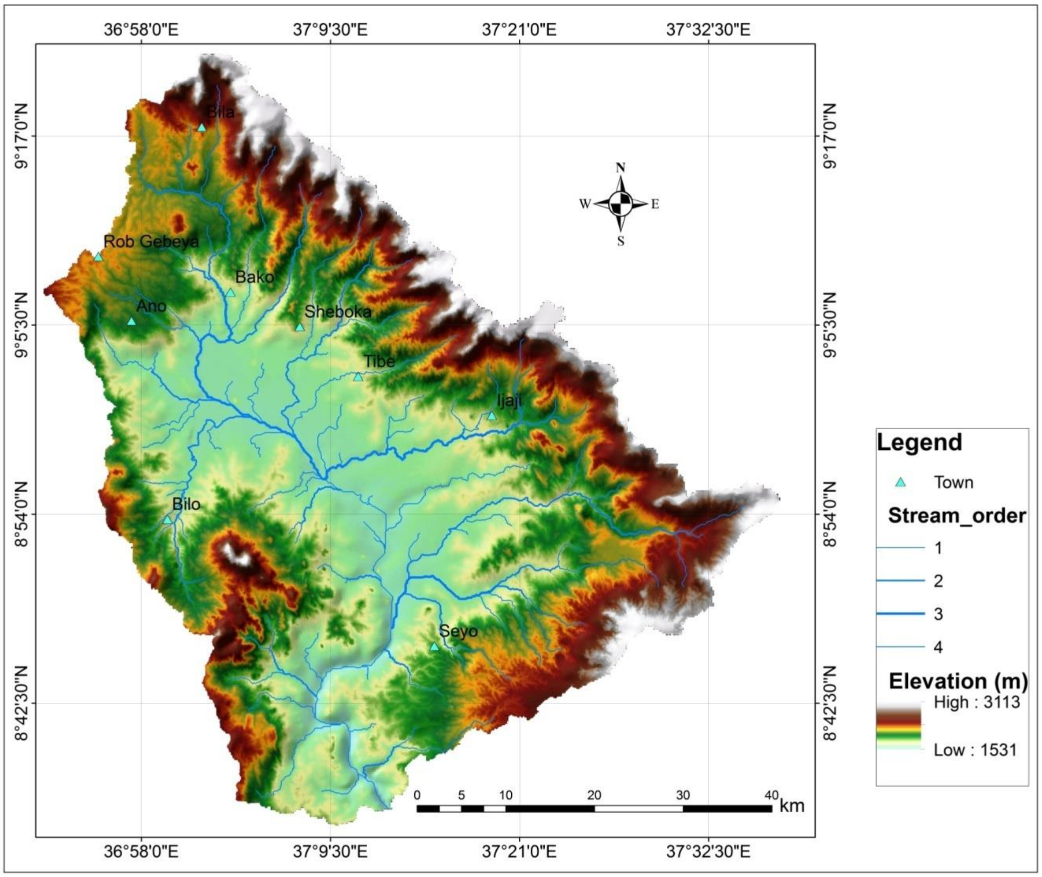


Figure 3.2: Physiography of study area watershed

3.1.2. Climate

Ethiopia is among the largest countries of Africa and it is characterized by a wide variety of landscapes, with marked contrasts in relief and altitudes ranging from about 155 m below sea level of Assale Lake, in the Danakil depression, to about 4,533 m a.s.l. at Ras Dejen (EMA, 1988). As Ethiopia is situated within the tropical belt, the major factor that influences its weather system is the Inter-Tropical Convergence Zone (ITCZ) of dry north-easterly and moist south-westerly winds. The seasonal rainfall distribution within the Gibe Basin results from the annual migration of the ITCZ. In general, rainfall levels throughout the Basin are high with a weighted average rarely lower than 1300 mm/year and frequently reaching values as high as 1800 to 2000 mm/year, particularly on the western slopes. The Upper Gibe watershed experiences high variations in daily maximum and minimum temperatures related to topographic settings where temperature decreases with increase in altitude. Based on the traditional climatic classification of Ethiopia, the climatic zones experienced in Upper Gibe watershed have three different climate zones according to elevation. Kolla (Tropical zone) - is below 1830 meters in elevation and has an average annual temperature of about 27 degree Celsius with annual rainfall about 510 millimeters. Woina Dega (Subtropical zone) - includes the highlands areas of 1830 - 2440 meters in elevation has an average annual temperature of about 22 degree Celsius with annual rainfall between 510 and 1530 millimeters. Dega (Cool zone) - is above 2440 meters in elevation with an average annual temperature of about 16 degree Celsius with annual rainfall between 1270 and 1280 millimeters (figure 3.3 to 3.5).(http://www.ethiopiantreasures.co.uk/pages/climate.htm).

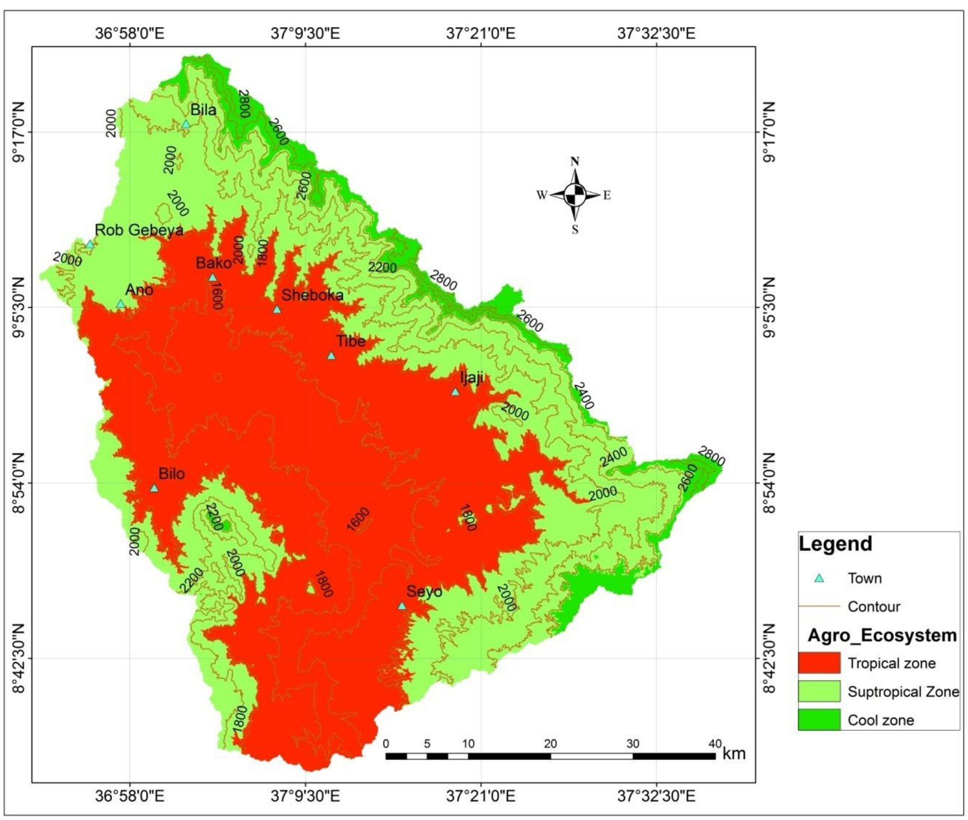


Figure 3.3: Agro_ecosystem of the study area watershed

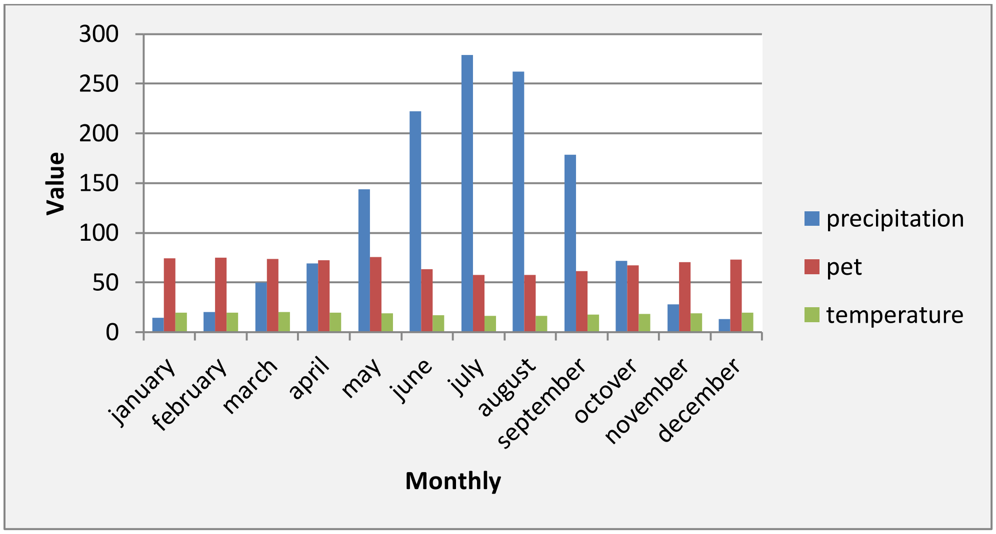


Figure 3.4: Monthly climate distribution of watershed

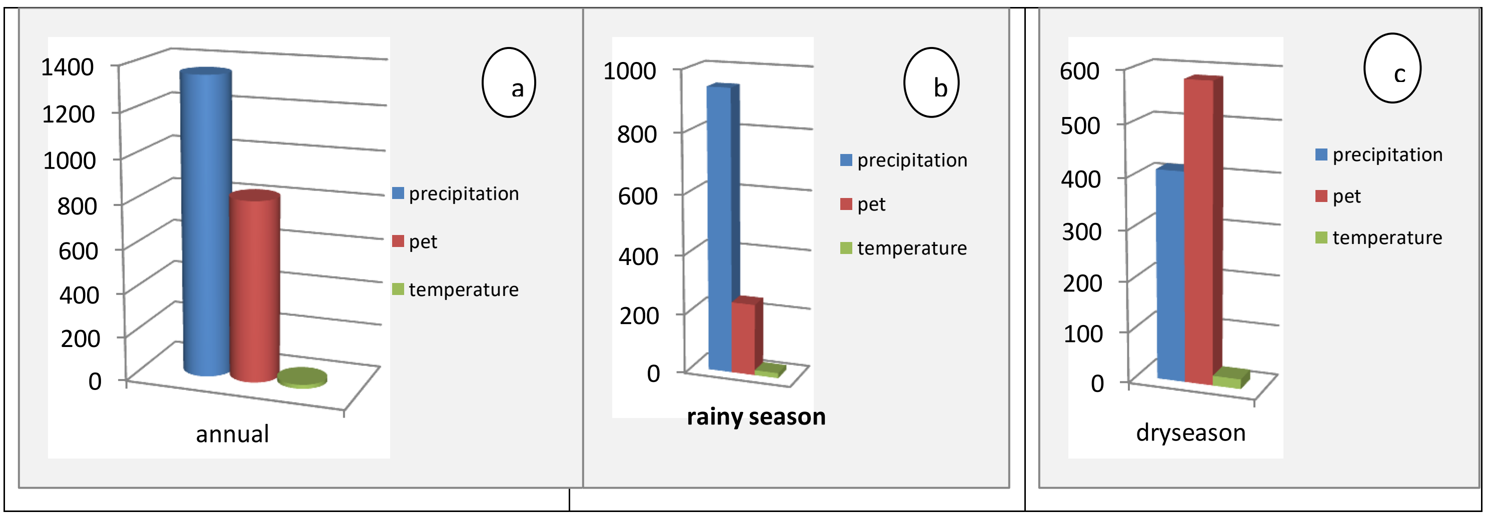


Figure 3.5: Annual (a), rainy (b) and dry season climate of watershed

3.1.3. Geology and Hydrology

According to the Ethiopian geologic survey, the lithologic unit of the study area contains alluvial and lacustrine deposits: sand silt, clay, diatomite limestone and beach sand (Q), Basalt flows, spatter cones and hyaloclastite a)Transitional type between alkaline and tholeiitic (Qb), Basalt flows, spatter cones and hyaloclastites (a) Transitional type between alkaline and tholeiitic (Qba), Chilalo Formation (Lower part): Trachyte,trashy- basalt, peralkaline,rhyolite with subordinate alkaline basalt (Nc), Adigrat Formation: Triassic-Middle Jurassic sandstone (Ja) and Makonnen Basalts (PNmb).

Chilalo Formation (Nc): A group of Early Pliocene shield volcanic complexes which developed on both sides of the rift shoulders and margins of Main Ethiopian Rift was named as the Chilalo Formation (Kazmin and Berhe, 1981). On the eastern escarpment of the MER, complex central volcanoes like Chilalo, Badda, Kaka, Enqoulo, and along the eastern rift margin of the MER and southern margins of the Afar centers like Gara Gumbi, Asebot, Afdem, Borate, Gara Adi and other.smaller centers (Gara Gumbi Trachyte) are considered with the Chilalo Formation. Along with the western margin centers such as Yerer, Wechecha, Furi, Gash Megel and their satellites centers represent the latest pulse of such felsic volcanism along the western escarpment. The lower unit (Nc) comprises intercalation of peralkaline ignimbrites and trachytes which show clear flow structures. The dominant rock type is a strongly porphyritic dark grey trachyte with sanidine phenocrysts. Lava flows of the predominantly trachytic volcanoes inter finger with the upper part of the Nazret Series (Nn) and in fact constitute part of the series.

Makonnen Basalts (PNmb): The name Makonnen Basalts was coined by Davidson (1983) for up to 700 meters thick of sub-horizontal flood basalts which cap the plateau in southern and southwestern Ethiopia (those of the Makonnen, Gecha, Nano and Gura Ferda plateaus). The Makonnen Basalts (PNmb) mostly directly overlie on the crystalline basement in the type area and yielded an absolute K/Ar age range of 34.8 to 23.1 Ma (Late Oligocene to Early Miocene) by Davidson (1983). The Makonnen Basalts are physically separated and are readily distinguishable on the basis of similar basal elevation, columnar form, the thickness of flows and the fact that they have a basal paleosol rather than residual sandstone.

Quaternary Sediments of different (origin fluvial lacustrine, eolian, eluvial, marine) are widely spread all over Ethiopia. According to Mohr, (1966) at the beginning of the Quaternary an ancestral lake which was almost certainly continuous from the Abaya - Chamo Lake to the south to the awash basin to the north existed until it shrinks to smaller ones by late Pleistocene tectonic movements. Adigrat Formation: Triassic-Middle Jurassic sandstone (Ja): The Adigrat Formation chiefly comprises sandstone with minor lenses of siltstone and conglomerate and laterite up to two meters thick (Garland, 1972). In the central part of the country, in the Abay Canyon, variegated sandstone, siltstone and shale correlable with the Adigrat Formation (Ja), occurs between the Precambrian Basement and the Abay Formation or Tertiary volcanic. Lithology distribution summery of study area shown in (table 3.1 and figure 3.6).

Table 3.1: Lithology distribution description of the watershed

Lithologic type	Area(km^2)	Area (%)
Alluvial and lacustrine deposites:sand silt,clay,diatomite limestone and beach sand (Q)	1548.9	42.3
Basalt flowes,spatter cones and hyaloloclastites a)Transitional type between alkaline and tholeiitic (Qb)	660	18.03
Basalt flows,spatter cones and hyaloclastites (a) Transitional type between alkaline and tholeiitic.(Qba)	474	12.9
Adigrat Formation: Triassic-Middle Jurassic sandstone (Ja)	99	3.17
Chilalo Formatio (Lower part): Trachyte,trachy- basalt, peralkaline, rhyolite with subordinate alkaline basalt (Nc)	378	10.53
Makonnen Basalts (PNmb)	400	11.03

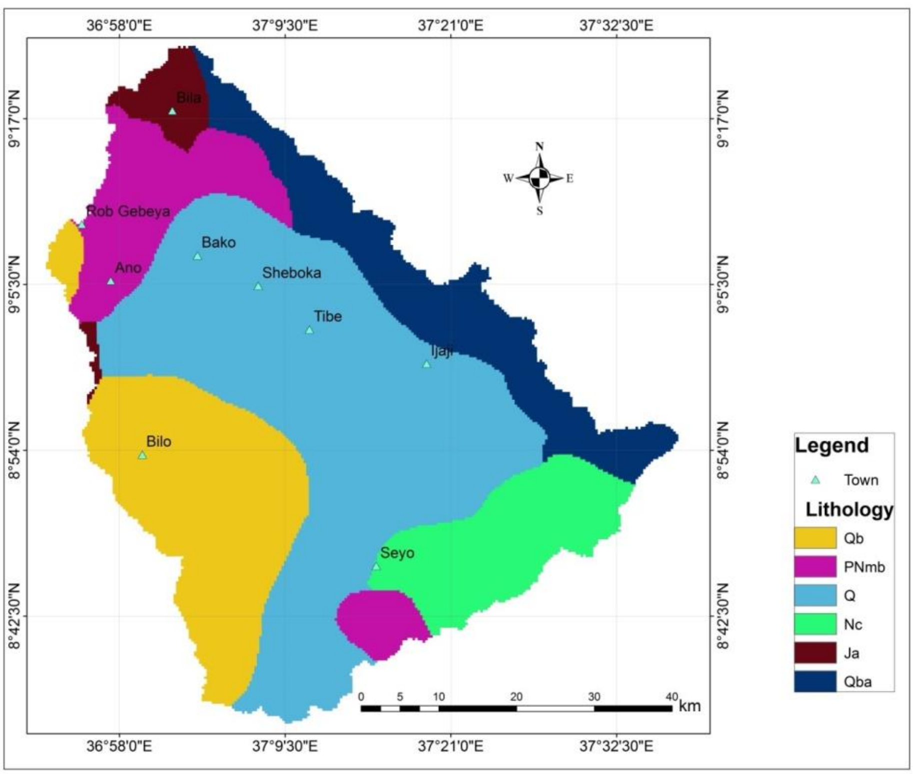


Figure 3.6: Lithological map of study watershed

The major water-bearing units for most of the boreholes within the upper Gibe watershed is the tertiary and quaternary volcanic which are fractured and weathered to become moderate aquifers. There are also productive wells in the quaternary deposits along the lowlands and river valley areas. A wide range of the groundwater residence times (ages) has been reported in an arid unconfined aquifer because recharge occurs under various climate conditions (Custodio et al., 2018). A borehole found in the area covered by basement rocks, which has limited exposure in the watershed, is a poor aquifer with low yield. There is a wide range of heterogeneity in Ethiopian aquifers related to variation in Geology, topography and Environmental conditions (Alemayehu 2006). From groundwater potential point of view, three broad aquifer classes are given in the hydrogeological map of Ethiopia.

1. Extensive aquifers with intergranular permeability (unconsolidated sediments:-alluvium, Eluvium, colluviums, lacustrine sediments, and poorly consolidated sandstone)
2. Extensive aquifers with fracture and/or karistic permeability (consolidated sediments and metamorphosed carbonates: Limestone, sandstone, shale, marl, evaporate, marbles)
3. Extensive aquifers with fracture permeability (volcanic rocks: basalts, rhyolites, trachytes, ignimbrites)

Each of the above three broad a category, in turn, is divided into high, moderate and low productivity, the aquifer systems found in the area are discussed as follows:-

- Extensive and High productive fissured Volcanic aquifers (T= 100-500 sq.km/d) with spring and well discharges 5-25 l/s)

This Aquifer type includes: - Nazret pyroclastics, welded pyroclastics interbedded with basaltic lava flows and welded to partially welded pyroclastic flows (Nnwp); Guder-Babich basalt, Aphyric Basalt (Npb) and Tarmaber-Magezez formation (Mtb). Lithological data obtained from drilled borehole logs in these units indicate that a volcanic sand layer (pyroclastics) with the lava flow is responsible for the high yields (up to 10 liters/second). It should be noted, that in many cases groundwater levels could be deeper than 60 m and that drilling for at least 100-180 meters may be necessary to obtain the above-indicated yield. These types of aquifer cover 4.63% (165 km^2) of the total area.

- Extensive and Moderate productive fissured Volcanic aquifers (T=50-100 sq.m/d) (with average spring and well discharge 0.51-5 l/s)

Moderately productive volcanic aquifers cover the area of the watershed which accounts for 23.7 % (845 km^2). Boreholes penetrating these volcanic suggest that groundwater quality and aquifer productivity depends on the depth of penetration. According to the available borehole logs, sandy pyroclastic sediments inter bedded with massive trachy-rhyolite horizons are the primary aquifers. In many boreholes, these aquifers are encountered at depths below 70 meters and some water levels are at >100 meters below ground level. Further common characteristics are that the yields are high (up to 10 liters/second), but because of low aquifer transmissivity (1.3 m^2/day in some cases), the drawdowns during pumping can be very high (of the order of 60 m).

- Extensive and low productive Volcanic Aquifers (T= 1-10 sq.m/d with spring and well discharge 0.05-0.5 l/s)

The following lithologies fall under these low productive aquifer types.

- Trachyte flows and plugs: light grey to grayish white and pinkish grey and porphyritic, subcircular to dome-shaped , columnarlly jointed (Ttr), and
- Wechecha trachytes, plagioclase & alkali feldspars phyric trachytic lava flows & domes (Nwt).A total area of around 16.44% (586 km^2) is covered by these aquifer types.
    - Extensive and Moderately productive Porous Alluvial Aquifers (T=50-100 sq.km/d) with spring and well discharge of 0.51-5 l/s)

Extensive and Moderately productive Porous Alluvial Aquifers cover the major area of the watershed which accounts 55.23% (1969km^2). Aquifer systems that are categorized under this group are -Quaternary stratified tuffs(Q): containing rock fragments, tuffs, pumice and channel deposits loosely or slightly compacted material (Qba), Quaternary alluvial sediments: Alluvium, alluvia,l soil, flluvial,colluvial, slope scree & debris deposits. Caldera,crater & graben floor fillings (Qa). Groundwater accumulates in the pore spaces of unconsolidated material. These deposits are often bogy with soft clayey soil. At place, they form loose thick soil of clayey-silt material that is not consolidated. Area description of watershed (table 3.2 and figure 3.7).

Table 3.2: Hydrogeology distribution description of the watershed

Aquifer productive class	Area km2	Percent (%)
Extensive and High productive fissured Volcanic aquifers	165	4.63
Extensive and Moderate productive fissured Volcanic aquifers	845	23.7
Extensive and low productive Volcanic Aquifers	586	16.44
Extensive and Moderately productive Porous Alluvial Aquifers	1969	55.23

Source: Oromia water works design and Supervision enterprise, 2018

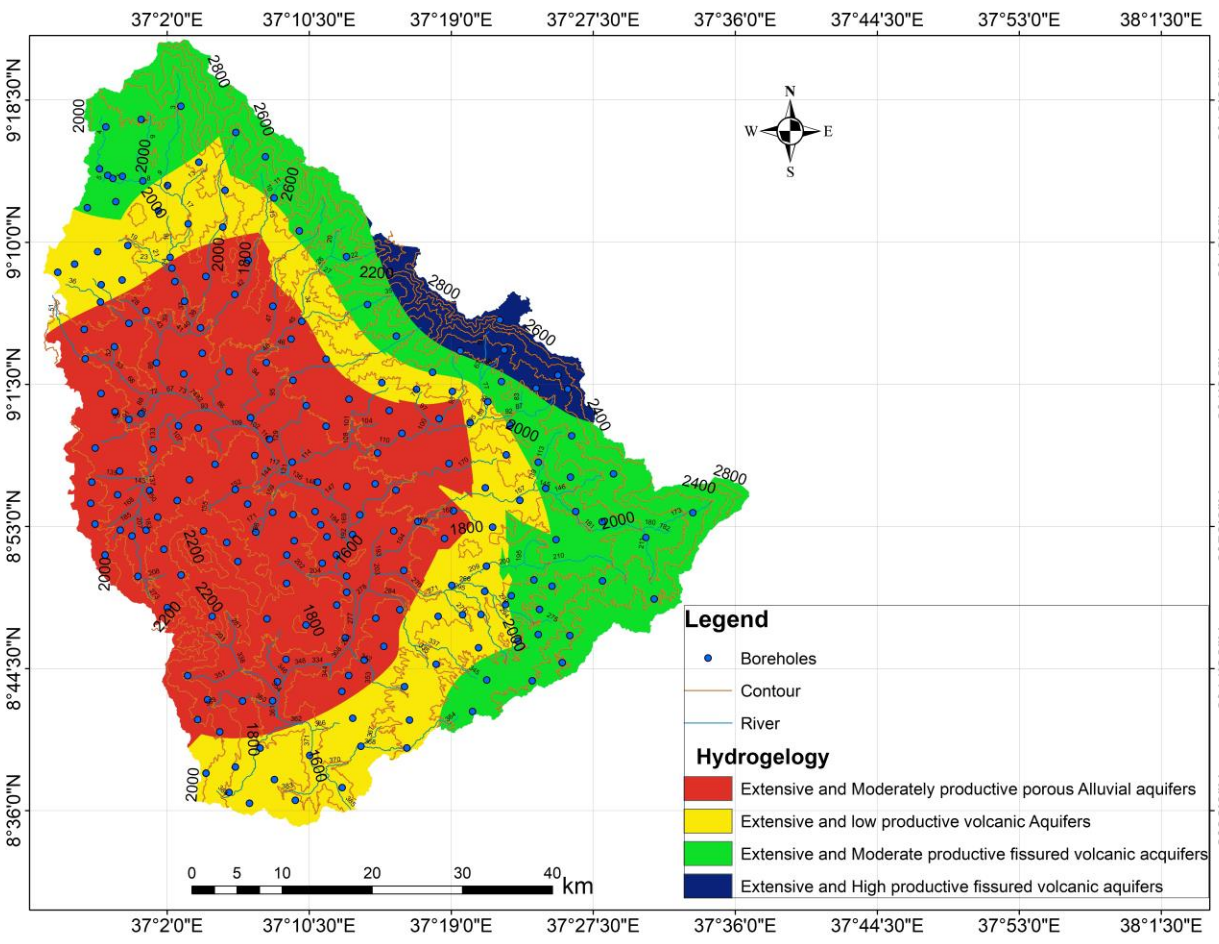


Figure 3.7: Hydrogeology of the study watershed

3.2. Method

This study focused on simulating climate variability and land use land cover change impact on groundwater recharge. In the first step, the spatial data were collected and prepared and used as inputs for the model, and finally groundwater recharge of the study area were quantified. The collected data include land use/cover data from satellite images, meteorological data, soil data, groundwater depth data, slope and elevation data. These data are prepared, stored, manipulated, analyzed and converted to raster grid cell by using GIS and remote sensing software. The methodology flow diagrams were shown in (figure 3.8). The next step is all raster grid data were combined with wetspass model and annual recharge amount of study area was quantified using wetspass model.

The model quantifies groundwater recharge of the study area by considering various factors; -such as variable climate, topography, soil texture, and change in land-use/cover. Wetspass stands for water and energy transfer between soil, plants and the atmosphere under quasi-steady-state conditions (Batelaan and De Smedt, 2001). WetSpass is especially suited for studying long-term effects of land use/ cover and climate changes on the water regime in a watershed and was founded on the time-dependent spatially distributed water balance model, called "WetSpa" (Batelaan *et al.*, 1996; Wang *et al.*, 1997; De Smedt *et al.*, 2000). Grid maps and parameter tables are required as inputs for the WetSpass model and were prepared with the help of Arc GIS software tools. These grid maps are land-use, soil, slope, topography, groundwater level, precipitation, potential evapotranspiration, and wind speed. The input files prepared as parameter tables were arranged in the database file format (.dbf). Arc GIS (version 10.5) was used in order to prepare these input parameters, and parameter tables were added to the maps as an attribute.

The runoff characteristics parameters table that include runoff coefficient, slope and soil type for each corresponding land use were also prepared. In addition, since values in these tables are considered to be universal, no modifications are required for parameters of these tables. Topography, slope, land use/cover, soil, potential evapotranspiration, and groundwater level (depth) maps were prepared. The topographic grid map and the slope map were derived from ASTER DEM data. Due to the lack of long term groundwater depth data, same map input was used for all three phases. Temperature, precipitation and wind speed parameters were prepared using the available Metrologic data collected from Ethiopian Metrologic agency. Description of Inputs data units of measurements were in (Table 3.3).

Table3.3: Description of Inputs data units of measurements

Inputs data	**Unit**
Temperature	Degree centigrade (°c)
Rainfall	Millimeter (mm)
Elevation	Meter (m)
Slope	Degree (°c)
PET	Millimeter (mm)
Wind Speed	Meter per second (m/s)
Groundwater Depth	Meter (m)

3.2.1. Data and materials

Preparation of thematic layers involves, digital image processing of remote sensing data, and integration of field data for the extraction of meaning full information. As described by Rwanga (2013), two types of inputs are required for the WetSpass model: grid maps and parameter dbf tables. De Vries and Simmers (2002) explain that interaction of climate, geology, morphology, soil condition and vegetation determines the recharge process. As such, the input data were prepared in the form of grid maps of meteorological, hydrological, and geographical elements in the watershed. All input grid maps were prepared using a grid cell size of 30 × 30 m which is similar to The Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER) digital elevation model. The inputs data parameters, Source and Spatial resolution description in (table 3.4)

Table 3.4: Description of inputs parameter data

Input parameter	The time period for data(year)	Spatial resolution	Source of data
LULC	1985,2000&2019	30*30m&10 m sentinel-2	(https://earthexplorer.usgs.gov/)
Topography DEM	Constant	30m*30m	(http://aster.usgs.gov)
Soil type	Constant	30m*30m	Oromia water works design and Supervision enterprise.
Rainfall	1985-2018	30m*30m	Ethiopian Metrologic agency
Temperature	1985-2018	30m*30m	Ethiopian Metrologic agency
Potential Evapotranspiration	1985-2018	30m*30m	Calculated from climatic data using the Thornthwaite method
Wind speed	1985- 2018	30m*30m	Ethiopian Metrologic agency
Groundwater level	constant	30m*30m	Ministry of Water Resources, Electric City and Irrigation and Oromia water works design and Supervision enterprise.

For preparation, analysis, store, manipulate, display and manage data the following software's were used (table 3.5).

Table3.5: Descriptions of software and material used

Name	Purpose
Arc GIS 10.5	Storing, managing, analyzing, displaying, and mapping, Grid data preparation, spatial data analysis, interpolation of point data and interpretation of the simulated results
ERDAS 2015	Satellite data preprocessing, classification, and change detection analysis
INVI 5.4	Preprocessing of both Landsat TM and Sentinel 2: Convert DN value to radiance and reflectance
IDRISI	Satellite data classification
Thornthwaite method	To generate PET
WETSPASS	To generate recharge, ET and surface runoff

3.2.2. Wetspass model and data source

The WetSpass model quantifies groundwater recharge, and determines the spatial distribution as a function of hydrometeorology, topography, soil texture, and land use/cover type factors. It is very important to have a knowledge that directly takes into account the impact of the spatial change of land use/cover, slope, meteorological condition and soil texture in the quantification of groundwater recharge. Data inputs to the model are digital maps prepared with the help of GIS packages and parameter files from spreadsheet tables with their specific extensions (Liu and De Smedt, 2004).

The input parameter files were the daily records of hydro meteorological parameters such as precipitation, evapotranspiration, temperature, and wind speed. The land use land cover, slope, groundwater depth, and soil types were the base maps from which the pixel model parameter files and maps were derived and combined. The time series data which contained land-use/ cover type described by rooting depth, leaf area index and vegetation height. It also contained soil parameters for each textural class, such as field capacity, wilting point, and permeability.

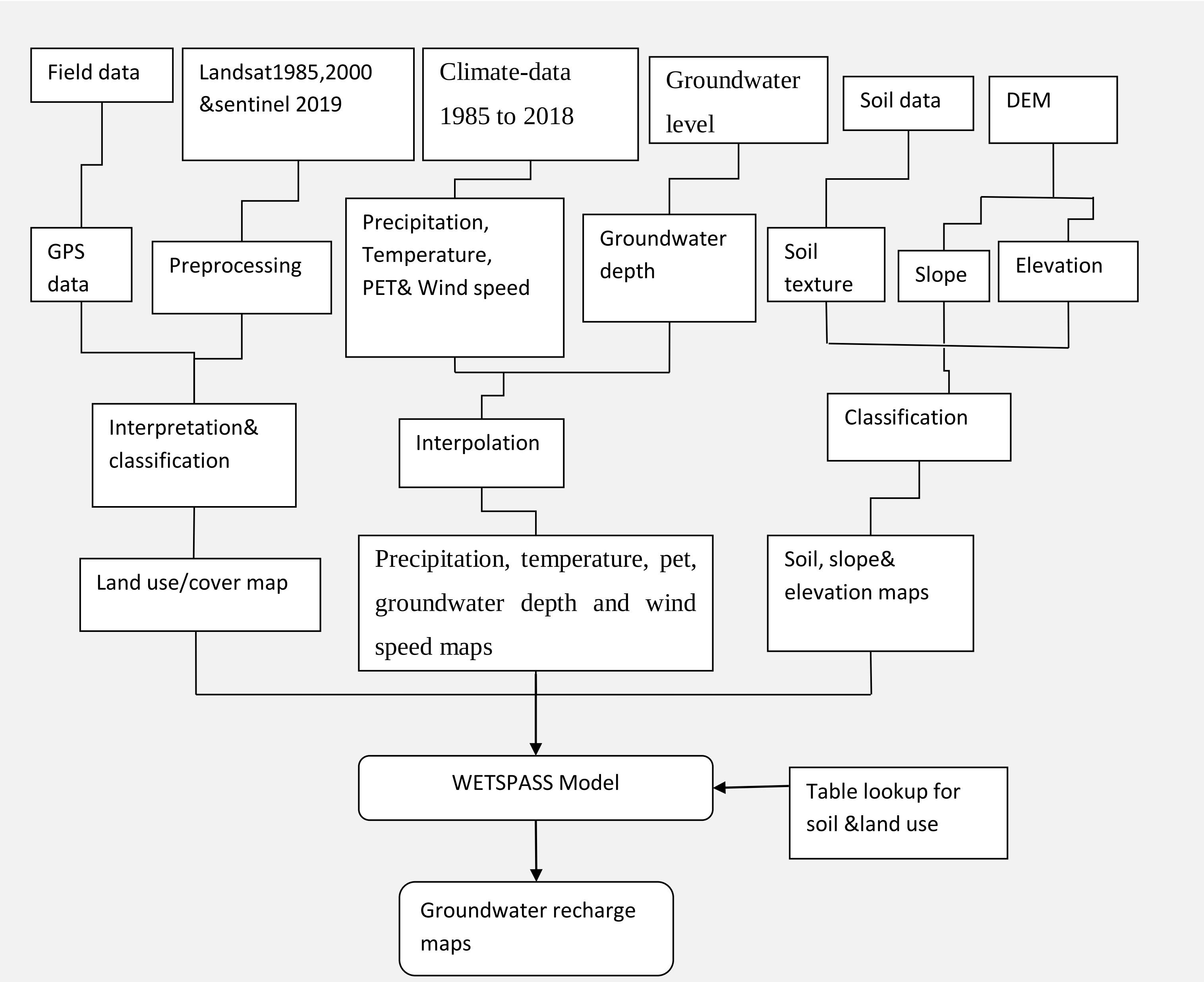


Figure 3.8: Methodological Flow Diagrams

3.2.3. Water Balance calculation per raster cell

The water balance components of vegetated, bare-soil, open-water, and impervious surfaces are used to calculate the total water balance of a raster cell using following equations (De Smedt and Batelaan, 2001):

$$ET_{raster} = a_v ET_v + a_s E_s + a_0 E_0 + a_i E_i \quad (1)$$

$$S_{raster} = a_v S_v + a_s S_s + a_0 S_0 + a_i S_i \quad (2)$$

$R_{raster} = a_vR_v + a_sR_s + a_0R_0 + a_iR_i$ (3)

Where ETraster, Sraster, Rraster are the total evapotranspiration, surface runoff, and groundwater recharge of a raster cell, respectively, each having a vegetated, bare-soil, open water and impervious area component denoted by av, as, ao, and ai, respectively, E is evapotranspiration. Precipitation is taken as the starting point for the computation of the water balance for each of the above-mentioned components of a raster cell. Other processes (interception, runoff, evapotranspiration, and recharge) follow in an orderly manner; - which becomes a prerequisite for the seasonal time scale to quantify the processes. The water balance for the different components is treated hereafter. The water balance components of vegetated, bare-soil, open-water and impervious surfaces are used to calculate the total water balance of a raster cell (Figure 3.9) as briefly mentioned.

3.2.4. Quantification of groundwater recharge

The water balance for the different components is treated hereafter.

Vegetated area

The water balance for a vegetated area depends on the average seasonal precipitation *(P)*, interception fraction *(I)*, surface runoff *(Sv)*, actual transpiration *(Tv)*, and groundwater recharge *(Rv)* all with the unit of $[LT^{-1}]$, with the relation given below

$R_v = P - S_v - ET_v - I$

Where *P* is the average annual precipitation, *ETv* is the actual evapotranspiration $[LT^{-1}]$, given as the sum of transpiration, *Sv* is the surface runoff over the land surface beneath the vegetation, *Tv* is the evaporation from bare soil between vegetation, *I* is the interception by vegetation, *i.e.* the part of the precipitation that evaporates from the wet surface of the vegetation, and *Rv* is the groundwater recharge, all variables have the unit of LT^{-1}. The equation described above can be employed for the estimation of the spatially distributed groundwater recharge as a function of vegetation, soil texture, slope, precipitation, groundwater depth, and other climatic variables (Batelaan *et al.*, 2003).

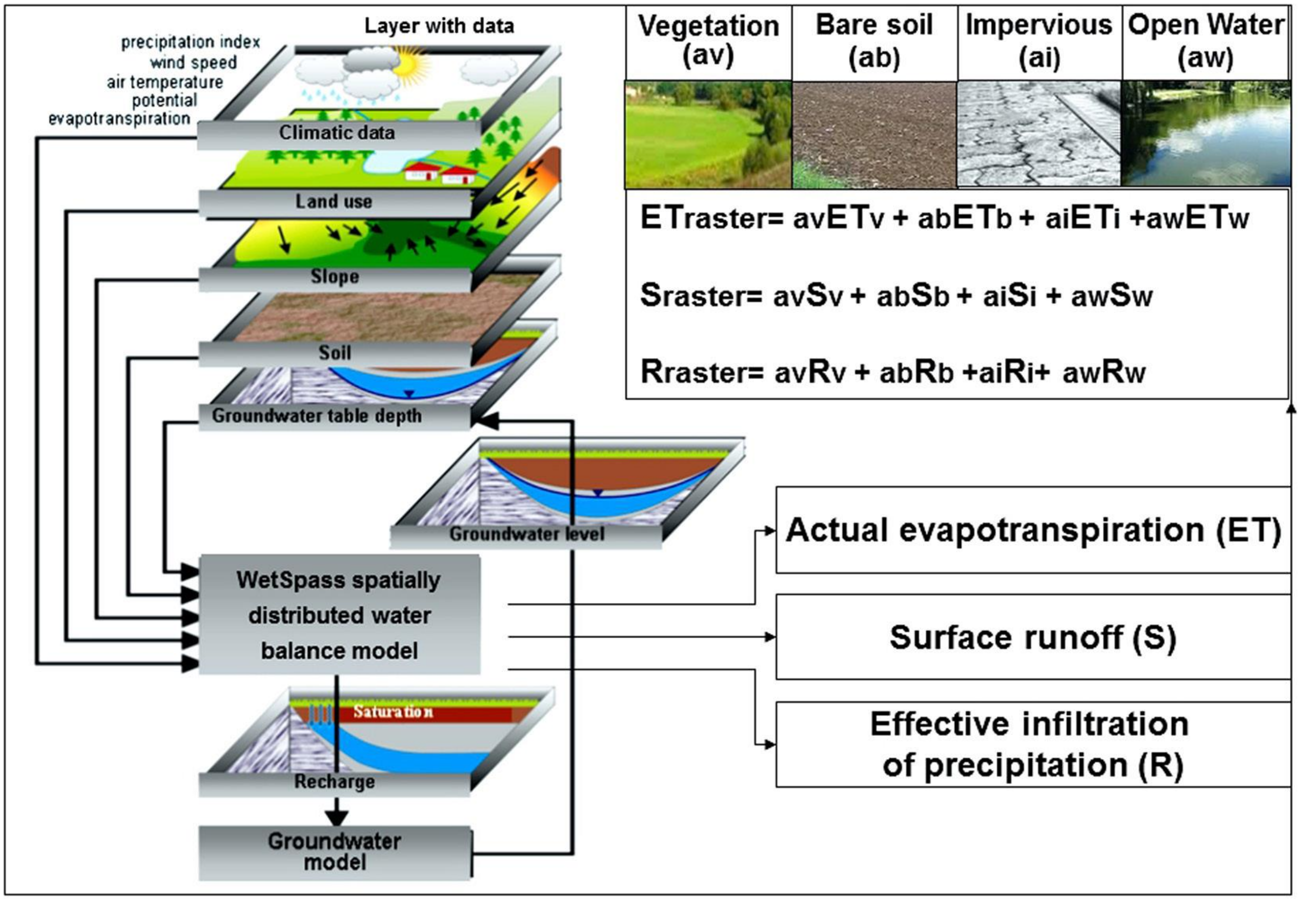


Figure 3.9: Conceptual diagram of the WetSpass model (modified after Batelaan & De Smedt, 2001; Graf, 2014)

Interception

Depending on the type of vegetation, the interception fraction represents a constant percentage of the annual precipitation value. Thus, the fraction decreases with an increase in an annual total rainfall amount (since the vegetation cover is assumed to be not constant throughout the simulation period).

Surface runoff

For the simulation of surface runoff, WetSpass model uses the runoff coefficient which on the other hand is a function of vegetation type, soil texture, and slope. As discussed by Batelaan and De Smedt (2007), in WetSpass, the surface runoff (S_v) is simulated in two stages. First, the potential surface runoff (S_{v-pot}) is calculated as a coefficient times the precipitation minus the interception (Eq. 5).

$$S_{v\text{ - }pot} = C_{sv}\,(P-I) \qquad (5)$$

Where, C_{sv} (as a function of vegetation type, soil type, and slope) is a surface runoff coefficient for vegetated infiltration areas based on the rational formula (Smedema and Rycroft 1988;

Pilgrim and Cordery 1992; and; Chow et al., 1988). Rubin (1966) indicated that, in the second stage, the potential surface runoff is actualized for recharge areas by taking into account differences in precipitation intensities in relation to soil infiltration capacities.

$$S_V = C_{Hor} S_{V\text{-}Pot} \quad (6)$$

where C_{Hor} is a coefficient that parameterizes the part of the seasonal precipitation which is actually contributing to the (Hortonian) surface runoff. As explained by Batelaan and De Smedt (2001), in groundwater discharge areas all intensities of precipitation contribute to surface runoff, i.e. C_{Hor} is 1. In infiltration areas, only high-intensity storms will generate surface runoff.

3.3. Preparation of input thematic layers

Preparations of input data are categorized into three phases for an indication of land use land cover change and climate variability impact on groundwater recharge.

3.3.1. Hydro-meteorological data

The basic input requirements for the WetSpass model consist of the table lookup parameters, meteorological data, and stream flow data for calibrating and validating model. The basic meteorological data requirements are Rainfall, Temperature, Potential evapotranspiration (PET) and wind speed. PET is calculated by the Thornthwaite method. Meteorological data obtained from the Ethiopian National Meteorological Agency of thirteen stations were used for the preparation of metrological input data for the WetSpass model. The meteorological time series data contain missed data in the selected stations of the study area. The missed data was fitted with averaging with existing value. However, the selected stations for the 33 years (from 1985 to 2018) had relatively consistent data records.

From these (1985 to 1996) is used for the first phase, 1997 to 2007 and 2008 to 2018 for the second and third phase, respectively. Each station's data was analyzed for the preparation of annual meteorological values and maps of the study area. Precipitation data were available for all the thirteen stations (figure 3.10& 3.11 and table 3.6) and temperature data were available for the ten stations while wind speed was available only for six stations. The annual grid maps of the climatic variables were developed using an interpolation method to predict values from a limited number of sample data points at unknown geographic point data. Kriging interpolation method was applied as it gives a consistent result with known values. Ordinary Kriging is a spatial estimation method where the error variance is minimized. It is based on the configuration of the data and on the variogram. Ordinary interpolation variance is a better measure of the accuracy of the Kriging estimate (Yamamoto, 2005). Variogram values express the relationship between the existing data and the estimation point, or by covariance in case of second-order stationarity (Malvić and Balić, 2009). The model parameters and initial conditions are described in the subsequent sections.

Table 3.6: Description of the selected rainfall station

Number	Station	Elevation	x	y	Mean annual rainfall (mm)
1	Ambo Agriculture	2068	37.83967	8.984667	1288.54
2	Woliso Giyon	2058	37.98333	8.55	1347.87
3	Biloboshe	1726	36.988	8.889167	1595.37
4	Ijaji	1732	37.31667	8.99	1522.23
5	Gedo	2520	37.4575	9.021	1309.73
6	Seyo	1772	37.27583	8.76783	1412.77
7	Alga	1714	37.10717	8.585733	1456.40
8	Fincha'a	2320	37.38	9.53	1334.20
9	Bako	1780	37.08	9.11	1507.20
10	Goben		37.31867	9.1725	1364.03
11	Nakemte	2080	36.46333	9.083333	1854.18
12	shambu		37.12	9.57	1497.91
13	sibusire	1760	36.87183	9.039667	1299.09

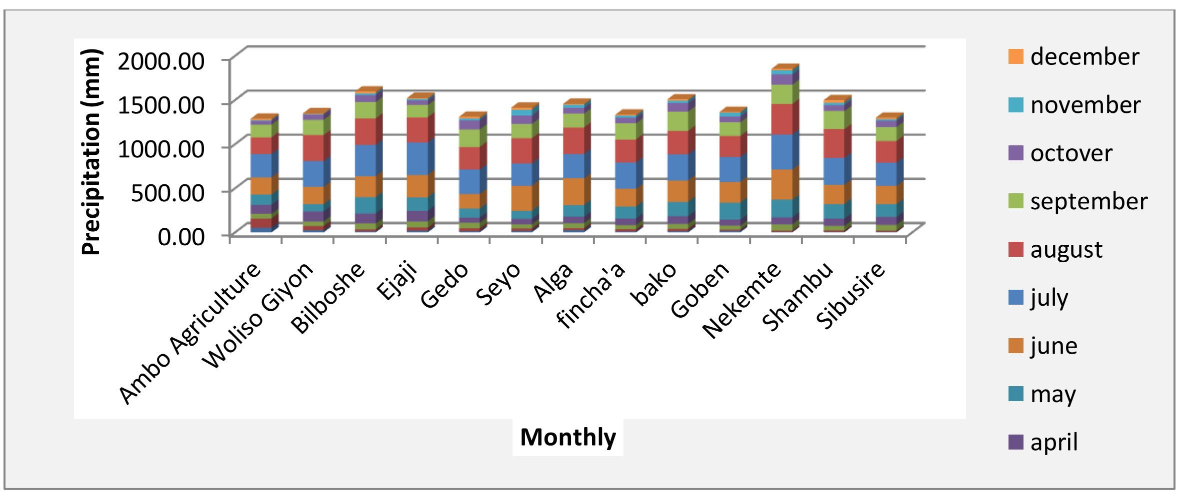


Figure 3.10: Monthly precipitation of selected station

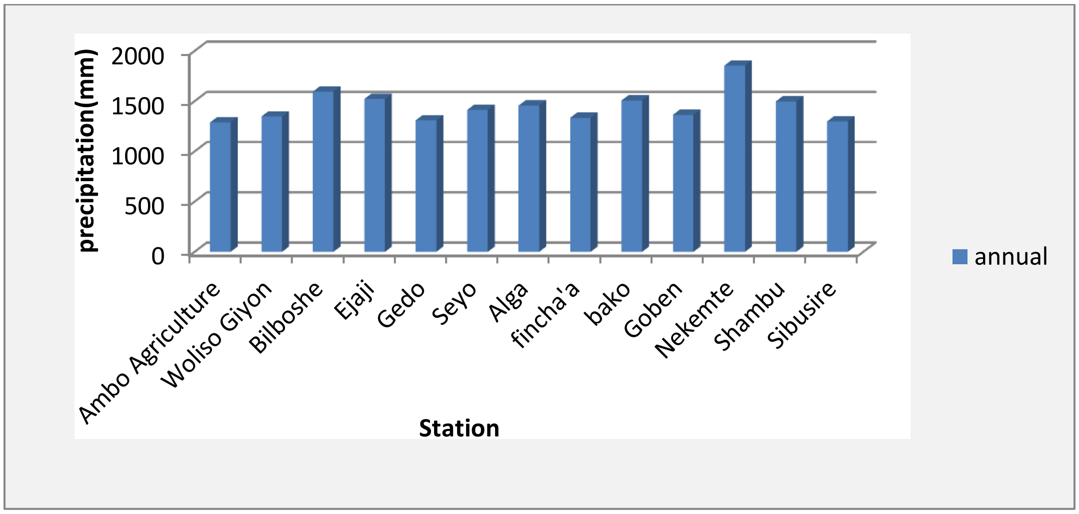


Figure 3.11: Annual precipitation of selected station

Precipitation

Rainfall of the watershed was considered and analyzed from the station within and around the watershed for 33 years. The analyses steps were divided into three phases by 11 years intervals. The value of rainfall shows major spatial variability in its amount, seasonality and year-to-year variation within the watershed. The precipitation of watershed was decreased in consecutive time series interval. Some studies such as Hastenrath (2001); Bewket and Conway, (2007) reported the observed patterns over East and Horn of Africa are affected by the presence of higher inter-decadal rainfall variability observed during the indicated period.

Rainfall and temperature are the two most important climatic variables that display high levels of variability across a range of spatial and temporal scales and exert significant impacts on human livelihoods, socioeconomic development, and ecosystems of East and Horn of Africa (Omondi et al., 2014). Global climate change is expected to worsen the prevalence of spatiotemporal climate variability in East and Horn of Africa. The analyzed time series precipitation data of three phases was used to evaluate climatic variability trends and quantify its impact on groundwater recharge. Precipitation is the fundamental driving force and pulsar input behind most hydrological processes. Rainfall-runoff models are particularly sensitive to the rainfall input in stream flow simulations.

The input rainfall series must be in the same interval as the model running step. The Kriging interpolation method was used to estimate areal precipitation for model input data simulation. Precipitation in the watershed varies with altitude. However, the correlation coefficient between precipitation and altitude is not very strong due to the orographic effect. Through 33 years, the precipitation amount was slightly decreased while temperature and PET were slightly increased. In order to run the model for the first phase the precipitation data interval is used from 1985 to 1996, 1997 to 2007, and 2008 to 2018, for the second, and the third phases, respectively (figure 3.12a and 3.12b). The mean yearly variability of precipitation, in the study area, the grid maps were shown in Figures 3.13a, 3.13b, and 3.13c respectively.

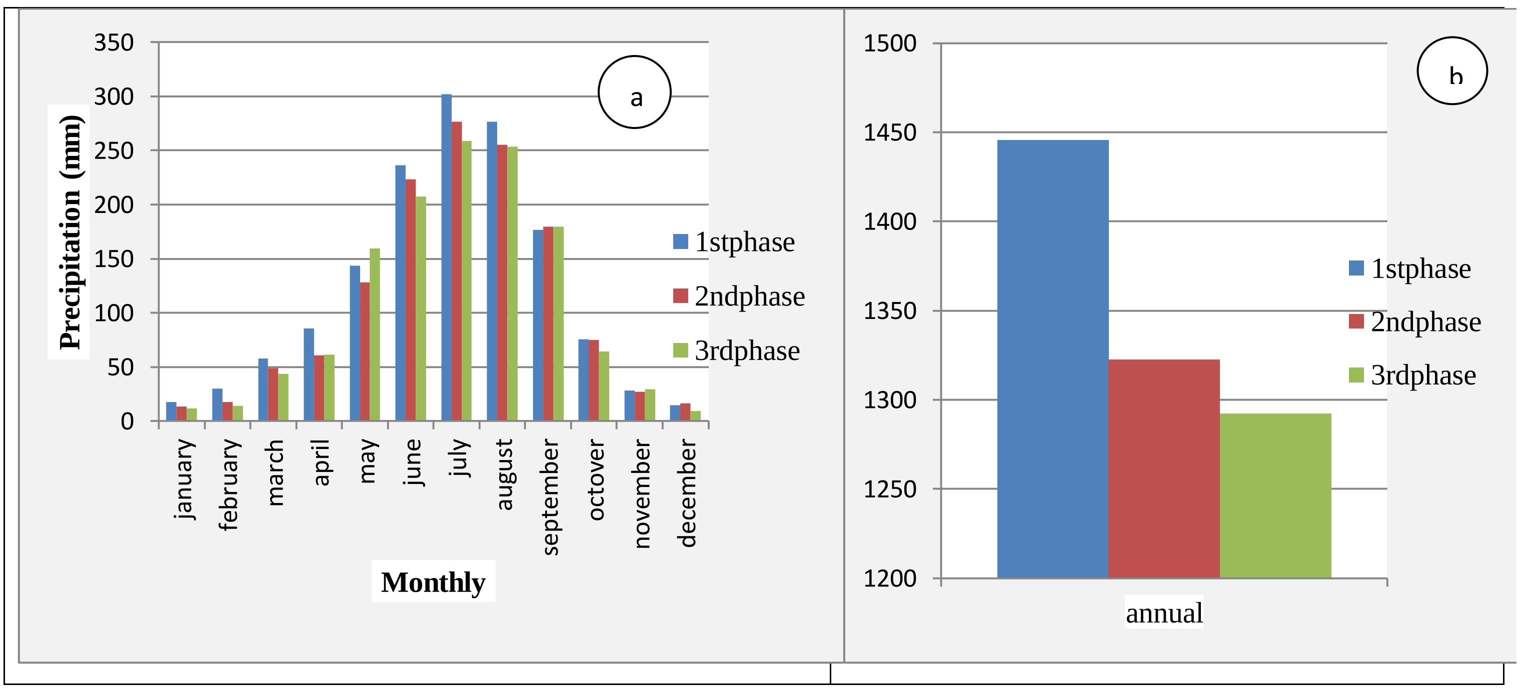


Figure 3.12: Monthly distribution (a) and annual (b) distribution of precipitation phase

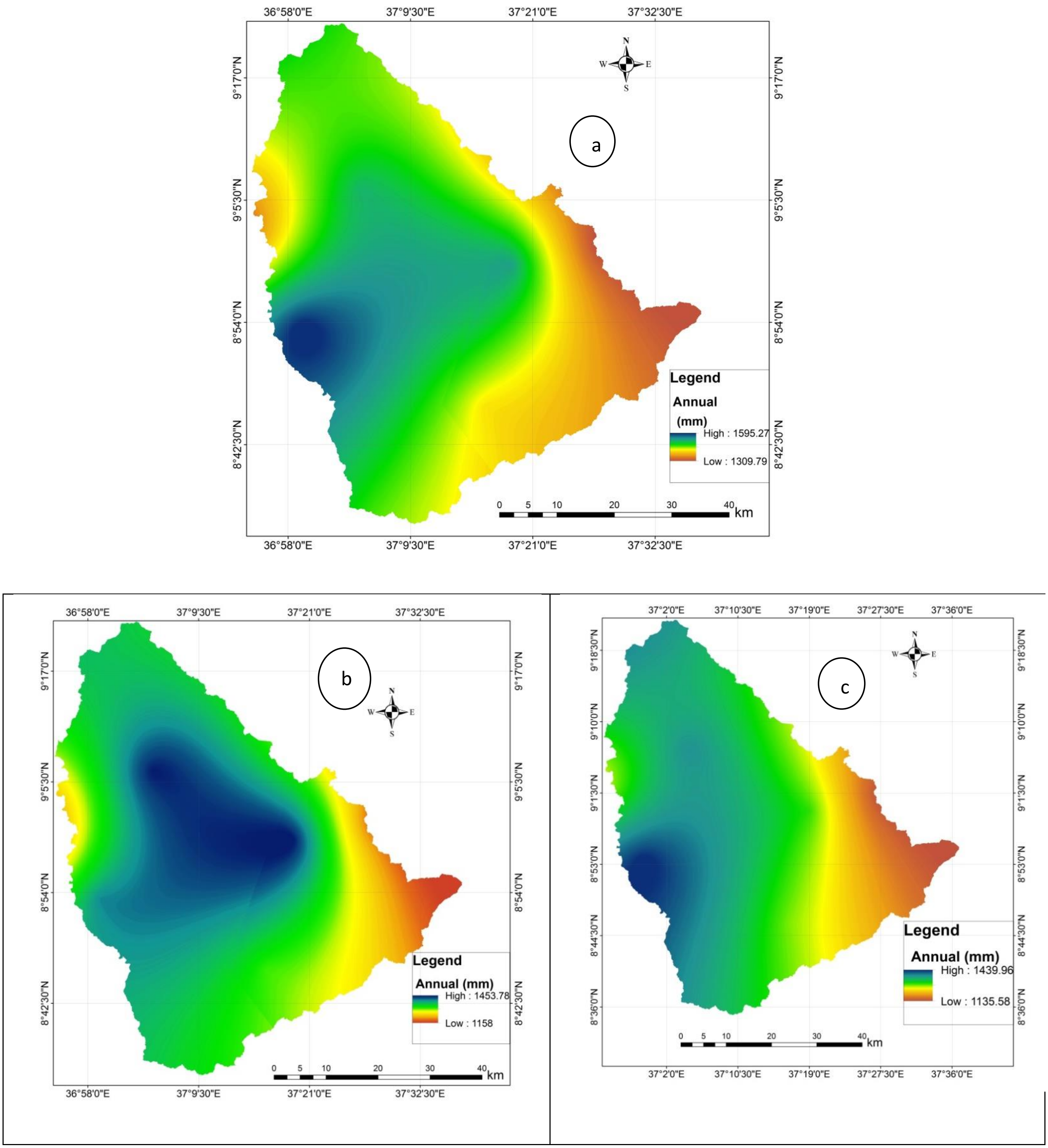


Figure 3.13: First (a), second (b) and third (c) phase annual precipitation maps of the watershed

Temperature

Maximum and minimum, temperature data are among the hydro meteorological data collected from the Ethiopian Meteorological Service Agency (NMA). Temperature data are available for the ten (10) Meteorological stations (figure 3.14 and 3.15). Starting from 1985 to 2018 data of temperature was analyzed at three phases by an interval of 11 years to generate a temperature variation maps. In order to run the model for the first phase the average temperature is used from 1985 to 1996, 1997 to 2007, and 2008 to 2018, for the second, and the third phases, respectively (figure 3.16a and 3.16b). Throughout 33 years increasing of temperature were observed within the watershed. The value is ranging from 16.85 to 19.95 of the first phase, from 17.09 to 20.96 and 17.16 to 21.58 for the second and third phase respectively. The grid maps were illustrated in (figure 3.17a to 3.17c).

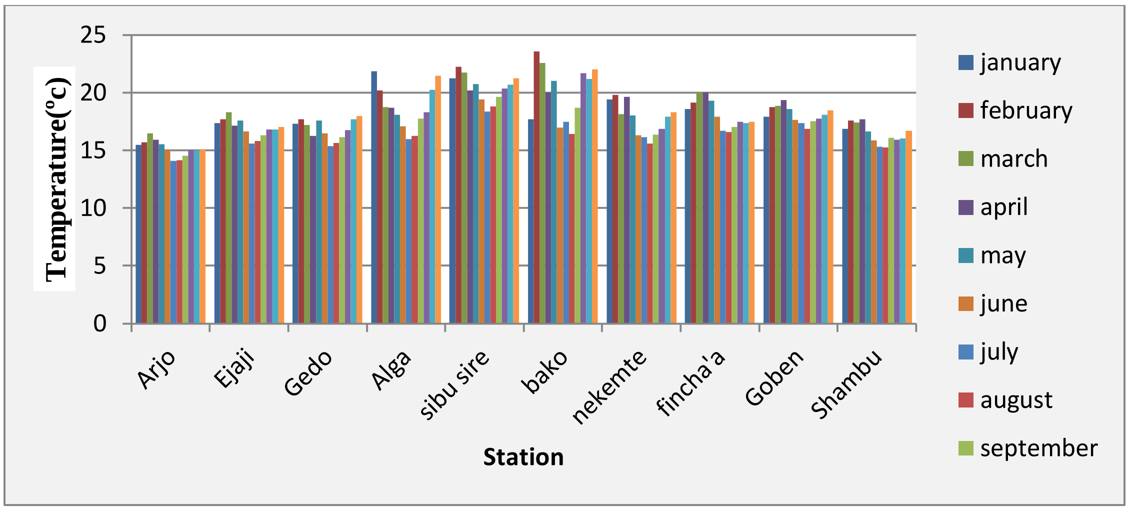


Figure 3.14: Monthly selected station temperature of watershed

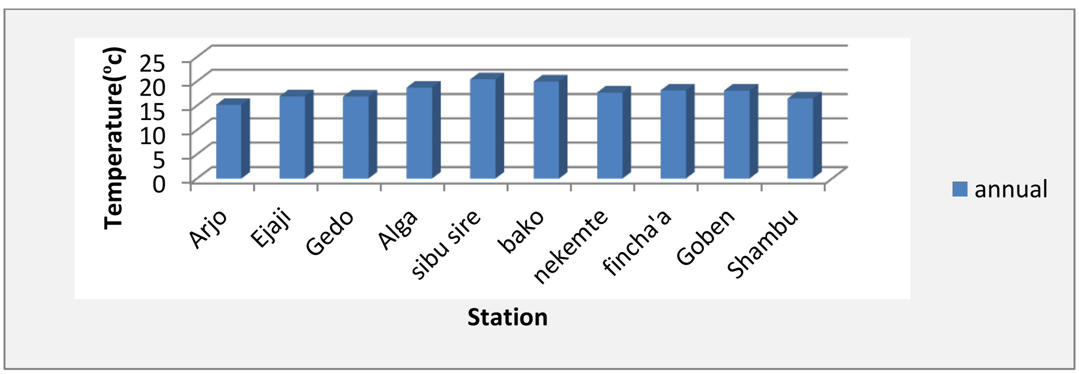


Figure 3.15: Annual temperature station of watershed

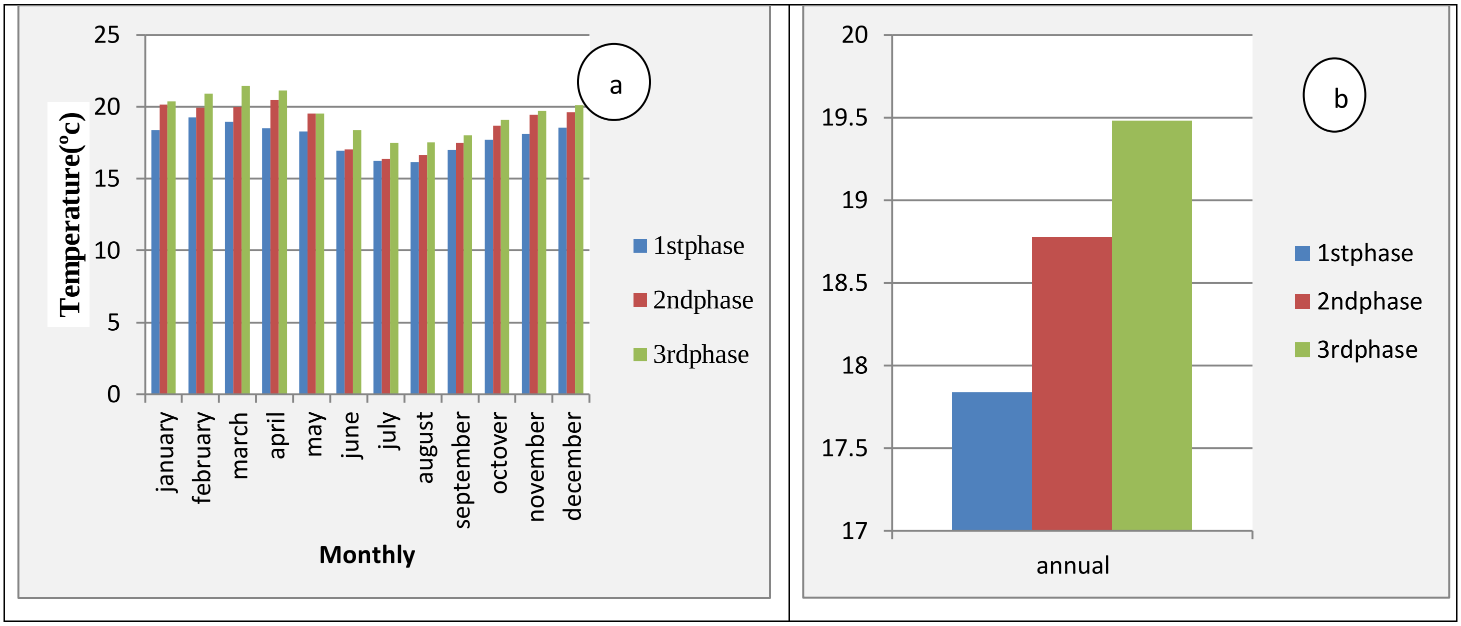
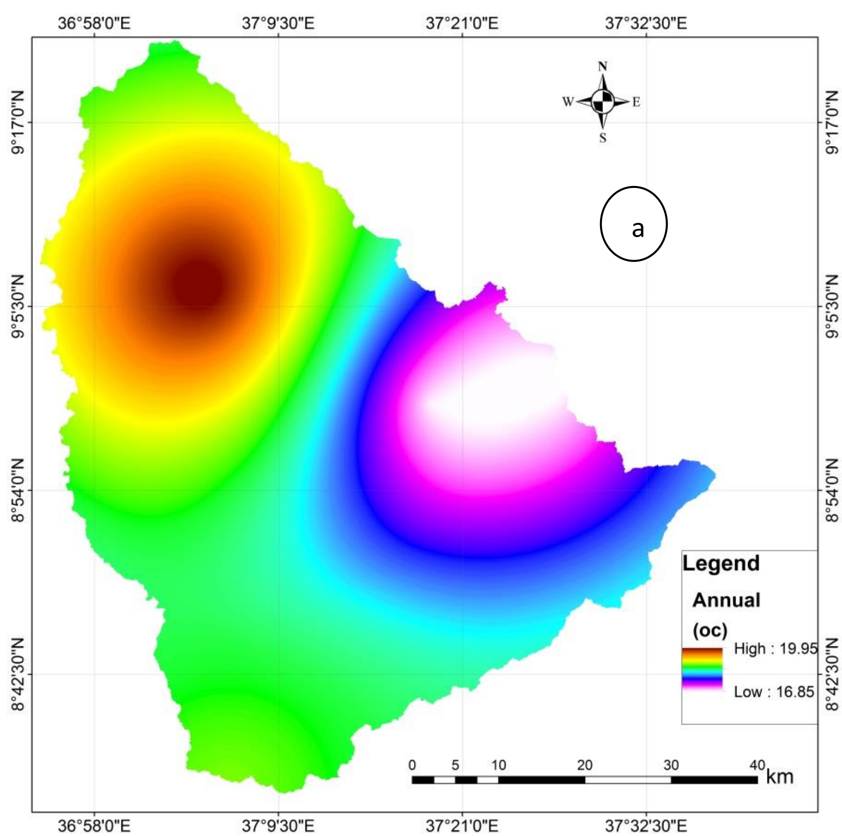


Figure 3.16: Monthly (a) and annual (b) temperature variability of watershed



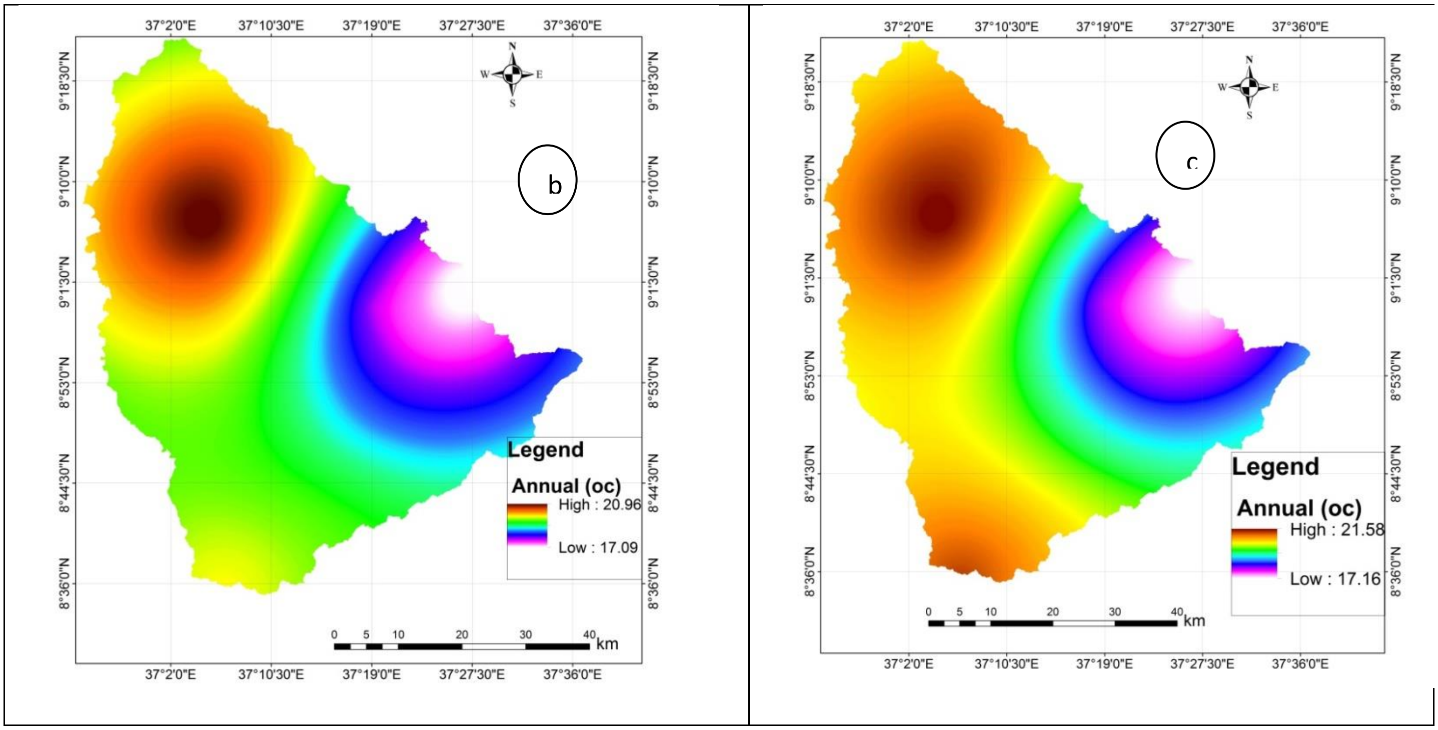


Figure 3.17: First (a), second (b) and third (c) phases annual temperature maps of study area

Potential evapotranspiration

WetSpass Extension requires PET data as one of the inputs with the same time interval as rainfall series, which can be obtained from field measurement or estimated by physical or empirical equations. Potential evapotranspiration (PET), of the watershed, is calculated by the Thornthwaite method. Thornthwaite (1955) method of estimating PET is based solely on air temperature. PET estimates are based upon a 12-hour day (amount of daylight) and a 30-day month (Eq. 7 and 8).

$$PET = 1.6x\left(\frac{10T_a}{I}\right)^a \qquad (7)$$

Where: T_a is the mean monthly air temperature, and I is the heat index;

$$I = \sum_{i=1}^{12}\left(\frac{T_{ai}}{5}\right)^{1.5} \qquad (8)$$

And a = .49 + .0179 * I - .0000771 * I^2 + .000000675 * I^3, where air temperature is summed over a 12-month period to a power. The interval of PET is the same with precipitation and temperature interval, from 1985 to 1996, used for first phase, when 1997 to 2007, and 2008 to 2018, for the second, and the third phases, respectively (figure 3.19a and

3.19b). Annual PET was interpolated and prepares the grid map. Final grid maps were converted to ASCII format and used as inputs of the model (figure 3.18a to c).

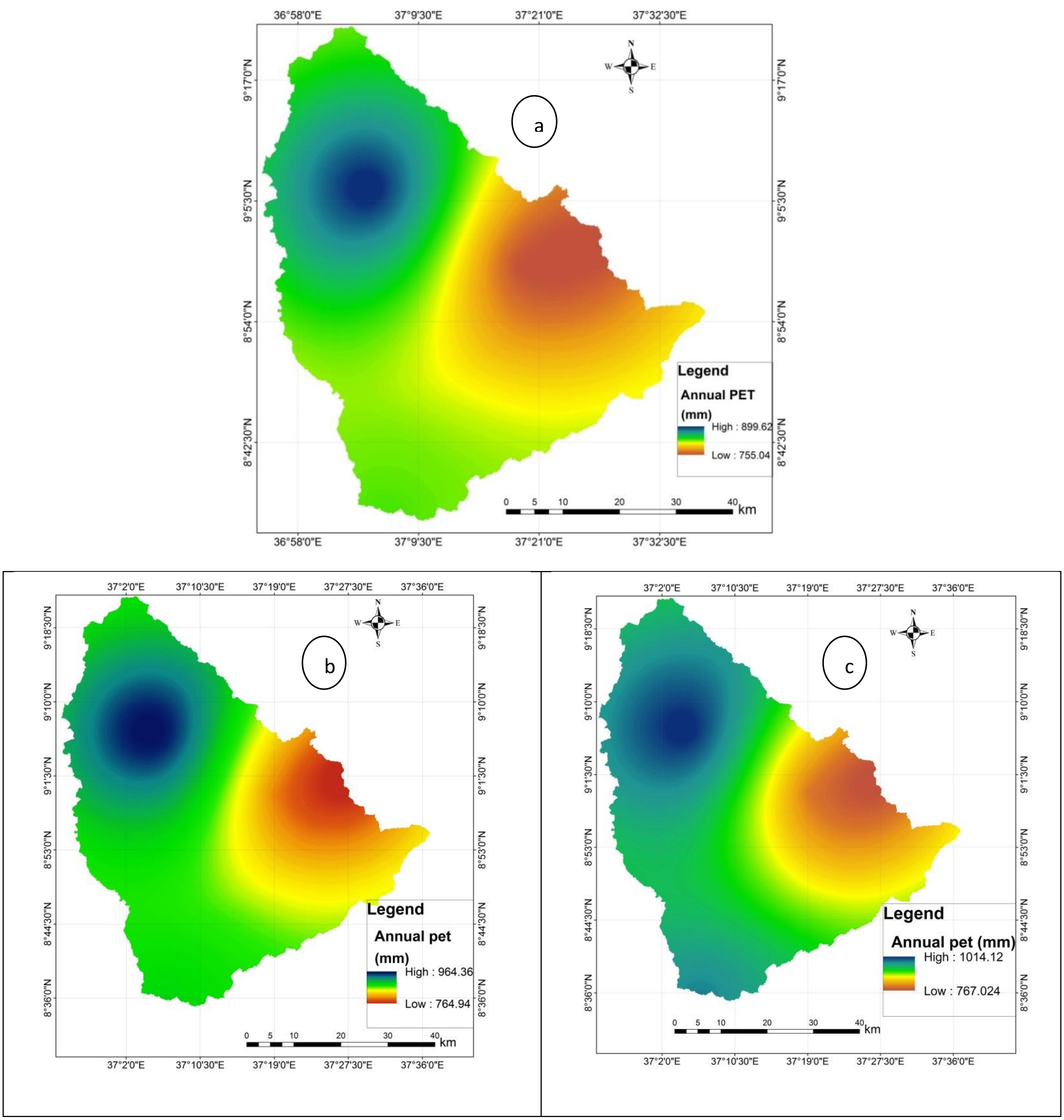


Figure 3.18: First (a), second (b) and third (c) phase annual PET map of the study area

Thornthwaite and Mather (1955) developed a detailed method to estimate evapotranspiration. Although this method for computing potential and actual evapotranspiration is highly accepted and widely used, it is unfeasible to perform these calculations with large data sets. Using the Thornthwaite method PET of upper Gibe watershed was calculated.

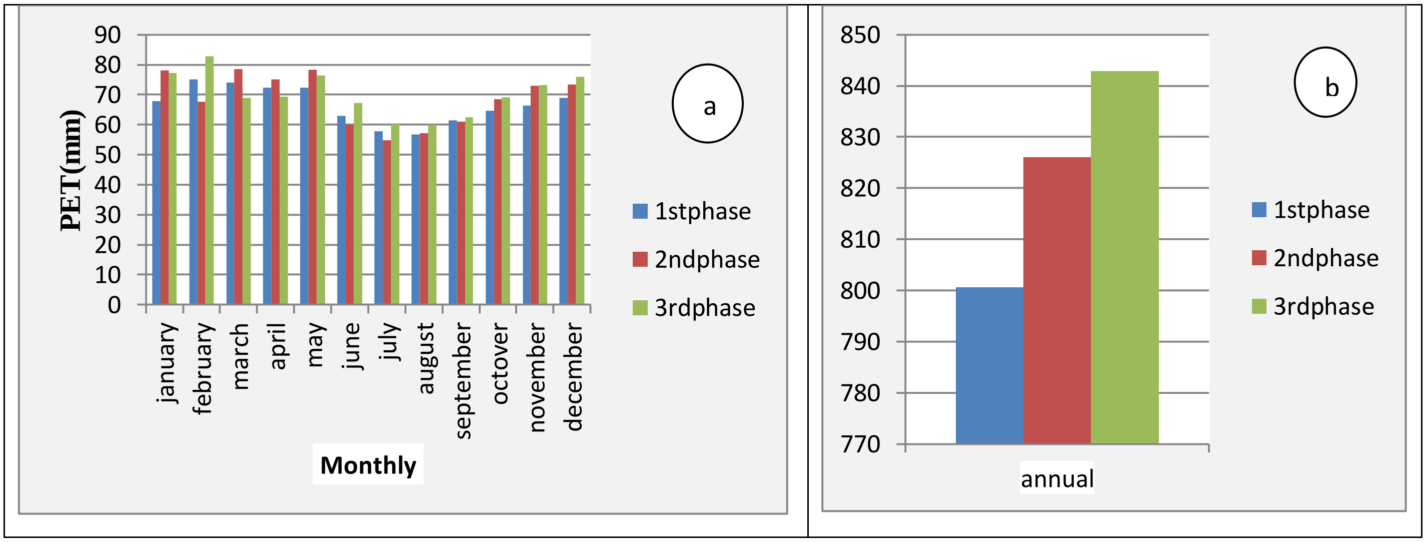


Figure 3.19: Monthly (a) and (b) annual PET variability of watershed

3.4. Soil texture and Land-use/land cover

Soil texture and permeability are important in recharge estimation because coarse-grained soils generally result in higher recharge rates than do fine-grained soils (Cook et al., 1992). Soil grid map of the watershed was collected from Oromia water works design and supervision enterprise (figure 3.20). The soils of the study area have five texture classes (table 3.7).

Table 3.7: Soil texture description of the study area watershed

Texture name	Area_km2	The area in percent (%)
Clay	1223.19	34.29
Sandy Loam	189.77	5.32
Loam	1035.92	29.05
Clay Loam	415.97	11.66
Silt Loam	701.74	19.68

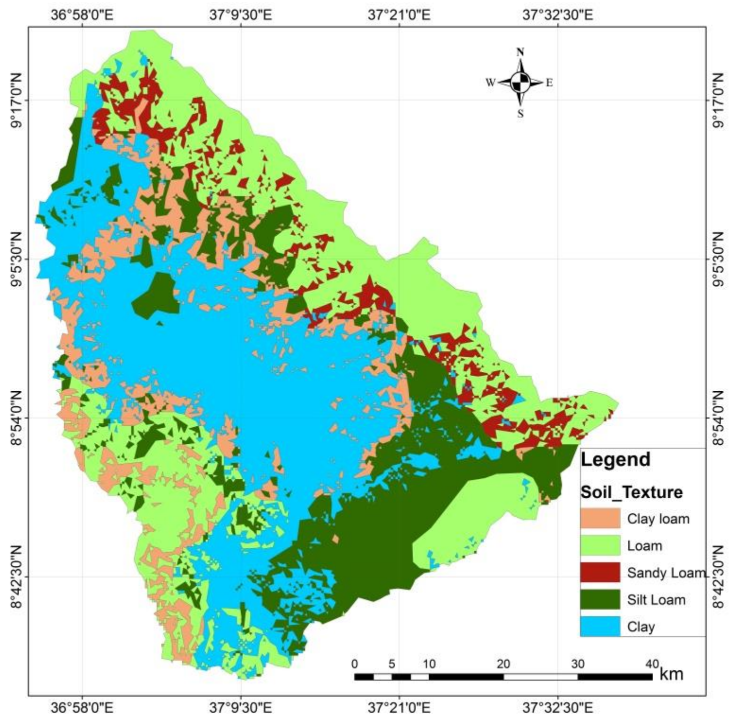


Figure 3.20: Soil texture map of the study area watershed

3.4.1. Satellite Images Preprocessing

Before processing, analysis and interpreting of the image data the various pre-processing routines, appropriate to the desired output, must be applied to the imagery. These enhance the quality of the image data by reducing or eliminating various radiometric and geometric errors caused by internal and external conditions. Geometric correction procedures address errors in the relative position of pixels due to factors such as variation in altitude, attitude, and velocity of the sensor platform, Earth curvature, panoramic distortion, relief displacement, and non-linearity in the sweep of a sensor (Lillesand and Kiefer, 1994).

Radiometric correction procedures account for errors that affect the brightness value of pixels due to both a sensor system detector error and an environmental attenuation error (e.g. changes in scene illumination, atmospheric conditions and viewing geometry (Lillesand and Kiefer, 1994). The preprocessing performed for this study was radiometric correction involving the conversion of the measured multispectral brightness values to top of atmosphere (TOA) reflectance units. This normalization procedure is crucial when creating a multi-temporal and multispectral image as it largely removes variations between these images due to sensor differences; Earth-sun distance and solar zenith angle (caused by different scene dates, overpass time and latitude differences). The process involved two steps. The first step involved the conversion of measured DN to radiance using inflight sensor calibration parameters. These parameters are supplied with the imagery and are determined from a comparison of inflight calibration sources with pre-flight absolute radiance values. The exact radiometric response function for each band could, therefore, be determined and applied to normalize temporal radiometric differences between sensors. The equation of the response function for each band is:

$$L = Gain * DN + Bias \tag{9}$$

where L = spectral radiance measured over spectral bandwidth of a channel

DN = digital number value recorded

Gain = $(L_{max}-L_{min})/255$ slope of response function

Bias = L_{min} intercept of the response function

L_{max} = radiance measured at detector saturation in $mWcm^{-2}sr^{-1}$

L_{min} = lowest radiance measured by detector in $mWcm^{-2}sr^{-1}$

The second step involved calculating top of atmosphere (TOA) reflectance for each band as per Equation 10, which corrected for illumination variations (sun angle and Earth-sun distance) within and between scenes. The correction was applied on a pixel by pixel basis for each scene in each era and the output reflectance values scaled to an 8-bit data range.

$$\rho\lambda = \frac{\pi d^2 L\lambda}{E0\lambda \cos\theta s} \tag{10}$$

where ρ_λ = reflectance as a function of bandwidth

d = Earth-sun distance correction

$L\lambda$ = radiance as a function of bandwidth

$E0\lambda$ = atmospheric irradiance

θs = solar zenith angle

Land-use/cover map was produced from cloud-free Landsat 5 TM Multispectral images of 1985, 2000 and sentinel 2 Multispectral images for 2019, using the standard supervised image classification. Pixel-Based supervised image classification with maximum likelihood classification algorithm was used to map the land-use land cover classes (Lillesand and Kiefer, 2000). Land-use/land cover of the watershed was classified into six classes (table 3.8): agriculture, build up area, shrub land, grassland, forest, and bare land. The land use/ cover map of the watershed are shown in (figure 3.21).

Table 3.8: Land use/cover Classes of 1985 of the study watershed

Class name	**Area_km^2**	**The area in percent (%)**
Agriculture area	976.92	27.39
Build up area	11.86	0.33
Shrub land	1029	28.86
Grass land	663.7	18.61
Bare land	121.59	3.41
Forest	762.4	21.38

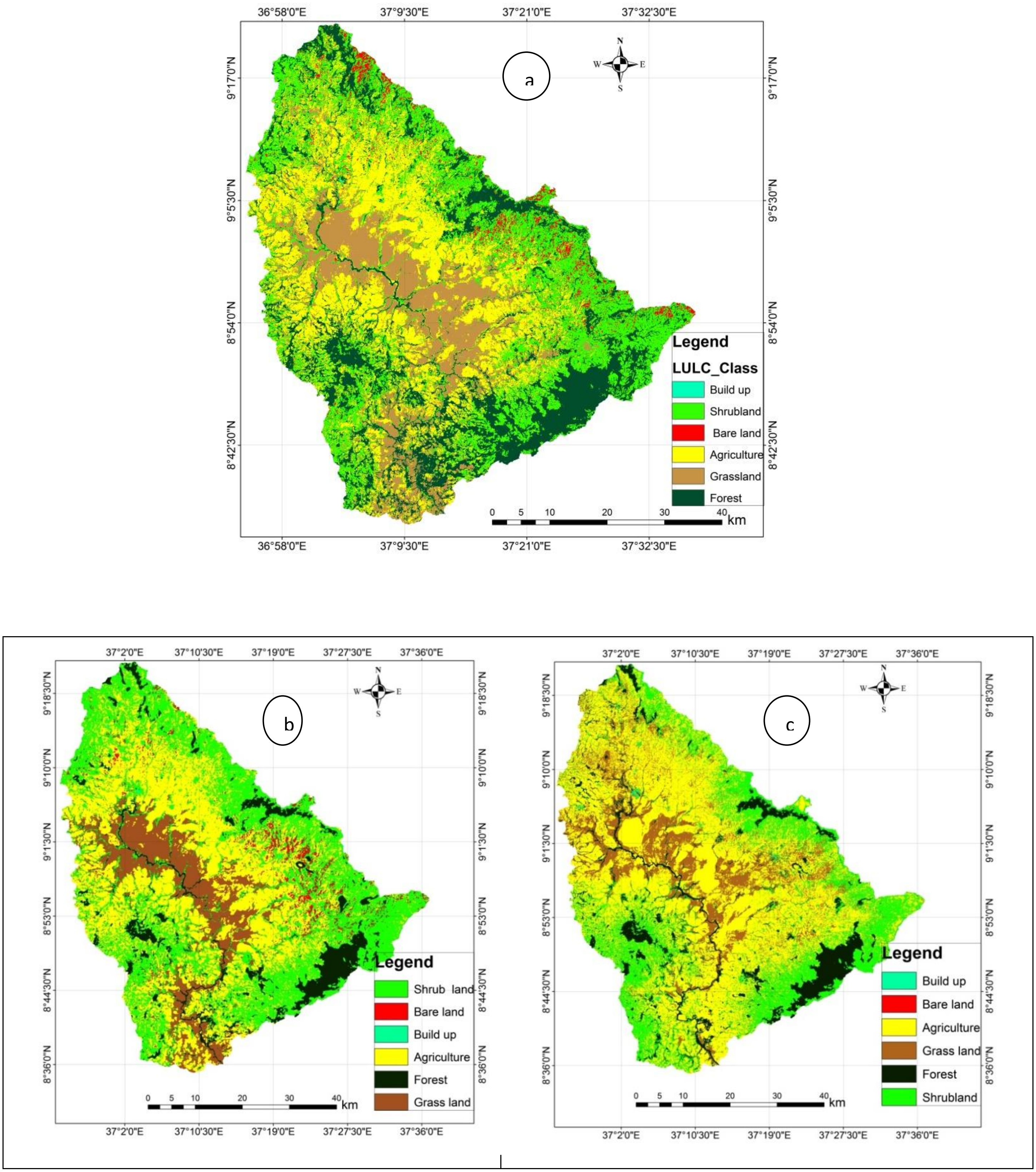


Figure 3.21: Land use/cover maps of 1985(a), 2000(b) and 2019 (c) of watershed

Table 3.9: Land use/cover Classes of 2000 and 2019 area descriptions

	2000		2019	
LULC name	Area km^2	Percent (%)	Area km^2	Percent (%)
Shrub land	1062.9	29.8%	769	21
Bare land	81.9	2.3%	19	0.5
Build up area	21	0.6%	36	1
Agriculture	1390	39%	1940	54
Forest	406.6	11.4%	169	8.5
Grass land	604	17%	533	15

3.4.2. Accuracy assessment

The accuracy assessment was done by generating points from Google earth and field collected ground truth data for the classified images, using ArcGIS. The ground truth point's data and the classification results was combined and statistically analyzed using GIS tool. Accuracy tested was produced for each result the overall accuracy, the users and producers' accuracy as well as the kappa coefficient for three satellite images. The overall accuracy and kappa coefficient for 1985 is 81 and 78 respectively. For the 2000 time series image the overall accuracy is 85 and kappa coefficient is 83. The overall accuracy and kappa coefficient for 2019 is 87 and 85 respectively.

3.5. Groundwater depth

Groundwater depth data was produced from the elevation of static water level measurements in boreholes and springs. The overall static water level measurements which were mostly concentrated in the study area were used for interpolation to produce the groundwater depth grid map (figure 3.22).

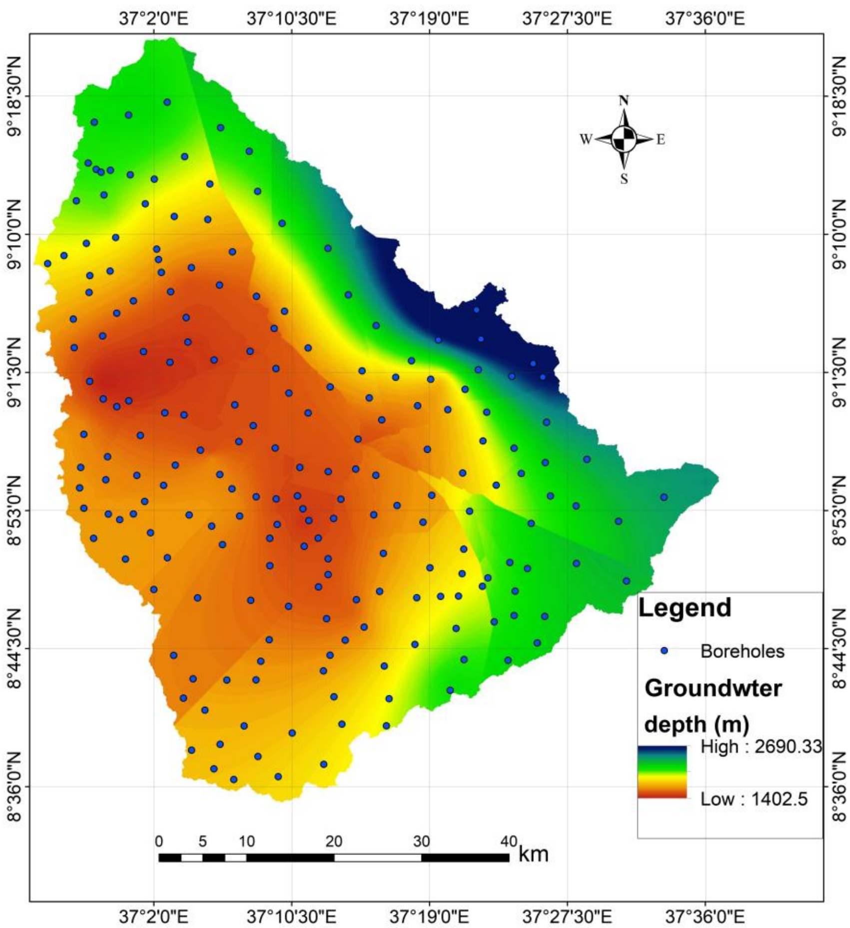


Figure 3.22: Groundwater depth map of the study watershed

3.6. Elevation and Slope

From the Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER), DEM 30m*30m data elevation and slope grid map were prepared by Arc GIS 10.5. ASTER DEM purports to be the highest resolution, 30 m (1 arc second) spacing as compare to SRTM DEM (Guth, 2010). Moreover, the ASTER sensor on board of spacecraft has an along-track stereoscopic capability due to a nadir and 27.6º backward-looking telescopes instrumental setup allows for photogrammetric DEM generation with vertical accuracies of ±15-30m (Toutin, 2008). Topographic parameters such as elevation and slope can be generated using ASTER digital elevation model (DEM) (Jing et al., 2014). The elevation and slope of study area shown in (figure 3.23a and b) respectively.

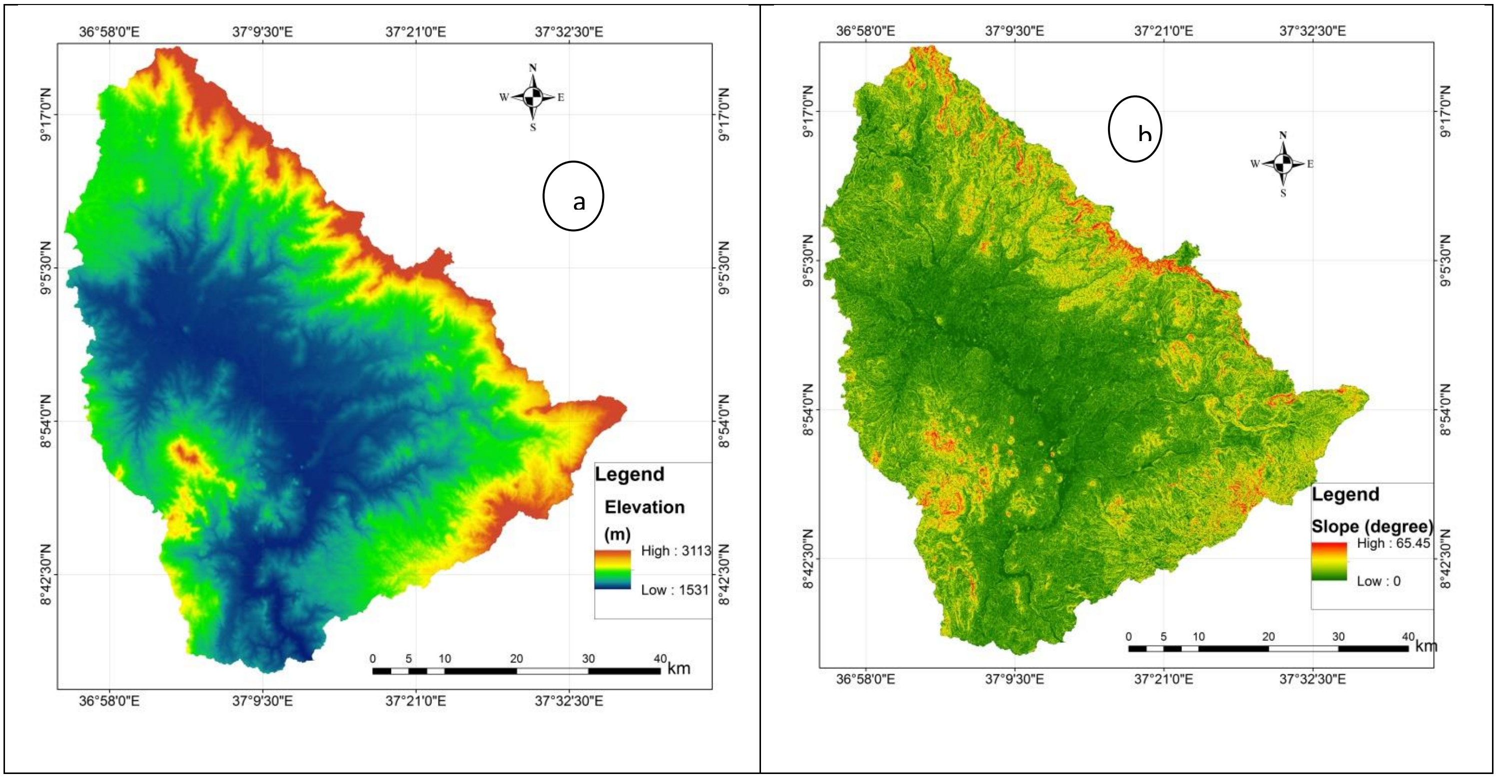


Figure 3.23: Elevation (a) and slope (b) maps of the study watershed

3.7. Wind speed

The wind speed map of the study area was collected from Ethiopian Metrologic agency and interpolated by ordinary kriging. The wind speed value ranged from 0.25 to 2.9 m/s from 1985 to 1996 years used for first phase input periods. Second phase starting from 1997 to 2007 and the third phase from 2008 to2018 were classified based on time series hydro-meteorological data of study area and surroundings. The first, second and third annual wind speed, which used as input to the WetSpass model were shown in (figure 3.24).

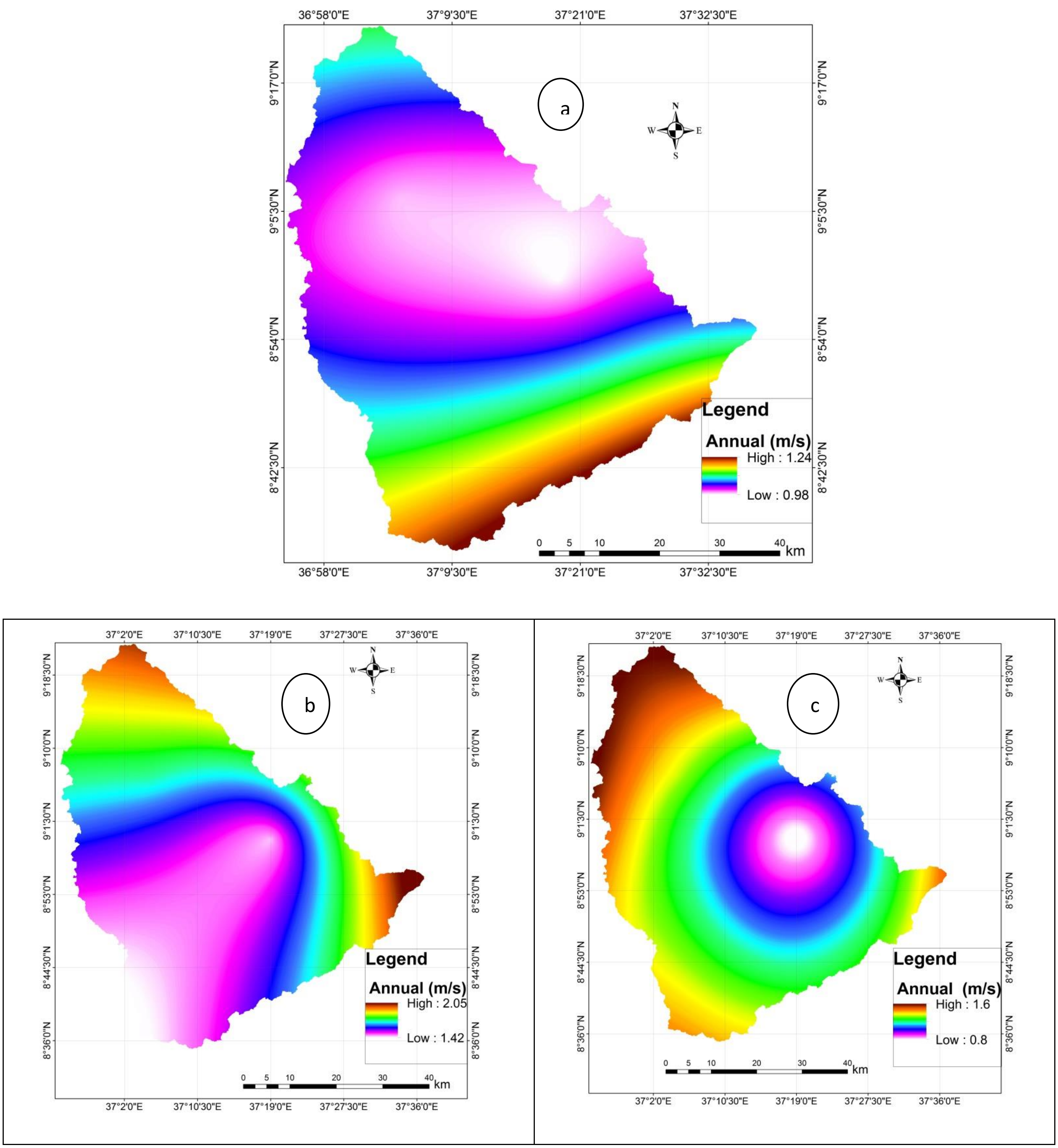


Figure 3.24: First (a), second (b) and third (c) annual wind speed of watershed

3.8. Parameter tables/lookup tables

Look up tables are also important for running the WetSpass model, so that, three parameter tables were prepared, they are land use land cover, soil texture, and runoff coefficient parameters in dbf (database file) format. Basically, the model user guide and some other literature reviews were used to adjust and develop the parameter values to the watershed characteristics. These different biophysical data are obtained and reviewed from scholarly published literature. However, some of the land use/cover parameter values are readjusted so as to fulfill the conditions in the study area. 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.

CHAPTER FOUR

4. RESULTS AND DISCUSSION

4.1 Land use/cover

Land use /cover data are one of the inputs for the Wetspass model. Land use land cover change affects groundwater recharge because of leaf area index (LAI) that influences evapotranspiration and interception. Spatially distributed hydrologic models have advantage in accounting the spatial distribution of the hydrological impact of LULC changes (Wang et al., 2013a, b). The land use/cover was classified into six land use/cover types using supervised image classification technique of maximum likelihood method (figure 3.20). The classification was based on identifying and delineating training sites for each land use /cover type by using Google Earth images and GPS field collected points.

4.1.1 Land use/cover Change Detection

Land use/cover of study area starting from 1985 to 2019 was categorized into three phases, 1985 year map was used at first phase of model inputs while 2000, and 2019, were at second and third phase respectively. Change detection matrix was computed for each phase and change of overall 34 years and identifies what is changed to what. The land use/cover change is a dynamic and continuous process (Mondal et al., 2016) and therefore, extensive research on land use/cover change pattern is important along with their social and environmental implications at different spatial and temporal scales (López et al., 2001). The impacts of LULC change on the sustainability of the ecosystems are becoming increasingly fundamental issues in global and local research. Ethiopia is part of the highly dynamic land use/ cover change where more than 90% of the country's highlands were once forested in the past, and currently, the percentage of forest cover is less than 4% (Hurni et al., 2010).

Human actions seem to lead to the greatest changes in the current state of the earth's surface. Alterations in the surface cover result in changes to the balance of energy, water, and the geochemical fluxes at the local, regional and global level and these changes will inevitably influence the sustainability of natural resources and socio-economic activities (Vescovi et al., 2002). The causes of LULC change are deforestation, agricultural intensification, urbanization and globalization as the prime causes and factors for global and regional land use/ cover changes.

The severity of the dynamic land use/cover changes as a result of population increment, expansion of the agricultural sector and climatic conditions were increasing in Ethiopia (Getachew and Melesse, 2012). The rapid increase in population has led to a change in land use/cover in terms of deforestation aimed at improving agricultural production (Lørup et al., 1998). The hydrology is affected by human activities through the conversion of forest and prairie grasslands to agricultural lands (Mao and Cherkauer, 2009).

To quantify the impacts of land use/cover change on groundwater recharge in the upper Gibe watershed, wetspass model was used to quantify the amount of recharge, runoff, and evapotranspiration of different land use/cover areas. Land use/cover change detection indicated that the agriculture area was increased by 26.61% while the forest was decreased by 12.88%. This is due to the rapid population increase; agriculture-based economies and lack of institutional and policy-based land use management are the major driving forces for the changes in land use/ cover of the watershed. Time series land use/cover changes were described in (table 4.1and figure 4.1).

Table 4. 1: Time series land use/cover changes from 1985 to 2019

Land use/cover Class	**1985**		**2000**		**2019**	
	Km^2	%	Km^2	%	Km^2	%
Agriculture area	976.92	27.39	1390	39	1940	54
Build up area	11.86	0.33	21	0.6	36	1
Shrub land	1029	28.86	1062.9	29.8	769	21
Grass land	663.7	18.61	604	17	533	15
Bare land	121.59	3.41	81.9	2.3	19	0.5
Forest	762.4	21.38	406.6	11.4	269	8.5
Total	**3565**	**100**	**3566**	**100**	**3566**	**100**

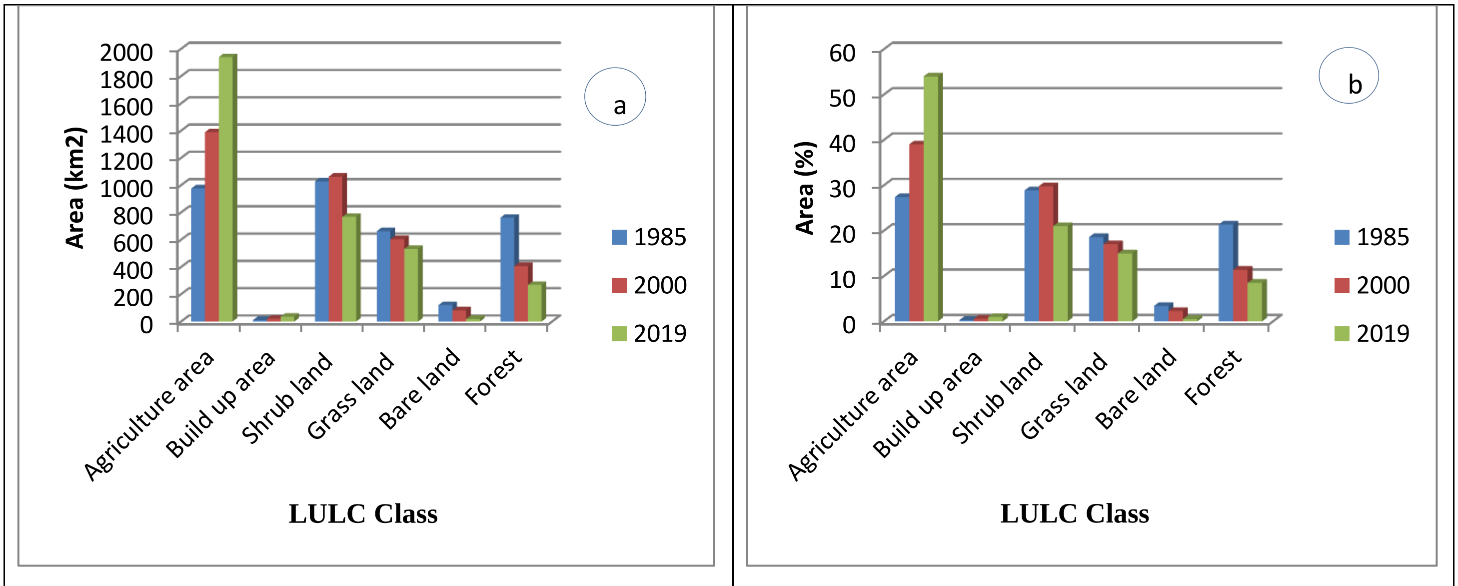


Figure 4. 1: land use/cover change in km^2 (a) and percent (b)

Table 4. 2: Over all land use/cover change description from 1985 to 2019

LULC Class	1985	2019	change	change
	Km^2	Km^2	Km^2	Percent (%)
Agriculture area	976.92	1940	963.08	26.61
Build up area	11.86	36	24.14	0.67
Shrub land	1029	769	-260	-7.86
Grass land	663.7	533	-130.7	-3.61
Bare land	121.59	19	-102.59	-2.91
Forest	762.4	269	-493.4	-12.88

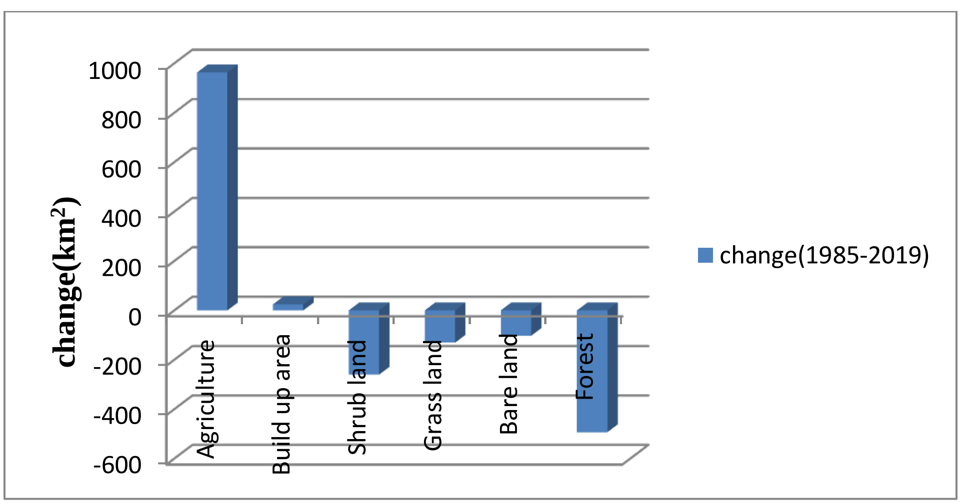


Figure 4. 2: Overall Land use/cover change from 1985 to 2019

The statistical change detection matrix report tables for each class are calculated. The below (table 4.3 and 4.4) shows change of one class to other class in percent, what is changed to what is clearly described, from 1985-2000 and2000-2019 respectively.

Table 4. 3: Change detection matrix from 1985- 2000

Land use/cover categories	change detection matrix from 1985 to 2000					
	Build up	Shrub land	Bare land	agriculture	forest	Grass land
Build up	75	8	1.4	6.8	1	4.5
Shrub land	0.07	59.7	3	29.9	1.7	3.7
Bare land	0.25	38.5	16	42.6	0.26	0.7
agriculture	0.15	15	2	75	0.33	5.9
forest	0.07	48	0.35	14	31.8	4.5
Grass land	0.03	9.8	0.5	33.6	0.33	55

Table 4. 4: Change detection matrix from 2000- 2019

Land use/cover categories	change detection matrix from 2000 to 2019					
	Build up	Shrub land	Bare land	agriculture	forest	Grass land
Build up	76.6	8.9	0.6	2.5	1.5	8.5
Shrub land	0.44	43.7	0.19	38	6	10.6
Bare land	0.2	14	3.2	69.5	0.27	12.6
agriculture	0.5	10	0.2	77.8	0.49	10.7
forest	0.06	10.6	0.02	7	79.8	2.3
Grass land	0.12	5.8	0.05	44.5	3.8	45.6

4.2. Hydro_ meteorological data analysis

The hydrometeorology maps of the study area were analyzed by interpolation and prepared as a grid map. Precipitation, temperature, wind speed and PET grid maps were prepared in order to quantify water balance of study watershed. The three-time steps of meteorological element data were quantified to identify the trend of climate variability and the impact on groundwater recharge.

4.2.1. Precipitation

The annual average rainfall ranges of the study area are between 1309 to 1595, 1158 to 1453 and 1135 to 1439 mm for first second and third phase, respectively. Trend analysis of annual rainfall in Ethiopia stated by (IPCC, 2007) shows that rainfall averaged over the whole country a declining has been observed. The seasonal and annual rainfall variations are results of the macro-scale pressure systems and monsoon flows which are related to the changes in the pressure systems (Tesfaye, 2003).

Precipitation is a key physical process that transports water from the atmosphere back to Earth's surface and links weather, climate, and hydrological cycle. The rainfall data is variable both in amount and distribution within the watershed seasonally and annually. For example, the highlands of Ethiopia experienced wetter conditions during the 1970s and drier condition during 1980s and 1990s (Mekonnen and Bewket, 2014a). Some studies in Ethiopia have identified downward trends in most parts of the country - mainly in the eastern, southern and southeastern regions (Seleshi and Camberlin, 2006; Omondi et al., (2014) also state the presence of statistically significant decreasing trends in total precipitation in wet days greater than one mm over the Horn of Africa Region. IPCC projections indicated that a 5-10% decrease in precipitation amount during the June-August (JJA) season in East Africa (IPCC, 2014). Ethiopia also shares these dynamics as one part of the East Africa country. Whatever the case, any change in the average global temperature will affect the spatial and temporal occurrence of rainfall.

This, in turn, will affect hydrological cycles, water balances, and the resulting availability of water resources. Intergovernmental Panel on Climate Change (IPCC) findings indicate that a country like Ethiopia will most likely be more vulnerable to climatic change because of its particular climatic, hydrologic, and economic circumstances. For example, Abdo, (2009) examine changes to rainfall in the Blue Nile Region of Ethiopia using the single HadCM3 GCM and reported decreasing trends at the beginning of the summer rainfall season. The National Metrological Agency (2001) revealed that in Ethiopia climate variability and change in the country is mainly manifested through the variability and a decreasing trend in rainfall and increasing trend in temperature.

4.2.2. Temperature

Maximum and minimum, average temperature data are among the hydro meteorological data collected from the Ethiopian Meteorological Service Agency (NMA). Starting from 1985 to 2018 data of temperature was analyzed at three phases by an interval of 11 years. In the first phase the meteorological data was used from 1985 to 1996, 1997 to 2007 and 2008 to 2018 for the second and third phase respectively. Throughout 33 years increasing of temperature were observed within the watershed. The first phase result was ranging from 16.85 to 19.95 °c while, from 17.09 to 20.96 °c and 17.16 to 21.58 °c is at the second and third phase respectively. Precipitation and temperature are two of the most important variables in the field of climate sciences and hydrology frequently used to trace the extent and magnitude of climate change and variability (IPCC, 2007). Temperature is - degree of hotness or coldness measured on a definite scale. Different from other tropical regions, East Africa experiences complex temperature conditions due to the effects of its varying topography.

The temperature in the region ranges from very hot (>40°c) at the Afar depression, Ethiopia (Awulachew et al., 2010) to very cold at the peak of Mount Kilimanjaro (Omondi et al., 2014). In Ethiopia, the mean annual temperature varies between less than 10°c over the Northwest, Central and Southeast highlands to about 40°c in the lowlands of Afar, eastern and southeastern regions (NMA, 2007; Awulachew et al., 2010) while In Kenya the central highland regions are substantially cooler than the coast, with the coolest (highest altitude) regions at 15°c compared with 29°c at the coast. There is also a year-to-year variation of the annual maximum and minimum temperatures in the region of East Africa.

Trend analysis for the last four to five decades has shown the presence of increasing trends in temperature from climate baselines. Several studies have reported a warming trend across the region at a rate broadly consistent with wider African and global trends (Christy et al., 2009; Conway and Schipper, 2011; Mengistu et al., 2014). In Kenya, mean annual temperatures have increased by 1.0°c since 1960, at an average rate of 0.21°c per decade (McSweeny et al., 2009). Omumbo et al. (2011) also reported warming trends in maximum, minimum and mean temperatures at Kericho in Kenya during the period 1979–2009. Using data from 60 stations, Christy et al. (2009) reported the presence of statistically significant upward trends in minimum temperature in the Kenyan highlands. In Uganda, the seasonal temperature has shown increasing trends at the rate of 0.9°c during March to May and September to October and 0.3°c during the dry season, June to August (Nandozi et al., 2012). In Ethiopia also NMA, (2007) reported that the average annual minimum and maximum temperatures increased at rates of 0.25°c and 0.1°c per decade during 1950-2000 respectively. Meikle, (2010) has also reported a warming trend on the minimum temperature at 0.37°c per decade in Ethiopia for the period 1951-2006. In the Ethiopian Blue Nile Basin, Mengistu et al., 2014 reported the presence of statistically significant increasing trend for minimum temperature, while contrasting trends for maximum temperatures at the annual and seasonal time scales.

Ethiopia, compared to the national average as well as data from the highland regions in the country, the temperature increase in the semi-arid lowland regions has been more pronounced. For example, in the southern lowland regions of Borena, Guji and South Omo temperature has increased by 0.4°c per decade during 1950-2000 (Aklilu, and Alebachew, 2009). Almost all the General Circulation Model (GCMs) and Regional Climate Models (RCMs) projections for the region (Conway and Schipper, 2011;Nikulin et al., 2012; Endris, 2013; Buontempo et al., 2014) indicate the future incidence of significant temperature increases across East and Horn of Africa. Climate projections generated by UNDP (cited in DFID, 2009) for Ethiopia, highlight the likelihood of mean temperature increases of 1°C in the 2020s and up to 3.9°c to 2080s. Using a multi-model dataset, the National Meteorological Agency (NMA) of Ethiopia also indicates that the mean annual temperature is likely to rise significantly when compared with the 1961-90 level by a maximum of 1.1°c by 2030, 2.1°c by 2050 and 3.4°c by 2080 (NMA, 2007).

4.2.3. Potential evapotranspiration

The annual PET ranges from 755 to899.62 for first, 764.64 to 964.36 and767 to1014 for second and third phase respectively (figure 3.18a to c). Potential evapotranspiration is described as the quantity of water evaporated per - unit area and time from an idealized, extensive free water surface under existing atmospheric conditions. Potential evapotranspiration (PET), as defined by the Soil Science Society of America (2008), is the “combined loss of water from a given area, and during a specified period of time, by evaporation from the soil surface and by transpiration from plants" Evapotranspiration is the loss of water to the atmosphere through evaporation from all surfaces; including evaporation from free water surfaces, soil, and manmade surfaces and transpiration from plants (Houghton, 1985). Evapotranspiration is the sum of evaporation and plant transpiration from the Earth's land and ocean surface to the atmosphere. Evaporation accounts for the movement of water to the air from sources such as the soil, canopy interception, and water bodies. It also the loss of water from the soil through evaporation from the soil surface and transpiration from the leaves of the plants growing on it. Factors that affect the rate of evapotranspiration include the amount of solar radiation, atmospheric vapor pressure, temperature, wind, and soil moisture.

Evapotranspiration from the land surface plays a key role in maintaining the balance of land surface water-lakes-reservoirs and the energy balance of the earth's surface (Brutsaert et al., 2015). The higher the air temperature, the more vapor it can hold, and similarly if the temperature of evaporating water is high, it can more readily vaporize (Shaw, 1994). A developing country like Ethiopia in East Africa may also experience greater variability of precipitation and evapotranspiration due to climate change and hence greater adverse impacts on its economy (IPCC, 2012). Evapotranspiration accounts for most of the water lost from the soil during the growth of a crop.

4.2.4. **Wind speed**

Wind speed is a fundamental atmospheric quantity caused by air moving from high to low pressure, usually due to changes in temperature. Wind speed varies with time. It also varies with the height above the ground or the height above the sea surface. For these reasons, the averaging time for wind speeds and the reference height must always be specified. The annual value of the first phase is ranging from 0.98 to 1.24, 1.42 to 2.05 and 0.8 to 1.6 m/s for second and third respectively. The average wind speed values of each annual are interpolated and converted to grid maps using ordinary kriging interpolation method. The grid maps of wind speed are converted to ASCII file format and used as input parameters in WetSpass model

4.3. WetSpass Model Outputs

WetSpass gives various hydrologic outputs on a yearly and seasonal (summer and winter) basis (Batelaan and De Smedt 2001). The spatial variations of recharge, actual evapotranspiration, and surface runoff can be obtained as a function of land-use/cover, soil types, and climate variability. Accordingly, the land-use/cover and soil maps were combined with surface runoff, recharge, and evapotranspiration map to visualize the impact of different land covers and soil texture on evapotranspiration, surface runoff and groundwater recharge. The water balances are significantly influenced by land use/cover change pattern via its effect on transpiration, interception, evaporation, and infiltration (Öztürk et al., 2013).

The results of the WetSpass model were comprised of digital images of the spatial distribution of annual average values of the water balance components such as surface runoff, actual evapotranspiration (AET), interception, transpiration, soil evaporation, and recharge were produced for long term of the 33(4) year period from 1985 to 2019 of study area. These maps are raster format in which every pixel represents the magnitude of the respective component of the water balance. The model runs three times for first, second and third phase. The results were discussed below one by one.

4.3.1. Surface runoff

The simulated annual surface runoff in the watershed ranges from 2.4 mm to 1080.96 mm with a mean of 292 mm and it account 20% of the annual average precipitation (1461) for the first phase. For the second phase, it ranges from 1. 2 mm to 987 mm with a mean of 290 mm and account 21.32% of the annual average precipitation (1360) while it ranges from 2mm to 975 mm with a mean of 292 mm and it accounts 22.4% of the annual average precipitation (1303) for the third phase (figure 4.3a-c).

According to Batelaan and Bewket, (2007), surface runoff is dependent on the availability of vegetation, soil type and slope of the watershed. The WetSpass model uses the runoff coefficient method for the estimation of surface runoff. The annual surface runoff of the upper gibe watershed was varied spatially with varied land use/cover, climate, soil types and topography characteristics. The land use/ cover change assessment shows that build up area (0.67%) and agriculture area is highly expanded by (26.6%), when forest (-12.88%), shrub (-7.865) and grassland (-3.61%) were highly decreased.

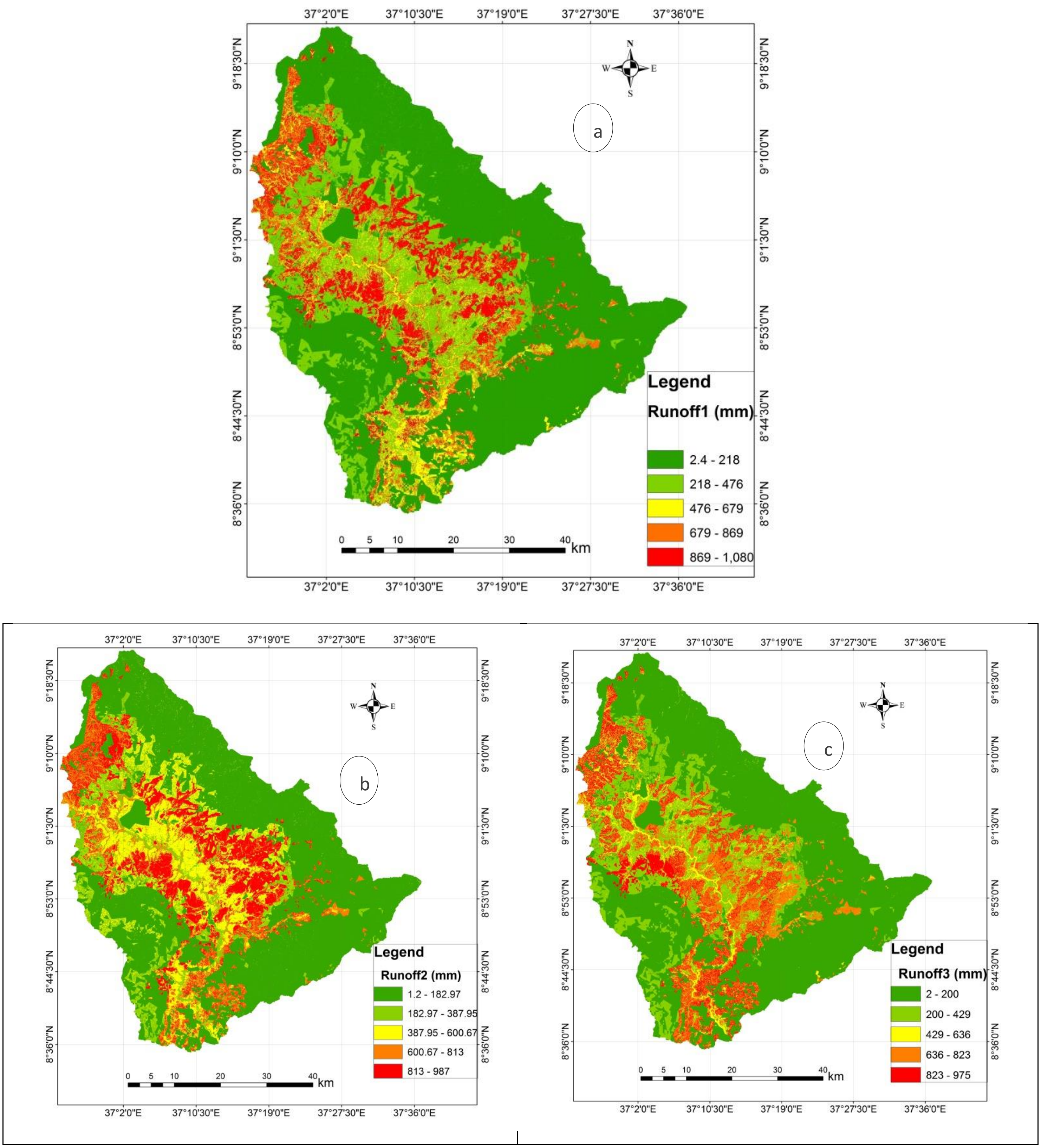


Figure 4. 3: First (a), second (b) and third (c) annual surface runoff

Memarian et al., (2014) and Gebremicael et al., (2013) showed that the expansion of agriculture land use causes a significant change in surface runoff. Both climate and land use change have adverse implications on the natural hydrologic system in terms of variation in the runoff, evapotranspiration (ET), subsurface flow, infiltration. (McColl and Aggett, 2007). The study conducted in Ethiopia and Eritrean highlands by Hurni et al., (2005) found an increase in surface runoff when the natural forest was converted to farmland. Other studies reported a reduction of infiltration and groundwater recharge associated with increased surface runoff (Bewket; Gebresamuel et al., 2010 and Pan et al., 2011).

4.3.2. Actual evapotranspiration (AET)

Actual evapotranspiration is the quantity of water that is actually removed from a surface due to the processes of evaporation and transpiration. Actual evapotranspiration is the sum of evaporation and plant transpiration from the Earth's land surface. It depends on atmospheric, soil and plant factors. The measurement of Actual evapotranspiration is a complex task. Direct measurement of the actual evapotranspiration (AET) is difficult; hence it is usually estimated from the potential evapotranspiration (PET). The model calculates the total actual evapotranspiration (AET) as a sum of water intercepted by vegetation, the transpiration of the vegetative cover and the evaporation from the bare soil between the vegetation. Evaporation from soils, water bodies, and plant interception and transpiration are considered collectively as Actual evapotranspiration (AET).

Total precipitation is not reaching the ground; some are stopped by vegetation, a process known as an interception. The proportion of the precipitation that does not reach the ground, the interception loss, depends on the type of vegetation, its age, and density of planting and the season of the year. Interception has been studied widely, and the literature cites interception values for many vegetative types. In excess of 20% to more than 40% of annual precipitation can be intercepted in forests while grassland ecosystems can intercept 10 to 20% of gross precipitation in periods when maximum growth has been attained (Brye et al., 2000). Where precipitation reaches the ground some part is evaporated and transferred as vapor from the land or ocean to the atmosphere. The rate of evaporation depends on temperature, humidity and wind speed. The greater the humidity the less the evaporation. The wind carries moist air away from the ground surface, so wind decreases the local humidity and allows more water to evaporate.

The actual evapotranspiration can be calculated in the WetSpass model as the sum of evaporation of the precipitation intercepted by the vegetation, transpiration by the vegetation, and evaporation from bare soil and open water bodies (Batelaan and De Smedt, 2001).The land surface evaporation rate depends on the type of soil and the extent to which the ground is saturated with water. Evaporation from a saturated sandy soil can take place nearly as quickly as it can from open water; whereas evaporation from a saturated clay soil is slower Total actual evapotranspiration (ET_{tot}) is expressed in Equation (11).

$$ET_{tot}=I+T_V+E_S \qquad (11)$$

where 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. Evaporation depends on atmospheric, soil and plant factors. Interception is occurred due to the presence of vegetation when rainfall rains in the watershed. Evapotranspiration takes place as a result of transpiration from vegetation cover and evaporation from water as well as soil surfaces. Interception and transpiration simulated during WetSpass model running process for the watershed were shown (Figure 4.4 and 4.5a-c) respectively below.

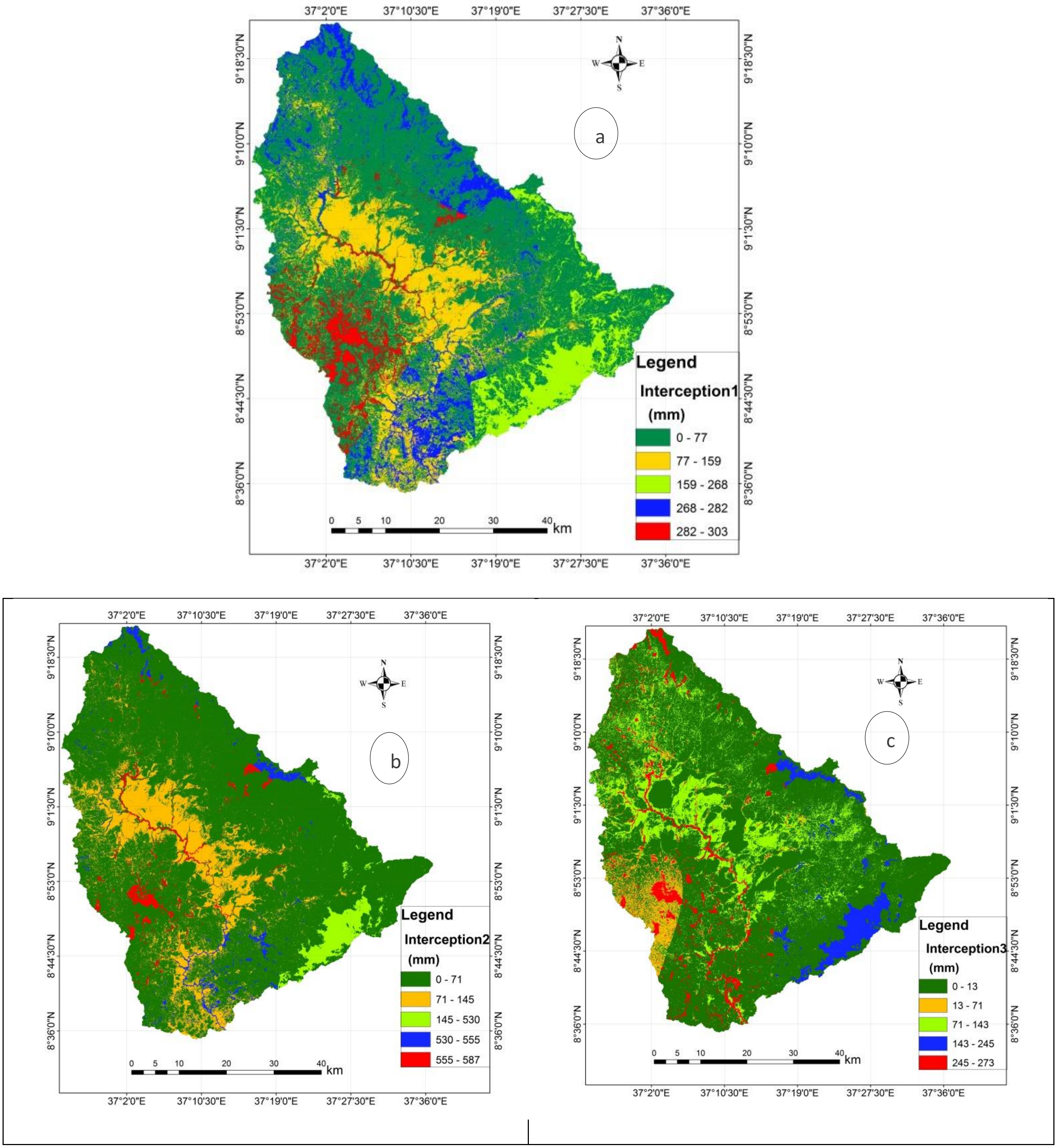


Figure 4. 4: First (a), second (b) and third (c) annual Interception

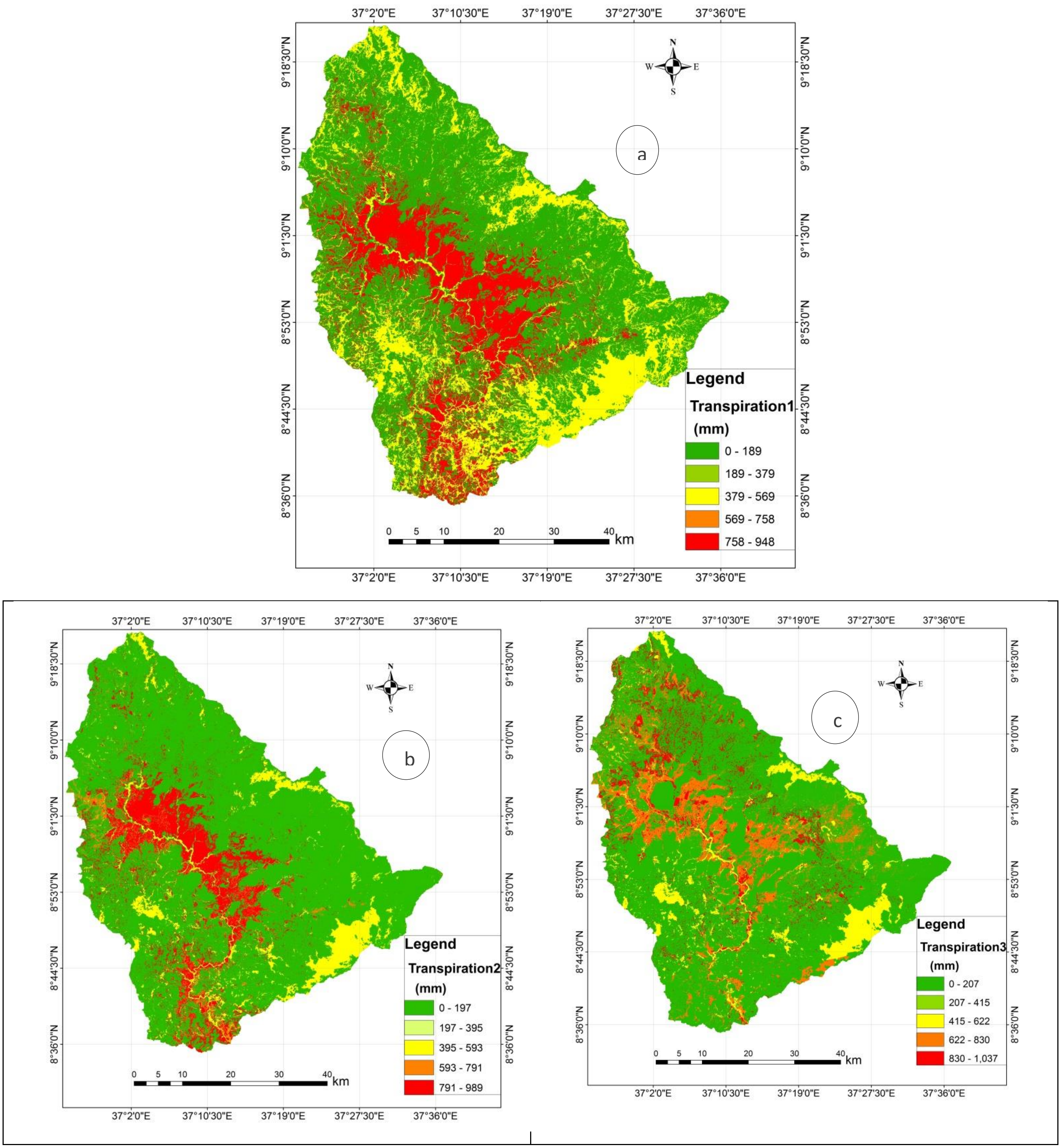
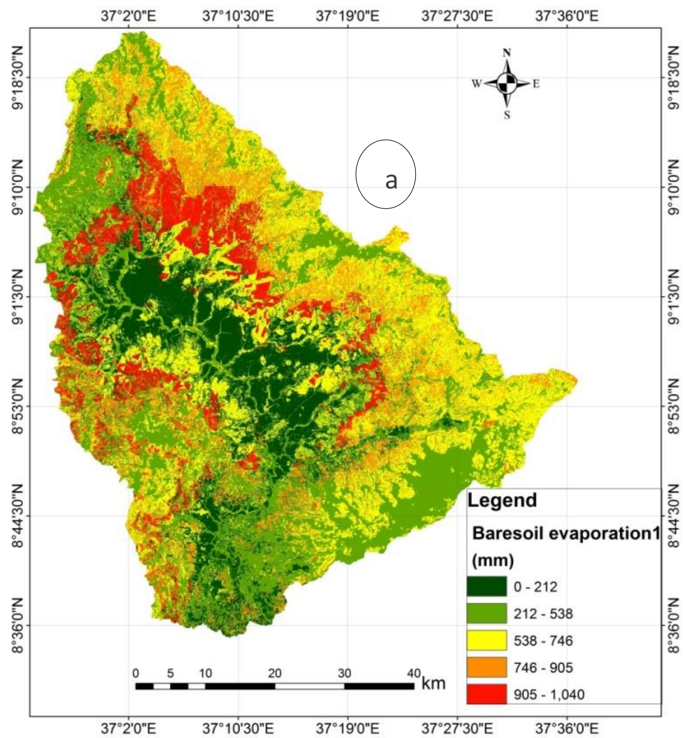


Figure 4. 5: First (a), second (b) and third (c) annual Transpiration

In addition to spatial variability of the important land surface characteristics such as topographic elevation, slope, vegetation, as well as climatic parameters including precipitation, temperature, and PET distribution the soil moisture dynamics also influence the hydrological processes. (Akbari and Singh, 2012 ; Wijesekara et al., 2012). Wet and dry of soil composition with land use/cover change and climate variability have no equal influence on evaporation. Bare-soil evaporation is high when soil is wet and underestimates bare-soil evaporation when soil is dry. The bare soil evaporation at first phase range from 0 to 1040 mm while 0 to 1084 mm for second and 0 to 1068.6 mm at the third phase (figure 4.6a to c).

Table 4. 5: Summary of annual water balance components for first phase

Water balance component	Annual value (mm)			
	minimum	maximum	mean	Standard deviation
Precipitation (PCP)	1309	1595	1461.6	56
Evapotranspiration (ET)	354	1099	818	171
Runoff (Ro)	2	1080	292.67	326
Recharge (Re)	0	856	350.6	276
Water balance	PCP-ET-Ro-Re=1461-818-292.67-350.33= 0.0			



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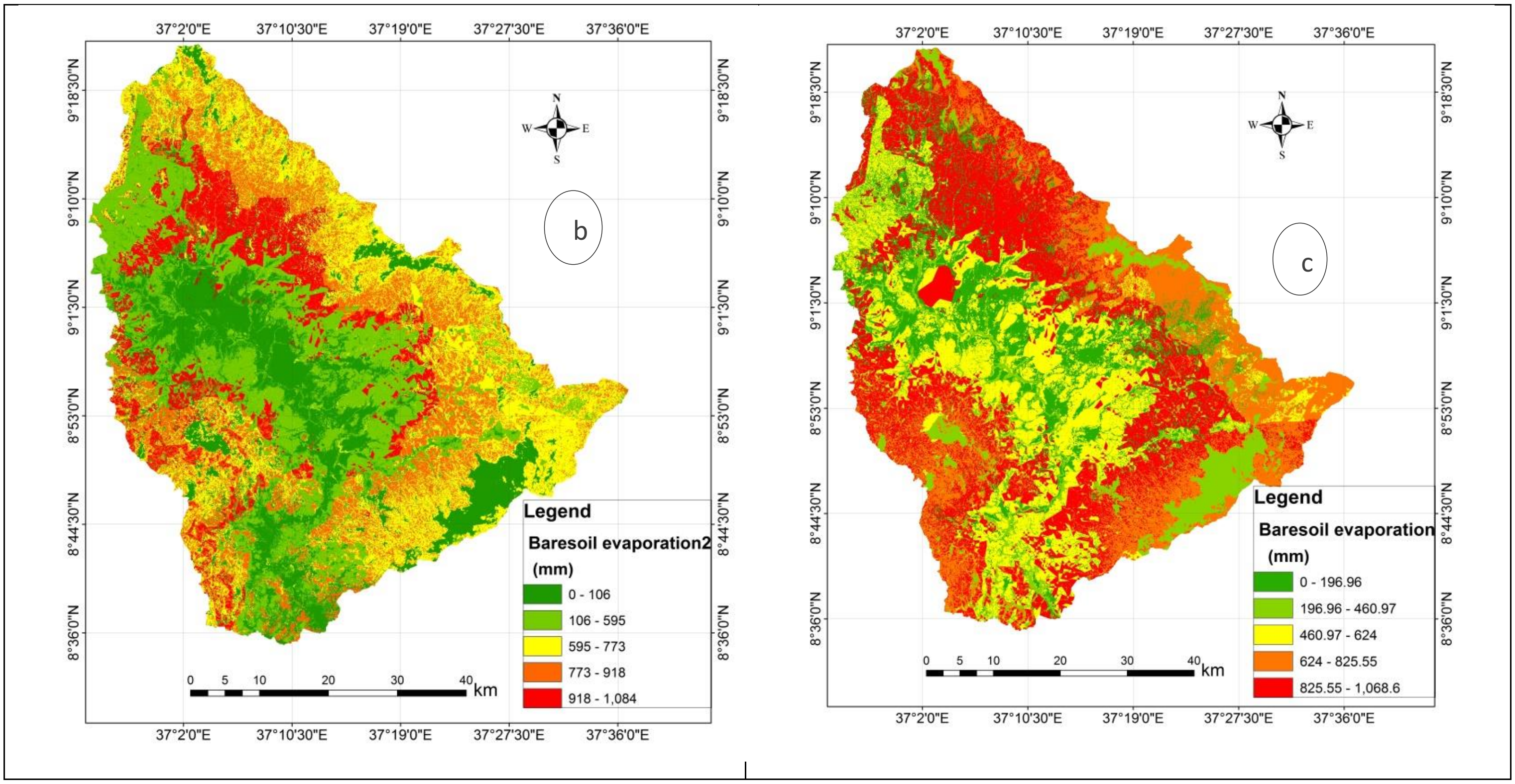
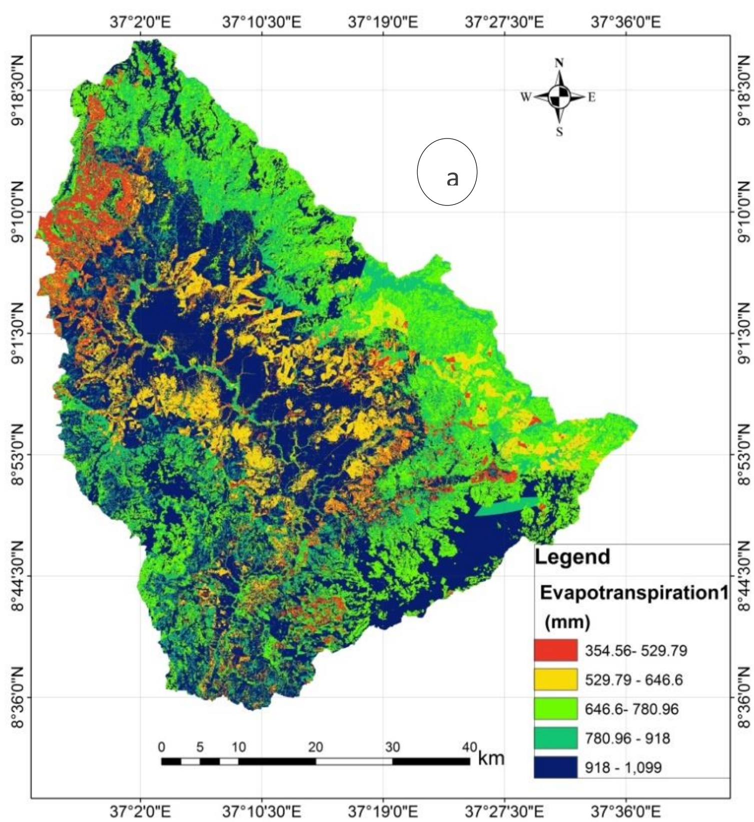


Figure 4. 6: First (a), second (b) and third (c) annual bare soil evapotranspiration

Hydro-climatic variables and the dynamic changes in land use/cover and their spatial distribution influence annual evapotranspiration of a watershed. WetSpass simulates the mean annual evapotranspiration of the watershed to be 818 mm with 354.56 mm and 1099 mm as a minimum and maximum, respectively for the first phase. This accounts 56% of the watershed annual precipitation. The mean annual evaporation for the second and third phase is 783 mm and790 mm respectively. It counts 57.57% and 60.6% of total precipitation of area for the second and third phase respectively (figure 4.7a to c). The results revealed that evapotranspiration is the major source of water loss in watershed than surface runoff and recharge.

Significant variation of evapotranspiration has occurred due to land use land cover and leaf area index change (Li et al., 2015). On a global basis, the mean land surface evapotranspiration (ET) accounts for approximately 60% of mean precipitation (Rivas et al., 2004). Many studies have shown that at least 60% of surface precipitation will return to the atmosphere through evapotranspiration and the value that rises to over 90% in drought areas. Evapotranspiration (ET) is a major component of the hydrologic cycle, and as such, its quantity is of major concern to water resource planners around the world.

The long-term average quantities of water available for human and ecological consumption in any region are roughly the difference between the mean annual precipitations and mean annual ET (Postel et al., 1996) with the latter frequently a majority fraction of the former. Thus, quantifying ET is critical to quantifying surface runoff to reservoirs or recharge to aquifers (Healy and Scanlon, 2010). Quantifying ET is also used for studies of ecosystem water balances components (Sun et al., 2011a). Measurement of evapotranspiration (ET), although possible directly at the land surface is usually made either indirectly by quantifying the energy balance at a local land surface or by eddy covariance at some distance above the land surface (Mu et al., 2007).



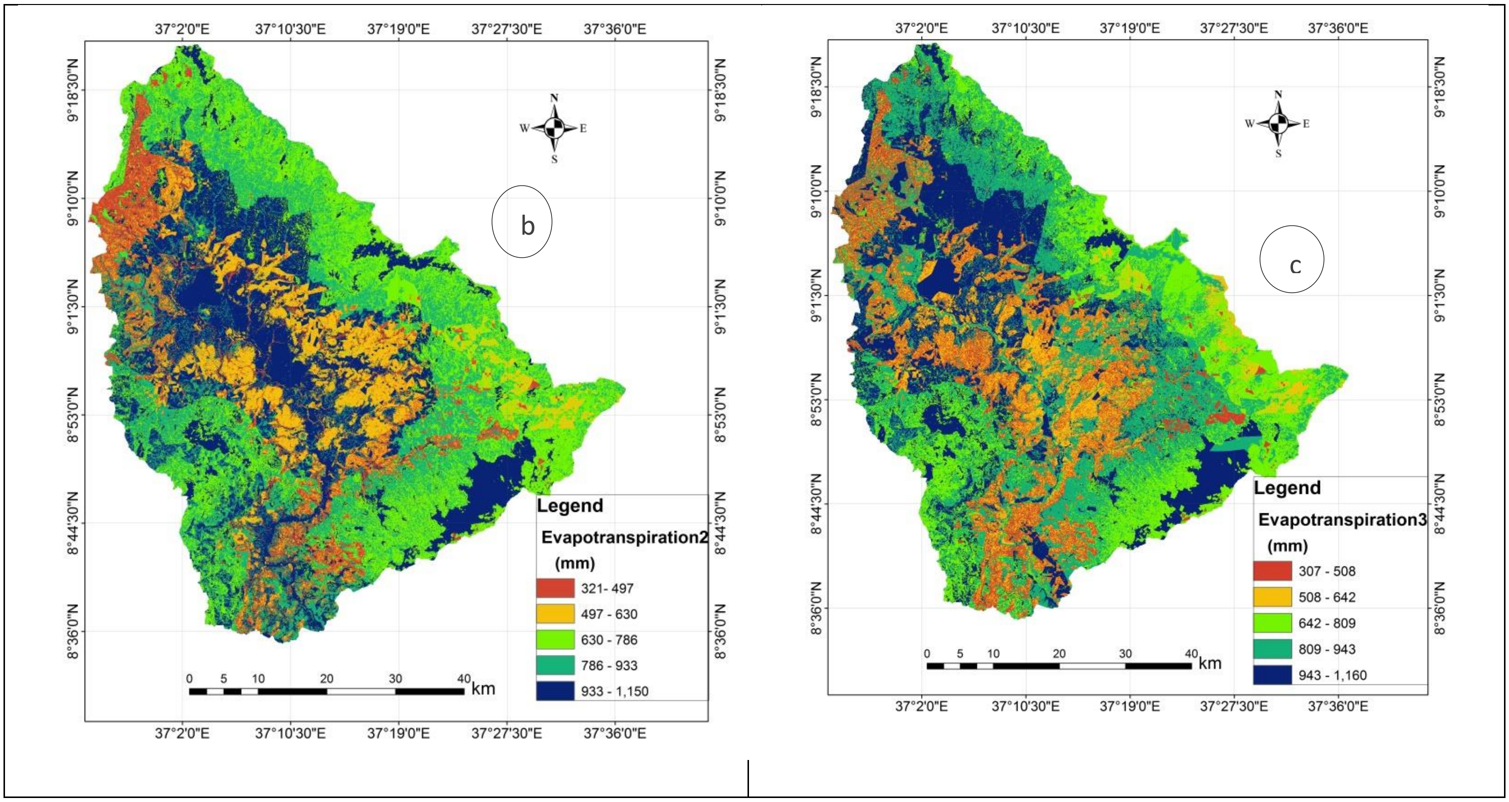


Figure 4. 7: First (a), second (b) and third (c) annual Evapotranspiration

4.3.3. Groundwater recharge

The findings show that both land use/cover change and climate variability contribute to changes in the water balance components, but each driver has a specific contribution to the each water balance components alterations. Wetspass quantify annual recharge at three times period for the upper Gibe watershed (Figure 4.8 a–c). The estimated annual groundwater recharges under land-use/cover change and variable meteorology ranges from 0 to 856 mm, with an average value of 350 mm for the first phase while ranges from 0 to 780 mm with average 287mm for the second phase. On the other hand, it ranges from and 0 to 696 mm with the average 221 mm for the third phase. This shows that 24%, 21.11% and 17% of the mean annual precipitation recharge the groundwater for the first, the second and the third phase respectively. The mean annual spatial groundwater recharge is variable depending on the factors that govern groundwater infiltration rate. The time series variations of land use/cover, rainfall, temperature and spatial variations of soil texture are the main factors leading to this change.

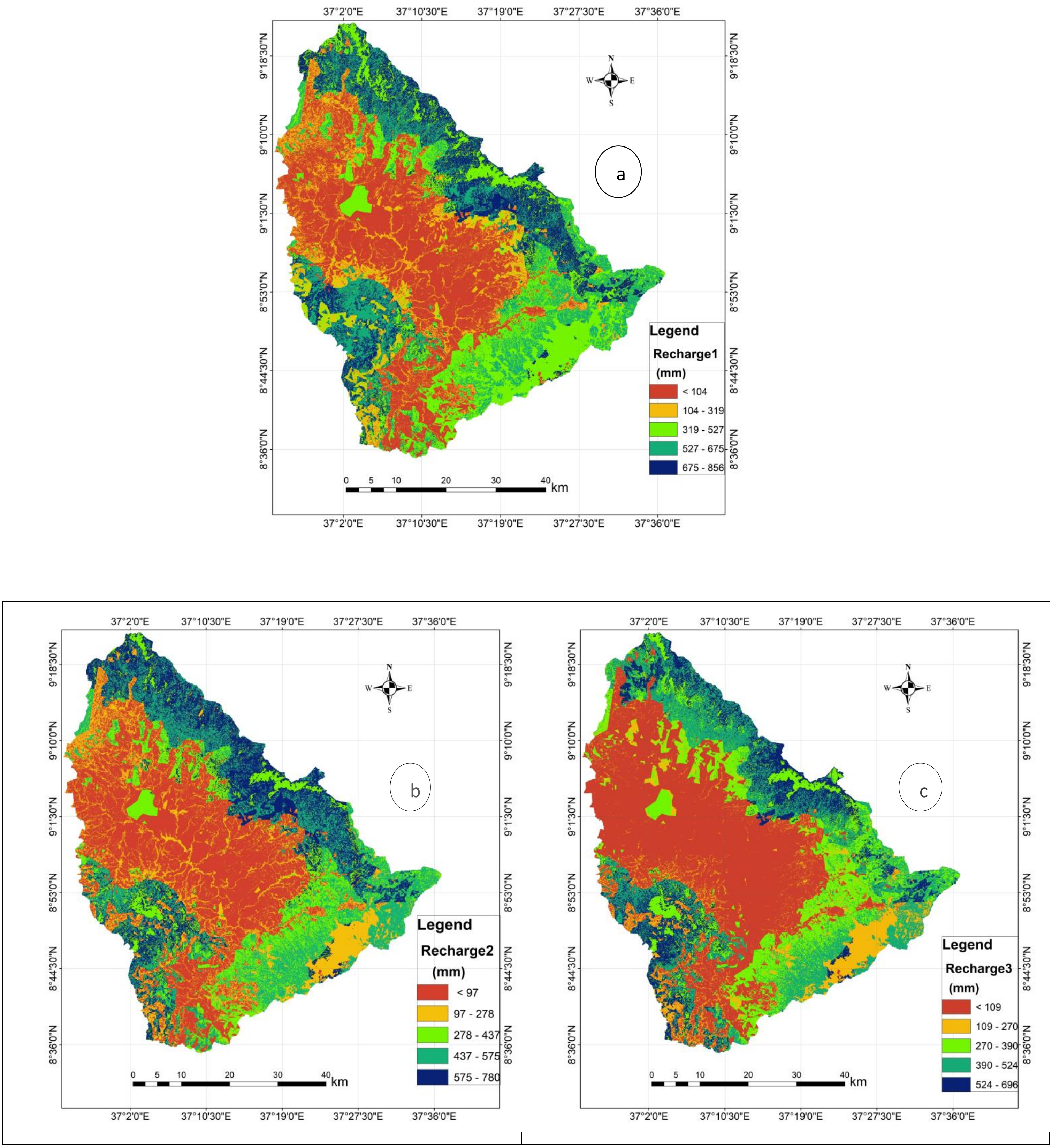
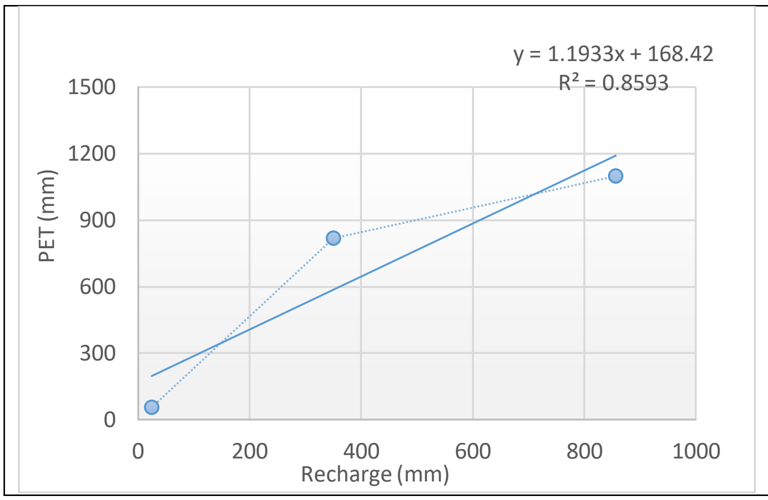


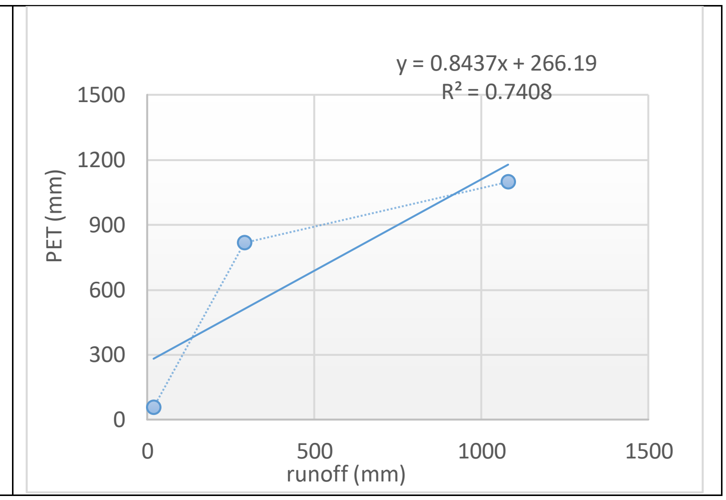
Figure 4. 8: First (a), second (b) and third (c) annual Groundwater recharge

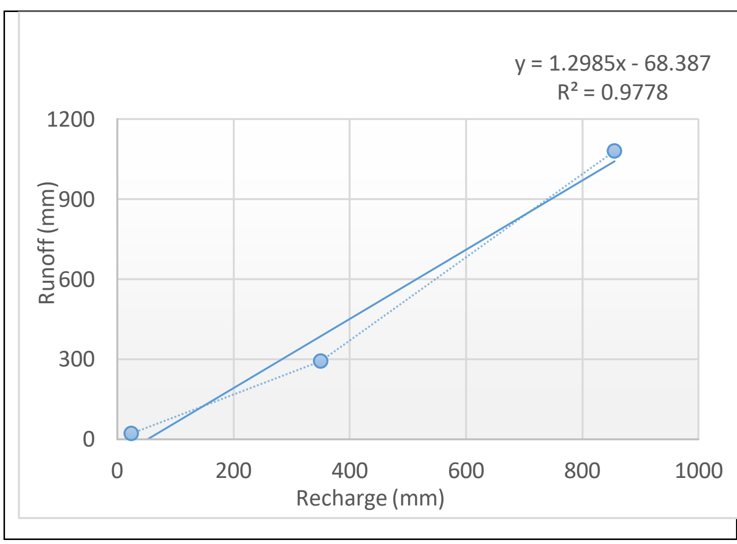
The WetSpass model quantifies annual long term spatial distribution amounts of groundwater recharge of the watershed by subtracting the annual surface runoff and evapotranspiration from the annual precipitation. Groundwater recharge was facing increasing pressure as build up area and agriculture activities was increasing and climatic variability condition are changing all over the watershed. The land use/ cover change assessment shows that build up area and agriculture area is highly expanded, while forest, shrub and grassland were highly decreased. This result shows an increase in paved area and agriculture area which lead to increase in runoff volume and decrease in time of concentration and in percolation rate, which directly affect, the groundwater recharge of study area.

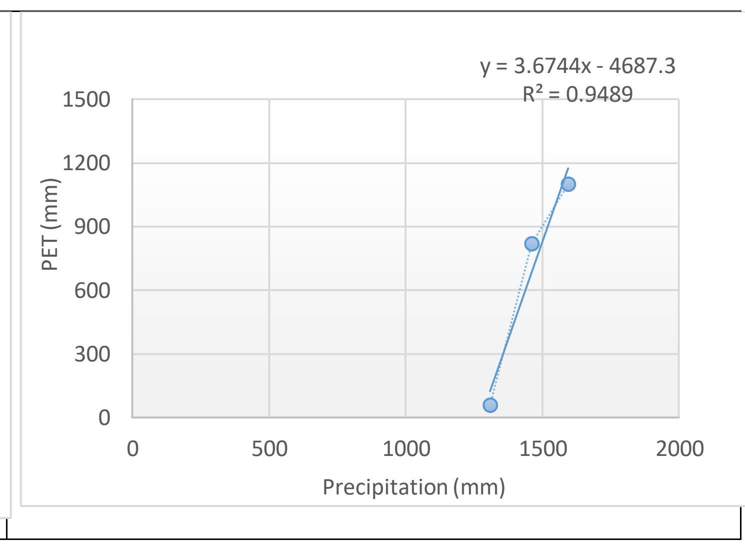
In addition due to excessive climate variability, increments of temperature and reduction of rainfall trend contribute in groundwater recharge amount are going down in upper Gibe watershed. Agriculture activity is intensively expanded within the watershed. These expansions accelerate surface runoff and reduce ground recharge of the study area. The expansion of agriculture and removal of forests reduces the infiltration opportunities which, in turn increases the amounts of water leaving the area as surface runoff and decrease infiltration to groundwater recharge (Kashaigili, 2013). The model simulates the spatial variability of hydrologic processes in respect of physically based spatial variability of land surface characteristics such as topographic elevation, slope, aspect, vegetation, soil as well as climatic parameters including precipitation, temperature, humidity, wind speed and potential evapotranspiration distribution. When compared to empirical and analytical models, the physically based models are characterized by higher intrinsic accuracy for quantifying the effect of land use/cover disturbances or climate variability with water movement (Shen and Phanikumar, 2010).

The amount of infiltration to the groundwater depends on the vegetation cover, slope, and soil composition, depth to the water table, and the presence or absence of confining beds (Al Kuisi and El-Naqa, 2013). Natural forest cover, flat topography, permeable soils, a deep water table and the absence of confining beds favors recharge. The WetSpass model quantifies the long-term average spatially distributed groundwater recharge depending on soil texture, frequent land-use/cover, slope and variables meteorological conditions. Land use/cover and climate changes have a great influence on the hydrological response of a watershed (Kashaigili and Majaliwa, 2013; Kirby et al., 2016). The hydrological processes which are affected by such changes include evapotranspiration, infiltration; surface runoff and groundwater recharge (Natkhin et al., 2015). Gadisa Deyassa, (2008) estimates the recharge of upper Gibe watershed to be 341mm using water balance method while 376mm using chloride mass balance method. In addition Tesfaye chernet, (1982), describes that western high land of Ethiopia receives high recharge that can reach about500mm/year on average. Therefore, the result of this study is in line with the previous results.









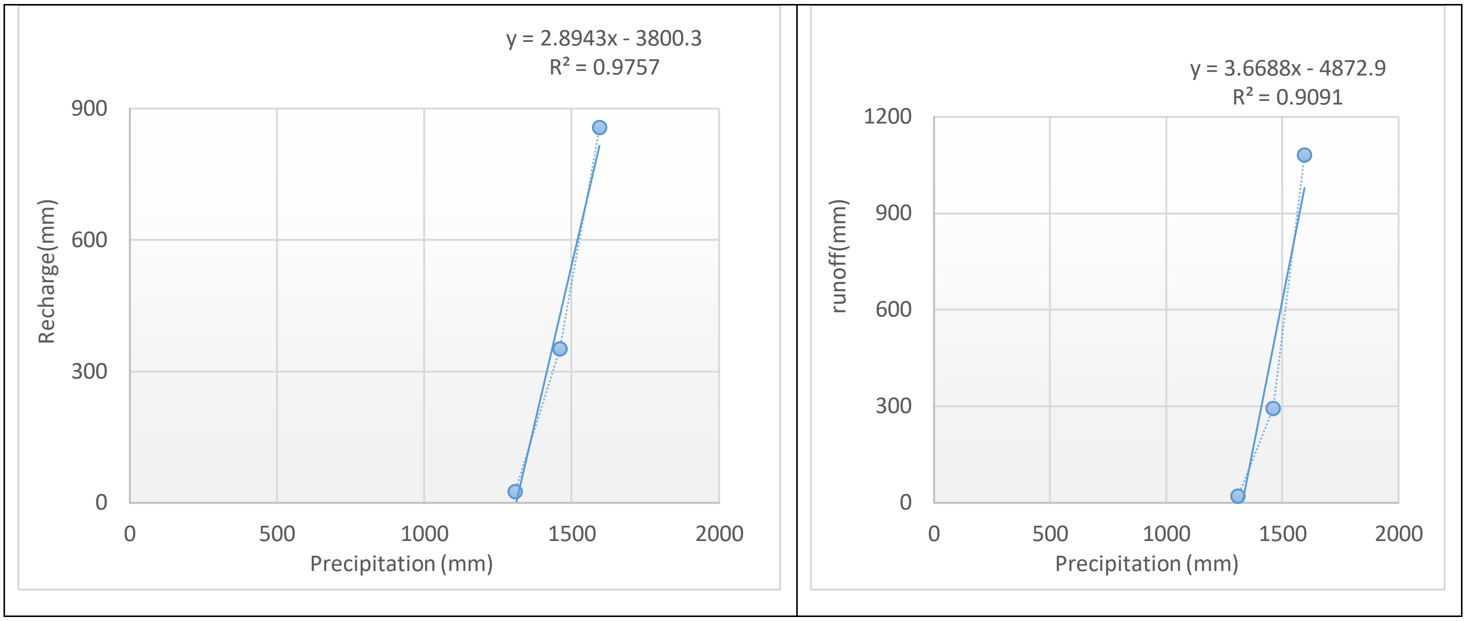


Figure 4. 9 The scatter plot shows relation of water balance components

CHAPTER FIVE

5. CONCLUSIONS AND RECOMMENDATION

5.1. Conclusions

The long-term impact of land use/cover change and climate variability on annual groundwater recharge, surface runoff, and evapotranspiration of the upper Gibe watershed was estimated through the use of the grid-based physically distributed model, WetSpass. It has the ability to quantify interception from vegetated surfaces, runoff from the landscape, evapotranspiration, and groundwater recharge at an annual time step. The model quantifies land use /cover change and climate variability impact on water balance component. In addition to LULC and climate, elevation, slope, groundwater depth, and soil data were used as constant in order to run the model.

Analyses of LULC and climate elements indicate variability in all phase within a study watershed. The expansions of agriculture and built-up area and the withdrawing of forest, shrub, and grassland during the 1985 to 2019 periods had shown in the study area. The main cause of this significant change was due to the expansion of the intensive agricultural practice in the area which causes a rapid reduction of the forest, shrub land, and grassland by 12.88%, 7.86%, and 3.61%, respectively. Bare land also showed dynamics during the comparison of the three times study period. The upper Gibe watershed and its surroundings selected meteorology stations showed year-to-year variation of temperature and rainfall values for the study period.

The temperature trend indicates that the maximum, minimum and mean temperatures over the watershed increased in the past 33 years in almost all of the stations while rainfall of the study area showed significant seasonal and annual decrease rainfall trends in the longtime series. Potential evapotranspiration was calculated from temperature by using the Thornthwaite method. Increasing temperature and potential evapotranspiration coupled with decrease precipitation can potentially reduce groundwater recharge. This variability has pronounced impacts on spatial and temporal water balance component such as surface runoff evapotranspiration and groundwater recharge. The variability of the climatic parameters associated with the change of land-use/land-cover, and variations of soil texture, groundwater depth, topography, and slope are responsible for variations of the water balance element within the watershed.

The model uses ASCII format data and parameter table look up and simulated long-term average values in a spatial grid map of interception transpiration, bare soil evaporation, and other water balance components. The model simulates interception value that range from 0 to 303 mm 0 to 587 mm and 0 to 273 mm for first, second and third phase, respectively. Interception depends on type, extent, and condition of vegetation and plant litter influence the pattern of deposition and the amount of precipitation reaching the soil surface. Transpiration value of the study area ranges from 0 to 948 mm, 0 to 989 mm and 0 to 1037 mm for the first, second and third phases respectively. This is due to the fact that the rate of evaporation depends on the rate of vapor flow away from land surfaces and climate condition in all instances. If one or more of these flows are changed, there is a corresponding change in the total evaporative loss from a surface. Bare soil evaporation is also varied in different landscape and climate environment. The bare soil evaporation at first phase was range from 0 to 1040 mm while 0 to 1084 mm at second and 0 to 1068.6 mm at the third phase.

The Wetspass hydrologic modeling technique simulates water balance based on biophysical and hydro-meteorological properties. Climate variability and land use/cover change influence process of water balance component with the watershed. Variability in climate and land use/ cover change are two main drivers affecting watershed hydrologic processes (Chien et al., 2013). The fact that a different number of variables and their interrelationships were taken into account in the WetSpass model, relating to regulating conditioning hydrological processes, has made it possible to obtain a more detailed assessment of the surface runoff, recharge of groundwater and evapotranspiration. The surface runoff at first phase ranged from 2.4 mm to 1080.96 mm which account 20% of total precipitation while at second phase, it ranges from1.2 mm of 987 mm accounting 21.32% from total precipitation. On the other hand, surface runoff for the third phase ranges from 2 mm to of 975mm that accounts about 22.4% of total precipitations.

The annual evapotranspiration values ranges from 354.56 mm and 1099 mm, which is 56% of total precipitation for the first phase. It is from 321mm to 1150mm and 307 mm to 1160 mm for the second and third phase, which account 57.57% and 60.6% of total precipitation, respectively. The long-term annual groundwater recharge for upper Gibe watershed ranges from 0 to 856 mm, with an average value of 350 mm at first phase. On the other hand it is 0 to 780 mm with average 287 mm and 0 to 696 mm with the average 221 mm for the second and the third phases, respectively. These 24%, 21.11% and 17% of the total annual precipitation for the first, second and the third phases, respectively. These differences in recharge value are attributed to differences in hydrometeorology amount with differences in the biophysical properties of the watershed. The overall water balance analysis of the upper Gibe watershed indicated that evapotranspiration is the main process of water loss in the watershed resulting mainly from the prevailing high rate of radiation and the persistence of strong dry wind. While the rest of the annual precipitations contribute to ground recharge and leaves the watershed in the form of surface runoff.

5.2. Recommendation

The study applies dynamic land use/cover and climate variability in the upper gibe watershed to quantify and characterize groundwater recharge timely. The WetSpass model which is a quantification model for groundwater recharge is based on biophysical and hydro-meteorological properties and it is important to estimate long-term annual average groundwater recharge used for wise utilization, proper management and future planning of water resources.

- Due to the low resolution of land use/cover in classification, some pixel may have been classified wrongly, that may lead to the wrong output which could lead to wrong decisions.
- Land and water management practices evaluated in this study have proved to be effective mitigation and adaptation measures for the observed adverse hydrological impacts of future climate and land use/cover changes requires more attention.
- The parameter values embedded in the currently existing model are basically prepared for the realities and conditions of temperate regions which might need to be modified for the actual situations and conditions of the study area. However, a further study could be needed to further fine the land use, soil as well as runoff coefficient parameter tables of the study area.
- The constant groundwater depth data were used, for these studies, because of data limitation within the watershed. However, a further study could be needed to focus on different time series data to understand impact of land use/land cover change and climate variability on groundwater level.

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ANNEX

Annex 1:Mean monthly temperature of Bako station (1985-2018)

Year	janu	febru	mar	april	may	june	july	augu	septe	octov	nove	dece
1985	18.40	18.23	19.51	19.01	18.07	18.18	15.57	15.67	14.77	17.18	17.73	16.99
1986	18.95	18.34	18.40	18.57	19.01	18.07	14.68	14.67	15.28	17.06	16.89	17.32
1987	19.46	18.72	19.06	17.57	17.62	18.62	13.18	16.06	16.32	18.34	17.84	17.51
1988	20.10	19.93	21.26	20.95	20.37	18.29	17.11	16.45	17.71	18.75	17.54	17.69
1989	17.87	18.77	18.99	18.79	18.96	18.70	16.69	17.08	15.60	15.84	16.44	18.96
1990	18.95	18.83	19.94	20.28	19.91	18.12	17.09	17.00	17.26	17.60	18.55	18.73
1991	20.33	19.93	20.15	19.07	19.95	18.10	17.68	16.96	18.18	18.23	122.7	18.49
1992	19.01	19.51	20.51	18.45	19.95	17.79	17.35	17.45	17.90	18.12	18.85	18.51
1993	18.78	18.48	20.99	19.66	19.63	18.49	18.06	17.69	17.75	18.33	19.66	18.88
1994	19.07	18.56	20.85	18.96	19.61	17.50	17.45	18.39	18.83	18.39	19.60	19.07
1995	17.51	19.23	20.18	20.07	19.33	18.46	16.28	17.77	17.34	18.89	17.73	19.62
1996	18.18	19.95	21.06	20.45	19.51	17.84	16.05	18.06	15.56	18.57	18.51	19.40
1997	19.00	20.00	20.50	21.12	19.33	17.79	15.96	18.16	18.15	18.50	18.82	19.06
1998	18.77	20.73	20.96	21.97	19.48	17.44	16.72	17.40	16.77	18.72	127.4	18.24
199	19.13	20.28	20.38	20.34	19.42	18.02	16.74	16.64	16.99	17.49	16.55	17.85
2000	18.97	20.15	21.91	20.13	19.22	17.57	17.18	16.87	17.51	17.85	17.81	17.78
2001	18.52	20.20	19.79	20.61	19.60	17.52	17.19	17.54	17.05	18.25	18.07	18.76
2002	18.78	20.37	19.79	20.62	21.14	18.66	17.99	17.36	17.88	18.59	19.31	19.61
2003	19.35	20.66	20.87	20.22	20.05	18.29	17.56	17.62	17.22	17.56	18.75	18.21
2004	20.11	20.25	21.02	20.48	20.07	18.57	17.18	17.36	17.36	17.88	18.54	19.02
2005	18.98	21.35	21.03	21.25	19.78	18.28	17.10	17.40	17.88	17.52	17.68	17.86
2006	19.88	20.89	20.03	19.85	18.67	17.97	17.59	17.45	17.62	18.74	19.07	19.45
2007	20.00	19.75	20.98	20.70	20.21	18.34	17.29	17.25	17.86	17.90	18.86	18.41
2008	20.29	20.93	21.96	21.49	19.67	18.42	17.36	17.03	17.76	18.61	18.10	19.04
2009	19.78	20.92	21.85	21.54	21.08	19.67	17.89	18.12	18.12	18.85	19.08	19.72
2010	20.37	20.84	20.67	21.65	20.80	20.70	18.26	18.72	19.69	21.09	20.21	19.79
2011	20.36	22.12	21.13	22.18	21.06	19.76	18.39	18.09	19.32	20.42	19.90	19.81
2012	20.57	21.42	22.09	21.31	21.42	18.73	17.28	17.65	17.53	18.32	19.04	19.27
2013	19.75	21.35	22.31	21.68	19.95	19.17	17.93	17.43	17.91	18.22	19.24	19.53
2014	20.29	20.66	21.14	21.13	19.83	19.20	18.33	17.52	17.96	18.77	18.80	18.91
2015	19.17	21.08	21.75	21.46	20.56	19.30	18.67	18.26	18.30	19.34	19.49	19.67
2016	20.24	21.60	22.74	21.50	19.99	17.96	17.99	18.11	19.29	19.04	17.95	18.18
2017	18.63	22.29	21.73	22.21	20.09	18.85	17.89	17.57	18.29	19.03	17.93	18.23
2018	20.17	21.46	21.96	23.07	20.62	18.35	18.21	18.15	18.34	19.01	18.34	19.06

Annex 2: Monthly precipitation of Bako station (1985-2018)

Year	janu	febru	marc	april	may	june	july	augu	septe	octov	nove	dece
1985	32	41.7	18	48.7	76	236.8	395.4	312.7	219.7	155.7	5	0
1986	25.6	63	45.8	116.9	58	197.5	279.4	386.7	186.7	97	4	7
1987	17.6	72.7	21.7	164.6	28.8	219.2	401.1	218.7	278.8	118.2	8	2
1988	21.5	29.4	10.4	35.3	43.3	195.4	366.9	373.5	262.1	110.6	0	0
1989	23.3	31.3	91.6	120.6	46.6	222.9	224.8	241.9	148.3	40.7	0	39.1
1990	11.3	127.2	34.6	85	92.7	169.7	194.8	378.7	156.1	9.3	0	0.2
1991	13.3	47.9	76.3	174.6	56.9	129.4	231.7	249.9	138.8	4.7	0	11.1
1992	43	108.1	54.9	95.3	56.6	202.4	239.8	354.9	124.3	90.9	7.7	9.2
1993	21.4	38.5	9.8	190.9	192.5	250.4	215	294	250.7	77.2	12.7	0
1994	0.5	0	88.2	64.3	80.6	124.6	407.3	198.7	115.8	0	2.5	0
1995	0	23.4	41.3	140.5	132.4	132.7	210.5	255.4	92.2	26.2	0	16
1996	70.3	0	145.6	113	113.5	279	332.4	269.1	112.2	2.7	8.9	0
1997	11.9	0	61.6	94.5	33.8	192.1	284	200.8	63.5	77.6	30.7	0
1998	58.2	52.9	61	83.6	179.3	157.6	258.6	279.5	160.2	83.6	6.1	0
1999	8.7	0	29.4	18.4	152	194.8	286.2	351.3	188.1	175.9	0	0
2000	0	0	4.2	110.3	101.1	120.4	327.3	249.7	171.7	23.2	15.6	12.6
2001	11.1	8.3	82.5	31	84.8	152.9	326.2	176.4	109.8	31.9	6.3	0
2002	24.6	26.3	82.1	58.9	58.9	243	270.3	263.4	60.3	0	0	26.6
2003	26.8	5.6	82.5	141.7	18.2	188.8	332.8	199.5	112.4	21.2	14	31.9
2004	55	33.6	48.7	93.5	49.1	215.5	282	233.6	171.8	38.8	8.2	0
2005	63.3	0	74.7	105.3	70.3	187.7	230.2	254.8	157.3	49.9	16.4	0
2006	2.1	59	91.3	90.9	102	214.2	302.6	324.6	174.6	20.9	17.8	0
2007	21.6	52.6	21.1	24	154.5	225.8	248.7	236.1	177.4	8.4	0	0
2008	0	1.1	5.4	43.3	127.3	177.6	326.2	262.8	159.6	50.6	88.3	0
2009	16.7	1.6	42.8	37.9	64.4	77.9	234.1	290.4	107.2	83.9	0	21.6
2010	8.7	48.7	28.1	88.3	133.8	228.9	306.7	359.1	147.8	0	5.4	28.2
2011	5.3	1.2	35.7	65.3	132.2	188.9	234.7	283.7	158.8	0	30	0
2012	0	0	33.3	78.4	60.6	173.7	186.8	195.6	215.6	1.8	3	6.2
2013	1.9	6.7	32.8	86	112	158	371	285.2	155.4	117.9	26.6	0
2014	11.1	4.8	49.4	39	179.1	137.9	262.2	197.4	128.5	94.3	14.5	5.7
2015	0	6	40.5	11.1	154.7	197.5	230.8	196.9	140.1	0.2	3.1	23.4
2016	22.3	0	62.9	215.2	159.1	148.4	143.3	314.8	184	114	0	9
2017	13	7	29.1	28.3	164.5	162.1	121	218	171	98.9	0	0
2018	4	17	24	16	129	280	342.5	235.9	90.9	22.3	0	0

Annex 3: Mean monthly temperature of Ijaji station (1985-2018)

Year	janua	febru	marc	april	may	june	july	augu	septe	octo	nove	dece
1985	13.39	14.04	14.33	14.06	13.96	13.83	13.57	14.39	15.05	14.93	13.34	14.88
1986	13.73	13.72	13.56	12.57	13.77	13.23	12.88	13.05	14.39	13.83	14.39	13.96
1987	14.49	13.08	15.33	15.44	13.72	14.33	14.65	13.44	13.88	13.50	13.29	15.44
1988	16.39	15.90	15.72	15.07	15.32	15.61	14.83	15.72	13.98	15.67	16.06	15.62
1989	16.09	15.96	16.34	16.14	15.86	14.55	13.74	14.02	14.72	15.28	15.93	15.44
1990	15.07	15.34	16.21	16.89	15.97	14.06	13.35	13.71	14.01	15.25	15.89	16.29
1991	16.44	17.61	17.76	16.87	16.29	15.23	13.68	13.78	14.94	15.46	16.02	15.50
1992	15.84	16.55	18.21	17.53	16.49	14.76	13.61	13.51	14.49	14.97	14.70	15.57
1993	15.69	16.08	17.38	15.95	16.20	15.01	13.76	13.97	14.45	14.57	15.00	14.55
1994	17.03	17.33	18.00	17.75	17.43	17.11	17.39	15.77	16.12	16.47	15.85	15.49
1995	15.77	16.38	17.44	16.98	16.28	15.50	12.33	13.84	13.77	15.15	13.83	13.82
1996	15.88	16.60	17.27	15.77	15.43	17.00	14.98	14.83	14.83	15.43	15.39	14.28
1997	17.02	16.00	15.55	16.23	15.32	15.78	15.67	15.55	16.27	14.59	14.83	14.66
1998	16.95	17.98	16.18	15.89	16.50	16.31	14.83	16.10	15.81	15.72	14.28	14.90
1999	17.29	18.12	18.73	16.41	15.78	14.95	13.85	13.98	14.56	15.44	15.43	10.49
2000	16.91	17.95	17.49	16.70	17.05	13.53	13.38	13.94	15.18	14.44	13.27	14.71
2001	16.83	17.89	17.49	16.04	17.29	13.72	13.83	13.84	15.39	14.44	15.39	14.16
2002	17.28	17.38	16.77	16.00	15.79	15.12	14.72	13.82	14.49	13.64	15.55	15.82
2003	17.34	17.88	17.06	18.23	17.82	13.90	13.81	13.26	14.74	15.36	16.47	16.46
2004	17.31	17.58	17.85	17.73	17.14	14.65	14.10	14.70	15.08	15.83	16.11	16.94
2005	17.15	19.10	18.58	18.96	17.70	15.63	14.66	15.00	15.30	15.73	16.30	16.77
2006	17.65	19.88	19.26	19.06	17.85	15.91	14.40	14.03	14.75	16.58	16.31	16.21
2007	17.12	18.33	18.99	18.06	17.16	15.77	14.90	14.88	15.28	16.85	17.23	17.30
2008	17.70	18.58	19.61	17.98	16.31	16.08	14.87	13.62	15.12	16.17	17.47	16.57
2009	15.99	18.21	18.79	18.75	18.38	17.71	16.15	15.00	15.85	16.36	16.84	16.86
2010	17.30	18.27	18.40	18.59	16.81	16.02	15.07	15.01	15.38	16.46	17.12	16.98
2011	17.07	18.75	18.48	18.51	17.56	16.16	15.87	15.54	16.19	17.55	17.22	17.27
2012	18.35	19.74	19.67	19.36	19.15	18.54	17.21	16.01	16.72	17.97	17.93	18.12
2013	18.79	19.92	18.92	21.08	18.94	18.25	18.15	17.74	17.42	17.77	18.02	18.71
2014	18.61	20.21	18.94	19.10	20.71	20.33	17.78	17.22	16.71	17.06	17.95	18.14
2015	18.11	18.60	18.93	18.77	18.28	17.73	17.58	17.35	16.52	17.23	17.36	17.23
2016	19.15	18.49	18.72	17.32	17.31	18.23	18.11	16.88	16.49	16.49	16.49	16.99
2017	18.61	18.67	18.88	19.06	18.72	17.33	17.33	19.38	17.38	18.32	17.66	17.66
2018	18.76	18.66	18.49	19.04	17.67	17.23	17.33	18.94	17.45	18.34	20.15	18.35

Annex 4: Accuracy assessment of 1985

LULC class	Build up	Bare land	agriculture	Grass land	forest	Shrub land	total	User accuracy
build up	34	1	1	0	0	1	37	91.89
Bare land	2	36	1	2	1	1	43	83.72
agriculture	4	2	35	1	2	4	48	72.92
grass land	1	3	2	37	1	2	46	80.43
forest	2	0	2	2	39	1	46	84.78
Shrub land	1	2	3	2	1	35	44	79.55
total	44	44	44	44	44	44	264	
Producer accuracy	77.27	81.82	79.55	84.09	88.64	79.55		
Over all accuracy= 81 , kappa coefficient= 78								

Annex 5: Accuracy assessment of 2000

LULC class	Build up	Bare land	agriculture	Grass land	forest	Shrub land	total	User accuracy
build up	36	0	1	1	0	0	38	94.74
Bare land	0	37	1	0	1	1	40	92.5
agriculture	4	2	36	1	2	2	47	76.60
grass land	1	3	2	40	2	2	50	80.00
forest	2	0	1	0	38	0	41	92.68
Shrub land	1	2	3	2	1	39	48	81.25
total	44	44	44	44	44	44	264	
Producer accuracy	81.82	84.09	81.82	90.91	86.36	88.64		
Over all accuracy= 85 , kappa coefficient= 83								

Annex 6: Accuracy assessment of 2019

LULC class	Build up	Bare land	agriculture	Grass land	forest	Shrub land	total	User accuracy
build up	38	0	1	1	0	0	40	95
Bare land	0	37	1	0	1	1	40	92.5
agriculture	2	2	36	2	0	2	44	81.82
grass land	1	3	2	39	2	0	47	82.98
forest	2	0	1	0	40	0	43	93.02
Shrub land	1	2	3	2	1	41	50	82
total	44	44	44	44	44	44	264	
Producer accuracy	86.36	84.09	81.82	88.64	90.91	93.18		
Over all accuracy= 87 , kappa coefficient= 85								

Annex 7: Land use attribute parameter table

Code	LUSE_TYPE	RUNOFF_VEG	VEG_AREA	BARE_AREA	IMP_AREA	OPENW_AREA	ROOT_DEPTH	LAI	MIN_STOM	VEG_HEIGHT	nManing	LandFactor	AerodynResistance
2	build up	grass	0.5	0	0.5	0	0.3	2	100	0.12	0.04	0.5	212.0135
7	Bareland	bare soil	0	1	0	0	0.05	0	110	0.001	0.09	0.222	426.6676
21	agriculture	crop	0.8	0.2	0	0	0.4	4	180	0.6	0.037	0.541	115.0131
23	Grassland	grass	1	0	0	0	0.3	2	100	0.2	0.07	0.286	177.4676
33	forest	forest	1	0	0	0	2	5	375	16	0.1	0.2	28.09757
36	shrubland	grass	1	0	0	0	0.6	6	110	2	0.05	0.4	66.32867

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: Openwater Area; Root_depth = Root depth; Lai = Leaf Area Index; Min_stom= Minimum Stomatal Opening; Interc_per = Interception Percentage; Veg_height = Vegetation Height.

Annex 8: Soil attribute parameter table

Code	SOIL	FIELDCAPAC	WILTINGPNT	PAW	RESIDUALWC	A1	EVAPODEPTH	TENSIONHHT	P_FRAC_SUM	P_FRAC_WIN
3	sandy loam	0.21	0.09	0.12	0.041	0.44	0.05	0.15	0.09	0.01
4	silty loam	0.29	0.1	0.19	0.015	0.4	0.05	0.21	0.26	0.07
5	loam	0.25	0.12	0.13	0.027	0.37	0.05	0.11	0.15	0.02
9	clayloam	0.33	0.19	0.14	0.075	0.27	0.05	0.26	0.62	0.41
12	clay	0.46	0.33	0.13	0.09	0.21	0.05	0.37	0.95	0.85

Soil table attributes

Code= 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.