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ADDIS ABABA UNIVERSITY
COLLEGE OF NATURAL AND COMPUTATIONAL SCIENCES
SCHOOL OF EARTH SCIENCES

**GEOSPATIAL APPROACH FOR GROUNDWATER RECHARGE ESTIMATION
USING WETSPASS MODEL: A CASE STUDY OF CHEMOGA WATERSHED,
ETHIOPIA**

By:

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A THESIS SUBMITTED TO

**SCHOOL OF GRADUATE STUDIES OF ADDIS ABABA UNIVERSITY IN PARTIAL
FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTERS OF
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Fulfillment of the requirements for the Degree of Masters of Science in
Remote Sensing and Geo-informatics

Addis Ababa, Ethiopia
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Addis Ababa University
School of Graduate Studies

This is to certify that thesis prepared by **BELETE BAYCHIKEN KASSANEH**, entitled: “Geospatial approach for groundwater recharge estimation using wetpass model: A case study of Chemoga watershed, Ethiopia” and submitted in partial fulfillment of the requirements for the degree of Masters of Science in Remote sensing and Geo-informatics complies with the regulations of the University and meets the accepted standards with respect to the originality and quality.

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Acronyms

AET	Actual evapotranspiration
DEM	Digital Elevation model
ET	Evapotranspiration
FAO	Food and Agriculture Organization
GIS	Geographical Information System
GPS	Global Positioning System
H2PL	Hydrology and Hydraulic Programming Library
JJAS	June, July, August, September
MoWIE	Ministry of Water Irrigation and Energy
NMA	National Metrological Agency
OLI	Operational Land Imager
PET	Potential Evapotranspiration
RS	Remote Sensing
SRTM	Shuttle Radar Topography Mission
USDA	United States Department of Agriculture
USGS	United States Geological Survey
WetSpass	Water and Energy Transfer between Soil, Plant, and Atmosphere at quasi-steady State
WMO	World Metrological Organization

Abstract

Geospatial Approach for Groundwater Recharge Estimation Using WetSpass Model: A Case Study of Chemoga Watershed, Ethiopia.

Belete Baychiken, Msc. Thesis

Addis Ababa University, May 2018

Groundwater recharge estimation is of critical importance for groundwater resources evaluation and management. There are several methods for water balance evaluation. Among which, WetSpass model is one, that has the ability to simulate spatially distributed recharges, surface runoff, and evapotranspiration for annually and seasonally averaged conditions. The spatial-temporal characteristics of the model allow distributed quantification of water balance components by preparing inputs in the form of digital maps using remote sensing, GIS tools, FAO databases, field reconnaissance and processing of meteorological and hydrological observations, that aimed at estimation of the annual and seasonal groundwater recharge, surface runoff and evapotranspiration amount in Chemoga watershed using WetSpass modeling method. Long-term hydrometeorological data and physical characteristics of the watershed such as land use/land cover, soil type, topography, groundwater level and slope are used as an input to the model. The long-term average annual rainfall of 1408.3 mm was distributed as 447 mm (31.8%) of surface runoff, 844.98 mm (60%) of actual evapotranspiration, and 116.3 mm (8.2%) of recharge, this recharge corresponds to 42,333,200 m³. Analysis of the simulated results tells that WetSpass works well to simulate the components of the hydrological balance for the Chemoga watershed.

Keywords: Chemoga watershed, Geospatial, Groundwater recharge, water balance, WetSpass model.

CHAPTER ONE

1 INTRODUCTION

1.1 Background of the study

Groundwater recharge is a hydrologic process where water moves downward from surface water to groundwater. Recharge occurs both naturally (through the water cycle) and through anthropogenic processes (i.e., artificial groundwater recharge), where rainwater and /or reclaimed water is routed to the subsurface (Pandian, et al., 2014).

Ethiopia is endowed with considerable surface and subsurface water resources potential, characterized by spatial and temporal variations. Nine lakes and 12 river basins are widely distributed in the country. Ethiopia has also groundwater potential, ranging from 2.6 to 2.65 billion m³, and an estimated 122 billion m³ of annual runoff water (Awulachew et al., 2007). However, <5% of the surface water potential is currently utilized by the people, and groundwater is a potential, but untouched resource (Tesfamichael et al., 2013).

Abstracting groundwater for irrigation could play a critical role in fulfilling basic human food needs at short and long-time scales, and irrigation could generate further benefits by producing market-oriented crops during the dry season. 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.

Recharge is estimated by chloride ion mass balance method, empirical method, water-balance method, water budget model method or by multiplying the magnitude of water-level fluctuations in wells with the specific yield of the aquifer material (Gebreryfael, 2008, Yun, et al., 2011). But commonly groundwater recharge is determined to a large extent as an imbalance at the land surface between precipitation and evaporative demand (Gebreryfael, 2008).

Understanding seasonal and annual variations of the water resources, especially runoff, evapotranspiration, and recharge, is necessary for efficient and sustainable management of groundwater (Obuobie, et al., 2008). Since groundwater resources are sensitive functions of climatic factors, geological formation, topography, soil properties, and land-use types (Dragoni &

Sukhija, 2013), a detailed understanding of watershed physical and biological characteristics are important.

Accurate quantification of groundwater resources involves identification of hydrological and biophysical characteristics of the watershed. Regional groundwater models used for analyzing groundwater systems (infiltration– discharge relations) are often steady state and, therefore, need long-term average recharge input. On the other hand, the spatial variation in the recharge due to distributed land-use, soil type, slope, etc., can be significant and should be accounted for regional groundwater models. Hence, WetSpass was built as a physically-based methodology for estimation of the long-term average, spatially varying, water balance components: surface runoff, actual evapotranspiration, and groundwater recharge. It was built upon the foundations of the time-dependent spatially distributed water balance model WetSpa (Batelaan et al.,1996, Wang, 1997).

From a volume perspective, most water use in Chemoga Watershed is appropriated from groundwater. Since the rainfall of the watershed is seasonal, most of the time, the tributaries, and the main river are ephemeral. Hence, this forces the local communities to use subsurface water not only for drinking but also for domestic uses and in some cases for irrigation purpose. Though this groundwater is recharged from precipitation, utilization of this resource is going on without a basic understanding of the recharge amount and its areal distribution as well as the temporal and spatial variation of the other water balance components which creates a critical problem for its management in the watershed. In this paper groundwater recharge, surface runoff and evapotranspiration are estimated for the Chemoga watershed using WetSpass modeling method.

The groundwater is an essential natural water resource all over the world owing to its good protection from surface pollution and its low effect by seasonal fluctuations compared to surface water (Zektser and Everett, 2006). The groundwater resources depend mainly on the recharge process, which can be defined as the rainfall fraction that joins the aquifer and takes part into its renewal (Tilahun and Merkel, 2009).

The rate at which water-table recharge occurs is variable, depending upon environmental factors, topographic, meteorological, hydrological and hydrogeological characteristics etc. For reliability and accuracy, groundwater recharge analysis on the large and complex scale is used by numerical models which are useful for spatial analysis and combination with Geographic Information System (GIS) in terms of providing a flexible toolset for resource management (Jaturon Kornkul et al.,

2013). WetSpass is an acronym for Water and Energy Transfer between Soil, Plants, and Atmosphere under quasi-Steady State.

WetSpass was built as a physically-based methodology for estimation of the long-term average, spatially varying, water balance components: surface runoff, actual evapotranspiration, and groundwater recharge. (Adnan, 2010). Since the rainfall of the watershed is seasonal, most of the time, the tributaries and the main river are ephemeral. Hence, this forces the local communities to use subsurface water not only for drinking but also for domestic and in some cases for irrigation purpose. Though this groundwater is recharged from precipitation, utilization of this resource is going on without a basic understanding of the recharge amount and its area distribution as well as the temporal and spatial variation of the other water balance components which creates a critical problem for the management in the watershed.

Estimation of rates of groundwater recharge in the area is crucial for sustainable utilization of the resource as well as its protection against pollution and depletion. In this study, a WetSpass model was used to estimate long-term spatial surface runoff, actual evapotranspiration, and groundwater recharge on a seasonal and annual average basis, using a 30-yr record of daily meteorological data (1987–2017). Since its development, WetSpass has been used worldwide (Rwanga, 2013). It has successfully applied in Belgium (Batelaan & De Smedt, 2001) and other environments such as Gaza Strip, Palestine (Aish, 2010), Geba catchment, Ethiopia (Tesfamichael et al., 2010, 2013), and Nile Delta aquifer, Egypt (Armanuos et al., 2016). Hence, WetSpass model used to simulate the long-term seasonal and annual runoff, actual evapotranspiration, and groundwater recharge and related water balance components in the Chemoga watershed.

1.2 Statement of the problem

For most rural households in the watershed agriculture (animal husbandry and crop production) is the main economic activity to generate their means of income. In recent years there has been a considerable agricultural practice & land cover change with increasing population in the area. Some human treats like inappropriate management of the watershed, depletion of water through pollution & environmental degradation have become apparently clear.

The demand for groundwater resources is increasing day by day due to the ever-increasing population. The study area has high potential groundwater resources but currently, there are many challenges including high spatial and temporal variability in rainfall, global climate change,

deforestation, land degradation, and high population growth rate. These challenges put immense pressure on the groundwater resources. This has resulted in abstracting more water from the groundwater reservoir (Woldeamlak Bewket ,2002). Therefore, quantification of the rate and seasonal changes of groundwater recharge is a basis for efficient groundwater resource management.

1.3 Objectives

1.3.1 General objective

The main objective of this study is to estimate groundwater recharge of Chemoga watershed using WetSpa model and Remote Sensing.

1.3.2 Specific objective

- ✓ To estimate distributed annual Groundwater recharge of the watershed
- ✓ To estimate distributed seasonal Groundwater recharge of the watershed
- ✓ To estimate distributed actual evapotranspiration and runoff of the watershed

1.4 Significance of the study

In this research, groundwater recharge of seasonal and annual amounts has been quantified both graphically and numerically. Since water shortage and surplus during the dry and rainy season, respectively, are the main problems affecting the sustainable development in the study area especially for sustainable agricultural production, quantifying the groundwater recharge amount will help to manage the water resource.

The research is significant to:

- Manage water resources effectively
- Making best use of available water and enhance water sources.
- Minimize the impact of drought and water shortage problems.

1.5 Structure of the study

The thesis is organized into five chapters. In the first chapter, the introduction part of the thesis that includes research issues related to hydrological processes, the problem statement and the objectives are presented.

In the second Chapter, the literature review related to the principle of groundwater modeling and recharge estimation methods are discussed.

The third chapter focuses on the methodology and materials which describes the study area, giving the description of the study area in relation to location, climate, geology etc. and the methods that have been followed to estimate groundwater recharge, the data collection method, data types, software used and data processing and analysis methods have been discussed.

In the fourth chapter Results and discussion have been described with illustration and discussion of the modeling results and result of the recharge estimated by WetSpss modeling methods.

The fifth chapter is about the conclusion and recommendations. Conclusions and recommendations will be made on the basis of the analysis result. In this final chapter, matters which cannot be addressed fully or partially are outlined and limitation of the research and possibilities of further research are indicated.

CHAPTER TWO

2 LITERATURE REVIEW

2.1 Water resources and Hydrologic cycle

Globally there is 1.36 Billion km³ of water from which 97.2% is salt water mainly in oceans and 2.8% is available as freshwater (Raghunath, 2006). Although the water available in water bodies, such as ocean and great lakes stores plenty of water in amount, it is not directly useful for human beings. The immediate use of water for human being is the one stored as groundwater and the remaining water found in land surfaces, lakes and streams as fresh water.

Ethiopia is relatively rich in water resources, and its outflows are of great importance for its neighboring countries. It has twelve river basins with total annual water resources estimated at 111 Billion m³ from which 75.5 Billion m³ is stocked in the Nile basin (Yazew, 2005). Furthermore, the country releases an annual runoff volume of 122 Billion m³ of water (Awulachew *et al.*, 2007). 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 the conceptual model which states the storage and movements of water between the biosphere, atmosphere, lithosphere and hydrosphere. Water in this planet can be stored in any of the following reservoirs: atmosphere, oceans, lakes, rivers, soils, glaciers, snowfields and groundwater. Water moves from one reservoir to another by ways of processes like evaporation, condensation, precipitation, deposition, runoff, infiltration, sublimation, transpiration, melting and groundwater flow.

The oceans supply most of the evaporated water found in the atmosphere. From this evaporated water, only 91% is returned to the ocean basins by way of precipitation. The remaining 9% is transported to areas over landmass where climatological factors induce the formation of precipitation (Karamouz *et al.*, 2003).

Water is a naturally circulating resource that is continuously recharged. Even if the stocks of water in natural and artificial reservoirs are helpful to increase the available water resources for human society, the flow of water would be the main focus in water resources valuations. (Oki, 2005). The hydrological cycle also defined as a water transfer cycle that occurs continuously in nature; at which the phenomena of evaporation and evapotranspiration, precipitation and runoff takes place during the water transfer system (Raghunath, 2006). Precipitation and runoff are only the visible

components of this process. Other components such as evaporation, infiltration, transpiration, percolation, groundwater recharge and discharge etc. are other important mechanisms of this cycle. The water exchange between land surface and atmosphere is based on the continuous evaporation of water from the Earth, the temporary storage of water in the form of water vapour in the atmosphere and the return of water to the land surface through several forms of precipitation such as rain, snow, sleet or hail. Even if these mechanisms are relatively simple to represent, the interaction between land surface and underground and in particular ground water movement is not so easy to visualize (Karamouz, *et al.*,2003).

2.1.1 Groundwater recharge

Groundwater recharge can be defined as the entry of water into the saturated zone of water made available at the water table surface together with the associated flow away from the water table within the saturated zone (Freeze *et al.*, 1979, Pandian, *et al.*, 2014). Most natural groundwater recharge is derived directly from rainfall and snowmelt that infiltrate through ground surface and migrate to the water table. To quantify recharge from precipitation, it is critical to understand rainfall-runoff relationships. The first step is to determine the fraction of precipitation available for groundwater recharge, after subtracting what is lost to overland flow (runoff) and evapotranspiration (ET). The vital to the rainfall-runoff relationship is the soil type, the antecedent moisture condition, and the land cover. Soils that are well drained generally have high effective porosities and high hydraulic conductivities, whereas soils that are poorly drained have higher total porosities and lower hydraulic conductivities. These physical properties combine with initial moisture content to determine the infiltration capacity of surficial soils. Land cover determines the fraction of precipitation available for infiltration. Impervious, paved surface prevent any water from entering the soil column, while open, well-vegetated fields are conducive to infiltration. Regardless of soil type, antecedent moisture, or land cover, the chain of events occurring during a storm event is the same (Xu, 2002).

Since the main source of recharge for the groundwater system is the rainfall, groundwater recharge system is variable as rainfall varies in both space and time. Recharge processes vary from one place to another, and there is no agreement that a method developed and used for one area will give reliable results when used in another. So, it is necessary to identify the probable flow mechanisms and the important features influencing the recharge in an area before deciding on the recharge method to use (Lerner *et al.*, 1990, cited in Daniel Nuramo,2016).

According to Lerner *et al.* (1990), there are three principal mechanisms of recharge. Those are:

- Direct recharge (Diffuse): water added to the groundwater reservoir in excess of soil moisture deficits and evaporation by direct vertical percolation from precipitation or irrigation.
- Indirect recharge: recharge to the water table through the beds of surface watercourses, such as beneath rivers and lakes.
- Localized recharge: an intermediate form of groundwater recharge resulting from the horizontal, near surface concentration of water in the absence of well-defined channels such as small depressions, joints, and rivulets.

Those mechanisms listed above usually do not occur separately rather in combination which makes the assessment complex. On the other hand, the recharge and discharge conditions of an area are controlled by several factors such as; climate (rainfall, temperature, etc.), topography, drainage, geologic framework, soil type, land use/land cover etc.

2.1.2 Estimation of Groundwater Recharge

Groundwater recharge cannot be measured directly and is difficult to accurately estimate it. Groundwater recharge estimation is very significant for effective and sustainable management of groundwater systems.

For estimating groundwater recharge different methods exist. According to Scanlon *et al.*, (2002) groundwater recharge methods have been classified based on hydrological zones from which the recharge data is obtained as surface water, unsaturated zone and saturated zone. The groundwater recharge estimation methods are further classified into physical techniques, tracers and numerical modeling within each of the hydrologic zones.

2.2 Groundwater Recharge models

Hydrological models are simplified systems to quantify the processes of the hydrological cycle in an entire river basin or parts of it. They are based on a set of interrelated equations that try to convert the physical laws, which govern extremely complex natural phenomena. Moreover, different varieties of models can be used, depending upon the considered output, the existing database, input variables and required analysis. Representation of physical processes described by rainfall-runoff models can either be based on a simple mathematical link between input and output variables of the basin or include the description of basic processes involved in the runoff generation. Various models have been developed for the past decades in different part of the world.

These models can be generally classified based on process description as physically based distributed models, conceptual models and data-driven models (Beven, 2001).

Two types of modeling approaches have proposed by Klemes (1983): a bottom-up and a top-down approach. Physically based distributed models are examples of a bottom-up modeling approach (Savenije, 2001; Sivapalan, 2003) which were developed starting from the 1980s at the same time with the development of Remote Sensing Techniques and Geographical Information System Tools and can provide the highest accuracy in the modelling of precipitation-runoff processes (Xu, 2002). These models are largely based on the principles of physical processes based on continuity and the conservation of energy, mass and momentum. In this modeling approach, hydrological processes are modeled by introducing a large number of model parameters that supposed to be measurable at a plot or micro-catchment scale, representing the different heterogeneities in the catchment.

In a top-down modeling approaches, the equations used to describe the physical processes often have (indirect) physical meaning but parameters are obtained through calibration. In this approach, the modeling procedure usually starts with a very simple model and progressively increased complexity through the step-wise incorporation of process descriptions (Sivapalan, 2003; Montanari *et al.*, 2006). In the recent time, advances have been made in hydrological process understanding and modeling using topography driven, flexible, conceptual, semi-distributed model structures (Gharari *et al.*, 2013; Gao *et al.*, 2014). Regional groundwater models used for analyzing groundwater system (infiltration-discharge relations) are often quasi-steady state and therefore need long-term average recharge input. Thus, WetSpass, which yields spatially varying groundwater recharge using spatially varying land-use, soil, and meteorological inputs, can be used for the purpose of understanding the characteristics of groundwater recharge (Batelaan and Woldeamlak, 2003).

Data-driven models are based on extracting information that is implicitly contained in hydrological data. These models involve mathematical equations that do not rely on realistic principles such as mass, momentum or energy balance equations (Solomatine, 2011). The applications of such models depend on proper analysis of the input/output time series (Bowden *et al.*, 2005).

2.2.1 WetSpass model

WetSpass stands for water and energy transfer between soil, plants and atmosphere under quasi-steady-state conditions (Batelaan and De Smedt, 2001). It is a physically based model for the estimation of long-term average spatial patterns of groundwater recharge, surface runoff and

evapotranspiration employing physical and empirical relationships. WetSpa is a quasi-steady state model developed as regional groundwater model 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.

The model was developed as a method to estimate long-term average, distributed water balance components (Batelaan and De Smedt, 2001). This model was developed on the basis of time-dependent spatially distributed water balance model WetSpa (Batelaan *et al.*, 1996; Wang *et al.* 1996; Batelaan and De Smedt, 2001). The model has been developed and applied to study the influence of long-term effects of land cover changes on the water regime in a basin (Batelaan *et al.*, 2003; De Smedt and Batelaan, 2003). By using long-term average standard hydrometeorological parameters as inputs, the model simulates the temporal average and spatial information of surface runoff, actual evapotranspiration, and groundwater recharge have been simulated.

The model estimates spatial groundwater recharge at seasonal and annual scales. Regional groundwater models used for analyzing recharge-discharge relations are often quasi-steady and need long-term average recharge input that accounts for the spatial variability of the recharge. Thus, they can use the recharge output from WetSpa for their computations. WetSpa is especially suited for studying long-term effects of land-use 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).

Inputs for this model include grids maps of land use, groundwater depth, precipitation, potential evapotranspiration, wind-speed, temperature, soil, and slope and parameters tables such as land-use and soil types are connected to the model as attribute tables of their respective grids. The model makes use of grid GIS technology and digital data to partition the precipitation into surface runoff, evapotranspiration and groundwater recharge.

Parameter tables such as land-use and soil types are connected to the model as attribute tables of land use and soil raster maps, which allow new definitions of climatic as well as land-use and soil types (Batelaan *et al.*, 2003).

WetSpa was originally developed for conditions in temperate regions for Europe in particular. WetSpa have been developed to be used worldwide (Rwanga, 2013). It has successfully applied

in different areas of the world. The WetSpass model has first applied successfully in Belgium (Batelaan & De Smedt, 2001).

In the WetSpass model total water balance for a raster cell is split into independent water balances for the vegetated, bare soil, open-water, and impervious parts of each cell. This accounts for the non-uniformity of the land-use per cell, which is dependent on the resolution of the raster cell. The processes in each part of a cell are set in a cascading way. This means that an order of occurrence of the processes, after the precipitation event, is assumed. Defining such an order is a prerequisite for the seasonal timescale with which the processes will be quantified.

A mixture of physical and empirical relationships is used to describe the processes. The quantity determined for each process is consequently limited by a number of constraints (Batelaan and De Smedt, 2001;2007). 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. The model estimates spatial groundwater recharge at seasonal and annual scales.

2.2.1.1 Application of WetSpass model

In this research, WetSpass model was used to estimate spatial groundwater recharge at seasonal and annual scales based on some relationships. WetSpass was used for the analysis of the effect of land use changes on the groundwater discharge areas for a basin, of the area (Batelaan *et al*, 2000; Asefa *et al.*, 2000, Batelaan *et al.*, 2002, Batelaan *et al.*, 2003). WetSpass recharge outputs for the river basins were used as an input for the groundwater model. Total discharge and surface runoff and base-flow were used for the calibration of the WetSpass water balance components. The associated groundwater model was also calibrated along with the WetSpass calibration. Lastly, the resulting groundwater discharge areas were verified by mapped areas.

WetSpass was also used in the analysis of the hydrological characteristics of the sub-basin (Van Rossum *et al.*, 2001). The modified WetSpass model is a physically raster-based water balance model that for each grid cell, partitions precipitation into interception, surface runoff, evapotranspiration and recharge (Abdollahi *et al.*,2017) which stands for water and energy transfer between soil, plants and atmosphere under quasi-steady-state conditions (Batelaan and De Smedt, 2001). The model conceptualizes a watershed hydrological system, based on physical and empirical relationships, being composed of atmosphere, plant canopy, soil zone, root zone and

saturation groundwater zone divided into grid cells/raster in order to deal with the heterogeneity of the watershed. The input data to the model are digital maps prepared within the help of GIS and remote sensing packages software and parameter files from spreadsheet tables with their specific extensions (Tesfamichael *et al.*, 2010).

The digital maps are seasonal or monthly records of meteorological parameters such as precipitation, potential evapotranspiration, temperature and wind speed, groundwater level, land-use, soil, slope and topography of the study area. The parameter tables are time series data which have an attribute data for the model which contains vegetation height, leaf area index, land-use type as rooting depth, soil parameter for each textural soil class as field capacity, wilting point, permeability and runoff for all combinations of land-uses, slope, and soil type.

By using the WetSpa model of the actual hydrological situation in the sub-basin as a starting point, the sensitivity of the discharge coefficients of the sub-basin towards climate and land use changes was analyzed. Numerous climate and land use scenarios were used and the geographical input data of the present situation was adjusted for their simulations by WetSpa.

2.3 Application of GIS and Remote Sensing for groundwater

Groundwater study in an area requires knowledge of lithological units, structural disposition, geomorphic set-up, surface water condition, vegetation, etc. These can be well understood with the help of Remote Sensing (RS) and Geographic Information System (GIS).

Remote sensing is the science of recording information about the earth surface without actually being in physical contact with it, from the ultraviolet, visible, infrared and microwave regions of the electromagnetic spectrum, by means of instruments such as scanners and cameras, located on mobile platforms such as aircraft or spacecraft followed by the analysis of acquired information by means of photograph interpretation techniques, image interpretation and image processing (Sabins, 1987).

For most of the earth surface and atmospheric observations, electromagnetic energy is considered to be the highest medium for two reasons. Firstly, this is the only form of energy that has the ability to propagate through free space and also a medium. Further, its property to interact with the media and the target in a variety of ways ensures the sensor to capture the subtle variations that exist in the nature of the earth features (Sabins, 1987, Radhakrishnan *et al.*, 1992). Geographic Information System(GIS) is a computer system for collecting, storing, manipulating, analyzing, displaying and

querying geographically related information (John *et al.*, 2013). GIS has provided a new environment to develop distributed hydrological models and represents a powerful tool to organize, process and visualize spatial data. The pixel format of digital remote sensing data makes it ideal for merging with Geographical Information Systems (GIS) and for being used in hydrologic and runoff modelling.

CHAPTER THREE

3 MATERIALS AND METHODOLOGY

3.1 Description of the study area

3.1.1 Location

In administrative terms, the Chemoga watershed is located in Amhara region, East Gojjam zone, Gozamen woreda (district). About 23,660 people inhabit the Chemoga watershed (Daniel Gebeyehu, 2016). The watershed lies between 10°18'N and 10°39'N latitude and 37°44'E and 37°53'E longitude (Figure 3.1).

The watershed is located at some 300 km northwestern of Addis Ababa and forms part of the northwestern highlands of Ethiopia. It covers an area of approximately 364 km². The Chemoga watershed is one of the headstreams of the Blue Nile basin. The mass of sediments transported increased because of environmental degradation in the highland area of Ethiopia (El-Swaify and Hurni, 1996).

The farming system of the area is a typical mixed crop-livestock system of the Ethiopian highlands. Land and livestock are therefore the most important resources to the people, with which they lead a sedentary life. The major source of income in the watershed population is crop production. But livestock such as cow, ox, sheep and poultry are also additional sources of income for the farmers. The farmers are highly dependent on the scarce forest for wood fuels and construction. They further support their income by selling its by-product such as charcoal.

A variety of crops are produced by the household because of the strong orientation towards self-sufficiency. Barley (*Hordeum vulgare*), Wheat (*triticum vulgare*), Oats (*Avena sativa*), Horse beans (*Vicia faba*), Potato (*Solanum tuberosum*), and Onion (*Allium cepa*) are grown in the upstream part of the watershed; and Tef (*Eragrostis tef*) is additionally cultivated in the downstream part.

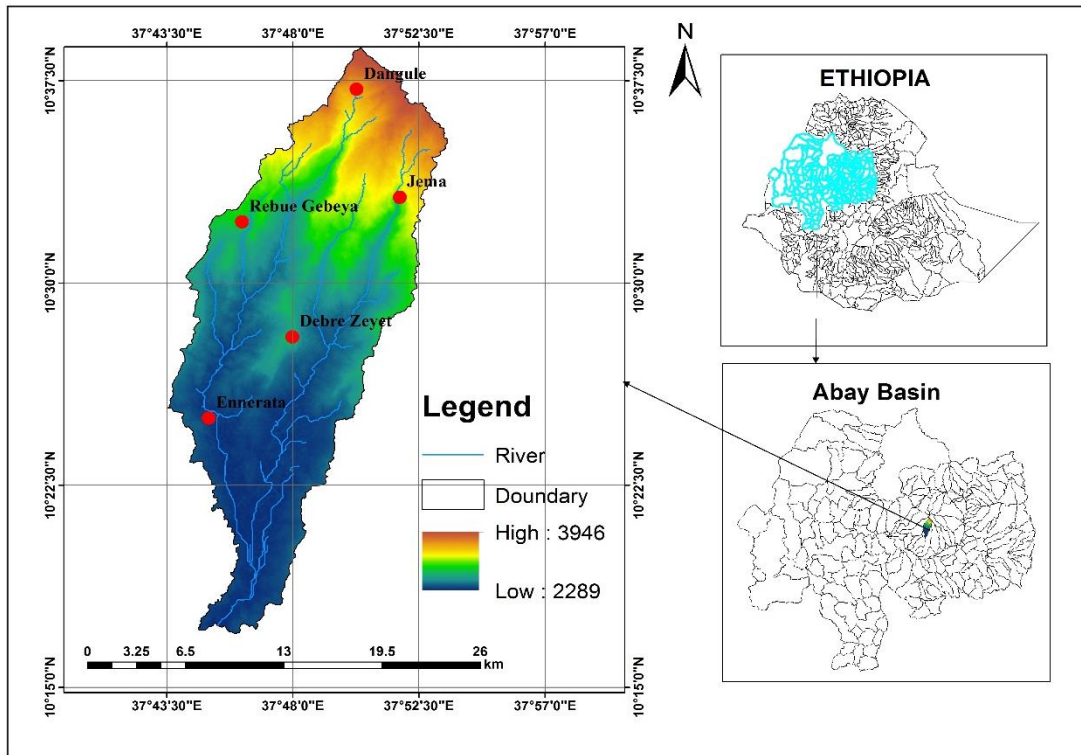


Figure 3.1: Location map of Chemoga watershed.

3.1.2 Topography

Chemoga watershed is characterized by diverse topographic conditions. The upstream part of the watershed is characterized by mountainous and highly separated terrain with steep slopes and an undulating topography and gentle slopes characterize the downstream part (Woldeamlak and Sterk, 2005). The elevation of the area ranges from 2289 m to nearly 3943 m above mean sea level (Figure 3.2).

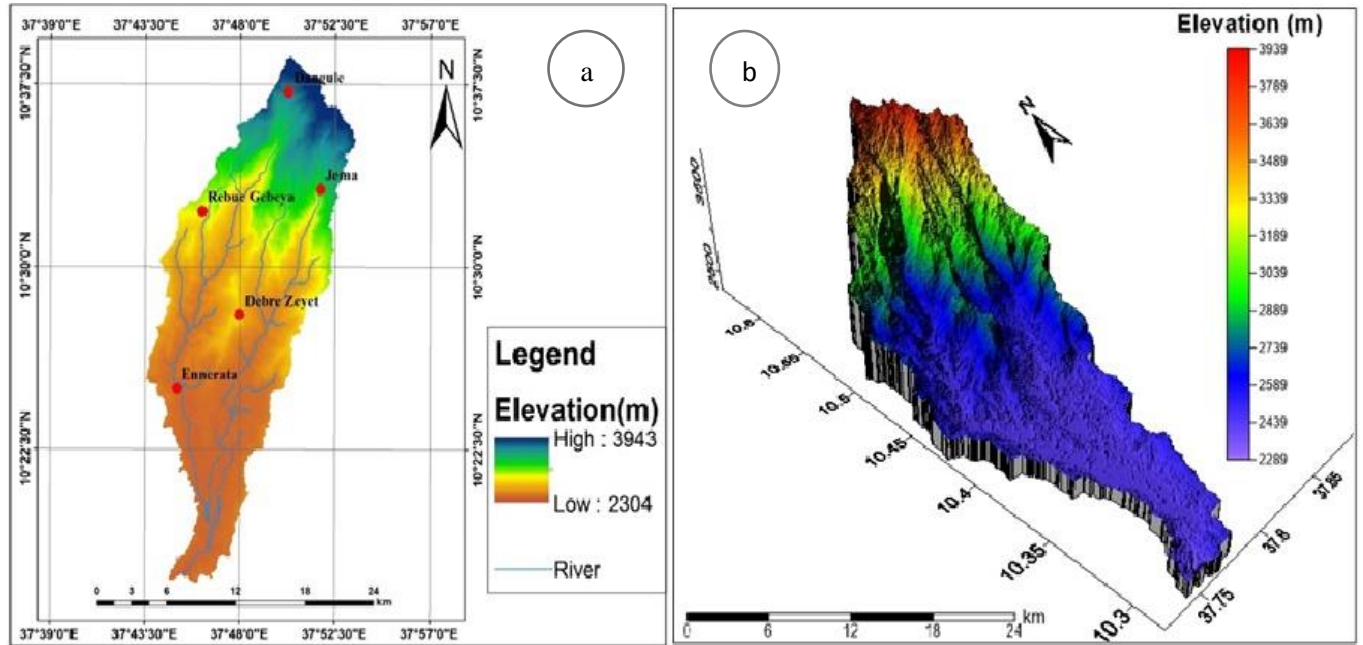


Figure 3.2: (a) Elevation map of Chemoga watershed (b) 3D view of Chemoga watershed.

3.1.3 Climate

The Ethiopian climate system is traditionally classified based on altitudinal range and temperature. Accordingly, there are five climatic zones in the country. Those climatic zones are Dega, Woina-Dega, Wurch, kola and Berha. The Berha zone is a very hot and hyper-arid region with less than 500 m.a.s.l. and Kola zone is also a hot and arid region which ranges between 500-1500 m.a.s.l. altitudes. Similarly, Woina-Dega zone that has an optimum temperature which ranges from 1500-2500 m.a.s.l. altitude. Dega and Wurch zones are found in highland regions with 2500-3000 and greater than 3000 m.a.s.l. altitudes respectively (NMA, 2001). Thus, chemoga watershed lies in between Dega and Wurch that includes Dega, upper Dega, Weyena Dega and wurch ecological zones (Figure 3.3).

As measured at the station in Debre Markos (10°20'N, 37°40'E at an elevation of 2411 m), the mean annual temperature is 14.5°C, ranging between 13.2°C in July and August and 17.3°C in March. The average annual rainfall is 1408.3 mm; more than 75% of the total precipitation occurs in the 4 months from June to September(JJAS) and the rest 25% occurs in the dry season of the year. Because the Chemoga watershed lies at a higher elevation than does Debre Markos (between 2420 and 4000 m), temperatures are significantly lower and rainfall is probably higher there.

The climatic condition of Chemoga watershed is generally humid climatic. The average annual rainfall ranges from approximately 1332.65 mm in the downstream part to over 1482.37 mm in the upstream part of the watershed as the minimum and maximum. The temporal distribution of the rainfall is highly uneven and this gives rise to a serious shortage of water during the dry season in some parts of the watershed (Woldeamlak Bewket and Sterk, 2005)

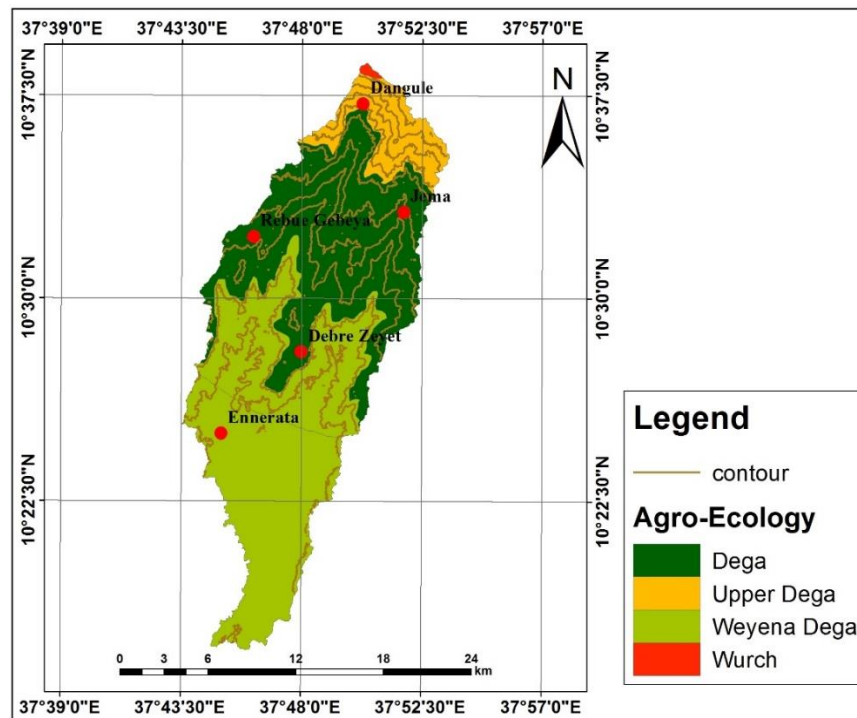
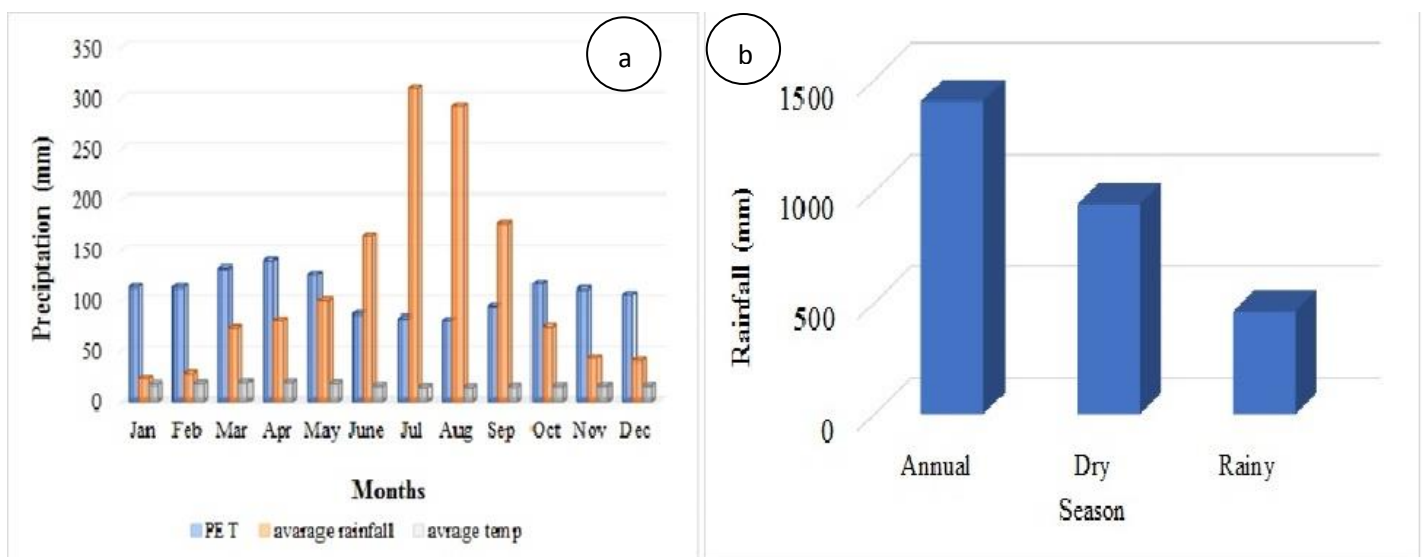


Figure 3.3: Ecological map of Chemoga watershed.



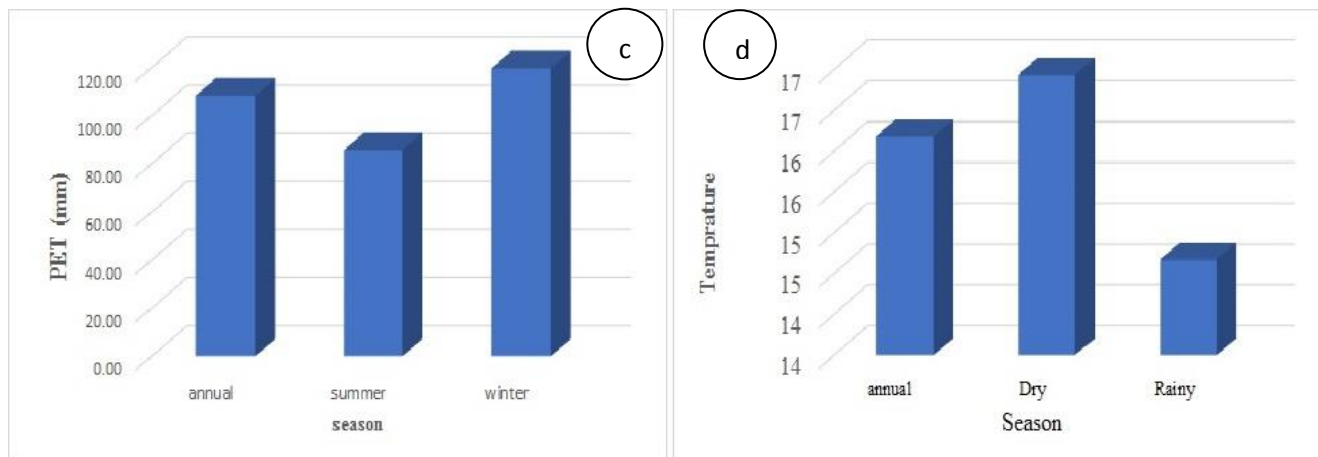


Figure 3.4: (a) Long-term mean monthly precipitation, PET, and Temperature (b) Seasonal Rainfall (c) Seasonal PET (d) Seasonal Temperature of Chemoga watershed.

3.1.4 Geology and Hydrology

According to the Ethiopian geological survey, the lithologic units of the study area include Tertiary and Quaternary volcanic rocks and Quaternary superficial deposits (Ferede Chumburo et al., (2015). Tertiary volcanic rocks (dominantly basalt with minor rhyolite, trachyte and pyroclastic tuff, and sedimentary rocks) and Quaternary volcano and superficial deposits. The Tertiary lava flow identified as flood basalts dated at 25.3 – 29.4 Ma and the Choke shield volcano dated at 22.4 – 23 Ma. The lithology of the study area has been described as per Ferede Chumburo et al. (2015).

Lithology of chemoga watershed is composed of Quaternary eluvial sediment (Qe) that covers 14.02% of the area, Debre Markose basalt (TV3) covers 16.62%, Lumame basalt flow (Tv4) which have 25.70% of area coverage, others that fall in the choke shield volcano group like, Rob Gebeya basalt (TCV1), Arat Mekeraker basalt (TCV2), Kutye basalt (TCV3) cover 43.66% of the total area of the watershed (Table 3.1).

The topmost part of TV3 unit overlain by hill forming pyroclastic tuff, lithic tuff, and the associated siltstone. The Tv3 basalt is dark with porphyritic (maximum plagioclase phenocryst is 8 mm) and aphyric texture and, has the blocky appearance and spheroidal weathering. Occasionally it is vesiculated and amygdaloidal with calcite amygdules. From the petrographic study, the Tv3 basalt represents olivine-plagioclase phyrlic basalt, plagioclase-olivine phyrlic basalt, and olivine phyrlic basalt one grade into another. The groundmass is composed of opaque, pyroxene, olivine and plagioclase laths in the increasing order, respectively.

The TV4 unit covers about 25.7% of the study area (Figure 3.5). This unit locally interlayered with pyroclastic tuff. The top most part of this unit overlain by the Choke shield volcano and the Islamo mountain Quaternary volcano. The Tv4 basalt is dark, porphyritic with a maximum of 1.1 cm size plagioclase phenocrysts and occasionally aphyric; sometimes vesiculated and amygdaloidal with silica amygdules.

According to Ethiopian geological survey of Kieffer et al., (2004) it is dated at 23.01Ma. The pyroclastic tuff and trachyte sills interlayered with Tvc1 basalt. This unit covers about 26.48% of the study area. The Tvc1 basalt is dark, porphyritic with occasional aphyric texture and, sometimes vesiculated and amygdaloidal with silica amygdules.

The TCV2 unit covers about 11.96% of the study area (Fig.3.5) and overlying the Tvc1 unit. At places the topmost position of the TCV2 basalt overlaid by pyroclastic lithic tuff, basaltic agglomerate and pyroclastic tuff with a thin layer of the coal seam, which are cross-cut by the basalt dyke.

The TCV3 unit covers about 5.22% of the study area (Fig.3.4) and overlying the Tvc2 unit. The trachytic sills and pyroclastic tuff interlayered with Tvc3. The Tvc3 basalt is dark, porphyritic and aphyric. The Tvc3 basalt represents plagioclase phyric basalt, olivine-plagioclase phyric basalt and aphyric basalt.

The eluvial sediments(Qe) in the study area developed from all rock types from the incipient alteration of the bed rocks to 4 m thick. A mappable unit of these sediments covers about 14.02% of the study area (Figure 3.5). The soil size varies from sand-silt-clay, silt-clay and clay size particles.

Table 3.1: Lithological type and area coverage.

Lithologic group	Lithologic type	Area (km ²)	Area (%)
Quaternary sediment	Quaternary eluvial sediment (Qe)	50.99	14.02
Choke shield volcano (22.4 – 23ma)	Rob Gebeya basalt (TCV1)	96.29	26.48
	Arat Mekeraker basalt (TCV2)	43.51	11.96
	Kutye basalt (TCV3)	18.97	5.22
Flood basalt(25.3-29.4ma)	Debre Markose basalt (TV3)	60.43	16.62
	Lumame basalt(TV4)	93.47	25.7

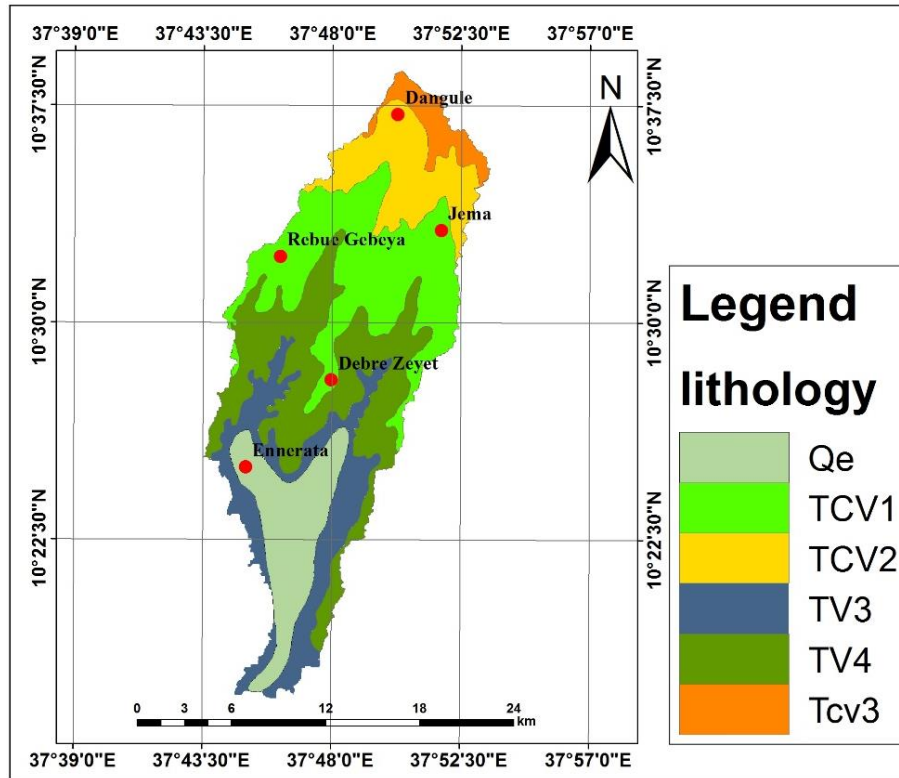


Figure 3.5: Lithologic unit of the watershed (Modified from Ethiopian Geological Survey).

According to geological survey of Ethiopia (2012), The nature and distribution of hydrogeologic units (aquifers and aquitards) in a geologic system are controlled by the lithology and structure of the geologic deposits and formations. The aquifer systems are defined based on transmissivity, conductivity and specific capacity Values. The Quaternary eluvial sediment is an important source of groundwater for private and communal use developed by hand dug wells. The aquifer types that exist in the study area includes very low productive of the intergranular aquifer that covers 13.25% of the area, very low to the low productive aquifer (59.04%) and moderate to the high productive aquifer (27.72%) (Table 3.2 and Figure 3.6).

Quaternary deposit, mainly elluvial sediments developed by hand-dug wells, in most parts of the area is an important source of groundwater for domestic water supply. The thickness of the unit is above 25 meters in areas of gentle slope and plain.

Table 3.2: Aquifer type and their area coverage.

Aquifer	Area(km ²)	Area (%)
Very low productive of intergranular aquifer	48.17	13.25
Very low to low productive aquifer	214.70	59.04
Moderate to high productive aquifer	100.79	27.72

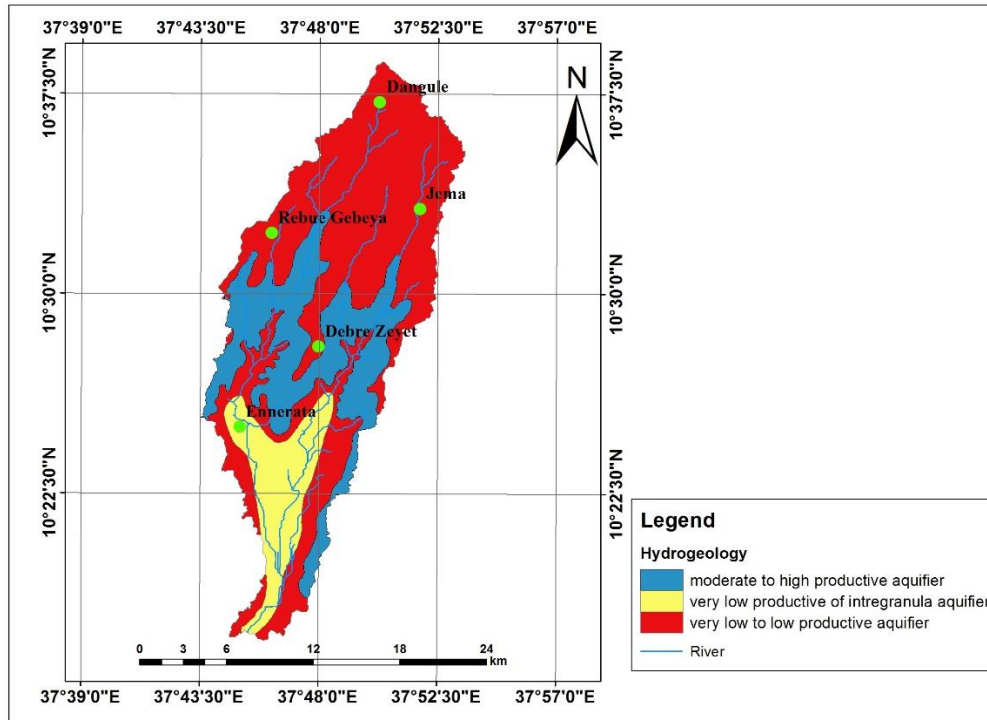


Figure 3.6: Hydrogeology of the watershed (Modified from Ethiopian Geological Survey).

Table 3.3: Main basic statistics of the Chemoga watershed.

Attribute	Unit	Mean	Min	Max	Standard deviation
Elevation	Meter (m)	2777.44	2289	3943	383.14
Slope	Degree (o)	9.75	0	62.34	7.16
Rainfall	mm	1408.3	1332.65	1482.37	31.55
Temperature	Degree centigrade(°c)	16.42	16.12	16.83	0.162
PET	mm	108.60	107.67	110.12	0.46

3.2 Method

The methodology consists of three major steps that are shown in Figure 3.7. In the first step, the spatial data is collected and prepared for the recharge modeling. These collected data consist of topographical data, meteorological data, soil data and satellite images to generate land use data.

The remote sensing and GIS software in storage, manipulating and analyzing the digital data. These data are adjusted and prepared to raster grid cell. Next, the raster data is used in the WetSpa model to calculate the annual and seasonal recharge maps in the study area. Finally, the results are correlated with water balance components and physical features, which are significant for groundwater recharge.

The land-use and land-cover map were produced using Landsat OLI8 satellite image taken in 2017 and control point field data were collected by using GPS. WetSpa modeling method was used to estimate groundwater recharge of the study area.

As WetSpa 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 parameter modification was used to apply it in the tropical region. In the temperate region, summer and winter have six months each whereas in Ethiopia summer (rainy season) contains four months (JJAS) and winter (dry season) covers eight months. In addition to this, the seasons of rainfall period and land-use/land-cover are not the same as temperate regions. Therefore, to apply the WetSpa for Chemoga watershed, input data of the meteorological grid map was done using four months of summer and eight months of winter. Also, modified summer and winter land-use parameter tables were used.

Two types of inputs are required so as to run the WetSpa model: Parameter tables (TBL file format) and grid map (ASCII file format). Inputs of land use, soil and runoff characteristics parameter tables were required for the model. ArcGIS (version 10.5) with its spatial analyst extensions has been used in order to prepare these input parameters, and parameter tables were added to the maps as an attribute. The runoff characteristics parameter tables contain runoff coefficient, slope and soil type for each corresponding land use. 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, soil, potential evapotranspiration and groundwater level

(groundwater depth) maps were prepared. Hence, the topographic grid map and the slope map were derived from SRTM DEM using ArcGIS10.5.

Due to lack of monthly data for groundwater depth, same map input was used for both seasons. Temperature, precipitation and wind speed parameters were prepared using the available meteorological data collected from Ethiopian meteorological agency.

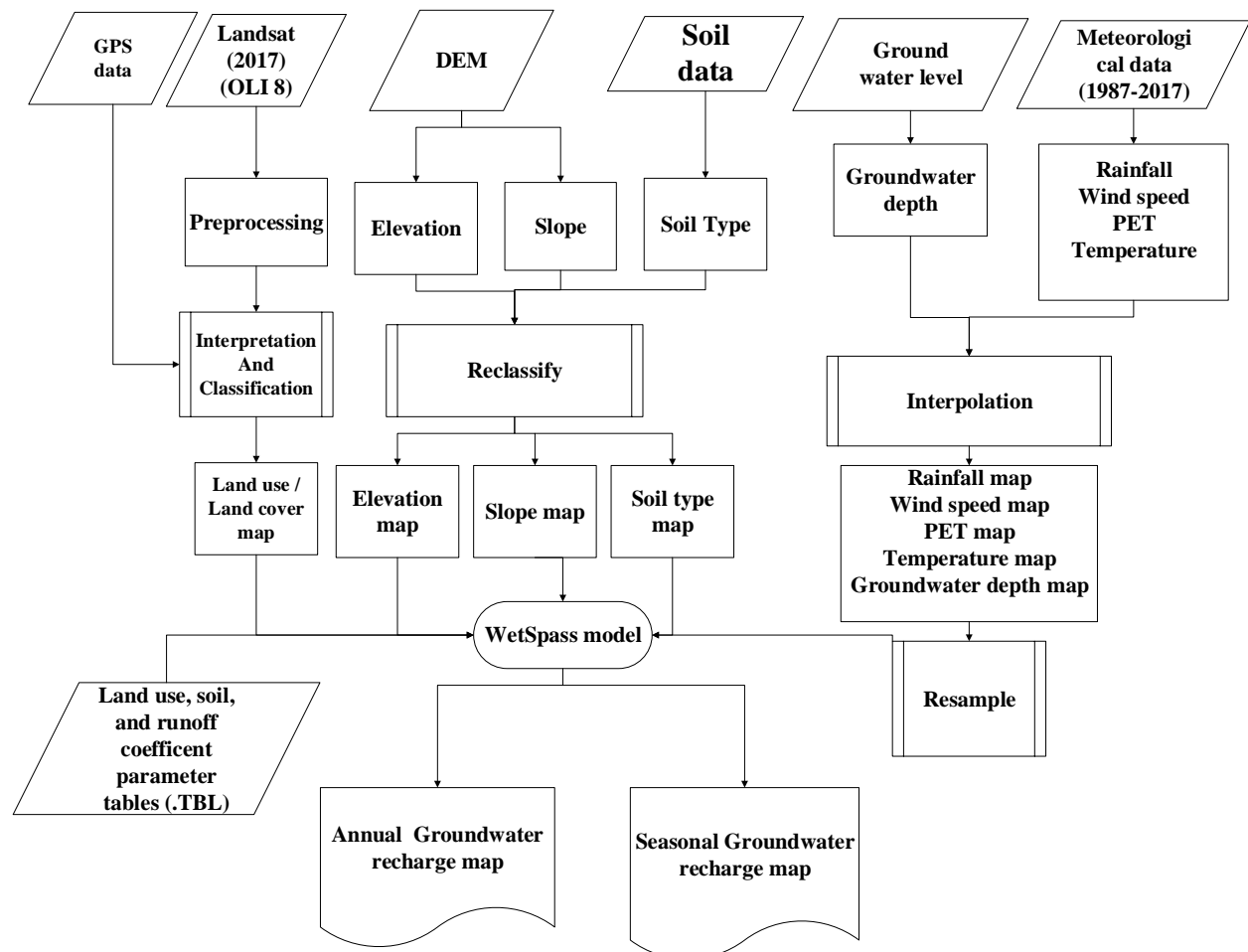


Figure 3.7: Methodological flow chart

3.2.1 Data availability and materials

For the compilation of this research the following data were collected; climatological data which includes monthly precipitation, potential evapotranspiration, minimum and maximum temperatures, sunshine hours, groundwater depth and wind speed data. Physical data of the area that includes 30m resolution SRTM DEM, 30 m resolution satellite image of landsat 8 OLI image to drive land use land cover of the area and soil textural type of the study area were collected and used as an input for the model to compute groundwater recharge of the study area.

3.2.2 Meteorological and hydrological data

Secondary data that consists of Meteorological and hydrological data inputs for the model used in this study were acquired from Ethiopian National Meteorological Agency (NMA) and Ethiopian Ministry of Water, Irrigation and Energy (MoWIE). Different meteorological data were collected from the meteorological stations found in and around the Chemoga watershed (Table 3.5). Precipitation, minimum and maximum temperature, relative humidity, sunshine hours data are among the meteorological data collected from the Ethiopian Meteorological Service Agency. The hydrological data, the available flow net data of the watershed's gauging station, were collected from the Ethiopian Ministry of Water, Energy and Irrigation.

For the processing of meteorological data (Precipitation, evapotranspiration, temperature and wind speed), the period 1987-2017 is chosen with an average value for each seasonal time step, i.e., the winter and summer seasons corresponding to the periods October-May and June-September, respectively. Annual and seasonal meteorological parameters were prepared from the available meteorological data. There are eight meteorological stations within and nearby the Chemoga watershed. Monthly precipitation recording data are available in all stations, but temperature records have only been recorded in five stations, and relative humidity, sunshine hours, wind speed are recorded only in five stations. Mean monthly values of precipitation were used to derive mean annual precipitation, wet (winter) season precipitation (June–September) and for dry season precipitation (October–May).

Meteorological variables required for applications in hydrology and water resources management are usually measured at meteorological stations, and the data are only valid for the point where it is measured. Spatial interpolation can be used to estimate meteorological variables at other locations.

Digital maps of seasonal precipitation were derived by spatial interpolation of the values observed in the eight stations, using the ordinary kriging interpolation module of ArcGIS.

Spatial Analyst offers different interpolation techniques for raster such as Inverse Distance Weighting (IDW), Spline, and Kriging. Each of these techniques was employed to generate a surface of mean climatological data of the watershed. To determine which interpolation method provided the most accurate surface the analyst must calculate the amount of error at each grid cell. Errors were calculated as actual minus predicted and the mean of these errors was calculated in four ways: mean error (ME), indicating the degree of bias; mean absolute error (MAE), providing a measure of how far the estimate can be in error, ignoring its sign; mean relative error (MRE),

providing a measure of how far the estimate can be in error relative to the measured mean; root mean square error (RMSE), providing a measure that is sensitive to outliers (Apaydin, *et al.*,2004). Based on those the above-mentioned criteria ordinary kriging interpolation method was used to prepare the meteorological data input for the model.

The resulting maps are shown in Figure 3.10 up to 3.15. The annual precipitation ranges between 1332.65 and 1482.37mm (Figure 3.10 a) for the summer (rainy) season between 942.305 (Fig 3.10 b) and 1047.44mm and between 366.24mm and 461.9 mm for the winter (dry) season (Figure 3.10 c). The average temperature was also computed for the same weather station using monthly measured values during the period 1987–2017. The maps are shown in Figure 3.12. The average temperature ranges between 16.8°C and 17.43°C in the winter (dry) season the mean is 14.98°C, it between 14.7°C and 15.44°C in the summer (rainy) season and the annual average ranges between 16.12°C and 16.18°C of the watershed.

Due to the absence of PET data, the potential evapotranspiration (PET) in the Chemoga watershed was calculated using Penman-Monteith based agricultural model CROPWAT 8.0 FAO software for the four meteorological stations (Debre Markos, Kuy, Rob Gebeya, Yenora and Dengay Ber) which have a record of wind speed, sunshine hours and relative humidity. The annual PET ranges between 107.67mm and 110.12 mm, for winter season it ranges between 118.37mm and 123 mm and between 89.5mm and 87.2 mm for the summer season.

Table 3.4: Climatological data source.

Climatological data set	Type	Unit	Source
Rainfall	Monthly and daily	mm	Ethiopian meteorological agency
Temperature	Monthly and daily	°c	
Relative humidity	Monthly and daily	%	
Wind speed	Monthly and daily	m/s	
Potential evapotranspiration	Monthly and daily	mm	Calculated using Penman-Monteith based FAO CROPWAT software

Table 3.5: Characteristics of rainfall stations.

Number	Station name	X-coordinate	Y-coordinate	Altitude	Average annual rainfall(mm)
1	Debre Markose	37.7392	10.3257	2446	1328.0
2	Dengay Ber	37.55	10.71667	2800	2202.0
3	Felege Berhan	38.0671	10.7427	2710	1378.3
4	Feres Bet	37.6085	10.8499	3000	1765.2
5	Kuy	37.594	10.3	1888	1344.2
6	Robe Gebeya	37.77	10.55	2940	1404.2
7	Yetmen	38.1466	10.3291	2418	1457.4
8	Yetnora	38.1083	10.2449	2420	1175.6

3.2.3 Land use, soil data and sources

The land use map of the watershed was derived from Landsat OLI 8 images of January 27 (path 169, rows 053) for the dry season and June 5 (path 169, rows 053) for the rainy season, 2017 using the standard ERDAS IMAGINE supervised image classification method. Landsat OLI eight satellite images of the years 2017 of the study area were downloaded from United States Geological Survey Global Visualization Viewer Website (<https://earthexplorer.usgs.gov>).

The soil map of the Chemoga watershed was found from the soil map data of the master plan of the Blue Nile river basin (scale 1:250 000), which was obtained from the Ministry of Water Resources, Irrigation and Energy (MoWIE). Soils of the study area are classified into five textural classes based on their grain size using the United States Department of Agriculture (USDA) textural classification methods, loamy sand, clay loam, silty clay loam and clay (Figure 3.16).

3.2.3.1 Preprocessing

Preprocessing refers to those image processing operations that precedes the main analysis. Several pre-processing methods were implemented before the image classification. Which includes, radiometric correction to adjust digital values for effects of a hazy atmosphere and/or geometric preprocessing to bring an image into registration with a map or another image. Once corrections

have been made, the data can then be used to the primary analyses such as land use land cover classification (Campbell and Wynne, 2011). Radiometric preprocessing influences the brightness values of an image to correct for sensor malfunctions or to adjust the values to compensate for atmospheric degradation. The technique that have used to correct the various types of geometric distortion existing in digital image data is to model the nature and magnitude of the sources of distortion and use these models to establish correction formulae.

Conversion to Top of Atmosphere (TOA) reflectance: To correct for illumination variations (sun angle and Earth-Sun distance) within and between scenes, TOA reflectance for each band was calculated. TOA reflectance value does not take into account the signal attenuation by the atmosphere, which strongly affects the inter-comparability of the satellite images taken on different dates. But atmospheric correction methods account for one or more of the distorting effects of the atmosphere and thereby convert the brightness values of each pixel to actual reflectance as they would have been measured on the ground.

$$L_{\lambda} = M_L * Q_{cal} + A_L \quad \text{Eq. 3.1}$$

where: L_{λ} = Spectral radiance ($W/(m^2 * sr * \mu m)$)

M_L = Radiance multiplicative scaling factor for the band (radiance_mult_band_n from the metadata).

A_L = Radiance additive scaling factor for the band (radiance_add_band_n from the metadata). Q_{cal} = Level 1-pixel value in DN

Image pre-processing was done on the initial processing of the raw data, which was applied in this study like geometric and radiometric corrections, image enhancement and topographic corrections. In the first step the acquired data were stacked and layer sub-setting was done into composite images of the study area. In order to make the data compatible with each other, the projection transformation was carried out and was assigned the Adindan _ UTM _ Zone_37N projection coordinate system.

3.2.3.2 Classification

According to John and Xiuping (2005), digital image classification is the process of assigning pixels into a finite number of individual classes, or categories of data, based on their data spectral

information values. Usually, each pixel is treated as an individual unit composed of values in several spectral bands. Common Digital image classification procedures can be divided into two broad subdivisions based on the method used: supervised classification and unsupervised classification.

Unsupervised classification uses statistical clustering techniques to combine pixels into groups (classes) according to the degree of similarity of their brightness value in each spectral band. The analyst then combines spectral classes into a real land cover type using maps and field-based knowledge (John and Xiuping,2005).

In a supervised classification, the analyst identifies in the imagery homogeneous representative samples of the different surface cover types (information classes) of interest. These samples are known as training areas (Campbell and Wynne,2011). In this study supervised maximum likelihood classification was used.

3.2.3.3 Accuracy assessment

Accuracy assessment was performed to assess the accuracy of the image classification process. A confusion matrix was prepared considering 244 randomly selected reference ground truth points for evaluation. Confusion matrices are a widely accepted method of determining the accuracy of classification. Commission, omission, producer's accuracy, and user's accuracy were calculated for each land-cover class.

3.2.4 Estimation of missed data

Different meteorological data were collected and checked if there is missed data. The missed records of the station were adjusted by commonly used method which is called the Averaged method. In the estimation of missing data from a rain-gauge station, performance of a group of neighborings stations including the one with missing data were considered. A comparison of the recordings of these stations are made by using their normal rainfall as the standard of comparison. The normal rainfall is the average value of rainfall at a particular date, month or year over a specified 30-year period. The 30-year normal is recomputed every decade. Thus, the term normal monthly precipitation at a station means the average precipitation for a particular month at the station based on 30-year of record. Insertion of missing data to a station must be done carefully. If too many data are estimated, the quality of the total data set may be weak due to interpolation.

Sometimes, if too many gaps exist in a record, it may be worthwhile to neglect that station than to have a station record with too much of interpolated data. According to a WMO (World Meteorological Organization) guideline, not more than 10% of a record should have interpolated data.

3.2.5 Software packages

In this study the software used mainly includes ERDAS Imagine 2015, ArcGIS 10.5, Microsoft Office Package 2016 and WetSpa model were used for this study. Obviously, ERDAS Imagine 2015 is important software for image preprocessing, enhancement, transformation, classification and accuracy assessment activities. ArcGIS10.5 is mainly used for map preparation and conversion of data format types and interpolation of different data that are collected in point data format to produce the raster maps. Another material such as GPS has been used for ground data collection for accuracy assessment of classified image and CROPWAT 8.0 software for preparation of potential evapotranspiration data. Microsoft Office Package (2016) Provides the necessary environment for MS Excel, MS Word, MS Powerpoint and MS Access.

3.3 Hydrologic model

Different types of models can be used, depending upon the considered output, the existing database, input variables and required analysis. Representation of physical processes described by rainfall-runoff models can either be based on a simple mathematical link between input and output variables of the basin or include the description of basic processes involved in the runoff generation. Various models have been developed for the past decades in different part of the world. These models can be generally classified based on process description as physically based distributed models, conceptual models and data-driven models (Beven, 2001).

The physically based distributed hydrological model WetSpa was used in the study estimation of groundwater recharge and water balance components of the watershed. It is physical conceptualized based on groundwater parameters such as land use type, soil textural type, precipitation, interception, surface runoff, infiltration, evapotranspiration and groundwater level. The following sections discuss the descriptions of the WetSpa model.

3.3.1 WetSpa model

The original WetSpa model is a quasi-steady state spatially distributed water balance model scripted in Avenue and used to predict hydrological processes at seasonal and annual time step. With rising popularity of Python programming language in the scientific and research areas, the model has been scripted in Python and using own spatial library Hydrology and Hydraulic Programming Library (H2PL). This newer version of the model has the ability to simulate interception from vegetated surfaces, runoff from the landscape, evapotranspiration, soil water balance, and recharge at monthly time step. The user may simulate the model using long-term monthly average values or unique monthly values for many years (Liu and De Smedt, 2004). Since the model is a distributed one, the water balance computation is performed at a raster cell level. Individual raster water balance is obtained by summing up independent water balances for the vegetated, bare soil, open- water, and impervious fraction of a raster cell. The total water balance of a given area is thus calculated as the summation of the water balance of each raster cell.

It is GIS based, spatially distributed hydrological model for estimating the spatially distributed yearly and seasonal actual evapotranspiration, surface runoff, and groundwater recharge. The model accounts for the spatial variation in the groundwater recharge, which is the result of distributed land use, soil type, slope, etc. Fig 3.8 gives a schematic water balance of a hypothetical grid cell for WetSpa from Batelaan & De Smedt (2001). This allows accounting for the non-uniformity of the land use depending on the resolution of the grid cell. The model treats a basin or region as a regular pattern of raster cells. Every raster cell is further sub-divided in a vegetated, bare soil, open water, and impervious surface fraction, for which independent water balances are preserved (Figure 3.8).

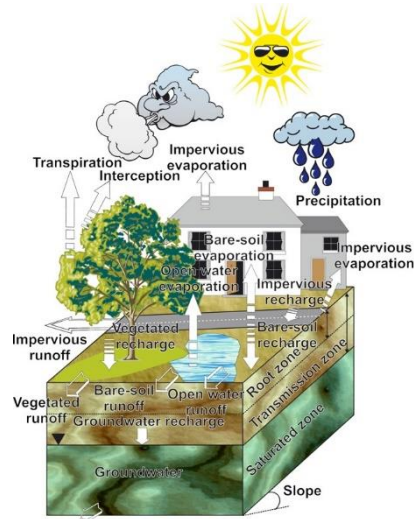


Figure 3.8: Schematic water balance of a hypothetical raster cell. (source: Batelaan & De Smedt (2001)).

3.3.2 Water balance components

Since WetSpa model is a distributed one, the water balance computation is performed at a raster cell level. Individual raster water balance is obtained by summing up independent water balances for the vegetated, bare soil, open water, and impervious fraction of a raster cell. The total water balance of a given area is thus calculated as the summation of the water balance of each raster cell. The water balance for vegetated surfaces which depends on the average seasonal precipitation (P), interception fraction (I), surface runoff (S_v), actual transpiration (T_v), and groundwater recharge (R_v) is calculated by:

$$P = I + S_v + T_v + R_v \quad \text{Eq.3.2}$$

Where, P is the average seasonal precipitation [LT^{-1}], I is the interception by vegetation [LT^{-1}], S_v is runoff over land surface beneath vegetation [LT^{-1}], T_v is the actual transpiration [LT^{-1}] and R_v is groundwater recharge [LT^{-1}]. The term actual evapotranspiration, ET_v , is used here for the sum of the transpiration, T_v , and the evaporation from the bare soil beneath the vegetation, E_s . ET_{tot} , the total actual evapotranspiration is the sum of the evaporation of water intercepted by vegetation, I , and the actual evapotranspiration, ET_v .

$$ET_{tot} = I + T_v + E_s \quad \text{Eq 3.3}$$

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

The interception fraction has been shown to be reasonably constant at a given annual precipitation value and exhibits a consistent decrease with increasing annual rainfall total (Roberts, 1983). Therefore, the intercepted value is parameterized as a constant percentage from precipitation, dependent on the vegetation type (Batelaan & De Smedt, 2001). 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 constant throughout the simulation period) (Batelaan and Woldeamlak, 2003).

Surface runoff is calculated in relation to precipitation amount, precipitation intensity, interception and soil infiltration capacity. The surface runoff, S_v , is calculated in two stages. Initially, the potential surface runoff (S_v-pot) is calculated as:

$$S_v-pot = C_{sv} (P - I) \quad \text{Eq 3.4}$$

Where, C_{sv} is a surface runoff coefficient for vegetated infiltration areas. C_{sv} is a function of vegetation type, soil type and slope. In groundwater discharge areas, saturated surface runoff is occurring. Here, the surface runoff coefficient is very high and assumed to be constant, due to its reduced dependency on soil and vegetation type and the generally near to river position of the runoff producing areas. In the second stage, the potential surface runoff is actualized by taking into account differences in precipitation intensities in relation to soil infiltration capacities.

In order to obtain a seasonal distributed evapotranspiration value, WetSpass proposes to convert the open-water evaporation value, as commonly available from the Penman equation to a reference transpiration (Federer, 1979) value based on a vegetation coefficient:

$$T_{rv} = C E_o \quad \text{Eq 3.5}$$

Where, T_{rv} is the reference transpiration of a vegetated surface [LT^{-1}], E_o is the potential evaporation of open water [LT^{-1}] and C is the vegetation coefficient [-]. The vegetation coefficient can be determined as the quotient of the reference vegetation transpiration, as given by the

Penman-Monteith equation, and the potential open-water evaporation, as given by the Penman equation, resulting in:

$$C = \frac{1 + \gamma/\Delta}{1 + \frac{\gamma}{\Delta} \left(1 + \frac{r_c}{r_a}\right)} \quad \text{Eq. 3.6}$$

Where, γ = psychrometric constant [$\text{ML}^{-1}\text{T}^{-2}\text{C}^{-1}$];

Δ = slope of the first derivative of the saturated vapor pressure curve (slope of saturation vapor pressure at the prevailing air temperature) [$\text{ML}^{-1}\text{T}^{-2}\text{C}^{-1}$]; r_c = canopy resistance [TL^{-1}] and r_a = aerodynamic resistance [TL^{-1}] which is calculated by:

$$r_a = \frac{1}{k^2 u_a} \left(\ln \left(\frac{z_a - d}{z_o} \right) \right)^2 \quad \text{Eq. 3.7}$$

Where, k is the Von Karman constant (0.4) [-]; u_a = the wind speed [LT^{-1}] at measurement level $z_a = 2\text{m}$; d = the zero-plane displacement length [L] and z_o = the roughness length for the vegetation or soil [L].

The Penman coefficient (γ/Δ) varies with temperature (Table 3.6)

Table 3.6: Variation of Penman coefficient γ/Δ with temperature.

T(°c)	-20	10	0	5	10	15	20	25	30	35	40
γ/Δ	5.86	2.83	1.46	1.02	0.76	0.59	0.45	0.35	0.27	0.25	0.17

The other water balance component is the groundwater recharge and is calculated as a residual term of the water balance, i.e.,

$$R_v = P - S_v - ET_v - I \quad \text{Eq.3.8}$$

Where, p is precipitation, S_v runoff over land surface beneath vegetation is interception by vegetation, and ET_v is the actual evapotranspiration [LT^{-1}] calculated as the sum of transpiration T_v and E_s (the evaporation from bare soil found in between the vegetation).

The spatially distributed recharge is therefore estimated from the vegetation type, soil type, slope, groundwater depth, and climatic variables of precipitation, potential evapotranspiration, temperature, and wind-speed.

A similar procedure as that for the vegetated surfaces is followed for the calculation of the water balance for bare-soil, open-water, and impervious surfaces. The only difference is that there is no interception and transpiration component in calculating the water balance of bare-soil, open-water, and impervious surfaces, due to the fact that there is no vegetation cover on those surfaces and the evapotranspiration(ET_v) component becomes evaporation(E_s).

3.3.3 Water balance 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. The total evapotranspiration, surface runoff and groundwater recharge of a raster cell have been calculated using equations (Eq 3.9,3.10, 3.11) which had described by (Batelaan and De Smedt, 2001):

$$ET_{\text{raster}} = a_v ET_v + a_s E_s + a_o E_o + a_i E_i \quad \text{Eq.3.9}$$

$$S_{\text{raster}} = a_v S_v + a_s S_s + a_o S_o + a_i S_i \quad \text{Eq.3.10}$$

$$R_{\text{raster}} = a_v R_v + a_s R_s + a_o R_o + a_i R_i \quad \text{Eq.3.11}$$

Where ET_{raster} , S_{raster} , R_{raster} 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 a_v , a_s , a_o , and a_i , respectively.

Precipitation is taken as starting point for the computation of the water balance for each of the above-mentioned components of a raster cell. The other processes (interception, runoff, evapotranspiration, and recharge) have been calculated in an orderly manner; which becomes a prerequisite for the seasonal time scale to quantify the processes.

3.3.4 WetSpa model input data

The WetSpa model requires five classes of input data: Climatic, catchment configuration, vegetation, soil properties and boundary conditions. The climatic data includes precipitation, potential evapotranspiration, wind speed and Penman coefficient and number of rainy days per month, while catchment configuration considers land use types, leaf area index (LAI), slope and groundwater depth. The soil parameters data consists of hydraulic properties and empirical

coefficients for modeling evapotranspiration and surface runoff. Boundary conditions take into consideration the extension of the area to be modeled.

According to Al-Kuisi and El-Naqa (2013), The interaction of climate, morphology, soil condition and vegetation determines the recharge process. These input data were prepared in the form of maps of selected meteorological, hydrological, and geographical elements in the watershed. The climate data for the Chemoga watershed was obtained from the National Meteorological Agency of Ethiopia (NME) for different stations and the data was prepared for the WetSpss model.

The basic input requirements for the WetSpss model consist of model parameter tables, meteorological data, land use, soil elevation and slope data are for model calibration and simulation. The basic meteorological data requirements are rainfall, PET and Temperature data. In the case of calculating PET by the Penman-Monteith equation, additional meteorological data are required, including air temperature, radiation, relative humidity and wind speed (Figure.3.9).

There are eight climatological stations in and around Chemoga watershed. Climatological data such as precipitation, temperature, relative humidity, sunshine hours, and wind speed are available for the period 1987 through 2017. All the input data will have discussed hereafter and generalized in Table 3.9.

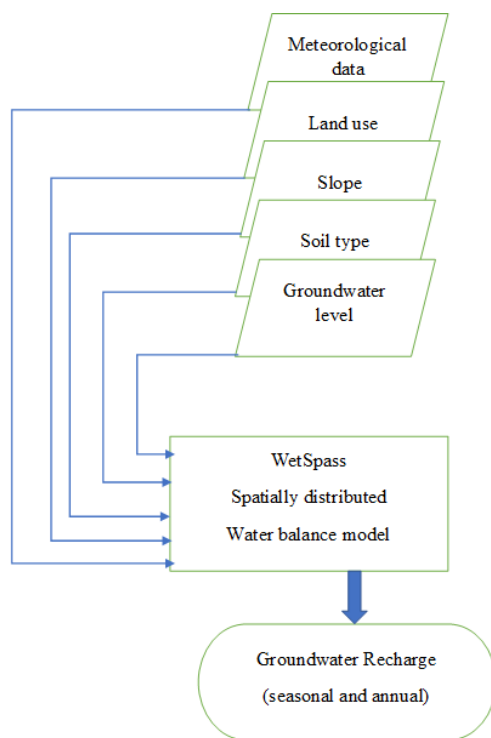


Figure 3.9: Schematic representation of the input data.

3.3.4.1 Rainfall (Precipitation)

Rainfall is one of the climatic variables that affect both the spatial and temporal patterns on water availability. Precipitation is taken as the starting point for the computation of the water balance of each of the components of a raster cell, the other processes (interception, runoff, evapotranspiration, and recharge) follow in an orderly manner.

Rainfall records are available from 1987 to 2016 for eight stations. In the watershed, the hydrological year is divided into two distinct seasons, a rainy season (summer) from Jun to September and a dry season (winter) that includes for the rest months of the year. Examples of the distribution of monthly rainfall within different localities in and around the watershed are shown in Figure 3.10.

The average annual precipitation is about 1408.3 mm with 1332.65 mm and 1482.4 mm as the minimum and maximum annual rainfall respectively, and the average precipitation of summer is 987.7 mm, where the winter is 420.48 mm.

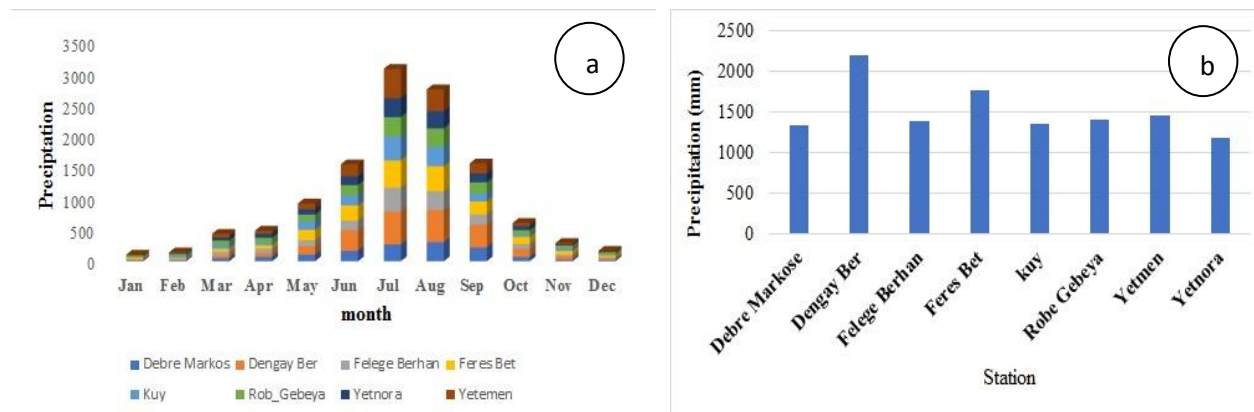


Figure 3.10: (a) Long-term mean monthly precipitation (b) Annual rainfall of each station.

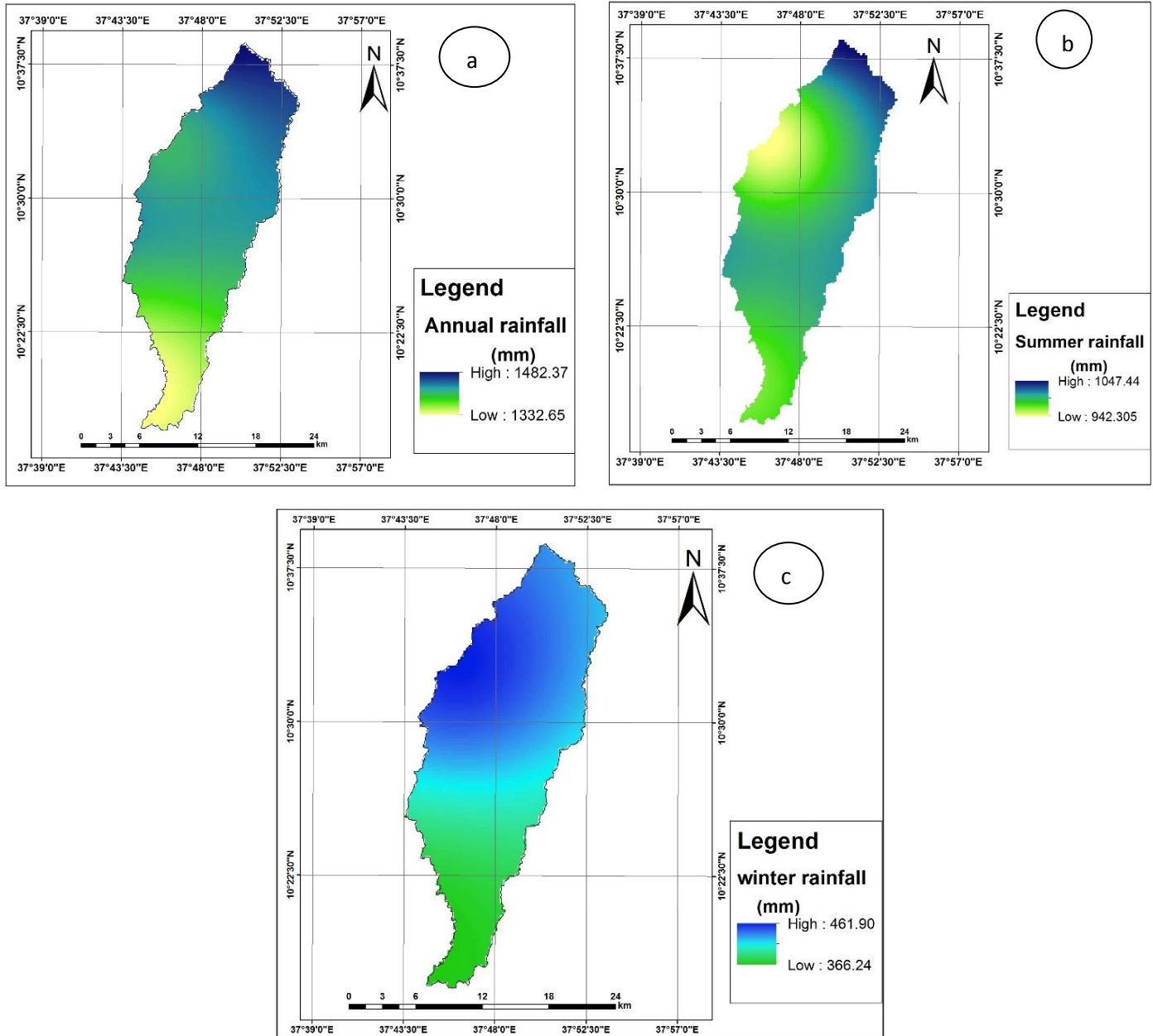


Figure 3.11: Precipitation map of Chemoga watershed, (a)annual precipitation, (b) rainy season precipitation, (c) dry season precipitation

3.3.4.2 Temperature

Temperature data are available for all the five weather stations. The winter(dray) season average temperature ranges between 16.8°C and 17.43°Cand the mean is14.98°C, it is between 14.7°C and 15.44°C for the summer(rainy) season and the annual average temperature ranges between 16.12°C and 16.83°C of the watershed (Figure 3.13). The average monthly temperatures are perceived

smaller during months of November, December and January. Meanwhile higher mean monthly temperatures were recorded in the months of March to May.

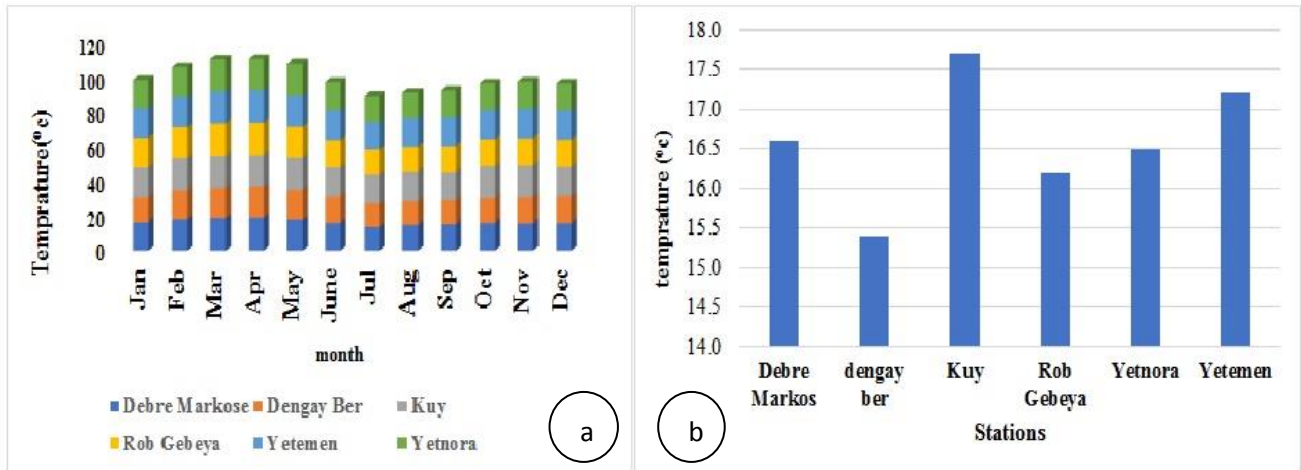
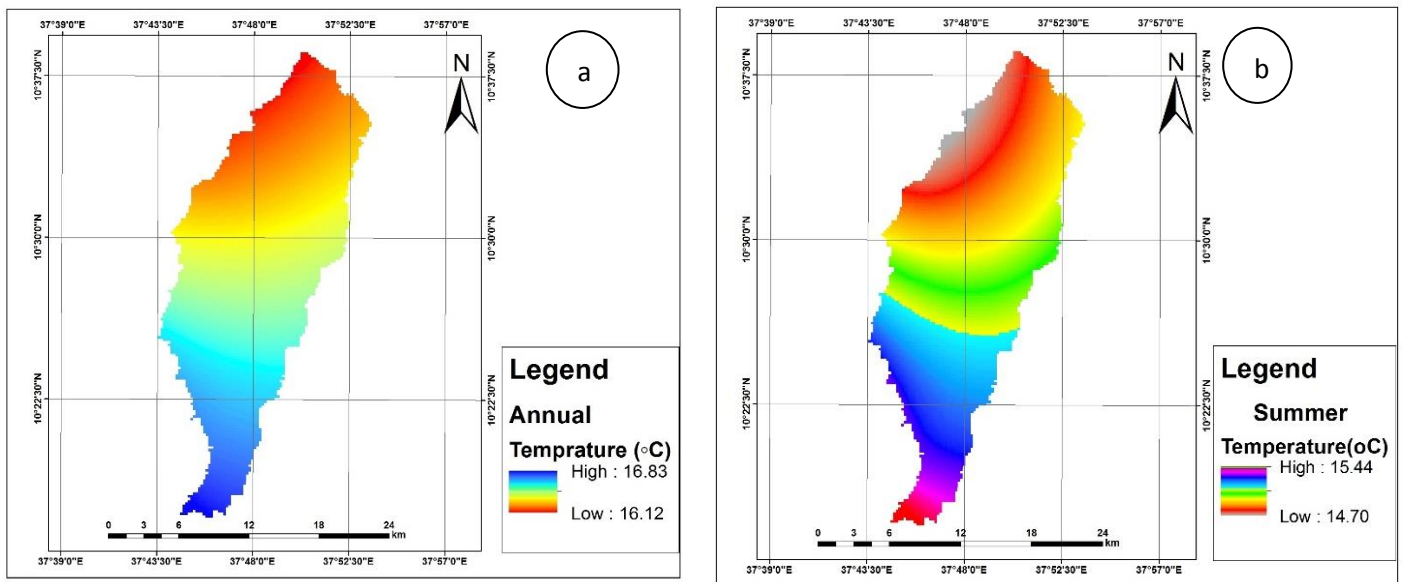


Figure 3.12: (a) Long-term mean monthly Temperature (b) Annual temperature of each station.



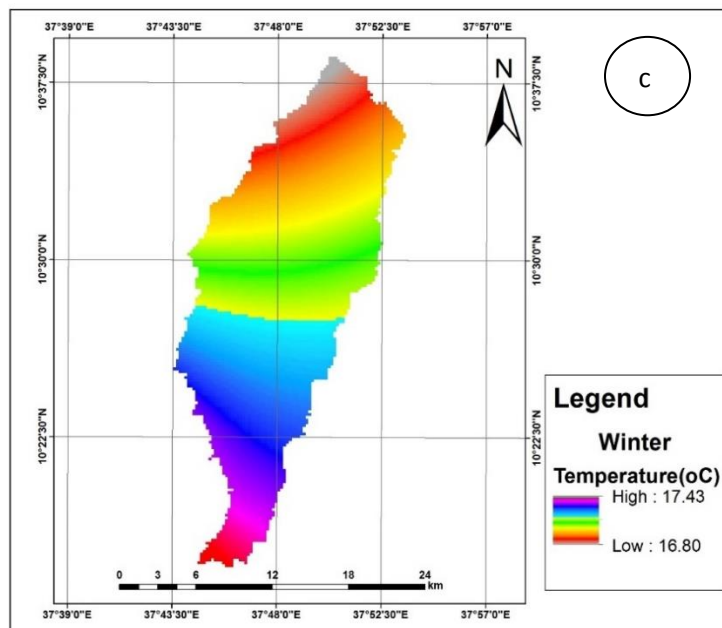


Figure 3.13: Temperature map of Chemoga watershed, (a) annual Temperature, (b) rainy season Temperature, (c) dry season Temperature.

3.3.4.3 Potential evapotranspiration

PET is defined as the quantity of water vapour, which could be emitted by a plant or soil surface per unit area and unit time under the existing conditions without water supply limit. The WetSpss model requires the measured PET in the watershed as an input. Similarly, to precipitation, PET is usually measured at meteorological stations or estimated using numerical and experimental methods i.e. Penman-Monteith equation. Spatial distribution of the PET is done in the same way as for the precipitation, using the ordinary kriging approach.

potential evapotranspiration (PET) in the Chemoga watershed was estimated using Penman-Monteith based FAO CROPWAT software for the four meteorological stations (Debre Markos, Yenora, Kuy and Dengay Ber) which have a record of wind speed, sunshine hours and relative humidity (Figure 3.14).

Calculated monthly results are subdivided into two main seasons i.e. 4 months of summer (rainy season) and 8 months of winter (Dray season). Finally, those PET values of each season, are converted to spatially distributed grid maps by means of interpolation. The grid maps of PET for both seasons are used with other input parameters in WetSpss model to estimate the recharge as well as actual evapotranspiration (AET). The average potential evapotranspiration of summer is 347.45 mm, where the winter is 958.5 mm, and the average annual potential evapotranspiration is

1303.66 mm with 1292.1 mm and 1322.3 mm as the minimum and maximum annual PET respectively.

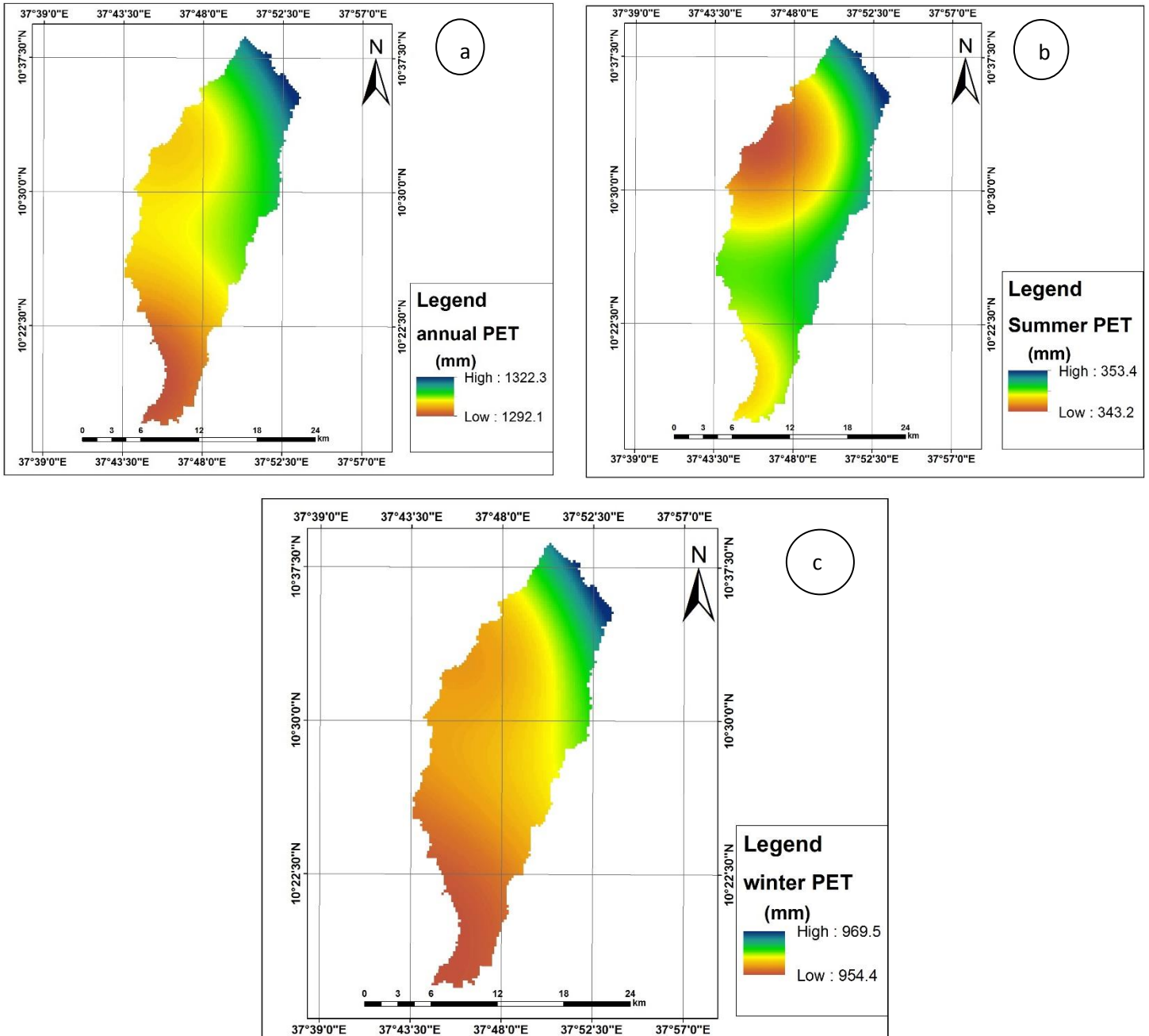


Figure 3.14: Potential evapotranspiration of Chemoga watershed. (a) Annual PET, (b) Rainy season PET, (c) Dry season PET.

3.3.4.4 Wind speed

Wind speed data are available for few meteorological stations. These data were used uniformly over the watershed: Average wind speed of summer is 1.06 m/s, winter wind speed is about 1.43 m/s, and the average annual wind speed is 1.24 m/s.

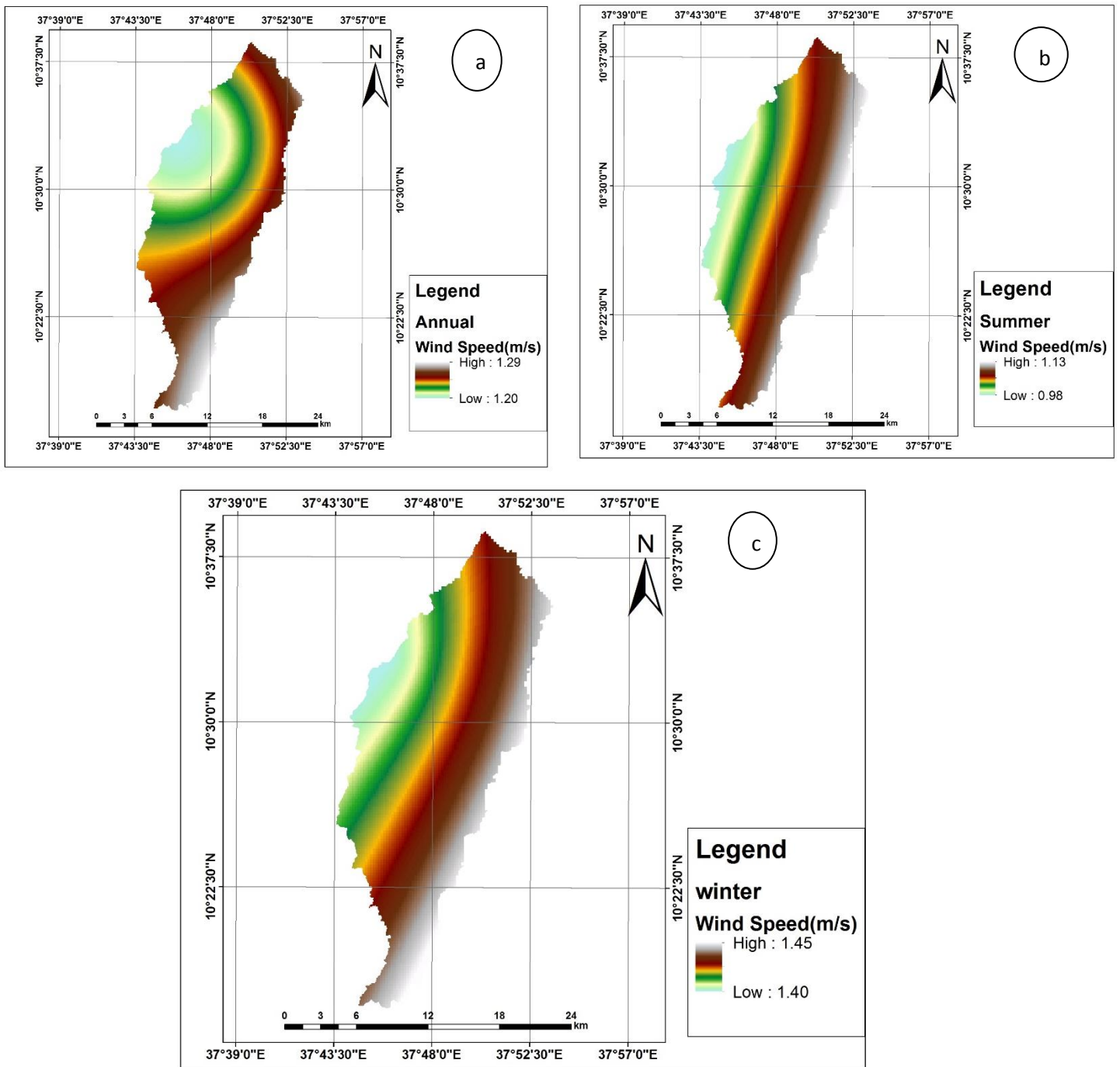


Figure 3.15: Wind speed map of the watershed. (a) annual wind speed, (b) rainy season wind speed, (c) dry season wind speed.

3.3.4.5 Land-use/ Land-cover

Land use/land cover is an important boundary condition, which directly or indirectly influences many hydrological processes. The most obvious influence of land use on the water balance of a catchment is on the evapotranspiration process. Different land use types have different evapotranspiration rates, due to their different vegetation cover, leaf area indices and root depth (Batelaan and DeSmedt (2001).

The land use map of the watershed was derived from Landsat OLI 8 satellite images using the standard ERDAS IMAGINE supervised image classification method. The image classification was based on identifying more than ten training sites for each land-use type, and by visualizing of Google Earth images. Seven land-use classes were identified, that includes cultivated land (agricultural land), bare land, grassland, shrubland, forests, settlements and water bodies. The accuracy of the resulting land-use classification was assessed using 244 ground truth data points obtained in the field work. The overall accuracy was used to perform a classification accuracy assessment and accordingly overall accuracy of the data is 85.66% and the kappa coefficient (K_{hat}) is about 0.83 (Annex X).

Land-use/land-cover is a major controlling factor of watershed hydrology (Fetter, 2001). Land-use/land-cover of the area is dominated by agricultural land, bushland, forest, settlement, and grassland. The agricultural land which consists 67.6% of the land cover is distributed throughout the study area and it is the principal land-use of the watershed. The land-use map (Table 3.7 and Figure 3.16) of the watershed shows that 67.6% of the watershed is agricultural land, whereas bare land and shrubs cover about 17.55%, and forest, settlement and grassland constitute 25.16%, of the watershed and the rest 0.37 % is covered day water bodies. The highland area is covered by open woodland and bushland now considered as an open area. There is no landcover change from summer to winter and thus it was not taken into account in the respective parameter tables for WetSpass modeling. Land-use/land-cover fractions are used as weighting factors for the calculation of the water balance at grid cell level.

Table 3.7: Land-use type and area coverage.

Land use type	Area (km ²)	Area (%)
Agriculture	245.85	67.6
Bare land	21.49	5.91
Forest	12.02	3.31
Grassland	37.12	10.21
Settlement	3.5	0.96
Shrubland	42.34	11.64
Waterbody	1.34	0.37

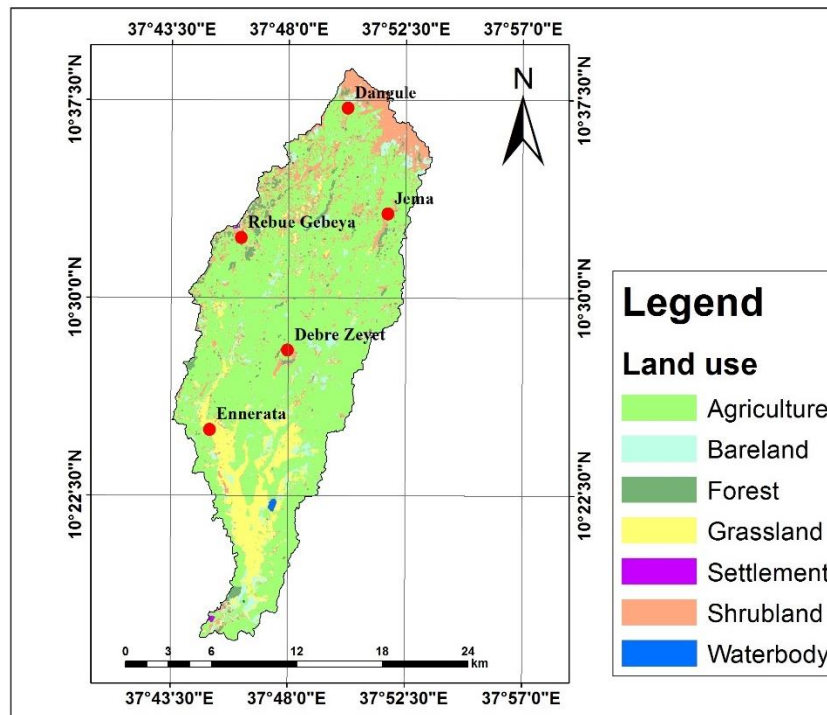


Figure 3.16: Land-use map of Chemoga watershed.

3.3.4.6 Soil

The soil map of the Chemoga watershed was extracted from the soil map data of the master plan of the Blue Nile river basin (scale 1:250 000), which was obtained from the Ministry of Water Resources, Irrigation, and Energy (MoWIE). The soil code system used in WetSpa is based on

the soil texture triangle developed by the United States Department of Agriculture (USDA), which is characterized by its percentage of clay, silt and sand, ranging from the fine textures (clay), through the intermediate textures (loam); and the coarser textures (sand) and the percentage of the topsoil textures (coarse, medium and fine) was used to look for the type of soil from the universal soil texture triangle, resulting in 39.07 % of clay, 15.81% of loamy sand , 13.75% of silty clay loam and 31.37% clay loam (Table 3.8 and Figure 1.17).

Table 3.8: Soil texture type and area coverage.

Soil type	Area (km ²)	Area (%)
Clay	142.1	39.07
Loamy sand	57.5	15.81
Clay loam	114.1	31.37
Silty clay loam	50	13.72

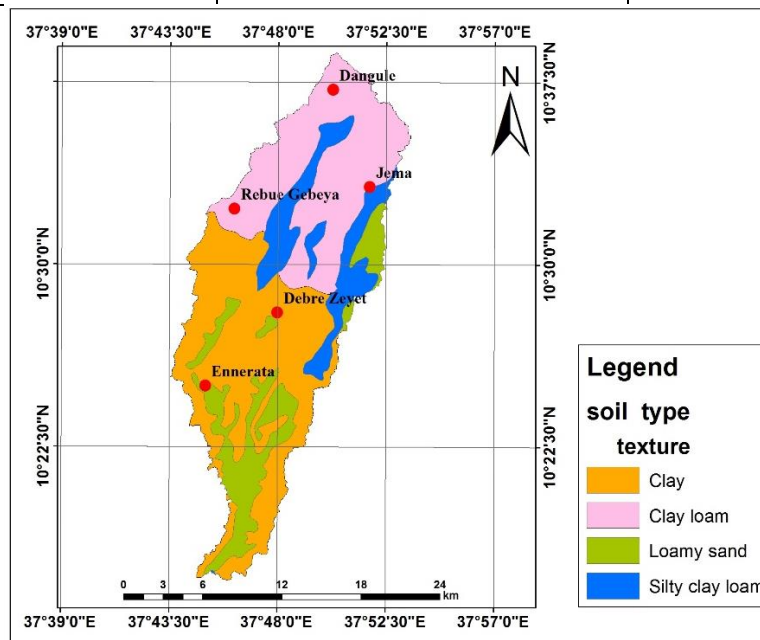


Figure 3.17: Soil type map of Chemoga watershed.

3.3.4.7 Elevation and Slope

The digital elevation model (DEM) is preprocessed (All sinks and peaks were filled in order to keep the continuity of flow to the watershed of study area before using the DEM to estimate any

parameters. DEM that has been processed to remove all sinks is called a depressionless DEM). Terrain features at each grid cell including elevation, flow direction, flow accumulation, stream network and stream order were extracted from the DEM. (Figure.3.18 a).

The topography (elevation) map of the watershed was obtained from DEM which is downloaded from the Shuttle Radar Topography Mission (SRTM) dataset of the United States of Geological Survey (USGS). The lowest (minimum) elevation point in the watershed is 2289 m in the downstream part and the highest is 3943 m in the upper stream part, while the mean elevation of the watershed is 2777.61m. The slope map of the watershed is derived from the digital elevation model using the ‘slope’ module in ArcGIS 10.5. The slope ranges from 0° to 62° with a mean of 9.8° and standard deviation of the slope is 7.19 (Figure 3.18 b).

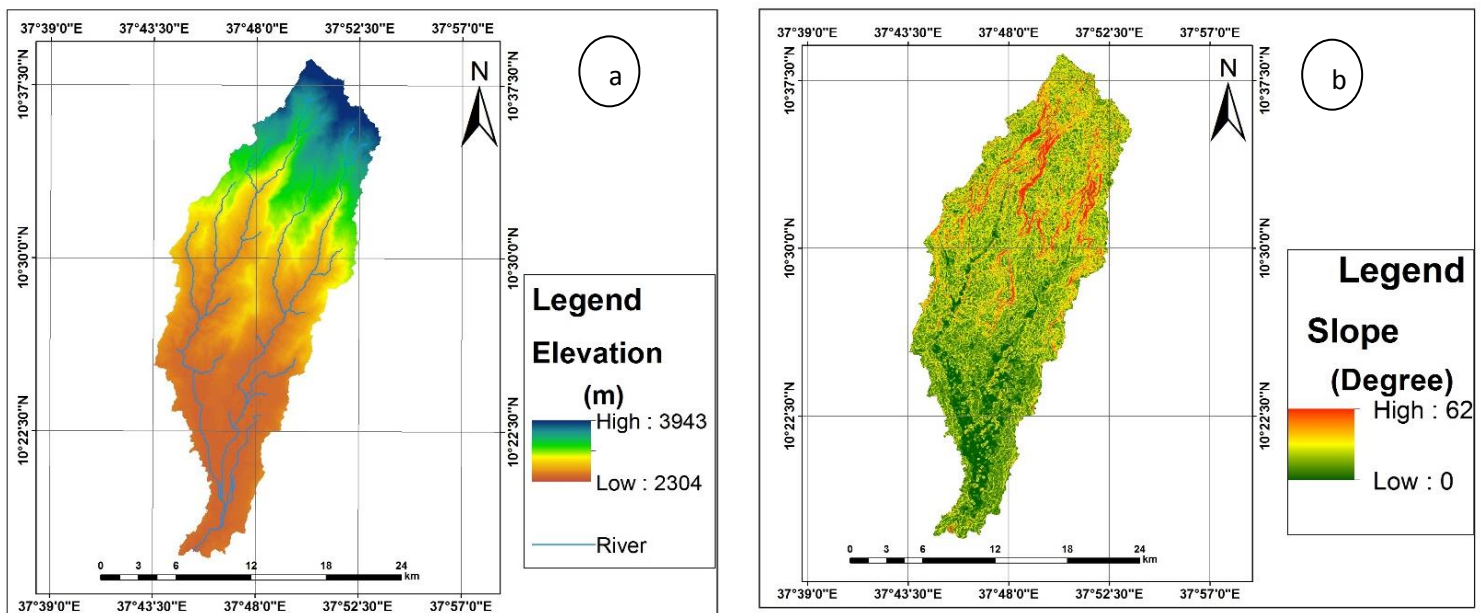


Figure 3.18: (a) Elevation (b) Slope map of Chemoga watershed.

Table 3.9: Input data of WetSpa model and description.

Input	Source	Resolution	Processing tool/ method
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Digital Elevation Model(DEM)	Shuttle Radar Topography Mission (SRTM)	30m*30m	ArcGIS10.5
Land cover map	USGS	30m*30m	ERDAS IMAGINE 2015, ArcGIS10.5
Soil map	Ministry of water, electric city, and irrigation	30m*30m	ArcGIS10.5
Slop map	Calculated from DEM	30m*30m	ArcGIS10.5
Rainfall map	Ethiopian meteorological agency	30m*30m	Ordinary kriging Interpolation in ArcGIS10.5
PET map	Calculated using FAO Penman-Monteith equation from observed climatic data	30m*30m	CROPWAT 8 and Ordinary Kriging Interpolation in ArcGIS10.5
Groundwater depth map	Ministry of water, electric city and irrigation	30m*30m	Ordinary Kriging Interpolation in ArcGIS10.5
Temperature map	Ethiopian meteorological agency	30m*30m	Ordinary Kriging Interpolation in ArcGIS10.5
Wind speed map	Ethiopian meteorological agency	30m*30m	Ordinary Kriging Interpolation in ArcGIS10.5

3.3.5 Physical and meteorological grid maps

To correctly run the model, the input grid maps must have similar number of columns and rows with the same cell size. Therefore, all the input physical and meteorological grid maps have similar number of columns and rows (613 and 1337), respectively.

The WetSpss model uses grid maps prepared based on seasonal (summer and winter) and without seasonal basis. Topography (Elevation), slope and soil type grid maps are fundamentally non-seasonal that couldn't show variability when the season changes.

On the other hand, land use, precipitation, temperature, potential evapotranspiration, wind speed and groundwater depth are variable in nature when the season changes. Therefore, these data were

prepared separately in winter and summer and annual so as to show the existing feature of the watershed that may appear when the season changes through time.

Seasonal precipitation, potential evapotranspiration, average temperature, Wind speed and groundwater depth were taken as grid map (ASCII file format) for the separate seasons of winter and summer and were prepared in grid map by ordinary kriging interpolation method. Seasonal precipitation, potential evapotranspiration, average temperature, Wind speed and groundwater level were made available in grid map were produced by ordinary kriging interpolation method. As a result, the average grid maps of the meteorological data were developed based on the interpolation technique.

The watersheds physical parameters of land use, soil type, topography and slope were also prepared with the help of ArcGIS toolsets.

3.3.6 Parameter tables

Four type of parameter tables are needed to run the model. Those types of parameter table were prepared in an appropriate format (TBL) for the effective model running process. Summer and winter land use parameter table (Annex I and Annex II respectively), soil parameters table (Annex III) and runoff coefficient parameter table were prepared as attribute lookup tables as an input of the model. These different biophysical data lookup tables are obtained and reviewed from scholarly published literatures. The developed grid maps and the parameter data together make the required interaction with each other so as to produce appropriate average values during the simulation processes.

CHAPTER FOUR

4 RESULTS AND DISCUSSION

4.1 Hydro-meteorological data analysis

To estimate hydrologic balance for the watershed, each of the hydro-meteorological elements has to be quantified. The basic and necessary meteorological data are rainfall, PET, temperature and wind speed. The rainfall, evaporation, temperature and wind speed during model simulation were interpolated using the ordinary kriging method from the readings that were collected at meteorological stations. Accordingly, actual evapotranspiration, surface runoff and groundwater recharge have been estimated and discussed hereafter.

4.1.1 Rainfall

Rainfall is the most variable and fundamental element in the climate system and its characteristics are not well manipulated in an easy way. The diversity of rainfall patterns is inherent and naturally explained as inconsistent in this area. Rainfall distribution analysis and its temporal variability which was done based on rainfall data obtained in and around the study area is characterized by unimodal rainfall pattern. The main rainy months are June, July, August, and September, which are considered as the rainy season and the rest months are considered as dry season in the modeling.

The dry season rainfall ranges between 461.9 mm and 366.24 mm, it is between 1047.44 mm and 942.31 mm for the rainy season and the annual average rainfall ranges between 1332.65 mm and 1482.37 mm as the minimum and maximum. About 75% of the total rainfall occurred in rainy season (June-September). The rest 25 % occurs in the dry season (October to May) (Figure 3.11).

4.1.2 Potential evapotranspiration

The term Evapotranspiration is the total amount of water lost due to the combined effect of evaporation from the soil and transpiration through the plant leaves. Evapotranspiration could be explained with the potential and actual evapotranspiration. Potential evapotranspiration is the rate at which evaporation would occur from a large area completely or uniformly covered with growing vegetation which has access to an unlimited supply of water.

Evapotranspiration is an important parameter in water budget which abstracts water from the system and controls the soil moisture content, groundwater recharge and streamflow components of a certain basin. Regarding the calculation of potential evapotranspiration, there are several

approaches and formulas. Among these methods, the Penman-Monteith formula has been used widely and helps to provide a more realistic evaluation of moisture content of a certain catchment (Shaw, 1994). Accordingly, the monthly PET of Chemoga watershed is calculated using the Penman formula. The monthly results are subdivided into two main seasons (4 months of summer and 8 months of winter). Finally, the summed PET values of each season, are converted to spatially distributed grid maps using ordinary kriging. The grid maps of PET for both seasons are used with other input parameters in WetSpa model.

The annual average PET ranges between 1322.27 mm and 1292.11 mm, it ranges between 353.39 mm and 343.22 mm for the rainy season and the dry season PET ranges between 969.53 mm and 954.44 mm (Figure 3.14).

4.1.3 Temperature

The monthly temperature results are subdivided into two seasons i.e. 4 months of summer (June to September) and 8 months of winter (October to May). Then, the average temperature values of each season, are converted to spatially distributed grid maps using ordinary kriging. The grid maps of temperature for both seasons are converted to ASCII file format and used with other input parameters in WetSpa model.

The dry season average temperature ranges between 16.8°C and 17.43°C and the mean is 14.98°C. It is between 14.7°C and 15.44°C for the rainy season and the annual average temperature ranges between 16.12°C and 16.83°C with the mean temperature 16.42°C (Figure 3.13).

4.1.4 Wind speed

Wind speed data are available for few meteorological stations. These data were used uniformly over the watershed. Similar to the other seasonal parameters, wind speed results are also subdivided into two seasons i.e. 4 months of summer (June to September) and 8 months of winter (October to May). Then, the average wind speed values of each season, are interpolated and converted to grid maps using ordinary kriging interpolation method. These grid maps of wind speed for both seasons are converted to ASCII file format and used as input parameters in WetSpa model.

Average wind speed of summer is 1.06 m/s and the maximum and minimum is 1.13 m/s and 0.99 m/s respectively. The winter wind speed ranges between 1.40 m/s and 1.45 m/s with the average

of 1.43 m/s, and the average annual wind speed is 1.24 m/s with 1.2 m/s and 1.29 m/s as the minimum and maximum wind speed, respectively (Figure 3.15).

Table 4.1: The correlation of various hydro-metrological data (R^2).

Hydro metrological data	PET	Temp	Rain	Wind
PET	-	0.9994	0.9977	0.9975
Temp	0.9994	-	0.9977	0.9987
Rain	0.9977	0.9977	-	0.9977
Wind	0.9975	0.9987	0.9977	-

4.2 Land use land cover

Since land use change causes changes in leaf area index that influences on evapotranspiration and interception. The image classification was based on identifying and delineating training sites for each land-use type by using Google Earth images and field collected points. Seven land-use classes were identified, i.e. agricultural land, bare land, forest, grassland, shrubland, settlements and water bodies. The overall accuracy of the resulting land-use classification is about 85.5%. The land-use map (Fig 3.15) of the watershed shows that about 67.6% of the watershed is cultivated land (agricultural land), 5.91% is bare land ,10.21% is grassland ,11.64% is shrubs,3.31% is forest cover, 0.96% is settlement and about 0.37% is water bodies (Table 3.7).

4.3 Output of WetSpass

As discussed in section 2.2 and 3.3 there are different types of groundwater modeling. In this research WetSpass model was used because of it advantage over other modeling. Ground water modeling like lumped sum models the whole catchment is considered as a single entity and considers meteorological data as inputs. But in spatially distributed models like WetSpass, spatial variability of processes, input, boundary conditions, watershed characteristics and outputs are considered in the pixel level and considers the land use, soil and groundwater level in addition to the meteorological data as an input.

After running the WetSpass model, spatial average grid maps for winter, summer, and annual periods were simulated for the Chemoga watershed. The water balance components such as surface runoff, actual evapotranspiration (AET), interception, transpiration, soil evaporation, and recharge

were produced for the watershed. These watershed-based physiographic maps are raster maps, in which each pixel represents the magnitude of different water balance component.

The WetSpass model results contain several annual and seasonal hydrologic outputs. The main outputs of the WetSpass model include the actual evapotranspiration, surface runoff, and groundwater recharge. The results of the modeling are presented in digital images of the spatial distribution of annual, dry season and rainy season average values of actual evapotranspiration, surface runoff, and groundwater recharge in the 30-year period from 1987 to 2017. These maps are presented as raster in which every pixel represents the magnitude of the respective component of the water balance.

The output grids maps include three sets of results with each set having different grid layers. The First set of grid maps are the winter output while the second set of grid maps are the summer and third sets are for yearly grid maps.

4.3.1 Actual Evapotranspiration(AET)

Actual evapotranspiration is the evapotranspiration at actual field condition. 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. WetSpass simulates the average annual evapotranspiration of the watershed to be 346 mm and 1100 mm as minimum and maximum values, respectively which accounts for 60% of the total annual rainfall. Total actual evapotranspiration (ET_{tot}) is expressed in Equation (3.3).

Precipitation that reaches the land surface is partially intercepted by vegetation. The amount of water intercepted by a plant, named interception, largely depends on plant type. Water held on the leaf surface can drop down reaching the ground or evaporate. Another part of water falls directly on the ground. Depending on the type of vegetation, the interception fraction represents a constant percentage of the annual precipitation value. The annual total interception ranges from 0 mm to 280.46 mm as the minimum and maximum interception and the average is about 24.5mm (Figure 4.1). The average vegetation transpiration ranges from 0 mm to 966.45 mm with the average of 150.3 mm and the annual average evaporation from bare soil between the vegetation is about 670.09 mm with the minimum and maximum is 0 mm and 1071.85 mm, respectively (Figure 4.1).

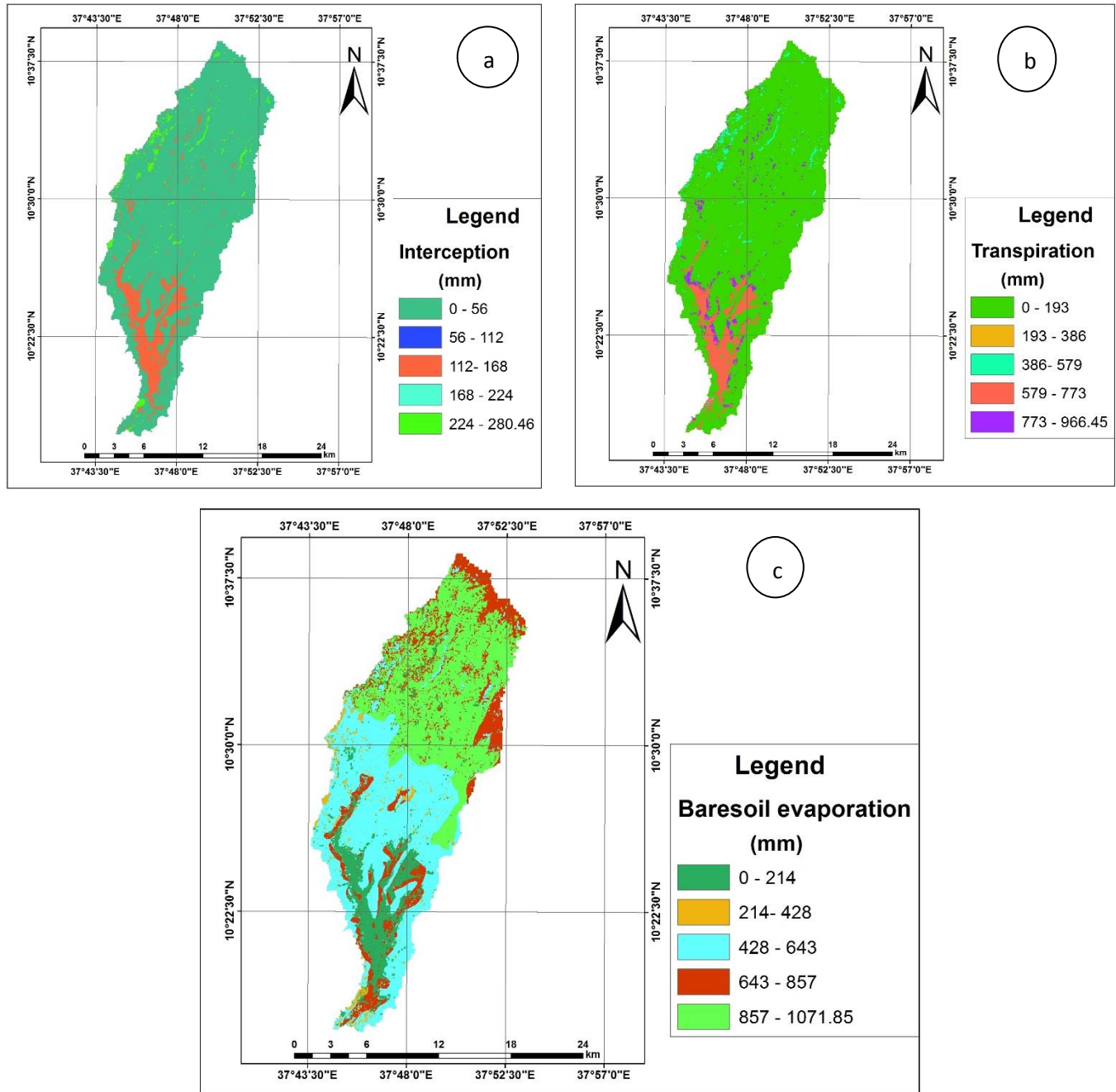


Figure 4.1: (a) Annual interception, (b) annual transpiration, (c) annual evaporation from bare soil.

WetSpss simulates the average annual evapotranspiration (ET_v) of the watershed to be 844.98 mm with 346 mm and 1100 mm as minimum and maximum ET_v , respectively. The mean and standard deviation of this distribution are 844.98 mm and 230.7, respectively. The mean ET_v of the watershed in rainy season is 450 mm and standard deviation of 24, whereas the mean and standard deviation value in dry season is about 260 mm and 90, respectively with the minimum and maximum value of 95 mm and 643mm. About 66% of the total annual evapotranspiration is

lost during rainy season and the remaining 34% flows out in the dry season. This variation occurs due to differences in precipitation within the two seasons and also due to the fact that the vegetation cover is less in the winter season.

The average evapotranspiration accounts for more than 60% of the total annual rainfall. This shows that ET is the main process of water loss in the watershed.

Table 4.2 gives the mean annual evapotranspiration values for different combinations of land-use and soil classes. From this table, it looks that silty clay loam and clay loam soils have the highest values of evapotranspiration, while clay soils with settlement, shrubland, and bare land uses have the lowest values. Mean annual evapotranspiration for different land uses indicate that forest, grassland, and shrubs have the highest values, while settlement, agriculture and bare land have the lowest values.

Table 4.2: Mean annual evapotranspiration with different combinations of land-use and soil texture.

	Clay	Clay loam	Loamy sand	Silty clay loam
Agriculture	507.5	1010.6	730.3	1034
Bare land	528	530	724	1035.8
Forest	785.5	1052	903.4	1065.6
Grassland	927.8	1017	856	1088
settlement	480.9	493	544	416.5
Shrubland	435.3	848.7	616.4	870
Waterbody	662	-	907.5	-

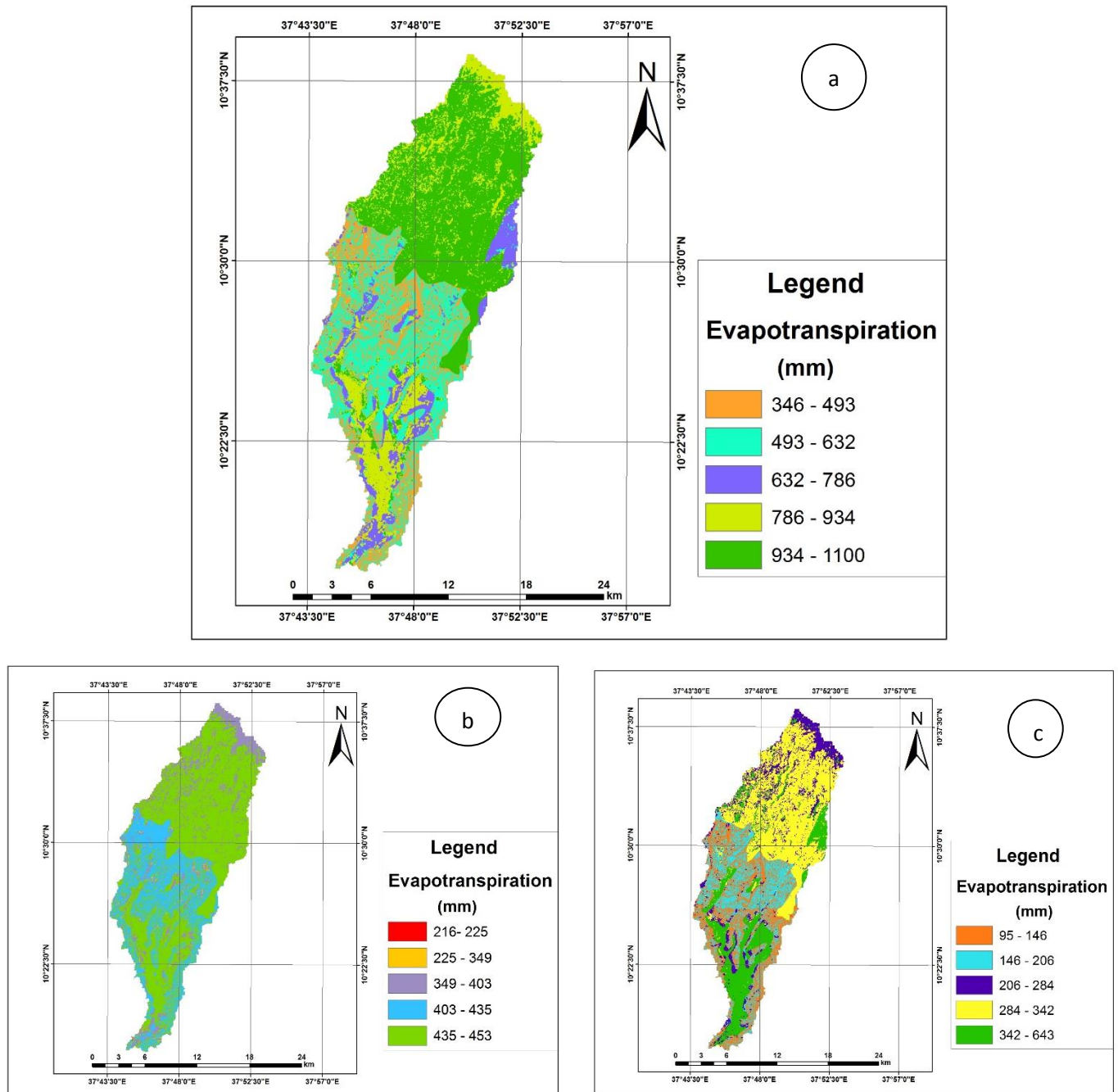


Figure 4.2: (a) Annual actual evapotranspiration, (b) rainy season actual evapotranspiration, (c) dry actual season evapotranspiration.

4.3.2 Surface runoff

The surface runoff depends on the soil, land-use, slope and precipitation intensity in relation to the capacity of the soil infiltration. The WetSpss model uses the runoff coefficient method for the estimation of surface runoff (S_v). The surface runoff coefficient is a function of vegetation type,

soil texture, and slope. Hence, S_v in the Chemoga watershed varies spatially with topography and other catchment characteristics.

The amount of surface runoff shows variation during summer and winter seasons. The simulated annual surface runoff varies from a minimum of 2.16 mm to a maximum of 1021 mm with a mean of 447 mm that accounts about 31.8% from the mean annual rainfall (1408.3). The mean surface runoff (S_v) of the watershed in rainy season is 280 mm, while the mean surface runoff (S_v) in dry is approximately 153 mm. The mean value accounts for 31.8% of the total annual precipitation of the Chemoga watershed. About 65% of S_v occurs during the wet seasons (June to September), while the remaining 35% occurs in dry months (October to may) (Figure 4.1). This variation comes from rainfall changes in the two seasons.

Table 4.3 gives the mean annual surface runoff for different combinations of land-use and soil classes. The largest surface runoff occurs on clay soils with bare land, settlement, and agriculture land-use, while the lowest values are for loamy sand soils with shrubland, forest and agricultural land uses. Surface runoff is more influenced by soil type than by land-use. The influence of the precipitation is also noticeable.

Table 4.3: Mean annual runoff with different combinations of land-use and soil texture.

	Clay	Clay loam	Loamy sand	Silty clay loam
Agriculture	755.5	348	13.8	328
Bare land	848	403.5	17	370
Forest	378.8	163	12.6	156
Grassland	443	217	6.4	200
settlement	805	854	654.6	916.6
Shrubland	589	262	10.7	248.8
Waterbody	847	-	267.8	-

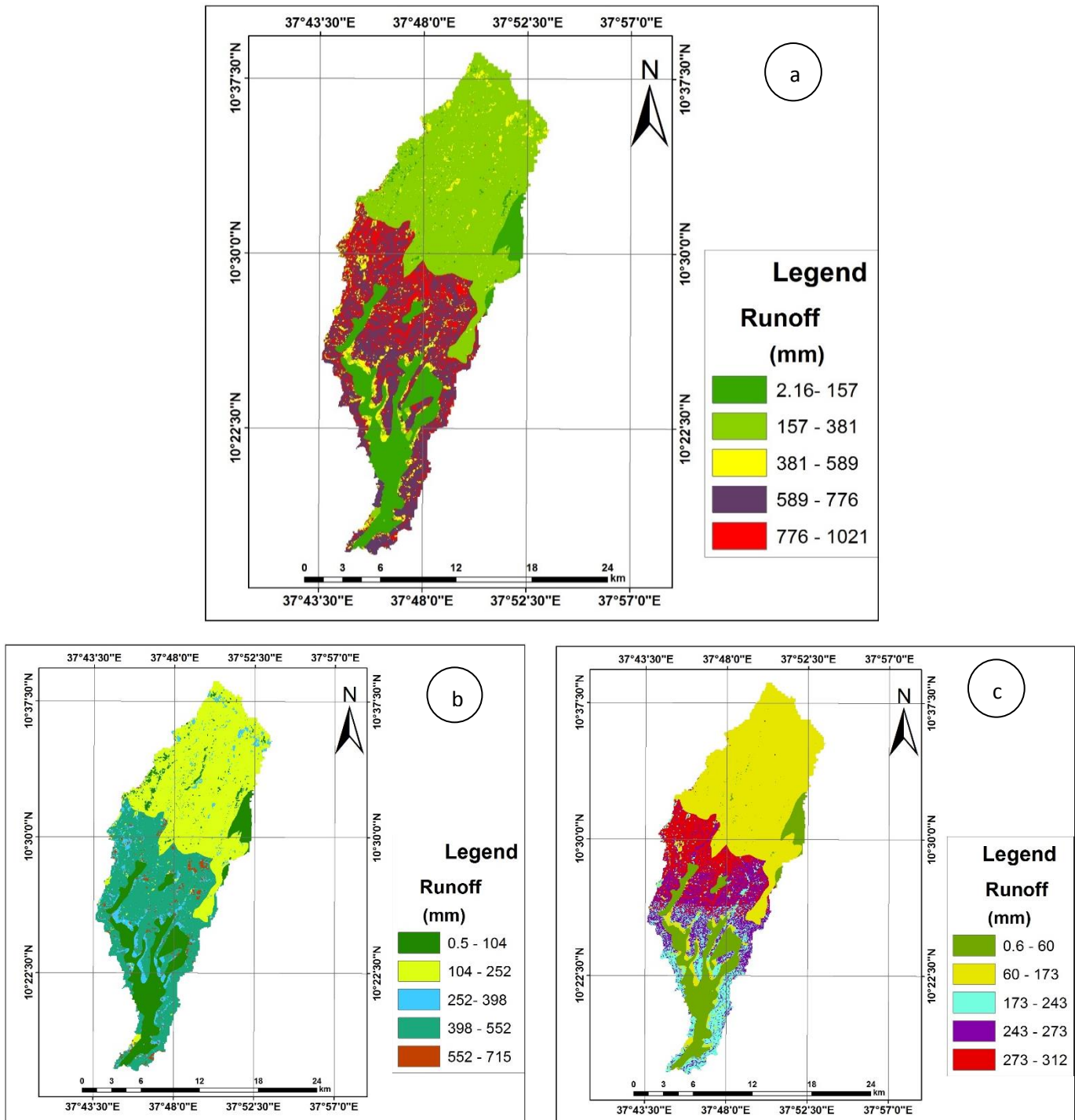


Figure 4.3: (a) Average annual runoff, (b) rainy season runoff, (c) dry season runoff.

4.3.3 Groundwater recharge

In general, the amount of infiltration into groundwater depends on factors such as vegetation cover, slope, soil type, water table depth, and etc. Recharge is more related to natural vegetation cover, flat topography, permeable soils, a deep-water table and others.

The model determines the long-term average spatially distributed recharge as a spatial variable depending on soil texture, land use, slope, and meteorological conditions (Batelaan et al., 1996), as indicated in Equation (Eq.3.6).

The WetSpa model has simulated average long-term (30-yr) seasonal and annual groundwater recharge. The result shows that an average recharge of 116.3 mm, 361 mm, and 11 mm simulated for annual, rainy season, and dry season, respectively. The average annual long-term groundwater recharge for the watershed is about 8.2% of the average annual precipitation (1408.3 mm) (Figure 4.3). Based on that, the groundwater recharge is estimated to be 42,333,200 m³/yr (364sq.km area). In the water balance of the watershed, total precipitation amount goes 60% to evapotranspiration, 31.8% to runoff, and 8.2% to recharge. About 90.5% of total annual groundwater recharge in the study area is occurred during the rainy season while the remaining 9.5% occurs in dry season, where a similar validation was reached with the annual groundwater recharge rates that ranges from 8-10 % amount of rainfall (Fedelu Hassen and Aschalew gurmu, 2012) which is similar to the simulated result of WetSpa model in this research (8.2%) and the overall summary of the water balance of the Chemoga watershed is given in Table 4.4. Only a small fraction of the annual precipitation remains to recharge (116.3 mm) the groundwater reservoirs, the rest leaves the watershed mainly through evapotranspiration (844.98 mm) and the rest is by surface runoff (447 mm). The mean annual water balance component difference (P-ET-Sv-R) is 0.02 mm which shows the simulated result of the watershed by the model is good in estimation of the water balance of the watershed.

Table 4.4: Summary of annual and seasonal various water balance components.

Water balance component	Annual (mm)			Dry season (mm)			Rainy season (mm)		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Precipitation	1332.6	1482.4	1408.3	366	461.9	420.5	942	1047.4	987.7
Evapotranspiration (ET)	346	1100	844.98	95	643	260	216	453	450
Runoff	2.16	1021	447	0.6	312	153	0.5	715	280
Recharge	0	820	116.3	0	680	361	0	129	11
Difference	P -ET - S - R = (1408.3-844.98-447-116.3=0.02)								

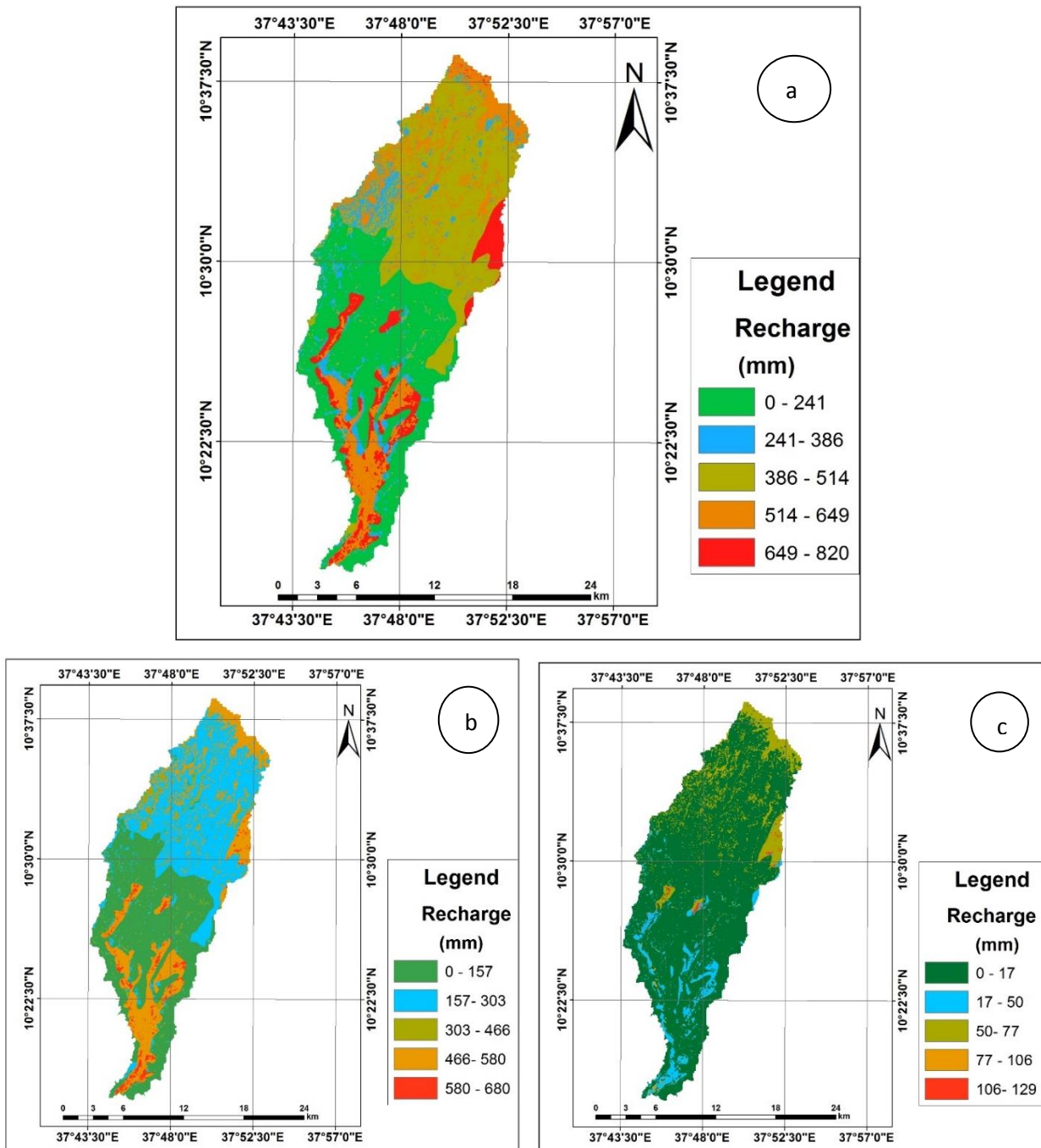


Figure 4.4: (a) Mean annual recharge, (b) Average rainy season recharge, (c) Average dry season recharge.

Groundwater recharge can have negative or zero values in the basin, mostly in the dry season because of higher evapotranspiration rates than surface runoff rates. In the case of Chemoga watershed, it has the minimum value of zero. However, the topographic and physical feature can have an effect on recharge.

Table 4.5: The relationship between land use and recharge rates.

Land use			Recharge (mm/year)			
LU Type	Area (km ²)	Area (%)	Min	Max	Mean	STD
Agriculture	245.85	67.6	0	820	121.3	256.205
Bareland	21.49	5.91	0	793.3	76.9	178.775
Forest	12.02	3.31	0	794.4	111.9	146.312
Grassland	37.12	10.21	0	816	207	73.568
Settlement	3.5	0.96	82.14	251	64.7	35.6
Shrubland	42.34	11.64	0	820	137.6	159
Waterbody	1.34	0.37	0	634	117.3	85.7

The relationship between land use and annual groundwater recharge are shown in Table 4.5 and Figure 4.4. In grassland and shrubland land use land cover types, recharge rates are the highest average (25%, and 16%), respectively, and lowest average recharge in settlement area land use type (8%). In addition, in the agriculture, bareland and forest land use types have the annual recharge of 15%, 9% and 13% respectively and waterbody covers the rest 14% of annual recharge.

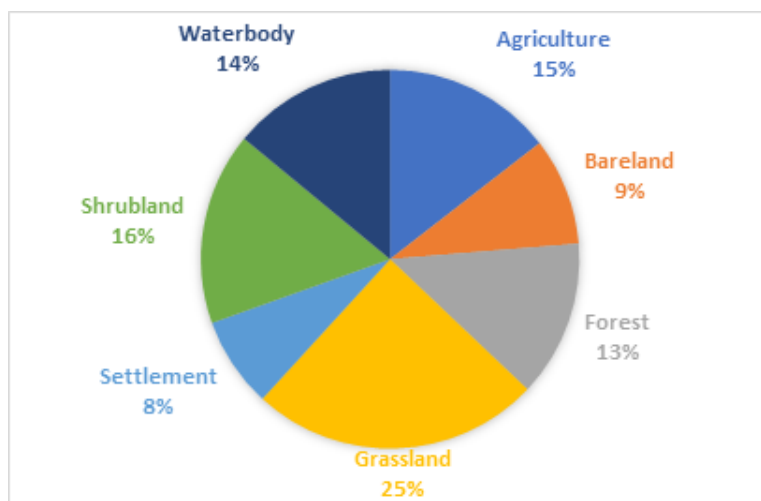


Figure 4.5: Recharge percentage of each land use type.

Table 4.6: The correlation of various water balance components linear regression (R^2).

Water balance components	precipitation	Runoff	Evapotranspiration	Recharge
Precipitation	-	0.9943	0.9323	0.9539
Runoff	0.9943	-	0.9483	0.9893
Evapotranspiration	0.9323	0.9483	-	0.8993
Recharge	0.9539	0.9893	0.8993	-

Table 4.7: Mean annual recharge with different combinations of land-use and soil texture.

	clay	Clay loam	loamy sand	silty clay loam
Agriculture	2.5	8.4	648	5.7
Bare land	5.6	11.7	623	7.5
Forest	14.8	544	461.6	560.6
Grassland	7	478	501.5	129
settlement	51	69.2	164.6	56
Shrubland	143.7	584.4	757	576.3
Water body	2.6	-	333	-

Table 4.7 gives the mean annual recharge for different combinations of land-use and soil classes. The largest recharge occurs on loamy sand soils with bare land, grassland, shrubland and agriculture land-use, clay loam soils with shrubland, forest and grassland and silty clay loam soils with forest and shrubland use, while the lowest values are for clay, clay loam and silty clay loam soils with agriculture, bare land and waterbody land uses.

CHAPTER FIVE

5 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The groundwater recharge estimation in Chemoga watershed has been successfully simulated for annual and seasonal conditions using the distributed hydrological WetSpa model which has been scripted in Python and uses its own spatial library Hydrology and Hydraulic Programming Library (H2PL). Spatial variation in recharge due to distributed soil texture, land-use, topography, groundwater level, and hydrometeorological conditions are very important parameters which should be accounted for in recharge estimation. Geographical Information System (GIS) and Remote Sensing (RS) provide the basic support for many distributed hydrological models. The GIS and remote sensing were used to improve, interpret and demonstrate the input parameters. The WetSpa model was successfully applied to the delineation of recharge areas, actual evaporation, and the surface runoff.

Water balance models like WetSpa model are important tools to improve the understanding of hydrological processes and for simulation of spatiotemporal changes of the water resources. The overall objective of this thesis work was to estimate spatial annual groundwater recharge and seasonal groundwater recharge of Chemoga watershed. Practically all groundwater originates as rainwater. Principal sources of natural recharge include precipitation, stream flow, lakes, and reservoirs but in this research, only the infiltrated water (recharge) from the rainwater have been considered. A spatially distributed WetSpa model was used to estimate annual and seasonal long-term groundwater recharge and the water balance components of the watershed.

In order to estimate the groundwater recharge of the watershed, land-use, soil type, hydro-meteorology, topography (elevation) and slope of the watershed have been considered. Emphasis was given to the collection of primary field information and gather existing data to produce full information relevant for quantifying the areal distribution of recharge and the other water balance component of the watershed.

The groundwater recharge estimation using WetSpa model has resulted in a reasonably good estimation using limited data. The highly variable distributions of the climatic parameters associated with variations of land-use/land-cover, soil type, topography, and slope are in control for variations of the water balance element within the watershed.

The rate of groundwater recharge is found to be higher in the rainy season (June -September) than dry season (October-May). Furthermore, the rates of groundwater recharge are also found to be higher in bare area land use land cover type. The results of the analysis show that precipitation is the most important hydrologic process in the study area, and evapotranspiration is significantly high for reduction of the recharge rates.

After running the WetSpass model, a spatially simulated annual, summer and winter runoff, evapotranspiration, interception, transpiration, soil evaporation and finally recharge of the watershed are obtained. These model results (outputs) are annual and seasonal average values for each simulated parameter. As a result, the average winter and summer groundwater recharge is estimated as 11 mm and 361 mm, respectively. The average annual long-term groundwater recharge for Chemoga watershed was found to be 116.3 mm which is 8.2% of the average annual precipitation (1408.3 mm) in the watershed. The water balance system of the watershed, from the precipitation amount, is simulated to be 60% evapotranspiration, 31.8% runoff, and 8.2% recharge.

5.2 Recommendations

The results obtained from this study can be taken as an initial investigation in the groundwater modeling of Chemoga watershed. The groundwater recharge map along with other thematic maps can serve as a source of information which can be updated from time to time by adding new information. Therefore, there should be well-organized database system in different governmental organization so as to provide accurate data about the hydrogeological as well as hydrological systems for future studies.

The result of WetSpass model can be improved further if more seasonal groundwater depth data and new meteorological stations become available at the watershed.

Performance of WetSpass model depends on the soil type and land use classes; hence lack of relevant land use map may lead to the wrong output which could lead to wrong decisions.

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

- Integrated hydrogeological study of the area is important to evaluate the resource from all points of view (quantity and quality) using high-resolution data sources for GIS and RS.

- The average annual amount in the watershed should be planned on the bases of the residents' demand for irrigation purposes, home use, livestock use and so on.
- Quantifying and knowing the annual and seasonal groundwater recharge and water balance is useful for groundwater resources assessment, development and improvement strategies.
- The simulated result is also useful for rainfall-runoff relationship modeling and hydrological change studies.

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Appendices

Land-use table attributes

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

Annex I: Summer land use parameter table of Chemoga watershed.

NUMBER	LUSE_TY PE	RUNOF F_VEG	NUM_V EG_RO	NUM_IM P_RO	VEG_ AREA	BARE_ AREA	IMP_A REA	OPENW_ AREA	ROOT_D EPTH	LAI	MIN_ STOM	INTERC _PRE	VEG_H EIGHT
21	Agriculture	crop	1	0	0.80	0.20	0.00	0.00	0.40	4.00	180.00	15.00	0.6000
7	Bare land	bare soil	4	0	0.00	1.00	0.00	0.00	0.05	0.00	110.00	0.00	0.0010
33	Forest	forest	3	0	1.00	0.00	0.00	0.00	2.00	5.00	375.00	35.00	16.0000
23	Grass land	grass	2	0	1.00	0.00	0.00	0.00	0.30	2.00	100.00	10.00	0.2000
1	Settlement	grass	2	1	0.20	0.00	0.80	0.00	0.30	2.00	100.00	10.00	0.1200
36	Shrub land	grass	2	0	1.00	0.00	0.00	0.00	0.60	0.60	110.00	15.00	2.0000
44	Water body	open water	5	0	0.40	0.20	0.00	0.40	0.30	2.00	110.00	10.00	0.5000

Annex II: Winter land use parameter table of Chemoga watershed.

NUMB ER	LUSE_TY PE	RUNOFF_V EG	NUM_V EG_RO	NUM_I MP_R O	VEG_ AREA	BARE_ AREA	IMP_ AREA	OPENW _AREA	ROOT_ DEPTH	LAI	MIN_S TOM	INTER C_PRE	VEG_H EIGHT
21	Agriculture	crop	1	0	0.00	1.00	0.00	0.00	0.35	0.00	180.00	0.00	0.6000
7	Bare land	bare soil	4	0	0.00	1.00	0.00	0.00	0.05	0.00	110.00	0.00	0.0010
33	Forest	forest	3	0	0.50	0.50	0.00	0.00	2.00	4.50	500.00	38.00	15.0000
23	Grass land	grass	2	0	1.00	0.00	0.00	0.00	0.30	2.00	100.00	10.00	0.2000
1	Settlement	grass	2	1	0.20	0.00	0.80	0.00	0.30	2.00	100.00	10.00	0.1200
36	Shrub land	grass	2	0	0.20	0.80	0.00	0.00	0.60	0.00	110.00	5.00	2.0000
44	Water body	open water	5	0	0.40	0.20	0.00	0.40	0.30	2.00	110.00	10.00	0.5000

Annex III: Soil parameter attribute table.

NUMBER	SOIL	FIELD CAPAC	WILTING PNT	PAW	RESIDUAL WC	A1	EVAPORATION DEPTH	TENSION HHT	P_FRAC_SUM	P_FRAC_WIN
12	clay	0.46	0.33	0.13	0.090	0.21	0.05	0.37	0.95	0.85
9	Clay loam	0.33	0.19	0.14	0.075	0.27	0.05	0.26	0.62	0.41
2	Loamy sand	0.15	0.07	0.08	0.035	0.47	0.05	0.09	0.09	0.01
8	Silty clay loam	0.36	0.19	0.17	0.040	0.29	0.05	0.33	0.62	0.41

Soil table attributes

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

Annex IV: Mean monthly annual rainfall for the last 30years of the Debre Markos station (1987 –2017).

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1987	0	26	109.2	53.9	188.9	178.8	219.9	258.2	128.1	86.8	6.1	17.1
1988	14.4	60.2	0.7	52.3	31.7	173.8	287.2	335.8	261.1	95.4	1.5	0
1989	6.5	22.8	142.5	91	25	163.1	355.4	330.7	204.4	9.4	7.7	85.9
1990	4.8	18.9	52.1	70.2	32.9	148.5	325.1	353.3	275.8	11.2	20.7	0
1991	8.8	25.25	41.55	97.05	58	146.7	221.3	311.8	168	50.8	32.5	51
1992	28.6	31.6	31	123.9	83.1	144.9	164.9	307.9	168.7	94.6	72.7	5.5
1993	8	27.4	37.8	83.3	197.6	209.6	305.8	304.45	322.1	51	5.5	0
1994	9.3	5	29.05	42.7	139.6	147.6	281.2	301	218.1	7.4	13.2	0.5
1995	0	1	20.3	90.4	146.6	126.4	246.1	344.6	151.2	14.4	12.4	95.5
1996	27.6	4.6	74.1	108	228	291.7	252.3	360.5	152.1	33.1	35.2	23.2
1997	14.3	0	29.6	97.5	118.7	151	286.8	338.8	205.8	183.5	85	6.7
1998	2.9	2.2	21	4.4	152.4	165.85	203.2	252.6	270.7	200.8	6.9	0
1999	72.6	0	2.8	43.2	46.8	180.7	252.1	340.3	164.3	210.5	2.5	28.3
2000	0	0	2.9	110.5	29.5	174.9	308.65	211.1	271	265.9	32.7	12.3
2001	0	3.7	58.1	101.2	129.6	154.7	365.2	322.3	170.3	66.9	0	2.2
2002	57	0	92.2	75.2	11.2	155.9	276.3	335.5	234.6	3.9	2.2	61.5
2003	3.6	57.4	69.6	19.2	5.3	212	205.5	351.6	256.8	10.7	0.3	18.8
2004	4.1	7.6	13.8	120.1	19.8	195	286.6	317.7	205.2	50.45	20.9	23.2
2005	2.3	0.6	110.6	93.75	43.7	150.4	314	220.5	235.3	90.2	41.5	0
2006	3.5	20.7	87.8	67.4	104.5	190.9	364.1	281.1	301.5	37.1	30.7	32.3
2007	1.7	15.6	77.5	71	162.9	188	250.6	325.9	269	37.9	0.4	0
2008	0	0	0	15.7	169.9	290.3	250.5	273.9	195.1	71.2	39.1	9.5
2009	11.7	21.1	17.7	50.2	16.8	159.3	276.7	452.3	98.5	44.35	10.9	21.8
2010	18.7	22.8	35.4	84.7	153.4	151	253.9	339.6	307	17.5	16.7	5
2011	2	3.1	110.4	68.9	237.8	143	231.1	288.3	282.9	7.5	97.3	11.5
2012	13.9	0	33.1	33.1	23.4	124.2	372.2	250.9	362.4	21.3	30.9	7.1
2013	11.5	4.7	16.4	11.8	125	161.3	282.8	245.4	194.8	147.3	34.2	0
2014	9.1	8.6	42.9	138.4	130.1	101.9	274.6	257.1	255.5	100.5	9.2	9.2

2015	6	14.6	45.5	20.1	244.1	119.1	149.7	237.2	129.4	12.7	65	16
2016	7.55	11.6	44.2	79.25	146.5	133.1	238.6	243.6	192.45	56.6	37.1	12.6
Average	11.7	13.9	48.3	70.6	106.8	167.8	270.1	303.1	221.7	69.7	25.7	18.6

Annex V: Mean monthly annual rainfall for the last 30years of the Rob Gebeya station (1987 –2017).

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1987	15.2	63.7	67.8	119.7	45.3	125.2	412.2	315.1	152.2	55.5	25.3	58.9
1988	32.0	62.3	87.5	113.2	55.1	127.2	416.7	451.6	189.3	111.1	4.1	0.0
1989	14.1	61.3	105.7	115.6	62.1	133.3	325.8	260.3	164.5	50.2	13.5	167.6
1990	45.0	52.0	70.2	74.5	38.2	78.9	346.4	183.0	190.9	23.4	31.7	1.7
1991	39.0	11.6	26.6	7.7	10.6	89.0	269.3	297.3	173.1	27.0	31.9	27.0
1992	36.3	45.6	121.0	122.6	59.2	94.3	270.2	470.0	182.0	126.6	27.0	94.2
1993	0.0	35.2	66.2	134.1	178.3	132.3	296.6	216.9	230.6	86.6	49.5	0.0
1994	26.9	18.3	38.7	28.0	100.8	211.2	329.3	326.5	186.8	14.3	25.7	37.7
1995	0.0	4.1	61.5	140.6	140.7	97.7	333.1	247.3	147.6	8.0	14.0	99.2
1996	48.0	19.0	134.0	163.0	148.0	143.7	313.1	215.0	194.5	4.5	116.0	34.5
1997	26.5	0.8	68.8	102.4	122.8	194.8	254.0	253.1	116.4	180.7	135.4	54.9
1998	98.5	25.7	38.3	35.5	191.0	205.2	340.9	310.6	150.5	160.7	1.8	0.0
1999	38.8	0.0	4.5	25.2	44.9	212.1	429.4	379.5	215.8	273.7	14.5	13.8
2000	3.3	0.0	8.1	131.3	137.0	188.1	257.3	270.8	213.1	188.5	109.9	40.2
2001	0.5	56.3	77.2	81.7	147.4	243.3	344.3	368.5	67.6	138.9	66.9	24.5
2002	73.6	49.6	177.0	35.4	28.7	271.3	323.1	288.9	175.1	7.2	16.0	58.8
2003	0.0	105.8	86.9	43.7	6.8	202.7	339.2	436.3	210.6	5.6	3.0	48.0
2004	5.3	18.3	39.2	183.3	26.8	230.6	378.4	243.6	192.3	88.9	31.5	51.4
2005	1.7	9.5	133.6	59.4	60.3	177.5	327.9	351.1	170.9	74.3	39.9	0.0
2006	2.3	26.3	89.7	83.5	128.1	183.8	374.4	367.8	201.5	75.2	28.8	50.9
2007	33.1	19.4	61.2	86.7	222.0	284.6	278.1	276.6	197.3	75.8	29.5	0.0
2008	11.9	0.0	0.0	83.5	142.2	205.2	258.8	278.8	115.6	59.1	25.3	48.3
2009	35.2	38.1	82.2	35.7	22.4	129.4	339.5	276.8	68.2	128.5	12.8	65.0
2010	54.2	26.2	77.6	73.7	111.7	188.2	284.4	274.4	196.0	32.5	64.1	33.6
2011	16.6	2.0	54.0	93.3	113.2	126.0	225.0	145.7	221.5	10.8	94.2	14.4

2012	0.0	0.0	104.2	34.4	52.8	116.5	268.9	192.8	167.5	13.1	94.1	41.6
2013	2.7	16.8	67.4	23.4	172.3	209.7	323.8	270.3	97.2	85.9	61.7	0.0
2014	0.0	20.2	89.2	72.4	161.7	100.4	200.2	237.4	309.3	45.6	56.1	57.3
2015	3.5	27.0	67.5	58.2	154.7	102.1	227.5	250.0	188.5	26.7	29.9	56.2
2016	15.7	28.9	78.9	65.4	123	107.1	204.8	320	202.3	36.2	28.3	36.1
Average	22.7	28.1	72.8	80.9	100.3	163.7	309.8	292.5	176.3	73.8	42.7	40.5

Annex VI: Mean monthly annual temperature for 30years of the Debre Markos station (1987 –2017).

year	Jan	Feb	Mar	Apr	May	June	Jul	Aug	Sep	Oct	Nov	Dec
1987	16.2	17.7	17.3	18.1	16.6	15.3	13.8	15.1	15.8	16.2	15.9	16.6
1988	17.3	17.9	19.4	19.3	18.4	15.9	13.1	14.9	15.1	22.6	13.8	14.4
1989	14.6	15.9	16.3	15.8	16.0	14.6	12.2	14.0	14.5	14.7	15.2	15.4
1990	15.8	16.7	17.4	17.7	17.4	15.6	13.1	14.5	14.8	15.3	16.2	16.15
1991	17.3	17.6	25.7	25.5	24.6	24.0	13.5	14.8	15.4	15.7	15.7	15.6
1992	15.8	16.7	18.8	18.4	17.2	15.6	13.2	14.4	14.6	15.4	15.0	16.1
1993	16.1	16.7	18.3	18.5	16.7	15.6	13.6	15.7	15.0	15.6	16.2	16.45
1994	17.2	18.2	18.7	19.2	17.6	15.7	13.6	14.8	15.5	16.4	16.8	16.6
1995	17.3	18.6	18.8	19.0	17.1	16.5	13.7	15.1	15.4	16.4	16.9	16.85
1996	16.7	18.0	18.3	18.1	17.0	15.4	13.6	15.0	15.5	15.6	15.9	15.7
1997	16.3	17.6	18.8	18.0	17.5	16.2	13.7	15.3	16.1	16.5	16.4	16.25
1998	17.0	18.1	19.4	20.7	17.6	16.1	13.9	15.2	15.5	15.7	15.0	15.15
1999	15.9	18.0	18.0	19.3	17.3	15.7	13.2	14.5	15.1	15.1	14.9	15.55
2000	16.5	17.9	19.5	17.6	17.6	15.9	13.3	14.7	15.4	15.6	15.3	15.4
2001	15.8	17.9	17.5	18.7	17.2	15.4	13.6	15.1	15.8	16.1	15.5	16.35
2002	16.5	18.2	18.4	18.9	18.9	16.3	14.0	14.9	15.5	16.5	17.0	16.5
2003	16.8	18.5	17.7	19.4	19.4	16.1	13.7	15.1	15.4	15.9	16.5	16.25
2004	17.1	17.9	18.9	18.6	18.5	16.2	13.5	15.1	15.1	15.2	16.1	16.25
2005	16.3	19.3	18.8	19.6	18.3	16.5	13.7	15.5	15.8	15.5	15.6	15.5
2006	18.0	18.6	18.5	18.6	17.5	16.0	14.1	15.2	15.3	16.6	16.3	16.5
2007	17.0	17.9	19.2	18.9	17.6	15.8	13.8	15.3	15.5	15.8	16.5	15.8

2008	17.4	18.2	19.5	19.5	17.0	15.8	13.9	14.8	15.8	16.1	15.4	15.95
2009	16.8	18.7	19.4	19.5	19.0	17.6	14.1	15.6	16.0	16.2	16.0	16.55
2010	16.9	18.4	19.2	19.5	17.6	16.7	13.9	15.5	15.8	17.0	16.6	16.4
2011	16.8	18.3	18.0	19.4	17.8	16.3	14.1	15.5	15.8	16.7	16.3	16
2012	16.9	18.5	19.1	19.1	18.9	16.6	14.0	15.4	15.3	16.2	16.7	16.55
2013	17.3	18.9	19.5	20.2	18.0	16.4	13.8	14.8	15.7	16.1	16.2	15.05
2014	17.1	17.6	18.8	18.4	17.2	16.8	14.4	15.1	15.5	16.4	15.9	15.8
2015	16.5	18.4	19.5	19.8	18.1	16.8	14.4	15.9	16.3	17.4	17.0	16.75
2016	17.1	18.3	18.6	19.1	17.1	17.0	14.5	15.3	17.1	18.3	18.6	19.05
Average	16.7	17.9	18.8	19.1	17.9	16.3	13.7	15.0	15.5	16.3	16.0	16.1

Annex VII: Mean annual and seasonal rainfall of stations in and around Chemoga watershed

Station name	elevation	X	Y	annual precipitation	summer precipitation	Winter precipitation
Debre Markose	2446	37.7392	10.3257	1328.0	962.7	365.2
Dengay Ber	2800	37.55	10.71667	2202.0	1729.4	472.5
Felege Berhan	2710	38.0671	10.7427	1378.3	988.4	389.9
Feres Bet	3000	37.6085	10.8499	1765.2	1278.5	486.6
kuy	1888	37.594	10.3	1344.2	982.4	361.8
Robe Gebeya	2940	37.77	10.55	1404.2	942.3	461.9
Yetmen	2418	38.1466	10.3291	1457.4	1162.8	294.7
Yetnora	2420	38.1083	10.2449	1175.6	854.8	320.8

Annex VIII: Mean annual and seasonal temperature of stations in and around Chemoga watershed.

station name	elevation	X	Y	annual Temp	summer Temp	winter Temp
Debre Markos	2446	37.7392	10.3257	16.60	15.10	17.30
dengay ber	2800	37.61	10.74	15.40	14.00	16.10
Kuy	1888	37.594	10.3	17.70	16.90	18.10
Rob Gebeya	2940	37.77	10.55	16.18	14.68	16.94
Yetnora	2420	38.1083	10.2449	16.50	15.60	17.00

Annex IX: Mean annual and seasonal PET of stations in and around Chemoga watershed.

station name	elevation	X	Y	annual PET	summer PET	winter PET
Debre Markos	2446	37.7392	10.3257	1291.11	345.73	954.38
Rob Gebeya	2940	37.77	10.55	1300.67	343.22	957.03
Kuy	1888	37.594	10.3	1300.67	353.12	947.55
Yetnora	2420	38.1083	10.2449	1349.22	384.73	964.49
dengay ber	2800	37.61	10.74	1295.14	352.5	942.64

Annex X: Accuracy assessment.

	Agriculture	Bare land	Forest	Grassland	settlement	Shrubland	watebody	Total	U. A
Agriculture	61	0	1	1	1	2	0	66	92.42
Bare land	0	28	0	1	2	1	0	32	87.50
Forest	0	0	23	1	1	0	0	25	92.00
Grass land	4	2	1	26	1	3	1	38	68.42
settlement	1	2	0	0	17	1	0	21	80.95
Shrub land	1	1	3	2	0	35	0	42	83.33
water body	0	0	0	1	0	0	19	20	95
Total	67	33	28	32	22	42	20	244	109
P. A	91.04	84.85	82.14	81.25	77.27	83.33	95		
P. A= producer accuracy; U.A =user accuracy. Over all accuracy =85.66; kappa (K_{hat})=0.83.									

DECLARATION

I the undersigned declare that this thesis is my original work and has not been presented for a Degree in any other university and that all sources of materials used for the thesis have been duly acknowledged.

Belete Baychiken Kassaneh

Signature _____ Date _____

School of Earth Science

May, 2018

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

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